ANDRA
Agence nationale pour la gestion des déchets radioactifs

Issuing organisation
Andra
Type of issuing organisation
Project Owner
Project Owner WBS code
CMRD
Order number
NA
Mission
NA

Distribution
Communicable

Safety Options Report – Post-Closure Part

(DOS-AF)

CG-TE-D-NTE-AMOA-SR2-0000-15-0062

THIS DOCUMENT IS THE PROPERTY OF ANDRA. NO UNAUTHORISED REPRODUCTION OR DISCLOSURE.
THE FRENCH VERSION IS THE REFERENCE VERSION FOR THE TECHNICAL CONTENTS OF THIS DOCUMENT

Rev.	Date	Written by:	Checkers		Approved by
			Technical	Quality	
		Group	S. VOINIS	N. PEREIRA	S. THABET
A	11/07/2016	(see list on the following page)	F. PLAS + group (see list on the following page)		F. LAUNEAU

AUTHENTIFICATION GED {389B0250-0CE6-4B81-B26F-5F3D6943AF87}

Authors

Deleted

Contents

Tables of illustrations 10

VOLUME I - Background - Objectives - Safety Strategy 22

1. Background and Purpose 24

1.1 The need 25

1.2 The Cigeo project – a step-by-step process 26

1.2.1 Safety iterations from the start of the project 26

1.2.2 Chronological milestones 29

1.3 Scope and purpose of the document 30

1.3.1 Scope 30

1.3.2 Purpose 31

2. General presentation of Cigeo 34

2.1 The disposal facility post-closure 35

2.2 Cigeo siting 37

2.3 Phasing of Cigeo after its final closure and time scales 39

3. Regulatory framework and standards 42

3.1 Regulations applicable to the Cigeo project 43

3.2 Guides and technical standards 43

3.2.1 Guides and basic safety rules: the specific case of the 2008 ASN guide 43

3.2.2 Andra's additional reference standards 43

3.3 International standards and practices 44

3.4 Consideration of national and international references 45

4. Safety strategy 46

4.1 Fundamental principles 47

4.2 Post-closure safety functions, general design principles and applicable requirements 48

4.2.1 Main functions 48

4.2.2 Practical expression of the "limiting transfer to the biosphere" function 49

4.2.3 General design principles 52

4.2.4 Requirements applicable to the design of Cigeo 54

4.3 Protection objectives 54

4.3.1 Radiological protection objective 54

4.3.2 Objective of protection from toxic elements 55

4.4 The global approach 55

4.4.1 A coordinated approach between safety in operation and post-closure safety 55

4.4.2 Application of the defence-in-depth principle to post-closure safety 57

5. Safety assessment 58

5.1 Objectives 59

5.2 Consistency with international practices 59

5.3 Assessment steps 60

5.4 Qualitative analysis of the uncertainties and risks 60

5.5 Scenarios 62
5.5.1 Normal evolution scenario 62
5.5.2 Altered evolution and "What-if" scenarios 62
5.5.3 Inadvertent human intrusion scenarios 63
5.6 Quantitative assessment of the scenarios 64
5.6.1 General system for using the calculations 64
5.6.2 Disposal system operational indicators 67
5.6.3 Indicator used to assess the impact on humans 68

6. Safety management 70

6.1 Safety management in the integrated management system 71
6.2 Requirement management 71
6.3 Compliance with applicable requirements 72
6.4 Managing design and construction 72
6.4.1 Managing contractors and interaction with scientific partners 72
6.4.2 Management of studies linked to the innovative nature of Cigeo - TRL scale 72
6.5 Tool management 73
6.5.1 An array of tools capable of conducting multiphysics numerical simulations on large temporal and spatial scales 73
6.5.2 A simplified simulation platform within an array of tools 73
6.5.3 An integrated simulation chain 74
6.6 Input data control 75
6.6.1 Data processing chain: from raw to integrated data 75
6.6.2 Processes for selecting data and scientific knowledge for the safety assessments 76
6.7 Internal and external review process 77

VOLUME II – Description of the Disposal System 78

1. Location Site Characteristics 80

1.1 A simple geological context well known through substantial geological survey work 81
1.1.1 Consecutive campaigns of geological investigations and scientific work to characterise the site 81
1.1.2 Geological history of the Meuse/Haute-Marne sector 81
1.2 Justification of the favourable properties of the Callovo-Oxfordian , and of the location of Cigeo 85
1.2.1 A very thick formation located at a considerable depth 85
1.2.2 A formation with considerable lateral continuity 87
1.2.3 A formation without structural heterogeneities 89
1.2.4 Properties favouring immobilisation and retention of radionuclides 89
1.2.5 Hydraulic characteristics that limit water circulation 90
1.2.6 Diffusion properties that limit radionuclide migration 92
1.2.7 Specific mechanical properties according to lithostratigraphic unit: absence of marked damage and/or hydraulic self-sealing 94
1.3 Well-defined representation of groundwater flows in the surrounding formations of the Callovo-Oxfordian 96
1.3.1 The superficial aquifer system of the Barrois limestone 97
1.3.2 Oxfordian limestone 98
1.3.3 The Dogger formation 99
1.4 Limited and slow internal geodynamics 100

1.5 A stable formation in an environment that shows little change over the next million years ***101***
1.5.1 A geodynamical evolution globally constrained over the next million years 102
1.5.2 Below the ZIRA, the Callovo-Oxfordian unaffected by the changes occurring at the surface over the next million years 103
1.5.3 Water flows in the aquifers above and below the Callovo-Oxfordian not significantly modified over the next million years 105
1.6 No sterilisation of natural resources ***107***
1.6.1 Mineral and hydrocarbon resources 107
1.6.2 Geothermal resources 107
1.6.3 Water resources 107
1.7 Other characteristics of the site involved in the safety assessment ***108***
1.7.1 Formations surrounding the Callovo-Oxfordian 108
1.7.2 Quantification of the seismic hazard 111
1.7.3 Biosphere change 112

2. HLW and ILW-LL Waste Packages in the Repository 114

2.1 Source and nature of waste families ***115***
2.1.1 Source 115
2.1.2 Waste inventory assumptions 116
2.1.3 ILW-LL and HLW waste package families 116
2.2 Radiological inventory used for post-closure quantitative safety assessment ***117***
2.2.1 Inventory construction and uncertainty processing procedure 118
2.2.2 Radiological inventory of waste packages 120
2.2.3 Inventory of toxic chemicals 125
2.3 Characteristics of the primary waste packages involved in the Cigeo safety functions ***125***
2.3.1 Primary packages of HLW waste 125
2.3.2 ILW-LL waste primary packages 126
2.3.3 Release models used for quantitative post-closure safety assessment 126
2.4 HLW disposal containers ***133***
2.4.1 HLW disposal container contributions to the safety functions 133
2.4.2 Design options selected for the HLW disposal container 134
2.4.3 Requirements with regard to the stress corrosion risk 136
2.4.4 Requirements with respect to radiolytic corrosion 136
2.4.5 Requirements with respect to other corrosion processes 137
2.4.6 Mechanical behaviour and assessment of container durability 137
2.5 ILW-LL disposal containers ***138***
2.5.1 ILW-LL disposal container design options 138
2.5.2 ILW-LL disposal container contributions to the post-closure safety functions 138

3. The Cigeo Repository After Closure 140

3.1 Overall architecture ***141***
3.1.1 Design options for function “oppose water circulation” 142
3.1.2 Design options for function “delay and attenuate migration” 143
3.1.3 Management of disturbances 146
3.2 HLW waste disposal sections and cells ***148***
3.2.1 Design options: contribution to post-closure safety functions 149
3.2.2 Feedback from operating experience 154

3.2.3 Temperature impact on delay and attenuation of radionuclide migration in the Callovo-Oxfordian 155
3.2.4 Specific requirements applicable to the sleeve 156
3.2.5 Specific requirements and performance parameters for the sleeve outer surface backfill material 157
3.2.6 Management of iron/clay rock interactions 158
3.3 ILW-LL waste package disposal section and cells 159
3.3.1 Design options 159
3.3.2 Contribution to post-closure safety functions 161
3.3.3 Feedback from operating experience 167
3.3.4 Management of physicochemical interactions 168
3.4 Closure structures 171
3.4.1 Safety functions and seal design options 171
3.4.2 Feedback from experience with seal performance 178
3.4.3 Clay plugs for closure of the HLW cell heads 191
3.4.4 Backfill 192

VOLUME III – Safety assessment 194

1. Management of Risks and Uncertainties 196

1.1 Introduction 197
1.2 Identification and management of uncertainties based on input data: emplaced waste packages and the geological medium 198
1.2.1 Radiological inventory and its distribution in the architecture on completion 198
1.2.2 Radionuclide and toxic element release models 202
1.2.3 Callovo-Oxfordian 202
1.2.4 Surrounding rock formations around the Callovo-Oxfordian formation 203
1.2.5 Surface environment: the biosphere 204
1.3 Intrinsic characteristics of structural components of the repository 208
1.3.1 Characteristics of clay-based structures 208
1.3.2 Intrinsic characteristics of concrete-based structures 209
1.3.3 Characteristics of backfill materials 211
1.4 Phenomena governing internal changes in the repository 212
1.4.1 Mechanical disturbance to the clay rock around the repository structures 212
1.4.2 Thermal transient 217
1.4.3 Hydraulic-gas transient 218
1.4.4 Chemical disturbances 219
1.5 Technological uncertainties 227
1.5.1 Uncertainties concerning technologies used in the HLW cells 227
1.5.2 Uncertainties concerning technologies used in the drifts 228
1.6 Risks and uncertainties relating to future events of external origin 229
1.6.1 Climate change 229
1.6.2 Geodynamic evolution 229
1.6.3 Post-closure criticality risk in the repository 230
1.7 List of scenarios adopted 230

2. Normal Evolution Scenario 234

2.1 Description and conceptualisation of the normal evolution scenario 235
2.1.1 Objectives and adopted calculation cases 235
2.1.2 Adopted repository architecture 236
2.1.3 Representation of the repository in the Callovo-Oxfordian formation 236
2.1.4 Radiological inventory 237

2.1.5 Release of radionuclides and toxic elements 238
2.1.6 Callovo-Oxfordian formation 239
2.1.7 Mechanical damage to the clay rock at repository closure 241
2.1.8 Thermal transient 244
2.1.9 Chemical disturbances 245
2.1.10 ILW-LL disposal section 250
2.1.11 The HLW disposal section 253
2.1.12 Drift closure systems 254
2.1.13 Surface-bottom connection closure structures 256
2.1.14 Backfilling the surface-bottom connection structures 258
2.1.15 Summary of hydraulic and transfer parameters for solutes 260
2.1.16 Surrounding rock formations 260
2.1.17 The biosphere 263

2.2 Analysis of the NES 265

2.2.1 Definition of transfer pathways 265
2.2.2 Adopted indicators 267

2.3 NES results 267

2.3.1 NES results regarding the "resist the circulation of water" function 267
2.3.2 NES results regarding the "limit the release of radionuclides and toxic chemicals and immobilise them in the repository" function 268
2.3.3 NES results regarding the "delay and attenuate radionuclide migration" function 271

2.4 Lessons from the NES 299

2.4.1 Analysis of NES structuring choices 299
2.4.2 Analysis of post-closure safety functions 299
2.4.3 Analysis of radiological impacts 302

3. Altered Evolution Scenarios (AES) 304

3.1 Altered evolution scenarios for seal malfunctions 305

3.1.1 Scenarios adopted 305
3.1.2 Description of the "Malfunction of seals via the interface" AESs 306
3.1.3 Analysis of the "Malfunction of seals via the interface" AESs 311
3.1.4 Results for seal malfunction AESs 311
3.1.5 Findings from the closure structure malfunction AESs 323

3.2 Altered evolution scenarios for HLW disposal containers 325

3.2.1 Adopted scenarios 325
3.2.2 Description of the HLW disposal container failure scenario 325
3.2.3 Analysis of the "HLW disposal container failure" AES 326
3.2.4 Results of the HLW0 disposal container failure AES 327
3.2.5 Findings of the "HLW0 section disposal container failure" AES 330

4. Inadvertent Human Intrusion Scenarios 332

4.1 Identifying inadvertent human intrusion scenarios 333

4.1.1 Methodology 333
4.1.2 Review of "borehole situations" 333
4.1.3 Selection of scenarios adopted 337

4.2 The "exploratory borehole in the Dogger" AES 340

4.2.1 Scenario analysis 340
4.2.2 Results 343
4.2.3 Lessons 346

4.3 The core sampling scenario 346

4.3.1 Scenario analysis 346

4.3.2 Results 349
4.3.3 Lessons 351
4.4 The What-if scenario for human intrusion 351
4.4.1 Scenario analysis 351
4.4.2 Results 353
4.4.3 Lessons 357

5. What-if scenarios 358

5.1 What-if scenarios for malfunction of closure structures 359
5.1.1 Adopted scenarios 359
5.1.2 Description and conceptualisation of closing systems malfunction What-if scenarios 360
5.1.3 Analysis of What-if scenarios for seals malfunction 363
5.1.4 Results for seal malfunction What-if scenarios 363
5.1.5 Lessons from the What-if scenarios for malfunction of closing systems 375
5.2 What-if scenarios for disposal container failure 377
5.2.1 Reminder of adopted scenarios 377
5.2.2 Description and conceptualisation of the What-if scenario for failure of all HLW disposal containers (HLW0, HLW1/HLW2) 377
5.2.3 Analysis of the What-if scenario for failure of HLW disposal containers 377
5.2.4 Results of the What-if scenario for malfunction of HLW disposal containers 378
5.2.5 Lessons 383

VOLUME IV – Teachings – Important components – Activities implemented right from the design phase 384

1. Teachings at the basic engineering design stage and forthcoming safety iterations 386

1.1 Components important to the post-closure robustness of the repository as of the basic engineering design stage 387
1.1.1 The Callovo-Oxfordian formation — the pillar of the repository's post-closure safety 388
1.1.2 The architectural measures and engineered components that play an additional role 389
1.1.3 Engineered components that play a more limited role in the operations of the repository 391
1.2 The robustness of the repository following its closure is an important element of the adaptability of the Cigeo project 392
1.3 The challenges of the forthcoming post-closure safety iteration during the detailed engineering design submitted with the construction licence application 392
1.4 Gradual integration of design changes and avenues of optimisation into the development of the Cigeo project 393

2. Important activities for the design and closure of the repository 396

2.1 Inspection and monitoring activities during construction and up to the start of the industrial pilot phase 397
2.2 Activities during the industrial pilot phase and then during routine operation 398
2.2.1 General process 398
2.2.2 Closure structure demonstrators 399

2.2.3 Reference disposal cells 400
2.2.4 Inspection and monitoring of the architecture 401
2.2.5 Inspection and monitoring of packages 401
2.2.6 Preliminary report 401
2.3 Post-closure inspection and monitoring 403
2.4 Observation — a supplemental means of monitoring 403

Appendices 404

Appendices to Volume I 406

Appendices to Volume II 418

Appendices to Volume III 447

Appendices to Volume IV 460

Bibliographic references 464

TABLES OF ILLUSTRATIONS

Figures

Figure 1.2-1:	Illustration of the iterative process	26
Figure 1.2-2:	Development of the Cigeo project: a step-by-step iterative process as regards safety since 1991	28
Figure 2.1-1:	Images of waste packages manufactured by AREVA; vitrified HLW packages (left); ILW-LL maintenance waste packages (right)	35
Figure 2.1-2:	Illustration of the Cigeo underground facility after its final closure (subject to a law giving permission being passed)	36
Figure 2.2-1:	Cigeo location zones: "shaft" zone and "ramp" zone and ZIRA	39
Figure 2.3-1:	Diagram showing the main phases in the life of Cigeo	39
Figure 4.2-1:	Tree structure of the functions used to limit the transfer of the radioactive substances (and toxic elements) via aqueous pathways	52
Figure 4.4-1:	Diagram illustrating the coordinated approach between safety in operation and post-closure	56
Figure 5.5-1:	Schematic illustration of the different stages of a qualitative safety analysis and of the link with the definition of the safety scenarios	63
Figure 5.6-1:	Sequencing of hydraulic and solute transfer models	65
Figure 5.6-2:	Principle of nested compartment calculation architecture	66
Figure 5.6-3:	Diagram showing the use of indicators other than dose, based on the half-life of the radionuclide and its behaviour in solution.	68
Figure 5.6-4:	Diagram showing the different stages in selecting and describing a biosphere	69
Figure 6.5-1:	Architecture of the Cassandra platform	74
Figure 6.5-2:	Calculation chain integrating the various simulation tools used for post-closure safety assessments	75
Figure 6.6-1:	Diagram of the scientific data processing chain from acquisition to use	76
Figure 1.1-1:	3D geological block diagram of the Meuse/Haute-Marne site	82
Figure 1.1-2:	Topographical map of the area around the ZIRA	84
Figure 1.2-1:	Thickness (m) of the Callovo-Oxfordian in the ZIRA (between surfaces SNC and LS0)	86
Figure 1.2-2:	Depth (m) of the geometrical mid-height of the Callovo-Oxfordian in the ZIRA (from the topographical surface)	86
Figure 1.2-3:	Lateral homogeneity of the vertical organisation of the Callovo-Oxfordian in the sector under study (gamma ray logging recording)	87
Figure 1.2-4:	Main geological units of the Callovo-Oxfordian: argillaceous unit (UA), transition unit (UT) and silty-carbonated unit (USC). The geological boundaries of the Callovo-Oxfordian are marked by the surfaces LS0 and SNC.	88
Figure 1.2-5:	Hydraulic head vertical iso-gradient lines at the scale of the Callovo-Oxfordian	91
Figure 1.2-6:	Map of the ^{238}U transfer times for a repository located at mid-height in the Callovo-Oxfordian	93
Figure 1.2-7:	Map of the ^{129}I transfer times for a repository located at mid-height in the Callovo-Oxfordian	94
Figure 1.2-8:	Fracturing generated around structures according to their orientation in relation to the major horizontal stress (a) Drift oriented along the minor horizontal stress (b) Drift oriented along the major horizontal stress	95
Figure 1.2-9:	Clogging illustration of fractures in the UA unit, from an SEM photograph (millimetric scale)	96
Figure 1.3-1:	Conceptual view of water flows in the geological formations of the Meuse/Haute-Marne sector	97

Figure 1.3-2: Vertical structure of the Oxfordian limestone aquifer system. The colours correspond to the different porous levels (violet, yellow, brown) and to the marl formations (orange, red). 98
Figure 1.3-3: Simulated piezometries of the two Oxfordian limestone aquifers (upper Oxfordian aquifer on the left) - Lateral piezometries of the middle and upper Oxfordian limestone 99
Figure 1.3-4: Simulated piezometries in the Dogger 100
Figure 1.4-1: Seismic zoning in France (left) and map of earthquakes recorded between 1962 and 2009 (right) 101
Figure 1.5-1: Change in the position of the zero head iso-gradient through the Callovo-Oxfordian formation over the next million years according to the geodynamic change 104
Figure 1.5-2: Modelling of the paths of particles emitted in the Oxfordian limestone below the ZIRA at t = 0 kyr (yellow) and at t = 400 kyr (green), i.e. taking account of the geodynamic change over the next million years 105
Figure 1.5-3: Modelling of the paths of particles emitted in the Dogger below the ZIRA at t = 0 kyr (yellow) and at t = 400 kyr (green), i.e. taking account of the geodynamic change over the next million years 106
Figure 1.7-1: Thickness (m) of the Barrois limestones and the more recent formations (in the ZIRA, the thickness corresponds to the thickness of the Barrois limestones) 109
Figure 1.7-2: MCE spectrum – acceleration (horizontal component) 112
Figure 2.2-1: Flow chart of construction of the radiological inventory used for Cigeo post-closure safety assessment 118
Figure 2.2-2: Change in the activity of the 10 radionuclides with the highest maximum activities over 1 million years after closure of Cigeo 121
Figure 2.2-3: Change in the activity of the 10 radionuclides with the highest maximum activities over 1 Myr for the HLW0 packages 122
Figure 2.2-4: Reference radiological inventory of highly-exothermic HLW waste. Change in the activity of the 10 radionuclides with the highest maximum activities over 1 million years 124
Figure 2.3-1: Logic diagram illustrating the selection strategy for radionuclide release models used in safety assessment 127
Figure 2.3-2: Logic diagram illustrating the selection method for the parameters of the selected release model 128
Figure 2.4-1: Illustration of an AVM two-package vitrified waste disposal container 135
Figure 2.4-2: Illustration of an R7-T7 vitrified waste disposal container 136
Figure 2.4-3: Illustration of the risk of crevice corrosion in the case of contact between the container and the sleeve (left) and prevention of the risk by intercalation of inert runners (right) 137
Figure 3.1-1: Basic engineering design stage illustration of the underground architecture on final closure of Cigeo. 142
Figure 3.1-2: Position of the underground facility on termination and hydraulic head gradients observed in the ZIRA 143
Figure 3.2-1: Schematic diagram of an HLW cell (case of HLW1/HLW2 waste) 149
Figure 3.2-2: HLW spacer for insertion in HLW1/HLW2 cell 152
Figure 3.2-3: Temperature change over time at various points in and around the warmest HLW2 cell (temperature change in the clay rock at the cell wall is given by the yellow curve) 153
Figure 3.2-4: HLW cell - Demonstrators at the Underground Research Laboratory 155
Figure 3.2-5: Schematic diagram of the impact of material constituents on the final pH. The height of a rectangle gives an order of magnitude of the proportion of the component in the material 157
Figure 3.3-1: A post-closure ILW-LL cell 159
Figure 3.3-2: Arrangement of waste packages in an ILW-LL cell 160
Figure 3.3-3: ILW-LL section on completion 161

Figure 3.3-4: Temperature change in a cell of non-exothermic waste (black) as a function of the location or grouping of cells of slightly-exothermic ILW-LL waste in its vicinity 163
Figure 3.3-5: Clay rock thicknesses for a repository with its median plane located on the surface of the geometrical mid-height of the Callovo-Oxfordian 164
Figure 3.3-6: Effect of underground structure orientation on the EDZ in the clay unit of the Callovo-Oxfordian 165
Figure 3.3-7: Estimated horizontal and vertical extents of the deconfined rock zone (ZF) and the connected fracture rock zone (ZFC) from the excavation wall as a function of the void fraction 165
Figure 3.3-8: Excavation of the tunnelling machine assembly chamber for test GVA2 at the Underground Research Laboratory (excavated diameter 9.1 m) 168
Figure 3.3-9: Time-dependence of ionic strength profiles according to distance from an ILW-LL saline waste package disposal cell 169
Figure 3.3-10: Osmotic effect related to the presence of salts from ILW-LL1 category waste on the hygrometry of a cell during the first thousand years after disposal 170
Figure 3.4-1: Schematic diagrams of inclined, vertical and horizontal seals 172
Figure 3.4-2: The "components" contributing to the hydraulic performance of the seals 178
Figure 3.4-3: FSS test design principle 179
Figure 3.4-4: Sealing test 179
Figure 3.4-5: Influence of clay core permeability on the overall permeability of the seals 180
Figure 3.4-6: Effective compressive stress in the ZFC over time for different swelling pressures of the clay core 182
Figure 3.4-7: Equivalent permeability of the component between the core and the clay rock as a function of maintaining/removing the liner sections 183
Figure 3.4-8: Change in hydraulic conductivity measured in the CDZ experiment from the start of resaturation for the 8 periodically tested intervals 187
Figure 3.4-9: Schematic diagrams of containment wall concepts currently being studied: (a) with one or more recesses; (b) with one recess anchored in the clay rock 188
Figure 3.4-10: Schematic diagrams of the technique for installing the containment wall using self-compacting concrete 189
Figure 3.4-11: Schematic diagrams of the technique for installing the containment wall using the shotcreting method 189
Figure 1.2-1: Schematic diagram of ILW-LL waste package distribution “independent of provisional shipment schedules”. 199
Figure 1.2-2: Radiological inventory distribution adopted for the ILW-LL disposal section for quantitative assessments of the normal evolution and altered evolution scenarios 200
Figure 1.2-3: Distribution of waste package families adopted within the HLW1-HLW2 section and geometric data selected as input assumptions for calculations at this stage. 201
Figure 1.2-4: Distribution of waste package families within disposal section HLW0 section and assumed geometric data adopted as assumptions for calculations at this stage. 202
Figure 2.1-1: Schematic diagram of the position of ILW-LL and HLW disposal cells in the host formation, NES reference situation. Real thickness and depth of the Callovo-Oxfordian are taken into account 236
Figure 2.1-2: Schematic diagram of the position of ILW-LL and HLW disposal cells in the Callovo-Oxfordian in the bounding situation (minimum undisturbed thickness defined by the requirements (50 metres) above the cells) 237
Figure 2.1-3: Conceptual diagram of the connected and discrete fracture zones and the deconfined zone around the ILW-LL 242
Figure 2.1-4: Schematic diagram of the zone affected by the thermal transient around an HLW cell 244

Figure 2.1-5: Schematic diagram of the influence of alkaline disturbance at the clay rock/conventional concrete interface on transport and retention characteristics (example from around the ILW-LL cells) 246
Figure 2.1-6: Schematic diagram showing how a plume of organic complexing substances is taken into account with respect to the transport and retention characteristics around an ILW-LL cell (reference situation example) 247
Figure 2.1-7: Schematic diagram showing how saline perturbation is taken into account with respect to the transport and retention characteristics around an ILW-LL cell (reference situation) 248
Figure 2.1-8: Conceptualisation of chemical disturbance plumes around the usable part of ILW-LL cells, depending on the type of waste (organic or saline) 252
Figure 2.1-9: Schematic diagram of the HLW disposal cells for HLW waste packages with transport and retention characteristics mobilised 253
Figure 2.1-10: Schematic diagram of the representation choice for transport and retention characteristics in drift seal components 254
Figure 2.1-11: Schematic diagram of the components of a backfilled drift in the reference and bounding situations 256
Figure 2.1-12: Schematic diagram of the representation choice for shaft seals and transport and retention characteristics (left: reference situation, right: bounding situation) 257
Figure 2.1-13: Schematic diagram of the representation choices for ramp seals and transport and retention characteristics (top: reference situation, below: bounding situation) 258
Figure 2.1-14: Schematic diagram of surface-bottom connection structures and drifts: backfill, liner/roof support, remineralised ZFC, mechanically damaged clay rock (ZFC and ZFD in the bounding situation). Taking into account the specific properties of USC/UT and UA units. 259
Figure 2.1-15: Schematic diagram of transfer pathways in the Callovo-Oxfordian and upper and lower surrounding rock formations 262
Figure 2.1-16: Conceptual diagram of radionuclide transfer pathways from potentially contaminated outlet water: wells in the Barrois aquifer to an individual representative of a multi-activity group with irrigation of cereal crops 264
Figure 2.1-17: Conceptual diagram of radionuclide transfer pathways from potentially contaminated outlet water: well in the Dogger aquifer to an individual representative of a multi-activity group with no irrigation of cereal crops 265
Figure 2.2-1: Schematic diagram of transfer pathways from waste packages to humans 266
Figure 2.3-1: NES - reference situation: iodine-129, chlorine-36 and selenium-79 source terms in the ILW-LL disposal section 269
Figure 2.3-2: Normal evolution scenario – Reference situation - Iodine-129, chlorine-36 and selenium-79 source terms in the HLW disposal section 269
Figure 2.3-3: Normal evolution scenario – Bounding situation - Iodine-129, chlorine-36 and selenium-79 source terms in the HLW disposal section 270
Figure 2.3-4: Normal evolution scenario – Bounding situation - Iodine-129, chlorine-36 and selenium-79 source terms in the HLW disposal section 271
Figure 2.3-5: Normal evolution scenario – Reference situation – Time-dependent evolution of molar flow rates for iodine-129 (top) and chlorine-36 (bottom) leaving surface-bottom connection structures and the reaching the upper and lower boundaries of the Callovo-Oxfordian. 272
Figure 2.3-6: Normal evolution scenario – Reference situation: Time-dependent evolution of molar flow rates at the top of the Callovo-Oxfordian (the molar flow rates are identical at the bottom of the Callovo-Oxfordian) 274
Figure 2.3-7: Normal evolution scenario - Reference situation – Plumes of uranium-238 and neptunium-237 concentration (in moles per m^3 of water) in the Callovo-Oxfordian clay rock around a HLW cell at 1 million years 275
Figure 2.3-8: Normal evolution scenario – Reference situation, HLW disposal sections (left) and ILW-LL disposal section (right). Time-dependent evolution of

molar flow rates for iodine-129 (above) and chlorine-36 (below) entering access drifts (HLW only), connecting drifts and the main zone, and leaving the surface-bottom connection structures and the top of the Callovo-Oxfordian. 276

Figure 2.3-9: Normal evolution scenario – Reference situation for ILW-LL disposal section, ILW-LL disposal cells with seal or with a closure distribution offering lower performance than a seal ("no seal"). Time-dependent evolution of molar flow rates for iodine-129 entering the access drifts (HLW only), the connecting drifts and the main zone, and leaving the surface-bottom connection structures and the Callovo-Oxfordian 278

Figure 2.3-10: Mapping of the isoconcentration of iodine-129 (10^{-11} mol.L^{-1}) in the geological medium at one million years. Blue trajectories: from the bottom of the Callovo-Oxfordian to the diffuse fracture zone; green trajectories: from the repository to the top of the Oxfordian limestone; yellow trajectories: Callovo-Oxfordian (in equilibrium with the Dogger) 279

Figure 2.3-11: Normal evolution scenario – Reference situation: Time-dependent evolution of molar flow rates for iodine-129, chlorine-36 and selenium-79 at the top and bottom of the Callovo-Oxfordian, in the Oxfordian (9km downstream of the flows), at the top of the Kimmeridgian and in the Dogger (at the diffuse fracture zone) 281

Figure 2.3-12: Normal evolution scenario – Reference situation: Time-dependent evolution of doses at the “pumping in the Barrois” and “pumping in the Dogger (diffuse fracture zone)” outlets for the temperate and hot biospheres 283

Figure 2.3-13: Normal evolution scenario – Bounding situation – repository located 50m from top (left) or bottom (right) of the Callovo-Oxfordian: Time-dependent evolution of iodine-129 (top figures) and chlorine-36 (bottom figures) flow rates leaving the surface-bottom connection structures and the Callovo-Oxfordian 286

Figure 2.3-14: Normal evolution scenario – Bounding situation: Time-dependent evolution of molar flow rates at the top of the Callovo-Oxfordian (“High positioning repository” located 50 metres from the top of the Callovo-Oxfordian) 289

Figure 2.3-15: Normal evolution scenario – Bounding situation – “High positioning repository” with 50 m of overlying host-rock, HLW (left) and ILW-LL (right) disposal sections: time-dependent evolution of molar flow rates for iodine-129 and chlorine-36 entering the access drifts (HLW only), the connecting drifts and the main zone, and leaving the surface-bottom connection structures and the Callovo-Oxfordian. 290

Figure 2.3-16: Normal evolution scenario – Bounding situation (“high positioning repository"), ILW-LL disposal section, ILW-LL disposal cell with a seal or lower performance closure system: time-dependent evolution of molar flow rates for iodine-129 entering the access drifts (HLW only), the connecting drifts and the main zone, and leaving the surface-bottom connection structures and the Callovo-Oxfordian 292

Figure 2.3-17: Normal evolution scenario – Bounding situation, time-dependent evolution of molar flow rates for iodine-129, chlorine-36 and selenium-79 in the geological medium at the top (left) and bottom (right) of the Callovo-Oxfordian, in the Oxfordian (9km downstream of repository footprint), at the top of the Kimmeridgian and in the Dogger (at the diffuse fracture zone) 294

Figure 2.3-18: Normal evolution scenario – Bounding situation: time-dependent evolution of doses at the “pumping in the Barrois” and “pumping in the Dogger (diffuse fracture zone)” outlets for the temperate and hot biospheres 297

Figure 2.4-1: Normal evolution scenario – Reference (left) and bounding (right) situations - HLW and ILW-LL disposal sections, iodine-129: summary of the distribution of the transfer pathways in the structural components and the

	geological medium from the package to the outlets – assessments normalised with regard to the initial inventory	301
Figure 3.1-1:	Schematic view of shaft seals under the "Malfunction of surface-bottom connection seals via the interface" AES (bounding situation)	307
Figure 3.1-2:	Schematic view of drift seals under the "Malfunction of drift seals via the interface" AES	308
Figure 3.1-3:	Schematic cross section illustrating the various repository components in the "Malfunction of all seals via the interface" AES – design with lower performance ILW-LL closing devices.	309
Figure 3.1-4:	Schematic illustration of transfers under seal malfunction AESs (release and transport pathways via the Callovo-Oxfordian and facilities)	310
Figure 3.1-6:	NES and seal malfunction AESs – reference situation: schematic view of solute transfer processes in the repository and the Callovo-Oxfordian	315
Figure 3.1-7:	"Malfunction of all seals via the interface" AES – Time-dependent evolution of iodine-129 molar flow rates entering air inlet and return drifts, entering the main zone and leaving surface-bottom connection structures and the Callovo-Oxfordian	316
Figure 3.1-8:	NES and seal malfunction AESs – time-dependent evolution of iodine-129 molar flow rates leaving surface-bottom connection structures and the Callovo-Oxfordian	318
Figure 3.1-9:	NES and seal malfunction AESs (reference and bounding situations) – Time-dependent evolution of chlorine-36 molar flow rates leaving surface-bottom connecting structures and the top of the Callovo-Oxfordian	321
Figure 3.1-10:	"Malfunction of all seals via the interface" AES (reference and bounding situations) – Time-dependent evolution of molar flow rates of radionuclides whose total molar flow rate at the top of the Callovo-Oxfordian exceeds 10-10 moles per year	322
Figure 3.1-11:	Time-dependent evolution of doses for the "pumping in the Barrois" outlet for temperate and hot climate biospheres – "Malfunction of all seals via the interface" AES (bounding situation)	323
Figure 3.2-1:	Schematic illustration of the HLW disposal container failure AES.	326
Figure 3.2-2:	NES and "HLW0 disposal containers failure" AES. Assumptions of the NES reference situation (left) and the NES bounding situation (right) – Source terms for iodine-129, chlorine-36 and selenium-79	327
Figure 3.2-3:	HLW0 section disposal container failure AES". Assumptions of the NES reference situation (left) and the NES bounding situation (right) – Time-dependent evolution for iodine-129 molar flow rate entering the drifts, in the main zone, and leaving the surface-bottom connections.	328
Figure 4.1-1:	Schematic diagram of the depths of geological formations on the ZIRA (indicative depths for the bottom of the formations)	334
Figure 4.1-2:	Schematic diagram of the "bounding" borehole situations adopted for the post-closure safety assessment.	339
Figure 4.2-1:	Schematic diagram of the HISBor-2b scenario - "Exploratory borehole in the Dogger abandoned at its planned depth ".	341
Figure 4.2-2:	Location of abandoned boreholes in the ILW-LL and HLW1 sections	342
Figure 4.2-3:	Human intrusion altered evolution scenario – borehole in the ILW-LL disposal section – Doses at the "Dogger" outlet for a temperate biosphere	345
Figure 4.3-1:	Schematic diagram of the SIHFor-1 scenario – "Exploratory borehole leading to core samples containing waste being brought to the surface"	347
Figure 4.3-2:	Schematic diagram of core sampling in a HLW disposal section	347
Figure 4.3-3:	Schematic diagram of core sampling in an ILW-LL disposal section	348
Figure 4.3-4:	Time-dependent evolution over 1 million years for the dose received by a drill operator from external exposure to a core sample taken at 500 years for the top five HLW and ILW-LL package families based on "external exposure risk".	351

Figure 4.4-1: Schematic diagram of the HISBor-3 'What-if' scenario - "Borehole intended for geothermal exploitation of the Trias abandoned at repository depth, linked to a Barrois (Tithonian) exploitation borehole ". 352
Figure 4.4-2: Mapping of hydraulic heads in the ILW-LL disposal section (horizontal cross-section crossing the repository structure) – With and without ILW-LL cell seal type closure structures – With and without intrusive borehole 354
Figure 4.4-3: Human intrusion What-if scenario – borehole in the ILW-LL disposal section (without ILW-LL cell closure structures): time-dependent evolution of doses at the "Barrois" outlet for a temperate biosphere for the 43 radionuclides whose peak dose exceeds 10^{-10} Sv/year. 355
Figure 4.4-4: Mapping of hydraulic heads in the HLW1 and HLW2 disposal sections in the horizontal cross-section crossing the repository structures with and without intrusive borehole 356
Figure 5.1-1: Schematic view of shaft seals for the "Malfunction of surface-bottom connection seals" What-if scenario" (bounding situation) 360
Figure 5.1-2: Schematic view of drift seals under the "Malfunction of drift seals" What-if scenario 361
Figure 5.1-3: NES and What-if scenarios for malfunction of closure systems, for the reference situation (left) and the bounding situation (right) – Hydraulic head field (m) in the ILW-LL zone. 366
Figure 5.1-4: NES and seal malfunction What-if scenarios (reference situation) – schematic view of solute transfer processes within structural components and across the Callovo-Oxfordian 368
Figure 5.1-5: "Malfunction of all seals" What-if scenario – time-dependent evolution of iodine-129 molar flow rates entering drifts and the main zone, and leaving surface-bottom connections and the Callovo-Oxfordian 369
Figure 5.1-6: What-if scenarios for seals malfunction – Time-dependent evolution of iodine-129 molar flow rates leaving surface-bottom connection structures and clay rock at the top of the Callovo-Oxfordian 372
Figure 5.1-7: NES and What-if scenarios for malfunction of seals (reference and bounding situations) – Time-dependent evolution of chlorine-36 molar flow rates leaving surface-bottom connection structures and the top of the Callovo-Oxfordian 373
Figure 5.1-8: "Malfunction of all seals" What-if scenario (reference and bounding situations) – Time-dependent evolution of molar flow rates for radionuclides whose molar flow rate reach 10<35568>-10</35568> moles per year at the top of the Callovo-Oxfordian 374
Figure 5.1-9: "Malfunction of all seals" What-if scenario (bounding situation): time-dependent evolution of the doses at the "pumping in the Barrois" outlet for temperate and hot climate biospheres 375
Figure 5.2-1: Reference and bounding situations of the NES and What-if scenario for failure of all HLW disposal containers – iodine-129, chlorine-36 and selenium-79 sources terms. 378
Figure 5.2-2: What-if scenario for failure of HLW disposal containers compared with the NES: time-dependent evolution of iodine-129 molar flow rates entering drifts and the main zone, and leaving the surface-bottom connection structures. 379
Figure 5.2-3: What-if scenario, failure of all HLW disposal containers: time-dependent evolution of iodine-129, chlorine-36 and selenium-79 at the top of the Callovo-Oxfordian. 382
Figure 2.2-1: Diagram showing the locations of the demonstrators at the basic engineering design phase (HLW cell and hydraulic cut-off demonstrators not shown). The location of the zone within the underground facility may change with design studies. 400
Figure 2.4-1: "Package/cell"-scale compartment: representation of an ILW-LL half-cell including the disposal packages and primary packages 413

Figure 2.4-2: "Geological medium"-scale compartment representing the multilayer geological medium and the Cigeo geological disposal facility 414
Figure 2.4-3: Evolution of the quantity of glass altered associated with different alteration rates as a function of time 436
Figure 2.4-4: Evolution of glass alteration rate and radionuclide release rate as a function of time for the different glass alteration phases 439
Figure 2.4-5: Release of salts and radionuclides as a result of water entering bituminised waste 442

Tables

Table 2.2-1: Margin factors applied to activities according to knowledge level 119
Table 2.2-2: Illustration of the allocation at this stage of the margin factors applied to the average radiological inventories in proportion to the number of waste packages 120
Table 2.2-3: ILW-LL waste: Total activities of a selection of long-lived radionuclides 121
Table 2.2-4: ILW-LL waste - Change in relative distribution of the radionuclides over time 122
Table 2.2-5: HLW0 waste (slightly to moderately exothermic): total activities of a selection of long-lived radionuclides 123
Table 2.2-6: HLW0 waste (slightly to moderately exothermic) - Change in the relative distribution of the radionuclides over time 123
Table 2.2-7: Highly-exothermic HLW waste HLW1 and HLW2 - Activities on the basis of the reference radiological inventory for a selection of long-lived radionuclides 124
Table 2.2-8: Highly-exothermic HLW waste HLW1 and HLW2 - Change in the relative distribution of the radionuclides over time 125
Table 2.3-1: Selection of vitrified HLW release models 129
Table 2.3-2: Selection of vitrified ILW-LL waste release models 130
Table 2.3-3: Release models selected for post-closure safety assessment by family of saline waste with bitumen matrix 131
Table 2.3-4: Release models selected for post-closure safety assessment by family of saline waste without bitumen matrix 131
Table 2.3-5: Release models selected for post-closure safety assessment by family of compacted metal waste (without cement matrix) 132
Table 2.3-6: Release models selected for post-closure safety assessment by family of metal waste with cement matrix 133
Table 2.3-7: Release models selected for post-closure safety assessment for the other ILW-LL waste families 133
Table 3.1-1: Design requirements and measures related to the general architecture of the underground facility 145
Table 3.2-1: Safety functions, requirements and design options associated with HLW cells 153
Table 3.3-1: Requirements and associated design options 166
Table 3.4-1: Contributions of seal types in the Callovo-Oxfordian to the function “Oppose water circulation” 173
Table 3.4-2: Requirements, specified performance and design options for the vertical and inclined seals 175
Table 3.4-3: Requirements, specified performance and design options for the horizontal seals 177
Table 1.2-1: Results from the methodology used to define the distribution of ILW-LL waste package types in the disposal section using iodine-29 for the first ten ILW-LL disposal cells (located in the west cell of the section) 200
Table 1.3-1: Methods for managing uncertainties related to the intrinsic characteristics of IWL-LL cell liners 210
Table 1.4-1: Methods for managing uncertainties related to mechanical processes 216

Table 1.4-2: Methods for managing uncertainties related to thermal transient 218
Table 1.4-3: Methods for managing uncertainties related to hydraulic-gas transient 219
Table 1.4-4: Methods for managing the remaining uncertainties related to oxidising and alkaline disturbance 222
Table 1.4-5: Methods for managing uncertainties related to the corrosion processes affecting HLW disposal containers 223
Table 1.4-6: Methods for managing uncertainties related to chemical disturbance from ILW-LL 226
Table 1.7-1: List of calculation cases associated with the normal evolution scenario 231
Table 1.7-2: List of post-closure altered evolution scenarios (AESs) (excluding inadvertent human intrusion) 232
Table 1.7-3: List of "What-if" scenarios (excluding inadvertent human intrusion) 233
Table 2.1-1: List of radionuclides selected for the quantitative assessment of the normal evolution scenario (including decay chains) 238
Table 2.1-2: Parameters applicable to the undisturbed Callovo-Oxfordian clay rock (SNC: stratigraphic unconformity surface, LS0: stratigraphic sequence boundary 0) 240
Table 2.1-3: Retention and transfer properties for the main radionuclides in undisturbed clay rock 241
Table 2.1-4: Parameters applicable to damaged Callovo-Oxfordian clay rock 243
Table 2.1-5: Corrective factors applied to the transport and retention parameters, according to temperature, in the undisturbed or mechanically damaged Callovo-Oxfordian 244
Table 2.1-6: Corrective factors (F) applied to the retention and transport parameters according to the chemical disturbances in the undisturbed or mechanically damaged Callovo-Oxfordian 249
Table 2.1-7: Transport dimensions and characteristics selected for the concrete liner of ILW-LL cells 251
Table 2.1-8: Retention properties (sorption and solubility) for the main radionuclides in the ILW-LL cell liner concrete 251
Table 2.1-9: Parameters applicable to the swelling clay -based clay core 255
Table 2.1-10: Parameters applicable to backfilled drifts 256
Table 2.1-11: Values of hydraulic and transfer parameters for solutes adopted for iodine-129, chlorine-36 and selenium-79 260
Table 2.1-12: Values of retention parameters adopted for iodine-129, chlorine-36 and selenium-79 260
Table 2.1-13: Parameters applicable to surrounding rock formations 263
Table 2.3-1: Normal evolution scenario – Reference situation – Assessment of molar flow rates cumulative over a million years and peak molar flow rates via transfer pathways through the Callovo-Oxfordian and through the access structures. 273
Table 2.3-2: Normal evolution scenario – Reference situation: assessment of iodine-129 and chlorine-36 molar flow rates (cumulative over a million years, as a percentage of the initial inventory in the HLW disposal sections and ILW-LL disposal section) entering access drifts, connecting drifts and the main zone, and leaving surface- bottom connection structures and the top of the Callovo-Oxfordian 277
Table 2.3-3: Normal evolution scenario – Reference situation, ILW-LL disposal section, ILW-LL disposal cells with seal and without seals: assessment of iodine-129 quantities (cumulative over a million years, normalised by the initial inventory of the total ILW-LL zone) entering connecting drifts and the main zone, and leaving surface- bottom connection structures and the top of the Callovo-Oxfordian 278
Table 2.3-4: Normal evolution scenario – Reference situation – Assessment of molar flow rates for iodine-129, chlorine-36 and selenium-79 from the Callovo-Oxfordian to the outlets, cumulative over a million years. Values normalised with regard to the total initial inventory 282

Table 2.3-5: Normal evolution scenario – Reference situation: peak doses and occurrences of peak doses at the "pumping in the Barrois" and "pumping in the Dogger (diffuse fracture zone)" outlets for temperate and hot biospheres 284
Table 2.3-6: Normal evolution scenario – Bounding situation ("high positioning repository") – Assessment of molar flow rates cumulative over a million years and peak molar flow rates via the Callovo-Oxfordian and structure pathway. 287
Table 2.3-7: Normal evolution scenario – Bounding situation ("low positioning repository") – Assessment of molar flow rates cumulative over a million years and peak molar flow rates via the Callovo-Oxfordian and structure pathway 287
Table 2.3-8: Normal evolution scenario – Bounding situation ("High positioning repository"): cumulative quantities of iodine-129 and chlorine-36 entering the access drifts, connecting drifts and the main zone, and leaving the surface-bottom connection structures and the Callovo-Oxfordian over a million years. Percentage of the initial inventory of HLW and ILW-LL disposal sections. 291
Table 2.3-9: Normal evolution scenario – Bounding situation ("high positioning repository"), ILW-LL disposal section, ILW-LL disposal cell with seals or with lower performance closure system: assessment of iodine-129 quantities (cumulative over a million years, normalised by the initial inventory of the total ILW-LL zone) entering connecting drifts and the main zone, and leaving surface- bottom connection structures and the top of the Callovo-Oxfordian 293
Table 2.3-10: Normal evolution scenario – Bounding situation – "High positioning repository" located 50m from top of the Callovo-Oxfordian: Assessment of iodine-129 and chlorine-36 molar flow rates cumulative over a million years, from the top of the Callovo-Oxfordian to the Barrois outlet. Values normalised with regard to the total initial inventory. 295
Table 2.3-11: Normal evolution scenario – Bounding situation – "Low repository" located 50m from bottom of the Callovo-Oxfordian. Assessment of iodine-129 and chlorine-36 molar flow rates cumulative over a million years, from the bottom of the Callovo-Oxfordian to the Dogger outlet. Values normalised with regard to the total initial inventory. 295
Table 2.3-12: Normal evolution scenario – Bounding situation: peak doses and occurrences of peak doses at the "pumping in the Barrois" and "pumping in the Dogger (diffuse fracture zone)" outlets for temperate and hot biospheres 298
Table 2.4-1: Normal evolution scenario: peak doses and occurrences of peak doses at the "pumping in the Barrois" and "pumping in the Dogger (diffuse fracture zone)" outlets for temperate and hot biospheres 303
Table 3.1-1: Altered evolution scenarios (AES) for seal malfunctions 305
Table 3.1-2: Water permeabilities of mechanically damaged clay rock for seal malfunction via the interface AESs (values degraded under these scenarios are shaded) 310
Table 3.1-3: Water flow rates leaving surface-bottom connections and flow velocities at the outlet of the ILW-LL section for the NES and for seal malfunction scenarios (using reference and bounding situation assumptions) 312
Table 3.1-4: NES reference and bounding situations – Assessment of the total amount of iodine-129 (cumulated over one million years, as a percentage of the total HLW and ILW-LL inventory) entering access and connecting drifts, entering the main zone, and leaving surface-bottom connection structures and the top of the Callovo-Oxfordian 317
Table 3.1-5: "Malfunction of all seals via the interface" AES – Peak iodine-129 molar flow rates leaving the top of the Callovo-Oxfordian and surface-bottom

connection outlets, occurrence dates and ratios between these peak flow rates 319
Table 3.1-6: "Malfunction of all seals" AES (reference and bounding situations). Assessment of the total amount of iodine-129 (cumulated over one million years, as a percentage of the total ILW-LL section inventory) entering connecting drifts, entering the main zone, leaving surface-bottom connection structures and leaving the top of the Callovo-Oxfordian 320
Table 3.1-7: NES and "Malfunction of all seals via the interface" AES: peak doses and occurrence dates for the "pumping in the Barrois" outlet, with temperate and hot climate biospheres (bounding situation) 323
Table 3.2-1: "HLW0 section disposal container failure" AES - reference situation: assessment of the quantity of iodine-129 (as a percentage of the total inventory of HLW) released at 1 million years entering the drifts and the main zone, and leaving surface-bottom connection structures and the Callovo-Oxfordian 329
Table 3.2-2: "HLW0 section disposal container failure" AES - reference situation: assessment of the quantity of chlorine-36 (as a percentage of the total inventory of HLW) released at one million years entering the drifts and the main zone, and leaving surface-bottom connection structures and the Callovo-Oxfordian 329
Table 3.2-3: "HLW0 section disposal container failure" AES - bounding situation: balance of the amount of iodine-129 (as a percentage of the total HLW inventory) released at 1 million years entering the drifts and the main zone, and leaving surface-bottom connection structures and the Callovo-Oxfordian 330
Table 4.1-1: Possible locations of boreholes with respect to the repository and radionuclide plumes 335
Table 4.1-2: Borehole situations based on borehole phases and repository resaturation state. 337
Table 4.3-1: Assessment of the dose received by a drill operator for external exposure to a core sample taken at 500 years, for the top 5 HLW and ILW-LL package families. 349
Table 4.3-2: Assessment of drill operator dose for external exposure to a core sample at 500 years for the top 5 HLW and ILW-LL package families in view of the "external exposure risk" combined indicator. 350
Table 5.1-1: What-if scenarios for malfunction of closure structures 359
Table 5.1-2: What-if scenarios for malfunction of closure structures – Water permeabilities of mechanically damaged clay rock. Values deteriorated under these scenarios are shaded 363
Table 5.1-3: What-if scenarios – Water flow rates leaving the surface-bottom connections and flow velocities leaving the ILW-LL disposal section (using the assumptions of NES reference and bounding situations) 365
Table 5.1-4: NES and What-if scenarios for malfunction of seals – assessment of the total amount of iodine-129 (cumulated over one million years, as a percentage of the total HLW and ILW-LL inventory) entering access and connection drifts, entering the main zone, and leaving surface-bottom connection structures and the top of the Callovo-Oxfordian. 370
Table 5.1-5: What-if scenarios for seals malfunction – Iodine-129 molar flow rates at the top of the Callovo-Oxfordian: Peak molar flow rates via structures and clay rock pathways, occurrence dates and ratio between peak flow rates 372
Table 5.1-6: NES and "Malfunction of all seals" What-if scenario: peak doses at the "pumping in the Barrois" outlet and when they occur, for temperate and hot climate biospheres (bounding situation) 375
Table 5.2-1: What-if scenario for failure of all HLW0 section disposal containers - reference situation: balance of the amount of iodine-129 (as a percentage of the total HLW inventory) at 1 million years entering the drifts and the

main zone, and leaving via surface-bottom connection structures and the Callovo-Oxfordian 380
Table 5.2-2: What-if scenario for failure of all HLW disposal section disposal containers – Compared with the NES reference situation: balance of the amount of chlorine-36 (as a percentage of the total HLW inventory at 1 million years entering the drifts and the main zone, and leaving via surface-bottom connection structures and the Callovo-Oxfordian 380
Table 5.2-3: What-if scenario for failure of all HLW section disposal containers - bounding situation: balance of the amount of iodine-129 (as a percentage of the total HLW inventory) at 1 million years entering the drifts and the main zone, and leaving via surface- bottom connection structures and the Callovo-Oxfordian 381
Table 1.4-1: The main optimisation opportunities and technical variants identified, at the basic engineering design stage, that may impact post-closure safety. 394
Table 2.2-1 Preliminary list of the estimated monitoring requirements for to post-closure safety 402
Table 2.4-1: Regulatory texts 410
Table 2.4-2: International standards 411
Table 2.4-3: International best practices 411
Table 2.4-4: List of ICRP publications 412
Table 2.4-5: Hypothetical reference groups identified for a temperate standard biosphere 447
Table 2.4-6: Hypothetical reference groups identified for a temperate standard biosphere 450
Table 2.4-7: Transfer and retention characteristics of connected fracture zones and discrete fracture zones 453
Tableau 2.4-8: Transfer and retention characteristics retained for fractured clay rock (connected fracture zone) under the influence of alkaline disturbance 454
Table 2.4-9: Chemical retention characteristics in the (undisturbed or damaged) clay rock affected by the plume of complexing organic substances 455
Table 2.4-10: Chemical retention characteristics in the cementitious materials affected by the plume of complexing organic substances 455
Table 2.4-11: Transfer and retention characteristics retained for materials affected by the saline plume 456
Table 2.4-12: Transfer and retention characteristics retained for the clay core 456

VOLUME I - BACKGROUND - OBJECTIVES - SAFETY STRATEGY

1

Background and Purpose

1.1 The need 25
1.2 The Cigeo project – a step-by-step process 26
1.3 Scope and purpose of the document 30

1.1 The need

The purpose of the Cigeo geological disposal facility for HLW and ILW-LL is to allow the safe disposal of radioactive waste in order to eliminate or reduce the burden to be borne by future generations, in accordance with Article L542-1 of the Environment Code.

The type of waste for which Cigeo is being designed is final waste, which is defined under Article L542-1-1 of the French Environment Code as radioactive waste "for which no further treatment is possible under existing technical and economic conditions. Treatment particularly entails extracting any part of the waste that can be recycled or reducing any pollutant or hazardous substances it contains".

The Planning Act 2006-739 of 28 June 2006 on the sustainable management of radioactive materials and waste states that "after storage, final radioactive waste unsuitable for disposal in a surface or shallow facility due to concerns pertaining to nuclear safety shall be disposed of in a deep geological formation."

Some of the radioactive waste to be taken into account in the design of Cigeo has already been produced; the rest is yet to be produced as part of ongoing French nuclear power production, and research and defence activities, including the dismantling of facilities.

Article L542-1-1 of the Environment Code states that *"the disposal of radioactive waste is the operation consisting of placing these substances in a facility specially designed to keep them potentially permanently in accordance with the principles set out in Article L. 542-1. Unlike a storage facility, this implies envisaging the possibility of closing*[1] *the Cigeo facility."*

For the Cigeo facility, protecting people and the environment is primarily based on the performance of safety functions during operation comparable to those performed at all nuclear facilities, and on safety standards, safety requirements and safety options adapted to the specific underground environment of the facility.

Following final closure, Cigeo is designed to isolate the waste from humans and the biosphere and to confine it within a deep geological formation to prevent dissemination of the radionuclides contained in this waste. These functions are performed over very long time scales (up to hundreds of thousands of years), passively, i.e. without the need for maintenance or monitoring, as explained by the safety guide for the final disposal of radioactive waste in a deep geological formation[2], published by the French Nuclear Safety Authority (ASN) in 2008 (1). This relies on the chosen geological medium, and specifically the host rock, and on the design of the disposal facility, and specifically its architecture and its engineered components.

---

[1] During examination of a construction licence application, the safety of the facility is assessed for the various stages of its management, including its final closure. A law must be passed to authorise final closure. (Article L542-10-1 of the French Environment Code).

[2] The safety guide published by ASN stipulates that (Part 4.1, Objectives):
- "Protection of human health and the environment constitutes the fundamental safety objective assigned to the disposal of radioactive waste in a deep geological formation. It must be insured against the risks related to the spread of radioactive substances and toxic elements. "
- "After the closure of the disposal facility, the protection of human health and the environment must not depend on institutional monitoring or control as there is no certainty that this can be maintained for more than a limited period. "
- "Consequently, the geological medium shall be chosen and the disposal facility shall be designed such that its post-closure safety shall be ensured passively to protect humans and the environment from the radioactive substances and toxic elements contained in the radioactive waste, without the need for intervention. "
- "To this end, the repository design opted for must ensure that any radiological impact is kept to the lowest level that can reasonably be achieved, taking account of current scientific knowledge and technology, as well as economic and social factors".

The geological disposal facility project for HLW and ILW-LL complies with Article L542-1 of the French Environment Code, which stipulates that "research into, and implementation of the required means for the safe disposal of radioactive waste must be undertaken (…) with a view to precluding or limiting the burden placed on future generations."

Passive post-closure safety is a specific feature of the Cigeo project that reflects this requirement. The implementation of these passive measures relies heavily on the favourable properties of the Callovo-Oxfordian ("clay rock"), which have been studied for a number of years, particularly by the Meuse/Haute-Marne Centre.

Research undertaken since 1991 on disposal in deep geological formations aims to achieve the objective of "precluding or limiting the burden placed on future generations".

1.2 The Cigeo project – a step-by-step process

1.2.1 Safety iterations from the start of the project

In 1991, the Act (2) on the management of high-level and long-lived radioactive waste gave Andra - the French National Radioactive Waste Management Agency - the task of assessing the feasibility of a waste repository in a deep geological formation, particularly through the construction of underground laboratories (the second line in the Act). The ASN issued a basic safety rule (RFS III.2.f) (3) in 1991 that set out the long-term safety expectations for the repository, the design principles, the criteria used to select suitable geological media and the terms of studies, and defined the fundamental objectives that must guide research on disposal.

Safety iterations were implemented as of this date, based on the acquisition of phenomenological knowledge, the development of methods appropriate to deep geological disposal, and research and development on technological solutions.

This iterative approach is thus based on the close link between design, acquired knowledge and safety assessments, as illustrated in the figure below.

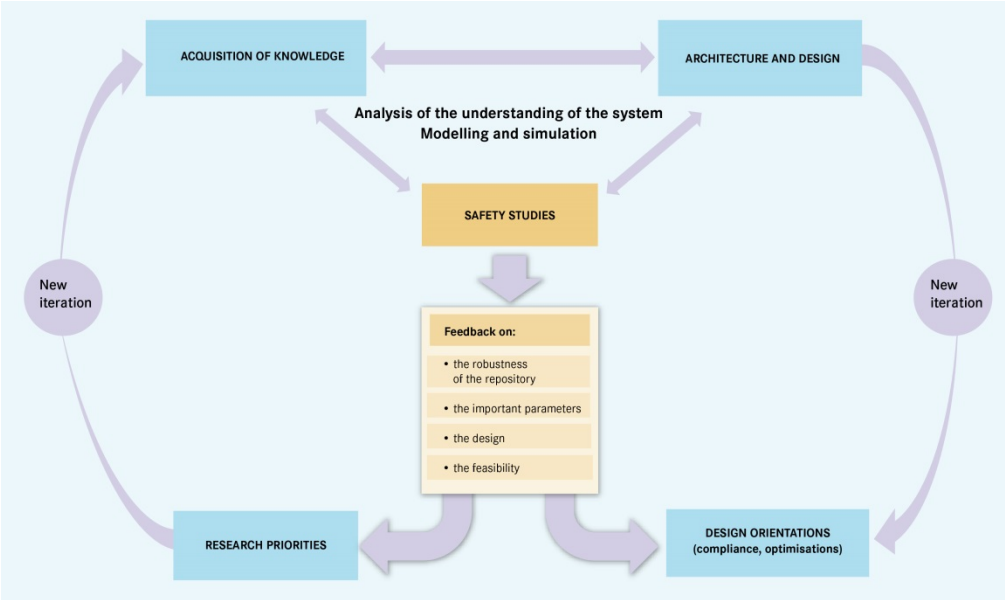


Figure 1.2-1: Illustration of the iterative process

Each iteration involves knowledge acquisition and a study of the architectural designs consistent with this knowledge. With this available knowledge, models, experiments and demonstrators can be used to understand the behaviour of the concepts studied.

Thanks to this approach, much has been learned through successive iterations, gradually helping to guide the choice toward solutions which demonstrate the greatest robustness in view of uncertainties in our knowledge and introduce prevention and protection measures to guard against the risks and uncertainties identified.

Each intermediate safety iteration associated with the various milestones in the development of the Cigeo project (known as HLW, then HLW-ILW-LL before 2010) was examined by the ASN and peer-reviewed. This contributed to the process of gradually identifying the safety issues, and led to the proposal of the safety options to which this document relates, in preparation for the construction licence application for Cigeo. These safety options therefore incorporate all experience feedback.

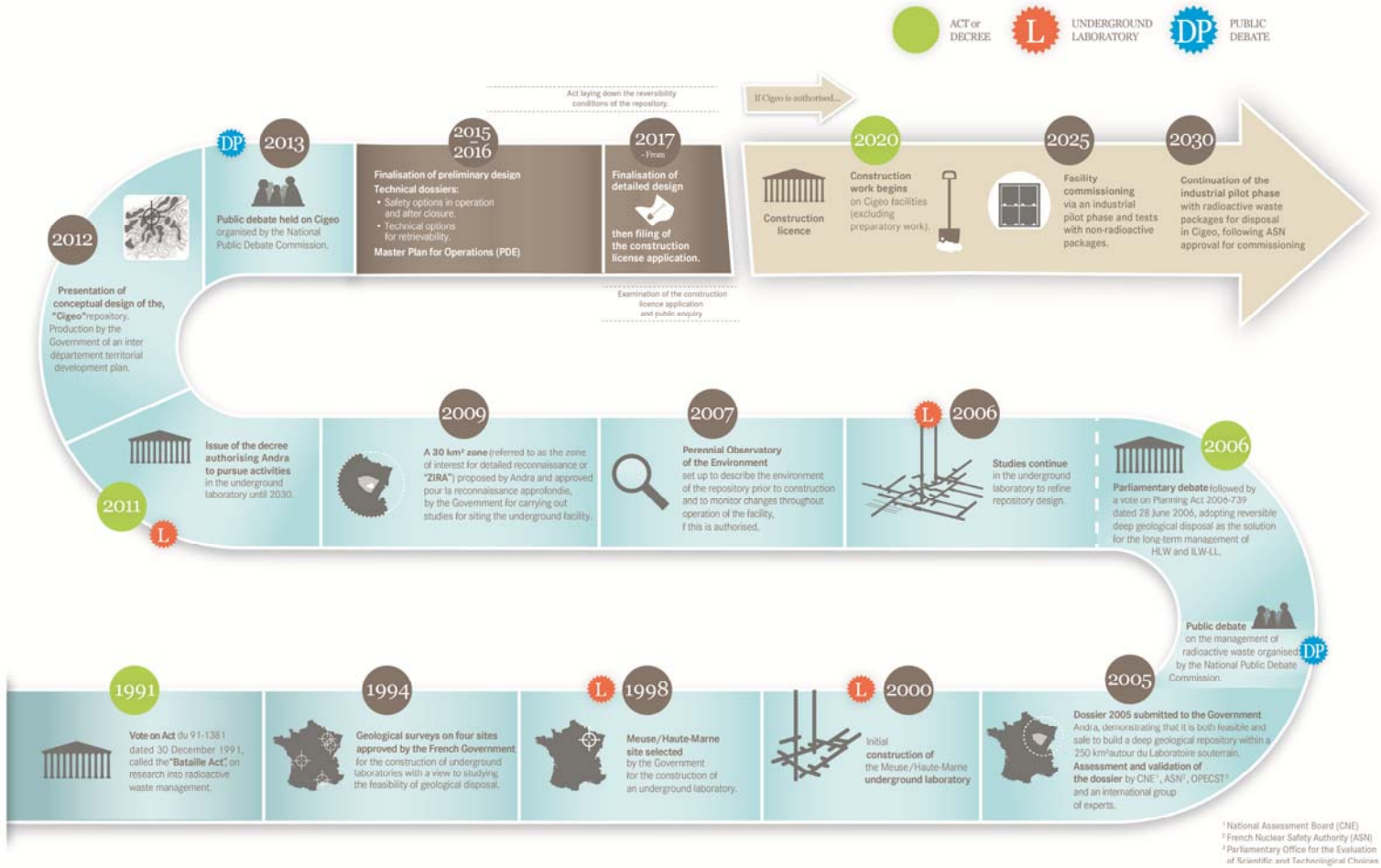


Figure 1.2-2: Development of the Cigeo project: a step-by-step iterative process as regards safety since 1991

1.2.2 Chronological milestones

In 1991 Andra began a major research programme to study disposal in a clay formation, including in particular the study of the Meuse/Haute-Marne site and of an argillaceous rock (clay rock) known as Callovo-Oxfordian, which is approximately 155 million years old and lies at a depth of 400 to 600 m.

In 1998 the government approved the construction of an underground research laboratory, the Meuse/Haute-Marne Centre. Construction of the Centre began in Bure in 2000 in parallel with Andra's ongoing local geological exploration programmes.

In 2005, on completion of the 15 years' research conducted under the Act of 30 December 1991, Andra produced the "Dossier 2005"(4) on the feasibility in principle of a reversible disposal facility for high-level waste and intermediate-level long-lived waste in the Callovo-Oxfordian clay rock formation studied at the Meuse/Haute-Marne Centre. At the time the "Dossier 2005" was produced, the aim of the feasibility study was to demonstrate the existence of technical solutions for the creation of a safe, reversible disposal facility, but not to fix them definitively. The solutions put forward in the "Dossier" did not claim to have been optimised, particularly in terms of safe operation or radiation protection. The position of the disposal facility was fixed within the 250 km² area defined around the Meuse/Haute-Marne Centre, to which the underground research laboratory's results could be transposed. The "Dossier 2005" made a distinction between two phases in the disposal facility's life and conducted two complementary safety analyses: one for its operation, and the other for post-closure evolution associated with the specific nature of the disposal facility. The Dossier then went through a scientific and technical evaluation process, addressed in the general report of the National Assessment Board set up under the Act of 1991, the opinion of the ASN and the report of the international expert review, conducted under the aegis of the OECD Nuclear Energy Agency at the request of Andra's supervisory ministries. This evaluation process confirmed Andra's results on the feasibility and safety of a deep geological disposal facility at the site studied in Meuse/Haute-Marne[3].

Following the evaluation of the "Dossier 2005" and the public debate in early 2006, on 28 June 2006 Planning Act No 2006-739 on the sustainable management of radioactive waste was passed (5). This Act stipulates that after storage, final radioactive waste which, for reasons of nuclear safety and radiation protection, cannot be disposed of in a surface or near-surface facility shall be disposed of in a deep geological formation. The Act of 28 June 2006 gave Andra the task of designing and building the reversible disposal facility for this waste.

In 2008, just as it had in 1991, the ASN updated basic safety rule RFS III.2f (3), replacing it with the safety guide for the final disposal of radioactive waste in a deep geological formation (1). In particular, the updated version takes into consideration the studies carried out by Andra and the review, as well as guidelines that had by then been defined in the Planning Act of 28 June 2006. The main changes incorporated in the project of the BSR update relate to the concept of reversibility, the control of nuclear materials, the objectives of facility monitoring and the definition of repository safety functions.

In 2009, in order to study the location of the underground facility Andra proposed to the French Government a 30 km² underground zone (ZIRA, or zone of interest for detailed reconnaissance) within the 250 km² zone defined in 2005. Taking an iterative approach, in 2009 Andra submitted a report to the ASN in compliance with Decree 2008-357 of 16 April 2008, which implements Article L 542-1-2 of the French Environment Code and sets the requirements for the National Radioactive Materials and Waste Management Plan. In particular this report included a "*Proposed zone of interest for detailed reconnaissance and surface siting scenarios*", and the ASN issued opinions on it, available on its website.

[3] Extract from the ASN's Opinion issued in 2006: "The Dossier 2005 Argile report submitted by Andra to its supervisory ministers in June 2005 has been reviewed by IRSN and is the subject of an opinion delivered by the expert advisory committee on radioactive waste management during its session of 12-13 December 2005. These reviews reveal that key results related to the feasibility and safety of a waste repository have been obtained at the Bure site. It is the ASN's view that deep geological disposal is the only disposal solution possible. "

In 2010 the zone proposed by Andra a few kilometres from the Meuse/Haute-Marne Centre was approved by the Government on the advice of the ASN, the National Review Board (CNE) and following consultation with elected officials and the Local Information and Oversight Committee (CLIS). Andra then carried out further geological reconnaissance, the results of which confirmed that the Callovo-Oxfordian formation in the zone exhibited characteristics favourable to the siting of a deep geological disposal facility. If Cigeo is licensed, the underground facility will be built in this zone.

In 2011 Andra began the industrial design phase of the Cigeo project, which has a number of key stages including a conceptual design phase and a more detailed basic engineering design phase. The results of studies related to the detailed engineering design are used as the basis of the future construction licence application. The orientations chosen as part of the conceptual design for the industrial project were set out in a project owner document used in 2013 to support the public debate on the Cigeo project.

From 15 May to 31 July 2013 and from 1 September to 15 December 2013, a public debate on the Cigeo project was organised by the French National Public Debate Commission (CNDP). As project owner of Cigeo, Andra presented in particular the provisional inventory of waste to be disposed of, proposals for the siting of Cigeo facilities, a set of Andra proposals regarding reversibility, and the results of the conceptual design studies.

Between 2009 and 2014, Andra released interim documents which were evaluated under the aegis of the ASN by its technical adviser, IRSN. For each evaluation, the ASN issued an opinion stating its position and asking questions related to the safety options report and for the construction licence application. All these documents are available on the ASN's website.

On 5 May 2014, following the public debate on the Cigeo project, the conclusions of which have been delivered, Andra's board decided (6) that "Andra will submit a set of documents to the government consisting of a master plan for the operation of Cigeo, the Safety Options Report and the Retrievability Technical Options Report to prepare for the examination of the construction licence application for Cigeo. "

On 19 December 2014, in its letter ref. CODEP-DRC-2014-039834, ASN set out its expectations as regards the safety options for Cigeo. In particular, it says that the Safety Options Report should "*explicitly set out the chosen objectives, concepts and principles for ensuring the safety of the facility in operation [...]. These demands are accompanied [...] by a detailed list of the information needed for the safety options report to be properly examined.*"

1.3 Scope and purpose of the document

1.3.1 Scope

This document corresponds to the basic engineering design phase of the Cigeo geological disposal facility project and forms part of a series of documents responding to the ASN demands expressed in its letter of 19 December 2014, listed below:

- the Safety Options Report for the Operating Phase [DOS-Expl], which presents the objectives, safety functions and associated technical options chosen, the safety options concerning risk management and the initial impact assessments (7);
- the Safety Options Report for the Post-Closure phase [DOS-AF] – which is this document – the purpose and content of which are explained below;
- the first version of the preliminary specifications for the acceptance of primary packages at Cigeo[4];
- the master plan for operation (8), which presents the phasing of the Cigeo project including the industrial pilot phase and the possibilities offered by reversibility in terms of managing the project (8);

[4] The preliminary specifications for the acceptance of primary packages are provided for the construction licence application.

- the Retrievability Technical Options Report (DORec), which presents the main technical options for the retrieval of waste packages (9);
- the study of Cigeo's adaptability to the possible disposal of fuels, presenting the associated technical information (10);
- the study of Cigeo's adaptability to the possible disposal of stockpiled waste, presenting the necessary technical information (11);
- the outline notice limited to the licensee's technical capabilities (12).

1.3.2 Purpose

This document presents the safety options proposed to ensure Cigeo meets its objectives in terms of post-closure safety. Its main purpose is to:

- describe the post-closure objectives, principles and safety functions of Cigeo and to highlight how these are taken into account in the project design and the choice of site, and particularly how the favourable characteristics of the Callovo-Oxfordian clay rock contribute to this;
- show that technical solutions exist for the closure structures;
- show that any uncertainties have been identified and taken into account by the design and the safety analysis;
- present a list of the scenarios chosen for the safety analysis and their classification in response to the safety guide for the geological repository (1) and in compliance with international practices;
- present the radiological impact of the disposal facility on its completion on the environment and humans for the main scenarios considered.

To do this, the document is divided into four volumes:

- Volume 1 establishes the post-closure principles, texts and approach to safety (including the safety functions) applicable to Cigeo;
- Volume 2 sets out the safety functions and the requirements applicable to the design of Cigeo. This volume also includes a description of the packages and more specifically of the package designs chosen for safety and the inventory on completion, of the site, and of the technical options chosen at the engineering design stage in terms of architecture, disposal cells, closure structures and the associated performance;
- Volume 3 discusses the post-closure safety assessment. It lists the chosen scenarios and presents quantitative assessments for the Safety Options Report;
- Volume 4 presents the lessons learned at the engineering design stage and identifies the activities that are important at the engineering design stage to be carried out particularly during construction and operation.

These safety options consider Cigeo to be a "disposal system".

In accordance with the safety guide for the geological repository published by ASN in 2008 (1), this system consists of a set of manufactured and natural components including the Callovo-Oxfordian. It is designed to robustly fulfil the three main post-closure safety functions mentioned in the guide:

- "to prevent water circulation in the waste disposal facility";
- "to contain radioactivity";
- " to isolate the waste from humans and from the biosphere so that the safety of the disposal facility is not significantly affected by climatic erosion or normal human activities".

At the end of the operation of Cigeo and from its final closure, which can only be authorised by law, Cigeo will be an underground facility "at completion" consisting of all the filled disposal cells and the backfilled drifts and including seals as well as backfilled and sealed shafts and ramps. This configuration is the basis for the post-closure safety assessment presented in this document, particularly in Volume III. In its current version, the master plan for the operation of Cigeo (8) envisages that the final closure of Cigeo will take place in around 2150. Until then Cigeo's operation will have developed incrementally and will have been deployed gradually, in particular giving future generations the option of incorporating improvements made possible by scientific and technical progress and experience feedback, whilst respecting the objectives of safety in operation and post-closure.

2

General presentation of Cigeo

2.1 The disposal facility post-closure 35
2.2 Cigeo siting 37
2.3 Phasing of Cigeo after its final closure and time scales 39

2.1 The disposal facility post-closure

In accordance with the safety guide for the final disposal of radioactive waste in a deep geological formation published by ASN in 2008 (1), the repository system post-closure consists of three main categories of components:

- Callovo-Oxfordian, the host formation in which the Cigeo underground facility is situated;
- the waste disposal packages;
- the closed waste disposal facility comprising the waste package disposal cells and the connecting access drifts.

The underground facility has separate areas for disposing of high-level waste (HLW) (and possibly also nuclear fuel that will not be reprocessed) and intermediate-level long-lived waste (ILW-LL) in order to limit phenomenological interactions between these different waste categories.

The HLW from the reprocessing of spent fuel consists of fission products and minor actinides separated from the uranium and plutonium, calcined and incorporated into a glass matrix, which is poured into a stainless steel canister.

The ILW-LL consists mainly of the structural elements of spent fuel and waste associated with the operation, maintenance and dismantling of nuclear facilities. The containers used by the waste producers for conditioning the ILW-LL are of different types, shapes and sizes. They can be made from non-alloy steel, stainless steel, standard reinforced or fibre-reinforced concrete.



Figure 2.1-1: Images of waste packages manufactured by AREVA; vitrified HLW packages (left); ILW-LL maintenance waste packages (right)

The waste is disposed of in "disposal packages" [5], which are placed in "cells" in the underground facility. The cells are spherical or ovoid underground excavations on a horizontal axis or slight slope dug out of the Callovo-Oxfordian formation.

[5] *These packages contribute to the safety of the waste disposal facility while it is in operation, and as necessary also to its post-closure safety.* (2008 safety guide for the final disposal of radioactive waste in a deep geological formation)

There are two categories of cells:

- HLW micro-tunnel cells containing only one disposal package per cell section; each micro-tunnel has a "sleeve" designed to provide mechanical support to the cell at least during its operation;
- ILW-LL tunnel cells containing several disposal packages per cell section. The mechanical stability of these during operation is guaranteed by a liner (left in place on closure).

Each cell is served by one or more access drifts for its construction, the loading of the waste packages and management until closure. The liner of the access drifts ensures their mechanical stability during the operating phase (it is also left in place for closure).

The cells are arranged in each of the zones mentioned above into one or more separate sections. One section is a dead-end grouping of cells and drifts. For the HLW packages, there is the HLW0 section for moderately exothermic waste packages, which will probably be used from the industrial pilot phase, and there are the HLW1/HLW2 sections that will be used for highly exothermic waste packages from 2075.

The sections are linked to the connecting structures between the surface and the underground facility by "connecting drifts". The connecting structures between the surface and the underground facility, known as "surface-to-bottom connections" consist of two ramps and vertical shafts in groups and a number of sections defined by their functions during operation [6] [see DOS-Expl Volume II]. After the final closure of Cigeo, all the drifts in the underground facility will be backfilled and sealed in places. The ramps and shafts will be backfilled and sealed.

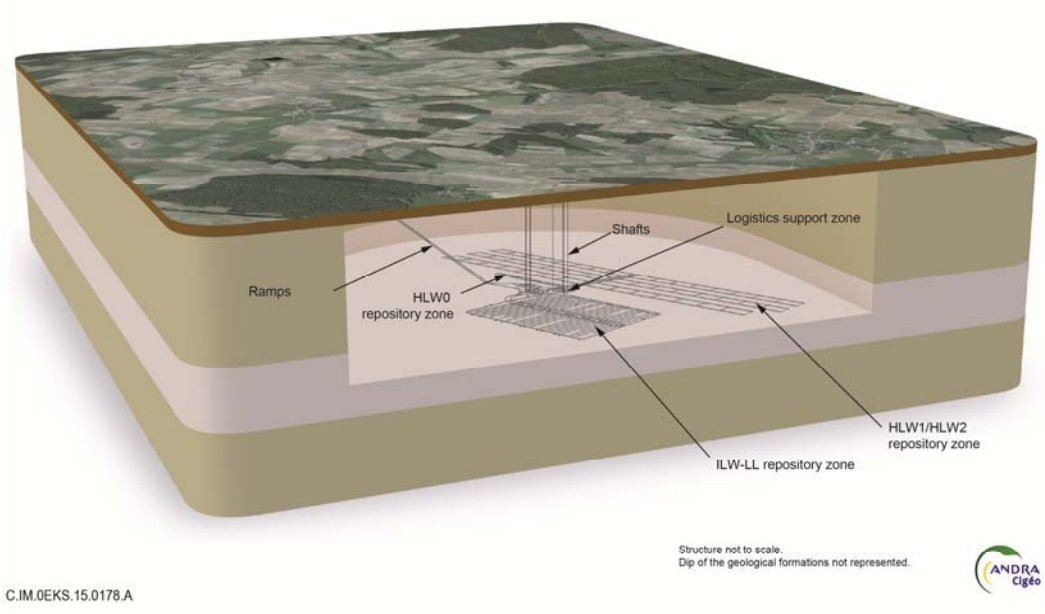


Figure 2.1-2: Illustration of the Cigeo underground facility after its final closure (subject to a law giving permission being passed)

[6] A liner ensures the mechanical stability of the connecting drifts and the surface-to-bottom connections during operation. It is left in place for closure, except where there are measures specific to the seals described in Volume II.

Cigeo, and more specifically the underground facility after its final closure, will be the facility as built.

At this stage, the underground architecture to which this document relates is only an illustration of what the architecture might be, based on the technical options chosen at the basic engineering design stage and not taking account of any improvements to the design.

With each change in the architecture and as Cigeo develops incrementally, the impact of any improvements on elements important for post-closure safety and the overall impact in terms of consequences for humans and the environment, will be checked.

The improvements and technical solutions being considered at this stage for which the results of industrial feasibility studies or demonstrations will be available only after the construction licence decree is issued, are presented in greater detail in Volume II and Volume IV.

2.2 Cigeo siting

The facilities of the future Cigeo geological disposal facility are located in eastern France, on the boundary between the Meuse and Haute-Marne departments. Research conducted by Andra since the 1990s, particularly in the underground research laboratory from 2002 (15), identified an area of the Paris basin that was a geographically favourable location for the siting of a disposal facility in a deep geological formation suitable for high-level and intermediate-level long-lived waste, then later a smaller area of around 250 km² (known as the transposition zone) within which the host formation of Callovo-Oxfordian had similar properties to those observed in the underground research laboratory (15).

The site for the Cigeo (surface and underground) facilities was chosen by means of a gradual approach carried out from 2006, with an important milestone in 2009. In 2009 Andra submitted a document proposing a smaller area within the transposition zone, the zone of interest for detailed reconnaissance (ZIRA) of approximately 30 km², as well as scenarios for the location of surface facilities (21). This document was examined by IRSN at the request of ASN.

On 5 January 2010, ASN submitted an opinion to the Minister of State, the Minister of Ecology, Energy and Sustainable Development and the Sea, and the Minister of Higher Education and Research on the Andra document. In its opinion, ASN stated that the criteria used by Andra to select the zone of interest for detailed reconnaissance (ZIRA) were pertinent and consistent with the 2008 safety guide for the final disposal of radioactive waste in a deep geological formation(1). The ASN believed that the location proposed by Andra for the ZIRA was satisfactory from a safety point of view and had no objection to the reconnaissance work planned by Andra in this zone(13).

Andra's proposal concerning the ZIRA for the siting of the Cigeo geological disposal facility was based in particular on:

- the results of geological investigations, especially those conducted in 2007 and 2008, which provided a uniform level of geological knowledge of the transposition zone, and analysis of the geological and safety-related criteria to be considered for the siting of the underground facilities;
- analysis of the environmental and safety-related constraints to be considered for the siting of the surface facilities;
- discussions with local stakeholders who helped to identify the territorial planning and local integration criteria to be considered in the repository siting process.

Reconnaissance work conducted in the transposition zone in 2007 and 2008 aimed to provide a uniform level of knowledge of the whole area of interest. On this basis, 14 boreholes were drilled and a

2D seismic campaign corresponding to a linear total of 170 kilometres was conducted, and 130 kilometres of old seismic profiles were reprocessed. The results confirmed the perimeter of the transposition zone, as defined in the "Dossier 2005"[7], and in particular confirmed the uniformity of the sedimentary context and the properties of the Callovo-Oxfordian, as well as the absence of minor faults. It was on the basis of this work and the geological model in the broader sense that it was decided that Andra could define a zone of interest for detailed reconnaissance (ZIRA), taking the following criteria into consideration:

- the ZIRA should preferably be sited in the zone identified as most suitable with regard to geological and safety-related criteria;
- there should be a sufficient area to allow the underground facility to be located in the ZIRA;
- it should be compatible with the potential siting of the ramp access;
- it should be compatible with a potential siting of the main access shafts.

During studies carried out from 2007 to 2009, the possibility of separating part of the surface facilities from the underground facility by means of a ramp was also examined, to provide flexibility with the siting of the entrance to this structure, so it could be up to 5 kilometres from the shaft zone (on the basis of a 10% slope). Two zones of surface activity, potentially separate, are therefore being considered: the "shaft" zone, which must, because of its function, be above the underground facility and the "ramp" zone.

On the basis of all the above criteria, a zone was defined for the siting of the underground facility covering an area of around thirty square kilometres. The depth of the underground facility's structures at the centre of the ZIRA would be approximately 525 metres and the thickness of the Callovo-Oxfordian at the centre of the ZIRA is approximately 148 metres. The figure below shows the zone where the Cigeo geological disposal facility will be located within the ZIRA.

[7] For the Dossier 2005, Andra defined the contours of an area known as the transposition zone, within which the containment properties of the Callovo-Oxfordian and the disturbances that a waste repository might cause could be considered equivalent to those determined in the underground research laboratory at the Meuse/Haute-Marne Centre. The delimitation of the zone was therefore based on geometrical criteria (thickness and depth of the Callovo-Oxfordian), but also on a set of sedimentological, stratigraphic and structural data, which allowed the proposal of this zone of about 250 km², in which the continuity and uniformity of the Callovo-Oxfordian's properties were guaranteed. The criteria used to delimit the transposition zone, chosen in 2005 and subsequently confirmed, were mainly intended to check the quality of the containment capabilities of the Callovo-Oxfordian formation. They are based on the thickness of the Callovo-Oxfordian, the structural framework, the mineralogy of the clay rock and the geomechanical behaviour of the rock.

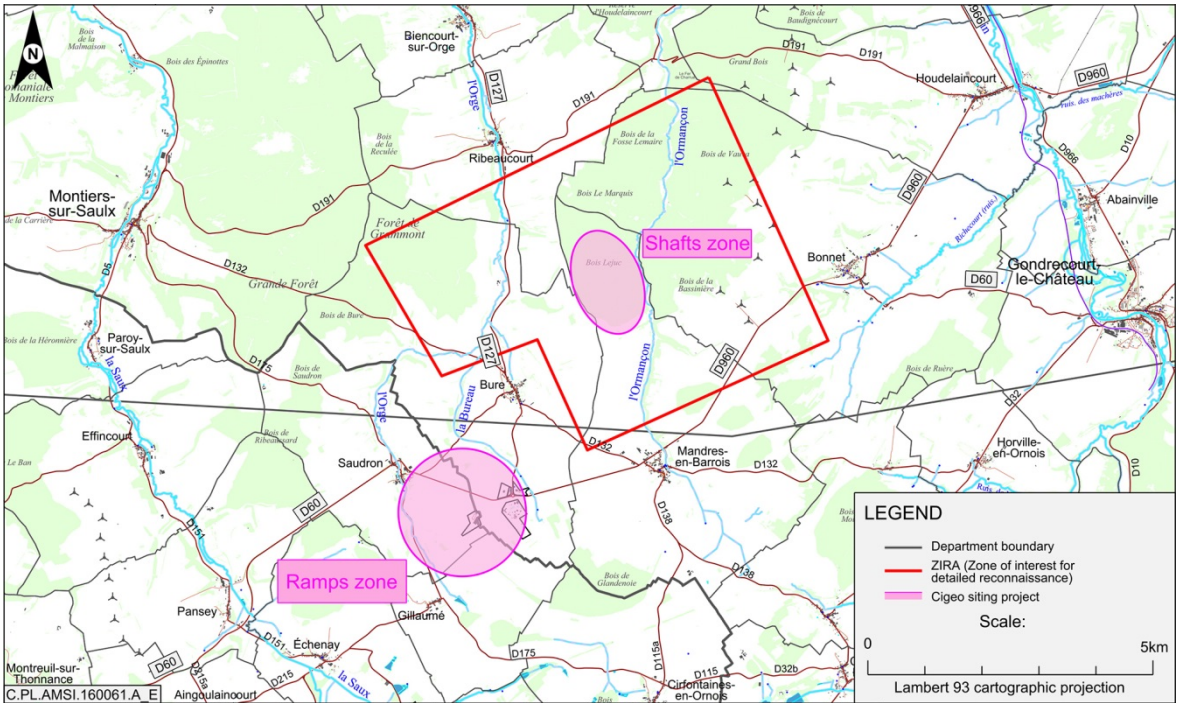


Figure 2.2-1: Cigeo location zones: "shaft" zone and "ramp" zone and ZIRA

2.3 Phasing of Cigeo after its final closure and time scales

As shown in the figure below, and as stated in the master plan for operation, there are three main phases in the life of Cigeo: an initial design and initial construction phase, an operation phase (including an industrial pilot phase) and a post-closure phase.

Cigeo will be closed in stages and the post-closure phase will only begin when the final closure of Cigeo has been authorised by a law.

According to the current schedule, Cigeo will close definitively around 2150.

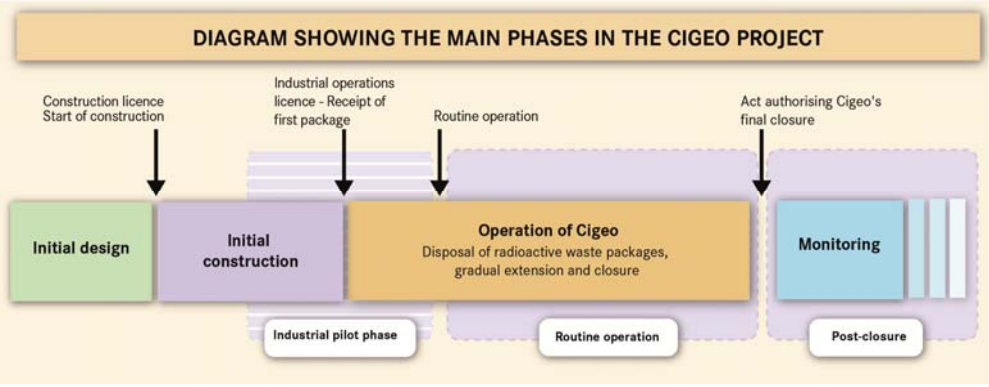


Figure 2.3-1: Diagram showing the main phases in the life of Cigeo

To meet the fundamental objective of protecting humans and the environment from radioactive waste over very long time scales passively and without the need for human action, once permission has been granted for the final closure of Cigeo, the whole underground facility will be backfilled, the closure structures will be put in place in the drifts and the surface-to-bottom connections, and the surface facilities will be dismantled[8].

In accordance with the 2008 ASN safety guide (1), one of Andra's principles is "*not to base the protection of human health and the environment on institutional monitoring or control as there is no certainty that this can be maintained for more than a limited period*[9]. "

Institutional monitoring and control combined with maintenance of the memory of Cigeo could nevertheless provide additional robustness; the objectives and the systems to be used will be set out in the Safety Analysis Report submitted in support of the construction licence application:

- during the period of monitoring by the operator, the duration of which is still to be decided, certain systems could be maintained after Cigeo is closed. This post-closure monitoring should not disturb the waste disposal system. A number of operational solutions for monitoring can be envisaged: non-intrusive surface-based techniques (geophysics, etc.), measurements in boreholes fitted with instrumentation drilled from the surface to the Oxfordian limestone above the Callovo-Oxfordian stratum, and measurements within the disposal structures themselves with wireless data transmission through the soil from bottom to surface. The monitoring phase will end with the declassification of the facility as provided for in Article L 593-33 of the Environment Code. The post-closure monitoring strategy for Cigeo will be explained in the Safety Analysis Report supporting the construction licence application[10];
- the institutional control period will include the maintenance of the public service easements registered, where necessary, on the basis of Article 43(II)(11) of Decree No 2007-1557 of 2 November 2007 mentioned above. This institutional control period could run for longer than the monitoring period;
- the period of preservation of the memory of the site post-closure would delay the occurrence of any human intrusion as a result of the existence of the disposal facility being forgotten. Andra's adopted memory management principle is based on two requirements:
  - ✓ finding technical, institutional and societal solutions for preserving the memory for as long as possible (see Appendix 2);
  - ✓ consideration in the safety assessment, in compliance with the safety guide (1), of the possibility that the memory could be lost after 500 years and inadvertent human intrusion could occur as a result after that.

[8] These operations correspond to the "final closure" mentioned in Article L 593-30 of the Environment Code.

[9] According to section 3.48 of the IAEA's Specific Safety Requirements, SSR-5: "For geological disposal and for the disposal of intermediate level radioactive waste, the passive safety features (barriers) have to be sufficiently robust so as not to require repair or upgrading. The long term safety of a disposal facility for radioactive waste must not be dependent on active institutional control (see Requirement 22). "

[10] The post-closure monitoring systems will be set up during the operational phase to allow cross-checking with data obtained by the operational phase monitoring devices. This objective involves in particular the ad-hoc instrumentation during the first phase of construction of one or more boreholes from the surface down to the Oxfordian limestone (inclusive), directly above the underground facility.

Furthermore, internal and external phenomena affecting the disposal facility, which could occur from the time of closure up to time scales of tens of thousands of years[11] have led to the identification of different post-closure time periods. These time periods depend (i) on the safety functions to be performed by the components over time, (ii) on the design of the components, taking account of any physicochemical changes in them (e.g. duration of performance of the safety functions), and (iii) phenomena and processes governing changes in the disposal facility (thermal (T), hydraulic-gas (H-G), mechanical (M), chemical (C) and radiological (R), climatic and internal geodynamic). These changes can be grouped into general phenomenon categories:

- internal geodynamic and climatic phenomena. These are changes in the geological medium taking account of geodynamics, climate change and erosion phenomena;
- thermal phenomena. These are mainly linked to the heat released by certain waste, which decreases over time with the radioactive decay of this waste;
- hydraulic phenomena linked to natural water flows in the geological medium, and desaturation/resaturation phenomena affecting the disposal structures, and gas production phenomena within the repository;
- mechanical phenomena mainly caused by the excavation of the structures;
- chemical phenomena concerning changes in the materials making up the disposal facility components (in the short and long term), particularly under the influence of interaction with water in the Callovo-Oxfordian (flows of this water within the structures and exchanges of materials in solution between the Callovo-Oxfordian and the structures);
- transporting of the radionuclides and toxic elements within the geological medium, particularly the Callovo-Oxfordian, and from the disposal structures to potential outlets.

[11] According to Requirement 9 of the IAEA's Specific Safety Requirements (SSR-5): "*The disposal facility shall be sited, designed and operated to provide features that are aimed at isolation of the radioactive waste from people and from the accessible biosphere. The features shall aim to provide isolation for several hundreds of years for short lived waste and at least several thousand years for intermediate and high level waste. In so doing, consideration shall be given to both the natural evolution of the disposal system and events causing disturbance of the facility.* "

3

Regulatory framework and standards

3.1 Regulations applicable to the Cigeo project 43
3.2 Guides and technical standards 43
3.3 International standards and practices 44
3.4 Consideration of national and international references 45

3.1 Regulations applicable to the Cigeo project

In addition to the 2006 Act, the regulations applicable to Cigeo include codes, decrees, orders and decisions. As a result of the Act of 13 June 2006 on transparency concerning nuclear safety [TSN] (14) and the publication of the Order of 7 February 2012 (15), ASN began the process of transposing this Order into a number of decisions. Some of these decisions have been published and apply to Cigeo either partially or entirely. Others are still being drawn up. They are listed for information; whether they are taken into account in the construction licence application will depend on whether they have been published and their scope of application. The table in Appendix 3: summarises the texts relevant to Cigeo.

3.2 Guides and technical standards

3.2.1 Guides and basic safety rules: the specific case of the 2008 ASN guide

With the exception of the safety guide for the final disposal of radioactive waste in a deep geological formation, published by the ASN on 21 March 2008 (1), the basic safety rules and guides concerning basic nuclear installation are for surface nuclear facilities, and therefore cover the Cigeo operating phase. As a consequence they are not considered applicable to the post-closure phase of Cigeo.

Only the safety guide for the final disposal of radioactive waste in a deep geological formation, published by the ASN on 21 March 2008 (1) is considered applicable to Cigeo post-closure. This guide sets out the human and environmental health protection objectives, the safety principles and the safety-related design bases of the waste disposal facility, as well as the method for demonstrating disposal facility safety. The fundamental safety objective of the waste disposal facility is defined as follows:

"*Protection of human health and the environment constitutes the fundamental safety objective assigned to the disposal of radioactive waste in a deep geological formation. It must be insured against the risks related to the spread of radioactive substances and toxic elements.*
After closure of the facility, the protection of human health and the environment must not depend on monitoring and institutional checks which cannot be maintained with certainty beyond a limited period. "

Consequently, the safety and design options chosen for Cigeo were chosen in order to fulfil the safety functions and associated requirements mentioned in the guide.

The safety guide for the geological repository (1) also makes recommendations concerning scenarios, in particular calling for justification of the selection of these. Volume II of this document therefore presents the chosen scenarios, their classification and the reasons why they were selected. Concerning the particular instance of human intrusion, in accordance with the guide, the evaluations were made assuming that the intrusion would occur immediately after the supposed loss of any memory of the site (i.e. after 500 years).

3.2.2 Andra's additional reference standards

For the assessment of consequences, Andra also follows the recommendations in the ASN 2008 safety guide (1), which require identification of a hypothetical reference group and of potential outlets. In Volume II Andra therefore presents the safety options chosen for assessing consequences.

In addition to this guide, Andra has prepared a document reference (16) on post-closure safety and more specifically on assessing the consequences for humans. It explains the approach taken for choosing and describing one or more biospheres, taking account of feedback from previous applications and the associated instructions, as well as international practices.

This approach is summarised in Chapter 5 of this volume.

3.3 International standards and practices

The approach to safety taken by Andra is in line with texts on safety issued by international bodies (IAEA safety standards, WENRA SRLs, OECD brochures) which set out the principles and make dialogue with the international community possible by establishing common references.

It should be noted that the safety options chosen for Cigeo follow the principle established by the IAEA in Specific Safety Requirements No SSR-5, of which point 2.17 states: "*The primary goal of the disposal of radioactive waste is the protection of people and the environment in the long term once the disposal facility has been closed. In this period, migration of radionuclides to the accessible biosphere, dispersion of radionuclides into the accessible biosphere and the consequent exposure of people may occur. This is a consequence of the slow degradation of engineered components and the slow transport of radionuclides from the facility by natural processes.* " Volumes II and III therefore attempt to present the practical expression of this principle.

Developments in international thought ("Post-closure safety case for geological repositories", OECD/NEA, Paris 2004; "The Safety Case and Safety Assessment for the Disposal of Radioactive Waste", IAEA SSG-23, Vienna 2012) also emphasise the concept of the "safety case" in addition to the "safety assessment". An extension of the risk analyses and impact assessments intended to check regulatory conformity, the safety case takes the form of a synthesis of multiple arguments contributing to the establishment of confidence in repository safety. It includes knowledge acquired on the "input data" of repository projects and the design of these projects. In response to this and to plot the arguments, the assessment procedure introduced by Andra includes the following core components:

- a functional analysis (functions, components and associated performance) establishing a strong link with the design;
- a phenomenological analysis of the repository situations (current knowledge taking account of the chosen design options);
- a qualitative analysis of the uncertainties (based on the first two analyses) complemented by a quantification of the scenarios chosen as a result of the analysis.

Andra also makes reference to current ICRP texts for issues related to radiation protection, in particular to set the limits and constraints relating to dose. The protection objectives chosen by Andra and presented in Chapter 4 of Volume I are consistent with the ICRP recommendations.

Furthermore, since the first European PAGIS (Performance Assessment of Geological Isolation Systems for Radioactive Waste; Disposal in Clay formations) exercise (1982-1989), participation in a number of exercises organised by the European Community (PAMINA, EG-DTP), the IAEA (GEOSAF, HIDRA, etc.) and the OECD/NEA (INTESC, EBS, AMIGO, MeSa, workshop scenarios, etc.) has enabled Andra to compare itself with its international counterparts and to check that they are using similar approaches.

The publications of the NEA (Nuclear Energy Agency) establish the state of the art in various fields. A number of documents cover the deep geological disposal of radioactive waste. These documents include a number that discuss the links between research topics, facility design and demonstration of the safety of facilities. This chapter only mentions the documents related to safety demonstration.

As far as scenarios are concerned, the approach taken by Andra makes it possible to identify scenarios corresponding to a deviation from the normal evolution of a disposal system. It is consistent with standards and international practices. In particular, it is consistent with point DI-36 of a WENRA document published in December 2014, which states: "*The licensee shall design the disposal facility giving due consideration to both normal evolution of the disposal system after closure and scenarios involving events and processes that might disturb the normal evolution of the disposal system*".

As far as the specific case of human actions are concerned, according to IAEA guide DS 355[12]:

- human activities that could lead to intrusion into a disposal facility at a depth of more than 30 m are generally linked to drilling activities;
- the impact of one or more intrusion scenarios should be assessed;
- given the many uncertainties over the definition of scenarios involving future evolutions in society, the scenarios should be "stylised", i.e. they should be simplified but be pessimistic in terms of estimating impact.

The tables in Appendices 2 and 3 list the main documents considered for the Cigeo project, distinguishing between standards and technical documents.

3.4 Consideration of national and international references

Andra is committed to taking into account the national references mentioned in this chapter. The three safety functions set out in the 2008 ASN safety guide (1) are therefore expressed as sub-functions and associated requirements in Volume II of this document.

This is based on a multi-functional approach to safety combined with verification of the correct performance level of these functions.

Andra's participation in international exercises also provides assurance that the safety strategy it has chosen is consistent with these references and practices.

[12] IAEA guide DS 355 states that if the intrusion is deliberate, it is considered that the people carrying out the action are aware of and responsible for the potential impact on the facility. In this case, it is not necessary to assess the situation in the safety analyses.

4

Safety strategy

4.1	*Fundamental principles*	*47*
4.2	*Post-closure safety functions, general design principles and applicable requirements*	*48*
4.3	*Protection objectives*	*54*
4.4	*The global approach*	*55*

4.1 Fundamental principles

The safety approach adopted for Cigeo follows the recommendations of the safety guide for the geological repository (1), which mentions: "*the objectives that must be met from the site investigation and design phases of a disposal facility, in order to guarantee the post-closure safety of the waste disposal facility*". This guide (referred to hereafter as the "Safety guide for the geological repository") states that (section 4.1, Objectives):

- "The fundamental safety objective assigned to the disposal of radioactive waste in a deep geological formation is the protection of human health and of the environment. This means ensuring protection against the risks linked to the dissemination of radioactive substances and toxic chemicals. "
- "After the closure of the disposal facility, the protection of human health and the environment must not depend on institutional monitoring or control as there is no certainty that this can be maintained for more than a limited period. "
- "Consequently, the geological medium shall be chosen and the disposal facility shall be designed such that its post-closure safety shall be ensured passively to protect humans and the environment from the radioactive substances and toxic elements contained in the radioactive waste, without the need for intervention. "
- "In this regard, the concept chosen for the disposal facility should enable the radiological impact to be kept as low as reasonably possible taking account of current scientific knowledge, existing technology, and economic and social factors."

The post-closure safety functions and the associated requirements are identified, taken into account from the design stage and checked throughout construction and operation.

The disposal system relies particularly on the Callovo-Oxfordian, a natural barrier that plays the main role, and the closure structures of the surface-to-bottom connections, which ensure passive post-closure safety over the long term.

Whether the disposal system is functioning correctly and more specifically whether the safety functions are being fulfilled are checked by means of indicators (see Chapter 5); the protection objective is verified by means of an impact assessment expressed in terms of dose.

An appropriate level of monitoring and control is applied to Cigeo from its construction and during its operation, to ensure the protection and preservation of the passive post-closure safety features, as necessary, so that they can fulfil their safety functions once the repository is closed. This level will be specified in the Safety Analysis Report supporting the construction licence application. Volume IV of this document makes a number of recommendations.

The disposal concept, and particularly the architecture of the underground facility chosen at the basic engineering design stage, can evolve to take account of scientific and technological progress. Every time it evolves, the concept will be checked to make sure that the post-closure safety functions are still fulfilled and the radiological impact remains as low as reasonably possible given economic and social factors.

The global approach to post-closure safety assessment is based on practical expression of the safety functions and associated requirements, analysis of component performance and analysis of the uncertainties related to the scientific and technological knowledge underpinning the design. These elements are presented in Volumes II and III of this document.

4.2 Post-closure safety functions, general design principles and applicable requirements

4.2.1 Main functions

In order to meet the fundamental objective of protecting humans and the environment against the risks associated with dissemination of the radioactive substances and toxic elements in the waste, Andra has identified and organised the Cigeo disposal system's post-closure safety functions as follows.

The first safety function consists of isolating the waste from surface phenomena and human actions. The site of the repository and the depth at which it is located protect it from surface phenomena, erosion and everyday human activities, which should only affect the ground down to a depth of less than 200 m on a scale of hundreds of thousands of years. In accordance with the safety guide for the geological repository (1), the protection of humans must be guaranteed "without depending on institutional control, which cannot be relied on with any certainty for more than a limited period of time (...) (500 years)". The memory of the repository will be maintained for as long as possible. The technical solution chosen will provide a reasonable level of confidence over a very long period of time, such that the possibility of inadvertent human intrusion does not have to be considered until after 500 years, in accordance with the safety guide (1).

The second safety function consists of limiting the transfer into the biosphere of the radioactive substances and toxic elements in the waste. This means controlling the physicochemical degradation of the waste, the packages and the engineered components, keeping the radioactive substances and toxic elements as close as possible to their sources, and controlling the transfer pathways that could, in the long term, lead these elements into the biosphere. They are:

- aqueous pathways, as the substances are liable to dissolve in water and migrate to the surface;
- gaseous pathways, as certain radionuclides can migrate in this form.

Water is the main factor in the alteration of waste packages and the main transfer vector of radioactive substances and toxic elements. Controlling the aqueous pathways is therefore a key objective of post-closure safety.

Limiting the transfer of radioactive substances and toxic elements by water is the purpose of the following three safety functions (Figure 4.2-1):

1. preventing the circulation of water;
2. restricting the release of radionuclides and toxic elements and immobilising them in the repository;
3. delaying and reducing the migration of radioactive substances and toxic elements released, from the packages and then from the disposal cells.

These three safety functions rely primarily on the favourable characteristics of the Callovo-Oxfordian formation. The design of Cigeo (architecture, engineered components) and its operation aim to preserve these favourable characteristics.

While the Callovo-Oxfordian formation plays a central role in long-term safety, the packages and the repository's engineered components, specifically the underground facility's architecture on completion and closure structures, also contribute to containment of the waste and to maintaining the conditions for flows of water through the facility to be very slow.

One particular objective is to control the criticality risk associated with the presence of fissile isotopes in the waste. Andra checks that this risk is controlled as part of the safety assessment, on the basis of the mass of fissile material per package, the distribution of the waste packages in the cells and the limited potential for the fissile isotopes to move or form concentrations, taking account of the evolution of the materials and of the void spaces in the cells.

4.2.2 Practical expression of the "limiting transfer to the biosphere" function

4.2.2.1 Preventing the circulation of water

Callovo-Oxfordian clay rock is initially saturated with water. Creating the disposal facility disturbs the hydraulic pressure and can lead locally to clay rock desaturation immediately around the structures. In the period following closure of the underground repository, a hydraulic transient can become established over time scales that vary depending on the structure in question, until the repository reaches total saturation and a new hydraulic equilibrium is reached in the repository and the surrounding Callovo-Oxfordian. After that, water flows generally follow the natural hydraulic gradient (vertical rising or vertical falling) in the Callovo-Oxfordian of the ZIRA.

During the transitional repository saturation period, limiting flows of water from the overlying geological formations that the backfilled and sealed surface-to-bottom connections pass through can delay the entry of significant amounts of water from overlying aquifers into the repository and into the waste packages, and can also make sure than the saturation of the structures is controlled predominantly by the water in the Callovo-Oxfordian.

Following resaturation of the underground structures, the aim is to make sure transfer by advection is severely limited within the disposal system, i.e. in both the Callovo-Oxfordian clay formation chosen for this purpose because of its low permeability and the low hydraulic gradient that applies to it, and in the underground repository and the surface-to-bottom connections.

This helps to create favourable conditions for two other functions that limit the transfer of radioactive substances or toxic elements by water (limiting the release of radioactive substances and toxic elements and immobilise them in the repository; delaying and reducing the migration of radioactive substances and toxic elements):

- the low turnover of water in the disposal cells helps to protect the waste packages and encourages the establishment of local chemical equilibria;
- the slow migration of solutes along the underground structures encourages their retention by the Callovo-Oxfordian, within which the dominant transfer process is diffusion.

To prevent the circulation of water in the disposal system, Andra has chosen the following sub-functions:

- limiting water flows, distinguishing between the flow of water from the Callovo-Oxfordian host formation drained by the underground facility, and the flow of water circulating via the surface-to-bottom connections between the disposal facility and the overlying aquifer formations (such as the Barrois limestone and the porous horizons of the calcareous Oxfordian);
- limiting the speed of circulation of this water from the cells to the top of the Callovo-Oxfordian through the surface-to-bottom connections.

The design measures adopted to perform these sub-functions are explained in more detail in Volume II.

4.2.2.2 Restricting the release of radionuclides and toxic elements and immobilising them in the repository.

To restrict the release of radionuclides and immobilise them in the repository, Andra has chosen the following three sub-functions (Figure 4.2-1):

- protecting the waste from water;
- restricting the dissolution of the radionuclides and toxic chemicals;
- restricting the mobility of the radionuclides and toxic chemicals.

<u>Protecting waste from water</u>

Some waste is conditioned in a durable matrix which isolates it from water: this is particularly the case with the vitrification process used for HLW. For other waste, the nature of the waste that contains the radionuclides itself isolates all or part of the radionuclides from water, e.g. activated metal waste, particularly the hulls of spent fuel assembly rods after reprocessing.

Efforts are made to take advantage as much as possible of the favourable properties of the conditioned waste, while taking account of the technical constraints. This means, on the one hand, understanding these properties and, on the other, creating a physicochemical environment within the cells that will delay the alteration of the waste and the conditioning matrices. Reduction conditions are favourable to the protection of metals. Alkaline conditions are avoided in the vicinity of vitrified HLW because they tend to accelerate the dissolution of the glass matrix. Conversely, an alkaline pH favours low corrosion kinetics in metal waste.

Restricting the dissolution of the radionuclides and toxic chemicals

To restrict the dissolution of substances accessible to water in the waste (e.g. where there is radioactive surface contamination of the waste, characteristic for example of technological waste) or those released due to alteration of the waste, physicochemical conditions are required that enable these substances to be precipitated in the cells, as close as possible to the waste, in particular:

- a reducing clay medium, with the Callovo-Oxfordian as a buffer, limits the solubility of very many radionuclides, particularly the actinides, technetium, etc. ;
- cement conditions are also favourable to low solubility of the vast majority of radionuclides (e.g. nickel, cobalt, americium, curium, neptunium, plutonium).

Temperature also has an effect on the solubility of radionuclides and toxic elements. Andra has chosen to avoid any contact of the waste with water while the temperature in the waste and its environment is higher than 70°C. The disposal facility is therefore kept within a range where the behaviour of the radionuclides and toxic elements is known (solubility and retention at the solid/liquid interface). This involves using a sealed disposal container for HLW and restricting the temperature in the cells for other waste (see Volume II).

Restricting the mobility of the radionuclides and toxic chemicals

Complexing phenomena can alter the mobility of radionuclides and toxic elements in the disposal system by increasing their apparent solubility. Certain organic materials, and possibly also certain salts, in some of the ILW-LL waste packages or produced by their degradation, tend to form complexing species affecting radionuclides and toxic elements.

In addition, the salts in some ILW-LL can alter the redox conditions in the near-field Callovo-Oxfordian, encouraging the transfer of certain radionuclides in solution.

To limit the consequences of these phenomena, Andra has defined restrictive design measures as regards co-disposal: definition of the waste packages, specifically containing ILW-LL, that can be placed in the same cell (measures described particularly as part of the design characteristics in Volume II of DOS-Expl), and minimum distances between cells containing different types of waste likely to interact (see Volume II of this document).

Similarly, the presence in the repository of engineered materials that can produce species in solution which increase the mobility of the radionuclides and toxic elements, is limited as far as possible.

4.2.2.3 Delaying and reducing the migration of radioactive substances and toxic elements

While the disposal system prioritises containment of the radioactive substances and toxic elements as close as possible to the waste by restricting their release from the packages and then from the cells, it should also delay and reduce the migration of any radioactive substances and toxic elements that are nevertheless released from the cells into the Callovo-Oxfordian, particularly the most soluble and most mobile substances.

Reducing their migration means reducing in the dual sense, in both time and physical extent. The migration of a quantity of radionuclides or toxic elements will have a much smaller impact if this quantity is dispersed over a large distance and if it is spread out in space and over a longer period of time when it reaches the biosphere. Increasing the time taken by radioactive substances to reach the surface could reduce their impact because of radioactive decay during their migration, given their radioactive half-life vs. the migration time.

To perform this function, out of preference the Callovo-Oxfordian is used as the transfer pathway. Migration can be delayed and reduced most effectively within the Callovo-Oxfordian by exploiting its thickness and retention capabilities, while taking account of the technical constraints on constructing Cigeo's underground installations within the Callovo-Oxfordian.

This also, as a corollary, means reducing as far as possible the flow of radioactive substances and toxic elements likely to leave the disposal system via the surface-to-bottom connections. A series of measures has been adopted to delay and reduce this flow, involving the geometry of the cells, the access drifts and connecting drifts, and also the surface-to-bottom connections: these will be explained in more detail in Volume II.

Finally, the natural dispersal and dilution qualities of the formations surrounding the Callovo-Oxfordian will be exploited as much as possible, even though they are not part of the disposal system in the strict sense.

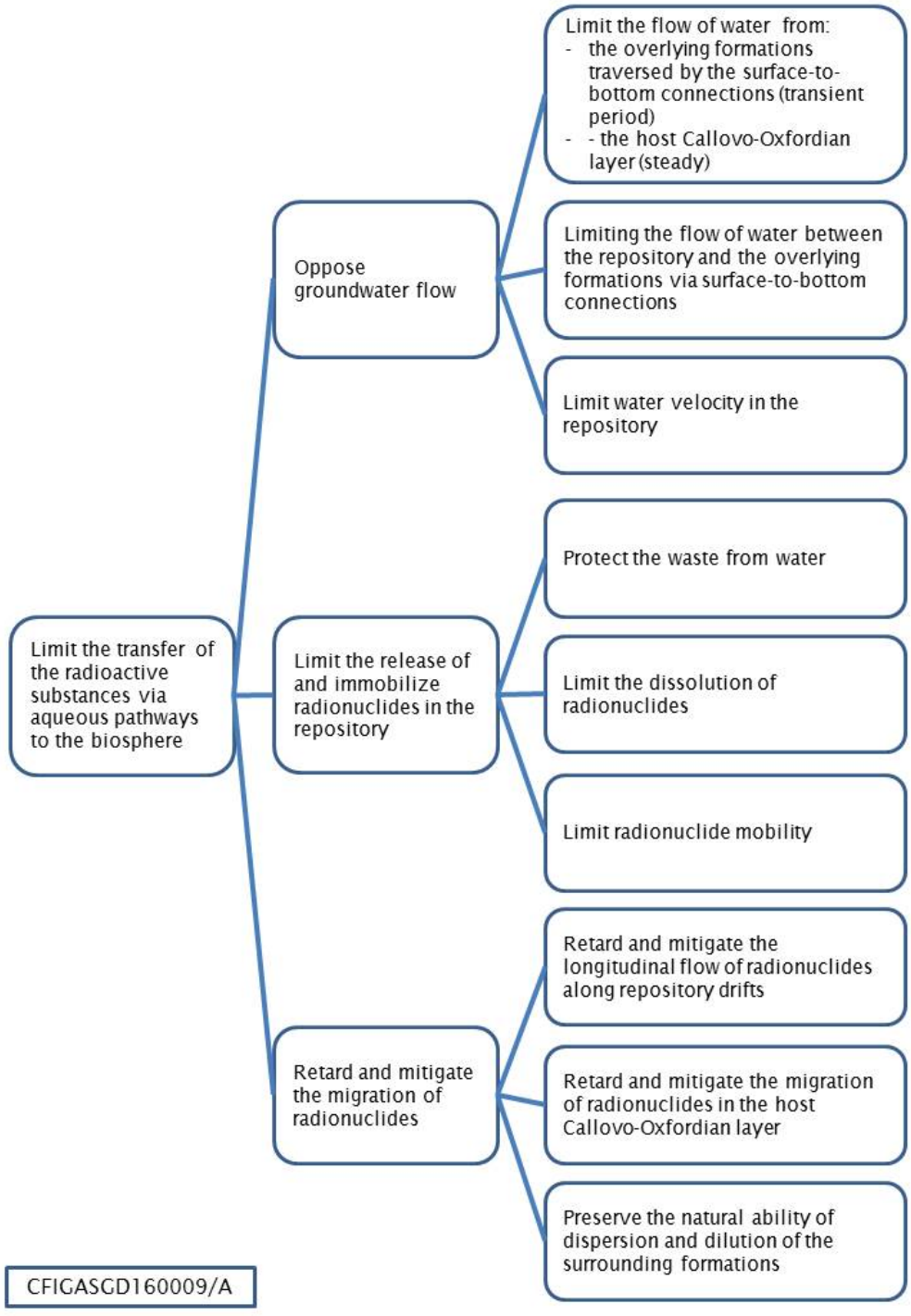


Figure 4.2-1: Tree structure of the functions used to limit the transfer of the radioactive substances (and toxic elements) via aqueous pathways

4.2.3 General design principles

To fulfil the post-closure safety functions, Andra has chosen some general design principles for Cigeo and for the choice of site. These principles also concern the construction and operation of Cigeo once the construction and operating licences have been granted. The table below presents the principles specific to each post-closure safety function.

Post-closure safety functions	General principles in terms of choice of site and design
Isolating waste from surface phenomena and human actions	• Location of Cigeo at a depth and in an area of low, uniform geodynamics ⇨ the disposal system is protected from erosion phenomena and is consequently protected in the long term from minor human intrusions; • No extractable or geothermal underground resources likely to lead to prospecting; • Maintenance of a memory of the disposal facility for as long as possible after its closure[13].
Preventing the circulation of water	• Low water flows in the Callovo-Oxfordian due to its low permeability and the low hydraulic head gradient applied to it in the ZIRA; • Location of the disposal system in a zone away from (potentially) hydraulically active geological structures; • Consolidation and sealing of the surface-to-bottom connections ⇨ potential water circulation via these links is minimised; • Disposal sections cut off from the rest of the underground facility ⇨ flows of water within the repository are limited, and use the small flows of water within the Callovo-Oxfordian.
Restricting the release of radionuclides and toxic elements and immobilising them in the repository	• Cells (particularly the materials used for them) designed to protect the waste and packages from a physicochemical point of view ⇨ alteration is limited as far as possible; • Physicochemical conditions in the cells limiting the release and mobility of the radioactive substances and toxic elements (choice of materials used; distancing of certain waste packages due to the disturbances they are likely to cause or the sensitivity of the substances they contain; favourable characteristics of the Callovo-Oxfordian: low water flows, reducing water chemistry, dominant transfer process is diffusion, etc.).
Delaying and reducing radionuclide migration	• Callovo-Oxfordian is very thick (at least 130 m in the ZIRA), has a high retention capacity, and neutral and reducing interstitial water ⇨ concentrations in solution of the radioactive substances and toxic elements in the waste are limited and migration of species in solution is slow ⇨ diluting effect over time and space for the most mobile radioactive substances and toxic elements; • Location of the underground facility in the middle part of the Callovo-Oxfordian, taking account of the technical constraints on construction and operation, the planar architecture of the facility ⇨ lower and upper undisturbed layers of the Callovo-Oxfordian on either side of the Cigeo underground installation are very thick; • Optimised geometries of the cells and drifts in the underground installation, particularly in terms of length ⇨ migration of the radioactive substances and toxic elements along the structures is limited and the preferred transfer pathway is through the Callovo-Oxfordian.

More generally, the design of Cigeo, from the selection of the main options to the detailed technical solutions, has been guided by research into the best available techniques for fulfilling the safety functions, taking account of technical and financial constraints.

[13] at least 500 years

Understanding the evolution of the disposal system in the long term and its impact on the safety functions relies on a robust phenomenological understanding of the processes associated with this evolution. This:

- limits as far as possible the physical and physicochemical disturbances caused to the Callovo-Oxfordian formation and the surrounding formations, particularly the overlying formations that the surface-to-bottom connections pass through. This means that their initial characteristics, which have been well characterised, particularly by the Meuse/Haute-Marne Centre (underground research laboratory), can be relied upon to perform the safety functions;
- limits as far as possible the physical and physicochemical interactions within the repository, which simplifies the processes to be taken into account;
- makes use wherever possible of simple, robust and proven materials and technical solutions. In particular Andra prioritises the use of natural materials for the closure structures.

4.2.4 Requirements applicable to the design of Cigeo

Each of the post-closure safety functions is associated with requirements that were identified by Andra in 2011 and were instrumental in the design of Cigeo.

These requirements come from the regulatory texts and safety guides directly applicable to Cigeo (e.g. the safety guide for the geological repository (1)). Various safety standards compiled by Andra by adapting texts and practices not directly applicable to Cigeo (e.g. fire standards) are associated with the requirements.

The requirements applicable to the Cigeo project also consolidate other needs and recommendations expressed by stakeholders (the government, the ASN, the National Review Board (CNE), HLW and ILW-LL producers, local stakeholders).

The requirements are based on experience acquired by Andra at the underground research laboratory and more generally by all of its research since 1991. In particular, this has meant that the long-term safety objectives could be transposed into design options constituting input data for studies to be conducted by contractors and for tests.

4.3 Protection objectives

4.3.1 Radiological protection objective

In accordance with the safety guide (ASN 2008) (1):

- Andra should use a dose constraint value of 0.25 mSv per year for the normal evolution scenario;
- for the altered evolution and inadvertent human intrusion scenarios, Andra should check that the consequences remain below the levels likely to cause deterministic effects.

The long term calculated dose remains a reference value for the impact on a theoretical population that seems to have had the greatest exposure.

Andra uses the effective committed dose at the outlet as the main radiation protection indicator. In accordance with ICRP 81, it does indicate impact, but it is not a predictive value. Other indicators are used to check the performance of the disposal system: they are presented in Chapter 5 of this Volume.

Impact is assessed by taking account of the likelihood of a situation occurring, of whether exposure is chronic or occasional, of the degree of pessimism of the assessment hypotheses, and on the basis of an analysis of the efforts made by the repository designer to ensure individual exposure is as low as reasonably possible, taking account of economic and social factors.

4.3.2 Objective of protection from toxic elements

The health risk acceptability targets defined in a Circular of 8 February 2007 on polluted sites and soils are as follows:

- for non-carcinogenic species: HQ < 1;
- for carcinogenic species: EIR < 10^{-5} (i.e. 1 extra case per 100,000 exposed individuals).

The protection of people and the environment is understood, above all, to be protection against the specific risk due to radioactive waste, that is, radioactivity and its induced effects. In the case of chemical risk, because the safety functions are similar (to prevent and delay the transfer of chemical elements to the environment), the solutions to the problem posed by radioactive substances as a general rule are similar to those for the risks posed by toxic elements. Andra assesses the chemical impact of the repository in general terms and, for the quantitative assessments, focuses on a few toxic elements chosen to represent those that are potentially the most harmful. They are: arsenic, boron, beryllium, cadmium, chromium (III) and (VI), inorganic and organic mercury, nickel, lead, antimony, selenium, uranium and asbestos.

For consistency with the approach used to assess the health risks associated with toxic elements, defined for impact assessments of environmentally regulated facilities, Andra has decided to use an approach based on toxicological reference values (TRV), as described by INERIS, for assessing health effects, expressing the chemical impact in terms of excess individual risk (EIR) for carcinogenic elements and hazard quotient (HQ[14]) for non-carcinogenic elements. This approach applies to chronic exposure scenarios (i.e. over several years).

4.4 The global approach

4.4.1 A coordinated approach between safety in operation and post-closure safety

An approach enabling design evolutions to be integrated throughout the development of Cigeo, while ensuring post-closure safety.

As part of an iterative process, all changes in technical solutions affecting the closure structures and all changes to the architecture on completion will be examined using the most relevant indicators to check that performance and safety are still guaranteed.

This approach links safety in operation and post-closure safety. It provides a means of managing the improvements and technical evolutions envisaged for Cigeo throughout its operational period and the operating experience feedback, as well as incorporating any changes to regulations or practices nationally or internationally, while still guaranteeing the principle of defence in depth.

The feasibility of using new technologies in the disposal system design will therefore be confirmed by analysing their compatibility with safe operation of the facility and their compliance with the post-closure safety requirements.

Although the final closure of Cigeo will come about a century after the start of its operation, Andra has established a process for incorporating the post-closure safety requirements from the design stage and for checking that these requirements are met using an iterative process as part of the gradual development of the waste disposal facility (see Figure 4.4-1).

[14] HQ: hazard quotient. This is the ratio of the level of exposure to the chemical (concentration in water or air, or daily exposure dose for transfers into the biosphere) to the toxicological reference value (below which there are no systemic effects). INERIS uses the term RI (risk index) instead of HQ.

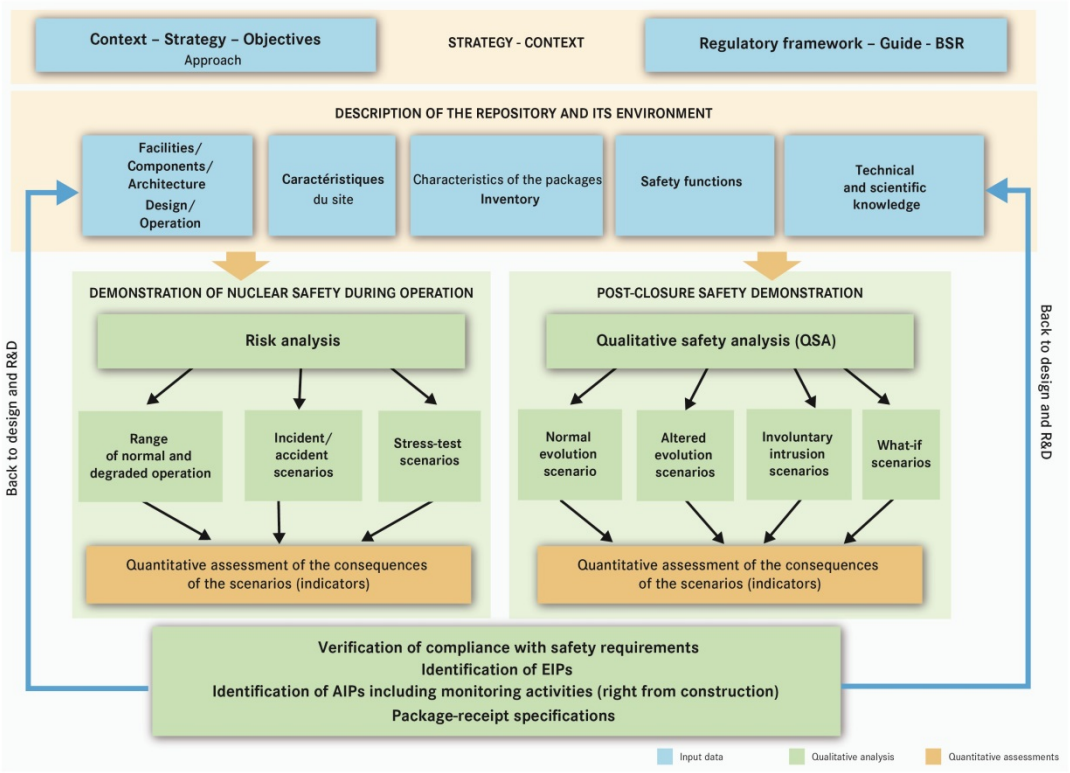


Figure 4.4-1: Diagram illustrating the coordinated approach between safety in operation and post-closure

The approach consists of:

- identifying standards, regulations and the positions of assessors, and the national and international practices that guide choices and design principles and are used as the framework for the safety analysis;
- identifying the post-closure safety functions;
- establishing current knowledge:
  - ✓ of waste packages (inventory and characteristics), and of the geological medium of the site;
  - ✓ of the facility at completion and its location in the Callovo-Oxfordian;
  - ✓ of the technical solutions, particularly by using demonstrators;
  - ✓ of the materials, and scientific understanding of the long-term evolution of the disposal system (engineered components and host formation) and its environment (surrounding formations, biosphere) taking into account Thermal, Hydraulic-Gas, Mechanical, Chemical and Radiological (TH-H-M-C-R) processes in time and space, and the pairing of these different phenomena, particularly on the basis of multiple experiments conducted in laboratories and in situ at the Meuse/Haute-Marne Centre;
- the assessment stage, which must demonstrate that the design options fulfil the safety functions by means of:
  - ✓ analysis of the safety in operation of the disposal facility, in particular by analysing the risks and where necessary introducing preventive and protective measures to reduce these risks;
  - ✓ analysis of the post-closure safety of the facility, in particular by analysing the post-closure uncertainties through a qualitative safety analysis that identifies and evaluates, component by component, the uncertainties concerning the way that the behaviour of the disposal facility will evolve, identified in the phenomenological analysis of repository situations (PARS), to ensure that they are covered by design choices or in scenarios.

4.4.2 Application of the defence-in-depth principle to post-closure safety

The application of the defence-in-depth principle to the post-closure phase is adapted to the specific nature of Cigeo compared to other nuclear facilities, and particularly to the fact that its post-closure safety is based on a "passive" system without any possibility of intervention, which could last for very long periods of time.

The defence-in-depth principle is tailored to the post-closure phase using the following principles:

- At level one, concerning the preventive measures:
  - ✓ various additional safety functions are assigned to the different system component classes to ensure there is a certain amount of redundancy of the safety functions, so that any plausible component failure does not, by itself, compromise the safety of the installation;
  - ✓ the functions are guaranteed for a sufficient period of time, taking account of their respective roles in the overall safety of the disposal facility and the decay of the radionuclides in the waste. The duration and standard of containment are defined on the basis of the nature of the waste;
  - ✓ the safety functions based on the characteristics of the Callovo-Oxfordian formation, the main component of the disposal system, are preserved despite the effects of geological events that could occur, while the dissemination of the residual activity of the waste could still cause unacceptable individual exposure during such events: as the Callovo-Oxfordian formation is located at considerable depth, it is protected from external hazards of human (aircraft crashes, construction sites, surface boreholes, etc.) or natural origin (erosion, climate, etc.); stable formation from a seismic point of view;
  - ✓ the technical solutions chosen are based on proven technologies. The options chosen at this stage are therefore based on a cautious approach. They may evolve between now and the closure of the waste disposal facility (e.g. improvements) on the basis of experience from other nuclear and mining operations, demonstrators at the Meuse/Haute-Marne Centre, feedback from the industrial pilot phase, then during operation and on the basis of scientific and technological progress;
  - ✓ the performance over time of the different disposal system components is checked with regard to the safety functions they must fulfil.
- At level two, to understand the normal evolution of the disposal system following its closure:
  - ✓ from the design stage, requirements and parameters important for post-closure safety are identified and require control and monitoring during construction and operation;
  - ✓ any deviations observed prior to closure are analysed and their impact on the required performance of components necessary for post-closure safety and their general impact in terms of dose is assessed.
- At level three, to test the multi-functional system and the contribution of the disposal system components:
  - ✓ from the design stage of the disposal facility, the possibility of failures is considered. The design aims to limit the occurrence of such failures as far as possible and reasonable. The post-closure safety studies of the repository include, from the design stage, the possibility of the surface-to-bottom connection closure structures failing, as part of altered evolution scenarios, to assess the consequences and check that they remain acceptable in terms of the protection objectives.
- At level four, to assess the robustness of the disposal system:
  - ✓ aggravating factors are taken into account as part of "What-if" scenarios, of which the consequences are assessed.

5

Safety assessment

5.1	*Objectives*	*59*
5.2	*Consistency with international practices*	*59*
5.3	*Assessment steps*	*60*
5.4	*Qualitative analysis of the uncertainties and risks*	*60*
5.5	*Scenarios*	*62*
5.6	*Quantitative assessment of the scenarios*	*64*

5.1 Objectives

In accordance with the safety guide for the geological repository (1), in order to check that the safety functions are fulfilled by the disposal system and that the protection objectives are met, Andra has structured the safety assessment around three objectives [2]:

- checking that, from a safety point of view, the performance of disposal system components designed to contribute to the safety functions individually (packages, engineered components Callovo-Oxfordian), and as a whole, is favourable. The complementary role of the different disposal system components is assessed particularly by demonstrating that, if an engineered component of the facility fails, the disposal system still meets the protection objective;
- assessing the disturbances caused within the disposal system by interaction between its different components and estimating the consequences of these disturbances for the fulfilment of the safety functions, taking account of the preventive and remedial measures included in the disposal system design to minimise these disturbances or their effects;
- modelling the behaviour over time of the disposal system for a set of scenarios, and estimating the impact associated with each of these scenarios. In this context, the evaluation of individual exposure involves studying a limited number of situations representative of the different families of events, or sequences or combinations of events, for which the associated consequences are most severe among all the situations that could be envisaged. This approach requires a selection of events considered to be reasonably plausible and representative of the risks and uncertainties. To comply with the 2008 safety guide for the geological repository (1), altered situations, particularly the occurrence of natural events on an exceptional scale (climate cycles, vertical movements, earthquakes) and events of human origin (drilling of boreholes, design defects or lack of knowledge, etc.) are also envisaged.

5.2 Consistency with international practices

Since the 1990s, in the context of international exercises starting with the PAGIS project, Andra has had regular opportunities to compare itself with its counterparts and to check that its safety approach is consistent with international practices.

In particular, Andra is reusing the global approach presented in the 2001 and 2005 Dossiers, which was evaluated by its peers under the aegis of the NEA in 2002 and 2005.

Since then, the MeSA project, a workshop run in Paris from 1 to 3 June 2015 by the NEA, has enabled Andra to establish international practices for the development and definition of scenarios.

The conclusions of this workshop stress that, since 1999 (NEA workshop on Scenario Development in Madrid), a number of organisations have made methodological developments in defining scenarios. These developments are generally motivated by the need for ""comprehensiveness" in the list of scenarios to be considered, traceability of decision-making, and logical and structured integration of knowledge from various disciplines". In the last few decades, methodological developments have started to take into account the uncertainties resulting from scientific and technical knowledge (FEP) in their scenario identification approaches. This means analysing the effects of these uncertainties on the safety functions. These analyses result in a series of scenarios that generally fall into four generic categories:

1. scenarios that aim to represent the expected evolution of the disposal system taking account of certain or highly likely events or processes;
2. "altered evolution" scenarios, representing events or processes that are less likely but plausible. This category includes scenarios in which disposal system components fail;
3. "What-if" scenarios based on the very unlikely nature of the events considered, or based on conventional choices, to consider for example the loss of one or more safety functions. These scenarios enable some failures to be "pushed" to the extreme and are used to demonstrate the robustness of the disposal system as a whole.
4. inadvertent human intrusion scenarios.

This workshop provided an opportunity to check that the scenario definition method and the scenario classification proposed by Andra were consistent with international practices (17).

5.3 Assessment steps

In accordance with Figure 4.4-1, the safety assessment includes in particular:

- a qualitative analysis of uncertainties and risks of all kinds, to decide on the relevant scenarios and their classification;
- a quantitative assessment of the scenarios chosen.

The qualitative analysis constitutes the basis for verifying that the uncertainties and risks are managed in line with the safety functions to be fulfilled by the design options and/or scenarios.

It demonstrates that:

- plausible component failures will not, by themselves, compromise the safety of the repository post-closure;
- the design measures chosen and the requirements applicable to the design of Cigeo limit their occurrence and consequences.

Definition of the scenarios also forms the basis for the quantitative assessments and assessments of the safety option with regard to the models and data to be used for these assessments.

The overall performance and potential impact of the waste disposal facility on humans and the environment are assessed for each scenario identified.

The quantitative assessment therefore makes it possible to judge the repository's safety functions and the system's overall robustness, and to check that post-closure safety is still controlled and that the requirement to protect humans and the environment is still met.

It constitutes a post-design check, providing assurance that the safety functions assigned to the different repository components are actually fulfilled.

Particularly through the failure and even the "What-if" scenarios, it also helps with the selection of technical solutions by analysing the weight of certain engineered components.

It includes quantification of the performance of the disposal system components using indicators of operation and impact on humans expressed in terms of dose, for a possible transfer of radionuclides to the surface.

5.4 Qualitative analysis of the uncertainties and risks

The qualitative safety analysis identifies and evaluates uncertainties in a systematic way, component by component, as regards their safety functions, and suggests methods for managing them. It evaluates:

- the risks associated with uncertainties about the behaviour of the components, taking account of their long-term evolution;
- the risks associated with future events of external origin.

For a component contributing to a safety function, the analysis examines whether the risks and uncertainties could:

- affect the fulfilment of the safety function and the associated performance required of the component;
- affect the ability of another component to perform its safety function and achieve its associated performance.

The effects produced by one component on another due to a disturbance are also taken into account. The analysis then examines which performance levels of which safety functions may be affected. A reasoned assessment based, where appropriate, on specific calculations is made for the risk of a significant reduction in the expected performance of the components contributing to the fulfilment of the functions. For example, the effect that the uncertainty (or risk) could have on the performance of the post-closure safety functions is evaluated if a worst-case value is used for the parameter in question.

The possible causes of failures of the component(s) in question are then identified and a qualitative judgement is made about their likelihood and effects. The analysis considers the potential transfer pathways of the radionuclides and toxic elements. It therefore looks at:

- the components fulfilling the post-closure safety functions for the repository (e.g. Callovo-Oxfordian, closure structures, etc.);
- components that do not contribute to the fulfilment of a safety function but that are necessary for the assessment (e.g. upper surrounding rock formations, biosphere);
- components that do not fulfil a post-closure safety function but that are close to a component that does fulfil a safety function and are likely to disrupt its operation (e.g. the alkaline disruption caused by the drift liners to the near-field Callovo-Oxfordian).

The uncertainties analysed in the context of post-closure safety are the type of uncertainties presented in the safety guide for the geological repository (1):

- uncertainties over the input data of the repository project (particularly concerning the radiological and toxic inventory of the packages disposed of, the geological medium including the host formation, surrounding rock formations and hydrogeology);
- uncertainties about the intrinsic characteristics of the repository components;
- uncertainties about the processes governing the repository's evolution, including the initial state on closure;
- technological uncertainties.

The risks analysed in the context of post-closure safety are mainly linked to external events, inadvertent human intrusions and criticality. They therefore include:

- uncertainties associated with future events of natural origin (climate-related, geodynamic, etc.);
- uncertainties associated with human activities (intrusions, anthropogenic effects);
- the presence of fissile materials after repository closure and uncertainty about the inventory and the behaviour of the cells over time.

The following methods are used to manage uncertainties or risks:

- repository design options in the form of technical measures that make the system robust with respect to these uncertainties: for example, the use of simple materials with known behaviour (non-alloy steel, concrete, etc.) or the use of a leaktight disposal container to prevent uncertainties about the behaviour of the radionuclides at temperature;
- the decision to use a conservative value for the normal evolution scenario if the effects remain within the normal evolution range (see section below);
- the definition of other scenarios if the effects fall outside the normal evolution range.

5.5 Scenarios

5.5.1 Normal evolution scenario

The normal evolution scenario (NES) encompasses all the possibilities for the expected evolution of the repository over time and space, from its closure, assuming that all the defined safety functions are fulfilled. These evolution possibilities include all the evolutions that seem likely enough to be considered "normal" as defined by the safety guide for the geological repository (1). For this reason the concept of "normal evolution range" is used.

The normal evolution scenario is defined by:

- a reference representation of the repository as designed, which is based on a set of assumptions and data selected on the basis of the best scientific and technical knowledge available. In this context, the characteristics and processes with the most solid scientific support are generally chosen: they produce models and data described as being "to the best available knowledge";
- a representation of the repository corresponding to the requirements applicable to Cigeo. This means that the values for the post-closure safety requirements or performance, used by the designer at this stage of the project, are used. If no requirements have been specified for certain characteristics of the components contributing to the safety functions, assumptions and data corresponding to the most "conservative" limits of the knowledge available are used (e.g. choosing conservative values for the parameters). This representation is described as "bounding" but the concept of bounding in this context does not mean that it ensures the impact is taken into account pessimistically, but that it corresponds to the operation of the repository as specified in the requirements applicable to Cigeo.

The overall approach enables account to be taken of uncertainties with effects still within the normal evolution range. The situation described as "bounding" is less representative of the probable evolution of the repository because it can consider the accumulation of a set of conservative assumptions, even though their simultaneous occurrence is unlikely. So it offers a less favourable vision of post-closure safety.

Furthermore, if a component does not contribute to the post-closure safety functions (e.g. the concrete liners of the drifts), conventional choices could be made that mean its characteristics are not taken into account, even though they could be favourable to delaying and reducing radionuclide transfers. So "pessimistic" models and values are assigned to the processes and phenomena involved (e.g. not taking account of the retention capacity of the drift liners).

5.5.2 Altered evolution and "What-if" scenarios

In the safety analysis, the causes of component failures that could lead to significant degradation of the component's performance or the loss of a function that would bring the disposal system out of the normal evolution range are identified and analysed:

- if the identified causes of the failure are unlikely, then altered evolution scenarios are defined. They aim to evaluate the consequences of the disposal system deviating over time and to check the lines of defence;
- if the causes of the failure are very unlikely, "What-if" scenarios are defined to test the robustness of the disposal system on the same basis as the additional safety assessments used for safety in operation.

The analysis also looks at certain combinations or accumulations of uncertainties, focusing on the effects of potential aggravating accumulations as part of the "What-if" scenarios. It should be noted that some scenarios are conventionally used to respond to the ASN's requests in order to test the robustness of the disposal system.

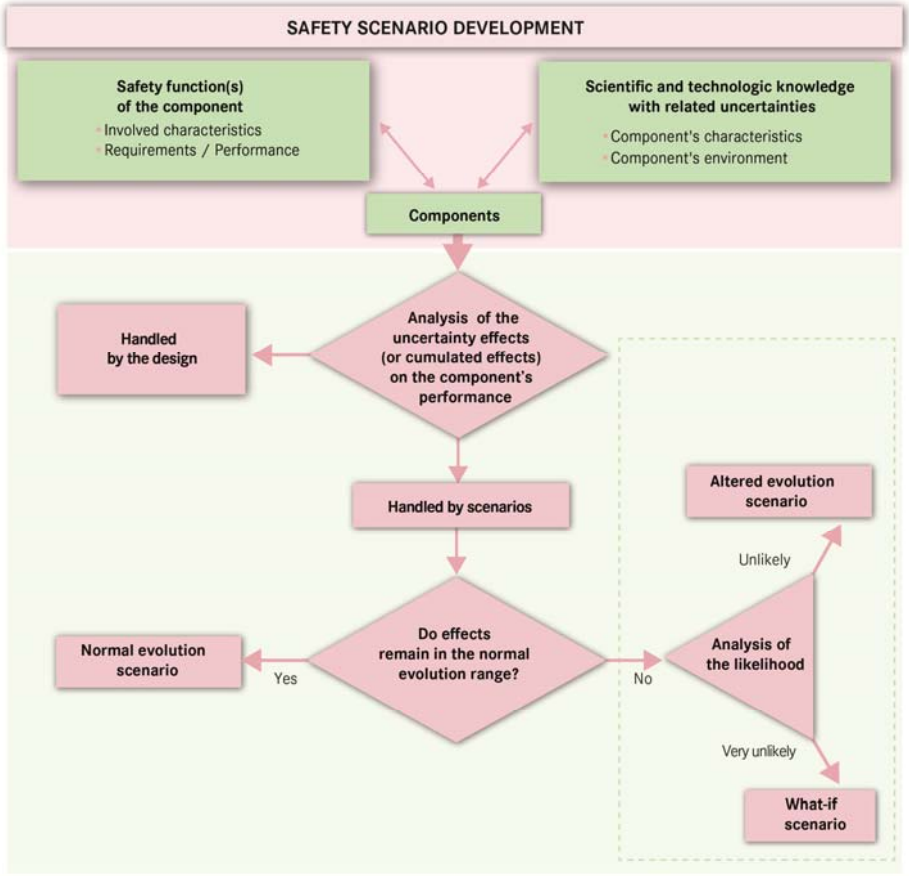


Figure 5.5-1: Schematic illustration of the different stages of a qualitative safety analysis and of the link with the definition of the safety scenarios

The analysis also leads to the exclusion of scenarios considered implausible, resulting from an accumulation of two causes of failure that are completely independent of one another.

5.5.3 Inadvertent human intrusion scenarios

The inadvertent human intrusion scenarios used for Cigeo respond to the requirements in the safety guide for the geological repository (1) (see Volume III). They are intrusion situations due to the drilling of boreholes.

In line with international practices, the description of the bounding scenarios chosen explains the objective and circumstances of the drilling, the location of the borehole in relation to the disposal system, the types of impact potentially generated, the number of boreholes to be considered, temporal aspects, the cases to be considered for evaluation and the associated parameters (see Volume III).

To identify the relevant scenarios and select the scenarios to quantify, a step-by-step approach is used starting with an analysis of the different borehole drilling situations that could occur at the Cigeo site, and arriving at a small number of "bounding" scenarios to be quantified.

- Step 1 - Review of the situations that could be envisaged

For the sake of being exhaustive, the first stage is to review the different situations likely to involve the drilling of boreholes at Cigeo. This review looks at three aspects: the aim and the target geological formation of the drilling operation, the location of the borehole in relation to the disposal structures and any radionuclide or toxic element plumes in the surrounding formations, and the time scale considered for the borehole itself and for the disposal system.

Analysis of combinations of these parameters produces an initial list of "drilling situations" that could affect the operation of the repository.

- Step 2 - Analysis of the situations and selection of the scenarios to be quantified

The chosen situations are examined in relation to the different types of potential impact and their ranking. The aim is to identify scenarios likely to be "bounding" in terms of impact and which, after processing, would provide "conservative" coverage of a series of situations.

In parallel, an analysis is carried out of the drilling situations as regards likelihood. The evaluation of the degree of likelihood is based on a series of factors likely to be involved in the decision to drill the boreholes: the attractiveness of the hoped for or verified resource, the potential for making use of the resource, and the target depth.

5.6 Quantitative assessment of the scenarios

5.6.1 General system for using the calculations

The quantitative assessment of the scenarios is based mainly on numerical simulation. In view of the aim of quantifying the operational indicators, the processes involved, and specifically the release and migration of the radionuclides and toxic elements, should be represented as finely and in as much detail as necessary and possible, particularly at the different scales of time and space (from a scale of tens of metres for the packages to a scale of tens of kilometres for the geological medium). This representation may be constrained by the limitations of the simulation tools' momentum and should reflect the fields of validity and numerical precision of these tools. Understanding numerical simulation as a tool for quantifying the impact of the scenarios therefore requires a structured and high-quality approach to simulation, in terms of both phenomenological and numerical conceptualisation.

At this stage, to represent the overall system combining all the spatial scales, Andra uses a breakdown of the chosen representative numerical model, which includes the multi-layer geological medium (Callovo-Oxfordian, overlying and underlying rock formations, multi-layer geological medium), the repository, and its engineered components (packages, cells, drifts, surface-to-bottom connections, etc.), in several compartments of nested geometric scales, arranged in a simulation sequence. These compartments range from the package to the geological medium containing the repository, as shown in Figure 5.6-2. The sequencing direction of the compartments depends on the process (hydraulic or radionuclide and toxic element transfer) and runs from hydraulics to transfers.

A calculation is made for each compartment and the links between the compartments are taken into account by means of the boundary conditions and release functions (i.e. for flows or radionuclide or toxic element concentration) produced by the previous model, checking how appropriate they are from a numerical and a physics point of view.

The sequencing of the models goes in opposite directions for the hydraulics and the radionuclide and toxic element transfers (Figure 5.6-1):

- for the hydraulics, the first calculation is performed on the largest compartment, which is the multi-layer "regional" geological model; calculations are then performed on the rest of the compartments in descending order of scale. The sequencing of the compartments is assured by the hydraulic boundary conditions (head, water flow rate) from the previous model;
- for the radionuclide and toxic element transfers, the first calculation is performed at package scale (release zone of the solutes) finishing up with a calculation on the largest compartment corresponding to the multi-layer "regional" geological model. The sequencing of the compartments is assured by historical records of the molar flow rates of solutes.

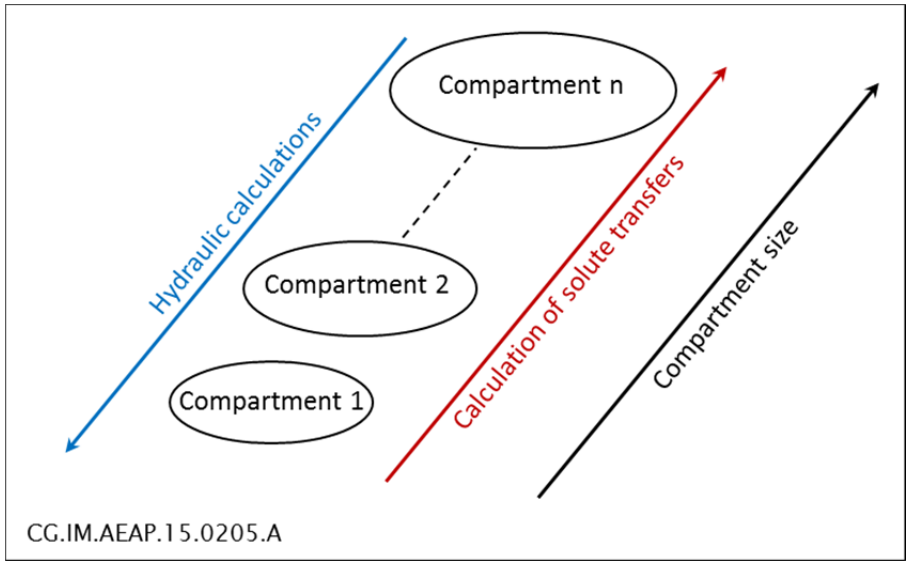


Figure 5.6-1: Sequencing of hydraulic and solute transfer models

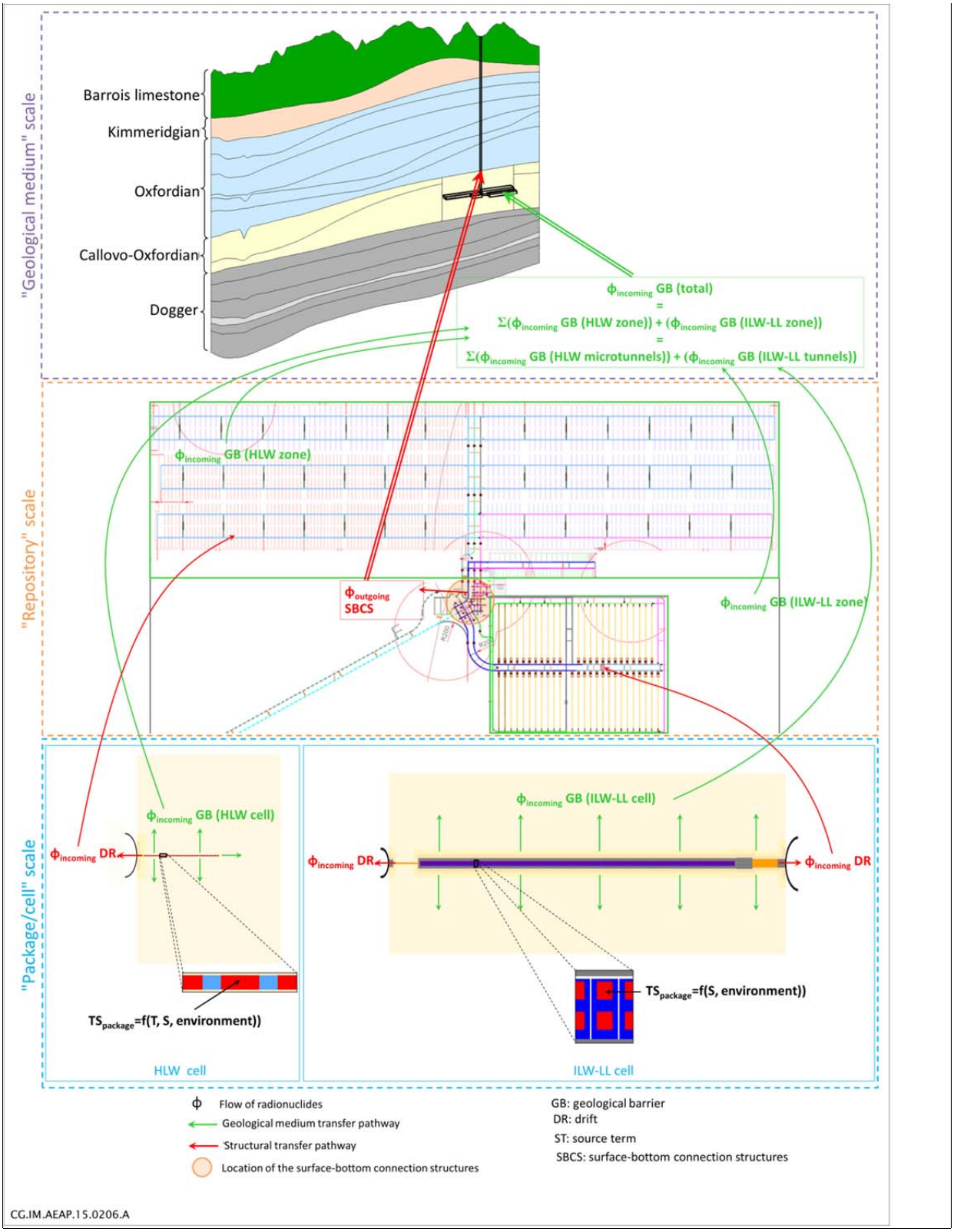


Figure 5.6-2: Principle of nested compartment calculation architecture

As shown in Figure 5.6-2, at this stage the calculation architecture can be broken down into three nested compartments of increasing scale, arranged in sequence as explained in Appendix 4.

5.6.2 Disposal system operational indicators

The post-closure quantitative assessment of Cigeo is based on the values of a set of indicators used:

- to check the individual operation of each component as regards transfers and to assess its performance as regards the post-closure safety functions (see presentation in Volume III, section 1) assigned to it, as well as overall operation;
- to judge the robustness of the repository;
- to eliminate certain uncertainties. For example, unlike the dose rate, the "radionuclide flow on exit from the host formation" is independent of the uncertainties associated with the surrounding formations and the biosphere.

The indicators used for the post-closure safety assessment of Cigeo are:

- the percentage breakdowns between the water flows and the radionuclide (and toxic element) flows by advection and diffusion within the repository and in the Callovo-Oxfordian. These indicators are used to evaluate the "preventing the circulation of water" function and the "restricting the release of radionuclides and immobilising them in the repository" function;
- the breakdowns between the quantity (masses, activities, percentages, etc.) of radionuclides (and toxic elements) emitted or released by the packages and the quantity transiting along and/or within the drifts and surface-to-bottom connections and migrating into the Callovo-Oxfordian, to assess the transfer pathways throughout the analysis duration, taking account of the initial quantity of radionuclides and toxic elements contained in the packages. These indicators are suitable for evaluating the "restricting the release of radionuclides and immobilising them" function and the "delaying and reducing radionuclide migration" function. Although radionuclides with a half-life of less than 1000 years decay entirely within the repository in normal evolution, they are used as appropriate for altered situations. In line with the half-life of the radionuclides, the quantity disappearing through radioactive decay is also taken into account for the quantitative assessment;
- the molar flow rates and activity of the radionuclides (and toxic elements) at the exit from each of the components (package, cell, seals, host formation) over time. These activity rates are used to estimate the reduction capacity of the different components, particularly the host formation (see Figure 5.6-3). These indicators are used to evaluate the performance of the "delaying and reducing radionuclide migration" function. More specifically, the following are considered: (i) the reduction in the flow of radionuclides (and toxic elements), i.e. the fraction of the mass that does not come out of the barrier(s) in question, (ii) the date of occurrence of the molar flow rate maxima, a relevant indicator for radionuclides with a very long half-life on which decay has little impact, and (iii) the reduction in the molar flow rate maxima coming out of the components;
- solution concentration mapping in the Callovo-Oxfordian and the surrounding rock formations, particularly the aquifer horizons. This indicator is used to assess the path of the radionuclides (and toxic elements) at different dates. A comparison of the quantities of radionuclides and toxic elements migrating out of the cell with the quantities released illustrates the "delaying and reducing radionuclide migration" function.

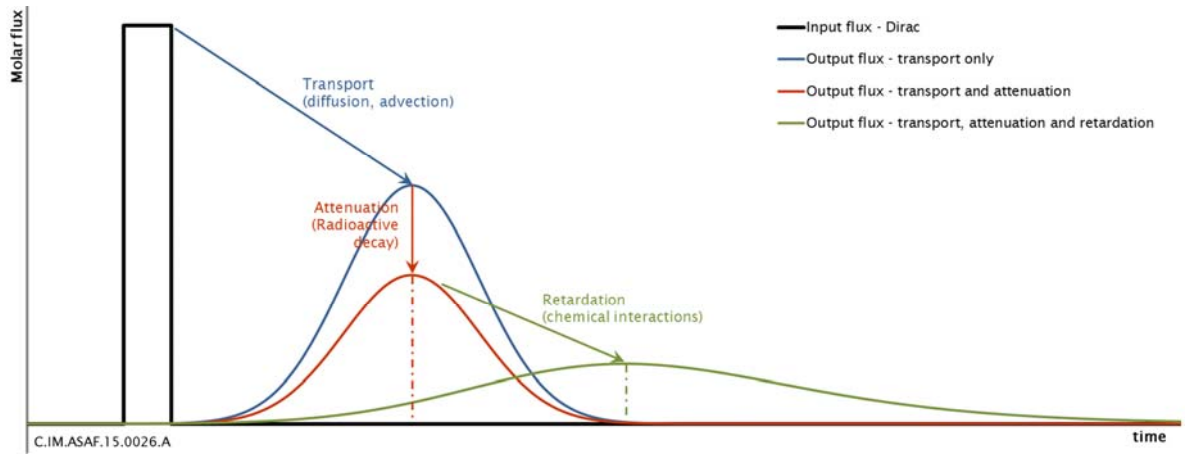


Figure 5.6-3: Diagram showing the use of indicators other than dose, based on the half-life of the radionuclide and its behaviour in solution.

5.6.3 Indicator used to assess the impact on humans

To check that the radiation protection objective set in section 4 is fulfilled, it is necessary to assess the impact of the possible transfer of radionuclides and toxic elements to a potential outlet on the surface. To do this, in accordance with the 2008 ASN guide, hypothetical reference groups are used that are representative of the individuals likely to be subject to the highest exposure. These individuals are assumed to live at least partially self-sufficiently, with a biosphere[15] consisting of the part of the environment easily accessible to their activities.

The biosphere therefore does not fulfil a safety function but is the last link in the chain for modelling transfers of radionuclides and toxic elements to humans from potentially contaminated water and allowing the calculation of their impact in terms of dose.

Taking account of the time scales to be considered, the major regional climatic events predicted are taken into account and the approach used is to identify standard biospheres representative of the different possible states of the biosphere on a larger scale, in view of these events.

In accordance with the standards, and consistent with the IAEA's BIOMASS approach, the selection and description of one or more biospheres to be applied for the quantitative safety assessments are performed in the following stages (see Figure 5.6-4). The approach is described in detail in Appendix 6.

[15] The biosphere is likely to allow the transfer of radionuclides from the disposal facility to these people, leading to internal exposure (inhalation, ingestion) or external exposure.

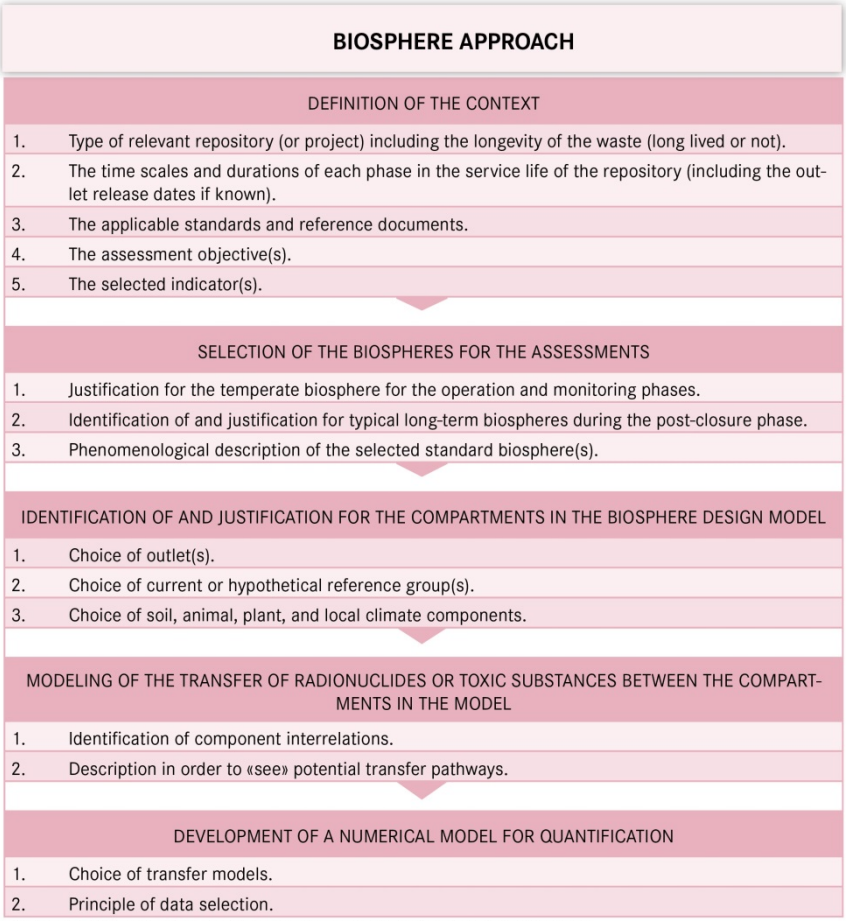


Diagram showing the different stages of the selection and description of a biosphere

Figure 5.6-4: Diagram showing the different stages in selecting and describing a biosphere

6

Safety management

6.1	*Safety management in the integrated management system*	*71*
6.2	*Requirement management*	*71*
6.3	*Compliance with applicable requirements*	*72*
6.4	*Managing design and construction*	*72*
6.5	*Tool management*	*73*
6.6	*Input data control*	*75*
6.7	*Internal and external review process*	*77*

6.1 Safety management in the integrated management system

Andra has set up a management system that meets the requirements of the standards ISO 9001, ISO 14001 and OHSAS 18001. This integrated management system meets the requirement for protection of the interests referred to by Article L.593-1 of the Environment Code. The Andra management system must demonstrate "its ability to regularly provide a product or service which meets customers' expectations and complies with the applicable legal and regulatory requirements, and which aims to improve its customers' satisfaction".

The Andra management system applies to the Cigeo project. In addition, a Cigeo project management plan has been drawn up for the engineering design phase. If defines the rules applicable to the organisation, operation and management of the project in the design phases, particularly as regards management of system and sub-system contracting. The main measures taken to ensure the requirements for protection of the interests mentioned in Article L. 593-1 of the Environment Code are systematically taken into account in all decisions concerning Cigeo are described in the following sections.

6.2 Requirement management

Andra has consolidated the requirements applicable to the Cigeo project in a document. They are arranged according to the functionalities expected of Cigeo. For the sake of completeness, these functionalities were identified on the basis of the functional analysis, which has been gradually developed during studies and research conducted since 1991.

To meet the post-closure safety objectives, the research prompted Andra to identify several specific safety functions (see above). On the basis of the results of studies and research conducted to date, the post-closure safety functions are expressed as a set of specific technical measures to be taken into account by the prime contractor to ensure the safety objectives are met.

The first version of the requirements applicable to the Cigeo project was submitted to a project review held in the first half of 2011 under the aegis of the DGEC. The conclusions of this review were taken into account in subsequent versions. They are kept up to date with scientific and technical advances in parallel with the industrial development of the project, and changes in external context. They include an examination of the technical, economic and time-related consequences of the project and may prompt changes to the project standards (technical specifications of requirements, etc.). The revisions are put before a requirements committee which meets periodically to examine any changes to the technical solutions brought about by advances in knowledge.

The post-closure safety assessment presented in the documents supporting the construction licence application will be based not only on the results of the Cigeo engineering design but also on the evidence of compliance, through this design, with all the requirements applicable to Cigeo concerning post-closure safety. The post-closure safety assessment of the repository requires specific expertise and the involvement of many different disciplines (civil engineering of the underground constructions and nuclear engineering, safety, earth sciences, materials sciences, numerical simulation, instrumentation and data management, etc.) so that the phenomena likely to be encountered can be characterised. Given the unusual nature of this assessment, which is reliant on an understanding of many phenomena (thermal, hydraulic, mechanical, chemical and radiological) in time and space, and the associated uncertainties, and on its years of experience in the field, Andra will be the contractor for this post-closure safety assessment.

The post-closure safety assessment should therefore tie in well with the design approach: Andra insists on taking account of specified requirements when choosing the design options; it must then make sure the proposed design options not only meet those specified requirements but also meet the functional requirements from which they stem. So for each new design option proposed, particularly in terms of repository architecture, Andra will check its impact on the repository's long-term performance in normal or altered evolution. To this end, Andra is conducting assessments characterising the safety level of the repository, as it did particularly when the 2009 and 2012 reports were produced.

6.3 Compliance with applicable requirements

The applicable requirements have been translated into technical specifications of need for the design of Cigeo.

Checking that the requirements for protecting the interests referred to in Article L. 593-1 of the Environment Code have been taken into account is part of the design control process. This process is performed continuously as part of project performance management. Design control is also performed at project progress meetings. It is backed up by the project reviews planned at the end of each phase.

The activities important for protection (AIPs) are performed in accordance with the provisions of the Order of 7 February 2012. The following sections describe the measures taken to perform the AIPs specific to post-closure safety.

6.4 Managing design and construction

6.4.1 Managing contractors and interaction with scientific partners

Where the studies require subcontracting, the subcontractors are bound by Andra's procedures, particularly as regards the quality of the services provided.

Monitoring of the services meets the requirements of the standard ISO-9001 concerning contract monitoring. An annual supplier audit programme is defined and implemented.

Andra is also responsible for coordinating many partnerships on various technical and scientific subjects. These partnerships are defined in line with Andra's scientific policy, based on the following three principles:

- scientific relevance;
- sharing of subjects of common interest;
- establishment of multi-annual research directions.

These partnerships are the subject of technical committee and/or steering committee meetings, particularly to check progress with the research and capitalisation on the knowledge acquired and its deployment, and to define how the research programmes should evolve.

6.4.2 Management of studies linked to the innovative nature of Cigeo - TRL scale

In addition to the engineering studies conducted by the contractors, Andra is continuing its own studies, tests and research to clarify design options, assess the contractors' technical proposals, develop production techniques for the structures, obtain additional substantiating evidence and demonstrations, and prepare documents for the construction licence application for Cigeo.

The new and special nature of the deep geological repository has led Andra to use the international TRL[16] scale as an indicator for assessing the technical progress of the Cigeo project and its various components. However, the project phasing and its decision-making and licensing milestones are not directly dependent on the TRL levels.

[16] The international TRL (Technology Readiness Level) scale is used to quantify the technological readiness of an element (equipment, component, system, etc.). It is described in ISO 16290:2013[7]. It was primarily developed for space systems, but can be transposed to other sectors, particularly to assess the technical readiness of a project or to measure the progress of a technology throughout its development.

6.5 Tool management

The simulation tools used for quantitative assessment of post-closure safety undergo a rigorous selection, development, qualification and approval process. Notably these tools are organised and structured within the Cassandra platform, developed to host them in a single environment (see 6.5.2).

These tools are accompanied by best practices for use and verification at the different stages of their implementation, on the basis of two closely linked needs:

- for the physical aspects, the need to ensure that the processes, models and data are correctly represented in the physics and mathematics functionalities of the calculation tools;
- for the numerical aspects, the need to ensure that the numerical parameters defined by the user allow the mathematical equations for the problem posed to be solved efficiently, accurately, convergently and correctly.

To achieve this, since Dossier 2005 Andra has pursued three types of interdependent action to obtain an array of powerful and properly mastered simulation tools that are capable of meeting the different physical and numerical needs, while guaranteeing the high standard required at each stage in a simulation, particularly for the performance and safety assessments presented in this report. These three types of action are explained below.

6.5.1 An array of tools capable of conducting multiphysics numerical simulations on large temporal and spatial scales

To ensure it has validated, proven tools, Andra's strategy has mainly been to used qualified, approved commercial software and to add to its functionalities so that it can produce fine-grained operational representations of the physical processes (and any coupling of such processes) on large temporal and spatial scales and minimise the errors associated with their use (human error, numerical errors, etc.).

This software development (addition of new physical and numerical functionalities) has been accompanied by the setting up of an application management agreement to provide (i) tool configuration management, systematic qualification of the tools whenever a development is introduced, and integration of feedback on tool use of the tools, including the documentation, (ii) corrective maintenance of the tools, including systematic non-regression testing, and (iii) software implementation, which ensures that the calculation tools are operational and effective Andra's working environment and that of its contractors.

6.5.2 A simplified simulation platform within an array of tools

Following the production of the Dossier 2005 Argile, Andra wanted to maintain a platform system for the performance and safety assessments for this report. However, in order to manage all the developments more efficiently, focus them effectively on its needs and ensure optimal portability and user-friendliness, Andra set up the simplified Cassandra platform for itself, the functionalities of which are described below.

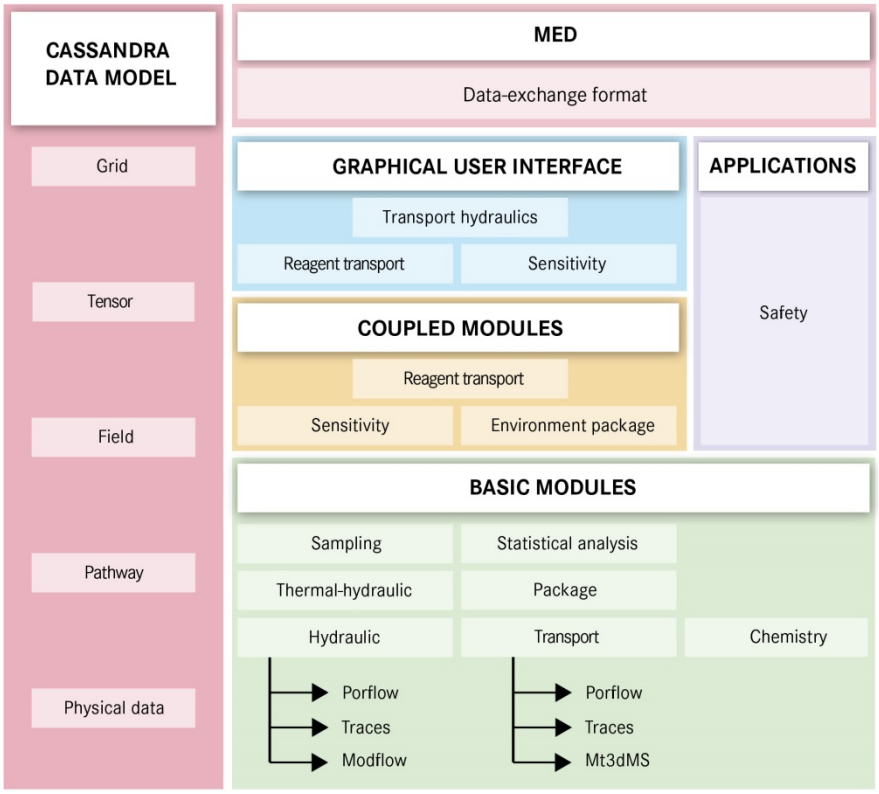


Figure 6.5-1: Architecture of the Cassandra platform

The qualification and validation phase was mainly carried out by physicists capable of performing a fine-grained analysis of the results and assessing the platform's user-friendliness. For the most complex cases, the team relied on external experts to validate the modelling choices and numerical choices used to implement the test cases.

6.5.3 An integrated simulation chain

To conduct the numerical simulations, Andra deployed a very diverse set of tools and associated operations in a simulation chain: (i) pre-processing tools (meshing applications, management tools for physical and geometrical data, CAD, etc.), (ii) processing or resolution tools (the calculation tools on and off the Cassandra platform), and (iii) post-processing tools (executables for extracting or converting information, graphics post-processing tools, etc.). In order to produce and use the simulation chain for safety assessments in a simple, readable, traced and repetitive way, Andra has deployed an integration application, the functionalities of which are described in the figure below.

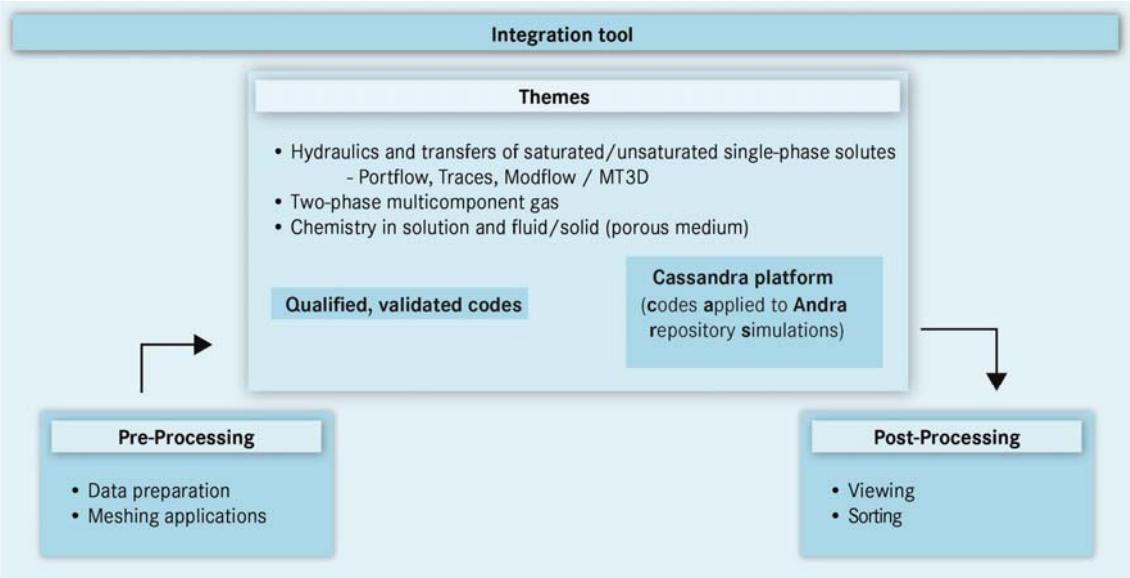


Figure 6.5-2: Calculation chain integrating the various simulation tools used for post-closure safety assessments

6.6 Input data control

The scientific and technical data used to support the preparation of this report play a central role in the selection of the models and the parameter values associated with these models for phenomenological assessments, design dimensioning and post-closure safety assessments.

Of these data, intrinsic knowledge of the waste packages is supplied by the waste producers and is subject to analysis and detailed examination by Andra.

The data concerning the site (geological medium and surface environment) and the materials and engineered components (forming and implementation technologies, physicochemical characteristics, etc.) are Andra's responsibility. They are acquired by Andra itself or through scientific partnerships or subcontracting agreements. This data is notable for its quantity and diversity (geomechanical parameters, geological logs, other types of log, seismic measurements, etc.; technologies for engineered component production and repository operation). Each type of data is acquired by means of various methods, directly or indirectly, and at different spatial scales (in boreholes, from samples, in the underground research laboratory, etc.).

More specifically, Andra is responsible, with the support of the producers, for obtaining data on the behaviour of the waste packages in a repository situation, particularly to ensure the consistency and relevance of the work and its results to intrinsic knowledge of the waste packages.

6.6.1 Data processing chain: from raw to integrated data

This scientific data is subject to a rigorous management and traceability process and needs a formal framework for distribution during internal decision-making processes within Andra.

Arrangements have therefore been put in place to strengthen the quality of the data used and ensure that they are not used in contexts for which they are not valid. This is the case with the data processing and traceability process, from acquisition of the data to their use for phenomenological simulations and simulations for the quantitative post-closure safety assessments, which is used to justify and give credibility to all the values selected and used by Andra. This management is essential, and is designed to:

- ensure data processing is rigorous, justified and appropriate to each type of data;
- trace the different stages in the processing of measurements, from their acquisition to their use;
- allow quick and easy access to all the data and knowledge and ensure they are high quality.

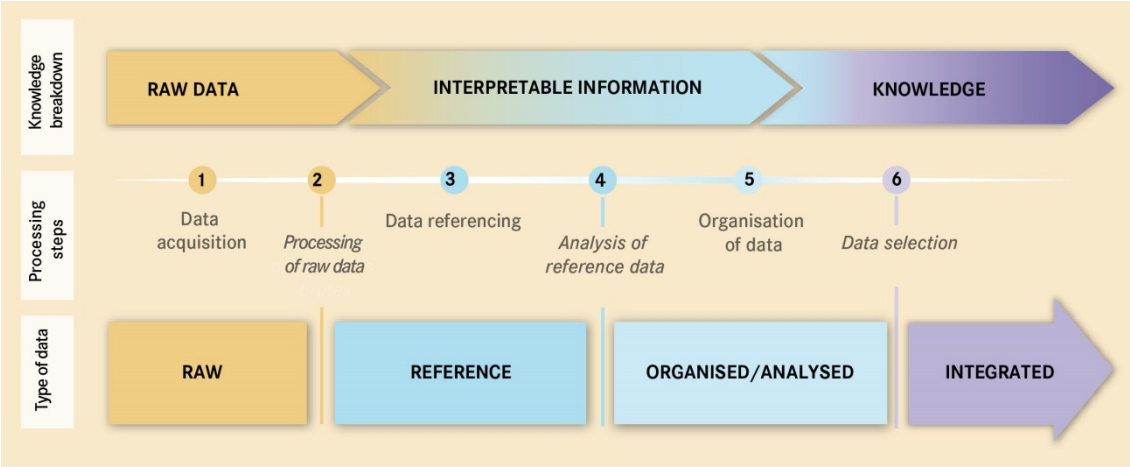


Figure 6.6-1: Diagram of the scientific data processing chain from acquisition to use

In this process, the scientific data are organised in four main categories depending on the processing they have received (sorting, statistical analysis, etc.):

- raw data: these are the scientific data acquired from boreholes, experiments and samples which have not undergone any processing;
- reference data: these are the raw data that have been processed to ensure their relevance and validity. During this processing (known as referencing), the raw data are checked (aberrant data are discarded and, in some cases, calculations are necessary to finish up with the reference data). These data are declared and may be used in analyses;
- structured/interpreted data: these are the reference data that, following statistical analysis and any processing, are put back to the scale of the object they are characterising (e.g. the scale of a geological formation, a geological unit or an engineered component of the repository). They are interpreted in terms of their representativeness, variability in space and time, and uncertainty;
- integrated data: these data come from data structured by making conceptual choices, usually a space/time assessment of processes on the scale of engineered components and/or the geological medium, or a performance assessment.

The management of these data relies on a series of databases and documents (knowledge reference documents, concept notes, etc.) that can be used to carry out critical analyses depending particularly on their nature and use.

6.6.2 Processes for selecting data and scientific knowledge for the safety assessments

Control of the data used for the models and calculations is based on a formalised process set up as part of the phenomenological analysis of repository situations, which requires every space and time scale to be taken into account in the evolution of the repository, and every type of interaction (thermal, hydraulic, mechanical, chemical and radiological).

In parallel, the production of knowledge reference documents on specific topics (materials, release models, site geology, the inventory model) provides overall consolidation.

Andra has identified model and parameter types and a classification for their position in relation to uncertainties, depending on whether they are "phenomenological", "conservative" or "pessimistic" models and values, defined on the basis of how they affect the quantitative safety assessments:

- a phenomenological value is a value that is deemed to be most likely or most representative and, if all other parameters are fixed, produces the best match between the model results and the measurement results;
- a "conservative" value is a value that, of all the values produced by studies and measurements, corresponds to the upper (or lower) boundary of the range of values available, and which produces a calculated impact within a high value range (all other parameters being fixed);
- a "pessimistic" value does not refer to the available phenomenological knowledge, but is conventionally chosen as definitely leading to an impact greater than that obtained from calculations using possible values.

This system means that data can be used in full knowledge of their confidence level as regards impact assessment as part of the quantitative safety assessment.

Andra has also introduced a system of internal reviews aimed at analysing the models and data used for the safety calculations, to ensure the justification for choosing these models and data for the safety scenarios envisaged is more widely supported and validated.

6.7 Internal and external review process

In addition to the process of reviewing the requirements described in section 6.2, Andra has also set up a system of internal reviews for analysing data, models and safety options to be used for the safety assessments. These reviews are used to validate the options chosen and their justifications:

- set up by decree, Andra's Scientific Council is responsible for issuing opinions and recommendations on the priorities of research conducted by Andra and evaluating its results, particularly with regard to the challenges of acquiring and using scientific or technological knowledge for the design and safety of the disposal system. On this basis, the Scientific council has systematically examined all or part of previous reports relating to this;
- in addition, Andra has made an effort to submit certain design and safety work for independent evaluation where this has appeared relevant. The development of Cigeo has been subject to a process of design reviews at every key stage (conceptual design, basic engineering design, detailed engineering design). This process has also involved safety experts. In 2012, Andra set up a safety committee to bring in external safety experts.

A number of different reviews or their external equivalents have also been and are being conducted:

- established by the Act of 30 December 1991, the National Review Board (CNE) assesses the quality of Andra's work and produces an annual report giving its opinion of this work. These opinions and recommendations are input data for refining the research programme’s priorities;
- as part of the Cigeo project development process, since 1991 Andra has submitted a number of interim reports to the ASN, and opinions and recommendations have been made with a view to the construction licence application. The ASN also carries out "monitoring inspections" particularly of the Meuse/Haute-Marne Centre, during which it assesses the quality of work in progress, particularly in the underground research laboratory;
- lastly, to check consistency with international practices, at the request of Andra's supervisory ministries, two peer reviews were organised in 2002 and 2005 by the OECD's Nuclear Energy Agency. At the ASN's request, a review is planned in 2016 under the aegis of the IAEA (18).

VOLUME II – DESCRIPTION OF THE DISPOSAL SYSTEM

1

Location Site Characteristics

1.1 A simple geological context well known through substantial geological survey work 81
1.2 Justification of the favourable properties of the Callovo-Oxfordian , and of the location of Cigeo 85
1.3 Well-defined representation of groundwater flows in the surrounding formations of the Callovo-Oxfordian 96
1.4 Limited and slow internal geodynamics 100
1.5 A stable formation in an environment that shows little change over the next million years 101
1.6 No sterilisation of natural resources 107
1.7 Other characteristics of the site involved in the safety assessment 108

Satisfaction of the safety functions is based in the first instance on the favourable characteristics of the Callovo-Oxfordian in its natural state (19) (20) (21)), which are required to play a central, long-term role.

Andra has carried out substantial survey work from the surface and in the Underground Research Laboratory on the Cigeo site, in particular in the Callovo-Oxfordian formation. The survey results show that the Cigeo site, and more particularly the Callovo-Oxfordian formation in which the underground facility of Cigeo is located, meets the site technical criteria of the 2008 ASN nuclear safety guide (1) to achieve the fundamental objective of long-term protection of the public and the environment. The 2008 ASN guide criteria are given in Appendix 6.

1.1 A simple geological context well known through substantial geological survey work

1.1.1 Consecutive campaigns of geological investigations and scientific work to characterise the site

The representation of the geological setting, and more particularly of the Callovo-Oxfordian, is based on the acquisition of knowledge of its geological history and its characteristics in its present state.

Until 2005, this was based on campaigns of geological investigations and on a major programme implemented in the Underground Research Laboratory on borehole samples and in situ measurements.

Since 2005, more detailed knowledge of the geological setting has been obtained by two seismic surveys: a 2D survey of the transposition zone (ZT) and a 3D survey of the zone of interest for detailed reconnaissance (ZIRA) in which the Cigeo underground facility is to be located. It has been supplemented by the drilling of 15 deep boreholes at various points in the transposition zone. Additional data has also been obtained by ongoing work in the Underground Research Laboratory. This body of work provides a detailed understanding of the geological environment of the Meuse/Haute-Marne site and a 3D model of the geological setting, close to the geological reality.

The body of knowledge can be used to:

- make sure that the Callovo-Oxfordian has the required properties with regard to the site selection criteria in the ASN safety guide (1);
- justify the location of the Cigeo facilities, including the underground facilities in the Callovo-Oxfordian, with regard to optimum satisfaction of their safety functions, taking account of the technical and territorial integration constraints;
- assess the long-term behaviour of the geological setting, including the effect of any disturbances generated by the repository (structures and disposal packages) and the effect of external (climate) and internal geodynamic changes.

A consistent overall representation of the site is obtained, for example of the sedimentological, structural, hydrogeological, geomechanical and geochemical aspects, giving a reconstitution of its geological history up to the present state and a projection of its future evolution. This representation serves as the basis for assessments of the performance of the repository.

1.1.2 Geological history of the Meuse/Haute-Marne sector

Geologically, the Meuse/Haute-Marne site belongs to the eastern boundary of the Paris basin. The general structure of the basin today takes the form of a bowl filled with a sequence of sedimentary layers deposited between 250 million and 135 million years before present, the oldest of which (Lower Triassic) outcrop on the edges of the basin and the most recent (Neogene) in its centre, in Ile de France.

The sedimentary sequence, more than 1800 m thick vertically below the site, has a regular dip of 1 to 1.5 degrees to the north-west, towards the centre of the Paris basin, with a low-amplitude undulation oriented east-north-east/west-south-west (Figure 1.1-1).

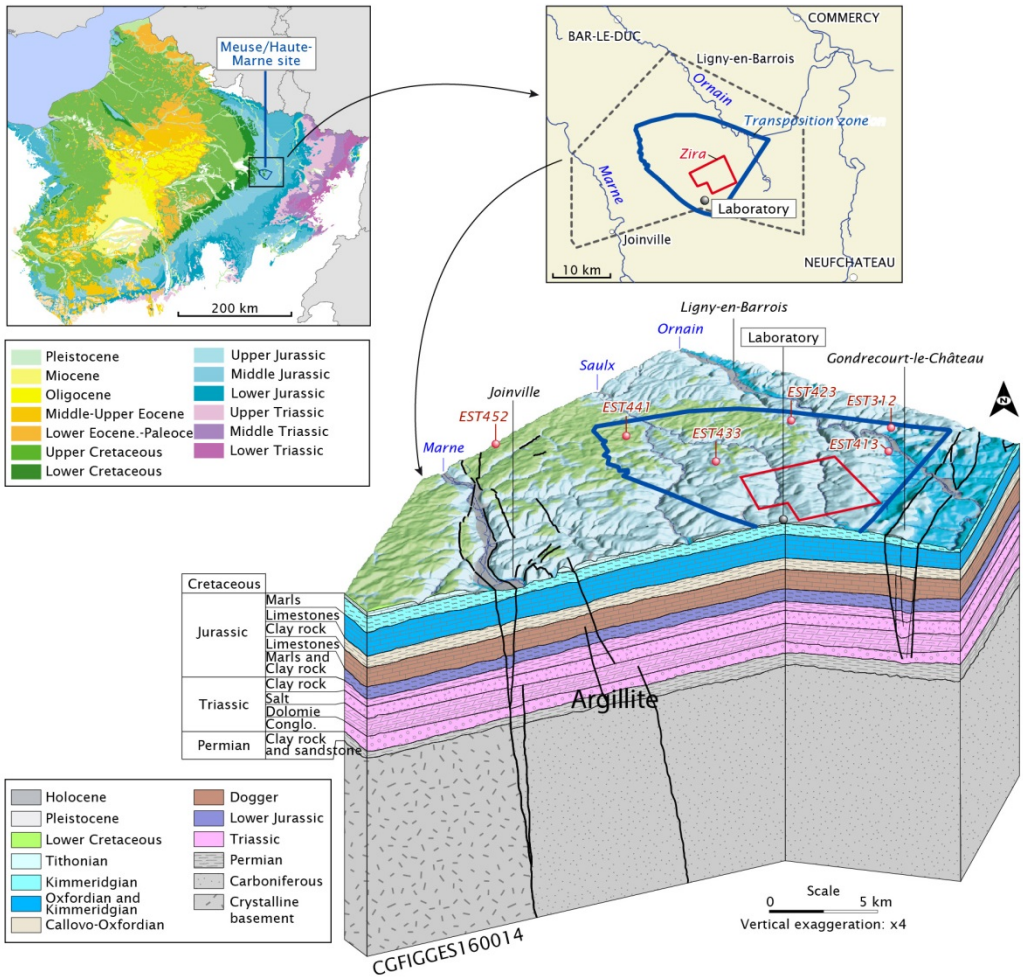


Figure 1.1-1: 3D geological block diagram of the Meuse/Haute-Marne site

The present structure of the basin formed gradually during the Tertiary epoch (65 million years BP) following various phases of tectonic activity (Pyrenean compression phase, Oligocene extension phase and Alpine compression phase). It has not subsequently been greatly affected by tectonic activity. It is a remarkable zone of the west European plate, where the lithosphere has uniform thickness and stands out due to its practically aseismic character.

Two major families of faults border the Meuse/Haute-Marne sector (Figure 1.1-1):

- the faults marking the Joinville graben to the south-west of the sector and Gondrecourt graben to the south-east of the sector: they are not rooted in the basement, cut straight narrow grabens in the Jurassic sedimentary cover and fade away deep in the base formations of the sedimentary cover (Triassic salts and Permian clay rock);
- the Marne faults: these are basement discontinuities.

In the west of the sector, this regional fault system is subdivided into small faults and forms a discrete fracture zone before disappearing towards the south-east, beyond the Gondrecourt graben.

Located within the block bounded by these faults, the ZT (and de facto the ZIRA) constitute a domain free of detectable faults in the Callovo-Oxfordian formation and its surrounding formations, demonstrated both by the surface mapping work and by the seismic reflection surveys of the ZIRA (throw detection threshold of 2 to 5 m with 3D seismic processing techniques).

In the zone under study, the sedimentary sequence consists of alternating predominantly argillaceous formations and predominantly limestone formations, as listed below from bottom to top (and from east to west at outcrops):

- the Dogger limestone formation overlying the Lias marls and clays,
- the Callovo-Oxfordian clayey formation,
- The middle-to-upper Oxfordian limestone formation ,
- the Kimmeridgian marl,
- the Tithonian limestone (or Barrois limestone), outcropping at the site,
- a few Cretaceous clayey-sandy superficial deposits of low thickness, capping the highest points of the relief.

The alternation of soft clayey formations and resistant limestone formations, along with the general dip of the layers towards the west and the north-west, gives a typical relief of cuestas at the outcrops. This relief is the result of continuous change since the emergence of the sector at the end of the Cretaceous, linked with tectonic change, in particular as a consequence of the alternation of glacial-interglacial cycles over 3 million years, including the formation and thawing of permafrost. The current model thus comprises (i) in the south and east of the sector, the Oxfordian limestone plateau, forming the Meuse cuestas, (ii) towards the west, the marly depression corresponding to the Kimmeridgian, within which intervals of clayey limestone form small hillocks, very visible in the landscape, (iii) the Barrois limestone, in the form of a broad plateau on which the Underground Research Laboratory is installed and the ZIRA is located, capped by Lower Cretaceous superficial deposits and cut into by rivers.

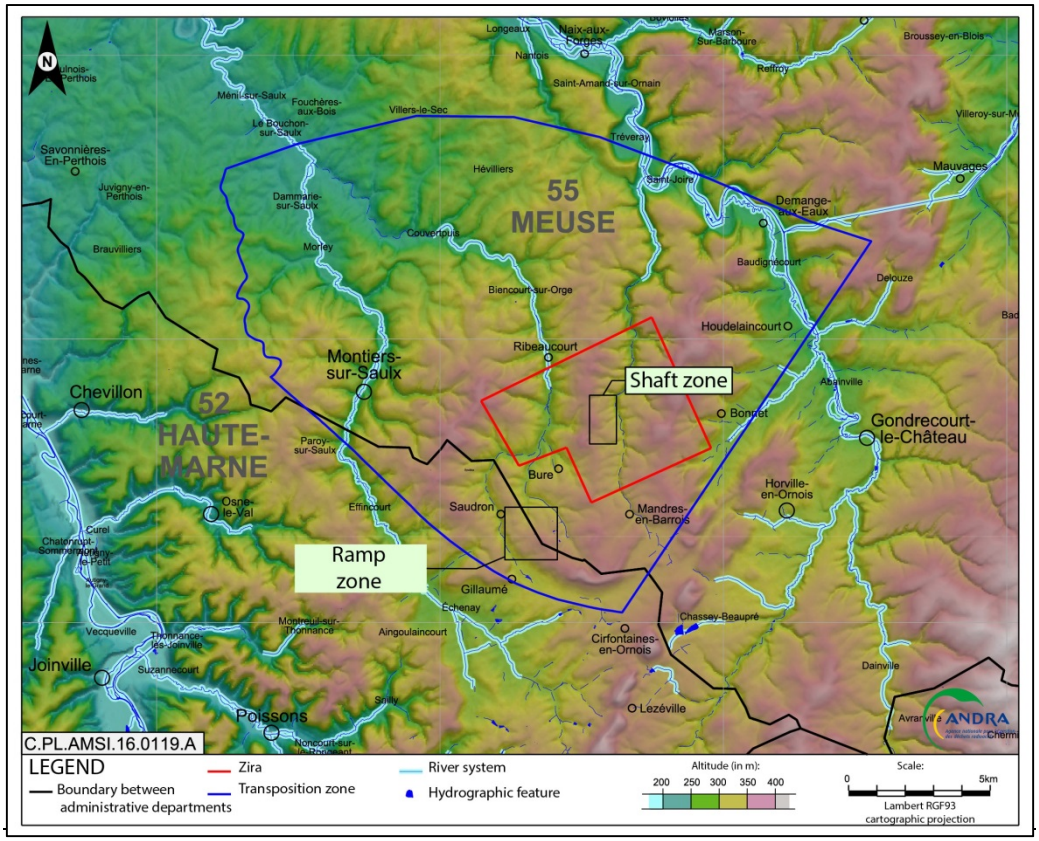


Figure 1.1-2: Topographical map of the area around the ZIRA

1.2 Justification of the favourable properties of the Callovo-Oxfordian , and of the location of Cigeo

1.2.1 A very thick formation located at a considerable depth

In the ZIRA, the depth of the Callovo-Oxfordian, and consequently of the Cigeo underground facility, substantially below 200 m ([17]), protects the disposal system from erosion processes (refer to § 1.5.2), from the effect of an earthquake, or from a simple 'normal' human intrusion, and ensures satisfaction of the function "isolate the waste".

The sub-planar layer geometry of the Callovo-Oxfordian and its thickness of at least 140 m in the ZIRA (see below) enable it to accommodate the underground facility while, given the planar architecture of the facility, leaving undisturbed Callovo-Oxfordian host rock of substantial thicknesses above and below it. These undisturbed host rock thickness of are an integral part of the disposal system and make a substantial contribution to the containment of the radionuclides and toxic substances contained in the waste over long timescales.

The geometrical boundaries and the depths of the Callovo-Oxfordian, along with the associated uncertainties, are well defined, identified and quantified inside the ZT, and more particularly inside the ZIRA thanks to the 3D seismic survey and the correlations with the numerous boreholes:

- the top and the bottom of the Callovo-Oxfordian formation are assimilated respectively with the SNC (non-conformity surface) and LS0 (sequence boundary 0) surfaces. These surfaces are recognised directly down the boreholes available outside the ZIRA and indirectly by interpretation of the 2D and 3D seismic surveys of the ZT and of the ZIRA. The dip of these surfaces is 1.9% on average and less than 2.8% for the majority of the values (90%);
- in the ZIRA, the thickness of the Callovo-Oxfordian formation (Figure 1.2-1) varies from approximately 140 m to 160 m from south-west to north-east, conforming to the main direction of the sediment sources came;
- the top of the Callovo-Oxfordian formation is located at depths between approximately 340 m and 530 m, its geometrical mid-height between approximately 420 m and 600 m (Figure 1.2-2) and its bottom between approximately 500 m and 675 m;
- the Callovo-Oxfordian formation is slightly tilted towards the north-west (1° on average).

[17] The 2008 ASN nuclear safety guide states that the thickness of the surface zone that could be disturbed in this way is in the region of 200 metres, in principle.

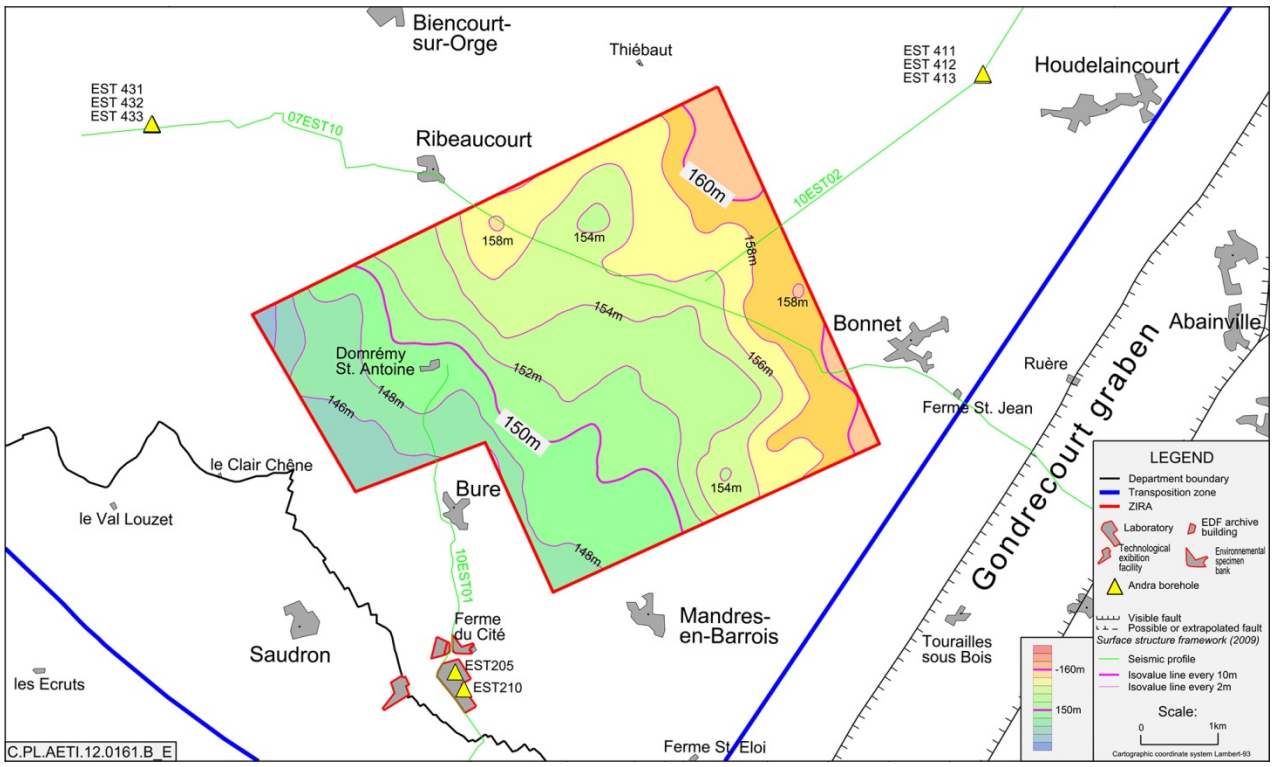


Figure 1.2-1: Thickness (m) of the Callovo-Oxfordian in the ZIRA (between surfaces SNC and LS0)

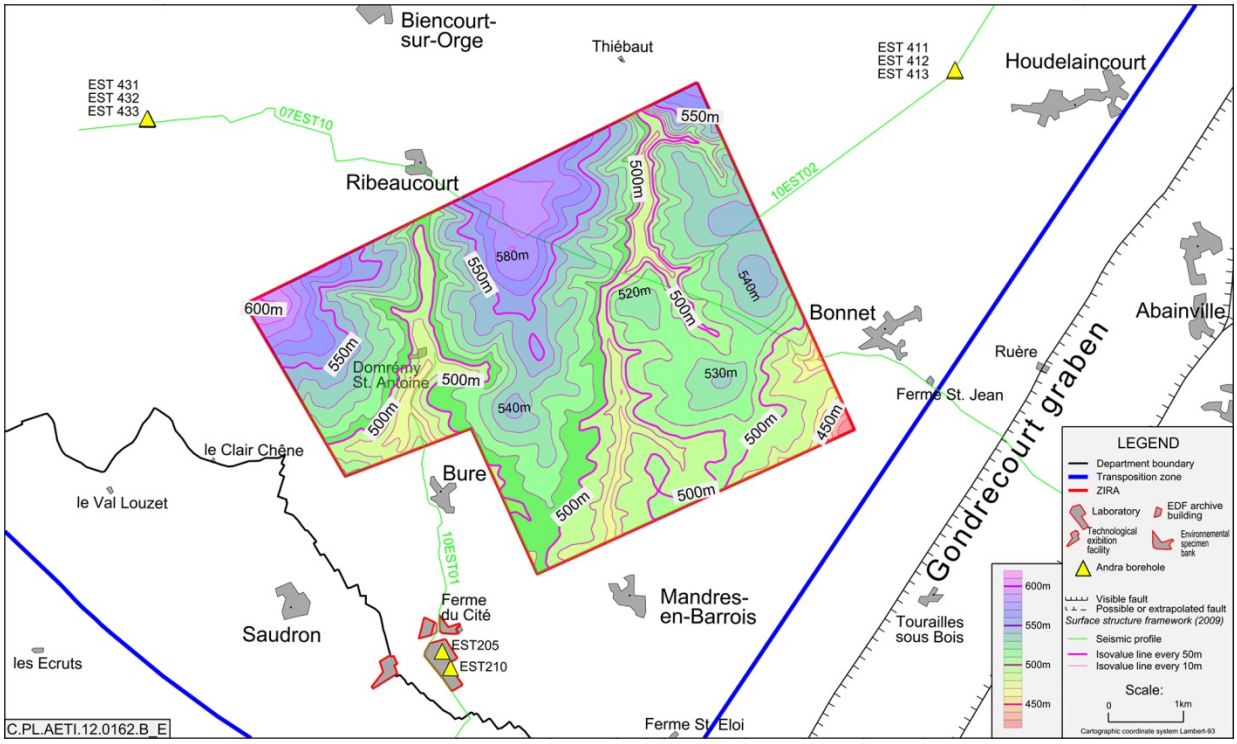


Figure 1.2-2: Depth (m) of the geometrical mid-height of the Callovo-Oxfordian in the ZIRA (from the topographical surface)

- Given the proximity of the calibration boreholes (i.e. points) and their number in the ZT and the resolution of the 3D seismic survey of the ZIRA, the residual uncertainties of the geometrical parameters of the Callovo-Oxfordian are quantified and controlled: a maximum of approximately

10 m for the depth of the geometrical boundaries of the Callovo-Oxfordian and a maximum of approximately 6 m for its thickness in the ZIRA.

1.2.2 A formation with considerable lateral continuity

Laterally, the Callovo-Oxfordian generally shows the same vertical organisation over an area of more than 350 km2 encompassing the ZT; this organisation is in fact practically identical in all the boreholes located within a radius of 15 km around the Underground Research Laboratory, according to the logging recordings and the mineralogical composition (Figure 1.2-3).

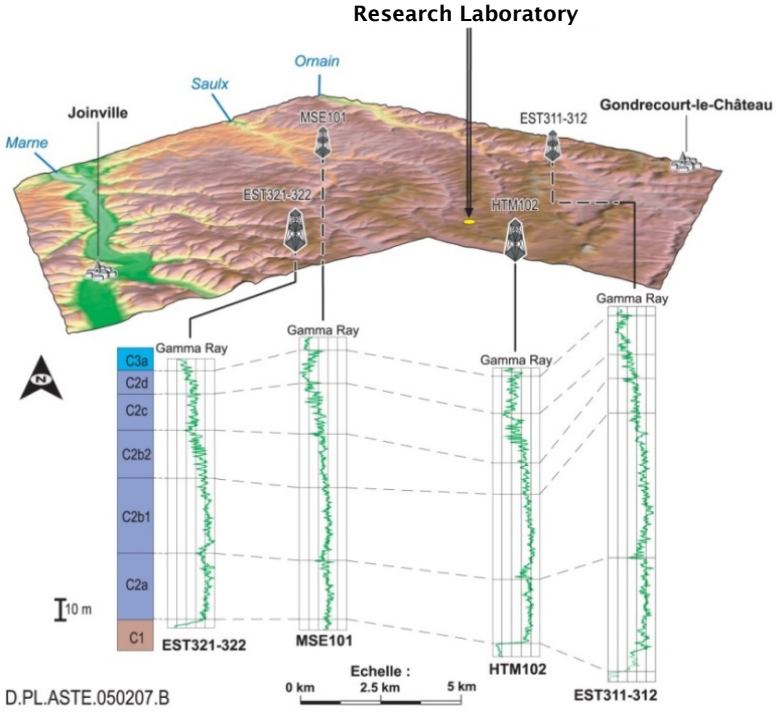


Figure 1.2-3: Lateral homogeneity of the vertical organisation of the Callovo-Oxfordian in the sector under study (gamma ray logging recording)

The lithological continuity of the Callovo-Oxfordian laterally over large distances is explained by the origin of its constituent sediments and the calm tectonic and sedimentary context of their deposition, about 155 million years ago. This context is a basis for predicting that there is no sedimentation hiatus in the transposition zone with an amplitude likely to disturb the vertical and lateral continuity of the Callovo-Oxfordian, as well as the absence of sandy lenses (turbidites), given the long distances from the sources of material.

The sediments were deposited under water of a depth of the order of a hundred metres during periods of high sea level, in an open and calm marine environment; the nearest emerged areas constituting the sources of sediments were located in the "London-Brabant" massif, corresponding to what is now the Ardennes. The distance from these sources explains the fine particle size of the mineralogical constituents. The Callovo-Oxfordian thus shows three main mineralogical phases: a predominantly clayey phase (40% to 45% on average), a calcareous phase (mostly calcite, with a few percent of dolomite) and a silty phase (of fine particle size: silts). The small variations of the proportions of these mineralogical phases are associated with the fluctuations of the relative sea level. These variations, coupled with the burial of the Callovo-Oxfordian in the past, are the main causes of petrophysical variations of the Callovo-Oxfordian. Nevertheless, the late and discrete diagenetic processes, regional in extent, were not able to alter the characteristics of the Callovo-Oxfordian locally and significantly.

Moreover, the Callovo-Oxfordian contains between 0.5% and 1% of organic matter. The predominance and persistence of the biomarkers in the hydrocarbon molecules and the abundance of thermally-unstable forms are evidence of the immaturity of this organic matter. This shows that the temperature of the Callovo-Oxfordian has remained low (about 45°C) throughout its history, which is compatible with its maximum burial in the Cretaceous.

Quantitative geostatistical analysis of the variability of the physical properties measured in logs and of the mineralogical and sedimentological data obtained from samples results in a representation of the Callovo-Oxfordian in three large geological units, from bottom to top (Figure 1.2-4):

- a clayey unit (UA), the thickest (approximately 100 to 120 m), the most homogeneous and the richest in argillaceous minerals (more than 40% on average) of the three. It includes the more carbonated Repère Inférieur Oolithique (RIO) (lower oolitic marker bed), at the Callovian/Oxfordian transition, and accounts for the lower two-thirds of the Callovo-Oxfordian formation. It can be divided into three subunits with small and progressive variations. Subunit UA2 corresponds to the stratigraphic level where the clay content is highest and in which the Underground Research Laboratory experiments are carried out;
- the transition unit (UT). It forms a transition between the mainly argillaceous rocks of the UA and the rocks of the silty-carbonated unit (USC) with the highest carbonate contents (40% to 90%);
- the silty-carbonated unit (USC), twenty to thirty metres thick, with considerable vertical petrophysical variability linked with the lithological alternations (carbonaceous marls and siltites). It comprises levels with more contrasted and heterogeneous mineralogical composition. These units show an alternation of carbonaceous siltites and marls. The gradual enrichment in carbonates in this unit marks the establishment of the upper Oxfordian carbonaceous platform. The unit includes the RSO "Repère Supérieur Oolithique" (upper oolitic marker) carbonaceous bed.

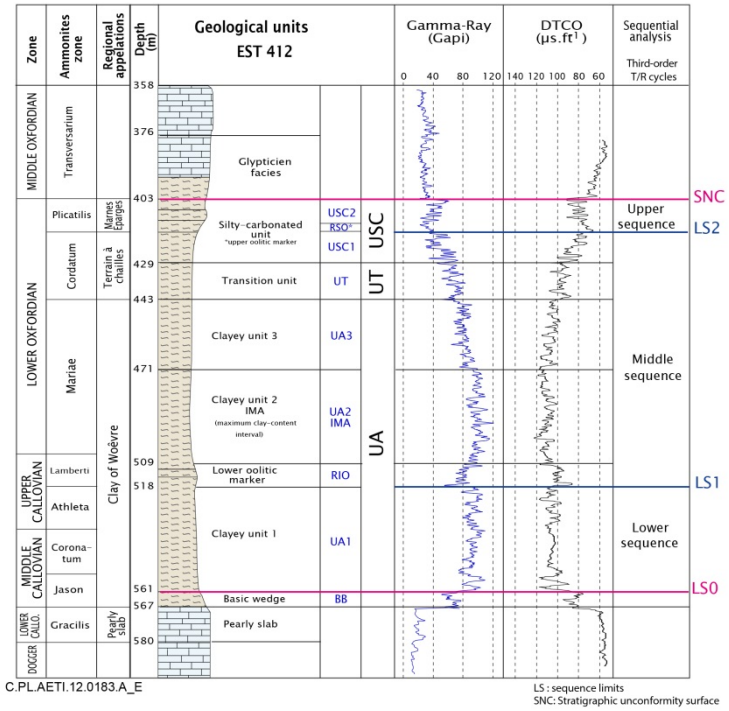


Figure 1.2-4: *Main geological units of the Callovo-Oxfordian: argillaceous unit (UA), transition unit (UT) and silty-carbonated unit (USC). The geological boundaries of the Callovo-Oxfordian are marked by the surfaces LS0 and SNC.*

1.2.3 A formation without structural heterogeneities

Detailed examination of 350 km of seismic profiles of the sector shows that the tectonic deformations that have affected the region in the last 150 million years are slight and limited to the large structures at the edge of the ZT (Gondrecourt graben and Marne graben). Between these structures, the Callovo-Oxfordian is uniform and has low dip.

According to the results of the investigations carried out by Andra (2D and 3D seismic surveys; boreholes, including the deviated boreholes in the Callovo-Oxfordian in proximity to the Underground Research Laboratory), no major fault (vertical throw greater than 10 m and decakilometric extent) or secondary fault (throw greater than 5 m and multikilometric extent) has been observed in the transposition zone in the Callovo-Oxfordian, nor in the overlying limestone formations.

On the site of the Underground Research Laboratory, the deviated boreholes did not pass through any minor faults (maximum extent a few hundred metres and vertical throw 2 to 3 m) below the detection threshold of the 2D and 3D reflection seismic methods, despite their orientation perpendicular to the two structural directions and their cumulative subhorizontal length of more than 1500 m. Furthermore, no minor fault has been intercepted by the Underground Research Laboratory drifts, which have a cumulative length of about 1600 m at present.

The structures observed in the boreholes are located at the top of the Callovo-Oxfordian; they correspond mainly to joints, tensile cracks and a few rare subvertical stylolithic joints. There are few of them, they have no displacement, and most of them are plugged (in particular by calcite or celestite). They do not affect the geometry or the permeability of the Callovo-Oxfordian.

1.2.4 Properties favouring immobilisation and retention of radionuclides

The physicochemical properties of the Callovo-Oxfordian are the consequence of the nature of the constituent minerals, in particular the clayey minerals and the carbonate minerals, and of their configuration. The configuration bounds the voids (pores) which are the locations of the interstitial water containing chemical species and dissolved gases likely to move by advection or by diffusion. The porosity (void volume as a proportion of the total volume) varies between 14% in the most calcareous levels of the Callovo-Oxfordian and 19.5% in the most clayey levels. The pores are nanometric in size, with a major diameter of about 20 nm. Because of this small size, the water is structured between bound water on the pore surface and free water in the centre of the pores. The bound water accounts for about 50% of the pore water, forms continuous films, and cannot be displaced by a pressure gradient (difference).

1.2.4.1 A well-defined chemical composition of the water favouring low solubility of most radionuclides

Knowledge of the chemical composition of the interstitial water has been refined gradually by analyses of clay rock samples and experiments in situ in the Underground Research Laboratory, following various protocols, and by geochemical modelling.

Some characteristics of the chemical system of the pore water are particularly important factors with regard to radionuclide behaviour: pH, redox potential (Eh), concentrations of natural ligands (including CO_3, SO_4, Cl and organic molecules), and concentrations of cations competing for sorption sites on the clays (including Na^+, K^+, Ca^{+2}, Mg^{+2}, Sr^{+2}, Fe^{+2}). They have been defined, in particular through the results of the PAC experiment in the Underground Research Laboratory on sampling for chemical analysis, which verified the validity of the Callovo-Oxfordian interstitial water geochemical composition model. This experiment supplied a narrow range of values at any point of the Callovo-Oxfordian in the transposition zone for the various parameters that determine the chemical composition of the interstitial water, and established this chemical composition over the complete thickness of the formation, consistent with the overall lithological evolution of the formation. The interstitial water has a neutral pH, slightly above 7. It is reducing (Eh - 180 to - 200 mV), as shown by the presence of stable pyrite and of organic matter. Chemically, the water contains calcium and sodium carbonates, with a sulphate and chloride component. The data on the stable isotopes of the carbon ($\delta^{13}C$) of the dissolved

bicarbonates supports the hypothesis of chemical and isotopic equilibrium between the interstitial water and the carbonate mineral phases (calcite, dolomite, ankerite).

The solubility, the aqueous speciation and the degree of oxidation of each radionuclide and toxic chemical has been evaluated using thermodynamic modelling, according to a sensitivity analysis approach, in order to cover a range of plausible compositions. In general, in the pH (neutrality) and Eh (reducing medium) conditions imposed by the Callovo-Oxfordian, most of the radionuclides have low solubilities, including the actinides and the lanthanides. Only the halides (Br, I, Cl) that are not controlled directly by the equilibrium with the mineral phase are completely soluble.

1.2.4.2 A proven capacity of retention by sorption

The retention capacities of the Callovo-Oxfordian are based on the clayey minerals, which interact strongly with the radionuclides by sorption. The characterisation, understanding and representation of the properties of retention by sorption of the Callovo-Oxfordian clay rock are based on various experimental programmes and a modelling approach integrating the various geochemical processes.

The determination of the solid-solution partition coefficients (Kd) of the radionuclides in the Callovo-Oxfordian is based mainly on measurements obtained in retention experiments on a batch system. The estimated measurement uncertainty is less than 30%. For the alkaline and alkaline earth ions (retention by cation exchange), a three-fold variability linked with the variability of the content and the nature of the clayey fraction is observed. For the majority of the radionuclides, the sorption is represented by a linear adsorption isotherm model (constant Kd).

The retention levels measured in the Callovo-Oxfordian depend essentially on the nature of the species. They show little variation in comparison with the vertical spatial variability of the Callovo-Oxfordian (mineralogy). Very high retention values (Kd greater than 1 m^3/kg) have been measured for most of the major actinides and lanthanides. Most of the transition metals and uranium and caesium have high retention values (Kd in the region of 0.1 m^3/kg or more). Only chlorine and iodine do not show any retention in the clay rock (in comparison with the experimental uncertainties).

The determination of the partition coefficients of some radionuclides, in the absence of experimental data, is based on (i) mineral matrix analogies (opaline clays), (ii) behavioural analogies between the various radionuclides, (iii) the geochemical modelling results supported by a body of experimental data.

1.2.5 Hydraulic characteristics that limit water circulation

The Callovo-Oxfordian has hydraulic characteristics (permeability and hydraulic head gradient) that limit water flows within the Callovo-Oxfordian itself and potentially in the underground facility over the long term after its closure.

1.2.5.1 Very low measured permeability to water

The permeability of the Callovo-Oxfordian is determined by the structure of the porosity and the distribution of the constituent minerals, and more precisely by relative area of the pore cross-sections where free water is located and by their degree of connectivity. It has been measured on more than 200 samples, oriented parallel or perpendicular to the stratification and several centimetres in size, by in situ tests on a scale from several decimetres to several metres in boreholes and in the Underground Research Laboratory. Two measurement methods have been used: a pulse test method based on transient conditions (measurements on samples and in situ) requiring an interpretation model, and a steady-state method (on samples). The measurements have been subjected to statistical and geostatistical analyses, distinguishing the methods used and taking the metrological uncertainties into account. According to the results:

- the permeability is very low, which can be explained by the clayey nature of the Callovo-Oxfordian and the fineness and very small diameter of the pores;
- no significant vertical or lateral variability of the permeability is observed at the scale of the Callovo-Oxfordian, in comparison with the measurement uncertainty (less than 1 or 2 orders of magnitude for the tests in situ and on samples with the pulse test method);
- the measurements acquired by pulse test:
  - ✓ show a large variability;
  - ✓ are on average an order of magnitude higher than those acquired in steady state;
  - ✓ show a low anisotropy ratio between horizontal permeability (Kh) and vertical permeability (Kv) (about 2 to 3);
  - ✓ show median values of Kv and Kh of about 2.10^{-13} m/s and 4.10^{-13} m/s, respectively;
- the measurements acquired in steady state show very low variability, with low anisotropy, and have a median value of about 4.10^{-14}/s.

1.2.5.2 Long-lasting low hydraulic gradients in the formation

The vertical hydraulic head gradients at the scale of the Callovo-Oxfordian formation are determined by measurement of the hydraulic heads in the surrounding rock formations (Oxfordian and Dogger limestone). The data have been acquired during consecutive survey campaigns on different measurement points and using different methods. The measurement uncertainties are less than one metre.

The measurements reveal a relative shallow hydraulic head gradient between the overlying and underlying formations (generally between - 0.1 m/m and + 0.1 m/m in the ZIRA with an uncertainty of less than 0.05 m/m). The measured and simulated hydraulic head iso-gradients in the Callovo-Oxfordian are illustrated in the figure below.

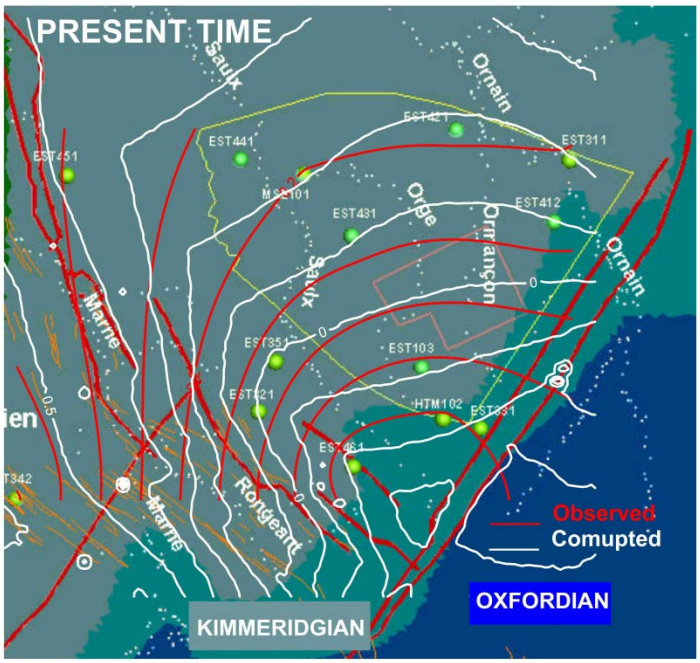


Figure 1.2-5: Hydraulic head vertical iso-gradient lines at the scale of the Callovo-Oxfordian

The measurements of hydraulic head in the Callovo-Oxfordian reveal an overpressure with respect to the hydraulic head profile determined by the heads at the top and the bottom of the Callovo-Oxfordian in the Oxfordian limestone and the Dogger, respectively. This overpressure is not uniform in the Callovo-Oxfordian: it is organised according to a bell profile skewed towards the top of the Callovo-Oxfordian, with a maximum value of about 40 m (to be compared with the hydraulic head values in the Dogger and the Oxfordian limestone of about 290 m and 305 m above sea level, respectively).

Overpressure is common in deep clayey formations of sedimentary basins and various hypotheses for its origin have been formulated (chemical osmosis, variation of hydraulic or mechanical boundary conditions at the top and at the bottom, etc.). The origin of the overpressure in the Callovo-Oxfordian is not yet fully explained, but its existence is an indicator of the very low permeability of the Callovo-Oxfordian. Whatever their origin, these overpressures have a negligible effect on water flows and on radionuclide transfer.

It thus appears that all the measurements acquired by the various methods confirm the very low permeability to water of the Callovo-Oxfordian and the shallow vertical hydraulic gradient in the formation; this results in very low water movement speeds in the Callovo-Oxfordian, of the order of a few tens of centimetres per 100,000 years, i.e. taking more than 40 to 50 million years to pass completely through the Callovo-Oxfordian.

1.2.6 Diffusion properties that limit radionuclide migration

1.2.6.1 Low diffusion coefficients

The diffusion properties of the Callovo-Oxfordian have been studied using various tracers. The diffusion behaviour of a series of anionic (chlorine, iodine), cationic (caesium, sodium, strontium, calcium, europium and others) and neutral (tritiated water HTO) tracers has been studied intensively with diffusion tests on samples of centimetric size. More than 130 measurements have been carried out for HTO, 70 measurements for chlorine and 30 for iodine. The spatial variability of the results is relatively low. Tracer injection tests carried out *in situ* in the Underground Research Laboratory (DIR [Diffusion of Inert and Reactive tracers] experiments) over several years and tests on models (decimetric samples), confirm the values obtained with borehole core samples.

The measurements show an expected difference in behaviour between anions, cations and neutral species due to their physicochemical interactions with the charged surfaces of the clayey minerals. The anions are repelled from the negatively-charged clayey surfaces, which excludes them from part of the pore system: this is the anion exclusion process, and it results in diffusion coefficients, and porosities accessible to diffusion, lower than those measured for HTO. In contrast, the cations are adsorbed on the clayey surfaces, resulting in effective diffusion coefficients (De) significantly higher than that of HTO (up to 10 times higher for caesium) as a function of the affinity of the cation for the clayey surfaces, but which nevertheless remain low. For example, the anionic species chlorine has a De of $5x10^{-12}$ m²/s, while the cationic species caesium has a De of $2.5x10^{-10}$ m²/s.

1.2.6.2 Small values of Porosities accessible to diffusion

Total porosity has been measured in samples by water content measurements and in boreholes by nuclear magnetic resonance logging, supplying a large number of measurements representative of the lithological variability of the Callovo-Oxfordian, with a very low uncertainty (a few percent). The total porosity is used as a reference value for the porosity accessible to radionuclide diffusion; because of anion exclusion, the porosity in which anionic radionuclides can diffuse, is smaller than the total porosity.

The porosities accessible to anionic, neutral and cationic radionuclides are determined by interpretation of the tests of diffusion of the reference tracers for anionic (chloride) and neutral (HTO) radionuclides.

The values of porosity accessible to diffusion measured by tritiated water diffusion tests are consistent with the total porosity values, whereas the values measured with chloride are lower than the total porosity, the majority between 4% and 10%, and show a dispersion through the whole of the formation.

1.2.6.3 Predominant transfer of solutes in the Callovo-Oxfordian by diffusion

Analysis of the hydraulic and diffusion characteristics of the Callovo-Oxfordian, and the natural distribution of certain solutes (ions, dissolved gases and isotopes) in the Callovo-Oxfordian, suggest that, in relative terms, diffusion is the predominant process for radionuclide transfer in the Callovo-Oxfordian. This transfer is nevertheless very slow because of the low diffusion coefficients: the times to peak molar flow rate for an unsorbed, highly soluble anionic radionuclide (such as chlorine-36), from the disposal facility to the top of the Callovo-Oxfordian with an overlying thickness of undisturbed Callovo-Oxfordian host rock of about 60 m, are approximately 750,000 years.

Figure 1.2-6 and Figure 1.2-7 below show the characteristic diffusive transfer times (here corresponding to the occurrence of peak molar flow rate at the top and bottom of the Callovo-Oxfordian) of uranium-238 and iodine-129, respectively, evaluated on the basis of (i) a repository 10 metres thick located at the geometrical mid-height of the Callovo-Oxfordian, (ii) observed diffusion and retention property parameter values. It can be seen that, in the predominant diffusion context, the sorption capacity contributes significantly to delaying the arrival of the radionuclides at the top or the bottom of the Callovo-Oxfordian (uranium-238 compared with iodine-129, which is not retained in the clay rock).

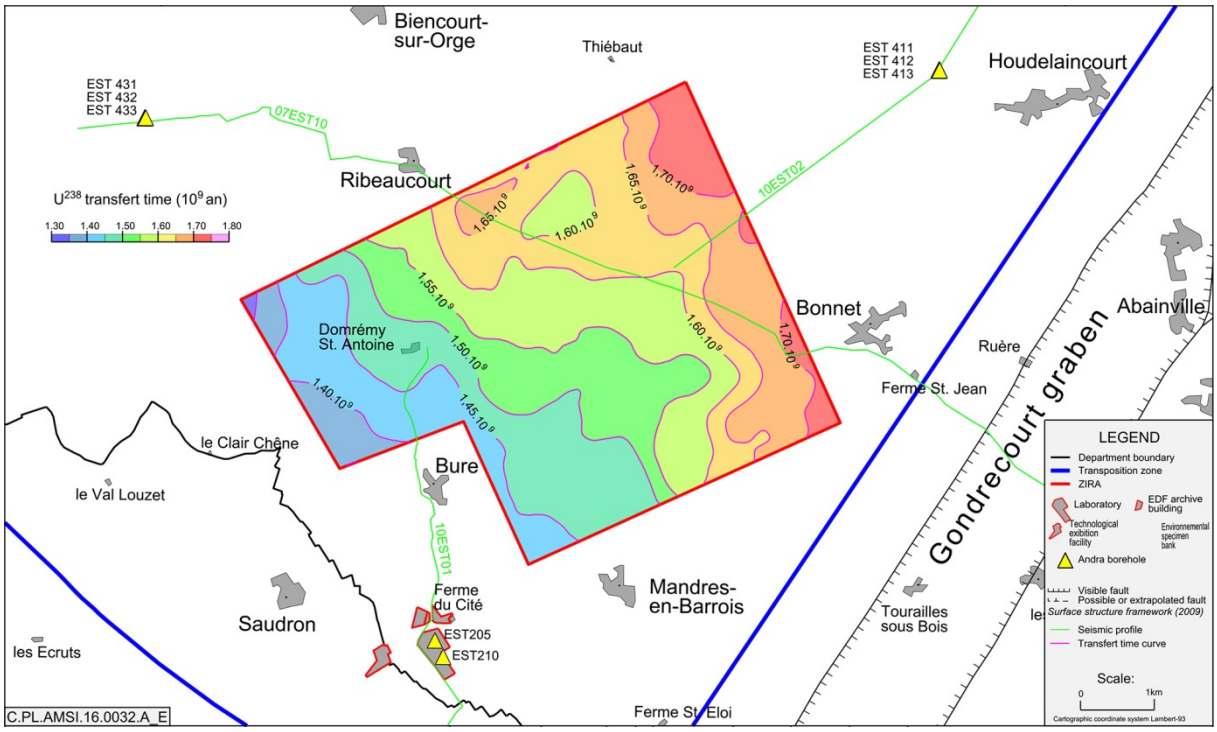


Figure 1.2-6: Map of the ^{238}U transfer times for a repository located at mid-height in the Callovo-Oxfordian

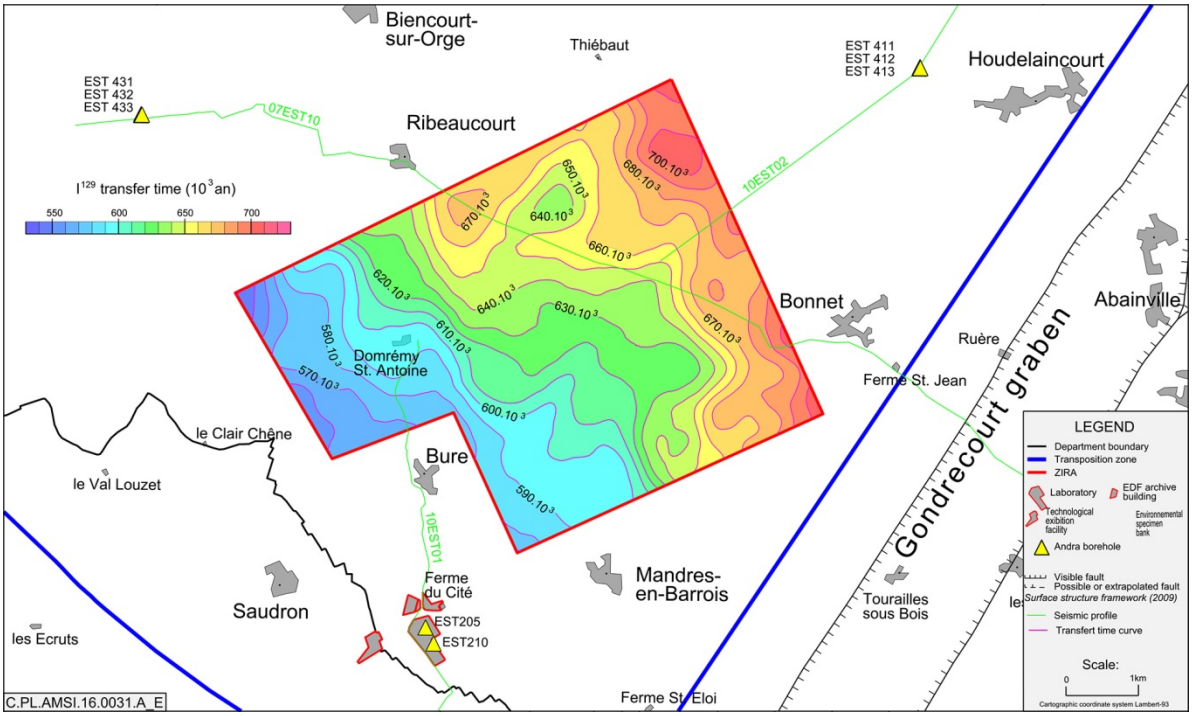


Figure 1.2-7: Map of the ^{129}I transfer times for a repository located at mid-height in the Callovo-Oxfordian

1.2.7 Specific mechanical properties according to lithostratigraphic unit: absence of marked damage and/or hydraulic self-sealing

Specific mechanical strengths between UA and USC units

The mineralogical characteristics of the Callovo-Oxfordian lithostratigraphic units impart specific mechanical properties and self-sealing capacities to the corresponding clay rock. Because of the high content of carbonates and their organisation in practically a 3D skeleton, the USC unit have higher mechanical strength than the UA unit, in which the non-clayey minerals, in particular the carbonates, are organised as inclusions in a clayey matrix.

Specific damage in UA and USC units

In the USC unit, where the clay rock has high mechanical strength, little damage is observed during the excavation of underground structures, with some tension gashes (multicentimetric) and microcracking, none showing continuity along the structures.

In contrast in the UA unit, where the clay rock has less strength is, substantial localised damage is observed, with the appearance of shear fractures forward of the excavation face and extension fractures after the face has passed. Whatever the diameter of the structure (within the range tested at the Underground Research Laboratory), a given fracture system is formed, organised in two zones from the wall:

- a connected fracture zone (ZFC). In this zone, several families of fractures coexist: shear fractures and extension fractures, but also mixed fractures, mainly fractures formed initially by shear and subsequently opened under the effect of the convergence of the structure. A dense 3D system of fractures is formed. Local geometric opening of the fractures varies greatly, and can reach several millimetres at/or very close to the wall;
- a zone with "discrete" fracturing (ZFD). Beyond the connected fracture zone, only the extremity of shear fractures remain. The fractures are not connected physically with each other, and show submillimetric opening.

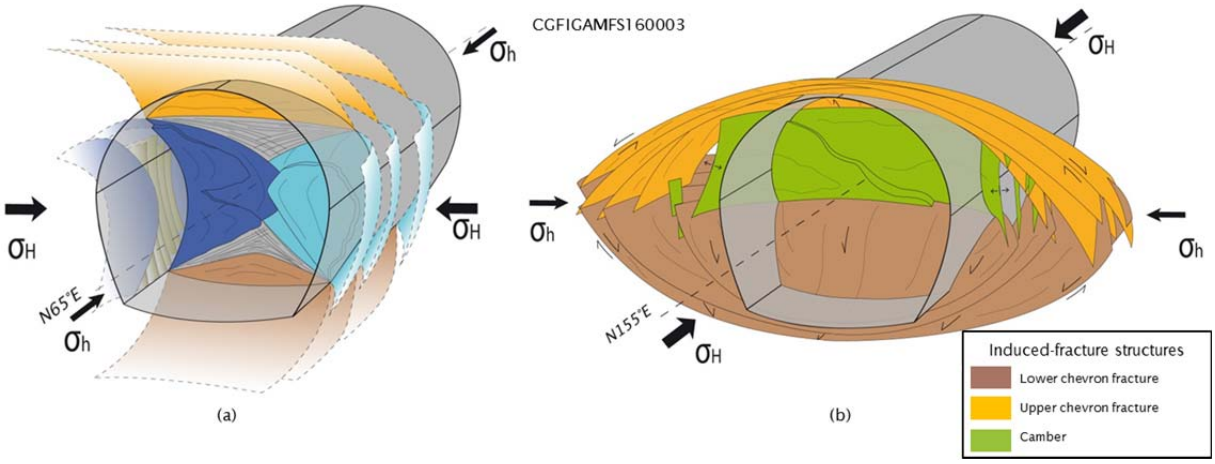


Figure 1.2-8: *Fracturing generated around structures according to their orientation in relation to the major horizontal stress (a)Drift oriented along the minor horizontal stress (b)*
Drift oriented along the major horizontal stress

Variable spatial organisation of damage around horizontal structures excavated in the UA unit according to the orientation of the structures

Analysis of the factors influencing the fracturing, based on all the data acquired at the main level of the Underground Research Laboratory, i.e. in the UA unit, shows that the direction of excavation has little effect on the nature of the generated fracturing, in contrast to the extent of the fractured zone, which is highly dependent on the orientation of the horizontal structure in relation to the major horizontal stress: for structures oriented along the minor horizontal stress (N65°E), the extent of the damaged zone is predominantly vertical, whereas in the direction of the major horizontal stress (N155°E) the extent is predominantly horizontal.

The different excavation/support methods tested at in the Underground Research Laboratory have not shown any significant effect on the nature and extent of the connected and discrete fracture zones.

Specific hydraulic properties of damaged zones in USC and UA units

- Little change of damaged zone permeability in the USC:

The initial characterisation carried out in 2005 around the drift at - 445 m shows low permeabilities (less than 10^{-11} m/s), which is consistent with the absence of connected (continuous) fractured zone. These observations have been confirmed by the measurements made in the main shaft. The permeability decreases from the drift wall, between 10^{-11} and 10^{-13} m/s, in the first two metres of the rock.

- Initial permeabilities of the damaged zone in the UA unit significantly modified in comparison with the permeability of undamaged clay rock, and a self-sealing capacity over time:

In the connected fracture zone (ZFC), the initial (i.e. soon after excavation) "local equivalent permeabilities", determined on the basis of hydraulic tests with water carried out at the Underground Research Laboratory, generally vary between 10^{-5} m/s and 10^{-10} m/s, sometimes with lower values. Permeabilities lower than 10^{-12} m/s measured on samples located between the fractures indicate the low volume of clay rock damaged between these fractures. The transmissivity of the connected fracture zone is attributed to the open fractures. Beyond the connected fracture zone, in the discrete fracture zone, the initial permeability decreases with the distance from the wall: the extent of the zone of permeability greater than or equal to 10^{-12} m/s, beyond the connected fracture zone, is estimated to be equal to the radius of the structure.

The hydraulic measurements around the structures in the Underground Research Laboratory show a gradual decrease in the permeabilities over time. The permeabilities can decrease by several orders of magnitude and tend towards those of undisturbed clay rock. This phenomenon, "self-sealing process" is also observed in laboratory samples, including for fractures with millimetric opening. Analyses of the fractures at very small scales show the role played in self-sealing by the smectite minerals contained in the clay rock, which swell in the presence of water and clog the fractures. Mechanical stresses can be added, helping the mechanical closing of the fractures and thus contributing to their clogging.

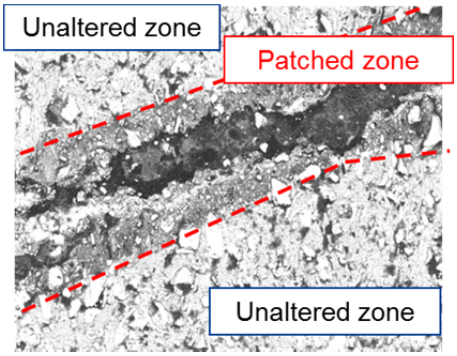


Figure 1.2-9: Clogging illustration of fractures in the UA unit, from an SEM photograph (millimetric scale)

- High hydraulic and gas fracturing:

The acquired data, in particular from in situ borehole, emphasise the high hydraulic and gas fracturing of the UA unit, about 12 MPa and between 10 and 12 MPa, respectively.

1.3 Well-defined representation of groundwater flows in the surrounding formations of the Callovo-Oxfordian

The hydrogeological (i.e. water flow) system below the Meuse/Haute Marne site and more particularly below the ZIRA is a multi-layer system comprising (Figure 1.3-1):

- aquifers in the formations of the Barrois limestone, Oxfordian limestone, the Dogger and the Upper and Lower Triassic formations;
- semi-permeable formations or levels: the Kimmeridgian marls, the Callovo-Oxfordian clay rock, the clayey formations of the Liassic and the clayey and evaporite levels of the Middle Triassic.

In the transposition zone, the flows in the rock formations immediately overlying and underlying the Callovo-Oxfordian (Oxfordian limestone and Dogger limestone) are independent, because of the hydraulic characteristics and the thickness of the Callovo-Oxfordian.

Outside the transposition zone, this aquifer system includes hydraulically-active faults, such as the Marne and Poisson faults (Figure 1.3-1), oriented parallel to the major tectonic stresses, less draining faults acting more as hydraulic barriers such as the Gondrecourt North faults and the Joinville faults, the NE-SW orientation of which is perpendicular to the direction of the major tectonic stresses, and the Marne-Poisson discrete fracturing zone, relatively active in hydraulic terms in the south-west of the transposition zone.

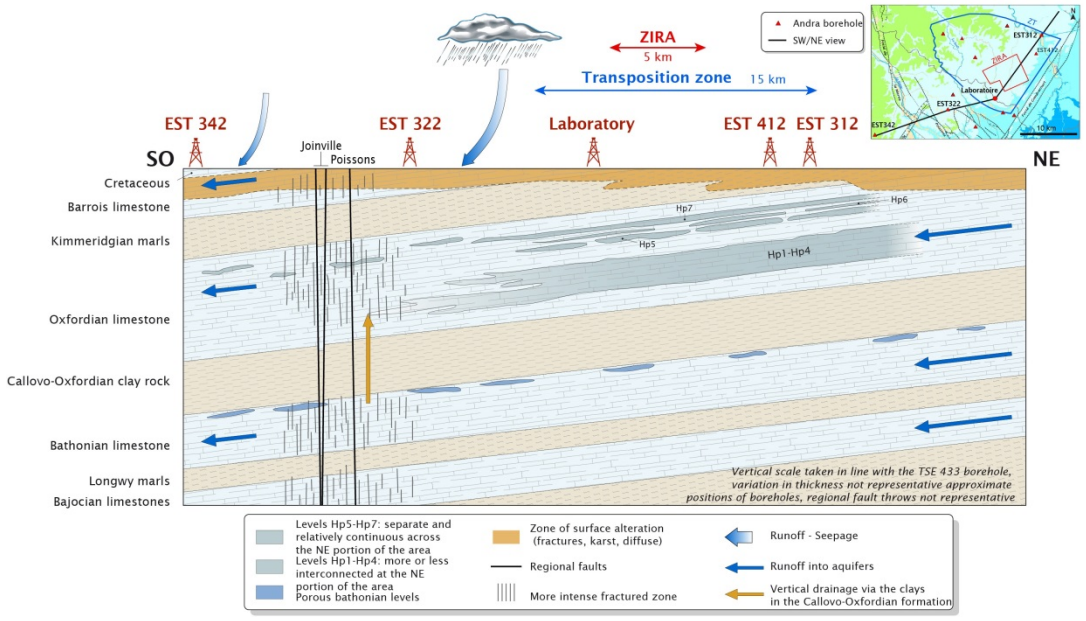


Figure 1.3-1: Conceptual view of water flows in the geological formations of the Meuse/Haute-Marne sector

1.3.1 The superficial aquifer system of the Barrois limestone

The Barrois limestone forms a karstic aquifer system consisting of three aquifer formations (sub-lithographic limestone, Dommartin limestone and "cariés" limestone) separated by semi-permeable formations (Pierre Châline and Bure Oolite formations). The flows are organised in each of the three aquifer formations by the fracturing and a system of karst channels in the north-north-east direction. These aquifers are connected locally by vertical karst channels.

Below the ZIRA, only the aquifers of the sub-lithographic limestones and the lower and middle Dommartin limestones are present. The Upper Dommartin limestones and the "cariés" limestones are found only on the high points of the sector and form a desaturated zone. The sub-lithographic limestone aquifer becomes captive under the Pierre Châline formation, and the boreholes in the valley of the Ormançon and the Orge are artesian at high water levels.

In the more calcareous zones, the permeability can be significant, and even high if the limestones are fractured and karstified. Pumping tests in boreholes at the Underground Research Laboratory site suggest an average permeability of about 10^{-6} m/s representative of the sub-lithographic limestones, the only formation penetrated by these boreholes, compared with 10^{-4} m/s given by the Banque du Sous-Sol of the BRGM (French geological survey) on the basis of pumping tests in the most karstified limestones.

The general flow of the two Barrois aquifers in the ZIRA (sub-lithographic limestones and lower Dommartin limestones) is towards the north, linked with the topography and the streams. The flow speeds are around 10 km/year. Simulated current piezometry gives a hydraulic gradient of about 0.2% on the plateaus, while it can reach 1% below the valleys.

The main natural outlets of the Barrois limestones are the springs in the valley of the Saulx and the Ornain.

1.3.2 Oxfordian limestone

Oxfordian limestone consists of (i) limestones with lithological variations characterising the occurrence of porous horizons (Hp) and (ii) a grey clayey marl sequence.

The porous horizons are characterised by porosities varying between 13% and 25% and permeabilities varying between 10^{-9} m/s and 10^{-7} m/s. Vertically, in the north-east part of the ZT, the first four levels (Hp1 to Hp4) form the middle Oxfordian aquifer and the last three levels (Hp5, Hp6 and Hp7) the upper Oxfordian aquifer.

In the north-east part of the ZT, the middle Oxfordian aquifer is separated from the upper Oxfordian aquifer by the semi-permeable formation of the "série grise"marls (Figure 1.3-2).

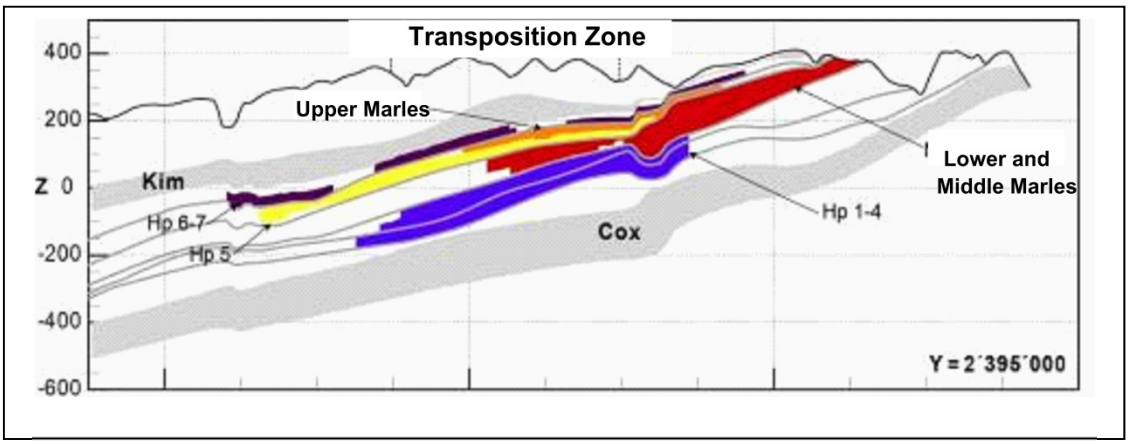


Figure 1.3-2: *Vertical structure of the Oxfordian limestone aquifer system. The colours correspond to the different porous levels (violet, yellow, brown) and to the marl formations (orange, red).*

In the south-west part of the transposition zone, the negligible thickness or absence of this semi-permeable formation means that all the Oxfordian limestone formations, including the porous horizons, form a single aquifer with generally a single flow field.

The transmissivities of the porous horizons are low, of the order of:

- 10^{-7} m²/s for Hp1 to Hp4, 10^{-8} m²/s for Hp5, and 10^{-8} m²/s to 10^{-7} m²/s for Hp6 and Hp7 in the region where they are well separated by the "série grise" formation;
- 10^{-8} m²/s to 10^{-7} m²/s where the Hp form a single aquifer.

The Oxfordian groundwater is recharged by the outcrops to the East and the South-East of the sector. Water circulation in the sector is predominantly north-west towards the centre of the basin.

The pore speeds in the region of 1 km per 100,000 years are confirmed by analysis of radioactive chemical elements (^{14}C, ^{36}Cl) in the water, based on their content in rainwater and their radioactive half-life, for a generally uniform and constant horizontal hydraulic head gradient in the region of 0.04 m/m.

The water system of the N150°E fault zone (Marne faults) is supplied directly by infiltration in the karst systems that have been developed on the part of these faults that intersects the Oxfordian where it outcrops. The piezometry and the salinity are different from those of the rest of the sector under study, depending on the connections within the fault system. The flows are generally SE-NW.

Below the ZIRA, the "série grise" formation, because of its low permeability of around 10^{-12} m/s and its extent limited to the north-east part of the transposition zone, structures the Oxfordian aquifer in two parts, each with its own flow field:

- the upper Oxfordian aquifer has piezometric levels varying from 305 m to 280 m. The flows are oriented to the North and the North-West with an average hydraulic gradient of 4%;

- the middle Oxfordian has piezometric levels varying from 295 m to 270 m, giving a horizontal gradient of 0.6%. The flows are oriented to the North-West with a uniform average hydraulic head gradient in the region of 4%.

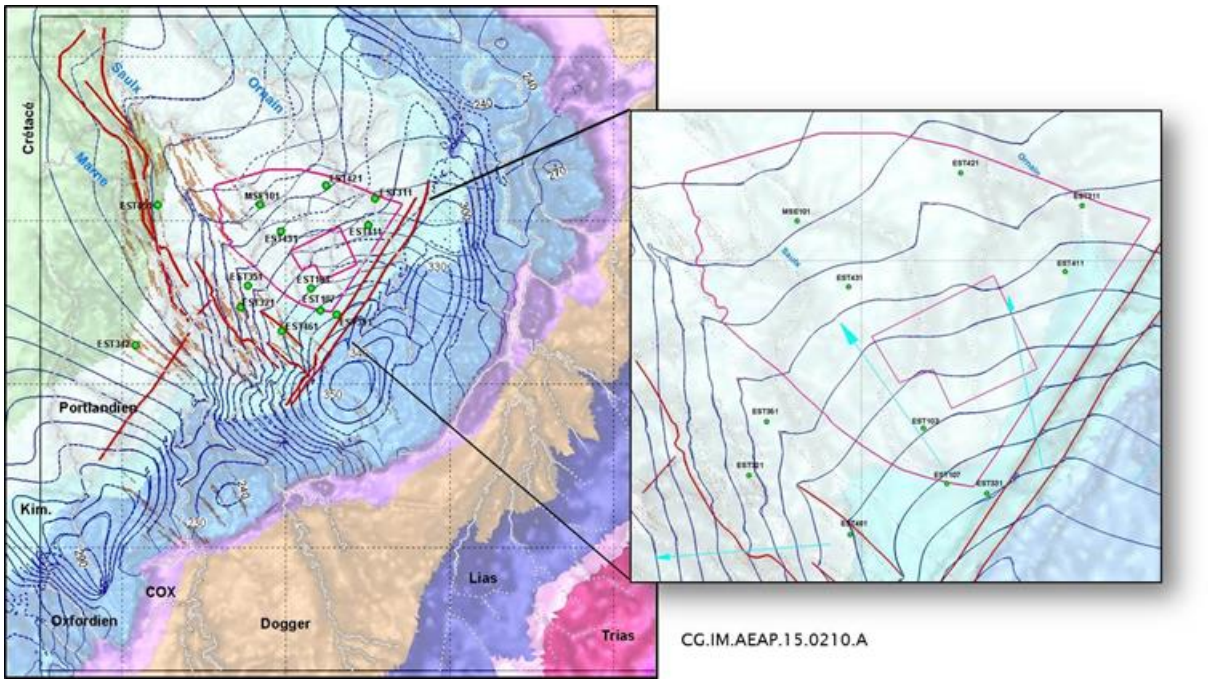


Figure 1.3-3: Simulated piezometries of the two Oxfordian limestone aquifers (upper Oxfordian aquifer on the left) - Lateral piezometries of the middle and upper Oxfordian limestone

1.3.3 The Dogger formation

The Dogger aquifer, represented by the Bathonian formations, is characterised by facies heterogeneity characterising a high local variability of the transmissivity (10^{-5} m²/s to 10^{-10} m²/s) in the transposition zone.

Water inflows from the Dogger are rarely observed in boreholes, and are localised in the upper layers of the Bathonian. Outside the fractured zones, they are associated with porous horizons located in granular limestones corresponding to a barrier reef environment. The high transmissivities measured down a single borehole at the centre of the transposition zone (10^{-5} m²/s) are characteristic of sparsely-cemented grainstones with well-connected macroporosity. These levels, present over some twenty metres, with relatively low porosity (10% to 15%), have a spatial distribution that appears to be related to early diagenetic alterations associated with emerged periods playing a role in the preservation of the porosity. The distribution and extent of these levels are in practice difficult to define. Similarly, their low thickness is difficult to detect in seismic surveys.

Water recharge takes places mainly via the outcrops about thirty kilometres to the East of the ZT. There is no natural outlet to this formation in the ZT. The main zone of the groundwater flows is constrained by the structure of the belt of barrier reef facies, where porous and permeable levels can potentially be developed, located at the centre of the ZT on a line running from the outcrops in the South to the NNW. The water displacement speed is faster than in the Oxfordian: the flows are generally oriented towards the North-West (Figure 1.3-4), with an average hydraulic gradient of 0.1%, giving a pore speed in the region of 5 km per 100,000 years in the transmissive zones.

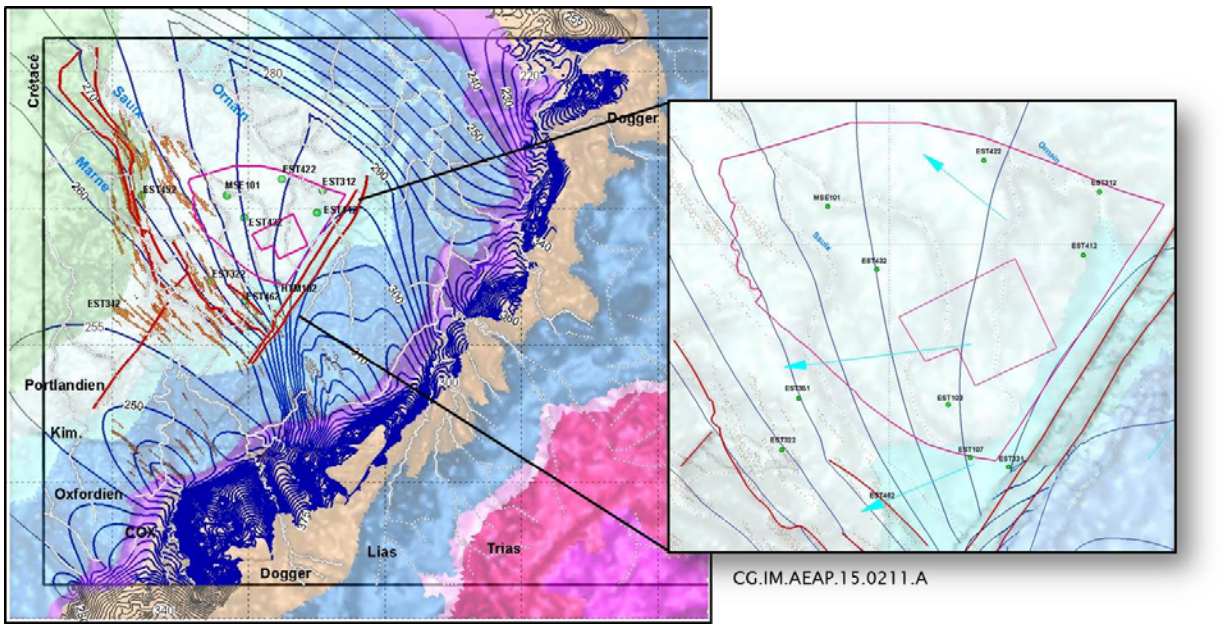


Figure 1.3-4: Simulated piezometries in the Dogger

1.4 Limited and slow internal geodynamics

It is established that the Meuse/Haute-Marne site is part of a stable geological domain, characterised by extremely low seismic activity, as shown by the instrumental seismicity records (seismic monitoring covering the whole of France since 1961, with a focus on the Meuse/Haute-Marne sector since 2001) and the historical records (earthquakes that occurred and caused damage over the last 1000 years). In the Meuse/Haute-Marne region, as in all the region to the north west of it, no historical or instrumental seismicity is reported; this region is considered aseismic(Figure 1.4-1).

The data on current deformations (5.10^{-9} $year^{-1}$) and paleoseismology confirm the hypothesis that most of the deformations are absorbed by those in the adjacent regions farther east, which are themselves poorly deformed.

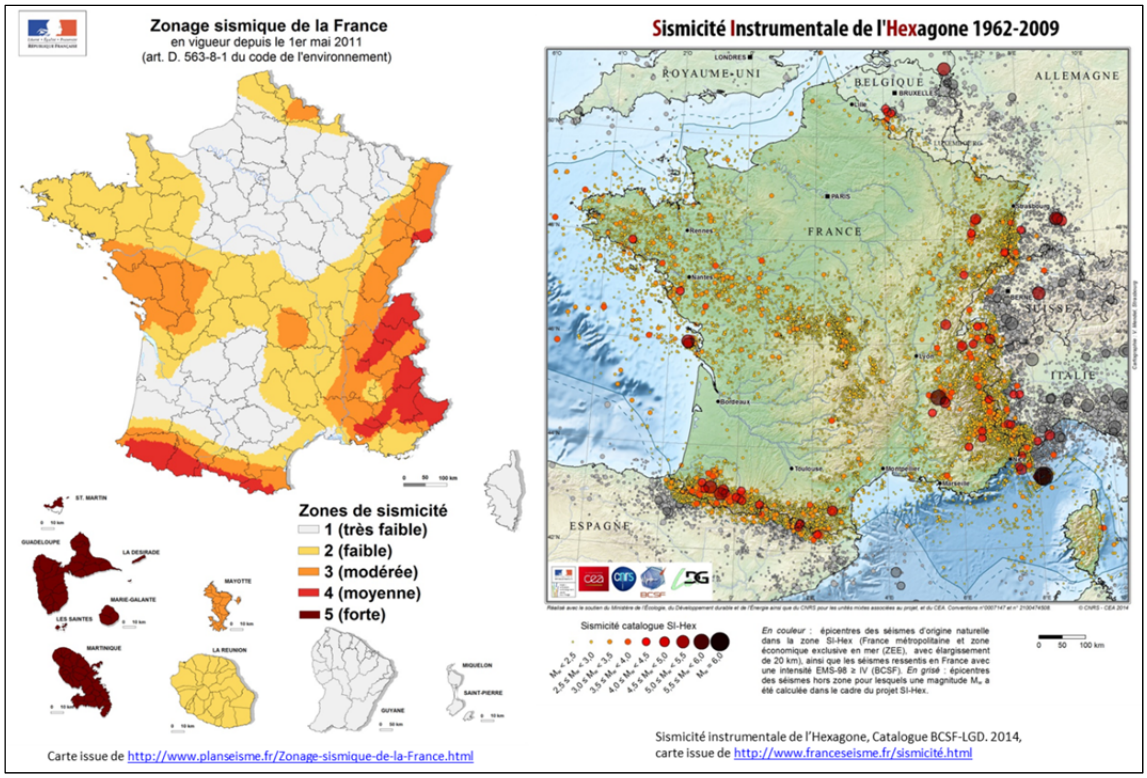


Figure 1.4-1: Seismic zoning in France (left) and map of earthquakes recorded between 1962 and 2009 (right)

Knowledge of seismic activity over the last 50 years (due to the development of seismic monitoring), extended to the last centuries by historical records, concerns the earthquakes that have a recurrence time consistent with these time periods. However, earthquakes with a longer recurrence time may occur near the site. Their probability of occurrence and their magnitude may become significant for the post-closure period of the repository and may significantly constrain the seismic hazard over this period.

Moreover, valley incision through the limestone plateaus during the last 2 million years clearly shows that there is a general uplift (60 to 80 m/million years in Meuse/Haute-Marne) which affects the whole of the western continental platform. This uplift produces deformations with very long wavelengths that may induce a background seismic activity on the regional faults, associated with earthquakes with very long recurrence time times.

1.5 A stable formation in an environment that shows little change over the next million years

In general, change in geological formations results from the combination of processes governed by internal geodynamic changes, with a very low uplift rate driven by plate tectonics , and by climate change characterised by very fast processes and greater amplitude of variations organised in cycles of different durations.

Estimates of future change are obtained using a deterministic approach, incorporating all the interacting processes. Given the state of knowledge of the natural environment and the extent of the uncertainties of all types involved when predicting the future, which increase with the lengths of the time periods covered, this change is estimated by means of scenarios, so that cases bounding the possible extremes can be determined and the range of physically-plausible changes over the period considered can be defined.

1.5.1 A geodynamical evolution globally constrained over the next million years

1.5.1.1 Internal geodynamic change

Over the next million years, the extremely slow deformation rate that affects the Paris basin will persist, the major part of the deformations being absorbed in the surrounding areas (the Alps and the Vosges, for example). This domain has only been slightly deformed over the last 20 million years, while the Alps were being formed. The Paris basin is affected by a general uplift, characterised by spatial variability generating low-amplitude undulations that deform the whole of the lithosphere very slowly but continuously. In the ZT, a relative upward displacement of the sedimentary pile will occur towards the North-West, of the order of 100 million years over a distance of 90 km, resulting in a gradual decrease of the dip of the sedimentary formation towards the North-West.

1.5.1.2 Climate change

For about the last million years, the climate of the region is characterised by a sequence of glacial and interglacial periods. Climate change prediction over the next million years depends on assumptions concerning the effects of the greenhouse gas emissions that will be generated by human activities. This major uncertainty is processed by the study of two climate scenarios covering the possible changes:

- natural climate change, that is a direct extrapolation of past change, determined taking account of the current fossil CO_2 emissions. This scenario predicts a sequence of temperate, boreal, periglacial and maximum glacial states, organised in 100,000-year cycles, over the next million years. Taking the current CO_2 level in the atmosphere into account leads to the extension of the current temperate climate period for the next 50,000 years before the next glaciation;
- highly-disturbed change, determined using what are considered upper-bound assumptions concerning CO_2 emissions over the next centuries (5000 GT of fossil carbon) and the atmospheric CO_2 cycle. This scenario is characterised by a break in the climatic evolution compared with the past, marked by a translation towards the warm pole which is completed very slowly, in 600,000 to 800,000 years.

1.5.1.3 Surface change on the site

Climate changes, together with ground uplift, determine two geomorphological change scenarios which modify (i) the topography (as a consequence of erosion and weathering processes affecting the outcropping geological formations) (ii) the flows on the surface and in the Barrois limestones, and (iii) the biosphere.

On the basis of the two climatic scenarios defined, two significantly different surface change schemes are considered:

In the case of natural climate change, the present stable landscape conditions would continue for another 50,000 years. Subsequently, geomorphological change would be marked by incision of valleys at the onset of each glacial period and slow ablation of the plateaus, combined with periodic development of permafrost which would affect all the formations at the outcrops and reach the Oxfordian limestones at depth on the Meuse/Haute-Marne site. New Oxfordian limestone outcrops may appear at the bottom of the Ornain valley, to the north-north-west of the ZIRA, where this formation is currently under cover. This event would occur after 750,000 years at the earliest (if a maximum uplift rate is considered) and more probably at a date around a million years, or even well beyond a million years if the potential river captures are taken into account.

In the case of disturbed climate change, during the first 500,000 years when the climate would be generally warm, the landscape of the Meuse/Haute-Marne sector would be modified in a very different way from that of the first scenario, as a consequence of erosion affecting the Barrois limestone plateau, while the valleys will be subject to aggradation. Incision of valleys would not be resumed until after 500,000 years. The outcome would be a flattened landscape with the relief lowered by around 35 m after the next 500,000 years and by 45 m in 1 million years (compared with 10 m and 20 m, respectively, in the case of natural climate change), combined with the retreat of the cuesta, which would reach the south-eastern boundary of the ZIRA in 500,000 years. In this scenario, the outcropping of the top of the Oxfordian limestone at the bottom of the Ornain valley to the north of the site would occur well after the next million years.

1.5.2 Below the ZIRA, the Callovo-Oxfordian unaffected by the changes occurring at the surface over the next million years

All the data and the simulations confirm that, below the site, the Callovo-Oxfordian formation, protected under about 500 m of limestone and marl cover, will not be reached by the erosion nor by the permafrost. The outcome when the next million years have elapsed is limited to a depth reduction in the region of 15 to 20 m below the zones of the present relief (for example the shafts zone) and in the region of 25 to 30 m below the Orge valley and the Ormançon valley either side of the shafts zone. The state of the tectonic deformations is not likely to be modified over the next million years. Only the vertical stress will be modified by the erosion processes. However, this erosion remains low (in the region of 20 to 45 m); the resulting modification of the vertical stress will consequently be negligible.

Over the next million years, geodynamic change will not cause any modification of the characteristics of the host formation. The thickness and the petrophysical and chemical characteristics of the Callovo-Oxfordian are not going to change, in large part because of the lack of differential change in the boundary conditions constituted by the surrounding formations (Dogger and Oxfordian limestone); the dip decrease will be barely perceptible, and no fractures of tectonic or climatic origin will be formed in the Callovo-Oxfordian. The Callovo-Oxfordian will only be subjected to very small temperature fluctuations at the rhythm of the climatic cycles, including cooling by around ten degrees compared with the present temperature during the cold climate periods.

The change in the vertical hydraulic head gradient through the Callovo-Oxfordian formation results from the change in the flows in the aquifers that bound it: Oxfordian limestone and Dogger. As the boundary conditions of these aquifers change at the same time (for example the formation of permafrost at the outcrops) and with low amplitudes, the gradient will not change much. During the next million years, the zero-gradient line separating the descending gradient zone (located to the East) from the ascending gradient zone (located to the West) should be displaced slightly to the North-West as a consequence of the regional tectonic uplift. The geodynamic change over 1 million years does not cause any increase in the hydrostatic pressure of the Callovo-Oxfordian compared with the values of the surrounding formations.

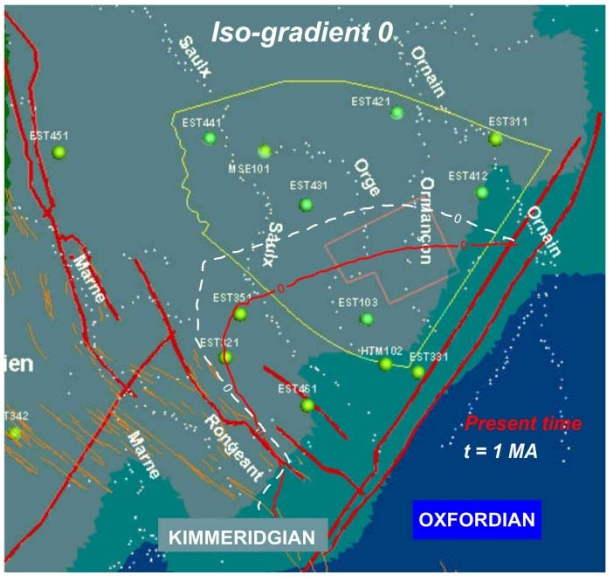


Figure 1.5-1: *Change in the position of the zero head iso-gradient through the Callovo-Oxfordian formation over the next million years according to the geodynamic change*

With regard to the post-closure safety function "Isolate the waste", the depth of the Callovo-Oxfordian and the location of the site mean that the formation and the repository structures have low sensitivity to the effects of internal (stress field variations, earthquakes) and external (climatic variations and surface effects) geodynamic processes.

The stress field, acquired for at least 20 million years, is not likely to be changed over the next million years. The vertical stress will be modified only by the erosion processes, but to a negligible extent.

The depth of the Callovo-Oxfordian protects it and the repository structures from the surface disturbances generated by climatic processes, including the 100,000-year glacial/interglacial cycles. The Callovo-Oxfordian is also located well below the maximum depth of permafrost likely to be formed during glacial maximum episodes.

The repository design aims to take advantage of all the favourable properties of the Callovo-Oxfordian while minimising the thermal, mechanical, hydraulic and chemical stresses likely to be generated by the repository. The aim is to keep the Callovo-Oxfordian in a state as close as possible to its current equilibrium state. The favourable physical and chemical characteristics of the Callovo-Oxfordian preserved in this way, along with its thickness, enable the radionuclides and toxic chemicals to be contained over long timescales while limiting their release and migration.

1.5.3 Water flows in the aquifers above and below the Callovo-Oxfordian not significantly modified over the next million years

1.5.3.1 Flow changes in the Oxfordian limestone

The outcropping of the Oxfordian to the north of the ZT in the Ornain valley as a consequence of geomorphological change, even if the earliest it can possibly occur is after 750,000 years, would not have significant impact on the directions of the flows in the Oxfordian limestone. These assessments are based on a 3D convective particle transport model using transient flow speed fields generated by the geomorphological change: the particle plumes emitted above or below the repository at t = 0 kyr and t = 400 kyr, resulting from the transient hydraulic change over 1 million years, are oriented in the same direction as the plume given by the model for the present (Figure 1.5-2).

In periglacial climate and glacial maximum periods, the permafrost that would be formed over the whole of the Meuse/Haute-Marne sector would reach the Oxfordian limestone below the transposition zone. Compared with the present, the flow field would then be characterised by lower hydraulic heads because of the near-closing of the recharge areas by the permafrost. This would result in a reduction of the flow speeds by about 10% to 25% compared with the present speeds.

As a consequence of the assumption concerning the tectonic uplift, stronger towards the North on the scale of the region, after a million years the speeds below the transposition zone would be reduced by about 8% compared with the present speeds, and the watershed between the water flowing towards the Ornain valley and the water flowing towards the Marne valley would be displaced towards the North-West.

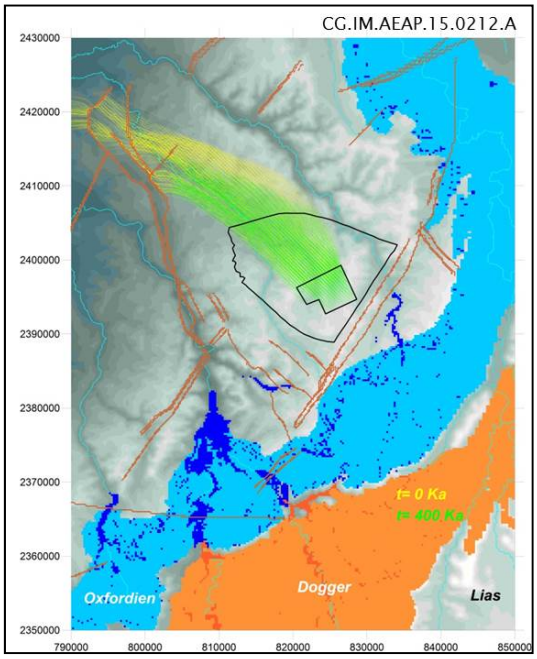


Figure 1.5-2: Modelling of the paths of particles emitted in the Oxfordian limestone below the ZIRA at t = 0 kyr (yellow) and at t = 400 kyr (green), i.e. taking account of the geodynamic change over the next million years

1.5.3.2 Flow changes in the Dogger

In the ZT, the Dogger is protected from the disturbances propagating from the surface. In either climate scenario, external geodynamic change over the next million years will not cause any significant modification of its characteristics.

The flow directions in the ZT would undergo only a slight displacement towards the East with respect to the present. The flow speeds would remain similar to the present values, a few kilometres per

100,000 years. During cold periods with permafrost, the reduction of the flow speeds would be markedly smaller than for the Oxfordian limestone.

The trajectories of particles emitted in the Dogger below the repository at t = 0 kyr and t = 400 kyr indicate natural outlets located respectively (i) in the Marne/Rognon valley and (ii) in the Marne valleys and the La Manoise valley. The appearance of a second outlet, located some thirty kilometres to the south of the ZIRA, can be explained by erosion in the valley of the La Manoise, which will cut into the Dogger limestones. To the south-west of the ZIRA, the plume of the particles emitted at t = 400 kyr is deviated to the east compared with the plume of the particles released at t = 0 years (Figure 1.5-3). This will result in an increase in the median length of the paths from 60 km to 80 km.

Below the transposition zone, the flow speeds would decrease gradually by up to 10% from the present flow speeds. To the South-East of the zone, the flow speeds would show a relatively small increase of about 30% from the present speeds.

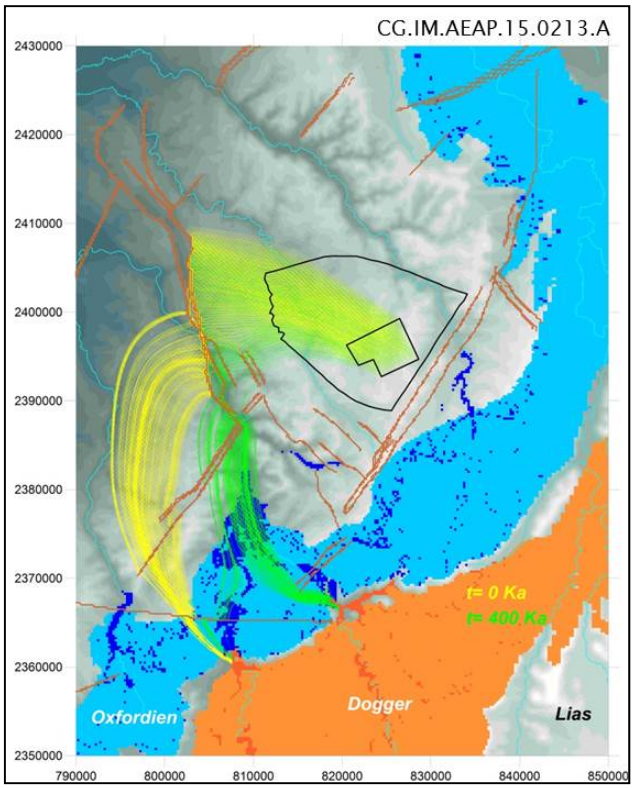


Figure 1.5-3: *Modelling of the paths of particles emitted in the Dogger below the ZIRA at t = 0 kyr (yellow) and at t = 400 kyr (green), i.e. taking account of the geodynamic change over the next million years*

Over the next million years, geodynamic change does not significantly modify the flows and the transfers from the repository to the aquifers above and below the Callovo-Oxfordian, i.e. Dogger and Oxfordian limestone.

Even in the case of the earliest possible appearance (in 750,000 years) of a potential outlet in the Oxfordian limestone, its location several kilometres to the north of the ZIRA and the low flow speeds in the Oxfordian limit its consequences with respect to any long-lived mobile radionuclides that might start to reach the top of the Callovo-Oxfordian at this time.

1.6 No sterilisation of natural resources

1.6.1 Mineral and hydrocarbon resources

In the whole of the transposition zone and in general in the sector:

- at present there is no operating quarry working the Barrois limestones to meet local needs for construction stone, or aggregate, according to the BGRM "Banque du Sous-Sol" (BSS). There is no resource of alluvial materials (sand, gravel, etc.), either proven or previously worked, because of the absence of a substantial alluvial plain;
- no mining resource is quarried anywhere in the sedimentary cover, because it does not contain any economically workable mineral;
- no potential workable coal resource is known in the geological data. This resource is developed about 40 km further to the west of the sector, in Westphalian formations that are not present below the sector;
- the geological conditions are not conducive to the potential presence of conventional hydrocarbons. The 3D seismic reflection survey of the ZIRA carried out by Andra in 2010 did not detect any structure likely to form a hydrocarbon reservoir. The nearest hydrocarbon fields are at Forcelles (oil) in Meurthe et Moselle about 54 kilometres to the east-south-east and at Trois-Fontaines (gas) near St Dizier 39 kilometres to the north-west. These two fields, no longer exploited, are structural fields located in the middle to upper Triassic strata.
- there is practically no probability of potential unconventional hydrocarbon resources. There is no Westphalian bedrock below the ZIRA; the western limit of the Westphalian is more than 10 kilometres to the N and NE of the ZIRA. The Stephanian bedrock present below the ZIRA has a very low content of coal and schists containing organic matter.

1.6.2 Geothermal resources

The data acquired in the sector by Andra, in particular from borehole EST433, drilled to a depth of about 2000 m and one of the scientific objectives of which was to estimate the local geothermal characteristics, showed that the characteristics (geothermal gradient and hydrodynamic characteristics of the upper aquifer of the Buntsandstein Triassic formation) were common and had no exceptional character compared with what can be found elsewhere in the Paris basin.

The geothermal gradient is about 3°C/100 m, which is in line with the national average. The water of the Buntsandstein aquifer (between about 1860 and 1890 m deep) has a temperature of 66°C and a very high salinity of 180 g/l.

1.6.3 Water resources

At present in the sector, the only exploitable water resource is the surface aquifer formation of the Barrois limestones outcropping in the ZIRA. This formation forms a karstic aquifer characterised by fast circulations in response to rapid rainwater infiltration reactions and underground channels that are probably also fast. This fast flow capacity greatly reduces the water storage capacity of this aquifer. The exploited water resources in the Barrois limestones are located mainly along the Orge, Saulx and Ornain streams.

The captive and deep Oxfordian and Dogger aquifers are not exploited in the sector, because of the salinity of their water and their low flow rates.

1.7 Other characteristics of the site involved in the safety assessment

1.7.1 Formations surrounding the Callovo-Oxfordian

1.7.1.1 Barrois limestones and Kimmeridgian marls

Barrois limestones, an upper Jurassic formation, are outcropping over most of the Meuse/Haute-Marne site. Their thickness, variable according to the dip and the topography, increases towards the north-north-west. The formation, consisting of five separate calcareous lithological levels, can have a maximum total thickness in the region of 150 m when it is complete.

The Kimmeridgian marls outcrop along the eastern edge of the ZT and to the south-east of the ZIRA, and their total thickness is about 110 m. The Barrois limestones and the Kimmeridgian marls constitute a series of six lithostratigraphic units, from bottom to top:

- Kimmeridgian marls formation: characterised by the very regular overlaying of three clayey-marly levels (exogyra marls), each several tens of metres thick, separated by two beds of "calcaires blancs" limestone 10 to 15 metres thick. A few limestone levels with thicknesses in the metre range are intercalated within the clays and marls. Mineralogical analyses of the whole of the sequence show that the clayey fraction is composed essentially of illite (50 to 65%), chlorite (5 to 10%), kaolinite (10 to 25%) and interstratified illite-smectite (I/S) R=1 (5 to 15%) and that these fractions show little vertical variation despite the lithology changes;
- upper Kimmeridgian sub-lithographic limestones: about 20-25 m thick, they consist of homogeneous micritic limestones with fine marly interbeds and occasional thin bioclastic levels;
- upper Kimmeridgian Pierre Châline: about 10-15 m thick, formed of an alternation of shelly levels, foraminiferal and shell debris limestones, micritic limestones and marls. It may be impermeable or semi-permeable, depending on its nature;
- lower Tithonian Dommartin limestones: 60 to 65 m thick, they consist of clayey, dolomitic and bioclastic limestones terminating in cavernous sub-lithographic limestones (upper Dommartin limestones). The three subassemblies (lower, median, upper) are bounded by multicentimetric marly intercalations;
- Bure oolite formation: about 2 metres thick, it consists of cemented oolitic limestone;
- decayed limestones, mottled limestones and tubular limestones over a thickness of about 35 m, dated as lower Tithonian; these units show very low spatial variability of composition and thickness. The sequence described at the scale of the sector is applicable for both the description and the thickness of the units at the scale of the ZIRA, except for the top part (uppermost metres) of the mottled limestones and the tubular limestones.

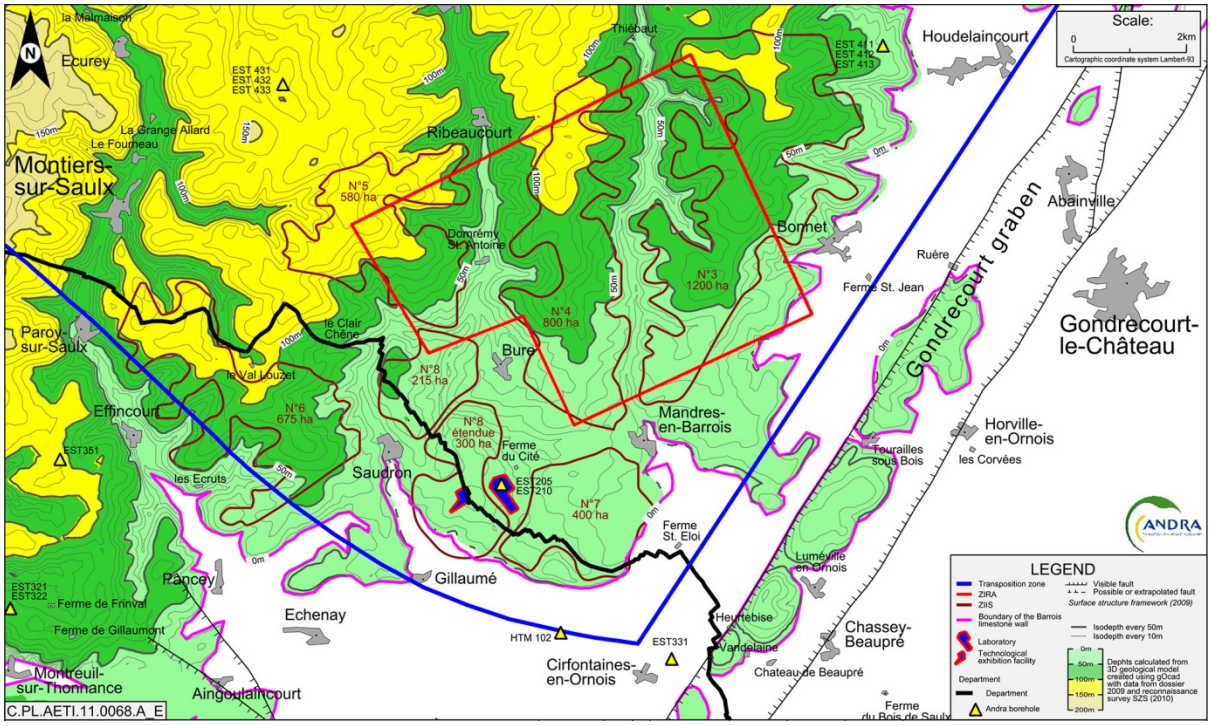


Figure 1.7-1: Thickness (m) of the Barrois limestones and the more recent formations (in the ZIRA, the thickness corresponds to the thickness of the Barrois limestones)

With the exception of the Savonnières oolite, the fracturing related to climatic processes affects the whole of the outcropping facies (Barrois limestones and Kimmeridgian marls) and is intense at the surface over thicknesses of 20 to 30 metres. It allows infiltration of meteoric water. This results in films and deposits of residual clay between the limestone blocks, the size and density of which decrease towards the surface, giving clayey soils with cobbly blocks at the surface. It is accompanied by karstic pipes and shafts, void or filled with residual clays, of metre-scale opening in the upper units of the Barrois limestones, rare and of small dimensions in the limestone units present in the ZIRA.

In the marly units proper, the water content is in the region of 14%. The porosity can reach 30% and the clayey fraction content is 60%.

1.7.1.2 Oxfordian limestone

The Oxfordian limestone is formed by the development of a single limestone platform extending from the middle Oxfordian to the lower Kimmeridgian. The thickness of the formation increases slightly from 275 to 335 m from East to West in the transposition zone. In the ZIRA, the formation has an average thickness of 280 metres.

The Oxfordian limestone is characterised by large facies variations both vertically and laterally. The transition between the Callovo-Oxfordian and the limestone platform is gradual and expressed by slightly bioclastic (containing fossil fragments) clayey-marly facies over some twenty metres (facies C3a). This formation, known as the Foug coral marls locally, has very similar characteristics to the top of the Callovo-Oxfordian.

The extent and the continuity of the various facies determine the distribution and the extent of the porous levels or horizons (Hp) identified as having the highest permeabilities and porosities in this formation (permeabilities greater than 10^{-8} m/s).

The data collected directly and indirectly show that the characteristics of the Oxfordian limestone in the ZIRA are in general equivalent to those determined at the Underground Research Laboratory. They can be summarised as follows:

- the first 20 metres of the Oxfordian limestone consist of an alternation of marls and clayey limestones with very similar characteristics to those of the silty-carbonated unit of the preceding Callovo-Oxfordian. Above this are some twenty metres of reefal limestone of low permeability (10^{-11} m/s to 10^{-12} m/s);
- the overlying unit, around a hundred metres thick, combines porous and permeable (10^{-8} m/s to 10^{-7} m/s) fine lagoon facies and very low porosity and permeability cemented limestones. Vertically above the laboratory, these lagoon facies are organised in four discontinuous porous levels (Hp1 to Hp4) reaching a combined thickness of nearly 80 metres. The low connectivity of these levels could explain their low productivity. According to the boreholes and the outcrops, the lagoon facies are present in the whole of the eastern and north-eastern part of the transposition zone;
- the next 100 metres consist of a series of beds of a marly sequence intercalated between oolitic limestone levels. At the top of each of these limestone levels is a more porous and permeable level. A total of three aquifer levels (Hp5 to Hp7) between 5 and 10 metres thick and with an average permeability of around 10^{-7} m/s have been identified. At the level of the Laboratory, the disturbances caused by the draining of the shafts show that the assemblies Hp1 to Hp4, Hp5 and Hp6 plus Hp7 are hydraulically independent. In the eastern and north-eastern part, the marly sequence is expressed as increasingly thick beds and forms a clear separation between the lower (Hp1 to Hp4) and upper (Hp 5 to Hp7) aquifer levels of the Oxfordian. As the continuity of the grey sequence between the East and the Laboratory is maintained, possible transfers between the lower and upper porous horizons and between each horizon Hp5 to Hp7 in the ZIRA should be limited. In the south-western part of the ZT, the negligible thickness or absence of this semi-permeable layer means that all the Oxfordian limestone formations, including the porous horizons, form a single aquifer with generally a single flow field;
- the last 30 metres consist of limestones of low porosities and permeabilities.
  - ✓ In all the porous levels of the Oxfordian, the transfers are both convective (horizontal) and diffusive. The Oxfordian limestone is considered to be in an equilibrium thermal state at present. The initial temperature gradient through this formation is about 2.5°C/100 m. Thermal transfer is by conduction. The estimated perpendicular thermal conductivity of the Oxfordian limestone is 2.2 W/m/K.

1.7.1.3 Dogger

The Dogger formation immediately underlies the Callovo-Oxfordian at a depth of between 510 m and 680 m in the ZIRA. The formation comprises two calcareous assemblies (lower to middle Bajocian and late Bajocian to lower Callovian) separated by a more marly interval (Longwy marls). Diagenesis causing major recrystallisation of the carbonates affects the whole of the sequence. This configuration is found in the whole of the eastern Paris basin.

The thickness of the Dogger increases from 210 to 280 m from East to West in the transposition zone and from 206 to 230 m in the ZIRA. In detail:

- the lower to middle Bajocian consists of coral platform facies of broad geographical extent with very high variability preventing any detailed lithological prediction. The thickness of this interval is around 60 m. Interpretation of the 1999 and 2010 3D seismic data has provided evidence of lineaments in direction N120 in the Bajocian limestone platform. These structures have been recognised by means of borehole EST210 and identified as reefal assemblies;
- the Longwy marls show relatively constant facies (alternation of silty marls and bioclastic limestones with varying clay and gravel contents) characterising an external ramp environment. Their thickness decreases from the West (more than 50 m at Joinville) towards the East (35 m at borehole MSE101, 26 m at HTM102 and 13 m at Commercy);

- the calcareous assembly from the late Bajocian to the lower Callovian (referred to as the Bathonian for convenience) is composed of calcareous facies that are highly variable both vertically and laterally (shell debris, calcareous sands, reefs, dolomitic facies, etc.), resulting in variability of the permeability (10^{-5} to 10^{-10} m/s) measured in the boreholes in the transposition zone. This assembly of relatively constant thickness across the sector (155 to 167 m) is overlain by the Dalle nacrée formation, a condensed facies consisting of oolitic and bioclastic limestones, some marly, located directly at the bottom of the clay rock at a depth varying between 500 m and 675 m.

The infrequent water inflows from the Dogger observed in boreholes are localised in the upper layers of the Bathonian. Outside the fractured zones, they are associated with porous horizons located in granular limestones of a barrier environment. The high transmissivities measured down a single borehole at the centre of the transposition zone (10^{-5} m²/s) are characteristic of sparsely-cemented grainstones with well-connected macroporosity. These levels, present over some twenty metres, with relatively low porosity (10% to 15%), have a spatial distribution that appears to be related to early diagenetic alterations associated with emergences playing a role in the preservation of the porosity. The distribution and extent of these levels are in practice difficult to define. Their low thickness is difficult to detect in seismic surveys.

1.7.2 Quantification of the seismic hazard

Uncertainties about the potential seismic activity during the very long post-closure period of the repository are taken into account by considering the maximum physically possible earthquake (SMPP) according to the size of the faults (potential sources of earthquakes) (22).

In the safety approach that takes precedence in the estimation of the seismic hazard, and in a deterministic approach in agreement with the current rules for estimating the long-term seismic hazard, it is considered that all the faults could be active and would accumulate stresses until the occurrence of maximum credible earthquakes (MCE) dimensioned by the size of the faults.

The MCE response spectrum calculated for the Underground Research Laboratory site is used as reference. It provides a single spectrum covering the possible movements in the ZIRA and the ZIIS (surface facilities zones). These movements differ significantly according to the locations considered in the ZIRA, as a function of the distance to the faults bordering the sector, close potential sources of strong earthquakes (magnitudes 6.1 ± 0.4 on the Marne fault system and 5.2 ± 0.2 on the faults of the Joinville and Gondrecourt grabens) dimensioning the high-frequency movements. The horizontal spectrum is shown in Figure 1.7-2.

The spectrum of the vertical component is obtained by multiplying the accelerations of the horizontal component spectrum by 2/3. For the record, this MCE level spectrum is close to the spectrum obtained by a probabilistic approach for a recurrence interval of the order of 100,000 years.

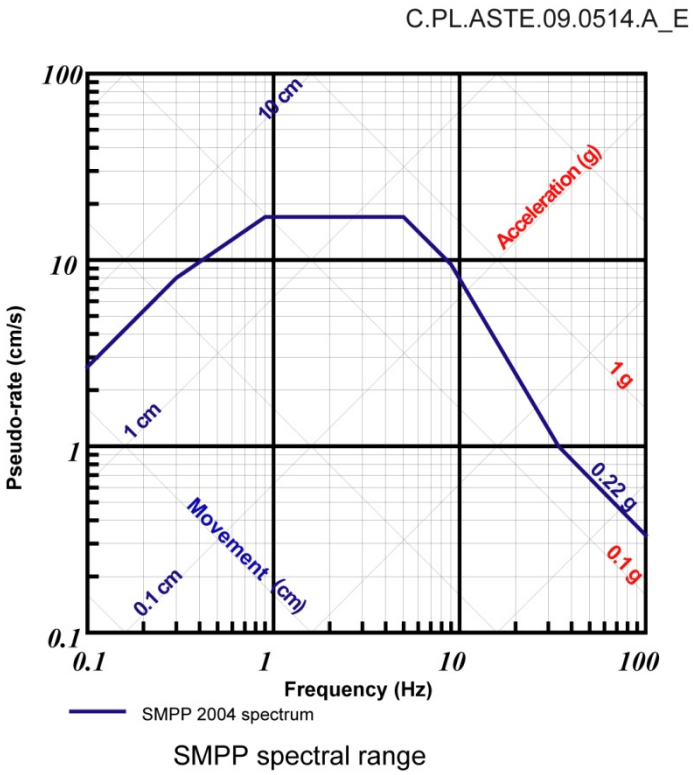


Figure 1.7-2: MCE spectrum – acceleration (horizontal component)

1.7.3 Biosphere change

Knowledge of biosphere change over time can be used to identify the typical biospheres to be defined when assessing the impact of any transfer of radioactive substances to an outlet in conformity to the biosphere approach described in volume I.

For example, changes in ecosystems (migrations of plant and animal populations) are linked with climate change and changes in the physical environments at the surface on the site (geomorphology, soils, hydrology, etc.) and with the adaptation of the environment to these conditions. The evolution is presented schematically as a series of typical biospheres for each climate change scenario (natural or disturbed).

When climatic conditions cool and become drier, the valleys become inhospitable and only the plateaus can still support infrastructure and cultivation. At the same time, plant productivity and surface water resources decrease, while groundwater extraction is rendered more difficult by permafrost.

In the case of climate warming, the space useable by humans also shrinks: the valleys become inhospitable, subject to severe flooding; the high ground of the plateaus, subject to drought and deprived of arable soils by erosion, is suitable only for extensive livestock production. Low-productivity "Mediterranean" agriculture can be considered only in marly outcropping zones (foreshore slopes and depression) and karstic depressions where soils eroded from the surroundings accumulate.

Analysis of these sequences of typical biospheres leads to the consideration of four reference biospheres according to the possible modes of exploitation of this environment by a human population:

- Temperate biosphere: intensive and varied agricultural exploitation with recreational hunting, fishing and fruit and vegetable picking opportunities; water resources are not limited; water is extracted from wells if necessary;

- Boreal biosphere: less intensive agricultural exploitation, restricted essentially to cereal cultivation, bovine and ovine livestock production and grassland, or semi-nomadic herding. Human communities have to transfer their activities to the plateaus, as the valley bottoms become inhospitable. Water extraction by wells is still possible if the boreal biosphere replaces a temperate biosphere, but not necessarily if it replaces a tundra biosphere (possible residual permafrost);
- Tundra biosphere: agricultural exploitation limited to livestock housing or extensive grazing, or semi-nomadic herding; surface water is available only in summer, but groundwater is accessible only if there are local discontinuities in the permafrost allowing water outlets in valley bottoms; the fauna adapts and migrates, which restricts food resources for herders, obliging them to become nomadic;
- Subtropical biosphere (applicable for Cr and Cs climatic conditions): varied, specialised and geographically limited agriculture (market gardening, wine growing and fruit production), and extensive livestock production exploiting the natural environment of the plateau regions.

The climate scenarios determine the periods (dates, durations) during which each of these biospheres is possible:

- in the case of the natural climate change scenario, the biosphere of the Meuse/Haute-Marne region should remain in a state similar to the state observed at present for the next 50,000 years. Subsequently, the temperate biosphere can be considered throughout the million years, in varyingly short episodes alternating with the other biosphere states according to the climate scenario. In the case of the natural climate change scenario, it should last for the next 50,000 years.
- the boreal biosphere can be considered at the earliest from 50,000 years in the case of natural climate change, and becomes possible in all cases from about 280,000 years.
- the tundra biosphere can be considered from 100,000 years, in the case of natural climate change, and becomes possible in all cases beyond 500,000 years, alternating with the temperate biosphere and the boreal biosphere. In the natural climate change scenario, a very long period during which tundra predominates should last for 150,000 years starting in about 400,000 years.

Many oscillations between temperate/boreal/tundra biospheres, with a clear predominance (in duration) of the cold biospheres, will occur throughout the next million years, starting in 50,000 years, in the case of natural climate change. The same would be the case in the disturbed climate change scenario, but much later, starting after 500,000 years.

The warm, subtropical biosphere applies only in the case of the disturbed climate change scenario. It could be in place nearly continuously during the next 160,000 years, and then episodically (alternating with the temperate biosphere and brief episodes of boreal biosphere) up to approaching 500,000 years.

2

HLW and ILW-LL Waste Packages in the Repository

2.1	*Source and nature of waste families*	*115*
2.2	*Radiological inventory used for post-closure quantitative safety assessment*	*117*
2.3	*Characteristics of the primary waste packages involved in the Cigeo safety functions*	*125*
2.4	*HLW disposal containers*	*133*
2.5	*ILW-LL disposal containers*	*138*

The waste disposal packages consist of primary packages made by the waste producers, supplemented as needed by a disposal container. The characteristics of the primary packages involved in post-closure safety of Cigeo and the disposal containers designed for the HLW and ILW-LL waste are described in this chapter.

2.1 Source and nature of waste families

2.1.1 Source

From the beginning of research on deep geological disposal of high level and intermediate level long-lived waste, Andra and the waste producers agreed to establish a single reference for identifying waste package families.

By definition, a package family includes a set of packages with similar characteristics (including manufacturing process, chemical and radiological content, thermal power, burnup), in terms of the uses that are made of these characteristics. The families used in the context of the Cigeo project are greater in number and more detailed than those used in the national inventory, as the level of precision required is not the same in the two cases. Each package family used for the Cigeo project belongs as a whole to a given family of the national inventory.

The main sources of waste production are:

- the nuclear power reactors of consecutive generations:
  - ✓ the first generation comprises nine graphite-moderated gas-cooled reactors (GCR) located on the CEA Marcoule site and on the EDF Chinon, Bugey and Saint-Laurent sites and now shut down;
  - ✓ the second generation consists of the pressurised water reactors (PWR) currently in operation. It comprises 58 reactors in operation located on 19 sites, and Chooz A, the first of the PWRs, now being dismantled;
  - ✓ the third generation is based on the EPR (European Pressurized water Reactor) under construction on the Flamanville site, which also uses the PWR system.
- In addition, there are prototype reactors that are now shut down: Brennilis heavy water reactor (EL4), Phenix and Superphenix fast reactors (FR).
  - ✓ Fuel cycle plants

    Uranium enrichment, nuclear fuel production and fuel reprocessing after use in the reactors are carried out in various plants operated by the Areva group. Reprocessing consists in separating the reusable materials uranium and plutonium from the waste, consisting of fission products and minor actinides (americium, curium, neptunium) contained in the fuel pellets, and of structural components forming the metal skeleton of the fuel assemblies.

  - ✓ CEA facilities

    To conduct its research, in particular in support of the French nuclear power programme, on the design of new-generation nuclear systems and on radioactive waste management, the CEA operates a number of facilities (experimental reactors such as the Rapsodie fast reactor or the Orphée and Osiris reactors, research laboratories on fuels or the back end of the cycle, such as the Atalante facility) located mainly on the Cadarache, Saclay and Marcoule sites. These sites also accommodate support facilities (waste storage, waste and effluent treatment). Some of these facilities are now shut down and undergoing cleanup and dismantling.

  - ✓ New facilities that have obtained their construction licence

In addition to the Flamanville EPR, the Cigeo inventory covers the Jules Horowitz experimental reactor (RJH), the test reactor (RES) and the ITER facility at Cadarache.

2.1.2 Waste inventory assumptions

To draw up a qualitative and quantitative inventory for Cigeo, the following industrial scenario for operation of the nuclear facilities has been applied in the industrial waste management programme (PIGD) defined jointly by AREVA, the CEA and EDF in liaison with Andra:

- for the nuclear power plant fleet, the scenario assumes that nuclear electricity generation continues, with reprocessing of all the spent fuels of the electricity-generating PWRs and FRs (Phenix, Superphenix). The reference operating life applied by convention for all the reactors, including the Flamanville EPR, is 50 years. This 50-year life should be viewed as a guideline average; a shorter operating life of some reactors may compensate for a longer operating life of other reactors, in terms of the waste produced;
- this scenario does not pre-judge the results of the ten-year safety review of the PWR reactors, nor the procedures related to any extension of the operating life of these reactors beyond the reference 50 years or to any renewal of the fleet by deployment of third-generation reactors (EPR) or of fourth-generation reactors. It considers that uranium and plutonium not reused in the current PWRs and the Flamanville EPR can be reused in future plants. The waste produced by any future reactor fleet is not included;
- the scenario considers that, by convention, the nuclear facilities related to fuel reprocessing activities (AREVA plants) match their operating life to that of the nuclear power plant fleet. The assumed operating life of the research facilities (CEA reactors and laboratories) currently in operation is 50 years. The assumed operating life of the Jules Horowitz reactor is 50 years, and that of the ITER facility is 20 years.

2.1.3 ILW-LL and HLW waste package families

A particular aspect of the waste packages intended for Cigeo is the coexistence of four levels of progress of waste production and waste package production, which may persist until after the construction licence application:

- families consisting of waste packages no longer in production[18], for which the definition of the repository design must be adapted;
- families consisting of waste packages currently in production, for which the conditioning of the waste is defined and there is a package production specification;
- families consisting of waste packages not yet in production for which the definition of the waste conditioning is already well advanced;
- families consisting of waste packages not yet in production for which the conditioning is still being researched.

All the waste families intended for Cigeo and belonging to these four categories are listed.

The design of Cigeo is based in particular on the knowledge of the primary packages provided by the producers with respect to the safety functions to be fulfilled under the various operating conditions of Cigeo, but also with respect to the risks and uncertainties in the post-closure phase.

The Cigeo basic engineering design and the post-closure safety studies use as input data the inventories by number of packages of the current issue of the PIGD, issue D at present. The inventories of some families will be updated in a later version; the inventories of some specific waste[19] are already taken into account. The information obtained from the scenarios and the safety options selected will consequently not be influenced by an update of the PIGD.

[18] Some families are subject to a production specification.
[19] Vitrified waste packages not conforming to their production specifications, CSD-RU, etc.

There are 79 families of ILW-LL waste packages. Most of them are for structural waste resulting from spent fuel reprocessing (35% of the ILW-LL waste packages), waste produced by reprocessing of liquid waste from nuclear facilities (35% of the ILW-LL waste packages) and activated (5% of the ILW-LL waste packages) or contaminated (23% of the ILW-LL waste packages) technological waste resulting from operation or dismantling of nuclear facilities.

There are 19 families of HLW waste packages. The HLW waste is mainly in the form of vitrified waste (99.5% of the HLW waste packages).

The knowledge relating to the waste packages intended for Cigeo is communicated by the producers to Andra, which incorporates it into its knowledge base. The safety options take account of the uncertainties in the knowledge of the waste package families.

Similarly, the quantitative aspects of some specific waste (nonconforming vitrified waste packages, CSD-RU, etc.) are now taken into account.

The details of the ILW-LL and HLW package families and the corresponding tables in Appendices 1 and 2 summarise the diversity of the ILW-LL and HLW package families selected for Cigeo.

2.2 Radiological inventory used for post-closure quantitative safety assessment

The radiological inventory is an essential input for the post-closure quantitative safety assessment described in volume III[20]. After distribution of the waste package families in the architecture of the underground facility, and in combination with the applicable release models (see below), it determines the source terms used for the quantitative safety assessments, including the assessment of the long-term radiological impact of Cigeo.

The radiological inventory is drawn up on the basis of the following two principles:

- all the waste package families of the PIGD, including those for which the conditioning is still at the research stage, are taken into account;
- the inventory construction takes account of all the information available from the producers, represented by a "knowledge level" assigned to each family and used for application of a margin factor to the radiological activities.

At this stage, ILW-LL and HLW waste accounts for about 5% and 95% of the total radiological inventory, respectively.

[20] Reminder: The ASN safety guide on deep geological disposal of radioactive waste stipulates:

- As regards the data needed – "Assessment of long-term individual exposures necessitates the availability […] of all the data describing the disposal system (inventory of the activity in the repository, characteristics of the different components, architecture of the repository, etc.). These data must be either conservative data tending to give an upper bound for the radiological impact, or average (or probable) data together with uncertainty ranges and estimates of possible variations over time." ;
- with regard to knowledge of the waste – "[…] It is important to determine the radioactive characteristics of the waste packages and their radionuclide inventory. In particular, a good estimate of the activity of the long-lived radionuclides and the activity of the volatile radionuclides must be obtained […]".

2.2.1 Inventory construction and uncertainty processing procedure

2.2.1.1 Introduction

The Figure 2.2-1 sequence of operations resulting in the radiological inventory used for the post-closure safety assessment is shown in Figure 2.2-1. It includes the following three key steps:

- definition of "perimeters of analogy" for the families lacking knowledge provided by the producer; these limits are used to make a "bounding" estimate of the missing radiological inventories;
- assignment of a "knowledge level" to each package family;
- application of margin factors modulated according to the knowledge level of each family.

Without prejudice to the selection of radionuclides eventually used for the assessments, all radionuclides with a half-life longer than 0.5 years and shorter than 50 billion years are considered. For each family, the data for these 144 radionuclides[21] are searched for systematically in the information available from the producers. These data are coded individually to enable specific processing. Once constructed, the radiological inventory is 'distributed' in the architecture of the Cigeo underground facility. This distribution is described in the chapter dedicated to the management of risks and uncertainties in Volume III.

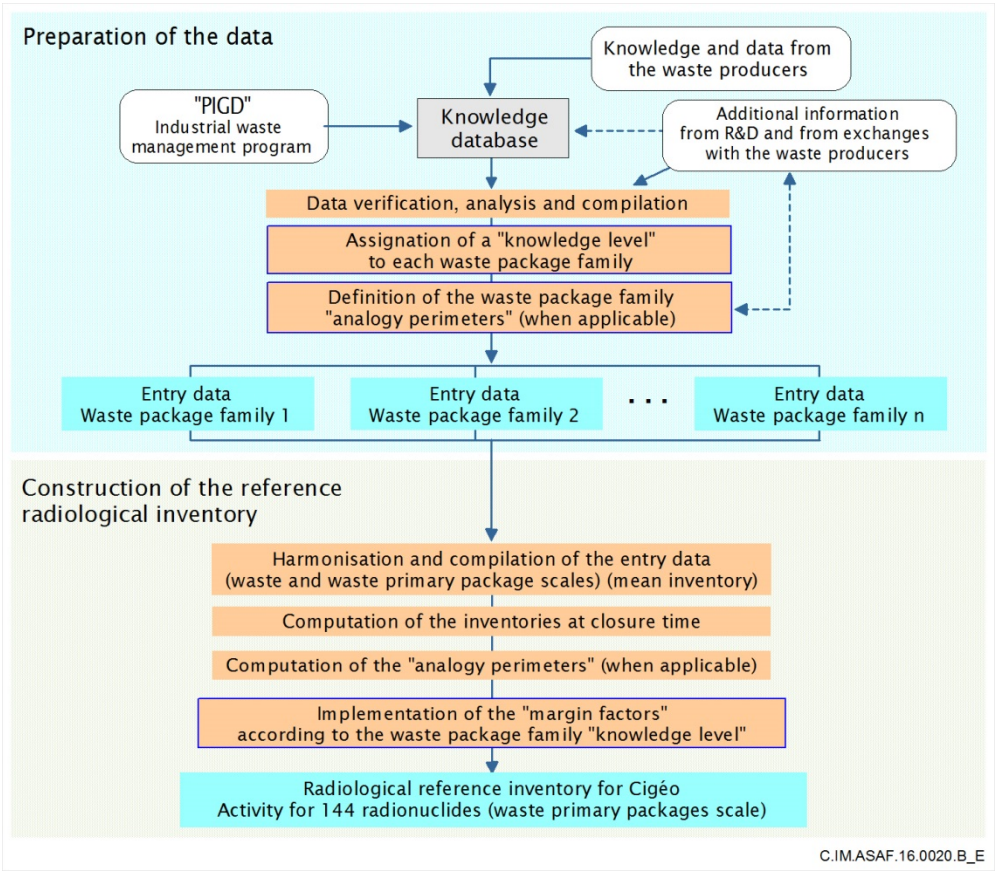


Figure 2.2-1: Flow chart of construction of the radiological inventory used for Cigeo post-closure safety assessment

[21] Curium-242, half-life 0.45 years, is also included, because its decay chain includes radionuclides with half-lives longer than six months.

2.2.1.2 Knowledge level assigned to the waste package families

The knowledge level assigned to each waste package family is defined on a four-level scale:

- level 3: knowledge level corresponding to low residual uncertainties in the radiological inventory; this level is assigned to families of packages that are already produced, or currently being produced, and for which the data are consistent with production feedback;
- level 2: intermediate knowledge level;
- level 1: knowledge level corresponding to residual uncertainties in the radiological inventory that are likely to be reduced; waste package families for which the radiological inventory has not been updated to the current state after a change in packaging plans are placed in this category;
- level 0: level assigned to families for which Andra does not have any information; the radiological inventories of package families to which this level is assigned are determined by application of an analogy perimeter[22].

At the present stage, the knowledge levels are assigned in a way consistent with the general approach aiming to obtain an upper bound assessment of the radiological inventory. This is true in particular for families consisting of waste packages currently in production[23], for which the conditioning of the waste is defined and there is a package production specification (refer to 2.1). Andra has chosen not to assign the highest knowledge level to these families as long as production has not been completed. Taking additional information such as production feedback into account may lead in the future to upgrading of the knowledge levels of some families.

2.2.1.3 Radionuclide activity margin factors

For Cigeo as a whole, taking the margins into account increases the total activity at the start of the post-closure phase by a factor of about 2.2 compared with a compilation without margin.

The margin factors are modulated according to the knowledge level and applied to the average activity per mass unit of each radionuclide given by the producer or deduced from the analogy perimeters (refer to Tableau 2.2-1). The resulting activities per mass unit are then compiled at the different scales: primary package, family, Cigeo disposal section.

Table 2.2-1: Margin factors applied to activities according to knowledge level

Family knowledge level		**Activity per mass unit multiplication factor**
Low residual uncertainties in the radiological inventory	(3).	1.5
Intermediate knowledge level	2	2.0
Residual uncertainties in the radiological inventory likely to be reduced	1	5.0
Families without radiological inventory (definition by analogy perimeter)	0	10.0

[22] The analogy perimeter enables upper bounds to be determined for the average mass of waste per primary package and for the activity per mass unit of waste.

[23] The concept of production status is related to the whole package family, not to the packages themselves. It should also be noted that: (i) when a family includes primary packages that have all been produced but must be placed in overdrums before delivery to Cigeo (the case of the Marcoule bitumens, for example), the production of the family is considered to be terminated; (ii) when a family includes primary packages that must undergo reconditioning, particularly if the primary container is defined by the producer as "to be determined", the production of the family is considered to be future production.

The margin factors are chosen with the strict aim of upper-bound quantification of the post-closure safety scenarios[24].

The compilation of the families enables the margin factors to be allocated in proportion to the number of waste packages (refer to the illustration in Table 2.2-2).

Table 2.2-2: Illustration of the allocation at this stage of the margin factors applied to the average radiological inventories in proportion to the number of waste packages

Cigéo - Reference radiological inventory		
Disposal areas	**"Margin factors" applying to mean activity for each radionuclide**	**Related percentage according to the primary waste package number**
High level waste	1.5	12.3%
	2	79.2%
	5	5.9%
	10	2.6%
Intermediate level long lived waste	1.5	5.2%
	2	43.8%
	5	45.1%
	10	5.9%

2.2.2 Radiological inventory of waste packages

The procedure was implemented to evaluate the inventory of the 144 radionuclides. The tables in the paragraphs below focus on the activities at the beginning of the post-closure phase for the following long-lived radionuclides:

- nickel-63 and nickel-59;
- americium-241, americium-243 and technetium-99;
- carbon-14;
- chlorine-36 and iodine-129;
- selenium-79.

2.2.2.1 Radiological inventory of ILW-LL waste packages

As part of the post-closure safety assessment described in volume III, the implementation of the above procedure leads to the adoption at this stage of an overall activity of 8.93×10^{18} Bq[25] at the beginning of the post-closure phase[26] [27]. The overall attenuation factor after closure is about 2 at 100 years, 15 at 500 years and 40 at 2000 years (refer to Figure 2.2-2).

Nickel-63 is the predominant radionuclide in terms of activity. It is followed by americium-241 at about 500 years, then nickel-59 up to beyond 100,000 years.

[24] The resulting radiological activities are not directly comparable with the activities used for the thermal dimensioning of Cigeo or for operational safety.
[25] This activity is equivalent to about 1/13th of all the HLW activity.
[26] All the radiological activities of the inventory at termination have been reset to a common arbitrary date, 2140.
[27] For the sake of simplicity, the decay calculations of the families for which the inventory is defined at "t production" are applied with effect from the end of the production period.

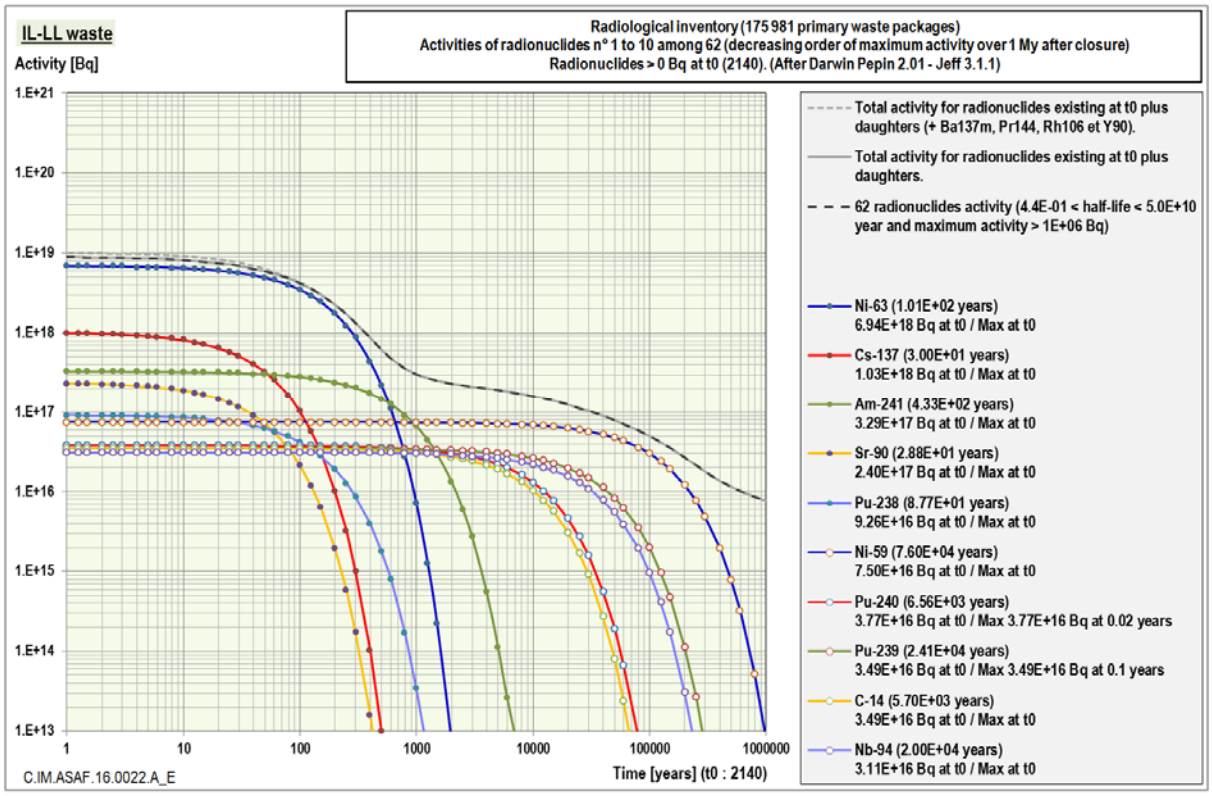


Figure 2.2-2: Change in the activity of the 10 radionuclides with the highest maximum activities over 1 million years after closure of Cigeo

Table 2.2-3 gives the activities of the long-lived radionuclides at the beginning of the post-closure phase.

Table 2.2-3: ILW-LL waste: Total activities of a selection of long-lived radionuclides

Radionuclide	Radioactive half-life in years (According to Jeff 3.1.1)	Activity at the beginning of the post-closure phase (Bq) (Reference radiological inventory)
^{63}Ni	1.01×10^{2}	6.94×10^{18} (52,800 moles)
^{241}Am	4.33×10^{2}	3.29×10^{17} (10,800 moles)
^{59}Ni	$7{,}60 \times 10^{4}$	7.50×10^{16} (431,000 moles)
^{14}C	5.70×10^{3}	3.49×10^{16} (15,100 moles)
^{36}Cl	3.01×10^{5}	8.25×10^{13} (1,880 moles)
^{79}Se	3.77×10^{5}	3.94×10^{13} (1,120 moles)
^{129}I	1.61×10^{7}	1.90×10^{12} (2,310 moles)
Total for the 144 radionuclides	-	*8.93×10^{18}*

Table 2.2-4 shows the change over time in:

- total activity;
- distribution of the activity between short-lived and long-lived radionuclides;
- proportion of the activity contributed by the actinides;
- distribution of the activity between alpha emitters and beta-gamma emitters.

Table 2.2-4: ILW-LL waste - Change in relative distribution of the radionuclides over time

Cigéo - Reference radiological inventory - IL-LL waste							Radionuclides with half-life between 0.45 years and 50 billions years					
175 981 primary packages	Year 2140	10	50	100	500	1 000	5 000	10 000	50 000	100 000	500 000	1 000 000
Total activity (144 RN) [Bq]	8.93E+18	8.18E+18	5.94E+18	4.18E+18	6.10E+17	3.05E+17	1.90E+17	1.59E+17	7.93E+16	4.97E+16	1.15E+16	7.67E+15
Short lived total activity [%]	14.8	12.7	6.9	3.2	1.3	2.4	2.2	2.1	3.8	6.0	18.5	20.2
Long lived total activity [%]	85.2	87.3	93.1	96.8	98.7	97.6	97.8	97.9	96.2	94.0	81.5	79.8
Actinides activity [%]	5.9	6.2	7.5	9.6	37.1	46.2	30.9	28.6	18.1	15.4	37.1	43.5
Alpha activity [%]	5.7	6.1	7.6	9.7	37.9	47.5	31.7	29.2	19.4	17.3	40.6	45.1
Beta gamma activity [%]	94.3	93.9	92.4	90.3	62.1	52.5	68.3	70.8	80.6	82.7	59.4	54.9

2.2.2.2 Radiological inventory of HLW waste packages

The overall activities of the HLW0 and HLW1-HLW2 disposal sections for the 144 radionuclides selected are in a ratio of 1 to about 90: 1.33×10^{18} Bq for HLW0 and 1.17×10^{20} Bq for HLW1 and HLW2 together.

Radiological inventory of the package families of disposal section HLW0

Figure 2.2-3 shows the change in total activity over 1 million years and the change in activity of the 10 radionuclides with the highest activity over 1 million years.

For the HLW0 waste packages, caesium-137 and strontium-90 have the predominant activities up to about 100 years post-closure. The activity of americium-241 then predominates up to about 2000 years. For all 144 radionuclides, the attenuation factor after closure is about 5 at 100 years, 25 at 500 years and 120 at 2000 years.

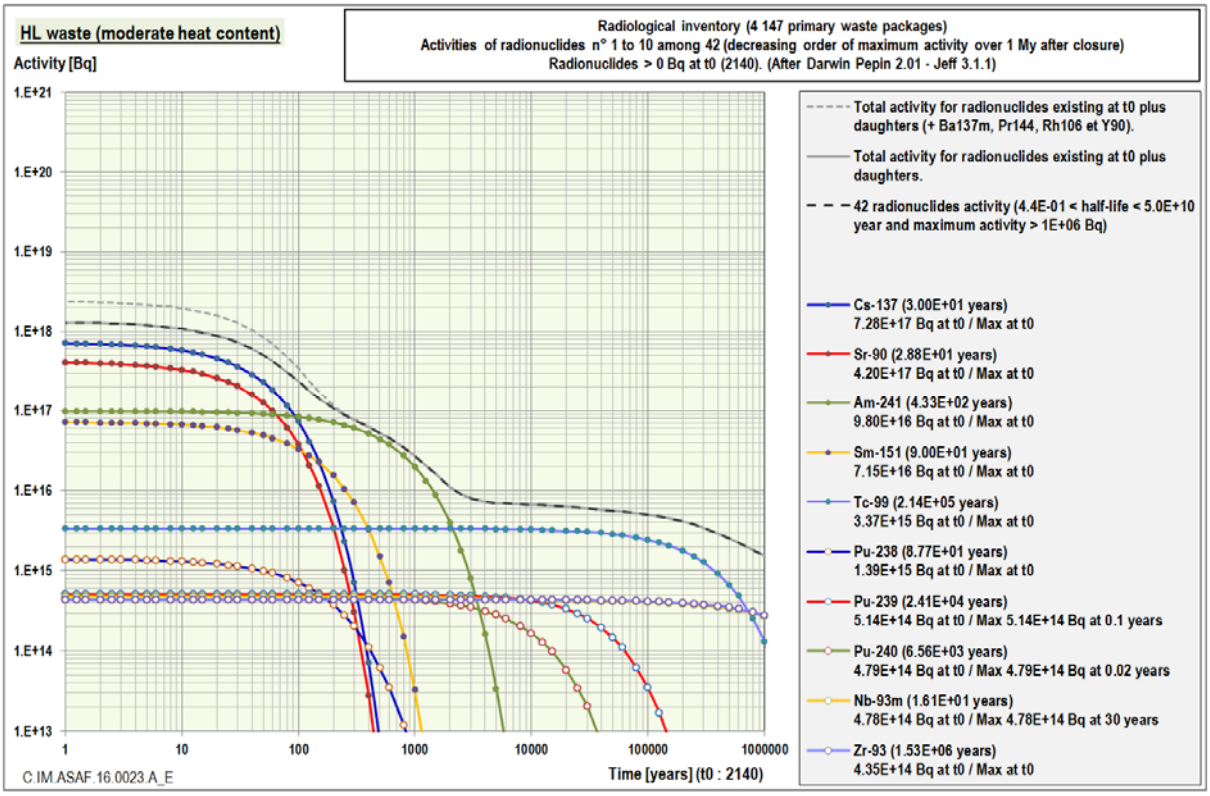


Figure 2.2-3: Change in the activity of the 10 radionuclides with the highest maximum activities over 1 Myr for the HLW0 packages

Table 2.2-5- gives the activities of the long-lived radionuclides on the closure date.

Table 2.2-5: HLW0 waste (slightly to moderately exothermic): total activities of a selection of long-lived radionuclides

Radionuclide	Radioactive half-life in years (According to Jeff 3.1.1)	Activity at the beginning of the post-closure phase (Bq) (Reference radiological inventory)
^{241}Am	4,33 x 10^{2}	9.80 x 10^{16} (3,220 moles)
^{99}Tc	2.14 x 10^{5}	3.37 x 10^{15} (54,900 moles)
^{79}Se	3,77 x 10^{5}	7.80 x 10^{13} (2,220 moles)
^{36}Cl	3,01 x 10^{5}	1.64 x 10^{11} (4.24 moles)
^{14}C	5,70 x 10^{3}	4.77 x 10^{10} (0.021 moles)
^{129}I	1,61 x 10^{7}	2.98 x 10^{10} (36.4 moles)
Total 144 radionuclides	-	*1,33 x 10^{18}*

Table 2.2-6 shows the change over time in the total activity and in the activity of the actinides, and the distribution between short-lived and long-lived and between alpha emitters and beta-gamma emitters.

Table 2.2-6: HLW0 waste (slightly to moderately exothermic) - Change in the relative distribution of the radionuclides over time

Cigéo - Reference radiological inventory - HL waste (moderate heat content)							Radionuclides with half-life between 0.45 years and 50 billions years					
4 147 primary packages	Year 2140	10	50	100	500	1 000	5 000	10 000	50 000	100 000	500 000	1 000 000
Total activity (144 RN) [Bq]	1.33E+18	1.08E+18	5.04E+17	2.35E+17	5.30E+16	2.71E+16	7.02E+15	6.67E+15	5.64E+15	5.01E+15	2.53E+15	1.54E+15
Short lived total activity [%]	86.6	84.2	70.8	47.2	1.3	2.5	9.5	9.8	11.2	12.1	17.1	20.5
Long lived total activity [%]	13.4	15.8	29.2	52.8	98.7	97.5	90.5	90.2	88.8	87.9	82.9	79.5
Actinides activity [%]	7.7	9.3	18.7	36.9	87.5	81.1	28.6	26.2	21.1	21.1	32.4	42.7
Alpha activity [%]	7.7	9.3	18.7	36.9	87.8	81.8	31.3	29.0	24.3	24.4	34.8	43.5
Beta gamma activity [%]	92.3	90.7	81.3	63.1	12.2	18.2	68.7	71.0	75.7	75.6	65.2	56.5

Radiological inventory of the package families of the HLW1 and HLW2 disposal sections

Figure 2.2-4 shows the change in total activity over 1 million years and in the activity of the ten radionuclides with the highest activity over 1 million years for the HLW1-HLW2 disposal section.

At the scale of these sections, caesium-137 and strontium-90 have the predominant activities up to about 60 years post-closure. The activity of americium-241 then predominates up to about 2000 years. For all 144 radionuclides, the post-closure attenuation factor is about 5 at 100 years, 15 at 500 years and 95 at 2000 years.

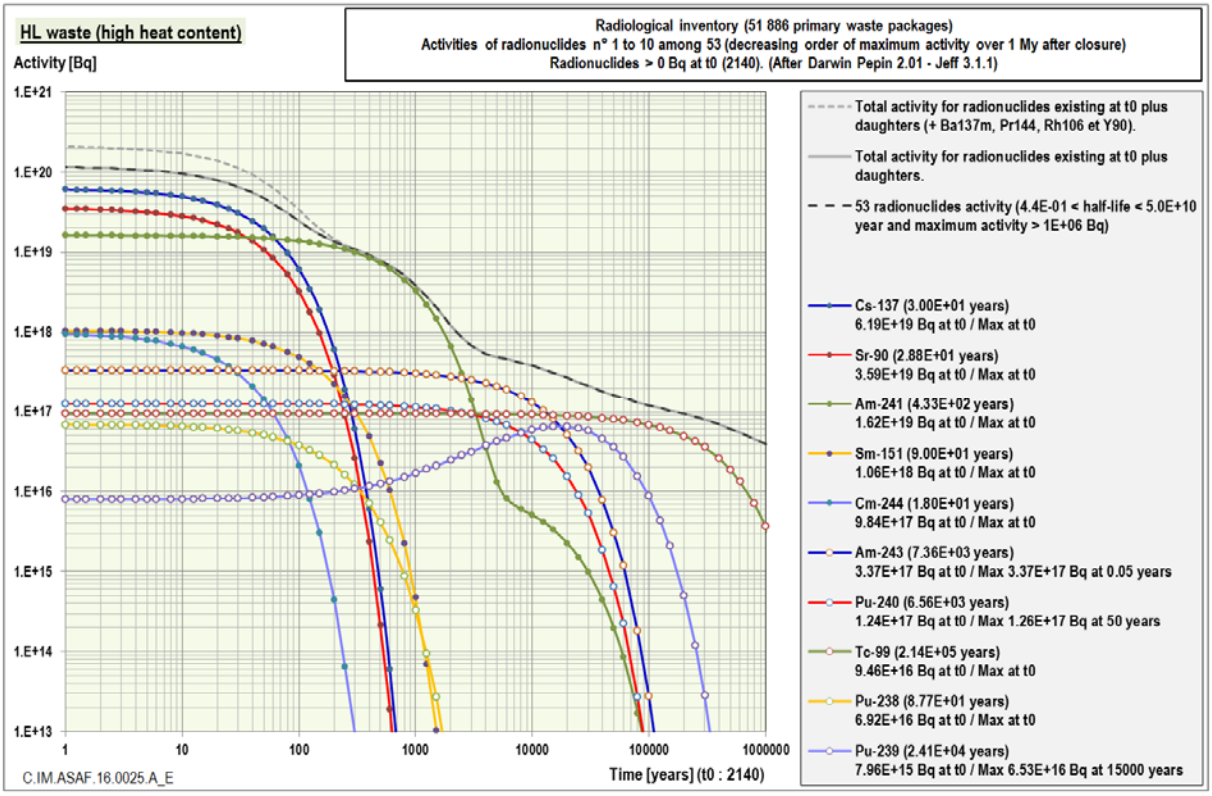


Figure 2.2-4: Reference radiological inventory of highly-exothermic HLW waste. Change in the activity of the 10 radionuclides with the highest maximum activities over 1 million years

The table below, for illustration, gives the activities of the long-lived radionuclides on the closure date.

Table 2.2-7: Highly-exothermic HLW waste HLW1 and HLW2 - Activities on the basis of the reference radiological inventory for a selection of long-lived radionuclides

Radionuclide	Radioactive half-life in years (According to Jeff 3.1.1)	Activity at the beginning of the post-closure phase (Bq) (Reference radiological inventory)
^{141}Am	4,33 x 10^{2}	1.62 x 10^{19} (532,000 moles)
^{143}Am	7,36 x 10^{3}	3.37×10^{17} (1.88×10^{5} moles)
^{99}Tc	2,14 x 10^{5}	9.46×10^{16} (1.53×10^{6} moles)
^{79}Se	3,77 x 10^{5}	1.28 x 10^{15} (36,600 moles)
^{14}C	5,70 x 10^{3}	3.41 x 10^{14} (147 moles)
^{36}Cl	3,01 x 10^{5}	1.72 x 10^{14} (3,920 moles)
^{129}I	1,61 x 10^{7}	2.15 x 10^{12} (2,620 moles)
Total for the 144 radionuclides	-	*1,17 x 10^{20}*

Table 2.2-8 shows the change over time in the total activity and in the activity of the actinides, and the distribution between short-lived and long-lived and between alpha emitters and beta-gamma emitters.

Table 2.2-8: Highly-exothermic HLW waste HLW1 and HLW2 - Change in the relative distribution of the radionuclides over time

Cigéo - Reference radiological inventory - HL waste (high heat content)							Radionuclides with half-life between 0.45 years and 50 billions years					
51 886 primary packages	Year 2140	10	50	100	500	1 000	5 000	10 000	50 000	100 000	500 000	1 000 000
Total activity (144 RN) [Bq]	1.17E+20	9.59E+19	4.69E+19	2.45E+19	7.95E+18	3.88E+18	4.93E+17	3.85E+17	1.63E+17	1.21E+17	6.09E+16	3.92E+16
Short lived total activity [%]	84.6	81.5	65.0	38.6	0.3	0.6	3.9	4.3	7.2	9.4	15.6	19.3
Long lived total activity [%]	15.4	18.5	35.0	61.4	99.7	99.4	96.1	95.7	92.8	90.6	84.4	80.7
Actinides activity [%]	15.3	18.0	33.5	58.9	98.0	96.6	73.9	67.1	30.5	17.2	29.0	41.6
Alpha activity [%]	15.2	18.0	33.4	58.8	97.9	96.4	72.4	65.8	30.4	17.2	29.0	41.6
Beta gamma activity [%]	84.8	82.0	66.6	41.2	2.1	3.6	27.6	34.2	69.6	82.8	71.0	58.4

2.2.3 Inventory of toxic chemicals

The construction of the inventory of toxic chemicals in the Cigeo waste packages follows a methodology similar to that used for the radiological inventory. The procedure comprises a first phase of compilation of the available data and a second phase of processing of the residual uncertainties related to the knowledge levels.

The inventory of toxic chemicals will be drawn up on the due date for the construction licence application for each of the 13 toxic chemicals stipulated by Andra: uranium, lead, mercury, antimony, cadmium, selenium, arsenic, nickel, chromium, boron, beryllium, CN radical and asbestos.

It will be used to check the absence of impact.

2.3 Characteristics of the primary waste packages involved in the Cigeo safety functions

In addition to their radiological inventory, other characteristics of the primary waste packages are involved in the fulfilment of safety functions after closure of Cigeo. In particular, the favourable containment characteristics of some waste and/or waste matrices of the primary packages are exploited after closure to limit the release of the radioactive substances contained in the waste.

2.3.1 Primary packages of HLW waste

The primary packages of HLW waste are characterised by heat release, which is taken into account in the dimensioning: Andra has chosen to limit the temperature and the thermo-hydro-mechanical effects on the Callovo-Oxfordian in a range (i) avoiding irreversible degradation of the disposal system characteristics contributing to the safety functions, particularly the Callovo-Oxfordian, and (ii) within which the processes governing changes in the disposal system can be represented and modelled reliably. In particular, it implies a cell temperature always below 100°C (in practice, the criterion applied in the clay rock is 90°C). Compliance with this range is based on the relationship between the heat output of the packages, which is related to their radiological content and the duration of their prior interim storage, and the dimensioning of the underground facility.

A large proportion of the HLW primary packages are vitrified. The vitrified waste effectively isolates the fission and activation products and the minor actinides from water. Radionuclides can be released only to the extent that the glass is altered in the presence of water (refer to appendix 7).

The alteration of glass depends on its intrinsic characteristics (composition, fracturing rate and specific surface area) and on the physicochemical environmental conditions, including:

- the alteration rates increase with temperature: this concerns both the initial rate established on contact with liquid water (V_0) and the residual rate after formation of a passivating reactive layer (V_R);
- the alteration of glass is also sensitive to the composition of water coming into contact with the glass.

In order to make best use of the containment capacity of glass, Andra has chosen to delay the arrival of water on glass, so that the temperature is lower when water finally comes into contact with it. This function concerns the leaktightness of the disposal container (see below). Measures are also taken to limit the concentration of alkalis and alkaline earths in the water present in the cell after loss of leaktightness: this involves limiting the quantity of cement in the HLW cell and giving preference to the use of cement with pH strictly less than 12.5, and keeping the waste packages away from drifts lined with concrete.

No function is assigned to the HLW primary container during the post-closure phase.

2.3.2 ILW-LL waste primary packages

The ILW-LL primary packages that have characteristics making a particular contribution to limiting post-closure release of radioactive substances include:

- activated metal waste (including spent fuel structural waste)

The activity associated with activation of the radionuclides in the bulk metal can only be released as the metal is corroded. After closure, the corrosion kinetics are limited (low) by reducing conditions and a basic pH in the packages and the cells;

- Waste within which the radionuclides are rendered insoluble in the form of low-solubility salts

Insolubilisation of radionuclides in the form of low-solubility salts contributes to the function "Limit the release of radionuclides and immobilise them in the repository" by limiting the dissolution of radionuclides.

Dispersal of these salts in a bitumen matrix provides additional protection against water. This protection remains effective as long as the coated material retains a geometry close to its initial geometry in the primary package, and the viscosity of the bitumen prevents salt sedimentation; this depends on the mechanical durability of the disposal container (see below) and on the temperature in the cell. A pH between 7 and 12.5 enables the waste to remain in a range where the behaviour of the coated material is well known.

It should be noted more generally that cement coating matrices favour containment close to the waste, for example by contributing to the application of a basic pH. However, this factor should not be over-emphasised in comparison with the larger alkaline mass contributed by the other cement components in the cells.

The gradual alteration of some ILW-LL waste packages may also generate chemical species likely to disturb the near-field chemical conditions. In particular, this concerns organic waste, alteration of which will form complex-forming species, and saline waste likely to affect the redox conditions. The design of the underground facility takes these processes into account so as to limit their effects on the behaviour of radionuclides in water. This involves rules on co-disposal of different families in a given cell and on physicochemical separation of cells (refer to Appendix 9).

- Vitrified waste

Vitrified waste contributes to the function "Limit the release of radionuclides and immobilise them in the repository" by limiting the dissolution of radionuclides and toxic chemicals.

2.3.3 Release models used for quantitative post-closure safety assessment

The quantitative post-closure safety assessment described in volume III uses release models to report the characteristics favourable to containment of the conditioned waste. This paragraph describes the procedure implemented by Andra to define these models and presents its main conclusions.

2.3.3.1 Definition procedure

The procedure for selecting the release models and the associated parameters is based on the level of knowledge of the behaviour of waste. The state of knowledge of the behaviour of HLW and ILW-LL waste, in particular vitrified waste, saline waste with bitumen matrix and activated metal waste, is summarised in appendices 7 and 8. This knowledge is based on several years of R&D studies.

For each waste package family, the definition procedure for the release models to be used for quantitative post-closure safety assessment follows the steps below, illustrated in Figure 2.3-1:

- the existing release models for each family of waste packages are identified, along with their areas of applicability. If no model can be defined because of a lack of knowledge or if the models identified are not applicable under the disposal conditions, an "instant release" model is used (involving instantaneous release on contact with water);
- for each of the applicable models, the level of acquired knowledge is assessed, particularly as regards the experiments carried out and the residual uncertainties inherent in the model or related to disposal conditions. On the basis of the results of this analysis:
  - ✓ if the knowledge level is high and the residual uncertainties are controlled, a "phenomenological" model is selected (23)
  - ✓ if the knowledge is subject to high uncertainties (of any kind), a "conservative" model is selected (23).

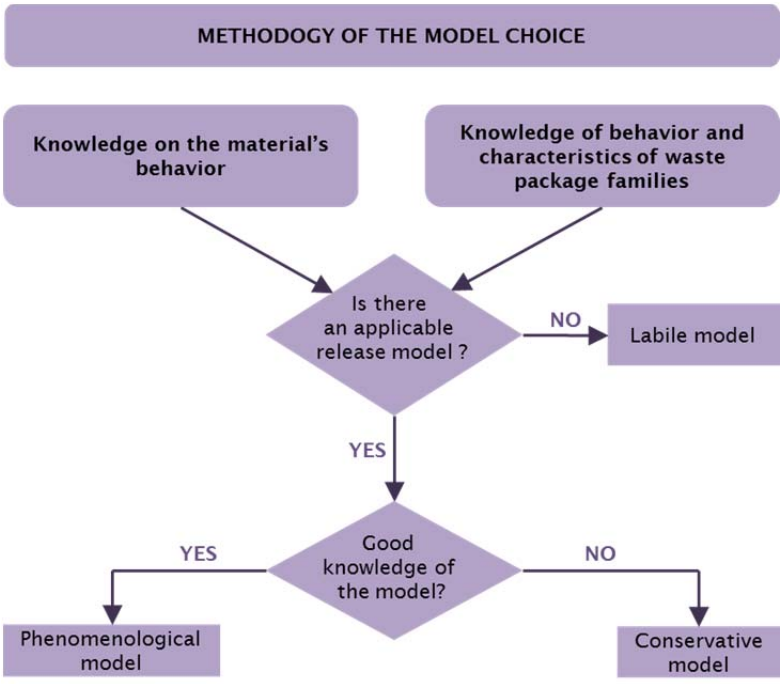


Figure 2.3-1: Logic diagram illustrating the selection strategy for radionuclide release models used in safety assessment

The release models are based on parameters related to the intrinsic characteristics of the conditioned waste (waste composition for example) and to their evolution over time according to the physicochemical conditions (temperature, pH, redox, etc.). Like model selection, the selection of the parameters is based on the following principles, illustrated in Figure 2.3-2:

- a good knowledge of the model parameters, in particular supported by experiments, leads to the selection of "phenomenological" parameters, derived from the available measurements;
- if the knowledge has less experimental support or is affected by residual uncertainties that are difficult to control, the strategy leads to the selection of "maximum" parameters.

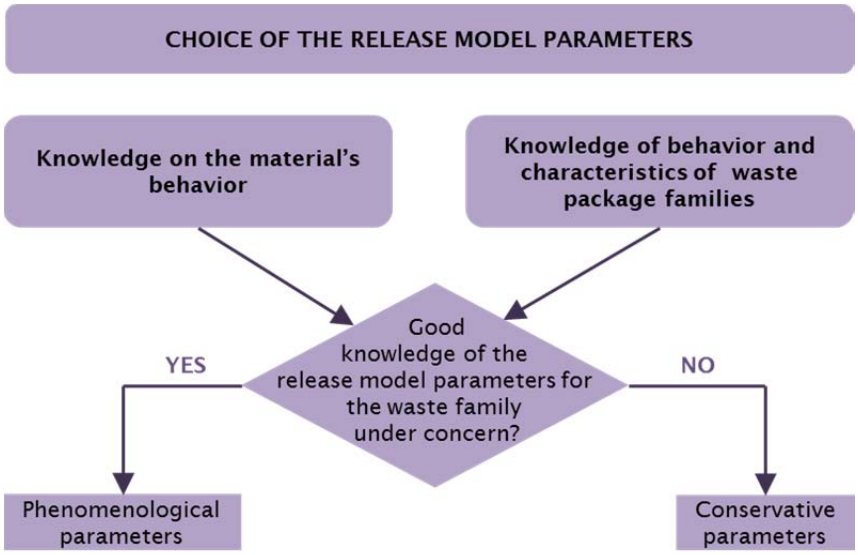


Figure 2.3-2: Logic diagram illustrating the selection method for the parameters of the selected release model

2.3.3.2 Selection of the models and associated parameters for HLW waste

Selection of the models and associated parameters for HLW waste is described in document (24). It takes into account the environmental conditions in the cells when liquid water comes into contact with the vitrified waste following loss of leaktightness of the disposal containers.

Vitrified HLW waste

The models selected for the vitrified HLW waste packages are summarised in Table 2.3-1.

- The model based on reaching a residual rate V_R is selected as reference. The model based only on the initial rate (V_0.S model, where S is the specific surface area of the glass) is considered as an upper bound taking into account the residual uncertainties regarding the transition time from the initial rate to the residual rate, in particular according to the influence of silicon, iron and corrosion products. In addition, these uncertainties lead to the selection of parameters maximising this transition time as reference.
- An "instant release" model is selected for some families that have low leaching resistance or for which the available data (glass composition , surface area accessible to water) are insufficient to define the model parameters.

In a conservative approach, the families for which the influence of the groundwater on the alteration rates has not been measured are considered like the families showing the largest difference between the rates in pure water and in groundwater, i.e. corresponding to the highest alteration rate.

The parameter values derived from experiments or models representative of the glass composition range of the family are given preference as references, in particular the values obtained by measurements representative of the disposal conditions.

For all the families, the maximum measured or calculated values are selected in a bounding situation.

Table 2.3-1: Selection of vitrified HLW release models

Waste family type	Waste package family	Model(s) selected as reference	Model(s) selected in a bounding situation
Vitrified HLW	• CEA-350 • CEA-1070 • CEA-1080[1] • COG-140 • COG-200 • COG-800 • COG-810[1] • COG-820[1] • COG-830 • COG-880 • COG-890 • COG-900	Model based on reaching a residual rate V_0 on loss of disposal container leaktightness with: • phenomenological parameter values, or maximum values for alteration rates V_0 and V_n, • parameters maximising the transition time to V_R.	COG-200, COG-810[1] and COG-830: "instant release" model on loss of disposal container leaktightness Other families: model V_0.S on loss of disposal container leaktightness with parameters maximising the release kinetics (measured maximum values or reference values with uncertainty or standard deviation)
	• CEA-200 • CEA-1080[1] • COG-150	V_0.S model on loss of disposal container leaktightness with phenomenological parameters or maximum parameters if the former are not available	For CEA-1080[28]waste packages: "instant release"model on loss of disposal container leaktightness Other families: model V_0.S on loss of disposal container leaktightness with parameters maximising the release kinetics (measured maximum values or reference values with uncertainty or standard deviation)
	• CEA-1190 • COG-810[1] • COG-820[1]	"Instant release "model on loss of disposal container leaktightness	Same as model selected as reference

[1] Depending on the variability of glass composition within a given family

- ***Non-vitrified HLW waste***

In the present state of knowledge, an "instant release "model on loss of disposal container leaktightness is selected for families COG-850, COG-860, COG-870 and CEA-1500.

2.3.3.3 Selection of the models and parameters for ILW-LL waste

The selection of the release models and the associated parameters is described:

- in document (24) for vitrified ILW-LL waste;
- in document (25) for non-vitrified ILW-LL waste.

- ***Vitrified ILW-LL waste***

For the vitrified ILW-LL waste, at this stage, a model based only on the initial rate is selected, given the cement environment of the disposal cell (see below). In this environment, a risk of resumption of alteration cannot be excluded.

An "instant release" model is selected for the CEA-1120 family containing beryllium, as the influence of this element in the glass in terms of homogeneity and long-term behaviour is not known at this stage.

[28] Originating from campaign SG8

In view of the results obtained in the experiments, in a similar manner to the vitrified HLW waste , the parameter values derived from experiments or models representative of the glass composition range of the family are given preference as references, in particular the values obtained by measurements representative of the disposal conditions.

For all the families, the maximum measured or calculated values are selected in a bounding situation.

The selection of release models for vitrified ILW-LL waste is summarised in the table below.

Table 2.3-2: Selection of vitrified ILW-LL waste release models

Waste family type	Waste package family	Model(s) selected as reference	Model(s) selected in a bounding situation
Vitrified ILW-LL waste	CEA-340 CEA-1120 COG-470	V_0.S model with the other phenomenological parameters, unless missing data or significant uncertainty	Model V_0.S with parameters maximising the release kinetics (measured maximum values or reference values with uncertainty or standard deviation)
	CEA-1120 (package containing beryllium)	"Instant release "model	Same as model selected as reference

- ***Saline waste with bitumen matrix***

The ability of bitumen to limit radionuclide release is assessed by the COLONBO release model. The model has been developed to take into account the capacity of the bitumen to limit water uptake and consequently limit the dissolution of radionuclides.

Application of the COLONBO model is based on the retention of the geometry of the coated material. As a consequence of swelling caused by radiolysis or water uptake, the coated material may potentially flow out of the primary package. The time during which the geometry of the bitumens is guaranteed, and the COLONBO model is applicable, depends on how long the mechanical strength of the disposal containers is maintained. During this time, COLONBO is the selected reference model for the waste package families for which it is applicable, in particular according to their soluble salt content per unit mass and the absence of mixing with other waste. When the integrity of the disposal container is no longer ensured, the release model based on salt solubility is selected.

To take into account the uncertainties about the applicability range of the COLONBO model, in particular with regard to maintenance of the concrete disposal container geometry, a model based only on salt solubility is selected in a bounding situation for these waste families.

For the families for which the COLONBO model is not applicable (23), only the release model based on salt solubility is selected.

For the parameters associated with the release model based on salt solubility, given the uncertainties about the association of radionuclides within precipitates (salts), all the radiological activity of waste is associated with the salt that has the highest solubility: $NaNO_3$ (sodium nitrate).

The release models selected at this stage for the saline waste with matrix are summarised in the table below.

Table 2.3-3: Release models selected for post-closure safety assessment by family of saline waste with bitumen matrix

Waste family type	Waste package family	Model(s) selected as reference	Model(s) selected in a bounding situation
Saline waste with bitumen matrix	CEA-1000 CEA-1010 CEA-1020[1] CEA-1021[1] COG-020[2] (97% of all the packages) COG-420[3]	COLONBO over the period of disposal container integrity then salt solubility ($NaNO_3$ solubility values)	Salt solubility only ($NaNO_3$ solubility values)
	CEA-1020[1] CEA-1021[1] COG-020[3] (3 % of all the packages)	Solubility of the salts ($NaNO_3$ solubility values)	Same as reference

[1] Depending on the coated material production method
[2] STE3 bitumen-coated materials produced according to specification 300AQ027
[3] Non-instrumented waste packages only

- ***Saline waste without matrix***

Selection of release models for saline waste without matrix is described in document (24).

For this waste, the selected model is based on salts solubility (23).

Given the uncertainties about the association of radionuclides within the precipitates (salts), all the radiological activity of the waste is associated with the salt that has the highest solubility: $NaNO_3$ (sodium nitrate).

The release models selected at this stage and the families associated with them are summarised in the table below.

Table 2.3-4: Release models selected for post-closure safety assessment by family of saline waste without bitumen matrix

Waste family type	Waste package family	Model(s) selected as reference	Model(s) selected in a bounding situation
Saline waste without matrix (non-bituminised sludges)	COG-430	Solubility of the salts ($NaNO_3$ solubility values)	Same as reference

- ***Compacted metal waste (without cement matrix)***

Release model selection is based on the location of radionuclides in the waste:

- for radionuclides activated within alloys, the proposed model is based on corrosion. However, this model cannot be applied to the activation products of shearing fines and millimetre-size fragments, given the small size of the pieces and their specific surface area. An “instant release” model is selected for these small products, and the corrosion-based model is selected for the other metal products;
- for the radionuclides located within zirconia and at the surface of various materials, an “instant release” model is selected at this stage.

For waste families containing potentially corrosive products such as organic material degradation products, an "instant release" release model is selected at this stage in order to cover the uncertainties of the associated corrosion rates. An "instant release" release model is consequently selected for the families containing small quantities of organic materials, for example family COG-070 containing ion-exchange resins (IER) and silicone seals.

For waste families containing mixtures of metals likely to produce galvanic coupling, an "instant release" release model is selected in order to cover the uncertainties associated with the corrosion rates.

For the release model based on corrosion rates, given the cementitious environment imposed by the disposal cell, the maximum corrosion rate in cementitious water is applied for each metal alloy considered (zirconium alloys, stainless steels and nickel alloys). For this model, the conservative assumption is made that all the activity is concentrated in the thinnest pieces:

- for zirconium alloys, the hull thicknesses without oxide layers are used;
- for stainless steels and nickel alloys, the thicknesses of the Inconel springs and the stainless steel rod springs are used.

For the package families containing a significant content of fines, the fines content given by the producers is used as reference.

A margin factor of 2[29] is applied to this value in order to take account of the uncertainties in the fines content and also in the corrosion rates of metal items.

The release models selected at this stage for the families of compacted metal waste are summarised in the table below.

Table 2.3-5: Release models selected for post-closure safety assessment by family of compacted metal waste (without cement matrix)

Waste family type	Waste package family	Model(s) selected as reference	Model(s) selected in a bounding situation
Metal waste without cement matrix	COG-100 COG-110 COG-120	Generalised corrosion of activated metal items "Instant release" model for fines and fragments, zirconia and surface contamination	Same as reference, with a margin factor of 2 on the value of the fines and fragments fraction
	COG-070 COG-540 COG-450 COG-550 COG-530	"Instant release" model	Same as reference

- ***Metal waste with cement matrix***

For metal waste with a cement matrix, the selection of release models is the same as the selection applied for the compacted metal waste (without cement matrix). Given that the matrix and the disposal cell both imply cementitious conditions, the applied corrosion rates taken into account for each alloy are representative of cementitious environment. The release models selected at this stage for the families of metal waste with cement matrix are summarised in the table below.

[29] Margin factor applied to the worst case of the scenarios.

Table 2.3-6: Release models selected for post-closure safety assessment by family of metal waste with cement matrix

Waste family type	Waste package family	Model(s) selected as reference	Model(s) selected in a bounding situation
Metal waste with cement matrix	EDF-080	Generalised corrosion of activated metal items "Instant release" for the other items	Same as reference
	COG-040 EDF-090 CEA-1050 CEA-1060	"Instant release"	Same as reference

- ***Other ILW-LL waste packages***

The knowledge of the other ILW-LL waste families is not sufficient to assign containment properties to them. An "instant release" model is selected at this stage for these waste families. The families concerned are listed in the table below.

Table 2.3-7: Release models selected for post-closure safety assessment for the other ILW-LL waste families

Waste family type	Waste package family			Model(s) selected as reference	Model(s) selected in a bounding situation
Other ILW-LL waste	AND-000	CEA-360	CEA-1510	"Instant release" model	"Instant release" model
	CEA-050	CEA-370	COG-020[1]		
	CEA-060	CEA-380	COG-030		
	CEA-070	CEA-400	COG-050		
	CEA-080	CEA-410	COG-400		
	CEA-090	CEA-420	COG-420[2]		
	CEA-100	CEA-430	COG-440		
	CEA-110	CEA-440	COG-460		
	CEA-120	CEA-450	COG-480		
	CEA-140	CEA-460	COG-490		
	CEA-150	CEA-480	COG-500		
	CEA-231	CEA-1040	COG-510		
	CEA-232	CEA-1090	COG-520		
	CEA-270	CEA-1100	EDF-100		
	CEA-280	CEA-1110	EDF-110		
	CEA-290	CEA-1140	EDF-120		
	CEA-300	CEA-1151	EDF-250		
	CEA-310	CEA-1152	ITER-010		
	CEA-320	CEA-1180			
	CEA-330	CEA-1200			

[1] STE3 bitumen-coated materials produced according to specification 300AQ027
[2] Instrumented waste packages of family COG-420

2.4 HLW disposal containers

2.4.1 HLW disposal container contributions to the safety functions

By delaying water coming into contact with vitrified HLW waste, the HLW waste disposal container contributes to limiting the release of radionuclide and toxic chemical substances and immobilising them close to the waste:

- it prevents exposure of the vitrified waste to aqueous alteration at temperature (see above);

- it consequently prevents the dissolution of radionuclides at temperature; increasing temperature tends to increase the dissolution kinetics and the diffusion rates; it increases the uncertainties about the behaviour of the radionuclides in solution and at the surface of the solid phases (sorption);
- more generally, it prevents any release of radionuclides during the first post-closure transient phases, more complex to model.

The disposal container on its own maintains the containment of the HLW waste packages as long as it remains leaktight. This corresponds to an initial post-closure period characterised by activity of the short- and medium-half-life radionuclides in the HLW waste that is still high. During this period it prevents unacceptable radiological exposure in any hypothetical situation that would result in a bypass of the capacity of the disposal system to delay and attenuate migration, as in the case of an unintentional intrusion occurring early on; subsequently, the radioactive decay of the short- and medium-half-life radionuclides will reduce the radiological impact of such a situation.

Andra is designing the HLW disposal container so that it remains leaktight as long as possible taking into account the scientific uncertainties, the technological limits and the economic factors. The design process parallels that of the cell, which imposes its environmental conditions on the container.

At this stage[30], Andra intends to ensure that the leaktightness of the HLW disposal container is maintained at least as long as the core temperature of the glass is greater than 50°C for the moderately-exothermic HLW0 waste delivered before 2075 and above 70°C for the highly-exothermic HLW1/HLW2 waste delivered after 2075. The higher value used for the HLW1/HLW2 waste is explained by the advances in knowledge about the behaviour of vitrified waste and of radionuclides in solution expected over the coming decades. With the architecture selected for the underground facility (chapter 3), these limits correspond to a period of less than 500 years after the closure of Cigeo.

2.4.2 Design options selected for the HLW disposal container

Andra has selected low-carbon unalloyed steel as the material of the container. This choice is based on the predictable corrosion kinetics of the material, in that general corrosion is the predominant mechanism rather than localised corrosion processes.

In an anoxic environment, the general corrosion rate of unalloyed steels is low, and these steels have low sensitivity to localised corrosion: the geological environment contains few oxidising species likely to feed the cathodic reaction of localised corrosion. Andra is conducting corrosion tests in representative environments of the evolution of the disposal cells in order to verify the preponderance of general corrosion, with an average rate of the order of 10 micrometres per year at the most.

Unalloyed steels are subject to coding and standardisation of production and inspection techniques, which ensures that the physical (mechanical, dimensional, metallurgical, chemical, etc.) properties of the items produced are reproducible and constant.

The container is designed to reduce the risk of occurrence of localised corrosion and stress corrosion cracking processes: the corresponding technical measures are described in paragraph 2.4.3 below.

The container body consists of a cylindrical shell made of unalloyed steel of effective thickness[31] between 65 and 53 mm, a welded base of a thickness matching the shell thickness, and a cover made of the same grade of steel. All the welded joints are made at full thickness to reduce their singular character in terms of strength and leaktightness.

[30] These temperature constraints may be reviewed between now and the construction licence application on the basis of advances in knowledge, in particular on the behaviour of the radionuclides at temperature.
[31] These thicknesses may still be subject to optimisations between now and the construction licence application.

The thickness of the steel ensures:

- mechanical strength;
- corrosion resistance: part of the thickness is 'consumed' over time by general corrosion;
- radiation attenuation: radiation is likely to speed up corrosion and favour pitting corrosion (see below).

Although in general mechanical strength, corrosion resistance and radiation attenuation increase with steel thickness, the technological constraints on production processes limit the thickness; in particular, welding and stress relief (see below) operations become more complex as thickness increases, which impacts product quality control. The choice of the container thickness is consequently a compromise taking these diverse parameters into account with a view to optimisation. The cylindrical disposal container is sized to accommodate one or two primary packages, according to the family considered. For some shorter primary packages, the possibility of inserting three packages is also open. Various HLW disposal container models are shown in appendix 5. The figures below illustrate the vitrified HLW waste disposal packages produced by the Marcoule vitrification facility (AVM) and the La Hague R7-T7 facilities.

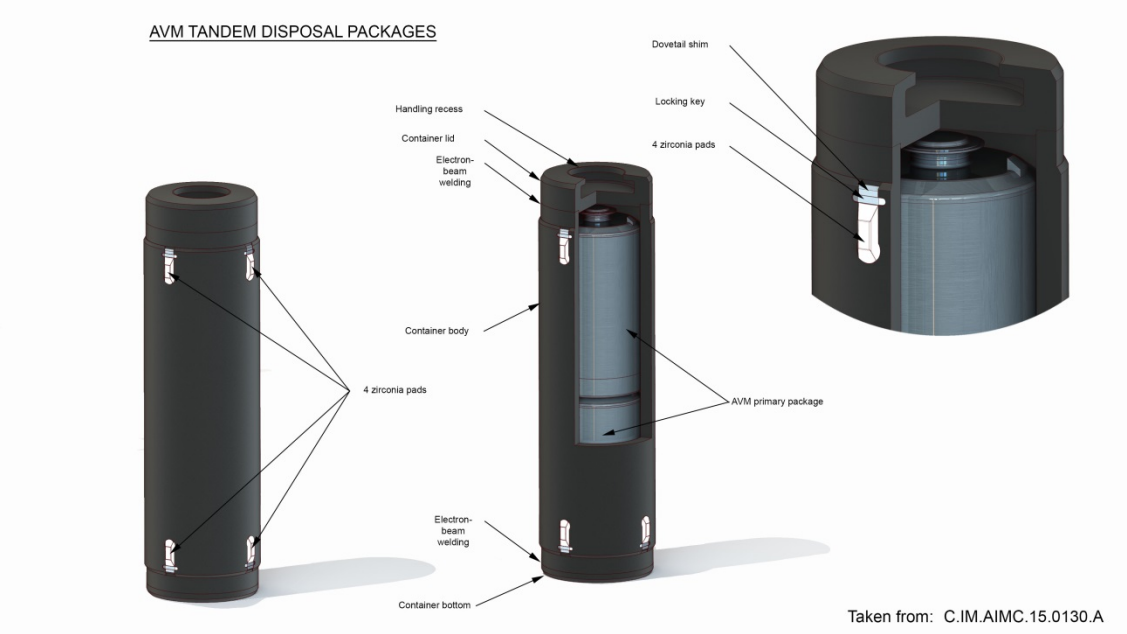


Figure 2.4-1: Illustration of an AVM two-package vitrified waste disposal container

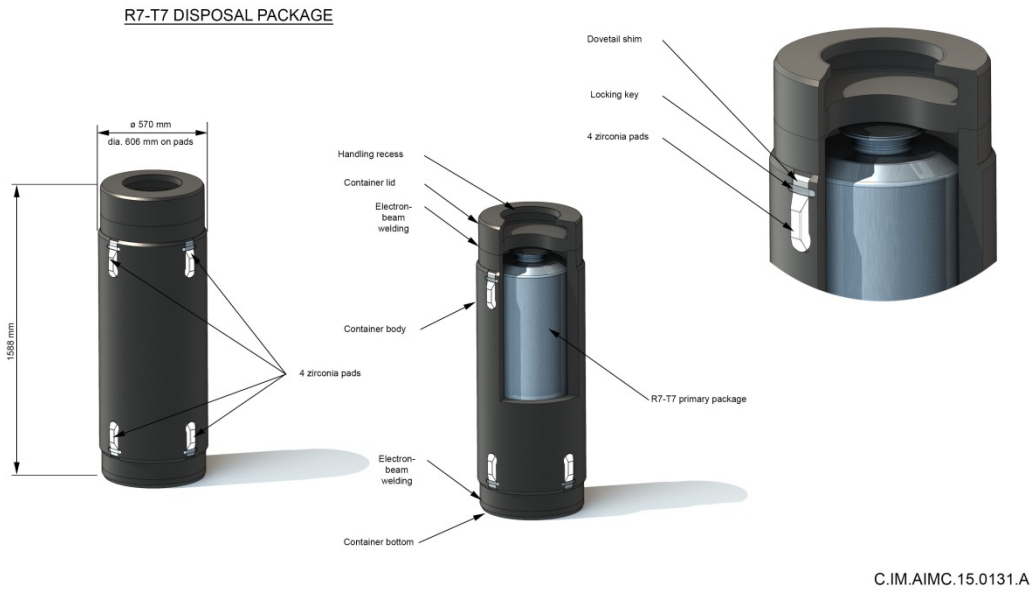


Figure 2.4-2: Illustration of an R7-T7 vitrified waste disposal container

2.4.3 Requirements with regard to the stress corrosion risk

Stress corrosion (SC) can occur under the combined action of:

- a tensile mechanical stress, which may be residual stress resulting from the shaping and welding processes or stress generated by the mechanical load applied to the container;
- an environment that promotes the influence of hydrogen on the mechanical properties of the material (embrittlement).

To reduce the stress corrosion risk, Andra defines two requirements:

- favourable mechanical stresses in the container steel: the design of the cell, in particular the function of its sleeve with regard to the mechanical loading of the container, the thickness of the container, taking into account its gradual 'consumption' by general corrosion, and the yield strength of the steel aim to keep the steel in the elastic domain as much as possible. In addition, stress relieving of all the container welds limits the residual stresses to less than 30% of the yield strength of the steel;
- selection of a grade of steel[32], its cleanness (including limitation of phosphorus and sulfur content) and its microstructure giving it (i) high ductility opposing the propagation of cracks in the case of plasticisation, and (ii) the lowest possible sensitivity to stress corrosion[33].

2.4.4 Requirements with respect to radiolytic corrosion

Radiation from HLW waste can, by radiolysis, cause the production of oxidising species (such as H_2O_2) or of chemical species modifying the pH of the medium locally (such as HNO_3). These chemical species contribute to increasing the kinetics of the general corrosion of the metal materials and favour the occurrence of localised corrosion. In the current state of knowledge:

- no effect of radiolysis of water on corrosion is observed at dose rates below 1 gray per hour;
- radiolysis has little influence at dose rates below 20 grays per hour. This influence is in any case strongly attenuated in the absence of oxygen.

[32] A high-ductility forged steel such as P285NH can meet these requirements.
[33] Reduction of impurities and inclusions limits stress corrosion cracking. The fine and homogeneous ferrite-perlite structure has low brittleness and low sensitivity to stress corrosion.

At this stage[34], Andra considers that the container thickness must limit the dose rate at the outer surface of the metal to less than 10 grays per hour, allowing for the gradual corrosion of the metal and the radioactive decay of the waste.

2.4.5 Requirements with respect to other corrosion processes

The materials of the container and the cell sleeve are chosen so as to avoid galvanic coupling. The use of durable inert runners[35] to facilitate sliding the containers into the sleeve in the operating phase prevents any risk of crevice corrosion at the container-sleeve contact (Figure 2.4-3).

During the operating phase, an additional corrosion risk arises from oxygen renewal by ventilation of the drifts as long as they are not closed; the risk covers both a higher general corrosion rate in the presence of oxygen than in an anoxic environment and pitting of the metal. This risk can be reduced by the design of the cell, in particular by establishing and maintaining an environment as anoxic as possible[36]. Furthermore, although pitting corrosion can develop at the surface of an unalloyed steel in the presence of oxygen, various work shows that the pits tend to widen, attenuating the depth of pitting over the long term compared with general corrosion.

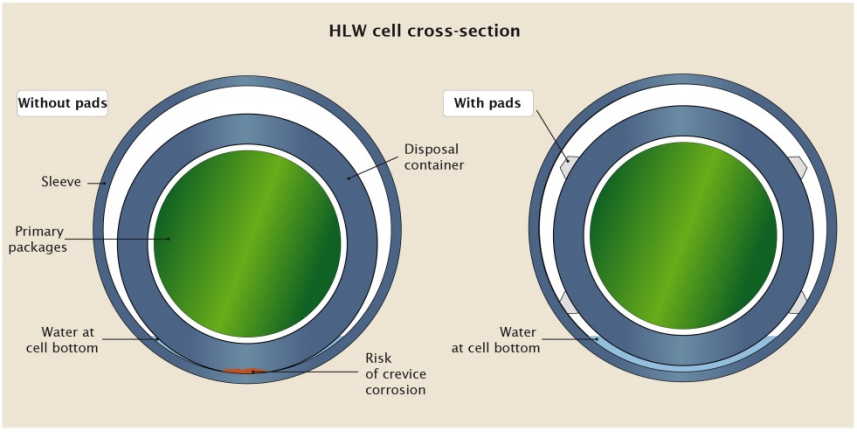


Figure 2.4-3: Illustration of the risk of crevice corrosion in the case of contact between the container and the sleeve (left) and prevention of the risk by intercalation of inert runners (right)

2.4.6 Mechanical behaviour and assessment of container durability

The container is subjected to mechanical stresses that it must withstand, taking into account the gradual loss of metal by corrosion: isotropic fluid loading as long as the sleeve is not in contact with the container, then heterogeneous loading by contact with the sleeve.

The mechanical behaviour of the container is checked, allowing for the loss of metal by corrosion, to ensure that it will enable the container to remain leaktight for longer than the thermal period defined above (refer to volume III). The minimum thickness necessary at this stage to prevent radiolytic corrosion covers the mechanical strength needs.

[34] This dose rate constraint may be reviewed between now and the construction licence application in view of advances in knowledge about radiolytic corrosion.
[35] At this stage, these runners are to be made of industrial ceramic.
[36] Analyses show that the container thickness already corroded when Cigeo is closed would be limited to a few millimetres at most.

2.5 ILW-LL disposal containers

It is planned that some or all of the ILW-LL primary packages will be inserted into disposal containers before they are transferred to the underground facility for placement in cells[37]. The functions of these containers concern essentially the operation of Cigeo (package transfer and handling, standardisation of Cigeo components, etc.).

2.5.1 ILW-LL disposal container design options

The disposal containers considered for the ILW-LL waste are shown in the figure in appendix 4. These containers have rectangular cuboid geometry[38]. The material is reinforced concrete for the majority of the families (case of disposal containers CS1 to CS5) and steel for some particular families (case of disposal containers CS6 and CS7). At this stage, the concrete containers are designed on the basis of a prefabricated body and lid. The formulation of the concrete is defined as a priority to meet the requirements of the Cigeo operating phase (refer to DOS-Expl).

2.5.2 ILW-LL disposal container contributions to the post-closure safety functions

With the other concretes in the cell, the concrete of the disposal containers contributes to containment close to the waste by maintaining a basic pH which:

- stays in a pH range in which the behaviour of the bituminised waste is known (see above);
- favours passivation of the activated metal waste, and consequently limits its corrosion and the release of activation products;
- favours low solubility values for radioactive elements such as nickel, cobalt, americium, curium, neptunium and plutonium.

In addition, for bituminised waste, the container favours the maintenance over time of a geometry of the bitumen-coated material close to its initial geometry in the primary package, making better use of the containment capability of the bitumen (see above).

Incorporation into the concrete (its admixture in particular) of organic materials or other substances likely to produce complexing species is minimised as far as possible, taking account of the technical constraints and in compliance with the requirements associated with Cigeo operation.

It should be noted that the other disturbances likely to be caused by the container on the disposal system, in particular on the clay rock (presence of voids, actions of cementitious, ferrous or oxidising products) are taken into account in the safety assessment. However, they do not justify the definition of specific requirements relating to the container design.

[37] At this stage, the following solutions are being considered: (i) for the majority of the waste package families, the primary package is placed in a disposal container on arrival at Cigeo; (ii) for some waste package families identified as "eligible for direct disposal", the primary package delivered to Cigeo is placed directly in the disposal cell, without being placed in a disposal container.

[38] This geometry tends to limit the residual void volumes in the cells.

3

The Cigeo Repository After Closure

3.1 Overall architecture 141
3.2 HLW waste disposal sections and cells 148
3.3 ILW-LL waste package disposal section and cells 159
3.4 Closure structures 171

In addition to the Callovo-Oxfordian and the waste packages, the disposal system comprises the Cigeo underground facility in the Callovo-Oxfordian and the surface-bottom connections passing through the various geological formations from the surface. These structures will have been closed by plugs, seals and backfill during the Cigeo closing operations.

The configuration of Cigeo after its final closure, and more particularly that of the underground facility, will incorporate all the changes between the present and the end of construction and operation over a century or so. The reference underground architecture used today for the studies is an illustration of what the architecture might be, extrapolating the technical options selected at the basic engineering design stage (Figure 3.1-1).

Implementing the safety functions and safety principles of Volume I, the underground disposal zones for HLW (HLW0, HLW1/HLW2) and ILW-LL waste are dimensioned according to the number of packages to be disposed of and the decay heat from the HLW waste, which has to be dissipated sufficiently in the clay rock. The ILW-LL zone consists of one section, the HLW0 zone also consists of one section and the HLW1/HLW2 zone consists of six sections. Their design meets both the operation requirements (refer to DOS-Expl) and the requirements defined to fulfil the post-closure safety functions.

Drifts connect the sections to the surface-bottom connections. The dimensioning of these connecting drifts (number and diameter in particular) meets operation needs first of all (construction of disposal cells, transfer of waste packages, industrial and nuclear safety in operation (refer to DOS-Expl)). The design of the drifts also meets a series of requirements related to the post-closure safety functions and safety principles covered in Volume I.

Similarly, the characteristics of the surface-bottom connections (shaft number and cross-section area[39]; ramp number, cross-section area and slope[40]) result from the operation needs (refer to Volume II of DOS-EXpl) and also take into account the post-closure safety requirements.

This chapter describes the design options and requirements for the general underground architecture of Cigeo, the HLW and ILW-LL waste disposal sections and cells and the closure structures, in response to the requirements of the post-closure safety functions.

3.1 Overall architecture

With regard to the post-closure containment of radionuclides and toxic chemicals, the overall underground architecture of Cigeo makes essential contributions to the functions “oppose water circulation” and “delay and attenuate the migration of radionuclides and toxic chemicals”. The associated design options and requirements are described below and summarised in Table 3.1-1.

The function “limit the release of radionuclides and toxic chemicals and immobilise them in the repository” is fulfilled close to the waste, so the corresponding design options and requirements specifically concern each disposal section (refer to 3.2 and 3.3).

[39] The total depths of the shafts range from 510 to 550 m. Their cross-section is circular, with an effective diameter ranging from 5 to 10 m according to the shaft. The dimensioning of the structures is based on the flows in transit during the operation and closing of the repository.

[40] The lengths and slopes (10% to 15%) of the ramps depend on the location selected for the surface nuclear facilities and take account of the technical constraints in operation (waste package transfer, evacuation/emergency services, maintenance, routing of materials/equipment).

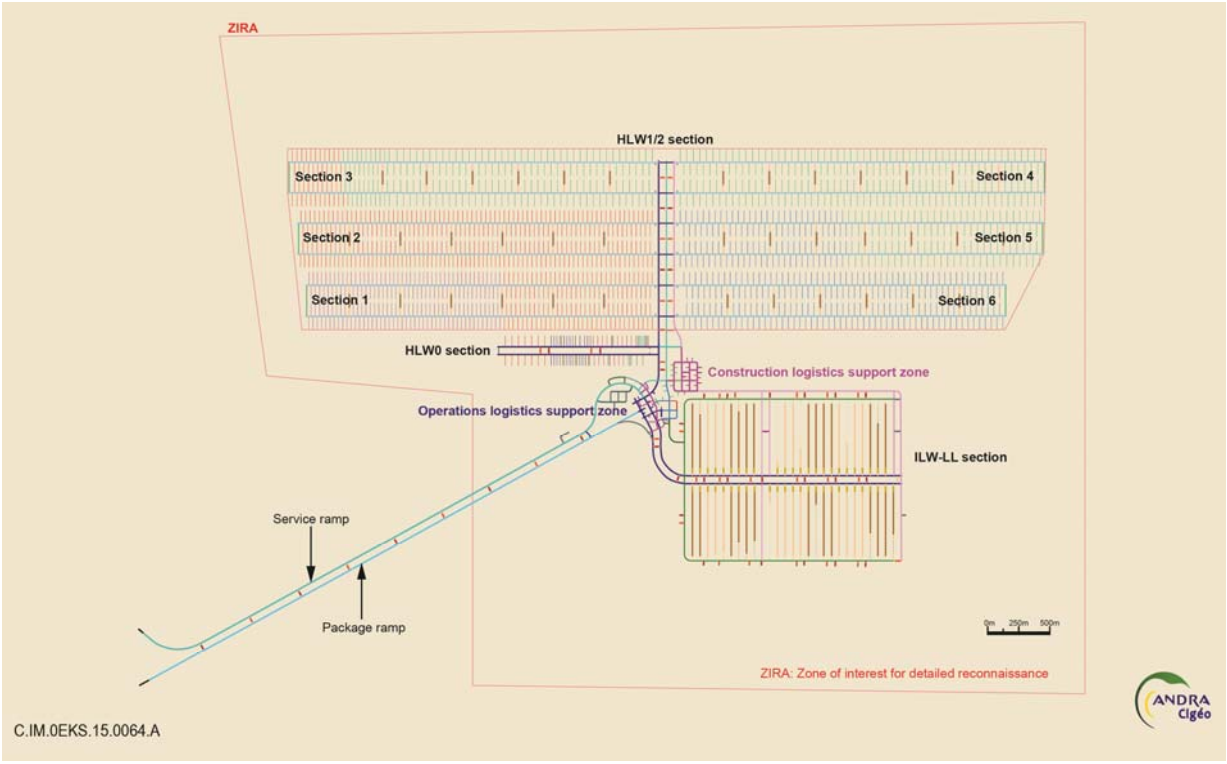


Figure 3.1-1: Basic engineering design stage illustration of the underground architecture on final closure of Cigeo.

3.1.1 Design options for function "oppose water circulation"

Control of water flows in transit through the repository is ensured first by the properties of the Callovo-Oxfordian, in particular its low permeability and its low vertical head gradient (refer to chapter 1).

The general underground architecture of Cigeo contributes to water flow control by limiting the draining capacity of the repository and by avoiding configurations of structures (shafts, ramps, drifts) favouring flows in them.

Grouped surface-bottom connections

The shafts and the ramp bottoms will be grouped in the same zone of limited footprint. This option avoids configurations likely to generate "hydraulic drivers" (establishment of preferential head gradients) tending to increase water circulations in the structures (Figure 3.1-2).

The shafts and the ramps are positioned in a zone where the vertical head gradient is very low or zero, which further limits the potential drain effects of the repository through these structures.

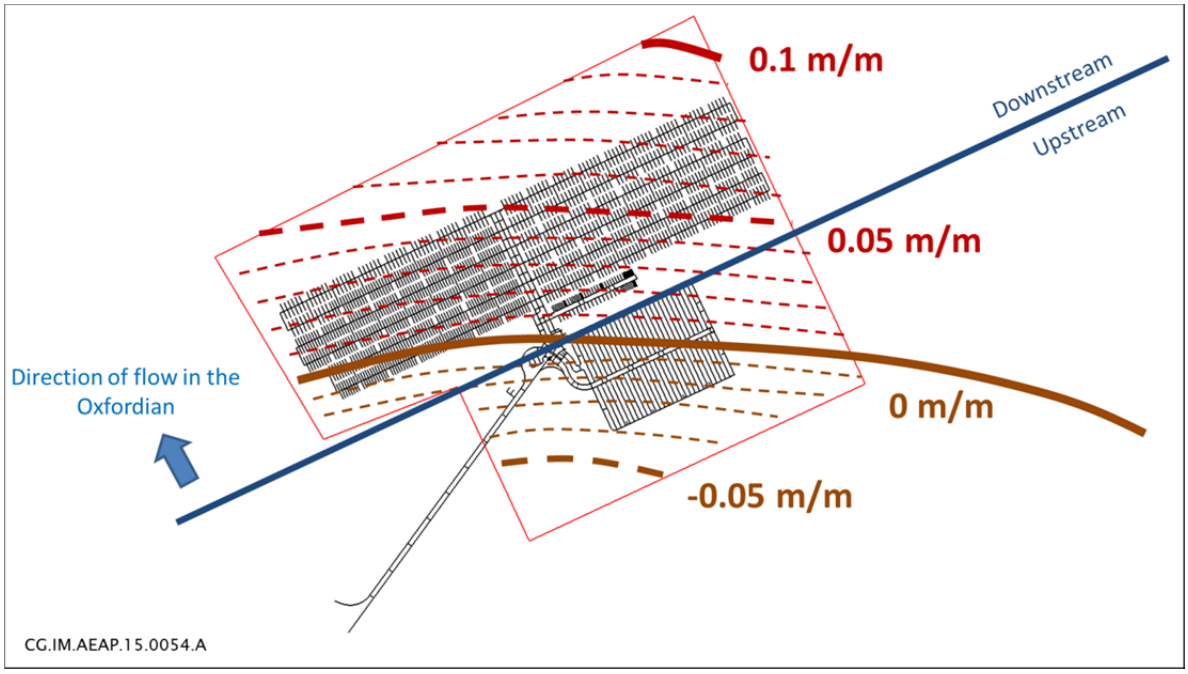


Figure 3.1-2: Position of the underground facility on termination and hydraulic head gradients observed in the ZIRA

Blind disposal sections

Each disposal section is blind with respect to the rest of the underground facility; the accesses to each disposal section are few in number and grouped.

The water flows drained towards the surface-bottom connections in each blind section are consequently limited to the flow that the section can exchange with the Callovo-Oxfordian. This limitation reduces advection within each section, favouring the pathway of solute transfer-retention by the Callovo-Oxfordian.

3.1.2 Design options for function "delay and attenuate migration"

To delay and attenuate the migration of radionuclides and toxic chemicals, two types of architectural measure are taken:

- structure lengths taking advantage of the slow advection rate in the disposal sections to give preference to the transfer pathway via the Callovo-Oxfordian rather than the pathway through the structures,
- the largest possible undisturbed clay rock thicknesses above and below the disposal structures, so as to make maximum use of the containment capacity of the Callovo-Oxfordian.

3.1.2.1 Geometrical characteristics delaying and attenuating longitudinal flow of radionuclides

Inside the disposal sections, the cells are made as long as possible, taking into account the technical constraints: refer to 3.2 and 3.3. Similarly, the length of each section contributes to delaying and attenuating longitudinal flow of radionuclides towards the connecting drifts: the longer this length, the lower the proportion of solutes leaving the sections and reaching the main connecting drifts[41].

[41] Beyond a length of 40 m, the HLW packages are no longer 'exposed' to the influence of the drift.

It should be noted that the other architectural parameters, in particular diameter and number of drifts, have a more moderate influence on solute transfer.

The assessments conducted by Andra show that with the measures taken:

- the transfer pathway through the surface-bottom connections has very markedly lower flow than the path via the Callovo-Oxfordian clay rock, and the flow distribution shows low sensitivity to the size of the sections and the length of the connecting drifts;
- most of the mass of solutes transferred through the surface-bottom connections comes from the nearest cells.

3.1.2.2 Maintenance of undisturbed clay rock thicknesses to maximise delay and attenuation of migration of radionuclides and toxic chemicals

As stated above, diffusion is the predominant solute transfer process through the Callovo-Oxfordian, related to (i) its low permeability to water, (ii) its diffusion properties and (iii) its low hydraulic head gradients. Consequently, the thicker the clay rock, the more solute migration will be delayed and attenuated.

Design measures and more particularly the organisation of the disposal sections in the thickness of the Callovo-Oxfordian are intended to maintain the thickness of clay rock above and below the disposal structures; these measures are described in 3.2 and 3.3.

Table 3.1-1: Design requirements and measures related to the general architecture of the underground facility

Function: Oppose water circulation
Requirements/performance **a)** The water flows from the Callovo-Oxfordian and drained by the repository shall be limited as far as possible.
Grouping of surface-bottom connections To limit the presence and forming of migration pathways and vectors other than diffusion in the host formation: (i) the shafts and the bottom ends of the ramps will be grouped in a single zone of small footprint, (ii) no disposal section will be located in the zone bounded by the bottom ends of the surface-bottom connections.
Blind disposal sections Each disposal section will be blind with respect to the rest of the underground facility, thus limiting the drained flow to the flow that it can exchange with the clay rock.
Orientation of the main connecting drifts The drift sections where the seals will be placed will be oriented parallel to the major horizontal stress. This is favourable for the installation of the seals, which also contribute to opposing water circulation.
Function: Limit the release of radionuclides and immobilise them in the repository
Requirements/performance **b)** The potential thermal interactions must be minimised. **c)** The potential chemical interactions must be minimised and the waste must be maintained in an environment in which processes are controlled.
Disposal of exothermic waste in sections separate from the sections for other waste has been decided. At this stage of the project, a minimum distance of 50 m is maintained between these two types of section.
Function: Delay and attenuate radionuclide migration
Requirements/performance **d)** The transfer pathway through the Callovo-Oxfordian must be favoured, in preference to the longitudinal transfer pathway through the structures. **e)** The undisturbed host rock thicknesses between the repository and the top and bottom of the Callovo-Oxfordian determine the radionuclide transfer times through the host formation. Minimum undisturbed host rock thicknesses are specified.
The disposal sections (area occupied by the cells and the access drifts) will be designed so that the distance between the first cell(s) of the section and the cell(s) furthest away from the section entrance is as long as possible. At this stage of the project, a minimum distance of 300 m is decided.
To increase the proportion of radionuclides migrating through the Callovo-Oxfordian (by flow reversal), the length of the connecting drifts between the sections with relatively low long-lived mobile radionuclide activity and the surface-bottom connections and the drift length between the other sections and the surface-bottom connections will be as long as possible. At this stage of the project, minimum lengths of 300 m and 500 m, respectively, are decided.
For the cells: the vertical thickness of undisturbed clay rock above and below the disposal cells of all waste categories is specified as high as possible taking account of technical constraints and costs, and at least 50 m. The length and the slope of the cells will be defined to comply with the minimum undisturbed clay rock thicknesses. Cell stacking on two disposal levels is forbidden.
For the access drifts to the ILW-LL cells (containing the ILW-LL cell seals): the vertical undisturbed thickness to top and bottom is at least equal to the undisturbed thickness required at the top and bottom for the ILW-LL disposal cells to which the drift sections provide access.
For the access drift sections inside the disposal sections and for the connecting drifts outside the disposal sections: the vertical undisturbed host rock thickness above and below the structures is specified as high as possible taking account of technical constraints and costs, and at least 50 m. Inside the disposal sections, drifts will cross at the same level.
The part of the underground facility location zone where the thickness of the Callovo-Oxfordian is highest is reserved for the expansion of the repository after 2075, in particular for any disposal of spent fuel.

3.1.3 Management of disturbances

Some waste causes thermal and chemical disturbances of the disposal system. The diversity of the waste requires separation between the disposal zones and, within each zone, between some disposal cells containing waste of different types. Separation by horizontal undisturbed host rock distances reduces interactions and their influence on radionuclide release and migration, and facilitates the modelling of the processes in each part of the repository.

With regard to the thermal disturbances caused by the waste, the overall architecture of the underground facility defined by Andra separates the waste packages in dedicated disposal sections according to their thermal behaviour:

- sections dedicated to the disposal of highly-exothermic HLW waste (HLW1/2 waste) located in the north of the ZIRA;
- a dedicated disposal zone for non- or slightly-exothermic ILW-LL waste in the south-east of the ZIRA;
- a disposal section dedicated to moderately-exothermic HLW waste (HLW0 waste) between the HLW1-2 and ILW-LL sections.

This ensures near-total thermal separation (to within a few degrees Celsius) between the exothermic waste sections and the sections accommodating non- or slightly-exothermic waste. Thermal disturbance is a particularly dimensioning factor for the HLW sections: the specific measures are described in 3.2. The specific measures concerning the ILW-LL section are described in 3.3.

The main chemical disturbances caused by the waste are (i) organic disturbance due to the degradation of ILW-LL waste rich in organic compounds and possibly due to admixtures in the concrete, and (ii) saline disturbance due to saline ILW-LL waste. The design options intended to reduce their effect are described in 3.3.

Other disturbances are generated by the construction and operation of the underground structures and by the degradation of the construction materials used (steel and concrete). Verification of the limited effects of these disturbances on the post-closure safety functions is covered below. The main disturbance results from the gases produced by anoxic corrosion and by radiolysis. Oxidising disturbance due to the ventilation in operation and alkaline disturbance due to concrete degradation are limited mainly to the immediate vicinity of the structures, in particular in the excavation-damaged clay rock zones.

3.1.3.1 Disturbances by gases produced by iron corrosion and by radiolysis

The steel in primary waste packages, disposal containers (solid steel of HLW containers and reinforcement of ILW-LL disposal containers) and underground facility structures (HLW cell metallic sleeves, reinforcement of the concrete liners of all the drifts and the ILW-LL cells, etc.) produces hydrogen by corrosion under post-closure anoxic conditions. Gas generation by radiolysis, mainly of organic materials in ILW-LL waste, is added to this hydrogen source term.

Estimated production of molecular hydrogen[42] is of the order of 10^{10} moles, with a distribution of 50% in the HLW cells, 40% in the ILW-LL cells and 10% in the access and connecting drift system and the central zone at the bottom of the surface-bottom connections. Production continues for several tens of thousands of years, and the production rate varies over time as a function of the available surface areas of steel in the case of corrosion and the decrease in dose rates in the case of radiolysis.

[42] Main gas produced in the repository, essentially by corrosion of metal components and by radiolysis of some ILW-LL waste.

Gas formation lengthens the unsaturated "transient" phase in the repository[43]: it can generate transfer of radionuclides in gaseous form by the gas transfer pathway or influence the transfer of radionuclides in solution by the water transfer pathway.

Andra does not define any particular post-closure safety function with respect to the gases, but checks that the containment performance of Cigeo is maintained despite this disturbance. The aim is to make sure that (i) the gases do not affect the performance of the various components of the disposal system, in particular the undisturbed clay rock around the disposal sections (for example by fracturing as a consequence of high gas pressure), and the engineered structural components contributing to the safety functions, and (ii) that the gas transfer pathway does not put the disposal system in communication with the biosphere.

According to the numerical simulations, because of (i) the large exchange surface areas available to the gases and (ii) closure structures that do not block gas flow[44], the major part of the hydrogen produced in the cells migrates through the connected fracture zone (ZFC) by gas-phase advection and by dissolution/diffusion towards the structures, and towards the undisturbed clay rock essentially by dissolution/diffusion. The undisturbed clay rock is very slightly desaturated or not at all during the hydraulic-gas transient.

During the hydraulic-gas transient, excluding the zones influenced by thermal processes, the water pressure in the repository only occasionally and slightly exceeds the water pressure in the Callovo-Oxfordian at the initial equilibrium (close to 5 MPa). In other words, the presence of dissolved hydrogen does not result in major overpressure of the water. Consequently, the hydraulic-gas transient does not generate overpressures in the Callovo-Oxfordian likely to influence solute migration significantly.

The reactivity of the dissolved hydrogen, in particular with the pyrite, will not significantly modify the mineralogy of the Callovo-Oxfordian and its overall redox conditions, which will remain reducing. Consequently, no significant effect of the presence of dissolved hydrogen is expected on the solubility limits (Csat) and the distribution coefficients (Kd) of the radionuclides in the Callovo-Oxfordian.

In the desaturated clay rock (essentially those in the ZFC) close to the structures, the radionuclide diffusion coefficients decrease sharply as a function of the degree of saturation, according to the measurements made using HTO, I- and Cs+.

Note: The use of iron is also likely to cause a chemical disturbance in the clay rock, particularly in the HLW cells which accommodate a large mass of steel: this topic is covered in paragraph 3.2.6.

3.1.3.2 Oxidising disturbance caused by oxygen in air during the operation phase

The excavation of the structures and their ventilation during repository operation lead to desaturation of the clay rock and penetration of oxygen into it.

In this partly-saturated environment, oxidation reactions can modify the geochemical conditions locally (modification of the interstitial water composition and of the reactions with some minerals, including pyrite) and cause microstructure modifications. These reactions result in an increase in ionic strength (by up to a factor of 2), a reduction in pH and an increase in redox potential.

[43] The repository introduces various marked hydraulic disturbances, the most significant of which are: (i) hydraulic head loss, linked with repository operation over a century or so, manifested by a pressure drop in the host formation that is more marked the closer to the structure walls; (ii)maintenance of a desaturated state of the disposal structures as a consequence of gas production. Gradual return to the initial undisturbed hydraulic conditions depends on the inward water flow contributed by the Callovo-Oxfordian, limited by the low permeability of the clay rock, and on the disturbance by the gases. It may take several tens to hundreds of thousand years.

[44] The closure structures allow gas flow at low pressure (ZFC and bentonite entry gas pressure or swelling pressure of a few MPa) compared with the in situ mechanical stresses (no mechanical weathering).

The assessments show that the oxidising disturbance is restricted to the damaged clay rock (ZFC).

Its effects on the transfer, retention and solubility properties in the clay rock are limited, and negligible at the scale of the Callovo-Oxfordian, given:

- the limited extent of the disturbance;
- the limited character of the salinity increase and mineralogical conversion effects;
- the transient character of the interstitial water pH reduction effect.

3.1.3.3 Alkaline disturbance caused by concrete degradation

The liner of the surface-bottom connections, the drifts and the ILW-LL cells consists of cementitious materials which produce alkaline fluids simultaneously with their chemical degradation.

Experiments and numerical modelling examining this disturbance show that in the clay rock it results in the formation of a remineralised zone in contact with the liner, corresponding to dissolution of the primary phases and precipitation of the secondary phases, and of a slightly-disturbed zone characterised mainly by destabilisation of the original smectitic phase. These disturbances also correspond to an increased in pH of the interstitial water.

Assessments of the extent of the alkaline disturbance in the clay rock under saturating conditions show an upper bound of a few tens of centimetres for the highly-remineralised zone and of the order of a metre for the slightly-disturbed zone, over a hundred thousand years. The disturbance consequently remains restricted to the damaged clay rock (ZFC and ZFD) and does not impact the undisturbed Callovo-Oxfordian.

The current uncertainties of these assessments are low and taking them into account tends towards a decrease in a process that already has little impact.

The increase in ionic strength due to the alkaline disturbance might increase the diffusion coefficients of anionic radionuclides and reduce those of cations. This effect has been studied and models are available for taking it into account (correction factors as a function of the ionic strength).

With regard to the retention and solubility properties:

- in the remineralised zone, data on the chemical retention characteristics of some established secondary phases are available;
- in the slightly-disturbed zone, the increase in potassium (K) concentration and in ionic strength may reduce the retention (Kd) of alkalis and alkaline earths and increase the solubility limits of the exchangeable radionuclides if the ionic strength is very high (more than four times the ionic strength of the undisturbed Callovo-Oxfordian water). These effects have been quantified for Kd, and a model taking them into account is available.

It should be noted that in line and in contact with the future seals, and for the purpose of preserving the properties of the seal cores, low-pH cementitious materials are used, reducing the alkaline disturbance (paragraph 3.4).

3.2 HLW waste disposal sections and cells

The HLW waste disposal cells and sections contribute to all the safety functions of Cigeo. As in the case of the disposal containers, Andra has selected design options on the basis of the best available techniques, with a view to making the best contribution to the safety functions while taking into account technical factors, in particular those relating to the operating phase, and economic factors. A close link should be noted between the design of the disposal containers and the design of the cells, particularly their sleeves.

A distinction is made between a disposal section for HLW0 (moderately exothermic) waste and disposal sections for HLW1 or HLW2 (highly exothermic) waste. The design of these sections and their cells differs in the moderate heat release from the HLW0 waste, which allows higher disposal density, and by the disposal schedule: disposal of HLW0 waste is programmed to begin during the pilot industrial phase, whereas HLW1/HLW2 waste disposal will not begin until 2075. This schedule difference means

that additional progress with regard to knowledge and technical demonstrations can be anticipated for the HLW1/HLW2 waste, offering greater prospects of optimisation as part of the incremental development of Cigeo.

The design options and requirements defined for the HLW cells and disposal sections in order to contribute to the accomplishment of the Cigeo safety functions are described below and summarised in Table 3.2-1.

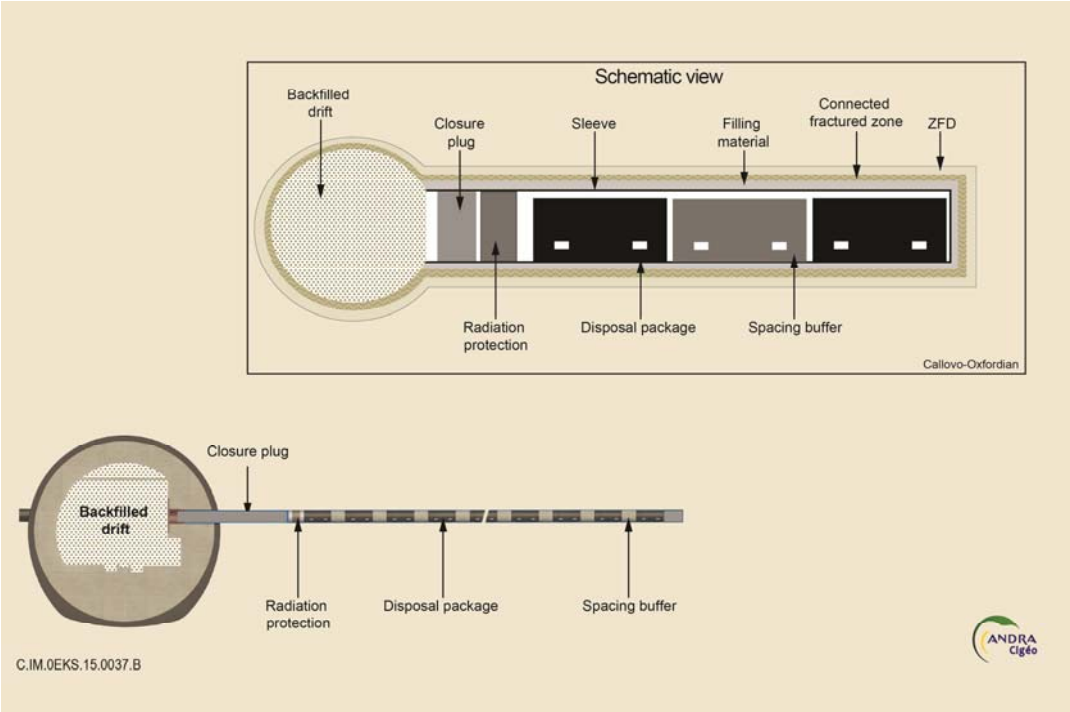


Figure 3.2-1: Schematic diagram of an HLW cell (case of HLW1/HLW2 waste)

3.2.1 Design options: contribution to post-closure safety functions

3.2.1.1 Contribution to the function "Oppose water circulation"

As stated above, each HLW disposal section of Cigeo is blind with respect to the rest of the underground facility in order to limit water flows between the underground facility and the overlying formations via the surface-bottom connections after closure. This means that the water flow circulating in each section is limited to what it can exchange with the clay rock. This limits the water flow speeds in the section. The flows do not combine until they are far from the cells, at the connecting drifts.

3.2.1.2 Contribution to the function "Limit the release of radionuclides and immobilise them in the repository".

It should be remembered that the limitation of the release of the radionuclides contained in the HLW waste is based in the first place on a low weathering rate of the vitrified waste. The weathering rate depends on the inherent characteristics of the glass and on the physicochemical environmental conditions in the HLW cell, in particular the pH of the water and the core temperature of the glass matrix when the water reaches the waste, which depends on the durability of the disposal container leaktightness. Andra is consequently designing the HLW cell to favour the durability of the disposal container initially and then, after loss of container leaktightness, the slow dissolution of the glass and the precipitation of most of the radionuclides.

The disposal container is protected by giving to the sleeve the highest possible mechanical durability, taking into account scientific uncertainties, technological limits and economic factors; this delays any contact between the sleeve and the disposal container for as long as possible. The container is also protected by avoiding a chemically-corrosive environment for both the container itself and the sleeve.

Like the disposal container, the sleeve is made of low-carbon unalloyed steel; this material withstands the mechanical stresses applied by the clay rock, and has a predictable long-term corrosion mode (refer to the paragraph above on the disposal container) that avoids any risk of galvanic corrosion between sleeve and container. The selected steel grade must be appropriate for the specific production and mechanical loading conditions of the sleeve (see below).

Observations at the Underground Research Laboratory have shown that there is a transient acid disturbance when water enters the cells from the clay rock. This disturbance results from oxidation of the pyrites in the clay rock face during cell excavation. It is attenuated over time. To prevent acceleration of sleeve and container from corrosion, the annular space between the sleeve and the rock is filled with a material intended to neutralise the transient acid disturbance. The formulation of the material is designed to reconcile this objective with the requirement that the pH of water coming into contact with the glass after loss of container leaktightness be as close as possible to neutrality (Andra requires in particular an initial pH of the backfill material less than 11). The design of this material is described below (paragraph 3.2.3).

Other disturbances can also be generated by the cell access drift. The design of the cell head is intended to prevent such disturbances affecting the durability of the sleeve and the container and subsequent weathering of the glass:

- During the operation period, the cell head (its length and a blanking system at the cell/drift interface) reduces gas exchange with the access drift, in particular oxygen in the drift ventilation air; this itself limits the sleeve and container corrosion processes[45] and also the oxidation of pyrites in the clay rock. Filling-in the annular space outside the sleeve close to the cell head may contribute to reducing oxygen access to the cell.
- After closure, the length of the HLW cell head (distance between the drift and the first package in the cell) and its backfilling form a thickness of undisturbed host rock against the physicochemical environment of the access drift, preventing the risk of propagation/short-circuit of the alkaline plume related to the presence of concrete in the access drift liner (see below, § 3.4.3).

3.2.1.3 Contribution to the function “delay and attenuate radionuclide migration”

The choice of horizontal, small-diameter cells (HLW cells) located in the median part of the Callovo-Oxfordian optimises the undisturbed clay rock thicknesses above and below in order to delay and attenuate radionuclide migration as much as possible.

In addition, cell orientation in the horizontal major principal stress direction (N155°E) tends to minimise the vertical extent of the damaged clay rock zone. This layout also facilitates cell construction and cell sleeve installation.

To draw maximum benefit from the containment capacity of the Callovo-Oxfordian, the cells are as long as possible, taking into account technical factors (construction and operation) and economic factors. This reduces the proportion of the radionuclides likely to migrate longitudinally as far as the access drift. The length of the cell head also contributes to this. Consequently Andra is adopting a cell head several metres long and a usable part several tens of metres long accommodating the disposal packages.

[45] This limits the phase of general corrosion of metal items under oxidising conditions; the occurrence of localised pitting or crevice corrosion processes favoured by oxygen is reduced. These corrosion processes may be associated with fast corrosion kinetics.

3.2.1.4 Preservation of the favourable properties of the Callovo-Oxfordian

To preserve the favourable properties of the clay rock, it should be prevented from overheating caused by the heat produced by the high-level waste. A temperature rise to above 100°C in the rocks can lead to complex coupled processes. Moreover, under such conditions, there are numerous experimental difficulties in acquiring knowledge about the processes. Following on from the 2005 and 2009 reports, it has been decided to define a maximum permitted temperature of 100°C for the clay rock, with a margin of 10°C, giving a design-basis maximum temperature of 90°C in the clay rock, allowing the uncertainties in the thermal properties and the thermal models of the repository to be taken into account.

A temperature increase also generates an increase in interstitial pressure in the clay rock[46]. Andra has also decided to dimension the HLW disposal sections so as to avoid a risk of fracturing. The selected indicator is the maximum Terzaghi effective stress[47] (σ_{eff}), linked with tensile behaviour with the following criteria[48]:

- σ_{eff} (Terzaghi) < 0 as reference;
- σ_{eff} (Terzaghi) < tensile strength of the rock (1.5 MPa), variant for HLW1/HLW2 waste.

Lastly, Andra has decided to verify that the temperature changes, on the scale of the Callovo-Oxfordian and for up to a million years, do not lead to significant irreversible mineralogical transformations of the clay rock. A clay rock temperature below 70°C after a thousand years is an initial indicator[49].

The planar microtunnel architecture of the HLW cells is particularly favourable to dissipation of the heat from HLW waste in the Callovo-Oxfordian, taking the economic factors into account[50]. Thermal and THM dimensioning of the HLW1/HLW2 sections leads to spacing out the waste packages in the cells to reduce the thermal load density. This provision is not necessary for the HLW0 waste. The space between two HLW1/HLW2 disposal packages is occupied by spacers with similar external geometry to the disposal packages (see figure below), reducing the residual voids in the cells. The spacer materials are defined so as not to generate any physicochemical disturbance in the cell, taking account of their gradual degradation (steel casing specified essentially to meet the needs of the operation phase, inert fill material[51]).

The spacing between the cells in a section is also determined so as to comply with the thermal and THM criteria above.

Reduced-scale and full-scale thermal tests at the Underground Research Laboratory have demonstrated the management of heat dissipation in the Callovo-Oxfordian (heat transfer predominantly by diffusion) and the validity of the models and the simulation tools for the thermal dimensioning of Cigeo.

---

46 The increase in interstitial pressure in the Callovo-Oxfordian results from its low permeability and the difference in heat expansion between the pore water and the solid phases of the clay rock. Depending on the interstitial pressure and stress levels reached, and the loading pathway followed (extension, shear, etc.), the combination of these two increases may lead to diffuse and/or localised damage to the clay rock (fracturing/break).

47 Sign convention: compression stress is negative, tensile stress is positive.

48 The prudent approach taken by Andra at this stage consists in verifying whether the break criteria have been met in post-processing of the elastic design calculations. The stress redistribution and the interstitial pressure reduction due to the onset of plasticity or of pre-break damage are not shown.

49 An incursion in a higher thermal operating range in terms of pair May be subject to case-by-case assessment.

50 In comparison with other designs such as vertical shafts, this architecture minimises the volumes of rock to be excavated, for identical thermal dimensioning criteria.

51 Dry sand, for example.

Based on this, at the basic engineering design stage the HLW0 section comprises about 75 cells of length 80 m and the HLW1/HLW2 sections comprise a total of about 1465 cells of length 100 m. The thermal dimensioning will be updated in the detailed engineering design phase.

Figure 3.2-3 below shows the temperature change in the clay rock around the warmest HLW2 waste disposal cell, with the present dimensioning. Note that the dimensioning criterion here is the THM criterion, not the criterion of 90°C maximum temperature in the clay rock.

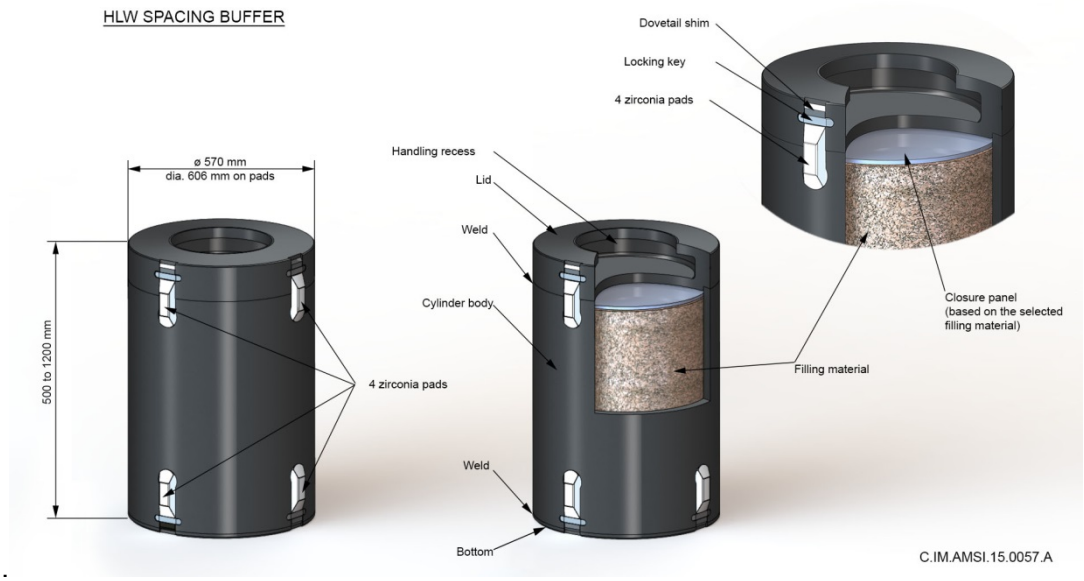


Figure 3.2-2: HLW spacer for insertion in HLW1/HLW2 cell

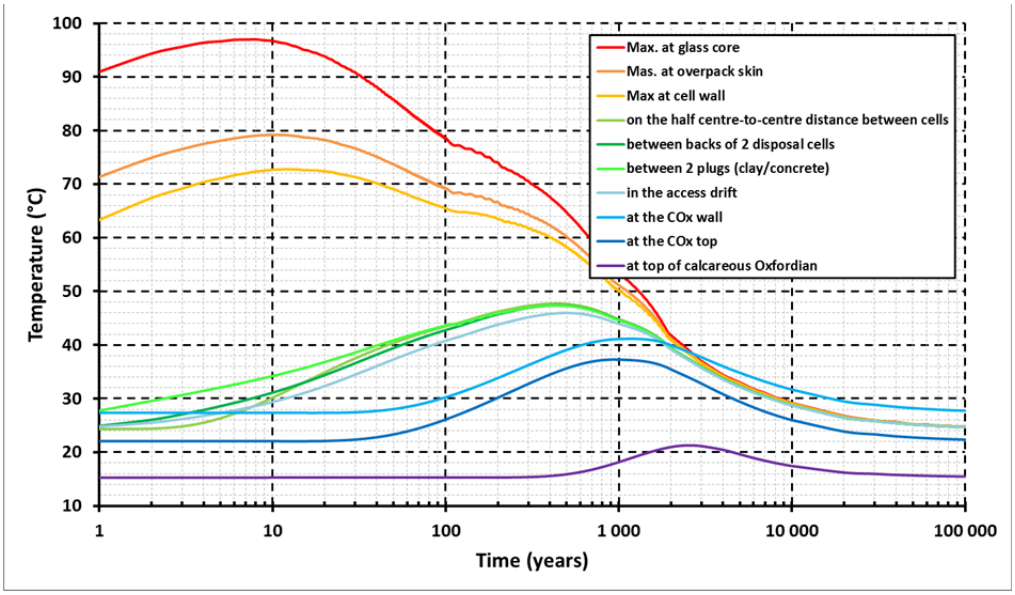


Figure 3.2-3: *Temperature change over time at various points in and around the warmest HLW2 cell (temperature change in the clay rock at the cell wall is given by the yellow curve)*

Table 3.2-1: *Safety functions, requirements and design options associated with HLW cells*

Requirements/performance	Design measures	Component
A physicochemical environment favouring waste package protection	The use of cementitious materials close to the packages will be limited as far as possible.	HLW cell head
	The interior space of the HLW cell heads close to the packages will be filled uniformly with a clayey material of pH close to neutrality (refer to the closure structures).	HLW cell head
	The HLW cell head design (in particular its length) will aim to favour the maintenance of anoxic conditions in the usable part of the HLW cell in the operation phase.	HLW cell head
	The initial annular space between the outer surface of the sleeve and the geological medium will be filled with a backfill material. The material used and the backfill process will aim to: > have a neutralisation effect on the transient acid disturbance caused by oxidation of the pyrites at the clay rock face; > limit as far as possible the chemical disturbances caused on the vitrified waste and on the mobility of the dissolved radionuclides (after loss of leaktightness of the disposal container); > reduce, at the cell head, the accessibility of the HLW cell head to oxygen from the access drift ventilation.	Filling material
The risk of crevice corrosion on contact between the disposal container and the sleeve and, if applicable, between juxtaposed containers must be avoided.	Intercalation of a material inert to corrosion (runners made of industrial ceramic, also intended to facilitate package sliding in the sleeve).	Runners

Requirements/performance	Design measures	Component
The risk of galvanic coupling between the sleeve and the outer surface of the disposal container must be prevented.	Selection of the metal materials of the container and the sleeve.	HLW disposal container Sleeve
Significant effects of radiolytic corrosion must be prevented.	The thickness of the disposal container will be such that the dose equivalent rate (DER) at the pseudocontact (5 centimetres) at the metal-corrosion products interface remains low and in any case less than or equal to the limit of 10 Gy/h.	HLW disposal container
The presence of impurities, the risks of localised corrosion, the size of the internal defects and the risks of hydrogen-induced embrittlement must be minimised.	Sleeve and HLW disposal container production processes.	HLW disposal container Sleeve
The risk of stress corrosion of the steels used to make the container and the sleeve must be reduced.	The overall design of the HLW disposal cell aims to maintain the mechanical function of the disposal container for as long as possible and that of the sleeve as much as possible in the elastic domain: > by the dimensioning of the sleeve; > by the grades and microstructures of the steels selected for their lowest-possible sensitivity to stress corrosion and for their high yield strength.	HLW disposal container Sleeve
Preservation of the favourable properties of the Callovo-Oxfordian		
Creep in the clay rock after sleeve rupture must be limited.	The volume of the residual voids in the cells after plugging will be low and distributed uniformly along the cell. In HLW cells containing highly-exothermic HLW1/HLW2 waste packages, the voids between the packages are occupied by spacers.	HLW disposal packages Spacers
The temperature in the repository must remain in a range within which the processes are managed: the maximum temperature of the clay rock must always stay below 100°C (a margin of 10°C is applied to allow for the uncertainties). The increase in the interstitial pressure in the clay rock must not lead to an increase in the risk of fracturing. Significant and irreversible mineralogical transformations of the clay rock must be prevented.	Thermal dimensioning of the HLW section and cells.	HLW section and cells

3.2.2 Feedback from operating experience

The HLW cells design options are based on Andra feedback from experience, in particular from the many demonstration tests carried out at the Underground Research Laboratory (Figure 3.2-4):

- which have shown the feasibility of (i) construction of HLW cells in the Callovo-Oxfordian with lengths of up to 100 m and a structure sufficiently straight for casing advancement operations and package insertion and possible withdrawal operations and (ii) installation of a metal sleeve consisting of sections of length 2 m and wall thickness 20 mm;
- which have assessed the damaged zone of clay rock around an HLW cell (structuring and extent) and the mechanical behaviour of a sleeve subject to loading by the clay rock over several years.

These demonstration tests have been supplemented by borehole tests providing an understanding of the anisotropic loading of a sleeve as a consequence of the anisotropy of the damaged zone and the bending behaviour of the sleeve (out-of-roundness). Lastly, a sleeve-clay rock annulus grouting test was carried out at the Underground Research Laboratory over a shorter length.



Figure 3.2-4: HLW cell - Demonstrators at the Underground Research Laboratory

The test programme includes tests on the behaviour of the sleeve and the interactions between the different materials (Cigeo components development plan). The results will be incorporated into the safety report in support of the construction licence application.

Studies and tests are also programmed for later on, before and then after the commissioning of Cigeo, with the aim of consolidating the acquired knowledge and optimising the technical solutions. Development and qualification testing of a longer (150 m) HLW cell will be carried out with a view to consolidating this option in readiness for reception of HLW1/HLW2 waste. These results will be combined with feedback from observation of the HLW0 cells (used in the pilot industrial phase) to optimise the design and feed into the demonstration of the performance of the future HLW waste disposal cells.

The design option selected at this stage is based on feedback from experience at the Underground Research Laboratory, and is part of a gradual approach for the dimensioning of the HLW cell, which will include:

- validation of the disposal design in pilot industrial phase with cells 80 m long for moderately-exothermic waste (HLW0),
- lengthening of the cells (100 m) for disposal of highly-exothermic HLW1/HLW2 waste, which will be used beyond 2075,
- optimisation consisting in extending the length of the HLW1/HLW2 cells from 100 m to 150 m, subject to demonstration of feasibility.

Evolving solutions fulfilling the same functions are under study. They may, for example, be based on a design with non-metallic components or with other measures for limiting corrosion.

3.2.3 Temperature impact on delay and attenuation of radionuclide migration in the Callovo-Oxfordian

The effects of temperature on the transfer and retention conditions have been studied extensively over a number of years:

- on the chemical composition of the water in the Callovo-Oxfordian, the models show that the main temperature effects are changes in pH, Eh and the Al and Si concentrations, the other major parameters remaining practically unchanged;
- on solubility, measurements have been made at 25°C and 60°C for a few families of radionuclides; the results show an increase in solubility with the temperature, by a factor of 2 to 5 for most of the radionuclides; above 60°C the uncertainties are high;
- on the solid-solution partition coefficients (Kd) in the Callovo-Oxfordian clay rock, the influence of temperature has been assessed over a temperature range from 20 to 80°C for several radionuclides

(Cs, Ni, Eu, Se(IV)); the results show that a temperature rise reduces the retention of radionuclides sensitive to ion exchange (by a factor of up to 10 at the test temperatures) and increases the retention of radionuclides that act by surface complexing; interpretation of the results has also enabled the definition of correction factors for the partition coefficients as a function of the temperature;

- on the diffusion properties of the radionuclides in the Callovo-Oxfordian clay rock, through-diffusion tests at 20°C, 50°C, 80°C and 90°C have shown that the temperature effects influence the mobility of the tracers in the water, that the accessible porosity is not impacted, and that the effect is reversible; the measurements have been used to define correction factors for the diffusion coefficients as a function of temperature; the uncertainties in these factors are limited to 10%;
- on the permeability, the effect is determined by the viscosity, which decreases by a factor of up to 2 or 3 at the highest temperatures.

The thermal transient can also cause thermal-hydraulic and thermal-osmotic water movements and thermal-diffusive solute transfer. However, the knowledge acquired on these processes shows that they remain broadly negligible compared with diffusion.

The state of knowledge on the influence of temperature on the hydro-dispersive properties of the Callovo-Oxfordian leads to the conclusion that the overall effect on radionuclide transfer is negligible in view of (i) the temperatures reached, limited by design and producing limited effects, (ii) the duration of the thermal increase transient (a few hundred years), much shorter than the radionuclide transfer times in the clay rock (a few hundred thousand years).

3.2.4 Specific requirements applicable to the sleeve

3.2.4.1 Requirements with regard to stress corrosion (SC)

As in the case of the disposal container, the stress corrosion (SC) process may occur under the combined action of a mechanical tensile stress and a medium corrosive for the material, in particular the presence of molecular hydrogen (embrittlement).

To reduce the SC risk, Andra selects the steel of the sleeve and its thickness[52] on the basis of the following criteria[53]:

- high yield strength;
- lowest possible sensitivity to SC;
- limitation of stresses in the sleeve, with a view to remaining below 2/3 of its tensile yield strength as far as possible, taking the technical factors into account.

3.2.4.2 Other requirements with respect to corrosion

As stated above, the risk of crevice corrosion on contact between the sleeve and the disposal packages must be prevented (paragraph 2.4.5). Similarly, the selection of sleeve section joining techniques must reduce this risk at the joints. Limiting the access of oxygen into the cell also contributes to limiting this process.

It should be remembered that the selection criteria for the sleeve and container steels include reduction of the risk of galvanic coupling.

[52] The mass of the sleeve is limited by the technical options for insertion in the cell.

[53] API 5L X65 line pipe steel meets these requirements in principle. In particular, it is now established that as long as the mechanical stresses applied to this type of steel remain less than 2/3 of the yield strength it is not vulnerable to SC (uncertainties remain above this limit). Additional tests are planned, including in alkaline medium on sleeve samples to assess the influence of the initial alkalinisation of the medium by the backfill material on the occurrence of stress corrosion, knowing that this alkalinisation is favourable in principle in an anoxic medium.

3.2.5 Specific requirements and performance parameters for the sleeve outer surface backfill material

Preliminary analyses show that, to neutralise the acid transient and form an environment favouring the passivity of the sleeve and container steels, the backfill material must have sufficient alkaline load. Conversely, to meet the requirements with respect to the waste, it must as far as possible be weakly alkaline in order to give a pH below 10 when water comes into contact with the vitrified waste.

At the present stage of the studies and the available experimental results, the formulation of a backfill material fully satisfying these two requirements is not yet defined, mainly due to the uncertainties about the duration and magnitude of the acid transient. The strategy adopted by Andra at this stage is to define a "methodological" formulation in order to guide the acquisition of new knowledge of the behaviour of the material and its environment in the repository and to carry out the tests.

A methodological formulation of the backfill material

The methodological formulation is a reference formulation consisting of a cement-bentonite assembly[54] (clinker/hydraulic admixture/pozzolanic admixture/clay/mineral fluidifier), variants of which can be formulated.

It meets the requirements regarding radionuclide mobility (no organic admixtures).

The ability of the reference formulation to neutralise the acid transient is established under certain conditions, including the level of oxidation of the clay rock pyrites, which determines the initial alkalinity level needed.

The methodological formulation allows margins of manoeuvre with regard to the requirements applicable to the backfill material, by varying the proportions of the constituents, some increasing the pH, others reducing it. The key constituents and their impact on the final pH are shown in the figure below.

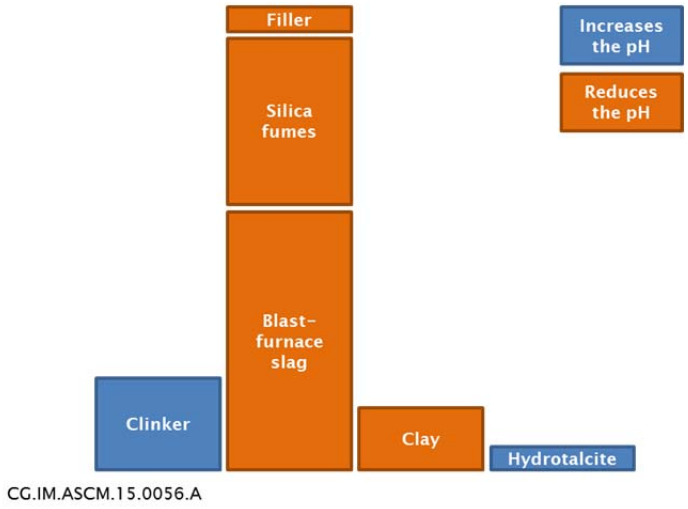


Figure 3.2-5: Schematic diagram of the impact of material constituents on the final pH. The height of a rectangle gives an order of magnitude of the proportion of the component in the material

[54] The starting materials are all available industrially without procurement difficulties. A production protocol has been developed and the first characterisations carried out. A first pilot-scale preparation (100 l reproduced three times), pumping and grouting test was successful.

Starting from the methodological formulation, a series of tests in the surface laboratory and in the Underground Research Laboratory, along with numerical simulations, are scheduled as part of the Cigeo components development plan (PDD) (28), in order to:

- obtain a range of materials meeting the requirements in terms of chemical properties, covering both less alkaline mediums and more alkaline materials;
- characterise the formulations in fresh state and hardened state, for the purpose of obtaining a behaviour model linking the formulation with physical and chemical parameters: permeability to oxygen, compressive strength, etc.;
- describe the change in the backfill material over time taking into account (i) its initial state, (ii) the thermal loading and (iii) the various physicochemical couplings it might be subjected to in the HLW cell context. The mechanical and transfer properties of the backfill material and changes in the materials in contact with it or in fluids that have passed through it will also be monitored.

In parallel, new knowledge will be acquired on clay rock oxidation and its effects on the chemistry of pore water in the Callovo-Oxfordian (pH, Eh, concentration of major elements), particularly in relation to temperature, through an approach combining testing in the surface laboratory, in situ experiments and geochemical modelling. The associated actions are intended in particular to reduce the uncertainties about the acid transient.

On completion, the operating range of the backfill material related to the requirements for the metal materials and for the glass will be defined with greater precision. Similarly, information will be available for better assessment of the potential contributions of the backfill material in mechanical terms and in terms of limitation of oxygen ingress close to the access drift (refer to Table 3.2-1).

Technologically-feasible installation of the backfill material

Tests at the Underground Research Laboratory have demonstrated the feasibility of placement of the backfill material over a length of 40 m. The overall homogeneity of the backfill material was checked in certain zones on the outer surface of the sleeve: no major discontinuity of the material was observed. Grouting with a cement-bentonite backfill material uniformly over the HLW cell with the longest length is technologically feasible, for example by grouting from the end of the cell immediately after its excavation. These are techniques used routinely in industry, for example the oil industry.

As part of the PDD (28), tests will be carried out to verify that the range of materials that are available, and which essentially meet the requirements regarding chemical properties, can be used to formulate materials that can be injected at full scale. To this end, four grouting tests are planned at the Underground Research Laboratory, on at least one of the formulations.

3.2.6 Management of iron/clay rock interactions

The disposal containers and the sleeve of the HLW cells contain a large quantity of steel, entailing the necessity of verifying the limited character of the impact of iron on the favourable characteristics of the Callovo-Oxfordian.

The iron/clay interactions at the HLW cells are well understood experimentally. They involve the formation of various secondary compounds: iron oxides, iron carbonates, iron silicates and aluminosilicates, sulphides and newly-formed iron-enriched clays. Hydrogen is also formed, some of which is dissolved in the aqueous phase.

Geochemistry-transport simulations show, at the end of the corrosion period, a remineralised zone several centimetres up to some decimetres in extent at the initial iron-clay rock interface and a slightly-disturbed zone a few metres in size in the Callovo-Oxfordian. The clay rock close to the HLW cells is consequently concerned by the disturbance.

In view of its small extent, this disturbance has a negligible impact on radionuclide transfer in the Callovo-Oxfordian host formation.

3.3 ILW-LL waste package disposal section and cells

3.3.1 Design options

The ILW-LL disposal cells are tunnels oriented along the direction of the major principal stress.

They consist of a cell head, a usable part accommodating the ILW-LL waste disposal packages, and a cell end part[55].

The length of the usable part of the ILW-LL cell is about 500 m.

Figure 3.3-1 shows the schematic configuration adopted for the ILW-LL cell in the post-closure phase.

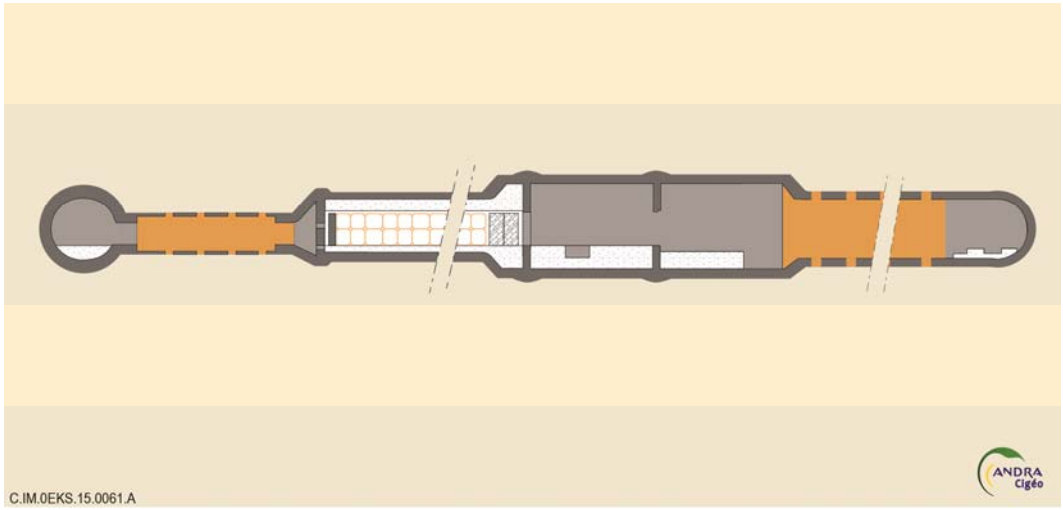


Figure 3.3-1: A post-closure ILW-LL cell

The standard cross-section of the usable part depends on the type of disposed package. The disposal cells comprise package layouts[56] on one, two or three columns/levels with excavated cross-section areas from 17 à 65-70 m^2. The dimensioning is based on the available feedback from experience (refer to paragraph 3.3.3). The arrangement considered for one disposal package type is shown in Figure 3.3-2.

A cross-section area of 110 m^2 is studied as a variant with a view to optimisation. It will be assessed by a demonstrator during the pilot industrial phase before industrial-scale implementation.

[55] The end part is reserved for the ventilation air outlet (filter room) in order to fulfil a safety function in operation (refer to Volumes II and III of the DOS-EXpl).
[56] The various layouts are defined in Volume II, chapter 3 of the DOS-EXpl.



Figure 3.3-2: Arrangement of waste packages in an ILW-LL cell

The construction of the ILW-LL cell is accompanied by the installation of bolts and a concrete liner to provide the minimum mechanical stability until closure. Filling concrete defines a rectangular disposal cross-section matching the volume occupied by the waste packages.

At the basic engineering design stage, all the ILW-LL cells are grouped in a single section (Figure 3.3-3). The dimensions of the section are determined by:

- the number of ILW-LL disposal cells needed to accommodate the inventoried ILW-LL waste packages, i.e. about 50 at the basic engineering design stage. This number is related in particular to the options of co-disposal of different families in a given cell (see below) and to the choice between placing the primary packages in disposal containers and direct disposal of certain primary packages (refer to Chapter 2);
- the distance left between adjacent cells; a distance of five cell diameters between centrelines has been adopted to ensure mechanical independence between structures[57]. This point will be the subject of detailed engineering design studies aiming to reduce this distance as far as possible, given that the minimum distance for compliance with the requirements regarding physicochemical interaction between cells containing salts or likely to generate complexing species and the other cells is 30 metres (see below);
- the network of access and air return drifts; "twin-tube" access drifts have been defined in order to reduce risks in operation and to offer more flexibility in facility management.

The ILW-LL section at the basic engineering design stage is shown in the diagram below.

[57] The mechanical stability of each individual structure ensures the overall stability of the disposal section.

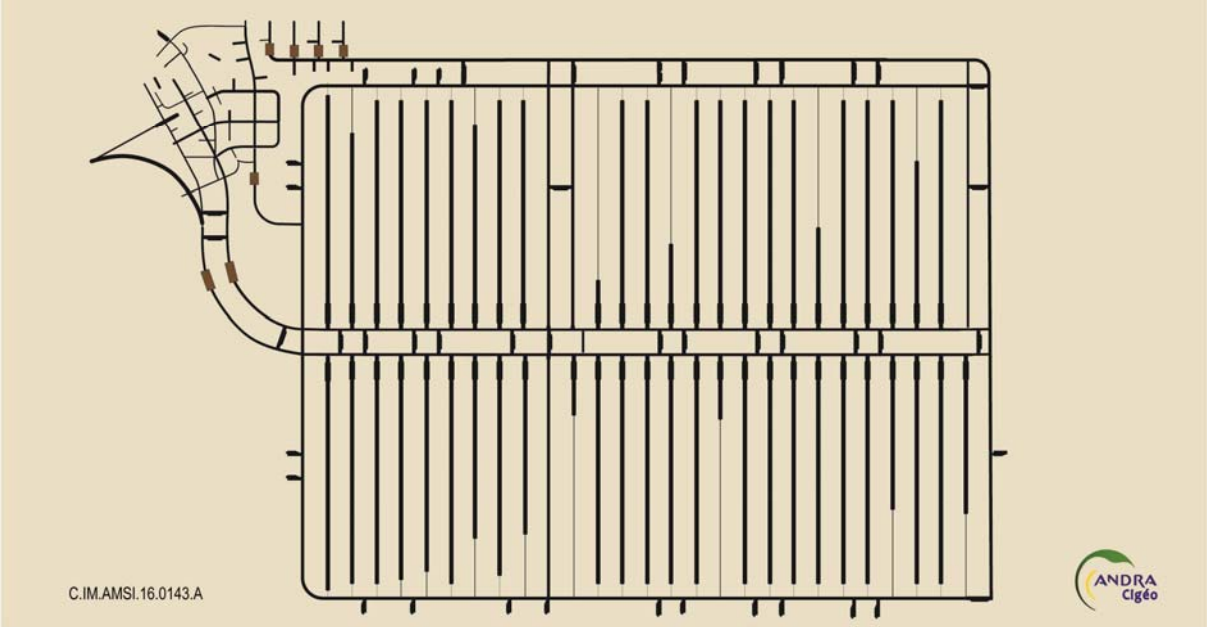


Figure 3.3-3: ILW-LL section on completion

An objective of optimisation of the ILW-LL section and cells is under study in the context of increasing the density of the repository; this involves reducing the number of cells by changing the package layout, increasing the number of columns and levels from one to three or four columns/levels.

The excavated cross-section areas associated with this density increase range from 30 to 110 m².

Evidence of compliance with the various criteria discussed previously will have to be provided for these cell configurations.

3.3.2 Contribution to post-closure safety functions

The requirements and design measures applied for the accomplishment of these functions are summarised in Table 3.3-1.

3.3.2.1 Contribution to the function "Oppose water circulation"

Like the other disposal sections, the ILW-LL disposal section is blind with respect to the rest of the underground facility in order to limit water flows between the structures of the underground facility and the overlying formations of the Callovo-Oxfordian via the surface-bottom connections.

3.3.2.2 Contribution to the function "Limit the release of radionuclides and immobilise them in the repository".

The ILW-LL cell contributes to limiting the release of radionuclides and toxic chemicals and immobilising them in the repository by imposing a cementitious chemical environment[58].

[58] The cementitious materials of the ILW-LL cells ensure high pH conditions over durations longer than 100,000 years. Subsequently, degradation of the concrete leads to a gradual decrease of the pH values until they reach a plateau, remaining above 10.5 over the next million years.

In addition to the effects favouring limitation of the kinetics of radionuclide release by activated metal waste and by bituminised waste packages (pH > 11 for metal waste; 7 ≤ pH ≤ 12.5 for bituminised waste[59] ; refer to 2.3), the cementitious environment limits the transfer of radionuclides, in particular actinides, to the Callovo-Oxfordian by favouring their precipitation and retention.

The large body of data acquired over many years on the characterisation of the properties of cementitious materials with respect to speciation highlights, for the physicochemical states of the concretes [60]:

- low solubility of the actinides: the values are based on a large volume of knowledge acquired from equilibrium calculations, apparent measurements made in cementitious solutions, and literature data where considered pertinent with respect to the cementitious water compositions and the measurement protocols;
- significant sorption properties of the cementitious phases: the values are based on direct measurements, models calibrated for a material of interest (on material or according to a top-down approach) and models developed using data obtained from simple systems, such as the calcium silicate hydrates (CSH) (according to a component additivity or bottom-up approach).

In addition, to limit the mobility of radionuclides and toxic chemicals in the disposal system, a requirement[61] stipulates the separation between ILW-LL waste packages likely to generate chemical disturbances, in particular complexing species produced by degradation of organic materials, and other waste packages. A minimum separation distance of 30 m is specified between ILW-LL cells containing different types of waste likely to interact negatively.

The temperature inside the ILW-LL cells is limited:

- to preserve the characteristics of the concretes: Andra defines a criterion of 65°C in contact with the cementitious components;
- to manage the behaviour of the dissolved radionuclides, which is temperature-sensitive: Andra is considering a criterion of 70°C in this context.

In the particular case of bituminised waste, the aim is to limit its disposal temperature as far as possible, taking account of the technical factors, so as to limit potential sedimentation of the salts which would cause a reduction in the containment capacity of the bituminised material (Table 3.3-1). This necessitates disposal in dedicated cells and a horizontal distance separating the cells containing slightly-exothermic ILW-LL waste such as structural waste (Figure 3.3-4).

[59] If CEM V concretes are used, the possibility of a high pH transient (> 12.5) in contact with bituminised waste cannot be excluded. Nevertheless, after this transient, the pH values in contact with bituminised waste decrease as a consequence of (i) the degradation of the cementitious materials and (ii) the degradation of the bitumen leading to the release of acidic species.

[60] Two states of the cement are considered: undisturbed state, i.e. cementitious material in equilibrium with the portlandite after leaching of the alkalis, and weathered state, i.e. cementitious material in equilibrium with the CSH phases after dissolution of the portlandite.

[61] This requirement impacts the operation of the repository, in particular the organisation of the disposal packages in the ILW-LL cell and the organisation in the ILW-LL section (refer to DOS-EXpl paragraph 1.6 on the dimensioning characteristics).

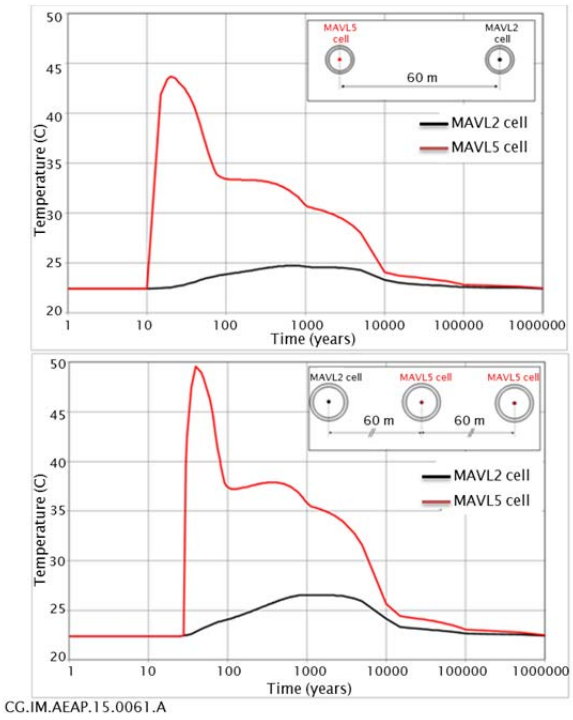


Figure 3.3-4: *Temperature change in a cell of non-exothermic waste (black) as a function of the location or grouping of cells of slightly-exothermic ILW-LL waste in its vicinity*

3.3.2.3 Contributions to the function "delay and attenuate radionuclide migration"

Like the other disposal sections, the ILW-LL section has a planar geometry.

It is located in the median part of the Callovo-Oxfordian to maintain the maximum thickness of undisturbed clay rock [62] above and below the section.

This necessitates adapting the length and slope of the cells to the dip of the Callovo-Oxfordian; for the dimensioning of the section, Andra has defined a minimum thickness criterion of 50 metres.

The figure below shows that the clay rock thicknesses above and below the ILW-LL section are about 70 m for a repository located at mid-height in the Callovo-Oxfordian.

[62] The vertical thickness of undisturbed clay rock is determined for each structure by subtracting the maximum vertical extent of the damaged clay rock zone at the roof and at the invert from the vertical thickness at the top and bottom of the structure, respectively.

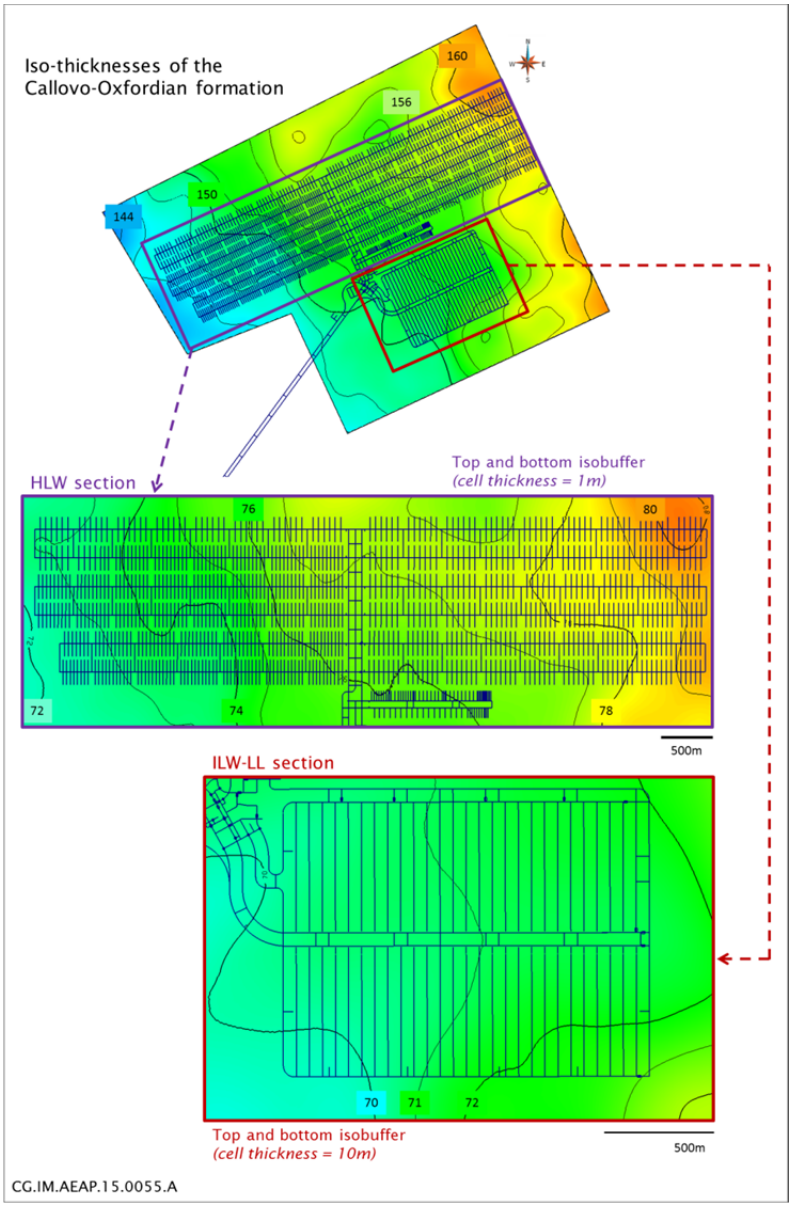


Figure 3.3-5: *Clay rock thicknesses for a repository with its median plane located on the surface of the geometrical mid-height of the Callovo-Oxfordian*

Observations at the Underground Research Laboratory have shown that the orientation of the ILW-LL disposal cells in the direction of the major principal stress limits the extent of the damaged zone.

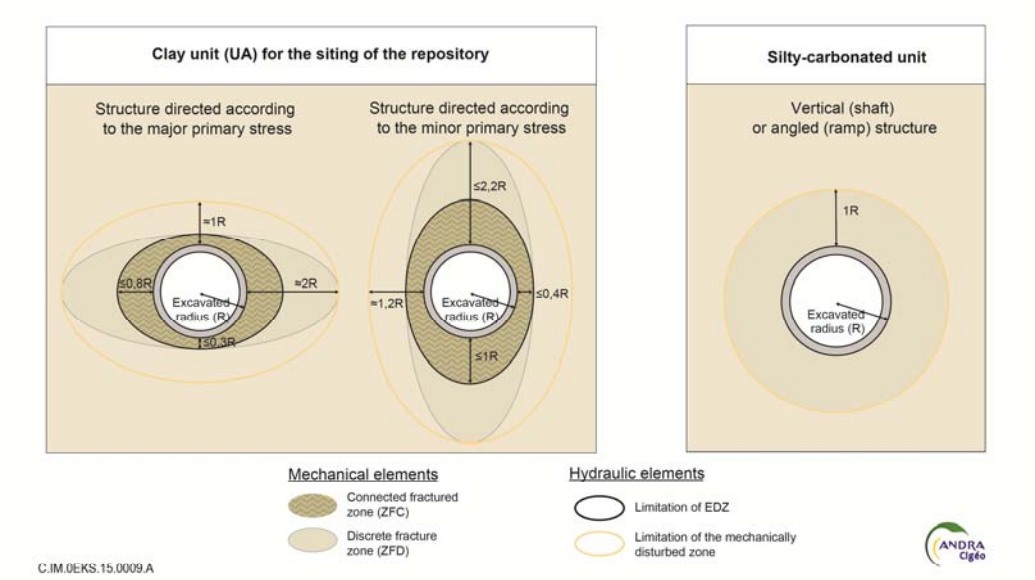


Figure 3.3-6: Effect of underground structure orientation on the EDZ in the clay unit of the Callovo-Oxfordian

In addition, Andra is limiting the residual void volumes and the compressible volumes in the ILW-LL cells to reduce as far as possible the creep of the clay rock after rupture of the liners and the establishment of a connected fracture zone (ZFC) of combined damage. The extent of this combined damage ZFC depends directly on the void fraction of the ILW-LL cell (Figure 3.3-7). For example, a void fraction of 10% results in damage at the roof with an extent of about one diameter and a lateral extent slightly greater than one diameter. The limits applied by Andra for void volumes are defined as a function of the excavated height (29).

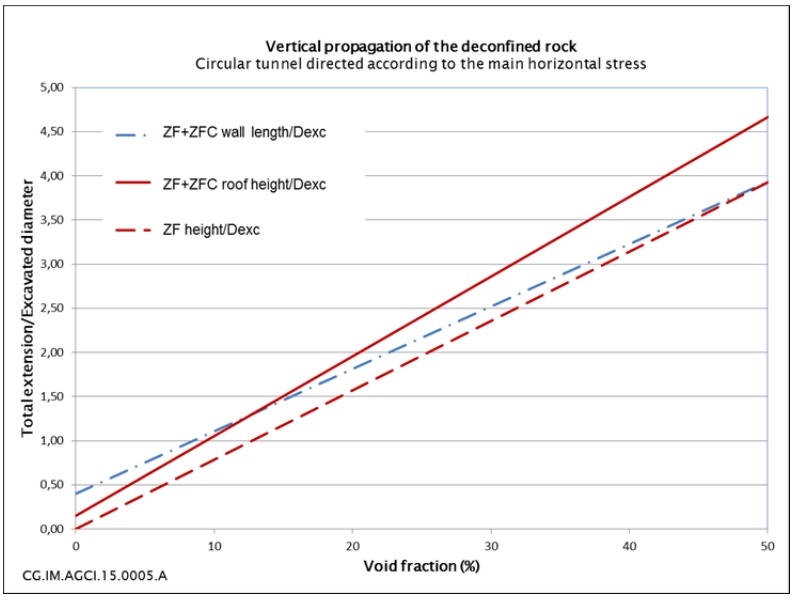


Figure 3.3-7: Estimated horizontal and vertical extents of the deconfined rock zone (ZF) and the connected fracture rock zone (ZFC) from the excavation wall as a function of the void fraction

This is based on:

- the filling concrete used to adjust the disposal chamber to the dimensions required for the disposal packages;
- the package geometry;
- minimisation of the clearances necessary for package handling in the cell, taking the other technical constraints into account.

In addition, an ILW-LL cell length (usable part and ends) as long as reasonably possible tends to minimise the proportion of radionuclides and toxic chemicals likely to migrate longitudinally towards the connecting drifts. The choice of a length of 500 metres for the usable part is based on optimisation taking other factors into account, in particular:

- the necessity mentioned above of limiting the length in order to preserve the clay rock thicknesses above and below the disposal section;
- the technical constraints of construction and operation;
- the constraints applied with regard to separation of waste packages according to their physicochemical interactions.

Table 3.3-1: Requirements and associated design options

Requirements/performance	Design measures	Component
Preservation of the containment performance of bituminised waste assumes that a geometry close to the initial geometry is maintained. The release models are valid only within a known range of geometry.	The primary packages of bituminised waste are maintained in vertical position.	ILW-LL disposal package (para. 2.5)
Bituminised waste is disposed of at a moderate temperature (30° C, but deviations from this reference value remain possible[63]) to limit the occurrence of a sedimentation process likely to modify its behaviour under irradiation and its weathering under water.	The bituminised waste packages are placed in dedicated cells.	ILW-LL disposal section and cell
Compliance with a basic pH range keeps the bituminised waste within the range of known behaviour. More specifically, the aim is to maintain the pH between 7 and 12.5.	Use of concrete in the ILW-LL cell	ILW-LL disposal container ILW-LL disposal cell
For the metal waste, a cementitious environment (pH > 11) is required, associated with anoxic redox conditions. These conditions favour slow corrosion kinetics by a passivation effect (for steels), and consequently slow release of the activation products contained in the metal parts.		
For waste containing significant quantities of radionuclides such as nickel, cobalt, americium, curium, neptunium and plutonium, cementitious conditions will be preferred.		

[63] During operation, the temperature in the disposal cell is controlled passively (refer to Volume III of DOS-Expl). Values up to 40°C are associated with exceptional conditions, for example in an abnormal situation, so as to protect against cumulative effects on the sedimentation associated with heating cycles.

Requirements/performance	Design measures	Component
The temperature in the ILW-LL waste and its environment is below 70°C.	The disposal cells for non- or slightly-exothermic waste are dimensioned and positioned at a distance sufficiently far away from other cells for the temperature to remain below 70°C in them at all times.	ILW-LL disposal section and cell
Creep in the clay rock after sleeve rupture must be limited.	In order to avoid the long-term spread of mechanical damage in the clay rock after loss of liner integrity, the volume of residual voids in the cells after sealing must be as low as possible and uniformly distributed along the cell and across its cross-section, taking into account the technical constraints.	ILW-LL disposal container ILW-LL disposal cell
Other than for the disposal cells for waste likely to generate complexing species, the use of organic materials or complexing substances will be reduced as far as possible in the composition of the disposal containers and the cells. In particular, the choice of materials and their quantities for fibre reinforcement and admixture of concretes must be justified with regard to this requirement.	Choice of materials for the disposal containers and the liner.	ILW-LL disposal container ILW-LL disposal cell

3.3.3 Feedback from operating experience

The priority scientific and technical issues of the ILW-LL disposal cell concern:

- excavation techniques;
- liner/support dimensioning according to cell cross-section area and excavation method considered;
- cell performance in terms of mechanical durability and EDZ limitation with regard to environmental conditions (i.e. internal and external stresses).

Regarding excavation techniques, the Underground Research Laboratory structures were built using methods representative of the methods used for the ILW-LL cells (road header) in the direction of the major principal stress. This technique has been tested up to a diameter of nearly 8 metres (section of drift GRD3), representative of disposal cells of cross-section area 65-70 m^2. Support by shotcrete and bolting has also been tested (supplemented with metal segments, depending on the case). A cast-in-place concrete liner has been tested on a smaller diameter.

For liner/support, the experimental strategy used on the main level of the Underground Research Laboratory was to build drifts oriented in the direction of the major principal stress with increasingly stiff supports/liners in order compare their short- and medium-term behaviour. The first concrete supports used were 'flexible' supports, i.e. they followed the convergence of the rock (shotcrete with or without compressible blocks). More rigid supports (thicker, with liners cast in place a few months after excavation) were also produced in order to limit deformations of the rock. Lastly, liners were installed quickly after excavation of the drift (thick shotcrete in 2012, concrete arch segments in 2013). All these structures are, or are going to be, instrumented. The comparison of stress and deformation measurements in and around these various supports/liners is an important input for the dimensioning[64] of the ILW-LL cells in the basic engineering design and detailed engineering design studies[65].

[64] In addition to calibration data for the models of the mechanical behaviour of the clay rock and the concrete, it provides access to the mechanisms of interactions between the rock and the structures, which may have a strong impact on the dimensioning.

[65] The connected fracture zone formed by the excavation has specific plasticity and creep characteristics. This generates anisotropic short-term loading of the liners even for structures oriented parallel to the major principal stress such as the ILW-LL disposal cells, subjected to an isotropic stress field.



Figure 3.3-8: Excavation of the tunnelling machine assembly chamber for test GVA2 at the Underground Research Laboratory (excavated diameter 9.1 m)

To support the option of increasing the cross-section area of the disposal cells, in situ tests are planned as part of the pilot industrial phase. This comprises the construction of a test cell incorporating all the elements of its design. The damage will be characterised and the stresses and strains in the liner will be monitored. Inactive operating tests will also be conducted in the cell.

Depending on the results obtained in the pilot industrial phase, construction of ILW-LL disposal cells of diameter greater than the currently-selected option may be considered subsequently according to the incremental development and gradual deployment process defined in the operation master plan (8).

3.3.4 Management of physicochemical interactions

3.3.4.1 ILW-LL waste package separation requirements

Andra has identified three categories of ILW-LL waste package likely to generate physicochemical disturbances (refer to appendix 9):

- ILW-LL1: package of non-bituminised waste containing a significant quantity of salts, generators of saline disturbance;
- ILW-LL2: package of bituminised waste, also generator of saline disturbance;
- ILW-LL3: package containing organic materials (polymers, cellulose), the degradation products of which may be complexing and affect the behaviour of the radionuclides.

Andra has chosen to dispose of the packages of these three categories in cells each dedicated to one of the categories and separated sufficiently to prevent the generated disturbances affecting the other waste package categories.

Four other categories of waste package are identified:

- ILW-LL4: package of cemented non- or slightly-exothermic waste containing neither organic materials[66] nor salts;
- ILW-LL5[67]: package of non-cemented non- or slightly-exothermic waste[68] containing neither organic materials[69] nor salts, including structural waste from fuel reprocessing;
- ILW-LL6: package of non- or slightly-exothermic vitrified waste, possibly after storage to allow decay so that it can be reclassified as HLW0 waste;
- ILW-LL7: package of waste containing sodium metal.F[70]

3.3.4.2 Saline disturbance

Degradation of salt-rich ILW-LL waste leads to release of nitrate and sulphate compounds likely to increase the ionic strength and consequently (i) modify radionuclide reactivity and migration in the clay rock[71] and (ii) cause hygroscopic and osmotic effects in the structures.

Modification of radionuclide reactivity and migration

Work has been done on the clay rock and on pure clay phases to assess the effects of saline perturbation on their radionuclide transfer properties. The anticipated effects in the near field are essentially:

- a slight increase in the diffusion properties of anionic species (decrease in anion exclusion, co-diffusion). Correction factors applied to the transport take these effects into account as a function of the ionic strength;
- a slight decrease in the sorption of alkaline and alkaline-earth ions. The effects of the ionic strength and of competing cations are taken into account in the Kd values.

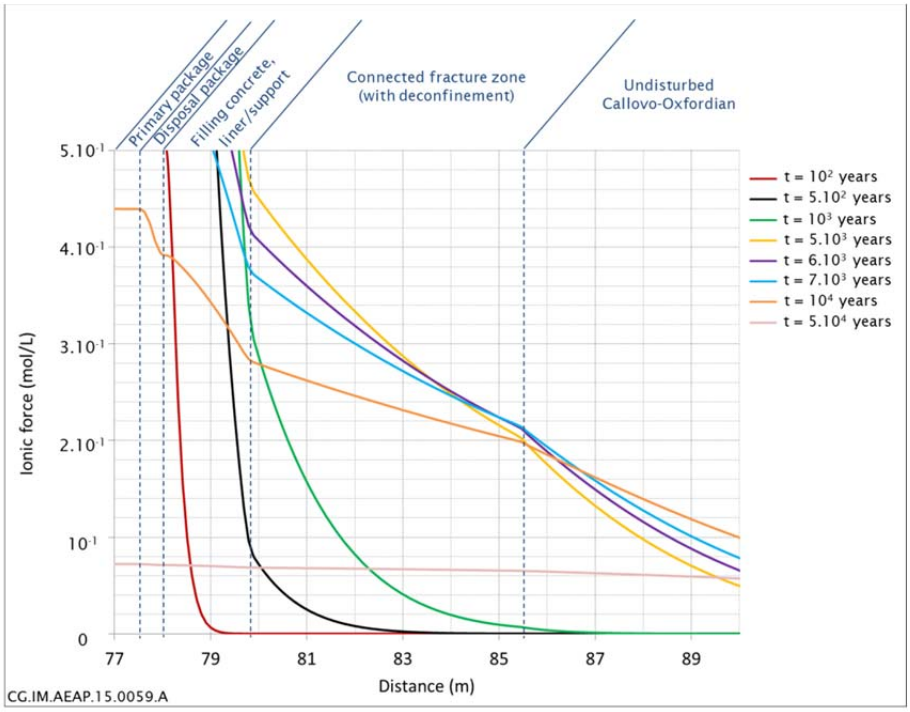


Figure 3.3-9: Time-dependence of ionic strength profiles according to distance from an ILW-LL saline waste package disposal cell

[66] Except for labels on intermediate canisters, glue and paint.
[67] The possibility of co-disposal of ILW-LL4 and ILW-LL5 packages is currently being studied and will be confirmed in the construction licence application.
[68] Geopolymer-based matrices are included in this category.
[69] Except for labels on intermediate canisters, glue and paint.
[70] Sodium metal prohibited at the current stage of the preliminary specifications.
[71] These effects are more marked the higher the ionic strength.

Hygroscopic and osmotic effects

The main effects related to modification of the activity of the water are:

- in an environment not saturated with water, hygroscopic effects on saline waste package disposal cells which may last a few hundred years after closure;
- after closure, osmotic effects (generation of water flows from zones with low salt concentrations to zones with high salt concentrations) lead mainly to modification of the organisation of the resaturation of the cell, resulting in faster resaturation of the waste packages; the overall duration of resaturation of the structure is not modified.

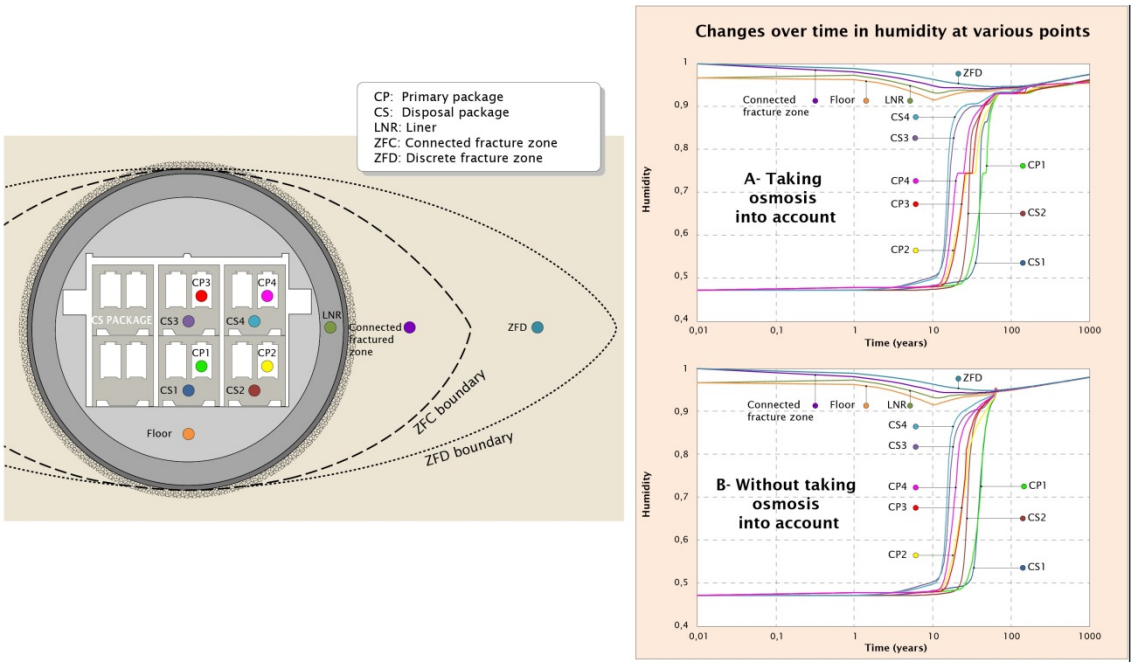


Figure 3.3-10: Osmotic effect related to the presence of salts from ILW-LL1 category waste on the hygrometry of a cell during the first thousand years after disposal

Estimation of the disturbed volume around waste of categories ILW-LL1 and ILW-LL2

Current estimates show that the nitrate plume spreads in the clay rock:

- only within the ZFC (taking account of the long-term mechanical change after loss of liner integrity, see above) with a concentration exceeding 0,2 mol.l^{-1} transiently;
- up to a maximum of 10 metres from the cell wall with a concentration of more than 0,1 mol.l^{-1} during about 10,000 years (to saturation with water).

This saline plume may be attenuated by bacterial activity in the cell (not taken into account in the above assessments).

The extents of the hygroscopic and osmotic effects are limited to the immediate vicinity of the packages and have no significant influence beyond the cell liner concrete.

Consequently, the effects of saline disturbance on delaying and attenuating migration of the radionuclides contained in waste of categories ILW-LL1 and ILW-LL2 remains limited, given the thickness of the undisturbed or slightly-disturbed clay rock thicknesses around the ILW-LL cells.

3.3.4.3 Organic disturbance

Degradation of ILW-LL organic waste packages results in the release of organic species in solution, some of which may form complexes with radionuclides and reduce their retention. These effects are observable only above a threshold concentration of organic materials in water.

Only a few organic compounds are identified as having a significant effect on radionuclide behaviour in the clay rock, including isosaccharinic acid (ISA) produced by cellulose degradation and phthalates released during PVC degradation.

The complexing power of these compounds also depends on the nature of the radionuclides. Sensitivity threshold concentrations of ISA greater than 10^{-4} mol.l^{-1} and of phthalates greater than 10^{-3} mol.l^{-1} have been determined for the clay rock.

Assessment of the extent of the organic disturbance around each ILW-LL cell by reactive transfer modelling shows that the threshold concentrations given above are found up to one metre away for ISA and up to about 15 m away for phthalates[72].

The extent of the effects of organic disturbance on the radionuclides around the ILW-LL3 category waste cells remains limited, so performance with regard to delaying and attenuating migration of the radionuclides contained in this waste is maintained. Nevertheless, at this stage, to ensure robustness, measures are taken for physicochemical separation of ILW-LL3 category waste from other waste.

3.4 Closure structures

The closure structures consist of seals, HLW cell plugs and backfill.

3.4.1 Safety functions and seal design options

3.4.1.1 Seal types and their contributions to safety functions

In general, the seals contribute to opposing water circulation in the disposal system. There are three categories of seal:

- vertical seals;
- inclined seals;
- horizontal seals (or bottom seals).

The vertical and inclined seals are installed in the surface-bottom connections that pass through the overlying formations, some of which (Barrois limestones and porous horizons of the Oxfordian limestone) are significantly more transmissive than the Callovo-Oxfordian. Seals located in the shafts at the level of the silty-carbonated unit (USC) and the transition unit (UT) of the Callovo-Oxfordian and in the ramps at the level of the USC contribute to limiting water flows between the disposal system and the overlying formations. Aquifer formation separation seals are planned at the level of the Kimmeridgian. These seals are involved in mobilising the natural dispersion and dilution capacities of the surrounding formations. It should be noted that Andra does not assign any post-closure safety function to the sealing structures at the level of the Barrios and at the top of the Callovo-Oxfordian for the operation of the surface-bottom connections.

The horizontal seals are installed in the clayey unit (UA) of the Callovo-Oxfordian, in the connecting drifts between the disposal sections and the surface-bottom connections. These seals increase the 'hydraulic resistance' of the drifts. There are at least two seals on each route between a section and the surface-bottom connections; this arrangement enables hydraulic head losses to be distributed within the drifts. Andra has chosen to position one of these seals close to the disposal sections[73]. In the event of loss of hydraulic function of the vertical or inclined seals, the horizontal seals limit the water flows and the flows of radionuclides in solution along the drifts to the bottom of the surface-bottom connections.

[72] The uncertainties associated with these estimates are related in part to the uncertainties associated with the inventories of organic materials and their variability in the various families.

[73] At the present stage, a maximum distance of 400 metres is considered between this seal and the closest cell.

The need for sealing the entrance of the ILW-LL cells and the sealing method are also being studied. At this stage, the principle of the horizontal seals can be applied, and Andra is also examining the possibility of using a high-density backfill with a specified permeability, possibly a mix of clay rock and swelling clay.

Schematic diagrams of the three seal types discussed above are shown in the figure below.

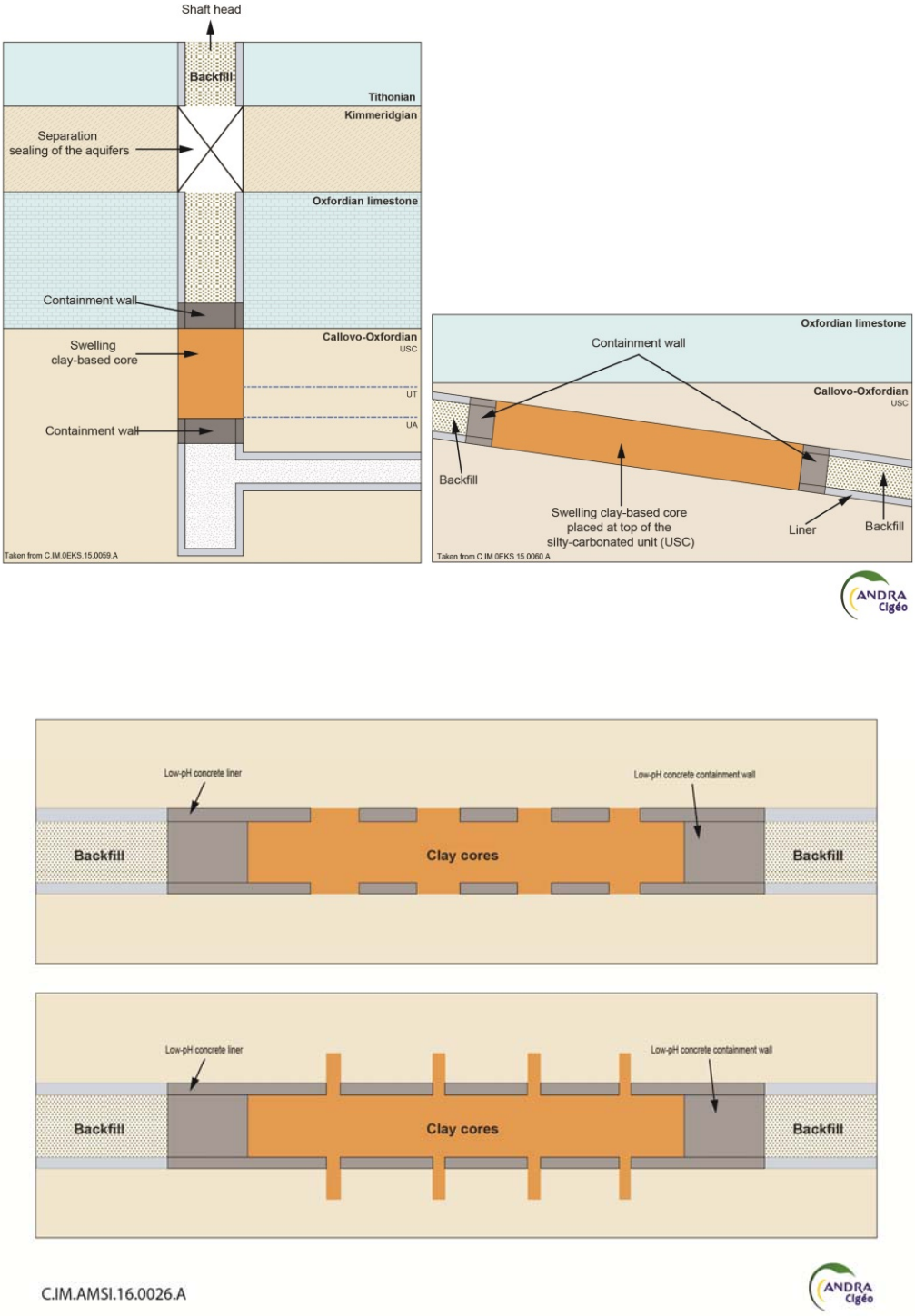


Figure 3.4-1: Schematic diagrams of inclined, vertical and horizontal seals

The contributions of the main types of seal to the Cigeo post-closure safety functions are summarised in the table below.

Table 3.4-1: Contributions of seal types in the Callovo-Oxfordian to the function "Oppose water circulation"

<table>
<tr><th>Safety sub-function</th><th>Objective</th><th colspan="2">Seal type</th></tr>
<tr><td rowspan="2">Limit water flows between the underground facility and the overlying formations through the surface-bottom connections</td><td rowspan="2">• During the repository saturation transient:
✓ limit water flows from overlying formations
• After total saturation of the repository (steady state):
✓ limit water flows from the Callovo-Oxfordian drained by the repository</td><td rowspan="2">Vertical and inclined seals of the surface-bottom connections (at the levels of the USC and the UT)</td><td></td></tr>
<tr><td rowspan="2">Horizontal seals (connecting drift seals and any ILW-LL waste cell seals)</td></tr>
<tr><td>Limit water circulation speed in the drifts</td><td>Organise the distribution of gradients in the repository</td><td></td></tr>
</table>

3.4.1.2 Design options for vertical and inclined seals in the Callovo-Oxfordian

Given their position at the outlet of the disposal facility, the surface-bottom connection structure seals are the ones that play the most important role in post-closure passive safety.

This safety option follows the recommendations of the 2008 ASN nuclear safety guide (1) which states that the surface-to-bottom connections and possibly some drifts and certain structures of the repository must have seals ensuring a specified quality of leaktightness. This concern must be included from the design phase.

Andra has chosen a design for the vertical and inclined seals based on the best available techniques; at this stage, their main component is a core based on swelling clay occupying the entire cross-section area of the ramp or shaft and in direct contact with the clay rock.

This design takes advantage of the inherent mechanical characteristics of the clay rock at the level of the USC, favouring (as observed at the Underground Research Laboratory at - 445 m) the absence of any connected fracture zone, and so ultimately the absence of any EDZ, and the good behaviour of the rock, which requires little support during excavation, which should facilitate liner removal before core construction.

The formulation of the core clay (swelling clay on its own or mixed with additives such as silica or limestone sand) aims to obtain a permeability as low as reasonably possible. At this stage, the material and its placement dry density will be selected so as to obtain a swelling pressure (effective pressure) remaining within a range up to a maximum of 4 MPa as it changes[74].

[74] Several techniques can be considered for placing the swelling-clay-based material: prefabricated blocks, tamping of clay pellets (or pellet-powder mixture), spraying. The placement method (which may combine more than one of the swelling clay placement techniques mentioned above) must minimise residual voids as far as possible, in particular at the highest point of the ramp roofs.

Similarly, Andra has defined an objective of core macroscopic permeability at saturation of the order of 10^{-11} m/s, on the basis of the results of assessments, studies, research and testing at the Underground Research Laboratory and elsewhere.

The clay core must be contained mechanically so that it can be loaded hydromechanically at constant volume, favouring any filling of placement voids and a good hydraulic interface with the clay rock. At this stage, the clay is contained by concrete containment walls, which must withstand mechanically the hydraulic and gas loadings at either end of the core that might occur over time, for example during the hydraulic-gas transient of the repository. Their length, considered at this stage to be about one diameter of the structure to be sealed, and the methods for possible anchoring of them in the rock (USC for the ramp seals, USC and Oxfordian limestone for the shaft seals) will be dimensioned to this end. The use of low-pH concrete formulations (pH of sound concrete [after setting] ≤ 11) is specified both for the blocks and for any liner portions that might remain in place (in particular at the interface with the blocks). This type of formulation contributes to (i) good placement ensuring performance of its mechanical function (shrinkage limitation by limitation of the heating related to the setting of the concrete), (ii) very slow chemical and physical change in the concrete over the long term and (iii) limitation of the chemical effect of the concrete on the clay core, favouring the hydraulic and hydromechanical properties of the core.

The length of the core gives it a margin of robustness, for example with respect to (i) a reduction of the permeability and swelling properties of the core at the interface with the concrete containment walls, which could be related to an alkaline disturbance, or (ii) a long-term decrease in the mechanical properties of the containment walls with consequent slight deconfinement of the core in the zone close to the blocks. In the shafts, the longest possible length is chosen given the thickness of the USC, taking advantage of the favourable mechanical properties of the USC clay rock. For the ramps, a minimum core length of 100 metres is considered.

The requirements and performance defined for the vertical and inclined seals and the associated design options are summarised in the table below.

Table 3.4-2: Requirements, specified performance and design options for the vertical and inclined seals

Requirements/performance	Design measures	Sub-component concerned
To ensure the most uniform core swelling and properties possible, the residual voids are limited to the lowest possible level.	Placement of the clay core in the form of pellets and powder of swelling clay on its own or mixed. An alternative is placement of the swelling clay core using compacted swelling clay bricks.	Clay core
To limit deformation of the clay rock in contact with the core and favour the mechanical closing of fractures in damaged clay rock, the target core swelling pressure is at least a few megapascals.	Choice of a placement density appropriate for the mineralogical nature of the swelling clay. Minimum core length: ▪ inclined seals: 100 m ▪ vertical seals: 40 m	
Given the hydraulic brake function of the seals, the target saturation permeability of the core and its interface with the other materials is of the order of 10^{-11} m/s.		
To prevent the liner forming a preferential water circulation pathway by-passing the clay core, its continuity must be interrupted.	Liner removal over the length intended to accommodate the clay core. .	Core/clay rock at the face interface; liners
Chemical disturbance originating from liner portions in proximity to the clay core must be minimised.	The liner portions left in place will be made of low-pH concrete (up to a distance at least equal to one diameter of the structure from either end of the core).	
In the USC, the increase in the water permeability of the clay rock zone around the structure must be less than or equal to two orders of magnitude compared with that of the undisturbed clay rock.	As far as possible, a surface-bottom connections excavation method that does not produce any 3D connected fracture zone of clay rock (ZFC) at the face, as in the UA.	Clay rock at the face

Requirements/performance	Design measures	Sub-component concerned
The swelling clay core must be contained mechanically so as to favour low macroscopic permeability and a good hydraulic interface with the clay rock.	Placement at each end of the clay core of concrete containment walls, the dimensioning of which (length, geometry, any anchoring): ▪ takes into account chemical degradation of the concrete, ▪ provides the highest possible stability and durability.	Concrete containment walls
Chemical disturbance originating from the clay core mechanical containment system must be minimised.	Use of a low-pH concrete formulation.	

3.4.1.3 Design options for seals at the level of the Kimmeridgian

Seals at the level of the Kimmeridgian are planned based on the same principle as the seals in the Callovo-Oxfordian (see above).

The seals are positioned in the upper part of the Kimmeridgian.

In terms of long-term seal operation, no specific feature likely to make the operation of these seals significantly different from that of the seals in the Callovo-Oxfordian has been identified.

3.4.1.4 Design options for horizontal seals

For the horizontal seals, Andra is studying a design with a clay-based core as main component. In comparison with the inclined seal described above, the presence of a ZFC around the drifts and the hydromechanical characteristics of the UA clay rock necessitate a specific approach for the horizontal seals in terms of both performance and design.

The data acquired on the hydraulic behaviour of the damaged zone show the existence of self-sealing related to swelling of the interstratified illite/smectite minerals of the clay rock, resulting in gradual recovery of low permeability, at least two orders of magnitude less than the initial permeability in the ZFC after excavation and close to that of the undisturbed clay rock in the ZFD. Nevertheless, at this stage Andra is keeping open the possibility of taking the self-sealing process into account by studying two options in parallel:

- as reference, the drift liner is removed completely, or by portions over the length of the core, so that the core is in direct contact with the clay rock over a cumulative length of at least a few metres when it is put into place (typically four liner removal zones each up to a few metres long); the performance of the seal in this case is based on mechanical closing of the cracks (favoured if applicable by the development of a core swelling pressure of up to 4 megapascals - see below) and self-sealing;
- as variant, radial hydraulic cut-offs of the EDZ are realised, supplementing the clay core: 3 to 5 cut-offs would be placed at regular intervals, consisting of saw-cut grooves 30 cm thick[75], filled with swelling-clay-based material (placement in the form of compacted pieces or pellets, at this stage). The liner is removed only at the interface with the hydraulic cut-offs.

The horizontal seals will be installed in drift sections oriented parallel to the major principal stress, in order to take account of development of the connected fracture zone on the facings and to a lesser extent in the roof, favouring (i) removal of the liner and (ii) realisation of the hydraulic cut-offs.

[75] The depth required for the grooves is about 0.8 times the excavated radius.

Andra has defined a performance target for the horizontal seals, expressed in terms of macroscopic permeability less than 10^{-9} m/s. This macroscopic permeability encompasses all of the components, including the core-clay rock interface, particularly important for dimensioning (see below).

Similarly to the inclined and vertical seals, low-pH concrete blocks can be placed at each end to contain the core mechanically, according to the swelling pressure that will be applied to it. Several concrete containment wall designs are being studied by Andra and their mechanical performance assessed, taking into account the friction between block and wall and/or the construction of recesses anchored in the UA clay rock.

The horizontal seal design options may change in order to optimise performance. The design requirements associated with this type of seal at this stage are summarised in the table below.

Table 3.4-3: Requirements, specified performance and design options for the horizontal seals

Requirements/performance	Design measures	Sub-component concerned
To ensure the most uniform core properties possible, the residual voids are limited to a level as low as reasonably possible.	Placement of the clay core in the form of pellets and powder of clay (swelling or mixed) [76].	Clay core
The core swelling pressure favours limitation of deformation in the clay rock in contact with the core and hydraulic healing of the fractures in clay rock damaged by mechanical closing.	- Choice of a placement density appropriate for the mineralogical nature of the swelling clay. - Minimum core length equal to twice the excavated diameter of the structure or 20 m	
To prevent the liner forming a preferential water circulation pathway by-passing the clay core, its continuity must be interrupted.	▪ <u>Reference solution:</u> Partial removal of the liner where the future clay core is to be placed, over a cumulative length of at least 4 m. The removal zones will be filled with a material similar to that of the clay core ▪ <u>Variant:</u> Realisation of 3 to 5 radial hydraulic cut-offs interrupting the continuity of the connected fracture zone (ZFC) and the continuity of the liner left in place.	Component located between the core and the clay rock in the face
Chemical disturbance originating from liner portions or the load bearing rings in contact with and in proximity to the clay core must be minimised.	The liner portion left in place will be made of low-pH concrete (up to a distance at least equal to one diameter of the structure from either end of the core).	
A swelling-clay core must be contained mechanically in order to allow the core swelling pressure to be established during resaturation and maintained throughout its evolution.	Placement at each end of the clay core of concrete containment walls, the dimensioning of which (length, geometry, any anchoring): ▪ depends on the core swelling pressure and the fluid heads at either end, ▪ takes into account chemical degradation of the concrete, ▪ provides the highest possible stability and durability.	Concrete containment walls
Chemical disturbance of the clay core must be minimised.	Use of a low-pH concrete formulation.	

[76] An alternative is core placement with compacted clay bricks.

3.4.2 Feedback from experience with seal performance

Assessment of the performance of seals with clay cores involves the following "components" (see next figure):

- the core;
- the component between the core and the clay rock in the wall, consisting as appropriate of sections of liner that have been left in place and clay material used to fill the liner removal zones;
- the zone of damaged clay rock in the structure wall;
- the low-pH concrete containment walls (depending on the core's mechanical containment needs);
- the hydraulic cut-offs (in the horizontal seals variant option), which break the continuity of the liner and the clay rock in the wall.

Andra has already carried out numerous tests and simulations linked to the seals. The configurations tested will not predetermine the design of the seals that will ultimately be used (typically from 2070 in the case of the first horizontal seals and from 2150 in the case of the vertical and inclined seals). They provide feedback concerning individual components on the possible implementation techniques and also on potential performance.

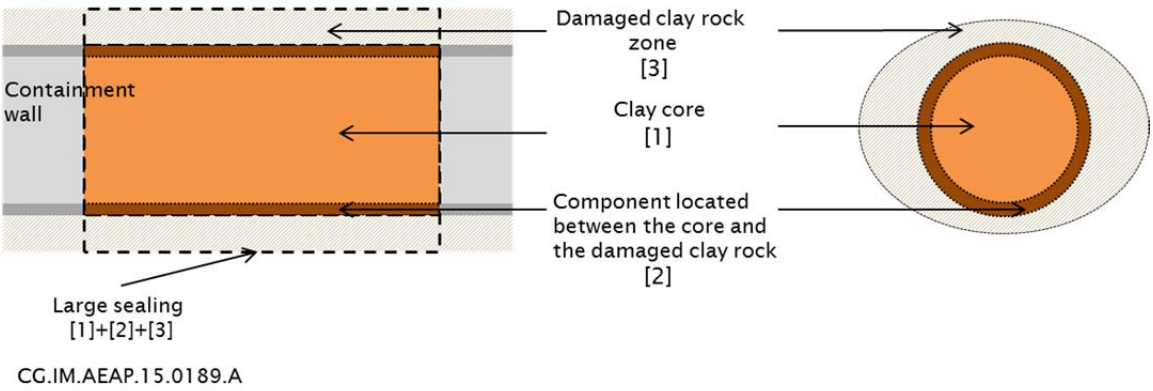


Figure 3.4-2: The "components" contributing to the hydraulic performance of the seals

3.4.2.1 Performance associated with the clay core

Proven techniques for clay core installation

Based on feedback from numerous tests carried out and models produced internationally and at the Meuse/Haute-Marne Underground Research Laboratory, up to multi-metric scales , Andra has acquired a sound understanding of swelling clays and the structures made from these materials. This experience indicates that a permeability below 10^{-11} m/s can reasonably be obtained with different types of swelling clay (on its own or mixed), on the basis of a wide range of dry densities at the time of emplacement, and of various methods for the shaping and emplacement of the clay material.

- ***Horizontal structures***

Experimental demonstrations in the early 2010s had already shown the feasibility of installing a swelling clay core of up to a vertical scale of 5 to 6 metres in the horizontal structures. More recently (in 2014):

- the NSC test to assess the performance of the core and the core/argillite interface was conducted at the Meuse/Haute-Marne Underground Research Laboratory, at half the scale of a horizontal closure structure at Cigeo. The test demonstrated the feasibility of installing the core in the form of compacted bricks, managing the interfaces by using a mixture of pellets and bentonite powder;

- the Full Scale Sealing (FSS) technology test of the full-scale construction of a horizontal seal, was carried out on the surface using an industrial method, under temperature and relative humidity conditions representative of conditions in the repository. The test learned some significant lessons concerning (i) the formulation of the swelling clay-based material; (ii) the installation of the clay core at full scale, with out-of-profile issues representing non-uniformities in the argillite wall where the liners were removed due to, for example, rock breakout from part of the ZFC when the liners were removed, and (iii) the achievement of dry densities on installation that meet the specifications for permeability and swelling pressure.

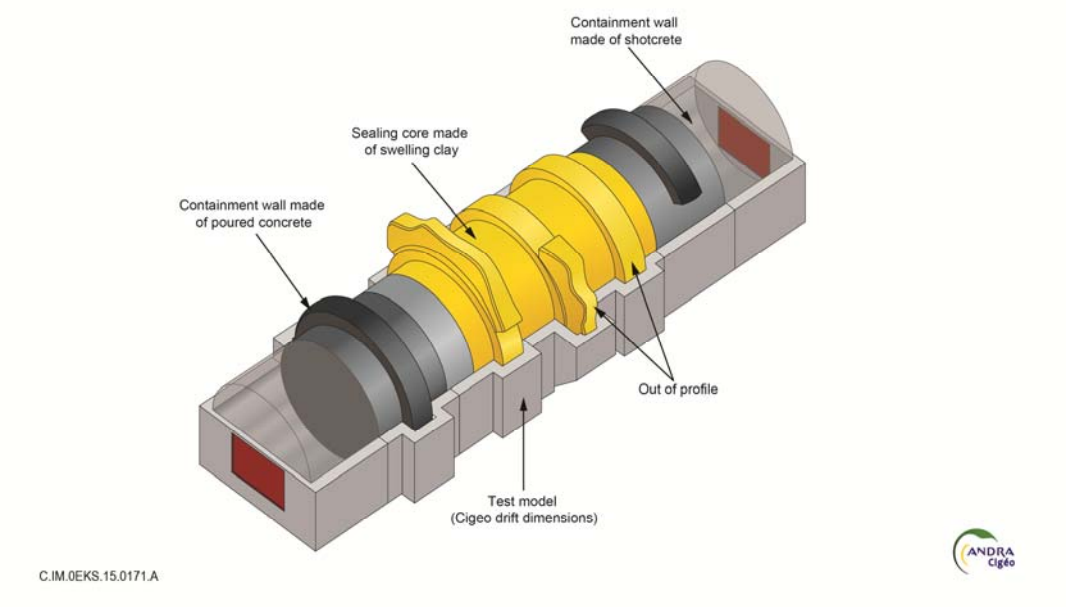


Figure 3.4-3: FSS test design principle

Results obtained in the FSS test represent major progress for the industrial demonstration of the installation of a full-scale seal. The lessons learned in terms of material formulation and more appropriate construction measures, particularly for the topmost part of the clay core, make an excellent basis for the next iterations, which will be full-scale demonstrators of the sealing of the drifts and the ramp in Cigeo, planned as part of the Cigeo project's component development plan (PDD) (28), more specifically from the industrial pilot phase.



Figure 3.4-4: Sealing test

- ***Structures in the shafts***

Verticality is an aid to installation. Experience with installing the seal in the small shaft at the Mol Underground Laboratory in Belgium and the access shaft at the AECL Underground Laboratory in Canada has demonstrated the feasibility of the vertical solution.

Capacity to achieve a hydraulic performance that helps to limit flows within the structures

Given the large cross-sections to be filled (up to 100 m² in the ramps) and the important role played by the seals in the surface-to-bottom connections, Andra has set a uniform permeability target on saturation for the core and for its interface with the other materials of around 10^{-11} m/s for vertical or inclined seals; a higher permeability of around 10^{-9} m/s seems appropriate for the horizontal seals. As the figure below shows, lower permeability levels would offer little gain as regards the overall permeability of the seals, given the hydraulic characteristics of the clay rock in the wall.

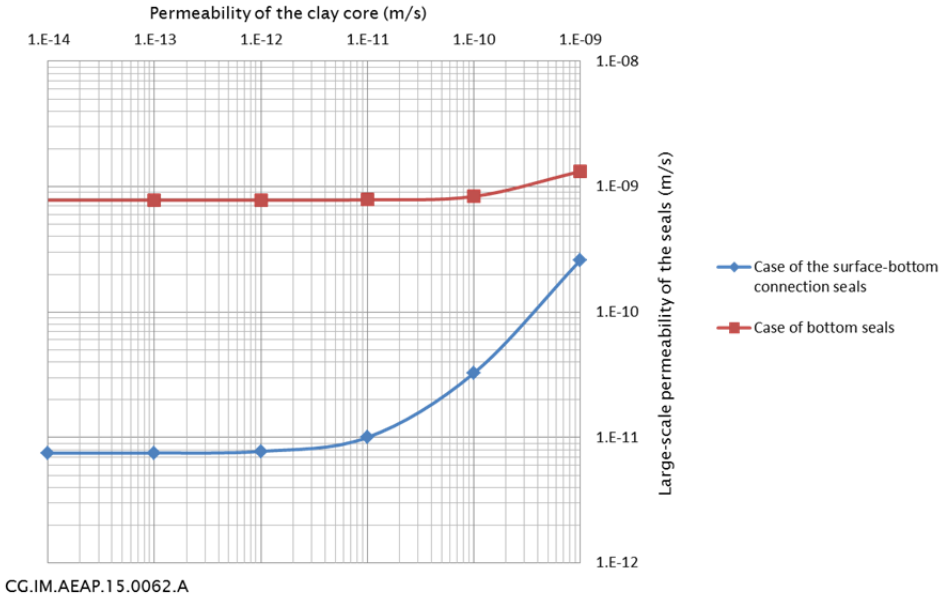


Figure 3.4-5: Influence of clay core permeability on the overall permeability of the seals

By means of numerous tests on a metre scale, the FSS experiment showed that several swelling clay pellet-based formulations enabled a hydraulic performance level of 10^{-11} m/s to be achieved. However, neither core saturation nor assessment of the core's hydraulic performance were attempted at full scale because the desired phenomena and parameters could not be achieved within the time scale of the test. Other tests in addition to FSS and on a smaller scale will be used to look at these aspects. For example:

- the REM experiment in a surface laboratory, which will be used to check the feasibility of resaturating the mixture used in FSS and to analyse the behaviour of the pellet mixture during resaturation on at least a metre scale (from the point of view of hydromechanics and gases). The different tests that will be performed as part of this will also enable the sensitivity of the bentonite mixture to different types of resaturation water (site water, synthetic water, concrete water at different pHs) to be studied;
- the NSC test performed in the Meuse/Haute-Marne Underground Research Laboratory on a smaller scale than FSS: by 2020 the artificial saturation of the NSC core will be complete, and its hydraulic performance will have been assessed. Until then, hydromechanical monitoring of the core, the low-pH concrete containment wall and the clay rock in the wall will be performed.

<u>The core's contribution to the healing of the damaged clay rock in the wall</u>

Developing and maintaining a clay core swelling pressure of at least a few megapascals will help to limit deformation of the clay rock in contact with the clay core, and will also assist the mechanical closure of the fractures in the ZFC (in the UA) and their self-healing (reduction of permeability) through resaturation..

The swelling pressure should be limited to the effective natural stress of the clay rock (of around 7 MPa) so as not to cause any mechanical problems. Similarly, it should be able to be accommodated by the concrete containment walls on either side of the swelling clay core so that deformation in the outer part of the core is significantly limited and the swelling is guaranteed to be as uniform as possible.

As indicated earlier, the FSS test allowed formulations suited to the Cigeo context to be produced, which could develop a swelling pressure at saturation of around 3.5 to 4 MPa on a scale of decimetre. The results of the REM test currently in progress will be used to check that switching from a scale of decimetre to a scale of metres has no impact on the hydromechanical behaviour of the bentonite mixture obtained in the FSS test (uniformity of behaviour and achievement of saturation and the desired swelling pressure). The assessment of whether a swelling pressure of 3.5 to 4 MPa is favourable looks at:

- research on the overall hydromechanical behaviour of the seals (representation of the clay core/clay rock/concrete containment walls/liner sections as an integrated unit). Numerical simulations are currently being performed. Ultimately, this research will make it possible to:
  - ✓ assess:
    - the resaturation transients of the different components, in connection particularly with the presence of voids from emplacement and the increase in swelling pressure;
    - the stresses on the near-field clay rock, on the liner portions left in place and on the containment walls in connection with friction at the interfaces and the creep of the clay rock;
    - the hydromechanical rebalancing after complete saturation of the core from the effect of the hydraulic head increase;
    - And ultimately the effects of the dual-porosity specific behaviour of the pellet mixture and of gradual chemo-mechanical degradation of concrete components.;
  - ✓ provide more precise data about the favourable core swelling pressure range in terms of (i) deformation of the clay rock and ultimately the mechanical closure and healing of the fractures in the ZFC and (ii) the longitudinal movement of the containment walls which has the effect of locally reducing the swelling pressure (In connection with the need to maintain a permeability of the ZFC lower than 10^{-9} m/s);

- the results of the NSC test currently in progress, which will help with assessing the hydraulic performance and hydromechanical behaviour of a seal in repository conditions;
- work in progress on the ZFC healing capacity in function of deformations;
- the design and mechanical performance of the containment plugs.

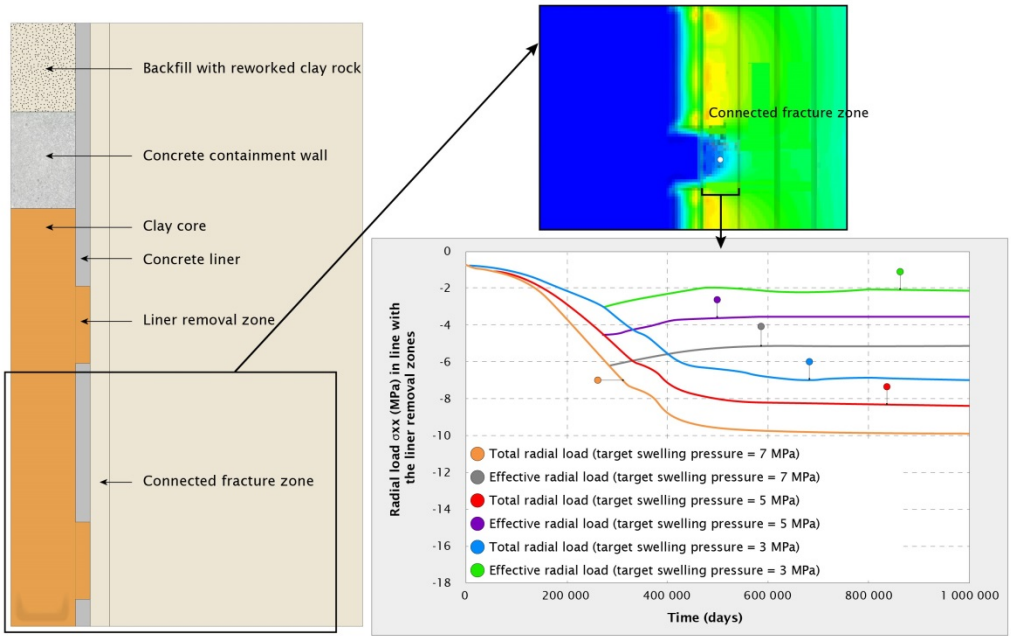


Figure 3.4-6: Effective compressive stress in the ZFC over time for different swelling pressures of the clay core

3.4.2.2 Performance associated with the component between the core and the damaged clay rock

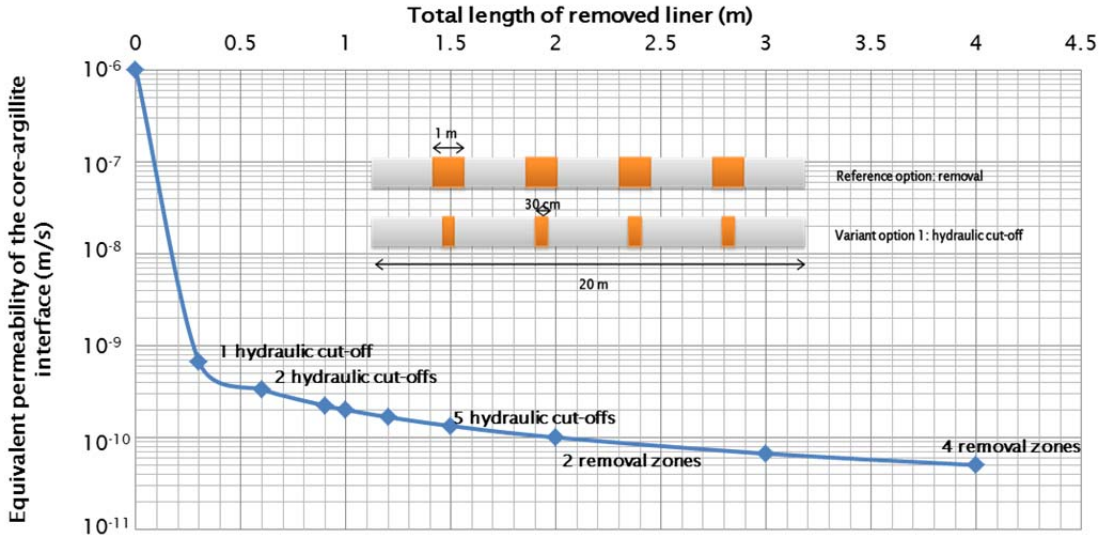
Concepts that deliver margins of robustness

- ***Vertical or inclined seals***

In the surface-to-bottom connection seals, removing the liner along the whole length of the core allows direct contact with the clay rock, unless liner portions are left in place by necessity. In that case, the analysis is the same as for horizontal seals (see below).

- ***Horizontal seals***

With the reference option, as with the variant option, the component between the core and the clay rock in the wall consists of a succession of liner portions and clay material. The figure below shows that the equivalent permeability of this component complies with the performance target (below 10^{-9}) once a few decimetres of liner have been removed, i.e. the equivalent width of a hydraulic cut-off. The realisation of 4 liner removal zones in the case of reference option or 3 to 5 hydraulic cut-offs in the variant option enables the performance target to be met for this component.



CG.IM.AEAP.15.0064.A

Figure 3.4-7: Equivalent permeability of the component between the core and the clay rock as a function of maintaining/removing the liner sections

Techniques for creating the component between the core and the damaged clay rock which ensure the target performance is achieved

The seal concepts require the ability to (i) remove all or part of the liner around the future seal and to repair the clay rock wall (removal of loose rock, surfacing) so that its surface is as even as possible, (ii) fill these liner removal areas with highly uniform swelling clay, (iii) form hydraulic cut-offs for the variant option of the bottom seals.

- ***Liner removal***

Techniques are currently being studied in liaison with those of excavation, installation of roof supports and liner of the structures. The aim is to be able to remove the liner while minimising changes in the clay rock in the wall (reactivation and spread of fractures).

Around the future seals of the surface-to-bottom connections, the mechanical properties of the clay rock help to limit the size of any damaged area and are therefore favourable to liner removal. A test of the removal of liner sections from the drift at a depth of 445 metres (USC) is in progress in the Underground Research Laboratory. The excellent observed strength of the unsupported rock is favourable from the point of view of technological implementation.

For the horizontal seals, a liner removal test is planned in the UA to check and evaluate the mechanical impact on the clay rock, particularly the extent and properties of the fractured clay rock zone.

In parallel to the liner removal tests, the development and testing of a "repair" process for the clay rock wall after the liner has been removed will be performed.

- ***Filling of the liner removal zones with swelling clay***

The permeability target makes it necessary to be able to fill the removal zones with highly uniform swelling clay, keeping voids to a minimum. This problem is similar to the problem of installing the full-scale clay core discussed earlier in the section on the clay core. The FSS test demonstrated the difficulty of filling the liner removal zones, but also enabled lessons to be learned about suitable formulations for the swelling clay and appropriate core emplacement techniques for these zones. The creation of demonstrators for ramp and drift seals in Cigeo, included in the PDD (28) will enable them to be tested.

A concrete formulation that limits alkaline disturbance

Alkaline disturbance in the clay core as a result of degradation of the containment plugs and portions of the low-pH concrete liner, after 100,000 years, results in the development of a highly remineralised zone at the interface with the containment walls (complete dissolution of the montmorillonite and precipitation of illite, saponite, quartz and calcite) and a slightly disturbed zone (fairly significant dissolution of minor primary phases). The size of these zones is respectively decimetre and metres. The total quantity of swelling minerals dissolved is below 10%.

In the clay rock, the highly disturbed zone of several centimetres is characterised by the dissolution of many minerals in the clay rock and the precipitation of saponite. Beyond that, a less disturbed zone marked by fairly significant dissolution of the calcareous primary phases (siderite, dolomite) and calcite formation extends over just under 2 metres.

In the hydraulic cut-offs (variant option for the bottom seals), the assessment of the change in smectite (swelling mineral) content after 100,000 years shows that approximately 10% of the original smectite is dissolved immediately around the liner. Further away from the liner, by the clay rock, no change is observed.

3.4.2.3 The "performance" associated with the clay rock in the wall

Characterised initial damage

The measurements acquired at the Underground Research Laboratory with various experiments using different configurations (in terms of excavated diameter, drift depth and orientation, excavation method and type of roof support, etc.) show that:

- the damage is mainly linked to the mechanical behaviour of the rock, to the in situ stress (i.e. the depth of the structures), and to the excavation/roof support method;
- the general structure of the damage is the same regardless of the type of structure (from 10 centimetres to 8 metres excavated diameter);
- the geometry of the damage is anisotropic and depends on the drift orientation in relation to the main horizontal stresses, and its extent evolves linearly as a function of the excavated diameter.

▪ ***At the bottom seals***

In the UA where the horizontal seals are installed, and where the clay rock is at its weakest in the Callovo-Oxfordian, following excavation and in the walls of the excavations, very significant localised damage can be observed, with the formation of two areas:

- a wall area characterised by a dense network of mixed (in terms of extent and shearing) interconnected fractures, known as the "connected fracture zone" (or ZFC);
- an area beyond the ZFC characterised by shearing fractures with little or no interconnection, known as the "discrete fracture zone" (or ZFD).

In the ZFC, the water permeability calculated from hydraulic tests performed at the Underground Research Laboratory varies between 10^{-5} m/s and 10^{-10} m/s, sometimes with even lower values. Permeabilities below 10^{-12} m/s have been measured on samples taken between the fractures, which means that the water permeability value of 10^{-5} m/s is representative of the permeability of the fractures.

Beyond the ZFC, the ZFD in the UA is characterised by water permeabilities measured at between 10^{-10} and 10^{-12} m/s.

- ***At the surface-to-bottom connection seals***

In the USC where the surface-to-bottom connection seals are installed, and where the mechanical strength of the clay rock is high, little damage is observed during excavation, with some extension cracks (several centimetres) and some microcracking.

Observations made during the initial characterisation in 2005 in the Meuse/Haute-Marne Underground Research Laboratory around the drift at a depth of 445 m, confirmed by measurements made nearby in the main shaft (SMR and REP), show a reduction in permeability between 10^{-11} and 10^{-13} m/s in the first two metres of the rock. This means that there is no ZFC formation; only a ZFD forms.

A damaged clay rock zone evolving towards the healing of its fractures

Following the excavation and mechanical unloading causing the initial damage, the area of damaged clay rock in the wall of the structure is likely to evolve in terms of its extent or hydraulic properties, in connection with various phenomena and stresses.

- ***Hydraulic fissuring with limited consequences***

During the operational phase, due to fact that, within the Callovo-Oxfordian formation, the liners of the surface-to-bottom connections and drifts are not waterproof, ventilation is leads to desaturation of the clay rock. This mainly occurs in the zone already damaged by the excavations and can cause pre-existing cracks to open due to shrinkage, if the stress state allows this.

In the UA, the resulting hydraulic fissuring is comparable to a ZFC and remains confined within it, without significantly increasing the damage. In the USC, where there is no ZFC, a ZFC can form. As its extent would be small because of the low level of desaturation of the ZFD (surface phenomenon), it will be removed once the liner has been removed.

Ultimately hydraulic fissuring does not alter the hydraulic properties of the damaged clay rock or its structure.

- ***Mechanical unloading in the liner removal zones managed by design***

Mechanical unloading as a result of the removal of the liner is likely to cause reactivation of the cracks and fractures in the damaged clay rock zone. Consequently, a series of design measures has been specified to keep this to a minimum.

- ***Evolution linked to the time-dependent behaviour of the clay rock, which remains limited***

In the USC (vertical and inclined seals), six years after excavation, the permeability measurements taken around the drift at a depth of 445 metres show a slight change with the appearance of a highly permeable area in the face (up to 0.5 metre) and a more marked change at the floor (up to 1 metre). This evolution of the damage in the USC with the appearance of highly permeable areas should be kept in perspective given that:

- (i) these areas are not always observed and the fracturing density is low (a few fractures in each borehole);
- (ii) the geometry of the drift at a depth of 445 metres is specific (a horseshoe) which means that the stresses are concentrated, amplifying the fracturing, and the drift is not well supported;
- (iii) there is currently no information about whether the fractures observed are connected in parallel with the drift axis, but it is unlikely that there is continuity.

If the development of the fractured area is not an artefact, the development of the cracks over time could be linked to the desaturation and/or time-dependent rupture of the clay rock linked to viscoplastic deformations. In Cigeo's shafts, which will have a rigid liner, deformation will be prevented and so it will be much more difficult for the fractures to spread than it would with a structure with little or no liner, which is the case with the drift at a depth of 445 m. This propagation should therefore be a surface phenomenon. The design measures of the surface-to-bottom connection seals require that, once the liner has been removed, the surface of any clay rock that appears to be altered or fractured should be repaired (removal of loose rock, surfacing, etc.).

Once the liner has been removed and the clay core has been installed, the core should be rigid enough to contain the clay rock and prevent any further damage from developing.

In the UA (horizontal seals), the time-dependent rupture phenomenon should have a limited impact on the damage. This is corroborated by measurements taken in the Underground Research Laboratory where, after 5 years' monitoring of the structures with "flexible" roof supports, no significant changes were observed and the high hydraulic conductivity levels remained in the original connected fracture zone (ZFC).

The description below of the time-dependent behaviour of the clay rock (in the USC and the UA) will be consolidated by activities planned by the PDD (28), namely:

- continuing observations at the Underground Research Laboratory until 2018, then during the 2018-2024 period, which will allow:
  - ✓ monitoring of the evolution of damage around the drifts;
  - ✓ a significant reduction in current uncertainties about the speed of time-dependent deformation of the clay rock in the long term;
- new tests on the time-dependent behaviour, which should provide a better understanding and characterisation of time-dependent rupture in samples and should clarify the potential evolution of the Callovo-Oxfordian clay rock' mechanical strength over time;
- new knowledge to be taken into account about time-dependent behaviour in integrated hydromechanical simulations of the seals.

▪ ***Capacity of the clay rock for hydraulic healing demonstrated***

The CDZ test conducted at the Underground Research Laboratory measured the effects of mechanical closure of the fractures and the effects of self-sealing through resaturation on the permeability of the ZFC and the ZFD. It showed that applying pressure to a drift wall results in reduction of the permeability of the fractured zone due to the geometric closure of the fractures. This reduction reached 3 orders of magnitude under a load of 4 MPa in the zone with the highest initial intrinsic permeability. Other tests performed at the different loading stages (2 MPa, 3 MPa, 4 MPa and after loading) showed that a load at 3 MPa leads to a reduction in hydraulic conductivity of around 1 to 3 orders of magnitude in the intervals under load.

Observations during the CDZ test also show that, in parallel with the geometric closure of the fractures, another process occurs that tends to reduce permeability: self-sealing through the resaturation of the damaged clay rock zone.. This is due to rearrangement of the minerals and ultimately the porosity in and around the fractures, through (i) interfoliar swelling of the smectite minerals, (ii) interparticular swelling due to osmosis, and (iii) the blocking of the cracks by particles accumulation. Mechanically closing the cracks will help this phenomenon.

Regardless of the type of fracture (shearing, extension or artificially created through trimming), self-sealing has been observed and could therefore develop equally well in the ZFC and the ZFD. A reduction in water permeability by 3 to 4 orders of magnitude due to hydration was observed particularly in the CDZ experiment in the intervals identified as most permeable (i.e. with a permeability initially identified as being greater than 10^{-7} m/s). The permeability of these intervals is found to stabilise rapidly at a value of around 10^{-10} m/s.

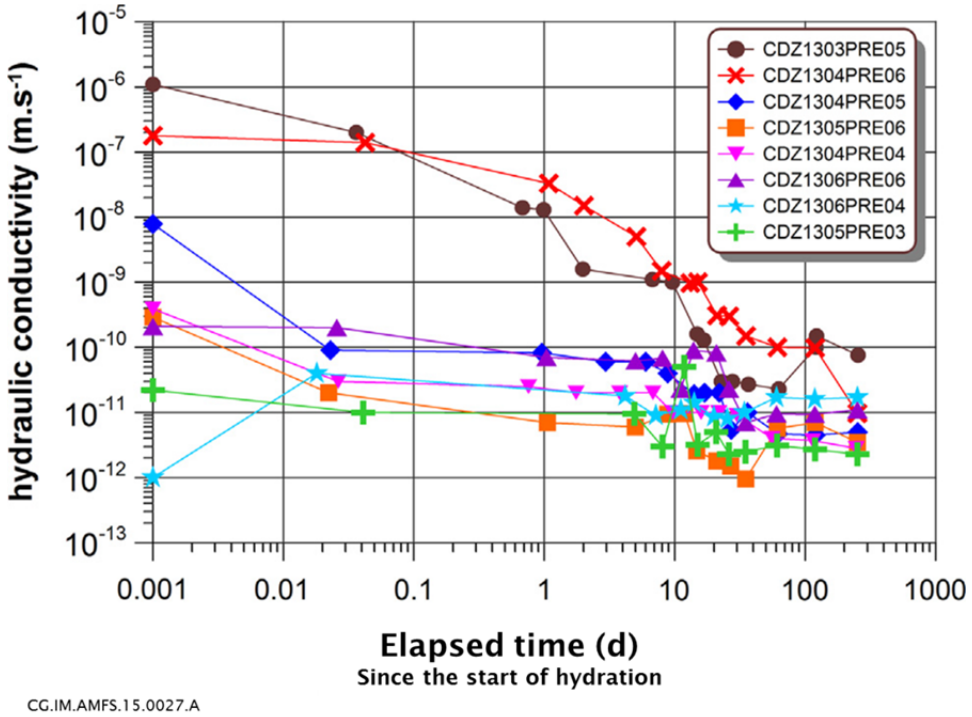


Figure 3.4-8: Change in hydraulic conductivity measured in the CDZ experiment from the start of resaturation for the 8 periodically tested intervals

The damaged clay rock (ZFC and ZFD) should therefore heal and recover a low level of water permeability (below 10^{-9} m/s) compatible with the performance targets for the seals (particularly the bottom seals) from the effect of:

- the mechanical closure of the fractures under the mechanical load of a swelling clay-based core: it has been established through simulation that a clay core swelling pressure does materialise, and at a good ratio, in the form of compression of the fractured clay rock at the liner removal zones, and therefore ultimately produces a reduction in permeability;
- the self-sealing of the fractures as a result of their resaturation with water.

The residual uncertainties at this stage about the healing of the damaged clay rock around the seals lie principally:

- in how the self-sealing should be taken into account in the evaluations (e.g. up to what width of fracture opening does this process continue?), but also in the fact that the characterisation of the self-sealing process in the USC needs to be continued (how is it linked to the mineralogy?). Tests currently being carried out at the Underground Research Laboratory or on the surface should reduce these uncertainties;
- in the hydromechanical coupling of a swelling clay-based core with clay rock and, more specifically, the core's capacity to reproduce by means of its swelling pressure the mechanical effect that helps to restore low permeability.

3.4.2.4 Performance associated with the concrete containment wall

Containment wall concepts designed for durability and long-term stability of the seal

As part of the design process, Andra is studying various technical solutions for containment wall made from low-pH concrete, taking account of the technological aspects, understanding of long-term THMC behaviour, and economic factors. These solutions cover:

- containment wall concepts with one or more recesses in the liners (Figure 3.4-9 – (a));
- a containment wall concept with a radial recess of several metres in the clay rock (Figure 3.4-9 – (b)).

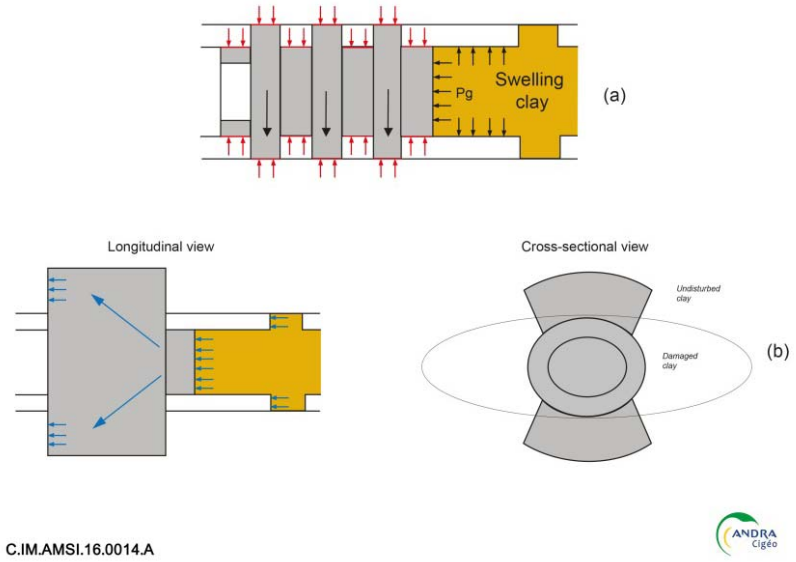


Figure 3.4-9: *Schematic diagrams of containment wall concepts currently being studied: (a) with one or more recesses; (b) with one recess anchored in the clay rock*

The work is continuing as part of the research and testing plan (PDD) (28) on the components of Cigeo: technological feasibility of the different types of recesses, reduction of the uncertainties about friction at the concrete/clay rock interface and how this will change over time.

Feasibility of concrete installation validated

The FSS test on the construction of a full-scale seal validated the feasibility of installing significant volumes of low-pH concrete in a drift configuration, in particular with mechanical characteristics that conform to those expected and measured in samples.

Two different installation techniques associated with two low-pH concrete formulations (pH of around 10.5) have been trialled in conditions representative of the repository (temperature and relative humidity; constraints on transporting and installing the concrete).

The first containment wall was made continuously with self-compacting concrete, in successive passes and using around 241 m³ of concrete. Once the casting was finished, a low-pH grout was injected to fill any voids. The volume of the voids turned out to be small. The measurements and observations made while the concrete was being cast and when the formwork was removed show in particular that the thermal criterion (T<50°C) was met, the concrete was even and the surplus volumes (simulating the liner removal zone and a possible out-of-profile zone) were completely filled.

The second containment wall was made using the shotcrete technique and approximately 271 m³ of concrete. The thermal peak in the core was 67°C, which is 17°C above the specification. It is also likely that, in some areas of the lower part of the containment wall, there was poor adhesion between layers due to the resumption of grouting between each vertical layer (poor rebound clearance before restarting the grouting). However, significant lessons have been learned in terms of adapting the low-pH concrete formulation and the projection method used (projection duration, thickness of layers, etc.).

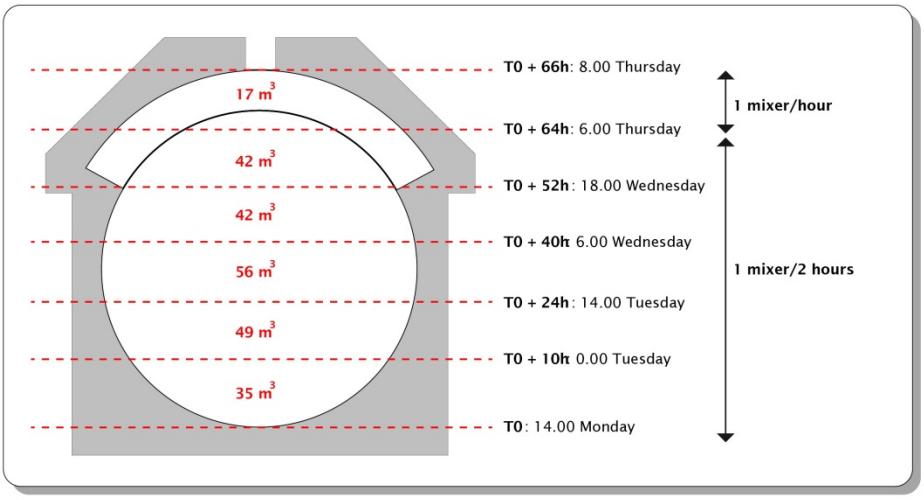


Figure 3.4-10: Schematic diagrams of the technique for installing the containment wall using self-compacting concrete

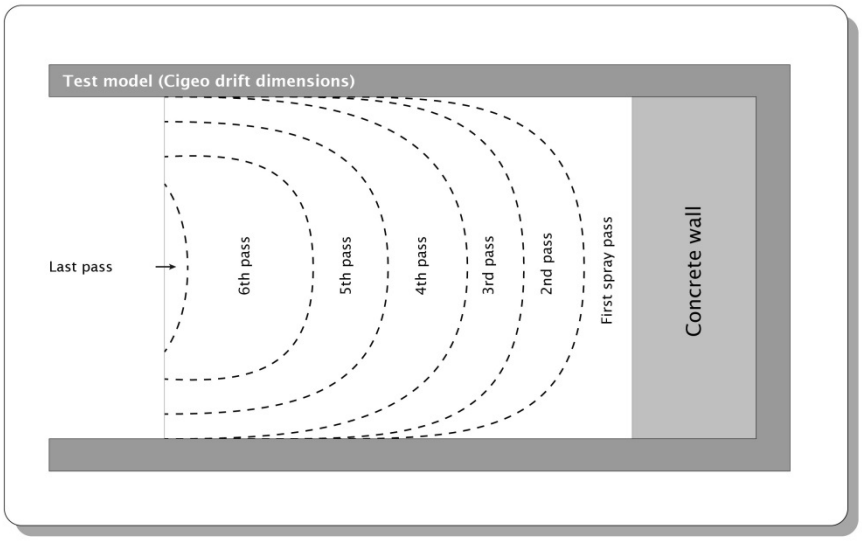


Figure 3.4-11: Schematic diagrams of the technique for installing the containment wall using the shotcreting method

<u>A concrete formulation that limits concrete degradation and alkaline disturbance</u>

The extent of the degradation due to water of the low-pH concrete containment walls is currently being understood by means of numerical reactive transport simulations. The results show that it is much less than with conventional CEM I type concrete. After 100,000 years, the transformation consists of:

- a highly disturbed zone at the interface with the clay rock, covering about 20 centimetres and characterised by dissolution of the CHS0.8 and massive precipitation of quartz and calcite; beyond that, a less disturbed zone extending for less than 2 metres, marked by the dissolution of the initial quartz, the precipitation of saponite and continuation of the CSH phase;
- two zones in succession at the interface with the clay core: the first covering approximately 10 centimetres, characterised by dissolution of the initial CSH0.8, C3FH6 and quartz, and the second extending for about a metre characterised by the dissolution of the quartz and the formation of small quantities of ettringite without major changes to the original minerals.

The containment walls should therefore maintain their mechanical properties for long periods, with the possible exception of the interfaces, where there could be significant mineralogical changes, though these amount among other things to precipitation in the concrete tending to reduce porosity and therefore to consolidate the material. Tests of the degradation due to water of low-pH concretes are planned, which should provide an understanding of the changes in their mechanical properties associated with chemical degradation.

3.4.2.5 Performance associated with the hydraulic cut-offs

This section concerns the variant option for the bottom seals. It consists of leaving the liner in place and excavating three to five 30-cm wide grooves, filled with swelling clay-based material. In this option, achieving the seal performance does not require the self-sealing process in the clay rock.

Making the grooves

The technique for making the grooves is to cut them with a saw (in several sections, as tested in the Underground Research Laboratory) or to use an equivalent technique. From the point of view of the technological feasibility of excavation, Andra has previous experience of making grooves of this kind, first in the Mont-Terri Underground Laboratory (EZ_A experiment) and then in the Meuse/Haute-Marne Underground Research Laboratory.

The technological feasibility of cutting 30-cm wide grooves to a depth of 2.5 metres has now been demonstrated. The surface condition of the last full groove of this kind (TSS1 experiment) dug at the Meuse/Haute-Marne Underground Research Laboratory in July 2011 was satisfactory and has remained stable since.

The characterisation results for the clay rock around the KEY groove dug at the Meuse/Haute-Marne Underground Research Laboratory in 2005 showed a small amount of additional damage to the clay rock around the groove, and little or no deformation of the clay rock. The numerical simulations performed corroborate these findings.

Filling the grooves

As regards the feasibility of filling the grooves and achieving the desired hydraulic performance (permeability at maximum saturation of 10^{-11} m/s), at this stage Andra has a number of test results. Following the test involving filling a groove with compacted bentonite bricks at the Mont-Terri laboratory in 2005 (satisfactory void rate limited to a few percent), the SET test to fill a void on the surface, performed in late 2013, provided further evidence demonstrating technical feasibility using an industrial method. This test, to fill a groove 2.5 metres in depth and 0.3 metres wide, performed in conditions representative of the limited space and difficulty of movement in situ, demonstrated the feasibility of the following operations:

- placing a stable assembly of pre-compacted bricks in the upper part of the grooves using a robot;
- filling the lower part of the groove with a powder mix (pellets and bentonite powder).

Hydraulic performance

A single hydraulic cut-off with water permeability of 10^{-11} m/s enables the continuity of the (high permeability) liner to be broken sufficiently so that ultimately a water permeability compatible with the desired performance target can be obtained for the "component between the clay core and the clay rock of the wall". The same applies to the connected fracture zone (ZFC) in the clay rock. Gas interference and helium tracing tests on either side of a resin-filled groove (KEY experiment) confirmed the effectiveness of the grooves at breaking the connectivity of the connected fracture zone (ZFC) when the groove penetrates the discrete fracture zone (ZFD) beyond the ZFC.

At this stage, the feasibility is still to be demonstrated of making hydraulic cut-offs of this kind at full scale (i.e. around 30 cm thick and with a depth of around 0.8 times the excavated radius, so approximately 3.5 metres for a structure with a cross-section of 65 m²) that can achieve the desired hydraulic performance. To do this, as part of the PDD (28), development work will be carried out to adapt the technologies developed in the SET test to full scale and operational conditions. In parallel,

tests will be carried out in the surface and underground laboratories on filling the grooves and monitoring the saturation.

3.4.3 Clay plugs for closure of the HLW cell heads

3.4.3.1 Design options and contribution to the safety functions

HLW cell head closures include a clay-based filler (or plug) at the sleeve intrados[77] (which is left in place). Overall the contribution of the cell head to the post-closure safety functions relies on the cell head length (as large as possible taking account of technical and economic factors), the portion of this length filled with clay (which should also be as large as possible; Andra chose a minimum length of 2 metres near the waste packages) and the characteristics of the filler clay used: low diffusion coefficient and porosity, residual voids kept to a minimum.

The primary contribution to the post-closure safety functions concerns limitation of the release of radionuclides (protecting the glass matrix of the HLW packages from alteration). It is a matter of playing a buffer role in relation to the physicochemical environment of the drifts, and more specifically of preventing the risk of propagation/short-circuit of the alkaline plume linked to the presence of concrete in the access drift liner.

Another contribution is to delay and attenuate the longitudinal flow of radionuclides and toxic elements. Because of the dominant diffusion conditions in the HLW cell, the longer the cell head and the bigger the clay plug it contains, the smaller the amount of solutes likely to migrate towards the access drift and the later the date of occurrence of the peak molar flow rates is likely to be. As a corollary to this, for a given cell head length, the reduction in the amount of substances entering the access drift and the delay in the occurrence of the peak flow rates depend on the diffusion performance of the filler materials.

Finally, like the backfilling of the drifts (see further on), the filling of the cell heads helps to preserve the favourable characteristics of the Callovo-Oxfordian clay rock locally: it reduces the compressible voids likely to be refilled when the sleeve in the HLW cell head ruptures.

It should be note that the HLW cell head and its closure method do not contribute to the "preventing water circulation" function.

3.4.3.2 Composition of the clay material

For the composition of the clay material, Andra is studying several options: clay rock or swelling clay[78], on its own or mixed.

The swelling potential obtained by using pure swelling clay or incorporating it into a mixture would help to deal with the residual gaps following installation and would prevent as far as possible the deformation of the plug itself or the clay rock around it. The chemical evolution of swelling clay-based materials in contact with metal components (which is the situation in the HLW cell head) is being understood by means of numerical simulations and experiments. These indicate that the degradation products formed in the swelling clay are similar to those observed in the clay rock on contact with iron, though the degradation is less intense. The main data produced by the experimental programme, which has focused mainly on the evolution of the iron/clay rock interface, indicates that the composition of the solution in contact with the products of the iron/clay rock interaction has a pH of between 6 and 9.

[77] Constructing such a plug does not pose any particular technological difficulty. As already stated in the previous section on the seals, the feasibility of installing a clay core in a horizontal structure has already been demonstrated experimentally up to a diameter of 5 to 6 metres.

[78] As stated earlier with regard to the seals, Andra has considerable experience with swelling clay. A wide diversity of types of swelling clay, either on their own or mixed with various additives associated with different shaping methods and different stresses, have been evaluated from a thermal, hydraulic, mechanical and chemical point of view, on the scale of the material or the structure it will be used for. These studies have highlighted the ability of swelling clays to adapt to different requirements and environmental conditions within the repository.

Using reworked clay rock could only be envisaged if its compatibility with the physicochemical protection of the vitrified waste after it has been stored on a muck pile can be demonstrated, linked to the disturbance resulting from oxidation of the pyrite in the clay rock. Work on the physicochemical characterisation of clay rock stored in muck piles is in progress.

The selection of materials with a pH close to neutral[79] will avoid adding a potential cause of alteration of the vitrified waste.

The composition of the clay material for closure of the HLW cell head will be defined in liaison with the studies currently in progress, which on the one hand will help to consolidate the technological knowledge acquired and on the other will improve knowledge of the phenomenological behaviour of the HLW cell head. These studies rely mainly on *in situ* experiments and numerical simulations. For example:

- the *in situ* (BHN) test monitoring the natural saturation of a clay core in direct contact with the clay rock, set up in a 75 cm-diameter borehole (a scale similar to that of the HLW cell head): it will provide evidence demonstrating (i) the installation of the clay material in the cell head and achievement of the specifications for density and for limiting the residual voids, (ii) the construction of a low-pH concrete containment wall;
- experimental work aimed at consolidating the chemical models of low-pH concretes and the processes of chemical interaction with natural and reworked clays, particularly on the basis of corrosion tests on ferrous metals (MCO tests) in the Underground Research Laboratory;
- work aimed at providing a detailed evaluation of the hydromechanical loading of the cell head, paying particular attention to the axial deformations of the clay material and the concrete containment wall.

3.4.4 Backfill

Backfill reduces as far as possible the (compressible) voids likely to be filled on rupture of the liners: it limits the amount of additional damage done to the clay rock around the drifts of the underground facility and the surface-to-bottom connections and helps to preserve the favourable characteristics of the Callovo-Oxfordian clay rock.

The backfill will consist of the excavated rock stored in muck piles awaiting reuse, possibly with the addition of additives.

To keep mechanical deformation of the clay rock to a minimum, the aim is to achieve a level of compressibility that is as low as possible and a dry density that is as high as possible. The backfilling will be done so as to fill the whole volume, and particularly the void at the top.

3.4.4.1 Previously tested installation

From the technological point of view of installation of the clay rock-based backfills, at this stage Andra has data from the surface backfilling demonstrator at Richwiller. The main objectives of this demonstrator were to assess the characteristics of the backfill *in situ* and in a laboratory, after two years' saturation, and compare them with the characteristics known from laboratory formulation tests and checks during the backfilling work.

Backfills consisting of clay rock only and of clay rock mixed with sand have been tested by means of a series of tests used to characterise them from a geotechnical, hydraulic and mechanical point of view.

[79] If it is necessary to introduce a mechanical containment system behind the clay filler material (in the case of a swelling clay), the use of cementitious materials will be kept to a minimum and they will only be used with "low pH" formulations (producing fluids with pH ≤ 11).

Observations during the dismantling of the demonstrator showed the feasibility of using backfills consisting of clay rock only or clay rock mixed with sand. The following aspects were noted:

- during backfilling works: good contact between the backfill and the walls everywhere except at the top, where voids of a few centimetres at most were observed, both for clay rock mixed with sand and for clay rock on its own;
- after two years' saturation: the voids at the top were of the same orders of magnitude as they had been initially, showing that the backfill was affected very little by settling or swelling in the saturation phase.

The tests performed on a laboratory sample showed that achieving high dry densities for placement was possible with both types of backfill (up to 2 g/cm³), while the *in situ* tests using a dynamic penetrometer showed that the compactness of the backfill was maintained after installation and two years' saturation, though with a tendency to diminish in the upper part of the demonstrator and with slightly higher values in the backfill consisting of clay rock mixed with sand.

3.4.4.2 Slow structural evolution favourable to healing of the clay rock in the wall

The mechanical evolution of the backfilled structures is mainly controlled in the medium term by the time-dependent deformation of the geological formation. During the first few decades and up to a century after closure of the drift, resaturation of the clay rock gradually reactivates the time-dependent behaviour of the clay rock. As long as the liner ensures the structure to be maintained mechanically, the damaged clay rock zone continues to "consolidate" as it did in the operational phase, through mechanical closure of the fractures. In parallel with the convergence of the clay rock, the stresses on the liner continue to increase until it ruptures. This rupture is held in by the backfill, which prevents or severely restricts the unloading of the fracture zone.

Due to the low time-dependent deformation kinetics of the clay rock ($<10^{-11}$ s^{-1}) and the gradual rupture of the liner in blocks, the evolution of the drifts is slow (i.e. almost static), in particular with small amounts of deformation in the clay rock. Combined with the compaction of the fracture zone, this should lead to the restoration of low permeability in the connected fracture zone (ZFC) through mechanical closure and self-sealing.

Uncertainties remain over the mechanical evolution of the backfilled drifts, linked to (i) the mechanical properties of the clay rock, particularly its time-dependent behaviour, (ii) coupling with the hydraulic-gas transient (an increase in gas pressure in the backfill leads to a reduction in water saturation, which could cause detrimental mechanical rigidification and settling; this should be limited in amplitude and space and should be transitory), (iii) the effect on the backfill material of alkaline disturbance due to the chemical degradation of the concrete.

VOLUME III – SAFETY ASSESSMENT

1

Management of Risks and Uncertainties

1.1 Introduction 197
1.2 Identification and management of uncertainties based on input data: emplaced waste packages and the geological medium 198
1.3 Intrinsic characteristics of structural components of the repository 208
1.4 Phenomena governing internal changes in the repository 212
1.5 Technological uncertainties 227
1.6 Risks and uncertainties relating to future events of external origin 229
1.7 List of scenarios adopted 230

1.1 Introduction

The following paragraphs describe the results of the post-closure qualitative safety analysis[80]. The methods adopted to manage risks and uncertainties in the post-closure phase aim at:

- repository design choices based on measures that make the system less sensitive to uncertainties. The aim of the analysis is therefore to identify any limits; it then focuses on remaining uncertainties after description of design measures;
- assumptions that integrate the uncertainty in the repository safety assessment in the following scenarios: 1) in the normal evolution scenario (NES), either in the reference situation or "bounding" situation, 2) in an altered evolution scenario (AES) and 3) in a "What-if" scenario, depending on the likelihood of the event taken into account.

The uncertainties will continue to be reduced with a view to submitting the construction licence application. The main paths for improvement (e.g. via research and experiments) and if necessary, the phenomena to be monitored during the operating phase are mentioned.

The analysis covers the types of uncertainties mentioned in the geological repository safety guide (1) and specifically:

- uncertainties concerning input data for the repository project (particularly data relating to disposal packages, including the inventory and release models, the site location (host formation, surrounding formations and surface environment), the underground facility at completion and its position in the host formation);
- uncertainties concerning the intrinsic characteristics of engineered components (which excludes disposal packages referred to in Chapter II) in the repository system;
- uncertainties concerning the processes that govern changes in the repository and geological environment (nature, extension, duration, representation model, model parameters, effects on component functions, in particular with respect to release and migration of radionuclides and chemical elements);
- technological uncertainties (in terms of the construction and/or installation of engineered components);

The analysis also takes into account the following internal or external events:

- risks and uncertainties related to future events of natural origin (climate-related events, internal geodynamics, etc.) or associated with human activities (inadvertent human intrusions, anthropic effects on climate and the environment);
- the seismic risk;
- the criticality risk.

[80] The qualitative analysis is conducted according to the procedures described in Volume I. It systematically identifies and assesses the risks and uncertainties for each individual component with respect to their safety functions and proposes management methods.

1.2 Identification and management of uncertainties based on input data: emplaced waste packages and the geological medium

1.2.1 Radiological inventory and its distribution in the architecture on completion

As indicated in Volume II, Section 2.2, the radiological inventory is an important input for quantifying the indicators of scenarios selected for the post-closure safety assessment. The aforementioned section presents the methodology used to establish a *radiological inventory* that takes into account the level of available knowledge for each of the waste package families.

The distribution of package families in the disposal cells, which depends on shipment schedules, will determine how the radiological inventory is arranged in the architecture[81].

At this stage, for the post-closure safety assessment, provisional shipment schedules should not be anticipated over a one-hundred year period.

Thus, an activity distribution method that does not take into account shipment schedules and enables quantitative "bounding" assessments of the impacts associated with the scenarios is applied. It distinguishes between the ILW-LL and HLW disposal sections[82].

1.2.1.1 Methods for determining the distribution of ILW-LL package types "independently of shipment schedules"

Methodology

The "bounding" approach adopted consists in considering a method for filling the ILW-LL cells by decreasing level of activities from the entrance towards the back of the disposal section:

- in the normal evolution scenario, safety functions are mainly provided by the Callovo-Oxfordian and the lengths of the disposal cells. The distribution of the radiological inventory has little effect on the flow of radionuclides and toxic elements that may pass through the Callovo-Oxfordian, the main migration pathway;
- for some malfunction scenarios, the transfer pathway along the drifts to the surface-bottom connections could become "more important". The quantities of radionuclides and toxic elements that could migrate via this pathway partially depend on the distance from the disposal cells: the inventories closest to the entrance to the ILW-LL disposal section are mobilised first.

The methodology for defining the distribution of the inventory includes two steps:

- waste package families are classified by decreasing level of linear activity (Bq per linear metre of the disposal cell), while taking into account the disposal methods (geometry of the waste packages, number of rows and stacks);
- disposal cells are gradually filled from the entrance to the back of the disposal section, in compliance with physicochemical co-disposal and geometric co-disposal rules (operating

[81] For any given waste package, the disposal cell determines:
- The vertical thickness of undisturbed Callovo-Oxfordian host rock available to restrict and delay the migration of radionuclides and toxic elements, based on the available Callovo-Oxfordian thickness, the excavation damaged zone thickness and the vertical position of the disposal cell;
- the distances along the drifts, between the disposal cell exit and the upper surrounding rock formation, for radionuclides and toxic elements that may circulate along this pathway in the event of sealing malfunction situations.

[82] In the ILW-LL disposal section, the substantial number of waste families to be disposed of determines a large number of possible filling combinations, even taking into account the rules governing the options for physicochemical co-disposal of different waste families; and the options for geometric co-disposal of different types of packages. In the HLW sections, there are far fewer possible filling combinations due to the limited number of waste families and the residual heat of packages. It is this residual heat that pre-determines the distance between the centrelines of successive HLW cells and, therefore, the most suitable disposal section layout design for each waste family. In this case, redistribution is limited to positioning waste families with the highest level of activity near the entrance of each of the sub-sections defined by specific distances between centrelines.

requirements); for cells no. 1 to 4 only (related to the industrial pilot phase) the shipment forecasts of the PIGD are taken into account.

Figure 1.2-1 shows the distribution of activity levels resulting from the implementation of this methodology.

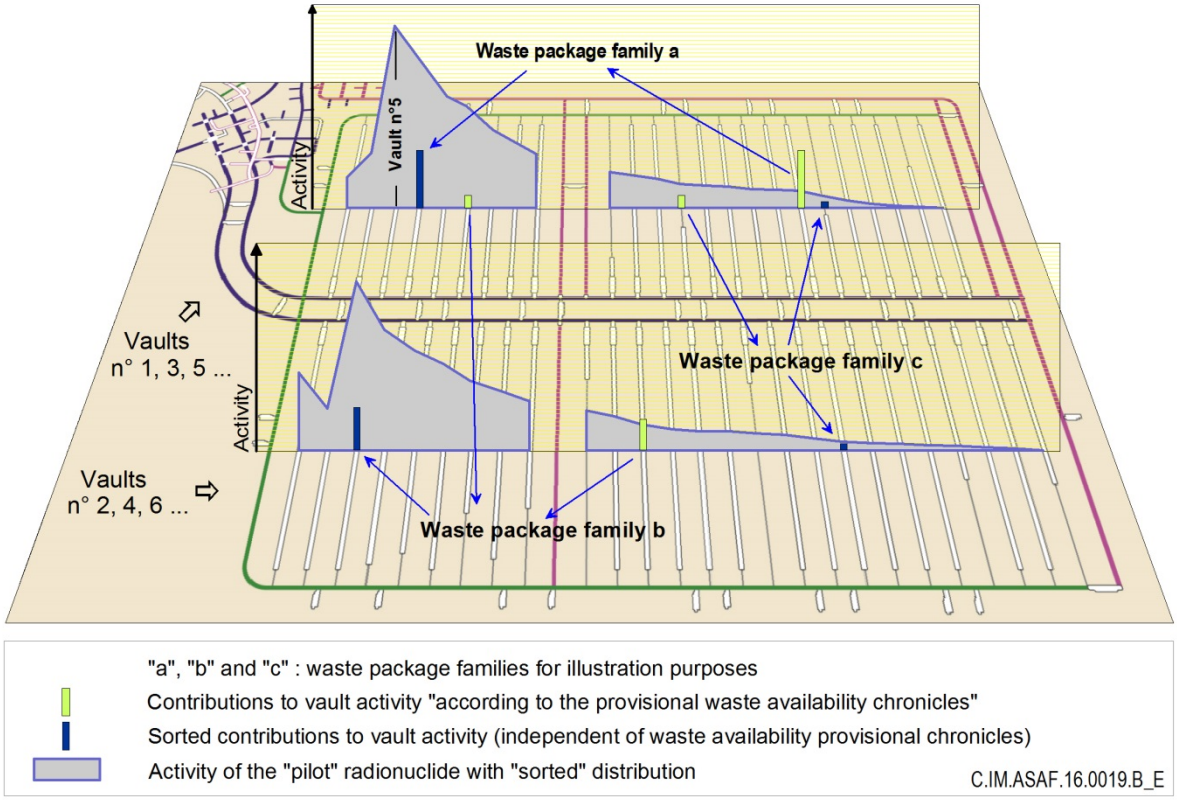


Figure 1.2-1: Schematic diagram of ILW-LL waste package distribution "independent of provisional shipment schedules".

Selection of the "pilot" radionuclide for distribution of ILW-LL waste package families

The result of ILW-LL package type redistribution depends on the radionuclide selected as the "pilot" among the 144 radionuclides in the inventory.

An exploratory analysis based on a scenario involving a malfunction of the closure systems has shown that a distribution of waste package families based on their iodine-129 activity would give the highest potential overall impact. This radionuclide was therefore adopted as the "pilot" for the distribution.

Table 1.2-1 shows the result of this distribution for the first ten ILW-LL cells.

For iodine, the first ten ILW-LL disposal cells account for more than 80% of the ILW-LL iodine-129 inventory[83]. This figure is close to 100% for the first twenty cells.

[83] It should be noted that for chlorine-36 (a mobile radionuclide with a shorter radioactive half-life than iodine-129), the activity of the first 10 disposal cells accounts for approximately 70% of the activity and that of the first 20 cells accounts for approximately 85%.

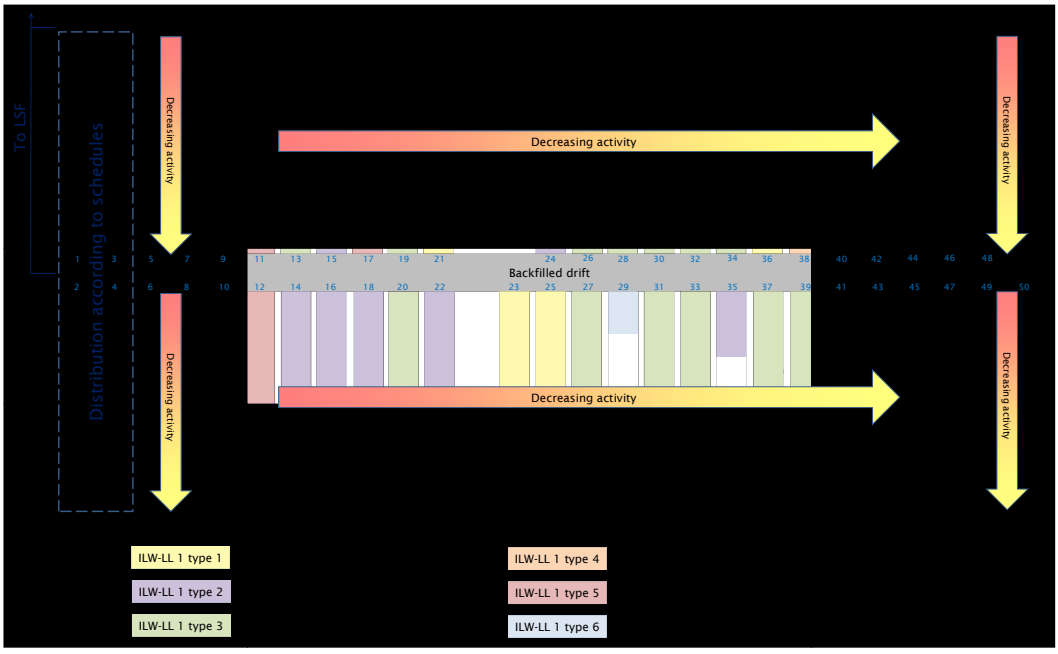
Table 1.2-1: Results from the methodology used to define the distribution of ILW-LL waste package types in the disposal section using iodine-29 for the first ten ILW-LL disposal cells (located in the west cell of the section)

ILW-LL cells from the entrance to the section		Iodine-129 "Pilot" radionuclide as a% of total activity in the section 1.9 x 10^{12} Bq
No. 1	Cells with "frozen" content (industrial pilot phase)	0.0
No.2		5.2
No.3		0.6
No.4		2.0
No.5	Cells with "redistributed" content	34.7
No.6		18.4
No.7		5.9
No.8		5.2
No.9		4.7
No.10		4.4
Total for first 10 cells		81.0
Total for first 20 cells		99.7

Distribution of the inventory within the ILW-LL disposal section

On the basis of preparatory calculations, ILW-LL waste package types are distributed (i) based on decreasing iodine-129 activity from the entrance to the back of the section, and (ii) with decreasing activity from north to south of each disposal cell in order to provide a conservative assessment with respect to transfer via the "structures" pathway.

No redistribution is performed for the waste package families disposed of during the first phase of operations (ILW-LL cells no. 1 to 4).



CG.IM.AEAP.15.0067.A

Figure 1.2-2: Radiological inventory distribution adopted for the ILW-LL disposal section for quantitative assessments of the normal evolution and altered evolution scenarios

Specific case of human intrusion scenarios

In human intrusion scenarios where a local "short-circuit" of the Callovo-Oxfordian vertical thicknesses is considered, less mobile and shorter-lived radionuclides may be mobilised.

The decision has therefore been made to superimpose distributions governed by each of the 144 radionuclides, although physically impossible simultaneously, and assume intrusive drilling into cell no. 5[84].

Method for defining the distribution of ILW-LL package families – Case of direct waste package disposal without use of a disposal container

For some ILW-LL waste families , disposal of waste packages without use of a disposal container is envisaged[85]. This leads to a higher number of packages in some disposal cells and fewer cells overall.

The distribution methodology for ILW-LL families "independently of shipment schedules" is also suitable for assessing the impact of the activity densification generated. However, in a conservative approach, redistribution will be considered from the first cell in this case[86].

At the current stage of assessment of this optimisation option, the inventory densification factor in ILW-LL cells concerned is between 2.5 and 3.5.

1.2.1.2 Methods for defining the distribution of HLW package types

For the HLW1-HLW2 disposal sections, six sub-sections characterised by specific distances between HLW cell centrelines are defined based on heat and package availability assumptions adopted at this stage.

In a conservative approach, for sub-sections with several package families, the decision was made to redistribute families by decreasing level of idodine-129 activity from the entrance of the sub-section (i.e. near connecting drifts) to the back. The following figures show the distribution of package families within the HLW1/HLW2 and HLW0 sections respectively.

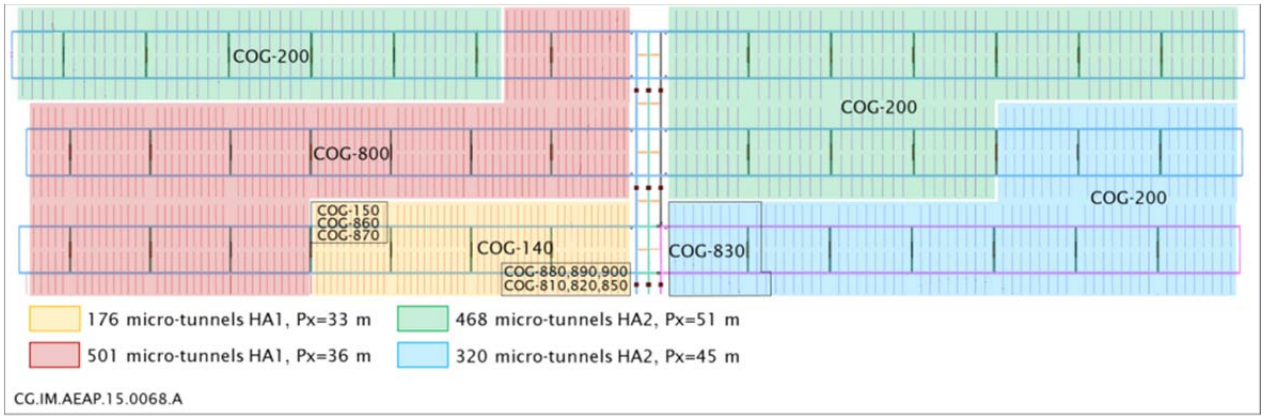


Figure 1.2-3: Distribution of waste package families adopted within the HLW1-HLW2 section and geometric data selected as input assumptions for calculations at this stage.

[84] The first four cells are still considered with a distribution based on the planned schedule, in accordance with the industrial pilot phase

[85] This disposal method has not undergone detailed analysis. This will be done before submission of the construction license application

[86] Direct disposal without use of a disposal container is planned for waste packages C1PG, CSD-C, CBFC2, from commissioning onwards, once Cigeo is authorised to operate (See DOS-Expl).

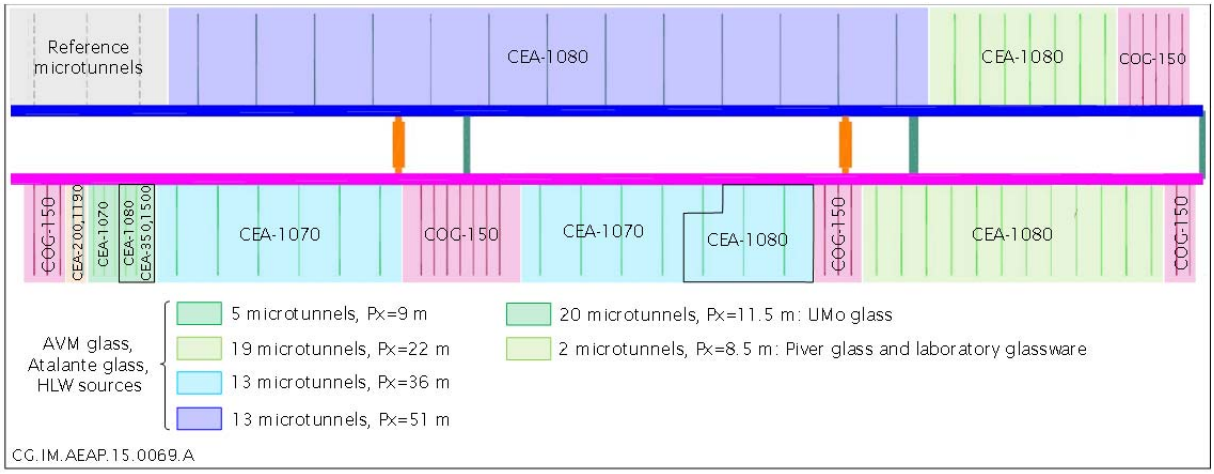


Figure 1.2-4: Distribution of waste package families within disposal section HLW0 section and assumed geometric data adopted as assumptions for calculations at this stage.

1.2.2 Radionuclide and toxic element release models

Knowledge of the processes and representation models of radionuclide and toxic element releases have been consolidated for most packages adopted in the Cigeo inventory, in particular for vitrified waste. The main information has been included in Appendices 7 and 8.

The general criterion that should be used for choosing "package" release models for the safety assessment is as follows:

- if the level of knowledge is considered satisfactory and the remaining uncertainties are well-understood, the safety option is based on a "phenomenological" model adopted in the reference situation of the normal evolution scenario ;
- if current knowledge includes any considerable uncertainties, the safety option is based on a conservative model adopted in the bounding situation of the normal evolution scenario and, if necessary, in the altered evolution scenarios (AES) if the malfunction in question affects the environmental conditions around the waste package.

The release models adopted at this stage for the quantitative safety assessment are detailed in Volume II, Chapter 2.

1.2.3 Callovo-Oxfordian

In view of the characterisation research work carried out over the last 20 years, there is a high level of confidence concerning the characteristics of the Callovo-Oxfordian. Research has particularly focussed on characteristics that determine the capability of the Callovo-Oxfordian to confine radionuclides (and toxic elements) over the long term (e.g. depth, geometry, thickness, flow, transport and chemical retention characteristics) and that contribute to the post-closure safety functions.

This information has made it possible to represent the Callovo-Oxfordian with "phenomenological" parameter values in the reference situation, based on the approach described in Volume I and to propose conservative values for the "bounding" situation. Therefore the ranges of values obtained over the last several years concerning the flow, diffusion and retention characteristics of the Callovo-Oxfordian formation (water permeability, diffusion coefficients, porosities accessible to diffusion, partition coefficients (sorption and solubilities) provide:

- defined reference values that take into consideration the conditions deemed the most

representative;
- defined minimum and maximum values.

In order to meet the request of ASN, vertical discontinuities (flexures and faults) which would not otherwise have been recognised and which could potentially be hydraulically active, will be taken into account in a conventional "What-if" scenario that will be described in greater detail along with its impact evaluation with a view to the submission of the construction license application.

As mentioned in Volume II, the Callovo-Oxfordian formation has been the subject of significant characterisation work at the scale of the zone of interest for detailed survey and over its entire thickness via:

- bore-hole measurement campaigns and core samples on the transposition zone;
- the 3D seismic campaign conducted on the zone of interest for detailed survey (ZIRA);
- experiments conducted in the Meuse/Haute Marne Underground Research Laboratory.

The geometry and structure of the Callovo-Oxfordian are also well-characterised (see Volume II) and the remaining uncertainties concerning the position of the top and bottom of the formation have been quantified.

All the bore-hole and seismic investigations carried out show that there are no fault throws greater than 2 metres in the zone of interest for detailed survey. In particular, the 3D seismic results in the zone of interest for detailed survey show the absence of faults of levelness on a ten-metre scale, with throws greater than two meters in the Callovo-Oxfordian. No structures likely to play a hydraulic role were observed.

The knowledge acquired from the survey programme confirm the lateral homogeneity of the formation and its large thickness (at least 130 metres) in the zone of interest for detailed survey. The design of the Cigeo underground architecture (for example, the length of ILW-LL cells) takes these data into account in order to preserve the minimum undisturbed thickness while taking into account the inclination of the formation and the variation in its thickness in the zone of interest for detailed survey.

The knowledge that has been acquired provides a considerable and reliable set of input data at different scales of the Callovo-Oxfordian formation for quantitative post-closure safety assessments.

1.2.4 Surrounding rock formations around the Callovo-Oxfordian formation

The surrounding rock formations around the Callovo-Oxfordian do not have a safety function. However they are a transfer pathway for radionuclides leaving the Callovo-Oxfordian towards outlets and are therefore represented in the quantitative safety assessments.

At this stage, the analysis distinguishes the limestone levels (where aquifers are located) and the marl levels, and is based on the best available knowledge[87]. Information on diffusion and retention properties in the marl levels provided by the characterisation work made it possible to take them into account in the reference situation of the normal evolution scenario. However, no retention properties are assigned to the limestone levels.

In order to cover the residual uncertainties related to the hydrodispersive properties of the marl levels and their lateral variability, they are represented taking into account the absence of retention in the bounding situation, as for limestone levels.

Overlying formations may be subject to erosion from the internal geodynamic evolution of the site and climate changes. Since 2005, underground work has helped to consolidate and clarify erosion processes, particularly between plateaus and valleys. The internal geodynamics of the site were also

[87] Borehole drilling campaigns have provided information on the following characteristics of surrounding formations (see Volume 1, Chapter 1):
- permeability, porosity, transport (diffusion coefficient) and chemical retention via sorption for marl levels;
- flow directions and rates, in connection with the identification of current and long-term potential natural outlets.

detailed. Coupling with potential bounding climatic changes shows that there are no significant erosion processes within the next million years, or at least, none that would start before 750,000 years from now.

The influence of these changes (even minimal) on flow over a one-million year period were evaluated via simulations integrating potential climate change cycles (including those related to anthropic effects) and surface erosion (including internal geodynamic evolution).

The hydrogeological model of the sector at present and for the next million years, coupled with geodynamic evolution models adopted as bounding situations was used to evaluate the changes to the hydraulic head fields in the Dogger and Oxfordian and changes to the vertical hydraulic head gradient field in the Callovo-Oxfordian (determined by the hydraulic heads of the Dogger and Oxfordian limestone) at present and over the next million years, in particular for the zone of interest for detailed survey. The results show that the hydrogeology of the sector (Dogger and Oxfordian limestone) does not present any significant changes between now and the next million years in terms of flow directions or flow rate.

Therefore transport simulations for particles introduced into the permeable horizons of the Dogger and Oxfordian limestone in the zone of interest and detailed survey (ZIRA) used to assess potential current and future trajectories of radionuclides do not show any significant changes. The main characteristics are:

- a natural outlet from the Dogger, located approximately 35 km south of the ZIRA, corresponding to long streamlines of approximately 60 km, which first head west, then south after crossing the fracture zone in the Poisson sector;
- a flow field heading north for the Oxfordian limestone, which means that there is no natural outlet around the zone of interest and detailed survey.

The consolidation and precision of assessments of climate-related, geodynamic and hydrogeological changes to the geological medium in the transition zone (TZ) and especially the ZIRA since 2005 underline the (relative) stability of the geological medium over one million years in particular. Consequently, the Callovo-Oxfordian is considered as a stable medium over a one-million year period and in turn, its characteristics will remain stable (besides transient or localised near-field effects related to disposal).

> The fact that there are no significant changes to flow in the Oxfordian and Dogger between now and the next million years means that the consolidated hydrogeological model can be considered for the entire assessment period, without distinction between now and the long term.
>
> In the reference situation of the normal evolution scenario, the hydraulic head differences between the various geological formations are based on the results from hydrogeological modelling.
>
> In the "bounding" situation, a conventional choice has been made to use hydraulic flows ascending or descending in the Callovo-Oxfordian resulting from the maximum uniform and constant hydraulic head difference over time in order to maximise the effects on the transfer of radionuclides and toxic elements into the top and bottom of the Callovo-Oxfordian formation.

1.2.5 Surface environment: the biosphere

In accordance with the approach presented in Volume I, the standard biospheres adopted for the assessments are based on "conventional" options. The main uncertainties are covered in the choice of the various components of the biosphere:

- choice of standard biospheres to be considered;
- choice of outlets;
- choice of hypothetical reference groups, age groups and their diet according to their activities[88] ;
- choice of transfer models.

The choices associated with each of these components are presented below.

1.2.5.1 Choice of standard biospheres

In accordance with the Safety Guidelines for the Final Disposal of Radioactive Waste in a Deep Geological Formation (ASN 2008) and the approach presented in Volume I, to cover the uncertainties related to long-term changes in the biosphere, different standard biospheres need to be considered in order to conduct radiological and chemical impact assessments. Their choice is based on simulations that take into account the following two climate and geomorphological changes (see Volume II):

- natural changes (climate not altered by human activities);
- changes from anthropic effects (climate altered by greenhouse gases).

Five standard biospheres are identified as plausible in the long term[89]. They are considered as equiprobable.

To evaluate the dose impacts within the context of post-closure quantitative impact assessments, three standard biospheres have been adopted:

- a temperate standard biosphere;
- a boreal standard biosphere;
- a hot and humid subtropical climate standard biosphere.

The "temperate" and "hot and humid subtropical" standard biospheres considered as bounding were covered during the Safety Options Report stage.

Permafrost prevents water from penetrating underground. Human activities are therefore only associated with the use of surface water. The tundra standard biosphere has been ruled out due to the absence of a natural outlet via rivers.

The boreal standard biosphere will be examined for the submission of the construction license application.

1.2.5.2 Choice of outlets

<u>Dogger outlet</u>

Knowledge and associated simulations make it possible to select the natural outlet in the Dogger located approximately 35 km south of the zone of interest and detailed survey.

From the zone of interest and detailed survey, the Bathonian and Pearly Slab unit flows are west-north-west, at an average pore flow rate of approximately 5 km per 100,000 years, then heading south after crossing the diffuse fracture zone. The streamlines reach their natural outlet after approximately 600,000 years of transfer time in the Dogger. Little change in the Dogger characteristics is expected over the next million years (see Volume II, Chapter 1) regardless of the climate scenario.

[88] This component includes the choice of animal and plant products consumed by the hypothetical group.

[89] The standard biospheres considered as plausible in the long term are (i) a temperate standard biosphere, (ii)a boreal standard biosphere, (iii) a tundra standard biosphere, (iv) a hot subtropical climate standard biosphere with a rainy winter season which would only exist over the next 50,000 years and, (v) a hot and humid subtropical climate standard biosphere that could exist for up to 600,000 years.

According to the biosphere approach that favours outlets that have been identified today or foreseen for the future based on hydrogeological models, or if necessary, the "conventional" outlet, acquired knowledge shows that:

- the natural Dogger outlet is quite far (35km) from Cigeo;
- there is a diffuse fracture zone along the trajectory towards the natural outlet that could potentially be an artificial outlet zone (via pumping);
- in the zone of interest and detailed survey, the Dogger is relatively unproductive and the water from it has chemical characteristics (salinity) that make it unfit for human and animal consumption compared to other available local sources, such as the Barrois.

These various elements have led to the choice of a conventional outlet with pumping in the diffuse fracture zone. In a bounding approach, the outlet is located before the diffuse fracture zone in order to capture as many radionuclides potentially released as possible and limit dilution.

The chemical characteristics of water from the Dogger, including their salinity and the low productivity of the Dogger in the ZIRA have excluded the option of pumping from the Dogger at the repository in the normal evolution scenario.

The conventional choice of a pumped outlet from the Dogger has been selected on the eastern edge of the diffuse fracture zone, as it is more productive and has lower salinity levels in the reference and bounding situation of the normal evolution scenario.

- ***In the Oxfordian limestone***

The hydrogeological model and particle transport simulations show:

- flows mainly oriented north-west with a steady and extremely slow mean pore flow rate over the next million years;
- trajectories from the zone of interest and detailed survey that do not head in the direction of the diffuse fracture zone, at the Marne faults (NW);
- the absence of a natural outlet from the Oxfordian limestone near the zone of interest and detailed survey, now or in the long term. The results from simulations show that a natural outlet could appear at the Ornain River, but at a later time, likely in over a million years.

Acquired knowledge indicates that the Oxfordian limestone is relatively unproductive in the TZ (and ZIRA); water flows slowly through it and offers limited consumption quality in terms of mineralisation in comparison with other water that is easily available elsewhere, particularly surface water in the Barrois limestone. The results from erosion assessments of overlying formations of the Callovo-Oxfordian over the next million years shows that:

- in the case of natural climate change, there is minimal erosion of the Barrois limestone. This limestone is a potential source of water and would still be present in the zone of interest and detailed survey over the next million years;
- in the case of disturbed climate change (taking into account global warming), there is more significant erosion of the Barrois limestone. However, it would remain locally present in the ZIRA, and would still be a potential water resource.

Borehole drilling for pumping in the Oxfordian limestone in the zone of interest and detailed survey (i.e. at the Cigeo location) is highly unlikely due to the possibility of more productive water source in the Barrois.

In view of the low productivity of the Oxfordian porous horizons (much less productive than the Barrois), the poor quality of their water compared with other water sources, and their depth, water supply pumping for human and animal consumption in the Oxfordian limestone around the repository has been ruled out.

By convention, for its impact assessment, Andra has selected a pumped outlet in the Barrois after ascending vertical transfer of the few radionuclides and toxic elements that would reach the overlying formations.

1.2.5.3 Choice of hypothetical reference groups

To evaluate the impact on humans, in accordance with the biosphere approach described in Appendix 1, Andra has adopted habits and assumptions corresponding to those currently observed for each of the standard biospheres selected and associated hypothetical reference groups adopted.

At this stage the hypothetical reference groups have been selected based on the lifestyles of populations currently living in the Meuse/Haute-Marne region for the temperate standard biosphere and a biosphere similar to the hot standard biosphere and the possible use of the potential outlets selected[90].

Several hypothetical reference groups have been identified for each of the temperate and hot standard biospheres, given the potentialities of the selected outlets (see Table 2.4-5 and Table 2.4-6 in Appendix 1). The diets are based on:

- the survey conducted in the Meuse/Haute-Marne region for the temperate standard biosphere;
- surveys conducted for a biosphere similar to the selected hot and humid tropical biosphere (particularly in Spain).

For the impact assessments, the multi-activity hypothetical reference group exposed to all transfer pathways was selected.

Assessments were conducted while taking into account:

- for the Barrois outlet, a multi-activity hypothetical reference group with irrigation of cereal crops;
- for the Dogger outlet, a multi-activity hypothetical reference group without irrigation of cereal crops.

To take into account uncertainties related to the level of self-sufficiency, the assumption was made that the multi-activity hypothetical reference group consumes all its own self-sufficiently produced products.

The exposure pathways include exposure via ingestion from consuming various self-

[90] Hypothetical reference groups have been selected based on: (i) the description of all the characteristics of the components of the type of biosphere adopted (climate, vegetation, fauna, soil, geomorphology, geology, hydrology, hydrogeology and human activities) and (ii) the potential use of the environment for each type of biosphere adopted, including the characteristics of the selected outlet and the potential human activities from using the outlet.

sufficiently produced plant and animal products and via inhalation and external exposure from outdoor activities.

All the identified hypothetical reference groups will be studied in view of the construction licence application.

1.2.5.4 Choice of transfer models in the biosphere

Radionuclide or toxic element transfer to humans is modelled via the food chain, starting from the selected outlets.

In accordance with the approach, transfer quantification is based on the following models:

- for ^{36}Cl, ^{3}H, and ^{14}C, a specific transfer model based on isotopic dilution.
- for all radionuclides, except chlorine-36, hydrogen-3 and carbon-14, a compartmental model using transfer factors between compartments at equilibrium.

1.3 Intrinsic characteristics of structural components of the repository

1.3.1 Characteristics of clay-based structures

The structures in question are seals made up of a clay core (see Volume II). The mineral composition of the clay material has not yet been identified[91].

Andra has acquired a considerable amount of knowledge concerning clay engineered materials, in particular swelling clay-based materials, including information on their behaviour and how to use them, obtained from numerous tests and models at scales of up to several metres. This knowledge shows that the clay core saturation permeability target of 10^{-11} m/s can be reached with different types of clay and corresponds to a wide range of dry densities and therefore a variety of shaping and setting methods.

In the normal evolution scenario, the saturation water permeability of the clay core has been adopted to correspond to the targeted hydraulic performance of seals.

The presence of clay in the seal core represents a characteristic that is favourable to radionuclide and toxic element retention and can therefore contribute to the safety function "Delay and mitigate the flow of radionuclides released into the structures", even though it is not a requirement. However, diffusion and retention properties have been adopted in the reference situation of the normal evolution scenario. No retention properties have been adopted in the bounding situation.

The permeability value set in the requirements has been adopted for the situations of the normal evolution scenario (reference and bounding situations).

A situation where the core does not reach the desired hydraulic performance is considered highly unlikely. This type of malfunction is therefore only considered within the context of a "What-if" scenario.

[91] Several types of swelling clays and in particular MX80 bentonite (sodium montmorillonite) have been studied for their physicochemical characteristics and implementation (technology). The performance characteristics associated with their use for the clay core have been assessed.

1.3.2 Intrinsic characteristics of concrete-based structures

Concrete is used as the liner and roof supports of repository structures (other than HLW disposal cells), containment walls of seals (depending on the seal core solutions adopted), and if necessary, to be used as a filler material for structures (such as the shaft station).

The concrete[92] used for the ILW-LL cell liner offers cement conditions that are favourable to low solubility of most radionuclides. This helps to restrict the release of radionuclides and toxic elements and immobilise them in the repository.

Over time, the liner-roof support concrete will deteriorate. It may undergo (i) mechanical stress eventually leading to fracturing and (ii) chemical stress, especially with water from the Callovo-Oxfordian.

1.3.2.1 Hydraulic and transport characteristics of concrete structures

Due to mechanical changes to concrete over the long term, leading to cracking and fracturing in most structures, the following assumption has been adopted for the reference and bounding situations of the normal evolution scenario:

- conservative water permeability, equivalent to sand (concrete is represented as an equivalent continuous porous medium);
- the absence of diffusive transport properties in concrete components.

1.3.2.2 Retention characteristics in conventional concrete structures

The long-term behaviour of concrete, in particular its chemical degradation over time, is well-understood. Based on acquired knowledge, a "Sound-Degraded-Altered" concrete [93] alteration model has been proposed: liners/roof supports of drifts and ILW-LL cells will deteriorate from water-driven carbonation and hydrolysis processes when in contact with Callovo-Oxfordian water. More specifically, due to the oxidation of clay rock in close proximity to the structures during operation, this water will transiently be enriched initially with sodium, potassium, carbonates, chlorides and sulfates. Design measures will therefore be taken to prevent sulfate attack in concrete via a special formulation.

Given the limited circulation of water used in the repository as a result of the low permeability of the Callovo-Oxfordian and solute exchanges between the concrete and Callovo-Oxfordian water, governed by diffusion, the knowledge acquired on concrete degradation processes provides the following conclusions:

- the "neutralised" chemical state is not reached over the million-year period and the degradation condition of the liner concrete is "altered" at most;
- carbonation generally develops from the outside of the liner/roof support and its extension is limited in the cracks/fractures.

The remaining uncertainty mainly concerns the extension of different states of degradation over time and space[94].

The solid/solution partition coefficients (Kd) have been obtained for the majority of radionuclides and toxic elements for fresh to altered (via hydrolysis) CEM I and CEM V cement and have been compared with measurements on cement pure poles (e.g. C-S-H, Aft, portlandite, calcite). The values do not apply to low-pH cements since the residual uncertainties relate to differences in material compositions and the measurement protocols used.

---

[92] Conventional concrete formulations have been studied and characterised (in particular CEM I and CEM V). These types of cement have different physical and chemical properties, providing a wide field of possibilities in terms of targeted properties.

[93] The alteration model considers the Callovo-Oxfordian environment.

[94] Retention properties are used only in the liners/roof supports of ILW-LL cells due to the cement medium which they offer. By convention, no chemical retention properties (sorption, solubility) are considered for concrete structures other than the ILW-LL cells.

The values of solubility[95] limits are established for a fresh and an altered condition of the concrete via thermodynamic calculations at equilibrium, taking into account different compositions of water and cement solid phases.

Table 1.3-1: Methods for managing uncertainties related to the intrinsic characteristics of IWL-LL cell liners

ILW-LL cell liner (including the filler material giving the shape of the usable part)		
Function: Limit the release of radionuclides and toxic elements and immobilise them in the repository **Intrinsic characteristics:** Partition coefficients and solubility limit		
Uncertainties	**Methods for managing uncertainty**	
	Design options	**Scenario assumptions**
Spatio-temporal extension of degradation of concrete via hydrolysis	Resistance to sulfate attack via an appropriate formulation.	The entire concrete thickness is represented by a single zone for the entire assessment period with the least favourable performance between sound and degraded condition, which leads to the use, for each radionuclide, of the values of retention parameters from among the conservative values obtained via measurements, calculation or by comparison.
Chemical retention parameters (sorption and solubility)	Conventional concrete (portlandite cement)	Chemical retention adopted only for ILW-LL cell concrete structures (due to the cement medium which they offer). For each radionuclide, the least favourable values of retention and solubility parameters from among the conservative values obtained via measurement or analogies with other concrete, between the "sound" condition and "altered" condition are adopted. No retention or solubility limits are adopted for the other structures.

The remaining uncertainty concerning the extension of chemical degradation of ILW-LL cell liner/roof support concrete over time and space is taken into account by considering the least favourable retention and solubility values between "sound" concrete and "altered" concrete and applying homogeneously for all concrete and in a constant manner over time from closure of the repository onwards:

- In the reference situation, adopted values are phenomenological;
- In the bounding situation, adopted values are conservative.

In the absence of measurements or analogies with other chemical elements, no retention or solubility limit values are adopted for the relevant radionuclides and toxic elements.

1.3.2.3 Mechanical characteristics of seal containment walls

The long-term evolution of the mechanical characteristics of interfaces caused by the various chemical and mechanical degradations (chemical-mechanical coupling) is not yet fully quantified at this stage. The design of the containment walls (length, type of anchoring) with respect to mineralogical (i.e. physicochemical) characteristics of the clay core take this uncertainty into account.

Failure of the various seals due to a major shift of the containment walls under the potential pressure from the clay core is therefore considered as highly unlikely. It is covered by the seal malfunction "*What-if*" scenario, which considers failure of the clay core to swell or in general, specific mechanical characteristics due to the use of materials other than those that have been defined or an unforeseen phenomenological change (see *below*).

[95] In some cases, the value adopted is taken from a comparative analysis with other chemical elements when measurements are not available.

1.3.3 Characteristics of backfill materials

The drifts will be backfilled when the repository is closed in order to maintain the mechanical stability of the underground facility after closure, and in particular, to limit the extension of the damaged clay rock zone over time.

Once backfilled, because of their length and diameter, the drifts provide a porous medium which, even with high permeability, help slow down longitudinal advection within. They therefore facilitate the diffusive transfer of the radionuclides and toxic elements into the Callovo-Oxfordian, alongside transfer in the drifts and the decay of some radionuclides, when applicable[96].

Operating experience feedback on re-engineered porous materials, in particular clay materials, does not identify any elements that prevent the physicochemical characteristics of backfill from being achieved in order to meet the requirement of restricting the extension of the damaged clay rock zone around the repository.

It is considered that when the backfill is put in place, checks to ensure that drifts are properly backfilled will rule out the possibility of space at the top of the drift in the normal evolution scenario.

At this stage, it is assumed that the backfill will be fully or partially made up of excavated and reconditioned clay rock (for instance, via grinding and screening).

In view of the acquired experience feedback, the backfill is represented as an equivalent porous medium with homogeneous properties, including hydraulic properties that are considered as reasonably achievable. No retention performance characteristics (sorption and solubility) are taken into account.

[96] No chemical retention is required of the backfill material.

1.4 Phenomena governing internal changes in the repository

After closure, the Callovo-Oxfordian clay rock and the structural components may undergo physical and chemical changes, mostly as a result of thermal, hydraulic/gas, mechanical and/or chemical interactions between the repository and the Callovo-Oxfordian or between structural components. The following sections address the various phenomena, considering the initial condition when the repository is closed and subsequent long-term changes in its condition.

1.4.1 Mechanical disturbance to the clay rock around the repository structures

Relative to mechanical effects, repository construction and operation will lead to mechanical damage to the clay rock. This chapter addresses the mechanical response of the Callovo-Oxfordian formation first to excavation (initial damage), leading to mechanical damage to the clay rock, and then to the time-dependent behaviour of this damaged zone in contact with the various repository structures.

Reminder: the repository design is aimed at conserving the favourable properties of the Callovo-Oxfordian, especially with certain measures taken to limit its long-term damage (e.g. restricting the void fraction (empty spaces) in the disposal cells).

1.4.1.1 Mechanical damage to clay rock at the repository closure (initial condition)

The numerous measurements and experiments that have been performed in the Underground Research Laboratory provide a large corpus of knowledge on the characteristics of the mechanically damaged clay rock zone close to the structures (extension, structure and water-permeability), both in the clay unit in which the Cigeo underground facilities will be built and in the silty-carbonated unit (USC) in which the surface-bottom connection seals will be built. The mechanically damaged clay rock zone comprises (or is conceptualised as) one connected fracture zone (ZFC) and one discrete fracture zone (ZFC). The ZFC and ZFD are not observed in the Callovo-Oxfordian unit USC.

The broad mechanisms that govern the mechanical behaviour of the clay rock, particularly during excavation, have been identified and the major natural mechanical stresses in the Callovo-Oxfordian have been determined. This knowledge serves to assess the extension of the ZFC and ZFD based on the dimensions (i.e. diameter) of the structure, its orientation with respect to the natural horizontal major stress, and the unit of the Callovo-Oxfordian in which the structure is built.

The hydrodispersive characteristics are discussed below, taking account of the time-dependent behaviour. It should nonetheless be emphasised that hydraulic tests have been performed in the Underground Research Laboratory, which has enabled a range of initial water permeability values for both zones (ZFC and ZFD) to be calculated.

The extension of the connected fracture zone and of the discrete fracture zone is based on measurements taken in the Underground Research Laboratory for a range of very different structures (dimensions, excavation method, liner/ support method, orientation with respect to the direction of the main horizontal stresses). On the basis of this knowledge, the following has been established:

- a representation of the ZFC, taking into account the difference in mechanical behaviour between the USC and clay unit (UA);
- the geometry and extension of the ZFC and ZFD, proportional to the diameter of the excavated structure, and also based on the orientation of the structure with respect to the direction of the main horizontal stresses.

In a conservative approach, the maximum extent of damage generated by the conceptual model has been adopted.

1.4.1.2 Time-dependent mechanical behaviour of the damaged clay rock and water permeability

Throughout the operating period, the time-dependent behaviour of the clay rock will be controlled by the design of the liners and supports (or sleeves for the HLW cells). After closure, this behaviour will be controlled by the closure structures (backfill, seals, concrete in-fill) and by the specifications requiring the void fraction in the repository to be limited, especially in the disposal cells.

Observations in the Underground Research Laboratory and simulations have consolidated knowledge on the time-dependent behaviour of clay rock. In the Callovo-Oxfordian clay unit, the fracture self-sealing phenomenon, which is related to the presence of the swelling mineral smectite, was reported on different scales, particularly in the Underground Research Laboratory. In combination with the presence of the liner/roof support, and subsequently with the backfill after failure of the liner/roof support in the post-closure phase, and along with the limited void fraction in the disposal cells, all of which limit strain on the damaged zone, this self-sealing effect leads to hydraulic healing of fractures in the damaged zone, in particular in the connected fracture zone (ZFC).

Based on this knowledge, the self-sealing and hydraulic healing processes are taken into account in defining the post-closure hydrodispersive characteristics of the ZFC and ZFD. Knowledge acquired on the permeability of the ZFD shows that its permeability characteristics are close to those of undisturbed rock. The ZFD is therefore represented in the "bounding" situation.

The usable part of the ILW-LL cells contains residual voids. Failure of the ILW-LL cell liner could therefore lead to the development of voids due to deconfinement of the clay rock, therefore resulting in additional damage to the clay rock. Based on knowledge acquired on the mechanical behaviour of clay rock and design provisions aimed at limiting the voids within ILW-LL cells, analysis of potential clay rock deconfinement has led to the following measures:

- adopting the maximum extension of the ZFD as the extension of the deconfined zone at the usable part of the ILW-LL cells;
- representing the full thickness of this "extended" ZFD with hydraulic and diffusive transport properties of the ZFC;
- considering the retention properties (sorption and solubility) of this "extended" ZFD to be identical to those of the undisturbed Callovo-Oxfordian formation.

In order to cover remaining uncertainty concerning the long-term behaviour of the mechanically damaged clay rock close to the repository, the following conservative choices have been made for the normal evolution scenario:

- the connected fracture zone (ZFC) in the clay unit, except at the zones where the liner is removed for the seals, shall be considered from the start of the post-closure period and maintained throughout the duration (reference and bounding situations);
- the discrete facture zone (ZFD) shall only be represented in the "bounding" situation.

The values for hydraulic characteristics include the hydraulic healing process, leading to adoption of the following assumptions:

- in the reference situation of the normal evolution scenario, water-permeability corresponding to that found at the zones where the liner is removed for the seals (10^{-11} m/s with hydraulic healing), downgraded by two orders of magnitude in the ZFC;
- in the "bounding" situation of the normal evolution scenario, water-permeability corresponding to that found at the zones where the liner is removed for the seals (10^{-11} m/s with hydraulic healing), downgraded by three orders of magnitude in the ZFC, and a conservative water-permeability value corresponding to the highest value measured in the Underground Research Laboratory for the ZFD (just after excavation).

These values are applied for the clay rock in contact with the disposal structures (back-filled drifts, disposal cells, back-filled parts of the surface-bottom connections), except those parts in contact with the clay seal cores.

In a conservative approach, the case of potential unfavourable evolution of the mechanically damaged clay rock at the seal locations that could lead to deteriorated seal performance is considered as part of a closure structure malfunction altered evolution scenario (AES).

Transport characteristics of the ZFC and ZFD (excluding thermal or chemical stress)

1.4.1.3 Transport characteristics of the ZFC and ZFD (excluding thermal or chemical stress)

- ***Diffusive transport properties (De, ω_{acc})***

Knowledge of diffusive transport properties within fractured clay rock, acquired in samples with calibrated fractures, shows that the fractures have a limited influence on diffusion-based transport characteristics.

The research has led to definition of corrective factors that can be applied to the diffusion parameters measured in the undisturbed Callovo-Oxfordian to give values for the connected fracture zone.

- ***Chemical retention properties (sorption)***

The solid-solution partition coefficients (Kd) are determined independently of the state of clay rock consolidation. Retention measurements are obtained via "batch" system experiments on crushed samples. Research has demonstrated that these measurements are applicable to undisturbed clay rock.

On the basis of this knowledge, and in order to cover any effects of oxidising disturbance, sorption in the connected fracture zone (ZFC) is represented by solid/liquid partition coefficients corresponding to the lower limit of Kd applicable to the undisturbed Callovo-Oxfordian.

For the ZFD, in particular because the fractures are not connected, the Kd values in the undisturbed Callovo-Oxfordian clay rock are applied.

- ***Solubility limits***

Solubility values are available for the undisturbed Callovo-Oxfordian clay rock. The connected fracture zone may be affected by an oxidising disturbance during the operating period. Conservative solubility values, corresponding to the upper limit of values for the Callovo-Oxfordian clay rock, have been adopted for the connected fracture zone in order to take into account any effects of this disturbance on solubility.

This oxidisation process does not affect the ZFD. The solubility limits used are those obtained for the undisturbed Callovo-Oxfordian clay rock.

1.4.1.4 Mechanical behaviour of clay rock in contact with the clay cores of drift seals

For the record, the assessment of the "large-scale" permeability of the seal takes into account the permeability of the clay core, the ZFC, the ZFD and portions of the liner that remain in place.

Knowledge acquired shows that no effect is expected from the load on the clay core due to the time-dependent behaviour of the Callovo-Oxfordian clay rock. The mechanical characteristics of the clay core contribute to limiting any evolution in the damaged zone and promoting hydraulic healing of the connected fracture zone.

A clay core malfunction related to an unexpected change in its mechanical loading is considered to be highly unlikely. Failure of the seal clay core to swell is therefore considered to be one of the "*What-if*" scenarios included by convention.

Current knowledge allows the hydraulic healing process to be taken into account in the normal evolution scenario, meaning that at the zones where the liner is removed:

- in the reference situation of the normal evolution scenario, water-permeability of 10^{-11} m/s is considered in the connected fracture zone (ZFC), which corresponds to "effective" hydraulic healing;
- in the bounding situation of the normal evolution scenario , water-permeability in the ZFC is considered, by convention, to be downgraded by one order of magnitude compared to the reference situation, and hydraulic healing is not considered in the ZFD.

The case of deteriorated hydraulic healing in the clay rock at the seal cores is covered by the altered evolution scenario, which considers a closure structure malfunction via the interface. Under this scenario, it is assumed that the hydraulic healing process is deteriorated, which means the water-permeability of the ZFC at the interface with the zones where the liner is removed is two orders of magnitude higher than the permeability considered in the bounding situation of the normal evolution scenario.

Unexpected evolution in the clay core is considered to be very unlikely and has been considered in a "*What-If*" scenario (e.g. conventional choice of lack of swelling of the seal clay core).

1.4.1.5 Mechanical behaviour of clay rock in contact with the clay cores of the surface-bottom connection seals

In the Underground Research Laboratory, the ZFC and ZFD are not observed in the USC unit of the Callovo-Oxfordian. In view of the mechanical processes responsible for excavation damage, this absence is in line with the mechanical characteristics of the clay rock in the USC unit, which is much stronger than the clay rock in the UA clay unit.

At this stage[97], a situation that considers the formation over time of a connected[98] fracture zone that is longitudinally continuous at the interface along the surface-bottom connection seal clay core cannot be totally ruled out. However, this situation is deemed to be highly unlikely, and is covered by the altered evolution scenarios involving malfunctions of the surface-bottom connection seal via the interface.

On the basis of knowledge acquired on the Callovo-Oxfordian, in particular observations conducted in the Underground Research Laboratory, the formation of a longitudinally continuous ZFC in the clay rock of the USC is deemed to be highly unlikely.

Andra therefore classifies the surface-bottom connection seal malfunctions via the interface in the category of altered evolution scenarios (see Volume III, Chapter 3.1).

1.4.1.6 Mechanical behaviour of the clay rock at the interface with the HLW cells

In the location of the HLW cells, the clay rock is in contact with a filler material on the outside of the metal sleeve.

Residual uncertainties concern the effects induced by injecting the filler material on the outside of the sleeve. Indeed, this material, whose precise nature has not yet been specified, could infiltrate fractures in the ZFC and limit the hydraulic healing process in this zone.

---

[97] Due to current uncertainty as to the time-dependent behaviour of the clay rock in the silty-carbonated unit (USC), despite the fact that the carbonated structure of this clay rock means that significant time-dependent behaviour is unlikely (and it would be limited by the presence of the seal core).

[98] In the sense of the structure of the ZFC observed in the clay unit, in which the disposal structures are located.

For all scenarios, given the uncertainties concerning the influence of the filler material on the outside of the sleeve on the hydraulic characteristics of the ZFC, Andra has adopted a conservative permeability value equivalent to that of sand in representing the ZFC around the HLW cells.

The chemical influence of the filler material on the clay rock is at this stage considered to be an alkaline disturbance affecting the whole ZFC.

Table 1.4-1: Methods for managing uncertainties related to mechanical processes

Mechanical damage to the Callovo-Oxfordian		
Functions: Preserving the favourable characteristics of the Callovo-Oxfordian		
Uncertainties	**Methods for managing uncertainties related to mechanical phenomena**	
	Design options	**Scenario assumptions**
Void resumption after failure of the liner/roof support by clay rock deconfinement	Limiting void fraction in ILW-LL cells	Consideration of a conservative extension value for the ZFC ensuring an undisturbed thickness of Callovo-Oxfordian of *at least* 50 metres.
Diffusive transport properties (De, w_{acc}) in the ZFC in the UA clay unit		To take into account the fracture effects in the ZFC, application of corrective factors (F>1) to the diffusion properties (De, w_{acc}) measured in the Callovo-Oxfordian clay rock.
Time-dependent behaviour of the Callovo-Oxfordian in the USC		Definition of a surface-bottom connection seal malfunction altered evolution scenario.
Intensity of the self-sealing process of fractured clay rock in the USC		Definition of a surface-bottom connection seal malfunction altered evolution scenario.
Hydromechanical interaction between the seal clay core and the clay rock	Choice of the swelling clay and its density	Covered in "seal malfunction" "*What-if*" scenarios that consider failure of the seal clay core to swell.

1.4.2 Thermal transient

The effects of temperature[99] increase are well understood and can explicitly be taken into account:

- with respect to transport and retention mechanisms within the Callovo-Oxfordian. The influence of temperature on transport and retention mechanisms and the values of associated parameters have been experimentally measured in the Callovo-Oxfordian clay rock:
  - ✓ diffusion coefficients: diffusion coefficient values measured as a function of temperature show that the influence corresponds with the phenomenological laws governing this process. The effects of a thermal transient on radionuclide diffusion are represented in accordance with current knowledge;
  - ✓ partition coefficients: on the basis of current knowledge, a corrective factor can be defined, for application to the partition coefficients of alkaline and alkaline-earth ions for temperatures higher than 50°C;
  - ✓ solubility limit: measurements taken for certain temperature-sensitive radionuclides can be used to determine corrective factors applicable to the solubility limits for temperatures of 60°C.
- with respect to radionuclide release and radionuclide behaviour in solution. After loss of disposal container integrity, current knowledge makes it possible to:
  - ✓ take into account the decrease in temperature at the core of the glass matrix over time in the HLW waste package release models after disposal container loss of integrity;
  - ✓ understand radionuclides and toxic elements behaviour in solution in the cell with temperature, after disposal container loss of integrity (Kd and solubility limits of certain radionuclides). Since sorption is not represented in the cell, the influence of temperature is not taken into account.

The effects of the thermal transient (including thermo-hydro-mechanical effects) are limited by design. For all scenarios, current knowledge makes it possible to:

- assess the intensity and spatio-temporal extension of the thermal plume resulting from the design measures, taking into account the thermal characteristics of the Callovo-Oxfordian;
- take into account the effects of temperature in the Callovo-Oxfordian volume affected by the residual thermal transient after the design measure has been applied (chemical transport and retention parameters);
- take into account the effects of temperature in the HLW cells (decrease over time in temperature in the vitrified waste release models, application of corrective factors to the solubility limits).

[99] The characteristics of the Callovo-Oxfordian that contribute to safety functions (especially the "delay and attenuate the migration of radionuclides" function) are temperature-dependent. The associated design and safety options are aimed at preventing irreversible effects of temperature on the Callovo-Oxfordian and to prevent its influence on the migration of radionuclides and toxic elements (see Volume II). In particular, these operations include:
- limiting the exothermicity of disposal packages;
- spacing between packages, where necessary, by using spacers;
- spacing between the exothermic disposal cells;
- Use of sealed disposal containers for vitrified waste;
- Separation of the ILW-LL disposal section from the HLW disposal section.

Simulations that take into account these design measures indicate a short-term thermal transient, when compared with the period required to dissolve the glass and the time it takes for radionuclides to migrate into the Callovo-Oxfordian.

Table 1.4-2: Methods for managing uncertainties related to thermal transient

Components affected	Uncertainties	Management of uncertainties related to thermal transient	
		Design options specified requirements	Scenario assumptions
HLW disposal cell	Induced effects of transient temperature increase on radionuclide release and behaviour (transfer and retention) in a thermal environment (50°C for HLW0, 70°C for HLW1/HLW2)	Option of a leaktight disposal container for a duration that is long enough for the temperature in the glass core to reach the following values by the time of water ingress: • 50°C for HLW0 vitrified waste packages • 70°C for HLW1/HLW2.	Normal evolution scenario and "HLW disposal container failure" altered evolution / *What-if* scenarios: • Corrective factors applied to chemical transport and retention parameters for temperature-sensitive radionuclides. • Incorporation of the temperature decrease over time in the HLW waste package release model after disposal container loss of integrity.

1.4.3 Hydraulic-gas transient

After closure, the repository enters a hydraulic transient phase involving gradual resaturation by the water from the Callovo-Oxfordian formation and transient hydrogen production, mostly due to anoxic corrosion of metal components and to the radiolysis of organic ILW-LL.

This phase is characterised by a non-saturated transient state affecting some or all disposal components. The duration of this transient varies from structure to structure and depends mostly on hydrogen production and dissolved hydrogen migration in the Callovo-Oxfordian clay rock.

Simulations of this transient have been performed, based on knowledge acquired about hydrogen production and the gas transfer characteristics in the different repository components and their interfaces. This transient is generally well described and understood. Knowledge acquired shows that hydrogen production and migration are not likely to alter the performance of structural components and the Callovo-Oxfordian. In particular, the clay rock is not likely to fracture as a result of gas pressure.

At this stage, the remaining uncertainties chiefly relate to quantifying the time taken to achieve total saturation of the various repository components and consequently its influence on the transport of radionuclides and toxic elements potential released over this period via the structures.

Assuming an initial "saturated" state immediately after repository closure, for all repository components, including the closure structures makes it possible to eliminate these remaining uncertainties.

This is a conventional approach and is conservative with regard to solute transfer of radionuclides and toxic elements. It does not benefit from the potentially delayed release of radionuclides and toxic elements during the non-saturation period and any limitation of water flow and radionuclide and toxic element transport via advection and diffusion in the non-saturated repository components and consequently the decay of certain radionuclides over this period.

At this stage, the scenarios defined (normal, altered evolution and "*What-if*" scenarios) consider only solute transfer in an initial saturated state within the repository and hydraulic equilibrium, from definitive repository closure onwards.

This initial saturated state is deemed to be a "bounding" situation with respect to solute transfer.

Representation of the hydraulic-gas transient in the scenarios is planned for the construction licence application. Gaseous radionuclide transfer, and specifically carbon-14, will be covered within this framework.

Table 1.4-3: Methods for managing uncertainties related to hydraulic-gas transient

Components affected	Uncertainties	Methods for managing uncertainty	
		Design options	**Scenario assumptions**
Callovo-Oxfordian HLW disposal cell ILW-LL disposal cell Backfilled drifts Seals	Time assessment for components to achieve total saturation	Not applicable	Initial saturated state from repository closure onwards considered to be bounding is taken into account in the Safety Options Report Description of a normal evolution scenario taking into account the hydraulic-gas transient for the construction licence application
Damaged Callovo-Oxfordian Backfilled drifts and surface-bottom connections	Influence of hydraulic-gas transient on gaseous radionuclide and toxic element transfer	Not applicable	Initial saturated state from repository closure onwards considered to be bounding and taken into account in the Safety Options Report Description of a normal evolution scenario taking into account the hydraulic-gas transient and gaseous carbon-14 transfer for the construction licence application

1.4.4 Chemical disturbances

Without anticipating their effect on the behaviour of radionuclides and toxic elements, various chemical processes of different types may occur within the repository, firstly as a result of its operation over a period of about one century and, secondly, because of the presence of the waste or materials that form the structural components. The main chemical processes are:

- "oxidising" disturbance caused by desaturation and oxygen penetration in the mechanically damaged clay rock around the structures during the operating phase;
- "alkaline" disturbance of the clay rock and clay-based structural components, which occurs in contact with alkaline fluids from cement-based materials (clay rock in contact with the liner/roof support in the drifts and ILW-LL cells; sealing clay core in contact with the concrete containment walls);
- "organic" disturbance related to the release of organic species by certain types of ILW-LL waste;
- "saline" perturbation related to the presence of salts in certain types of ILW-LL waste;
- "iron/clay" disturbances in contact with the metal components.

The processes involved in these chemical stresses are well-known and their extent is well-understood. They are generally fairly small in thickness and mostly limited to the initial damaged clay rock zone.

These chemical disturbances, in terms of extension and potential effects on the component characteristics that are required for safety functions (i.e. permeability, radionuclide transport and chemical retention), are described individually below.

1.4.4.1 Oxidising disturbance

In the clay rock

Ventilation during the repository operating phase causes ingress of oxygen into a part of the ZFC.

Current knowledge, particularly based on data acquired in the Underground Research Laboratory, leads to the following conclusions:

- the extension of the oxidising disturbance is limited and only affects the surface of those fractures in the ZFC that are closest to the structure wall;
- the disturbance causes oxidation of the pyrite on the surface of the factures in the clay rock;
- the water from the clay rock that resaturates the structures will temporarily have a chemical composition that is different to that of undisturbed clay rock, notably an acidic pH and higher sulfate, Na, CO_2 concentrations, etc.

The processes involved are well known. The remaining uncertainties at this stage mostly concern the extension of the disturbance, related to the extension of clay rock desaturation in the ZFC from the wall of the structures (radial extension and extension from the fracture surface).

The oxidising disturbance is not explicitly represented. It is covered by conservative choices for the chemical retention characteristics in the ZFC.

Cement-based materials

Design measures (in particular through appropriate formulation) shall be taken to protect the concrete from sulfate attack, and specifically that associated with pore water from the clay rock that is temporarily corrosive due to the oxidising disturbance (change in pH, increase in sulfate concentration, etc.).

Atmospheric carbonation may take place in the concrete components during the operating period. Its extension is estimated to be limited to ten centimetres at the most by the time the repository is definitively closed, and the quantity of carbonated concrete is estimated to be low. In a prudent approach at this stage, this atmospheric carbonation is covered by conservative choices regarding the retention parameters in the ILW-LL cell liner/roof supports.

In the HLW cell

Concerning the HLW cell, water from the oxidised and damaged Callovo-Oxfordian clay rock during operation is buffered by design, by the cement-based filler material on the outside of the sleeve. This effect is therefore not considered under the normal evolution scenario. Any possible effect is considered in the analyses of the disposal container corrosion processes, which cover the environmental conditions (see *below*).

Given its extension, which is limited to one part only of the ZFC, oxidising disturbance is not explicitly represented. It is covered by conservative choices for the chemical retention characteristics in the ZFC.

With respect to corrosion process affecting the metal components, it is managed by the design that includes a specified filler material on the outside of the sleeve.

1.4.4.2 Alkaline disturbance of clay rock in contact with concrete

Knowledge acquired through experimental studies and simulations over many years has led to the following conclusions:

- the main processes responsible for concrete/clay rock interactions are well known. This has enabled the conceptual model to be consolidated by defining two zones that are affected in different ways by the disturbance:
  - ✓ one so-called "remineralised" zone in which the texture, mineral and geochemical characteristics of the clay rock are significantly changed;
  - ✓ a second zone referred to as the "zone affected by an alkaline plume without remineralisation", which includes clay rock that has undergone little, if any, remineralisation, but with high pH.
- simulations of concrete/clay rock interactions have enabled the spatio-temporal extension of these two zones to be understood and estimated. The extension of the remineralised zone is a few decimetres over a million years, depending on the structure in question. It is therefore limited with respect to the undisturbed clay rock thickness (at least 50 metres).

In particular, remineralisation leads to dissolution of the clay phases, and the precipitation of secondary phases such as saponites, zeolites or other hydrated phases. The expected mineralogical changes lead to changes in the pore structure and consequently influence the diffusion coefficients and the accessible porosity.

At this stage, the remaining uncertainties limit:

- the predictability of radionuclide behaviour in this zone. Additional research is envisaged to consolidate the results acquired to date;
- the predictability of the self-sealing process in this zone (in particular related to the swelling of smectic minerals).

Under a conservative approach, it is assumed that the remineralised clay rock zone has hydraulic characteristics and transport properties similar to those of sand (i.e. conservative permeability, De and accessible porosity values). Self-sealing processes are not taken into account.

Data regarding chemical retention characteristics are available for some proven secondary phases. They are taken into account only in the reference situation.

In the non-remineralised zone:

- corrective factors are defined, enabling the anion diffusion coefficients to be corrected according to ionic strength;
- corrective factors are defined, enabling the Kd values for alkaline and alkaline-earth ions to be corrected in the reference and bounding situations, according to potassium concentration and ionic strength;
- conservative solubility limit values are taken for the radionuclides if the ionic strength is very high (greater than 4 times the ionic strength of undisturbed Callovo-Oxfordian water).

1.4.4.3 Alkaline disturbance in contact with low-pH concretes (e.g. seals)

<u>In the clay seal cores</u>

In the clay seal cores that are in contact with the low-pH concrete containment walls, numerical simulation assessments indicate that the alkaline disturbance would correspond to the dissolution of 5 % of the initial smectite in the swelling clay at most, at a distance of one metre from the interface with the containment walls, which is negligible in comparison with the length of the clay core.

These results show that the low-pH concrete formulation used around the clay core of the seals limits the disturbance generated by their degradation. Similarly, its effects on the core diffusion and retention properties are limited.

This design measure does not therefore jeopardise the core swelling capacity. Any downgraded performance of the clay core as a result of alkaline disturbance is considered highly unlikely. It is not therefore included as a cause of failure. It is, however, covered by the "seal malfunction" "*What-if*" scenarios that consider failure of the clay core to swell.

Current knowledge makes it possible to represent the clay core without influence from any alkaline disturbance from the containment walls and low-pH concrete liners that remain in place.

In the clay rock at the interface with low-pH liner portions

Assessments carried out by numerical simulation indicate that total dissolution of the smectite phase would take place over a maximum extension of one centimetre from the interface, and a moderate evolution of the sodium- and calcium-bearing fractions of the ion exchange site after 100,000 years. Similarly, the ionic strength and potassium concentration (K) undergo very little change in the clay rock.

On the basis of this knowledge, alkaline disturbance of the clay rock at the interface with the low-pH concrete is not represented in the scenarios.

Table 1.4-4: Methods for managing the remaining uncertainties related to oxidising and alkaline disturbance

Components affected	Uncertainties	Methods for managing uncertainties related to oxidising and alkaline disturbance	
		Design options	Scenario assumptions
HLW disposal cell	Intensity of acidic transient resulting from pyrite oxidation	Design measure to buffer the acid fluid from the clay rock by using a filler material on the outside of the HLW cell sleeve	Effective filler material on the outside of the HLW cell sleeve
Damaged Callovo-Oxfordian	Influence of mineralogical evolution and pore structure on the transport parameters for clay rock remineralised by the effect of alkaline disturbance from conventional concrete	Use of low-pH concrete for the seal containment walls.	Representation of the clay rock remineralised zone to include hydraulic properties equivalent to sand.

1.4.4.4 Corrosion of metal components and chemo-mechanical coupling

The long-term behaviour of metal components such as the HLW cell sleeves, HLW disposal containers and other components such as concrete reinforcements is dominated by corrosion.

The corrosion processes (generalised, localised etc.) and the associated kinetics have been studied for various different physicochemical conditions (experiments in the surface laboratories and *in situ* experiments in the Underground Research Laboratory). All the corrosion processes are well known. On the basis of the knowledge acquired, there is generally very little uncertainty concerning corrosion mechanisms and rates.

In addition, Andra has established a number of design requirements for waste that requires a leaktight container (see Volume II).

These measures relate in particular to the HLW disposal container, in order to protect it from certain corrosion processes (stress corrosion, radiolytic corrosion) or to limit the effects of such corrosion.

In addition, different design measures have been implemented to limit oxygen ingress into the HLW cell during operating phase (the cell head is designed to limit oxygen ingress when the access drift is ventilated). Monitoring and control systems shall be put in place to ensure these technical measures operate properly.

The initial annulus between the outside of the sleeve and the geological medium shall be filled with a filler material, whose aim is to provide a chemical buffer against the acidic disturbance transient caused by oxidation of the clay rock in the wall, in order to prevent an acidic environment in contact with the sleeve[100] (and the HLW disposal container), which would lead to high corrosion kinetics.

Although it is highly unlikely, the ingress of oxygen into the cell is envisaged, and this would lead to higher corrosion rates inside the usable part of the HLW cell and cause premature loss of disposal container leaktightness).

Feedback from the operating phase on the first HLW0 cells, optimisation of the construction processes and future technological upgrades should enable this situation to be ruled out for HLW1/HLW2 disposal containers disposed of after 2075. The failure of all HLW disposal containers would therefore fall under a "*What-if*" type scenario.

The following have been adopted:

- an altered evolution scenario involving an HLW disposal container defect, which considers loss of leaktightness as soon as the disposal container repository is closed in the HLW0 disposal section;
- a "*What-if*" type scenario, which considers the loss of container leaktightness as soon as the repository is closed for all HLW0, HLW1 and HLW2 disposal containers;

Table 1.4-5: Methods for managing uncertainties related to the corrosion processes affecting HLW disposal containers

Corrosion processes affecting HLW disposal containers		
Relevant safety functions: Protecting waste packages from water		
Remaining uncertainties	**Methods for managing uncertainty**	
	Design options	**Scenario assumptions**
Uncertainty about the development of oxidising corrosion (generalised and localised)	• System at cell head to limit oxygen ingress during operation • -Filler material on outside surface of sleeve	NES: corrosion under anoxic conditions Altered evolution scenario: premature loss of disposal container leaktightness in the HLW0 disposal section due to oxic corrosion from repository closure onwards *What-if*: loss of leaktightness in all disposal containers due to oxidising corrosion, from closure onwards

1.4.4.5 Iron/clay disturbance

The filler material used on the outside of the HLW cell sleeve limits interaction between corrosion products and the clay rock around the HLW cells. The conservative choice of unfavourable conservative hydraulic characteristics and not adopting any retention properties for the damaged clay rock zone covers all effects.

[100] This material also helps to reduce oxygen accessibility to the cell via the outside surface of the sleeve during the operating period.

The composition of the clay material at the HLW cell head has not yet been specified. Iron/clay disturbance is not explicitly represented in this component and it is automatically covered by the conservative choice of adopting hydraulic performance equivalent to sand and not considering any chemical retention, in relation with the indeterminate nature of its composition.

1.4.4.6 Disturbance related to the presence of organic complexing substances

When they deteriorate, the ILW-LL waste packages that contain organic components may produce complexing species of radionuclides and toxic elements and thus influence their migration.

Studies have been carried out on organic molecules such as monocarboxylic acids (formic acid and acetic acid), dicarboxylic acids and hydroxycarboxylic acids (isosaccharinic acid, ISA) Measurements enabled the transport of some complexed radionuclides to be characterised. Experimental data are available concerning the diffusive transport properties of complexed radionuclides via organic molecules.

On the basis of these data, the extension of the organic disturbance, and in particular the organic compound concentration levels were estimated via reactive transfer simulations using the ILW-LL packages with the highest concentration levels of organic compounds. The results show that the influence of organic complexing substances on the migration of radionuclides within the Callovo-Oxfordian is very limited (only a few metres, approximately[101]).

Corrective factors with respect to partition coefficients and solubility limits have been defined, in relation to the concentration of organic compounds, in order to incorporate this influence. They have been applied at the interface with the ILW-LLL cells containing organic waste packages, in (i) the liner, (ii) the mechanically damaged zone, and (iii) the Callovo-Oxfordian (a few metres) respectively.

The effect of organic complexing molecules is taken into account, differentiating the effects related to the presence of ISA and the effects of other organic compounds, which are handled similarly to phtalates (see Table 2.4-10, Appendix 1).

1.4.4.7 Saline perturbation

Saline perturbation interacts with other disturbances around the ILW-LL containing salt-rich waste.

In the clay rock, the influence of disturbance by nitrate salts on the retention properties was measured using $NaNO_3$ and $NaClO_4$. The acquired knowledge makes it possible to determine corrective factors to apply to the partition coefficients for certain alkaline radionuclides (K, Rb and Cs) and alkaline earth radionuclides (Be, Ca and Ra). For other radionuclides, various experiments have shown a limited effect on Kd.

Simulations based on Na^+, K^+, NO^{3-} and SO_4^{2-} concentrations have made it possible to assess the plumes of corresponding concentrations and to identify the areas of the Callovo-Oxfordian or liner affected by an ionic strength that has effects on the diffusive transport and retention properties.

The results show that the influence of saline perturbation on the radionuclide transfer properties within the Callovo-Oxfordian is limited to the ZFC.

The effect of the presence of soluble salts in cement-based materials has been measured in experiments involving radium and uranium (VI). The effect is only significant for ionic strength values higher than 0.8 M. In this case, conservative Kd values are adopted for radionuclides in the liner.

[101] Low concentration levels of complexing compounds are found in the clay rock (e.g. any ISA concentration levels that are higher than 10^{-3} M go no further than 2 metres from the ILW-LL cell).

Summarises the ways in Table 1.4-6 which these uncertainties are managed.

The knowledge acquired makes it possible to define a threshold ionic strength (approximately $2x10^{-1}$M) above which the ionic strength has a significant effect on diffusive transport and retention properties.

This effect is taken into account through the post-closure quantitative safety assessment period by means of corrective factors applied to the transport and retention factors for radionuclides that are sensitive to this ionic strength (see Appendix 1).

1.4.4.8 Bacterial activity

The knowledge acquired indicates that the nano- to micro-scale of the pores in the undisturbed Callovo-Oxfordian clay rock or clay seal cores do not allow for significant bacterial growth, due to a lack of space, free water or nutrients.

Within the cement-based materials, it is expected that microbial activity will be unlikely, in particular at the interfaces and/or in fractures.

In the ZFC, the occurrence of bacterial activity will depend on the size of fractures. Any activity that did develop would be limited due to the diffusion conditions and the pore size. The possibility of migration can only be envisaged in a medium that presents high porosity and under the effect of convective transport conditions.

No effect from bacterial activity in the concrete components, undisturbed clay rock or clay seal cores has been adopted in the scenarios.

1.4.4.9 Colloid transport phenomena

Knowledge acquired shows that colloids cannot migrate through the network of pores in the clay rock due to the small size of pores and connections between the pores (a few nanometres). Colloids might potentially migrate through unhealed parts of the ZFC, but in this case, transport would only go through the factures and not the inter-fracture blocks of clay rock, whose texture is assumed to be undisturbed. The corresponding flows would therefore be limited.

The possibility of colloid transfer is therefore limited to the structure pathway and via the ZFC. The possibility of colloid transport by advection corresponds to the possibility of migration in a porous medium that presents high porosity and under the effect of convective transport conditions (e.g. if the ZFC has not undergone hydraulic healing due to a lack of self-sealing). These conditions are taken into account in the seal malfunction scenarios via an imperfect interface that would provide the colloids with a convective transfer pathway.

Based on available knowledge, the possibility of colloid transfer is not included in the normal evolution scenario.

Colloids are represented with no chemical retention in the situations involving seal malfunction via the swelling clay/clay rock interface (altered evolution scenario - see Chapter 3.1, and "*What-if*" scenario - see Chapter 5.1).

1.4.4.10 Summary of methods for managing the uncertainties related to chemical disturbance

The table below summarises the analysis of uncertainties related to chemical disturbances.

Table 1.4-6: Methods for managing uncertainties related to chemical disturbance from ILW-LL

Components affected	Remaining uncertainties	Methods for managing uncertainty	
		Design options	Scenario assumptions
ILW-LL cell liner, mechanically damaged clay rock, Callovo-Oxfordian clay rock	Extension of the plume of organic complexing compounds	Physicochemical co-disposal rules for ILW-LL	Covered by a bounding assessment that considers the ILW-LL cell that is potentially most loaded with organic compounds.
ILW-LL cell liner	Evolution of partition coefficients (Kd) and solubility values in the presence of organic complexing compounds	Physicochemical co-disposal rules for ILW-LL	Effects taken into account around ILW-LL cells (liner and Callovo-Oxfordian) by applying corrective factors, differentiating between ISA and other organic compounds, when the estimated concentration level is higher than the threshold effect. (all scenarios)
Damaged Callovo-Oxfordian clay rock and undisturbed Callovo-Oxfordian clay rock	Evolution of partition coefficients and solubility values in the presence of organic complexing compounds	Physicochemical co-disposal rules for ILW-LL	Effects taken into account around ILW-LL (liner and Callovo-Oxfordian) cells by applying corrective factors, differentiating between ISA and other organic compounds, when the estimated concentration level is higher than the threshold effect (all scenarios)
	Evolution of diffusion coefficient in the presence of organic complexing compounds	Physicochemical co-disposal rules for ILW-LL	Since the organic molecules have a lower diffusion coefficient than the complexed radionuclides, it was decided not to represent them.
	Effects of cumulative chemical disturbance on partition coefficients and solubility values	Physicochemical co-disposal rules for ILW-LL	Effects taken into account around ILW-LL cells by applying corrective factors.
ILW-LL cell liner, mechanically damaged clay rock, undisturbed Callovo-Oxfordian	Extension of saline perturbation	Physicochemical co-disposal rules for ILW-LL	Covered by a bounding estimate based on Na^+, K^+, NO^{3-}, SO_4^{2-} concentration levels and ionic strength.
ILW-LL cell liner	Evolution of adsorption equilibrium (Kd) and solubility values in the presence of a saline plume	Physicochemical co-disposal rules for ILW-LL	Effects taken into account around ILW-LL cells by applying corrective factors.
	Evolution of adsorption equilibrium (Kd) and solubility values in the presence of a saline plume	Physicochemical co-disposal rules for ILW-LL	Effects taken into account for ILW-LL cells by applying corrective factors based on ionic strength and the potassium concentration.
Damaged Callovo-Oxfordian clay rock and undisturbed Callovo-Oxfordian clay rock	Evolution of diffusion coefficient in the presence of a saline plume	Physicochemical co-disposal rules for ILW-LL	Effects taken into account for ILW-LL cells by applying corrective factors based on ionic strength.
Damaged Callovo-Oxfordian	Uncertainty concerning the influence of microorganisms on radionuclide retention, solubility and transfer	Physicochemical co-disposal rules for ILW-LL	Not considered in the normal evolution scenario.

1.5 Technological uncertainties

This section addresses questions related to the implementation of the structural components in various parts of the repository: cells, drifts and seals.

1.5.1 Uncertainties concerning technologies used in the HLW cells

1.5.1.1 HLW disposal containers

HLW disposal container manufacture and quality control and risk of damage during emplacement operations

The research programme on HLW disposal containers is aimed at defining the most appropriate available and proven manufacture and control processes in order to ensure that the container remains leaktight for as long as possible. The highest level of quality control is planned, involving controls on all disposal containers.

In addition, the choice of low-alloy steels has been adopted due to their resistance to corrosion processes (e.g. stress corrosion)

Various design measures will be implemented to prevent the risk of damage in operating phase, such as the inclusion of sliding runners and measures to ensure the reliability of handling equipment. Any damage to the container leading to loss of leaktightness will be detected during the operating phase via the monitoring systems used.

> Because of the level of quality control and measures taken for in-cell emplacement, defective HLW disposal containers are not envisaged in the normal evolution scenario.
>
> Despite the different quality control efforts and measures taken, any undetected defect would be covered by the "*What-if*" scenario under which all disposal containers in disposal sections HLW0 and HLW1/HLW2 are considered no longer leaktight from repository closure onwards.

Filler material on the outside of the HLW cell sleeve

The type of material to be used on the outside of the sleeve is still being defined. By design, the criterion for this choice will be based on the ability to buffer the acidic transient from surrounding oxidised clay rock. It will be known material e.g. cement/clay-type material.

The ability of the filler material to buffer the acidic transient has been verified through modelling, but it will also be verified through experiments (see Volume II, Chapter 2).

A test in the Underground Research Laboratory has demonstrated the feasibility of injecting a cement-based grout over a 40-metre length. The overall homogeneity of the filler material was tested on some portions on the outside of the sleeve and no significant heterogeneity was detected.

The insertion of a homogeneous filler material, for instance by injection is considered technologically feasible for a 100-metre HLW cell: and this has been adopted as a reference solution in the design options.

In addition, quality controls shall be implemented after the filler material has been put in place, in order to verify that there is no significant heterogeneity.

At this stage, a filler material defect (e.g. significant heterogeneity) in each HLW cell cannot be ruled out, even though it seems unlikely. This type of defect would lead to a local failure to buffer the acidic transient caused by oxidation of the nearby clay rock, which would cause a generalised corrosion rate that is higher than the value adopted in the normal evolution scenario. This could lead to premature loss of leaktightness in the container(s) near the heterogeneous filler material. By convention, it is considered that one disposal container would lose integrity at the location of the heterogeneity for HLW1-2 and that two disposal containers would be affected in the relevant cell for HLW0.

On the basis of previous tests and technological knowledge, the filler material used on the outside surface of the HLW sleeve is considered to be effective in buffering the acidic transient.

A situation involving significant heterogeneity of the filler material is covered by the "*What-if*" scenario, under which all disposal containers in the HLW cell prematurely lose their leaktightness.

1.5.2 Uncertainties concerning technologies used in the drifts

Backfill of the drifts

From a technological perspective, the Richwiller demonstration facility provides Andra at this stage with data for the implementation of excavated clay rock as backfill. This test has shown that it is possible to produce a fairly homogeneous and fairly high-density backfill using excavated clay rock.

Any ducts and cable trays required for repository operations and which could form preferential flow pathways or voids in the post-closure phase, shall be removed at the time of repository closure or filled in with backfill.

Design specifications have not yet been defined for the backfill, but the design provisions (emplacement density, initial saturation) should enable it to perform its function of limiting the extension of the damaged clay rock zone following liner failure. Current industry standards in backfilling techniques suggest that it will not be impossible to achieve the mechanical characteristics required to fulfil this function.

Knowledge available on clay backfill and data so far acquired on the excavated clay rock enables the backfill to be represented as a continuous equivalent porous medium with homogeneous properties, filling the whole space of the drifts and limiting the extension of the damaged clay rock zone around the drifts.

Under a conservative approach, no transport or chemical retention properties have been assigned.

Construction of seals

Andra has significant operating experience feedback to characterise clay-based materials that could be used for the clay seal core and could achieve the target performance characteristics. Shaping and implementation tests in configurations similar or identical to those of a repository, or demonstration facility tests on the surface (see Volume II, Chapter on seal performance) have proven the following:

- feasibility of installing a swelling clay core for a structure diameter of up to 5 to 6-metres and with outside-profile dimensions of one metre concerning the drifts. For the shafts, the verticality is helpful for installation and contributes to ensuring that shaft seal implementation does not pose any particular problems;
- feasibility of a range of solutions for shaping the core, in particular using pellets, in order to provide optimum filling and thereby ensure the best possible and perfectly controlled contact between the core and the Callovo-Oxfordian clay rock;
- feasibility of installing significant volumes of low-pH concrete in a drift configuration, and in particular, ensuring a good interface with the rock (or liner) and mechanical characteristics that comply with expectations and the measurements taken on samples;
- feasibility of hydraulic cuts.

Quality control of seal implementation shall be performed. This control will make non-compliance with materials and installation specifications highly unlikely.

The Cigeo project component development plan includes demonstration versions of a drift seal and a ramp seal within the Cigeo facility.

Based on operating experience feedback, in particular from experiments and surface-level demonstration facilities, seal malfunction due to construction operations is considered to be highly unlikely.

This situation is addressed in the "*What-if*" scenarios, covering (i) failure of the clay core to swell following installation of materials other than those specified or unforeseen evolution, and (ii) any swelling clay/clay rock interface defects.

1.6 Risks and uncertainties relating to future events of external origin

In accordance with the 2008 ASN Guide, the foreseeable evolution of the repository and its geological environment includes the effect of certain or highly probable events such as climate change, subsidence, uplift and seismic movements.

Alongside these natural events, there are also human activities, Anthropogenic effects (e.g. greenhouse gas emissions) from activities that could lead to intrusion are distinguished. This section only addresses anthropogenic effects on climate cycles. Human intrusion is analysed specifically and is presented in the next chapter.

The choice of site and the repository design mean that the risk of volcanic activity and diagenesis can be ruled out.

The risk of effects related to an earthquake is also limited by the choice of site in a low-seismicity zone. At this stage, the spectrum for the maximum physically possible earthquake calculated for the Underground Research Laboratory site has been taken as a reference. Nevertheless, the seismic hazard for a repository in the zone of interest for detailed survey will be further investigated for the construction licence application.

The next chapters therefore focus on climate change, geodynamic evolution (excluding earthquake) and the criticality risk.

1.6.1 Climate change

Climate change has been simulated, in particular as part of European projects such as BIOCLIM.

The simulations have been consolidated and results are available for simulations that consider two climate change scenarios (i) natural evolution and (ii) change that considers anthropogenic effects (climate affected by human activities, taken into account through greenhouse gases).

In cold climates, it is possible that permafrost might appear, with a maximum depth of around one hundred metres. This would not therefore reach the Callovo-Oxfordian layer. The possibility of permafrost is included in simulations associated with the revised hydrogeological model.

1.6.2 Geodynamic evolution

Simulations of geomorphological evolution have been performed, which include uplift rates and erosion phenomena. Risks related to geodynamic evolution are understood and managed. The knowledge acquired has been included in:

- the consolidated and hydrogeological model over the scale of the next million years;
- simulations that consider climate change.

The knowledge acquired enables a best estimate representation of knowledge in the normal evolution scenario and does not identify altered evolution or "*What-if*" scenarios.

1.6.3 Post-closure criticality risk in the repository

The aim of the cell design is to create an environment to limit radionuclide release and migration (in particular by limiting the transfer pathway via the structures) and to limit re-concentration of fissile material by limiting the voids. From design, the aim of the systems used is to manage post-closure criticality risk, in particular through the design of the disposal cells, whose environment is favourable to:

- restricting the release of radionuclides;
- encouraging preferential migration to the transfer pathway via diffusion in the Callovo-Oxfordian layer.

Furthermore, measures will also be taken to limit the in-cell voids and to reduce the re-concentration of fissile radionuclides. Analysis of the post-closure criticality risk in Cigeo shall be provided at the time of the construction licence application[102].

1.7 List of scenarios adopted

Based on the knowledge acquired so far, the qualitative safety analysis has identified:

- risks and uncertainties whose effects remain within the range of the normal evolution scenario. The analysis led to the definition of methods for managing such uncertainties, according to the approach adopted:
  - ✓ for reference situations, where the choices were made by generally considering the characteristics and processes that are the most scientifically and technologically substantiated, i.e. according to best knowledge;
  - ✓ for situations corresponding to the Cigeo requirements (referred to as "bounding" situation in this document), where the choices included a level of conservatism, depending on current knowledge;
- risks and uncertainties that could lead to deterioration of a safety function and the performance of the component that contributes to this function. The analysis identified causes of component malfunction that could lead to significant deterioration in its performance. Depending on their likelihood, these causes of malfunction led to the definition of altered evolution scenarios (AESs) or "*What-if*" scenarios that serve to cover remaining uncertainties at this stage and test the robustness of the repository design.

Note:

As stated in Volume II, Chapter 3, the need for a seal and the sealing method at the ILW-LL cell entrance and their air return has been studied. At this stage, the requirements for horizontal seals can be adopted, but Andra is also examining the possibility of using high-density backfill with a specified permeability (lower permeability, possibly a mix of clay rock and swelling clay).

In order to test the robustness of the repository design, two cases have so far been adopted for ILW-LL closure structure performance assessment:

- one case with closure performance of approximately 10^{-11}m/s taken as a reference (requirements for horizontal seals) and a performance of approximately 10^{-10} m/s for the bounding situation;
- one case with lower performance, of approximately 10^{-7} m/s.

These cases are identified hereinafter as "calculation case with seal" and "calculation case with lower performance", sometimes referred to as "without seal".

[102] The post-closure criticality risk analysis takes account of the various changes in the repository over time: mechanical changes to the packages and disposal cells, evolution of physicochemical conditions (materials, re-concentration phenomena) and changes in the fissile radionuclide inventory.

The analysis of the risks and uncertainties, based on knowledge acquired and the safety options adopted, led Andra to adopt the following:

- two situations associated with the normal evolution scenario: one reference situation and one bounding situation;
- three "closure structure malfunction" altered evolution scenarios (AESs);
- two "HLW disposal containers malfunction" altered evolution scenarios (AESs);
- four "closure structure malfunction" "*What-if*"-type scenarios;
- one "HLW disposal containers malfunction" "*What-if*"-type scenario;
- one "*What-if*"-type scenario related to the Callovo-Oxfordian formation.

These scenarios are listed in Table 1.7-1, Table 1.7-2 and Table 1.7-3.

Table 1.7-1: List of calculation cases associated with the normal evolution scenario

Normal evolution domain	
Reference situation	**Initial saturated state. Reference situation - with ILW-LL seal** This situation is based on a set of assumptions and data selected on the basis of the best scientific and technical knowledge available.
	Initial saturated state. Reference situation taking into account an another ILW-LL cell closure solution having a lower performance than a seal. This situation is defined on the same basis as the previous one ,i.e. using the best available knowledge, considering seals at the ends of the ILW-LL cells represented with minimum performance levels.
	Inclusion of the hydraulic-gas transient. This transient will be defined for the construction licence application.
Bounding situation	**Initial saturated state. Bounding situation - with ILW-LL seal** This situation involves taking into account the requirements applicable to Cigeo. In the absence of requirements specified for certain component characteristics, the most conservative limits from the acquired knowledge have been selected. This situation also involves conventional choices which lead to the exclusion of certain characteristics that would be favourable to delaying and attenuating radionuclides.
	Initial saturated state. Bounding situation taking into account another ILW-LL cell closure solution having a lower performance than a seal. This situation is defined on the same basis as the previous one, considering the requirements applicable to Cigeo, and considering seals at the ends of the ILW-LL cells represented with minimum performance levels.
	Inclusion of the hydraulic-gas transient. This transient will be defined for the construction licence application.

Table 1.7-2: List of post-closure altered evolution scenarios (AESs) (excluding inadvertent human intrusion)

Altered evolution scenarios(AESs)	
Seal malfunction scenarios	**Malfunction of surface-bottom connection seals via the interface between the clay core and the Callovo-Oxfordian (with drift seals operating)** This scenario involves a malfunction of the surface-bottom connection seals via the interface It considers the formation of a connected fracture zone (ZFC) at the location of the clay core in the silty-carbonated unit(USC) and the transition unit (UT), which are lithostratigraphic units in the upper part of the Callovo-Oxfordian layer.
	Malfunction of drift seals via the interface between the clay core and the Callovo-Oxfordian (with surface-bottom connection seals operating) This scenario involves a malfunction of the drift seals via the interface. It considers a hydraulic healing failure in the ZFC within the clay unit in which the deep repository facilities are located, in particular at the zones where the liner is removed.
	Malfunction of all seals (surface-bottom connection and drift seals) via the interface between the clay core and the Callovo-Oxfordian This scenario involves a malfunction of all seals (surface-bottom connection and drift seals) via the interface, through the creation of a ZFC in the silty-carbonated unit and the transition unit at the clay core location, and through a hydraulic healing failure in the ZFC where the liner is removed. Two calculation cases are used to define two ILW-LL seal performance levels and to assess sensitivity.
HLW disposal container malfunction AES	**Failure of two disposal containers per HLW cell in the HLW0 zone** This scenario involves premature loss of leaktightness of two disposal containers per HLW cell. It considers a heterogeneous filler material on the outside of the HLW cell sleeve, leading in some places to a high generalised corrosion rate, due to the presence of acidic water.
	Failure of all disposal containers in the HLW0 disposal section This scenario involves premature loss of leaktightness of all disposal containers in the HLW0 disposal section. It considers oxidising corrosion due to the presence of oxygen in the HLW0 cell.

Table 1.7-3: List of "What-if" scenarios (excluding inadvertent human intrusion)

"*What-if*" scenarios	
Seal malfunction "*What-if*" scenarios	**Malfunction of surface-bottom connection seals due to the combined effect of a clay core failure and failure of the interface between the clay core and the Callovo-Oxfordian** This scenario involves the failure of the surface-bottom connection seals via (i) the clay core having the same hydraulic properties as backfill and (ii) the liner having been left in place, representing an interface failure because of its high permeability.
	Malfunction of drift seals due to the combined effect of a clay core failure and failure of the interface between the clay core and the Callovo-Oxfordian This scenario involves the failure of the drifts seals through (i) the clay core having the same hydraulic properties as backfill and (ii) a hydraulic healing failure leading to high permeability of the ZFC at the clay core.
	Malfunction of all seals (surface-bottom connection and drift seals) through both failure of the clay core and failure of the interface between the clay core and the Callovo-Oxfordian This scenario involves combined failure of the surface-bottom connection and drift closure structures. It considers: • failure of the surface-bottom connection seals via (i) the clay core having the same hydraulic properties as backfill and (ii) the liner having been left in place, representing an interface failure because of its high permeability; • and failure of the drifts seals via (i) the clay core having the same hydraulic properties as backfill and (ii) a hydraulic healing failure leading to high permeability of the ZFC at the clay core.
HLW disposal container malfunction "*What-if*" scenario	**Failure of all HLW disposal containers (HLW0 disposal section and HLW1/HLW2 disposal section)** This scenario involves premature loss of leaktightness of all HLW disposal containers (HLW0 and HLW1/HLW2 disposal sections). It considers oxidising corrosion due to the presence of oxygen in the HLW cell.
Callovo-Oxfordian "*What-if*" scenario	**Undetected discontinuity in the Callovo-Oxfordian layer** A "conventional" scenario to comply with the ASN recommendation; to be defined for the construction licence application.

2

Normal Evolution Scenario

2.1	*Description and conceptualisation of the normal evolution scenario*	*235*
2.2	*Analysis of the NES*	*265*
2.3	*NES results*	*267*
2.4	*Lessons from the NES*	*299*

2.1 Description and conceptualisation of the normal evolution scenario

2.1.1 Objectives and adopted calculation cases

The purpose of this chapter is to present the calculation cases for the post-closure normal evolution scenario in Cigeo.

For the record, the approach described in Volume 1 has led to the definition of two calculation cases:

- the first case corresponds to a representation of the repository defined according to the best knowledge available at this stage of the Cigeo project (see Volume I, Chapter 5). This case is defined hereinafter as the reference situation.
- the second case is based on a less phenomenological approach. This case is sometimes defined as the bounding situation hereafter. It is defined considering:
  - ✓ values specified in the requirements, whenever these are defined;
  - ✓ the most conservative limit in the available knowledge (including knowledge acquired via simulations and/or by analogy with data from the literature if possible), for any components with no specified requirements.

Furthermore, any characteristics that might be favourable for delaying and attenuating radionuclides are not adopted if conventional choices are made, unless these characteristics are required for safety functions.

These situations are described on the basis of the analysis of risks and uncertainties presented in the previous chapter.

Each calculation case provides a simplified description of how the radionuclides and toxic elements in the waste may reach humans and their environments, and the structural choices made to represent the components they pass through. It thus considers all repository components involved in radionuclide transfer via the Callovo-Oxfordian pathway or via the “structures” pathway, which includes the underground drifts and the surface-bottom connection structures. For example, the surrounding rock formations and the biosphere that do not provide a safety function are nonetheless described because they are required for calculating the radiological impact.

This representation includes the conceptualisation that is performed for the purpose of the calculations and the indicators used to quantify the NES.

At the safety options phase, the safety assessments do not quantify the impact related to the presence of toxic elements.

The normal evolution scenario considers only solute transfers, based on an initial saturated state, which is deemed to be “bounding" with regard to solute transfer. The decision was made to represent the repository in a saturated state right from closure, in other words, with surface-bottom connection structures closed.

The representation of the repository takes account of the initial state of the repository at closure and its long-term evolution, taking account of all processes and events that seem sufficiently probable, as defined in the 2008 ASN Guide to safety for deep geological waste disposal (1).

Not all phenomena governing repository evolution are necessarily represented. However, this does not mean they have been neglected or ignored in the analysis. They may have been studied separately, prior to the safety assessments. Alongside the qualitative analysis, the conclusions of these preparatory studies may mean that these phenomena are not to be represented or can be represented in a very simplified manner.

2.1.2 Adopted repository architecture

The architecture adopted for the safety assessment is the architecture on completion presented in Volume II, Chapter 3. The following are taken into account in the evaluations: 50 ILW-LL cells, 72 HLW0 cells of 80 m long (+3 test cells), and 1465 HLW1/HLW2 cells of 100 m long (+8 test cells).

2.1.3 Representation of the repository in the Callovo-Oxfordian formation

The Cigeo underground repository is represented in the Callovo-Oxfordian clay formation at a depth of approximately 500 metres. Different configurations are planned for each situation in the normal evolution scenario.

2.1.3.1 Reference situation

All the structures are placed in the middle of the Callovo-Oxfordian formation (see Figure 2.1-1). The undisturbed thicknesses are defined in accordance with the real thickness of the Callovo-Oxfordian in the zone of interest for detailed survey (ZIRA), minus the maximum vertical extension of the connected fracture zone (ZFC) at the roof and floor of the structures. This representation generates iso-thicknesses on undisturbed Callovo-Oxfordian on either side of the repository structures. These undisturbed thicknesses are greater than the minimum requirement (50 metres) at the HLW and ILW-LL disposal cell locations.

In this configuration, the differences in hydraulic head between the surrounding rock formations are based on the results of hydrogeological modelling operations described in detail in Volume II, Chapter 2. These values are given in Table 2.1-2.

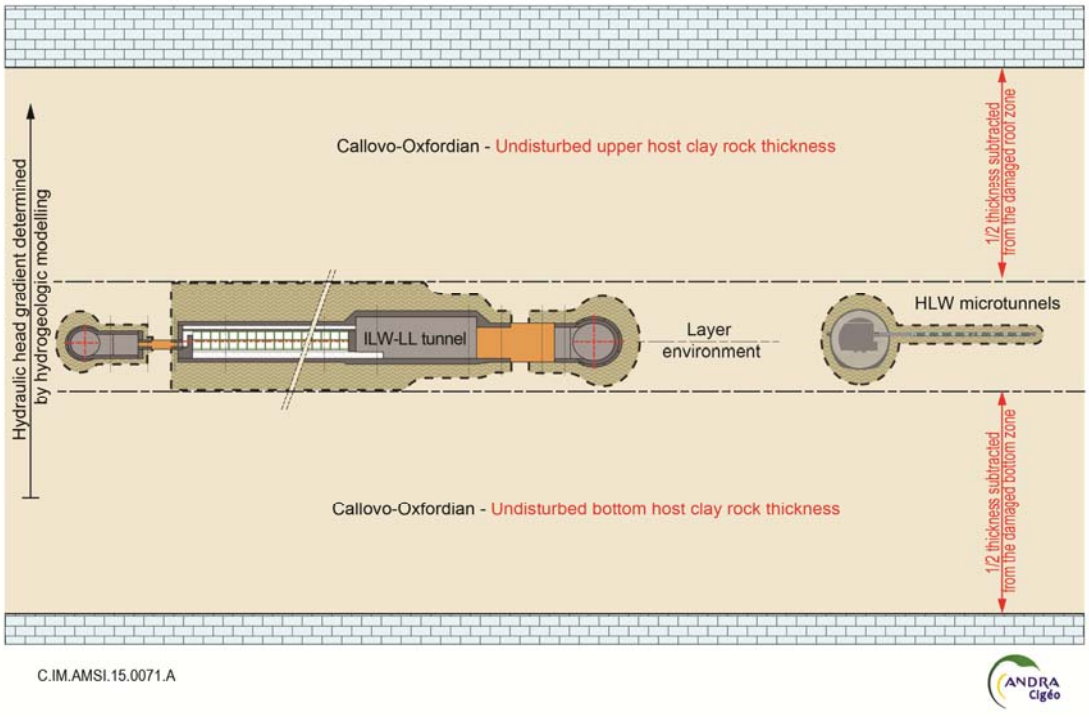


Figure 2.1-1: Schematic diagram of the position of ILW-LL and HLW disposal cells in the host formation, NES reference situation. Real thickness and depth of the Callovo-Oxfordian are taken into account

2.1.3.2 Bounding situation

The second representation, adopted for the "bounding" situation, is aimed at positioning the repository in order to maintain an undisturbed clay rock thickness equal to the minimum thickness specified in the Cigeo requirements (50 metres - see Volume II, Chapter 1).

The Callovo-Oxfordian formation is represented with a uniform thickness equal to the minimum thickness measured in the repository location (i.e. 142 metres). The HLW and ILW-LL disposal sections are positioned (see Figure 2.1-2), such as to ensure:

- either an undisturbed thickness of 50 metres in the upper part of the Callovo-Oxfordian. The HLW cells are thus represented in a different plane to the ILW-LL cells;

The thickness of the undisturbed Callovo-Oxfordian below the structures is deduced from the minimum Callovo-Oxfordian thickness, subtracting the maximum vertical extension of damaged clay rock at the roof and floor of the disposal cells.

- or an undisturbed thickness of 50 metres in the lower part of the Callovo-Oxfordian formation.

The thickness of the undisturbed Callovo-Oxfordian above the structures is deduced from the minimum Callovo-Oxfordian thickness, subtracting the maximum vertical extension of damaged clay rock at the roof and floor of the disposal cells.

In both configurations, the upwards or downwards hydraulic flows resulting from a difference in maximum hydraulic head are represented uniformly and in a constant manner over time, in the direction of the Oxfordian and Dogger formations respectively.

These values are given in Table 2.1-2.

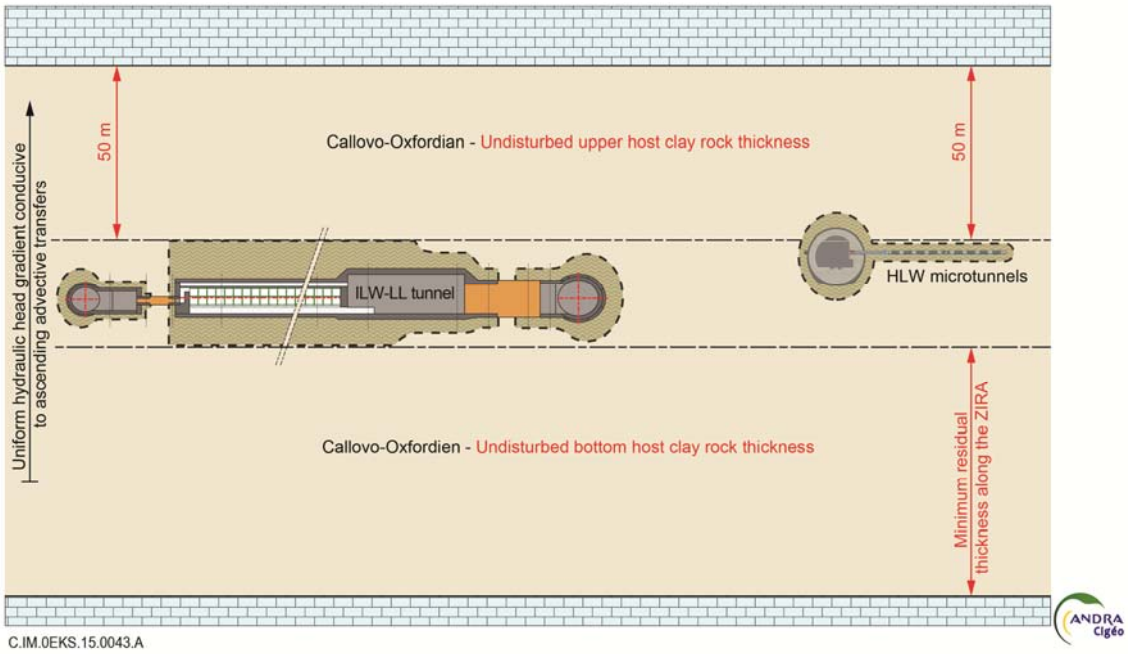


Figure 2.1-2: Schematic diagram of the position of ILW-LL and HLW disposal cells in the Callovo-Oxfordian in the bounding situation (minimum undisturbed thickness defined by the requirements (50 metres) above the cells)

2.1.4 Radiological inventory

2.1.4.1 Selected radionuclides

Out of the 144 identified radionuclides, given the transfer times in the Callovo-Oxfordian formation and inside the repository, the only radionuclides not covered by the normal evolution scenario are those with a half-life of less than 1000 years. This gives a list of 60 radionuclides that are adopted for the assessment of both situations. This list is presented in Table 2.1-1 below.

Table 2.1-1: List of radionuclides selected for the quantitative assessment of the normal evolution scenario (including decay chains)

RN	Half-life (years)
Be10	1,60E+06
C14	5,70E+03
Al26	7,17E+05
Cl36	3,01E+05
K40	1,27E+09
Ca41	1,03E+05
Mn53	3,68E+06
Fe60	1,50E+06
Ni59	7,60E+04
Se79	3,77E+05
Kr81	2,10E+05
Rb87	4,81E+10
Zr93	1,53E+06
Nb92	3,50E+07
Nb93m	1,60E+01
Nb94	2,00E+04
Mo93	4,00E+03
Tc97	2,60E+06
Tc98	4,20E+06
Tc99	2,14E+05
Pd107	6,50E+06
Sn126	2,30E+05
I129	1,61E+07
Cs135	2,30E+06
La137	6,00E+04
Sm146	1,00E+08
Gd150	1,82E+06
Dy154	3,00E+06
Ho163	4,57E+03
Ho166m	1,20E+03
Lu176	4,00E+10
Hf182	9,00E+06
Re186m	1,90E+05
Pb202	5,30E+04
Pb205	1,53E+07
Bi208	3,68E+05
Bi210m	3,00E+06

RN	Half-life (years)
Ra226	1,60E+03
Th229	7,34E+03
Th230	7,54E+04
Th232	1,41E+10
Pa231	3,28E+04
U233	1,59E+05
U234	2,46E+05
U235	7,04E+08
U236	2,37E+07
U238	4,47E+09
Np236	1,52E+05
Np237	2,14E+06
Pu239	2,41E+04
Pu240	6,56E+03
Pu242	3,74E+05
Pu244	8,00E+07
Am243	7,36E+03
Cm245	8,50E+03
Cm246	4,73E+03
Cm247	1,60E+07
Cm248	3,40E+05
Cm250	8,00E+03
Bk247	1,38E+03

Decay chains considered
Zr93→Nb93m,
4N (Cm244→Pu240→U236→Th232→Th228→Ra228),
4N+1 (Cm245→Pu241→Am241→Np237→U233→Th229),
4N+2 (Cm246→Pu242→U238→U234→Th230→Ra226→Pb210)
4N+3 (Am243→Pu239→U235→Pa231→Ac227).

CG.IM.AEAP.15.066.A

2.1.4.2 Radiological activities adopted

The inventories adopted for the radionuclides studied are inventories taken from the Inventory Construction Table (TCI), with a margin added, depending on the level of knowledge. The inventories are presented in Volume II, Chapter 2.

2.1.4.3 Distribution of radiological activity in the repository

The methods concerning distribution of the radiological inventory and distribution within the architecture, as adopted for the safety assessments, are represented in Chapter 1 of this Volume.

Two distribution modes have been adopted for the quantitative assessments of the normal evolution scenario, depending on the nature of the waste, i.e. HLW or ILW-LL.

2.1.5 Release of radionuclides and toxic elements

2.1.5.1 Intermediate-level long-lived waste (ILW-LL)

The release models adopted for the quantitative safety assessments associated with the normal evolution scenario are presented in Volume II, Chapter 2.

Depending on the type of ILW-LL, the following are adopted:

- a generalised corrosion model for the activated metal items for metallic waste;
- the COLONBO model for the reference situation only, for saline waste with a bitumen matrix, for the duration of container integrity (estimated to be 1000 years);
- a "V_0.S" type glass dissolution model for vitrified ILW-LL (with values that maximise the release kinetics in the "bounding" situation).

2.1.5.2 High-level waste (HLW)

The release of vitrified HLW is initiated following disposal container loss of leaktightness. This release takes into account the alteration kinetics affecting the vitreous matrix in disposal conditions.

The safety options concerning the release models for each type of HLW package and the associated parameters are presented in Volume II, Chapter 2. Depending on the intrinsic qualities of the glass, two releases models have been adopted in the reference situation:

- one alteration regime that takes into account residual rate "$V_0 \rightarrow V_R$" in the clay medium;
- one alteration regime taking into account the initial rate "V_0.S".

In the "bounding" situation, only the alteration regime taking account of the initial rate "V_0.S" is adopted.

2.1.6 Callovo-Oxfordian formation

The main characteristics of the Callovo-Oxfordian are based on the good level of understanding of this formation (see Volume II, Chapter 1).

Based on the range of values proposed, the adopted parameters are "phenomenological" for the reference situation and "conservative" for the bounding situation.

Geometry of the Callovo-Oxfordian formation

The top and the bottom of the Callovo-Oxfordian formation are assimilated with the SNC (stratigraphic unconformity surface) and LS0 (stratigraphic sequence boundary 0) surface respectively. The average thickness of the Callovo-Oxfordian is 153 metres in the zone of interest for detailed survey (ZIRA). It varies from 142 to 162 metres from South-West to North-East.

For a repository located in the mid-height plane of the Callovo-Oxfordian (reference situation), variability of the undisturbed formation (above or below cells) is 72 to 80 metres for the HLW disposal sections, and 70 to 72 metres for the ILW-LL disposal section.

Homogeneity of the Callovo-Oxfordian formation

The Callovo-Oxfordian is represented as a laterally homogeneous layer with no fractures.

Hydraulic head gradients

Advective transport in the Callovo-Oxfordian and surrounding formations is determined by the hydrogeological model. The model has given a low hydraulic head gradient at the repository location (see Volume II, Chapter 1).

- in the reference situation, the vertical hydraulic head gradients have been estimated using the hydrogeological model, considering the real geometry of the Callovo-Oxfordian formation and the position of the various repository structures in the ZIRA, leading to the adoption of the values presented in Table 2.1-2;
- in the bounding situation, by conventional choice, the maximum hydraulic head gradient in the ZIRA has been applied throughout the zone and over the full duration of assessments (i.e. 0.1 $m.m^{-1}$ in direction of the Oxfordian formation with an upper undisturbed formation of 50 metres, and 0.05 $m.m^{-1}$ in the direction of the Dogger formation with a lower undisturbed formation of 50 metres).

Intrinsic characteristics of the Callovo-Oxfordian formation

The characteristics of the Callovo-Oxfordian clay rock adopted for the assessments are given in Table 2.1-2 and Table 2.1-3. For the record, the parameter values presented in these tables are "to the best of knowledge" values for the reference situation and the values specified in the requirements or conservative values (if not specified) in the bounding situation.

Table 2.1-2: Parameters applicable to the undisturbed Callovo-Oxfordian clay rock (SNC: stratigraphic unconformity surface, LS0: stratigraphic sequence boundary 0)

	Reference situation	Bounding situation
Criteria and dimensions	Callovo-Oxfordian bounded by the SNC and LS0 Real thickness, ranging from 142 to 162 metres in ZIRA Undisturbed formation: 72 to 80 metres for the HLW disposal sections, and 70 to 72 metres for the ILW-LL disposal section, located in the middle of the Callovo-Oxfordian.	Minimum total thickness (145 metres) applied throughout. Lower or upper undisturbed formation of 50 metres
Permeability (K), in m/s	Kh=Kv=4 x 10^{-14} m/s	Kv=2 x 10^{-13} *m/s* Kh=3 x 10^{-13} *m/s*
Hydraulic head gradient, in $m.m^{-1}$	From hydrogeological modelling: Between -0.04 $m.m^{-1}$ and 0.08 $m.m^{-1}$	Min/max values applied throughout: 0.1 $m.m^{-1}$ in the direction of the Oxfordian formation (upper undisturbed formation of 50 metres) 0.05 $m.m^{-1}$ in the direction of the Dogger formation (lower undisturbed formation of 50 metres)
Kinematic porosity (ω_{cin}), no units	Total porosity / 2 = 9%	Total porosity / 4 = 4.5%
Dispersivity, in m	α_L=Thickness / 10 α_T=Thickness / 100 Negligible dispersal	

(SNC: stratigraphic unconformity surface, LS0: stratigraphic sequence boundary 0)

Table 2.1-3: Retention and transfer properties for the main radionuclides in undisturbed clay rock

Radio-nuclides	Ionic form	Effective diffusion coefficient (De) (10^{-12} $m^2.s^{-1}$)		Kinematic porosity (ω_{acc}), no units		Partition coefficient (Kd) in $m^3.kg^{-1}$		Solubility limit (Csat) in $moles.L^{-1}$	
		Reference situation	Bounding situation	Reference situation	Bounding situation	Reference situation	Bounding situation	Reference situation	Bounding situation
^{14}C	Organic	2.75	6.5	0.07	0.05	0	0	Infinite	Infinite
^{26}Al	$Al(OH)_4^-$	2.5	6.5	0.07	0.05	0	0	2×10^{-8}	6×10^{-6}
^{36}Cl	Cl-	5	6.5	0.07	0.05	0	0	Infinite	Infinite
^{40}K	K+	110	220	0.18	0.18	5×10^{-3}	1×10^{-3}	9×10^{-4}	1×10^{-3}
^{41}Ca	Ca^{2+}	65	220	0.18	0.18	4×10^{-3}	1×10^{-3}	8×10^{-3}	3×10^{-2}
^{76}Se	HSe-	2.5	6.5	0.07	0.05	0	0	2×10^{-9}	1×10^{-7}
^{93}Mo	MoO_4^{2}	2.475	6.5	0.07	0.05	3×10^{-3}	0	2×10^{-7}	2×10^{-5}
^{129}I	I-	3	6.5	0.07	0.05	0	0	Infinite	Infinite
^{235}U ^{238}U	$Ca_2UO_2(CO_3)_3^0$	4.4	30	0.18	0.18	0.1	0.01	2×10^{-6}	2×10^{-6}

2.1.7 Mechanical damage to the clay rock at repository closure

The mechanically damaged to clay rock is conceptualised as a connected fracture zone (ZFC) and a discrete fracture zone (ZFD). In order to simplify numerical conceptualisation, these zones are represented as circles with a surface area equivalent to that of the ellipses of the geomechanical model (Figure 2.1-3).

The ZFC and ZFD are represented as continuous along the structures, except at the zones where the concrete liner will be removed for the seals (see Figure 2.1-10), for the full duration of the assessments.

Representation of these zones takes into account:

- the difference in behaviour depending on the Callovo-Oxfordian unit (clay unit (UA), silty-carbonated unit (USC) or transition unit (UT)) - there is no ZFC in the USC and UT.
- the geometry and proportionality of the damaged zone extension with respect to the diameter and orientation of the excavated structure, and for the ILW-LL cells, the void fraction.

The drifts are orientated either along the major stress or the minor stress. The drift conceptualisation considers a damaged zone whose extension corresponds to the largest damaged area (i.e. σ_h).

The choice of transport and retention characteristics in the connected fracture zone (ZFC) and discrete fracture zone (ZFD) is presented Table 2.4-7 (Appendix 1). The values for the adopted parameters are presented in Table 2.1-4. The additional damage zone around the ILW-LL cells is represented with the same hydraulic parameters (permeability) as the ZFC and the same retention and transport properties as undisturbed rock.

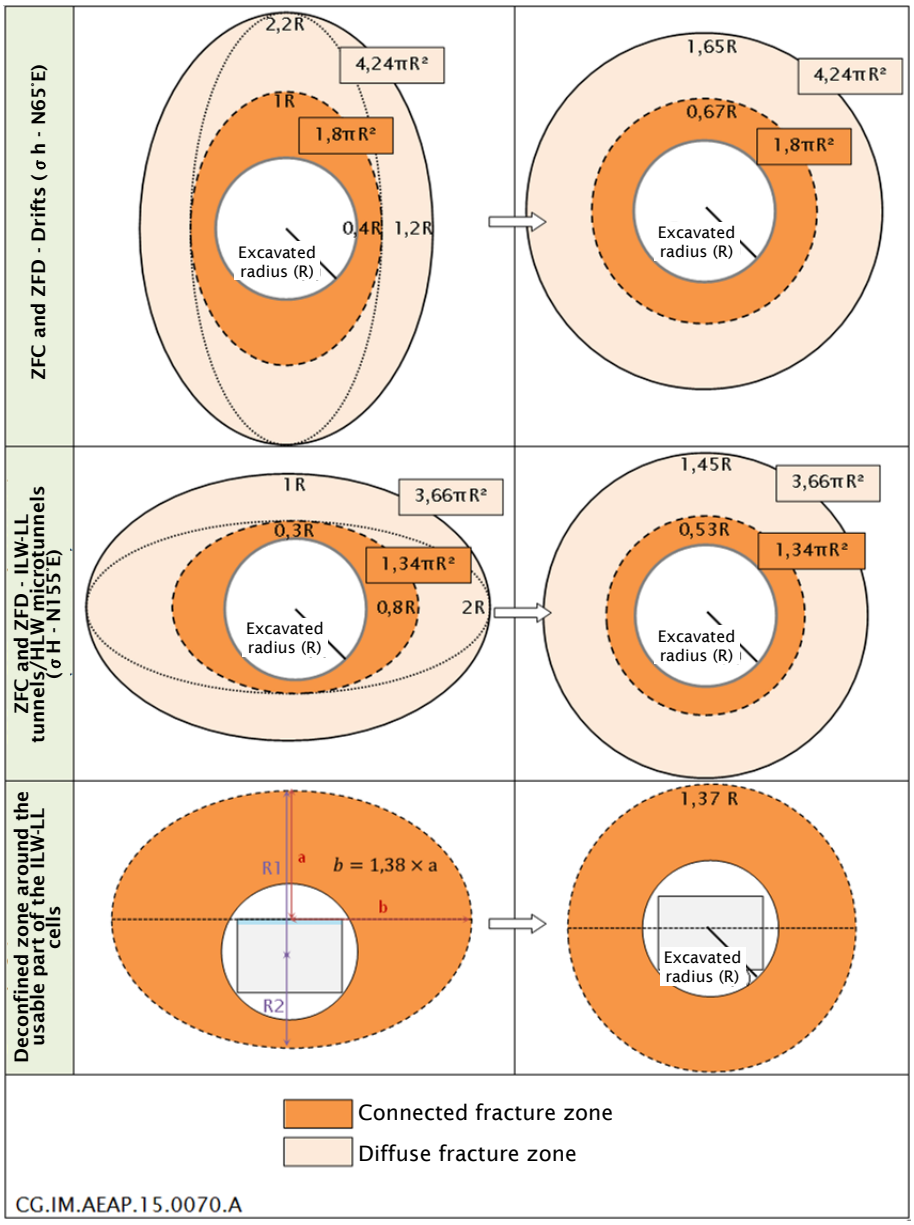


Figure 2.1-3: Conceptual diagram of the connected and discrete fracture zones and the deconfined zone around the ILW-LL

2.1.7.1 Connected Fracture Zone (ZFC)

Hydraulic characteristics

In line with the analysis presented in the chapter on management of risks and uncertainties (Chapter 1.4.1), the permeability value has been defined so as to take hydraulic healing into account (see in Table 2.4-7, Appendix 1):

In the reference situation, permeability is:

- 10^{-11} m/s at the zones where the concrete liner is removed for the seals;
- 10^{-9} m/s at the standard sections of the drifts, ILW-LL cells and HLW cells and at the portions of clay core where concrete liner/ is left in place.

In the bounding situation, permeability is:

- 10^{-10}m/s at the zones where the concrete liner is removed for the seals;
- 10^{-8} m/s at the standard sections of the drifts, ILW-LL cells and HLW cells and at the portions where concrete liner is left in place between the clay rock and the seal clay core.

In line with the analysis presented in Chapter 1.4.1, corrective factors are applied to the diffusion parameters, and the chemical retention parameters (excluding coinciding chemical and thermal stresses) are conservative. These values are presented in Table 2.1-4, in relation to the values adopted for the undamaged Callovo-Oxfordian clay rock (Table 2.1-3).

2.1.7.2 Discrete Fracture Zone (ZFD)

Because the self-sealing and hydraulic healing processes are taken into account, the discrete fracture zone is not represented in the reference situation, only in the "bounding" situation. The ZFD is not represented around the ILW-LL cells, beyond the additional damage zone related to consideration of the void fraction (deconfinement).

The ZFD is represented with the maximum extension defined for it in the conceptual model (Figure 2.1-3). It has a conservative permeability value, taken from Underground Research Laboratory post-excavation measurements: 10^{-11} m/s in the silty-carbonate unit (USC) and 10^{-10} m/s in the clay unit (UA) (Table 2.1-4).

Table 2.1-4: Parameters applicable to damaged Callovo-Oxfordian clay rock

	ZFC (reference situation)	ZFC (bounding situation)	Deconfinement around the ILW-LL cells (reference situation)	ZFD (bounding situation)
Criteria and dimensions	ZFC with a circular cross-section of equivalent area to the ovoid cross-section: Uniform thickness 0.67 R around the drifts 0.53 R around the ILW-LL cells		Circular cross-section of equivalent area to the ovoid cross-section: Uniform thickness 1.37 R	ZFD with a circular cross-section of equivalent area to the ovoid cross-section: see Figure 2.1-3
Permeability (K), in m/s	1×10^{-09} m/s (1.10^{-11} m/s at the zones where the concrete liner is removed for the seals)	1×10^{-08} m/s (1.10^{-10} m/s at the zones where the concrete liner is removed for the seals)	1×10^{-09} m/s	In the UT/USC: 1×10^{-11} m/s In the UA: 1×10^{-10} m/s
Kinematic porosity (ω_{cin}), no units	Total porosity / 2	Total porosity / 4	Total porosity / 2	Total porosity / 4
Diffusion coefficient in $m^2.s^{-1}$	De(RN) * 2	2* (De(tracer) + 30%)	De(RN) * 2	De(tracer) + 30%
Accessible porosity (ω_{acc}), no units	Anions 7% Neutrals and cations Total porosity	Anions 5% Neutrals and cations Total porosity	Anions 7% Neutrals and cations Total porosity	Anions 5% Neutrals and cations Total porosity
Partition coefficient (Kd) in $L.g^{-1}$	Conservative Kd and Csat values used in the Callovo-Oxfordian in the bounding situation	Conservative Kd and Csat values used in the Callovo-Oxfordian in the bounding situation	Conservative Kd and Csat values used in the Callovo-Oxfordian in the reference situation	Conservative Kd and Csat values used in the Callovo-Oxfordian in the bounding situation
Solubility limit (Csat) in $mol.L^{-1}$				

(R: radius of the structure, RN: radionuclide)

2.1.8 Thermal transient

Spatio-temporal evolution in the thermal plume has been estimated using simulations (Volume II, Chapters 3.2.1.4)

For the exothermic HLW disposal cells, the influence of temperature has been incorporated into the radionuclide release model (see Chapter 2.3.3.2).

The influence of the thermal transient is taken into account in the Callovo-Oxfordian (whether mechanically damaged or otherwise) around the exothermic waste disposal sections, in the volume of rock assessed by simulations (Figure 2.1-4).

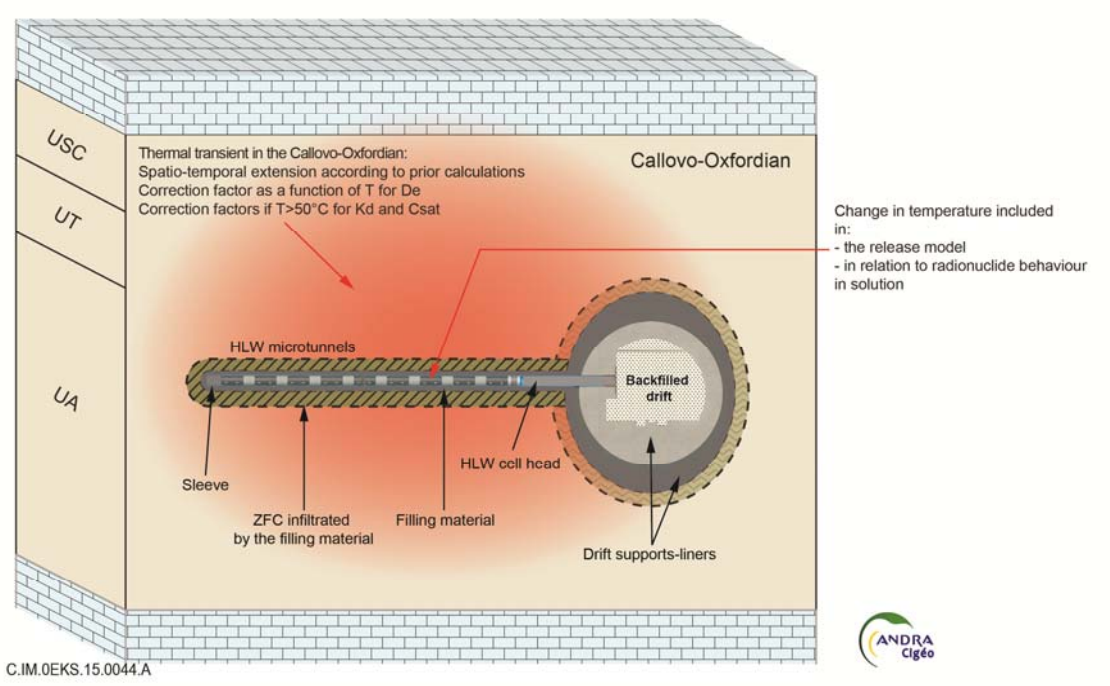


Figure 2.1-4: Schematic diagram of the zone affected by the thermal transient around an HLW cell

The influence of temperature on transport and retention properties is taken into account by applying corrective factors to the effective diffusion coefficients and the retention parameters of certain radionuclides. These corrective factors are presented in Table 2.1-5.

Table 2.1-5: Corrective factors applied to the transport and retention parameters, according to temperature, in the undisturbed or mechanically damaged Callovo-Oxfordian

	Radionuclides	Influence of temperature
Permeability and kinematic porosity	N/A	Effect not taken into account
De	All	F > 1 as defined by the Stokes-Einstein relation
ω_{acc}	All	No effect
Kd	Alkalines and alkaline earths	F=0.1 if T>50°C
	Others	No effect
Csat	Alkalines and alkaline earths	F=10 if T>50°C
	Others	No effect

2.1.9 Chemical disturbances

The chemical disturbances represented are as follows:

- "alkaline" disturbance, which occurs in contact with alkaline fluids from cement-based materials as they gradually deteriorate;
- "organic" disturbance related to the release of organic species by certain types of ILW-LL waste;
- "saline" perturbation related to the presence of saline fluids from certain types of ILW-LL waste.

The methods used to represent these disturbances are defined on a case-by-case basis, in terms of extension and the potential effects on the characteristics of components required to perform the safety functions (e.g. permeability, chemical transport and retention of radionuclides).

2.1.9.1 Alkaline disturbance from the degradation of cement-based materials

The alkaline plume caused by hydrolytic degradation of the cement-based materials is represented by two zones:

- the first so-called "remineralised" zone, where the interactions have a significant effect, leading in particular to the transformation of smectites;
- a second zone referred to as the "zone affected by an alkaline plume without remineralisation", where there is a plume of elements from the concrete degradation, but no remineralisation.

Alkaline disturbance is represented in the clay rock in contact with cement-based structures. It is not represented in the seal clay core or in the drift backfill.

The spatio-temporal extension of the two zones takes into account the nature of the cement-based material (conventional or low-pH concrete). The volumes of rock affected correspond to the maximum spatio-temporal extension given in the preparatory calculations until the alkaline source generating the disturbance runs out.

Since the extension of the alkaline disturbance is more limited than that of the connected fracture zone (ZFC), it is not represented in the undamaged Callovo-Oxfordian.

In a conservative approach, these representations are maintained from repository closure and throughout the duration of assessment, with no effect of gradual alteration over time taken into account.

Table 2.4-8 in Appendix 1 summarises the methods used to represent alkaline disturbance, depending on the different interfaces involved. These methods are illustrated in Figure 2.1-5.

Conventional concrete/ clay rock interface at the usable part of the ILW-LL disposal cells and backfilled drifts.

<u>In the remineralised ZFC:</u>

Under a very conservative approach, the remineralisation part of the ZFC is represented with hydraulic characteristics and transport properties similar to sand (i.e. conservative permeability, De and accessible porosity values).

Nevertheless, to take into account the favourable effects of new mineral phases, the partition coefficients taken into account in the reference situation are conservative, compared to measured values (see Table 2.4-8 in Appendix 1).

<u>In the non-remineralised ZFC, affected by the alkaline plume:</u>

In the affected volume of rock (defined in the preparatory calculations):

- the effect of ionic strength on anion diffusion is the same as for the saline perturbation described below. The same corrective factors are applied (as summarised in Table 2.1-6);
- the competing effect of the disturbance on alkalines and alkaline-earths is taken into account by applying the same corrective factors to the partition coefficients as for the saline perturbation. These factors are summarised in Table 2.1-6. ;

- the effect of the alkaline plume on solubility is taken into account according to ionic strength by applying the same corrective factors to the solubility limits as for the saline perturbation. These factors are summarised in Table 2.1-6.

▪ ***Interface between clay rock or clay core and low-pH concrete***

Low-pH concrete is envisaged as a material for the seal containment walls and portions of the liner between the clay core and the clay rock.

Only the plume with no remineralisation is represented (see Figure 2.1-10 and Chapter 1). Sorption and diffusive transport properties (De, accessible porosity) of the clay core, which are represented in the reference situation, take account of the potential influence of this alkaline plume (Table 2.1-9).

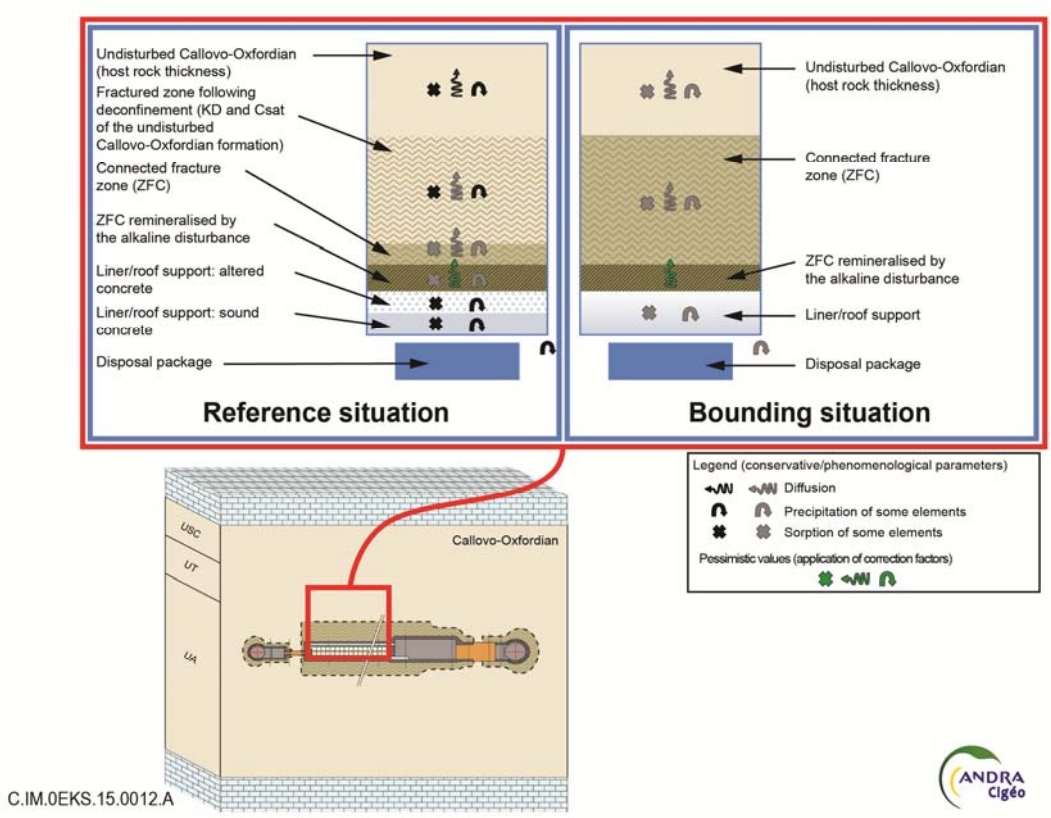


Figure 2.1-5: Schematic diagram of the influence of alkaline disturbance at the clay rock/conventional concrete interface on transport and retention characteristics (example from around the ILW-LL cells)

2.1.9.2 Disturbance related to the presence of organic complexing substances

Given the influence of organic complexing substances on retention, they are taken into account and their effect is explicitly represented in the liner concrete and the clay rock (whether mechanically damaged or otherwise) around the ILW-LL cells that contain such substances (see Figure 2.1-6).

In these components, the effect of organic disturbance is taken into account by applying corrective factors to the partition coefficients (Kd) and the solubility values (Csat) of all radionuclides except mobile anionic radionuclides (in the clay rock) and alkaline cations. These factors are presented in Table 2.1-6 for the Callovo-Oxfordian clay rock and in Table 2.4-10 (Appendix 1) for the concrete. In a conservative approach, they are applied throughout the assessment duration.

These corrective factors are applied on the basis of the organic molecule concentration and depending on their type (ISA or other ligands), as presented in Table 2.1-6. These concentrations are assessed using preparatory calculations, based on the ILW-LL disposal cell containing the highest quantity of organics.

For the clay core of the ILW-LL cell seals, the same corrective factors used for the clay rock are applied in the reference situation.

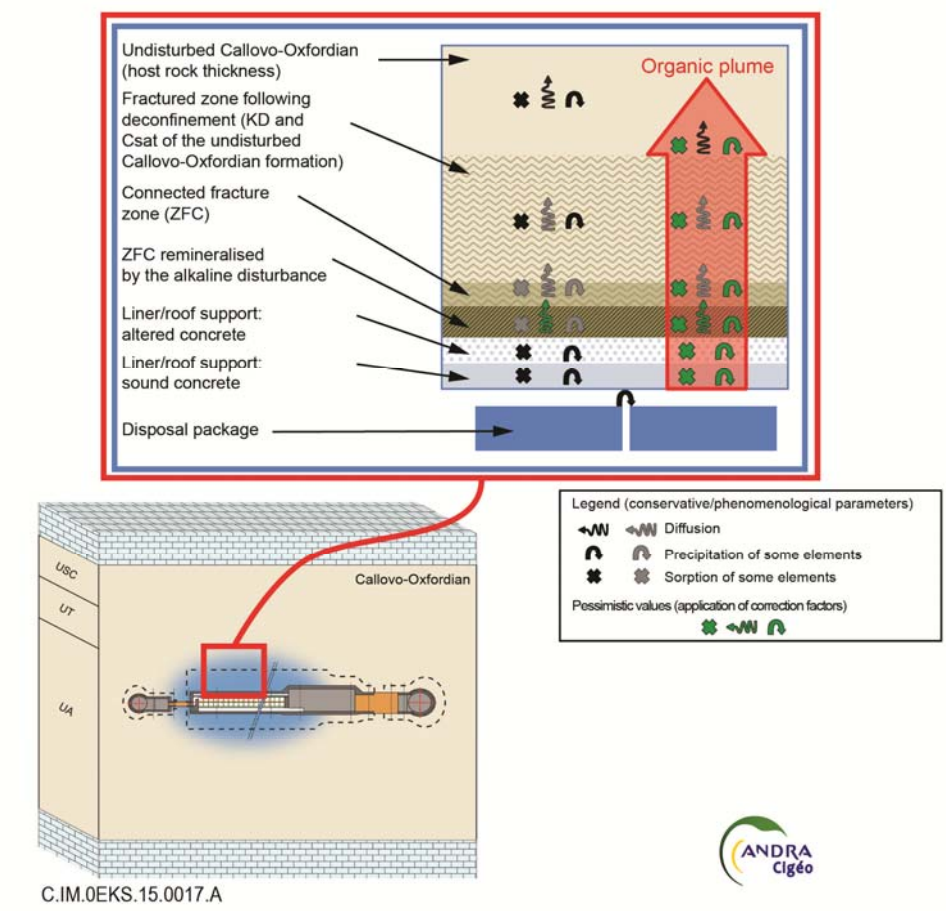


Figure 2.1-6: *Schematic diagram showing how a plume of organic complexing substances is taken into account with respect to the transport and retention characteristics around an ILW-LL cell (reference situation example)*

2.1.9.3 Saline perturbation

To take into account the effect of saline fluids from certain types of ILW-LL, corrective factors are applied to the transport and retention properties of certain radionuclides within the concrete liner of the ILW-LL cells, in the mechanically damaged clay rock zone (deconfined zone around the usable part of the ILW-LL cells) or undisturbed clay rock around any ILW-LL cells containing such fluids.

In a conservative approach, these corrective factors are applied throughout the assessment duration.

In the clay rock, these corrective factors are applied according to the ionic strength obtained from preparatory calculations. If ionic strength is greater than 2M, chemical retention is not represented.

The influence of saline perturbation on the diffusion coefficients in concrete is not represented, since the diffusion coefficients chosen are already conservative.

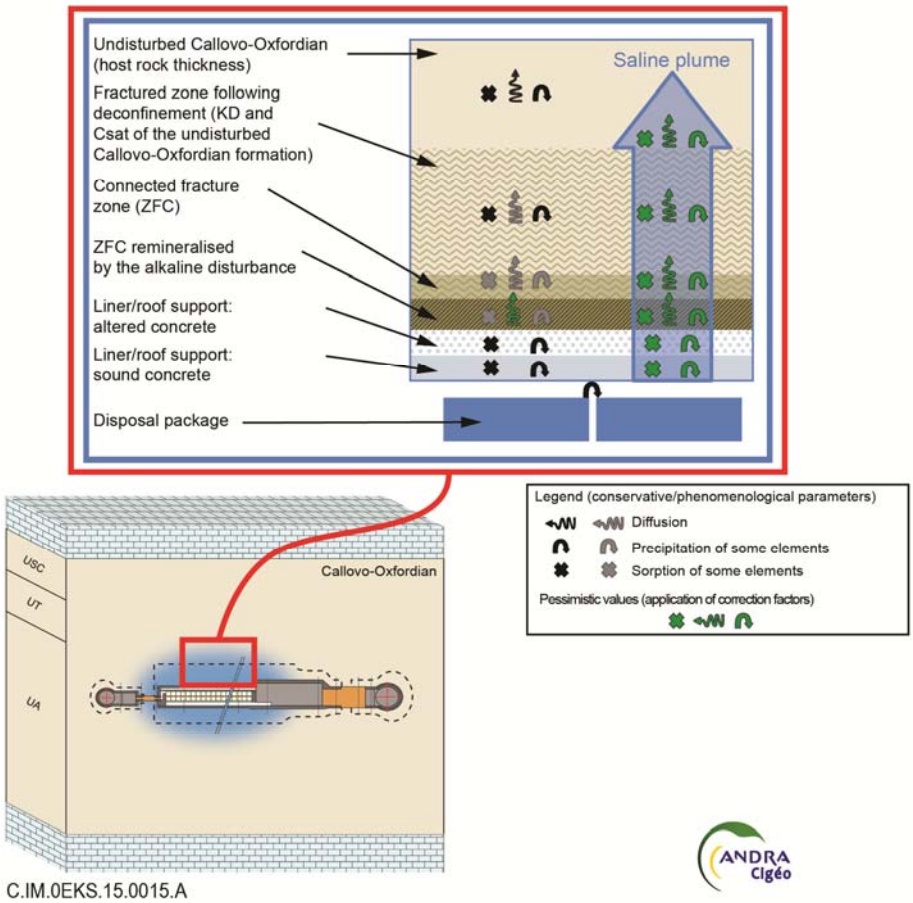


Figure 2.1-7: *Schematic diagram showing how saline perturbation is taken into account with respect to the transport and retention characteristics around an ILW-LL cell (reference situation)*

Table 2.1-6: Corrective factors (F) applied to the retention and transport parameters according to the chemical disturbances in the undisturbed or mechanically damaged Callovo-Oxfordian

<table>
<tr><th></th><th>Radionuclides</th><th colspan="2">Alkaline or saline perturbation</th><th colspan="2">Organic disturbance</th></tr>
<tr><td>Criteria and extension</td><td></td><td>Ionic strength</td><td>[K] > 10^{-2} mol.L^{-1}</td><td>[ISA] > 1 x 10^{-4} mol.L^{-1} (or [L]* > 1 x 10^{-3} mol.L^{-1})</td><td>[ISA] > 1 x 10^{-3} mol.L^{-1} (or [L]* > 1 x 10^{-2} mol.L^{-1})</td></tr>
<tr><td>Permeability and kinematic porosity</td><td>N/A</td><td>No effect</td><td>No effect</td><td>No effect</td><td>No effect</td></tr>
<tr><td rowspan="3">De</td><td>Anions</td><td>I<0.2M: F=1
0.2M<I<0.5M: F=1.5
0.5M<I: F=2</td><td rowspan="3">No effect</td><td rowspan="3">No effect</td><td rowspan="3">No effect</td></tr>
<tr><td>Neutrals</td><td>No effect</td></tr>
<tr><td>Cations</td><td>I<0.2M: F=1
0.2M<I<0.5M: F=1/1.5
0.5M<I: F=1/2</td></tr>
<tr><td rowspan="2">ω_{acc}</td><td>Anions</td><td>I<0.2M: F=1
0.2M<I<0.5M: F=1/1.3
0.5M<I: F=1/1.5</td><td rowspan="2">No effect</td><td rowspan="2">No effect</td><td rowspan="2">No effect</td></tr>
<tr><td>Neutrals and cations</td><td>No effect</td></tr>
<tr><td rowspan="4">Kd</td><td>Mobile anions (chlorine-36, iodine-129, aluminium-26, selenium-79)</td><td colspan="4">No sorption</td></tr>
<tr><td>Alkalines (K, Cs)</td><td rowspan="2">I<0.2M: F=1
0.2M<I<0.5M: F=0.2
0,5M<I<1M: F=0.1
1M<I<2M: F=0.05
2M<I Kd=0</td><td rowspan="2">[K]<0.01M: F=1
0.01M<I<0.1M: F=0.25
0.1M<I<0.5M: F=0.1
I<0.5M: F=0.04</td><td colspan="2">No effect</td></tr>
<tr><td>Alkaline earths</td><td rowspan="2">F=0.1</td><td rowspan="2">F=0.01</td></tr>
<tr><td>Other RNs (including actinides and lanthanides)</td><td>Kd=0 if I>2M</td><td>No effect</td></tr>
<tr><td rowspan="4">Csat</td><td>Mobile anions (chlorine-36, iodine-129, aluminium-26, selenium-79)</td><td rowspan="4">If I > 0.4M, F=10
If I > 2M, Csat=∞</td><td rowspan="4">No effect</td><td colspan="2">No effect</td></tr>
<tr><td>Alkalines (K, Cs)</td></tr>
<tr><td>Alkaline earths</td><td rowspan="2">F=10</td><td rowspan="2">F=100</td></tr>
<tr><td>Other RNs (including actinides and lanthanides)</td></tr>
</table>

RN: radionuclide

2.1.10 ILW-LL disposal section

The ILW-LL disposal containers are placed in ILW-LL disposal cells fitted with a concrete liner.

The ILW-LL disposal section is represented according to the architecture on completion presented in Volume II, Chapter 3. The ILW-LL cells are sub-horizontal and excavated along the principal major stress. They are spaced as defined in the architecture on completion.

The ILW-LL disposal cells are represented with three distinct parts:

- a usable part where waste packages are disposed of;
- a concrete containment wall at each end;
- a seal at each end.

One design option with an ILW-LL disposal cell seal of lower performance is being studied. It is represented with ILW-LL closure structures of equivalent performance to backfill.

Note: For the altered evolution scenarios and "What-if" scenario assessment, the base case considered is ILW disposal cells with less effective closure systems, and the alternative case is ILW disposal cells with standard seals.

The usable part where waste packages are disposed of is represented with a length of 500 metres. Given its roles and/or functions, the conceptualisation of the usable part of the ILW-LL cells distinguishes between (i) disposal containers and primary packages, (ii) cell shaping concrete, (iii) the cell concrete liner, and (iv) the mechanically damaged clay rock zone.

2.1.10.1 ILW-LL waste disposal packages

ILW-LL waste disposal packages comprise:

- a primary package containing waste and, in some cases, a bitumen and/or cement matrix.
- a reinforced concrete disposal container (except for CS6 and CS7 disposal packages). The ILW-LL disposal containers have no post-closure safety function, and are therefore only represented for their period of mechanical integrity, which is estimated at 1000 years at this stage. They are not assigned any transport or chemical retention properties.

The release models selected are described in Volume II, Chapter 2.

2.1.10.2 Concrete liner/roof support of the usable part of the ILW-LL waste disposal cells

The concrete liner of the ILW-LL waste package disposal cells helps "*limit the release of radioactive substances and toxic elements and immobilise them in the repository*." The anticipated contribution is expressed in terms of a chemical environment that facilitates precipitation and sorption phenomena.

No hydraulic or diffusion transport properties are anticipated. The concrete liner and the cell shaping concrete are therefore represented with an equivalent permeability to sand and conservative diffusion parameters throughout assessments, in both the reference and bounding situations.

The whole thickness of the concrete liner is represented by a single zone. For each radionuclide, the retention parameters selected are those which are the least favourable to retention:

- For the reference situation:
  - ✓ the partition coefficients (Kd) are the lowest "phenomenological" (or best estimate) values for sound and altered concretes;
  - ✓ the solubility limits (Csat) are the highest "phenomenological" (or best estimate) values for sound and altered concretes.
- For the "bounding" situation:
  - ✓ the partition coefficients are the lowest conservative values (Kd min) for sound and altered concretes;
  - ✓ the solubility limits are the highest conservative values (Csat max) for sound and altered concretes.

For the radionuclides for which we have no measurements or analogies, no chemical retention is considered (Kd=0 and Csat=∞).

Table 2.1-7: Transport dimensions and characteristics selected for the concrete liner of ILW-LL cells

	Reference situation	Bounding situation
Dimensions	ILW-LL cell concrete liner: thickness = 0.95 m Concrete sections removed in the seals: 4 ring-shaped sections with an individual length of 1 metre	
Permeability (K), in m/s	1×10^{-06} m/s	
Kinematic porosity (ω_{cin}), no units	20%	
Partition coefficient (Kd) in $m^2.s^{-1}$	Dp = D_0(HTO) = 2.3×10^{-9} $m^2.s^{-1}$	De = D_0(HTO) = 2.3×10^{-9} $m^2.s^{-1}$
Accessible porosity (ω_{acc}), no units	20%	

Table 2.1-8: Retention properties (sorption and solubility) for the main radionuclides in the ILW-LL cell liner concrete

Radio-nuclides	Ionic form	Partition coefficient (Kd) in $m^3.kg^{-1}$		Solubility limit (Csat) in moles.L^{-1}	
		Reference situation	Bounding situation	Reference situation	Bounding situation
^{14}C	Organic	0	0	Infinite	Infinite
^{26}Al	$Al(OH)_4^-$	0	0	3×10^{-5}	1×10^{-3}
^{36}Cl	Cl^-	0.02	0	Infinite	Infinite
^{40}K	K^+	0	0	Infinite	Infinite
^{41}Ca	Ca^{2+}	0.001	3×10^{-4}	1.9×10^{-2}	3×10^{-2}
^{76}Se	HSe^-	0	0	1.5×10^{-4}	5×10^{-3}
^{93}Mo	MoO_4^{2-}	0.003	10^{-4}	1.5×10^{-5}	3×10^{-4}
^{129}I	I^-	0.001	0	Infinite	Infinite
^{235}U ^{238}U	$Ca_2UO_2(CO_3)_3^0$	30	3	2.2×10^{-7}	7×10^{-6}

2.1.10.3 Callovo-Oxfordian clay rock surrounding the ILW-LL cells

The mechanically damaged zone is represented according to the methods set out in Chapter 2.1.7.

Both organic disturbances and saline perturbations are represented at the ILW-LL cells containing organic waste (physical and chemical type ILW-LL 3) and saline waste (ILW-LL 1 and 2).

For the organic plume, two distinct zones are represented, depending on the concentration of complexing agents (see Figure 2.1-8):

- an initial zone with a thickness of 10 metres around the excavated diameter of the ILW-LL cell, where the concentration is: [ISA]>10^{-4} mol.L^{-1} or [other ligands]>10^{-3} mol.L^{-1} ;
- a second zone with a thickness of two metres around the excavated diameter of the ILW-LL cell, where the concentration is: [ISA]>10^{-3} mol.L^{-1} or [other ligands]>10^{-2} mol.L^{-1} ;

For the saline plume, the following distinctions are made, depending on the ionic strength (see Figure 2.1-8):

- a zone with a thickness of six metres around the excavated diameter of the ILW-LL cells for ILW-LL 1 physicochemical type waste (waste containing a significant quantity of salts) where the ionic strength is between 0.2 and 0.5 mol.L^{-1};
- a zone with a thickness of four metres around the excavated diameter of the ILW-LL cells for ILW-LL 2 physicochemical type waste (bituminous waste) where the ionic strength is between 0.2 and 0.5 mol.L^{-1};
- and a zone corresponding to an ionic strength of over 1 mol.L^{-1} in the concrete.

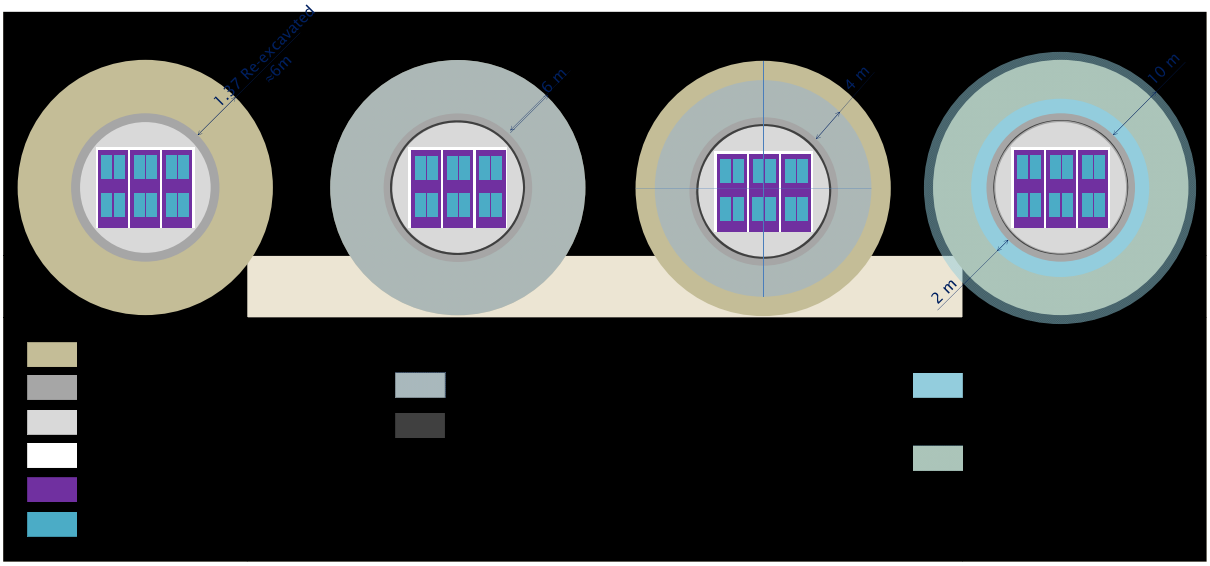


Figure 2.1-8: Conceptualisation of chemical disturbance plumes around the usable part of ILW-LL cells, depending on the type of waste (organic or saline)

The corrective factors applied for the disturbance affecting the clay rock are presented in Table 2.1-6. Transfer by colloids is not represented.

The values adopted for the assessments are presented in the summary tables provided in Chapter 2.1.15 (Table 2.1-11 and Table 2.1-12).

2.1.10.4 ILW-LL cell seals

The seals installed in the ILW-LL cell access drifts are represented in a similar fashion to the drift seals presented in Chapter 2.1.12.1. Chemical disturbances are handled in the same way as for the Callovo-Oxfordian.

2.1.11 The HLW disposal section

The HLW disposal containers are placed in HLW disposal cells fitted with a steel sleeve. They are distributed in specific sections:

- the low exothermic waste packages (HLW0), delivered before 2075, are disposed of in a specific disposal section. The HLW0 cells are conceptualised with a length of 80 metres;
- the HLW1 and HLW2 exothermic waste packages, delivered after 2075, are disposed of in separate disposal sections. The HLW1/HLW2 cells are conceptualised with a total length of 100 metres.

The HLW disposal sections are represented according to the architecture on completion presented in Volume II, Chapter 3. Disposal cells are sub-horizontal and excavated along the principal major stress. They are spaced according to the heat produced by waste.

The HLW disposal cells are represented with two distinct parts:

- a usable part where the HLW packages are disposed of and, in some cases, spacers are inserted between each package of highly exothermic waste delivered after 2075;
- a HLW cell head, represented explicitly by a homogeneous porous material with equivalent permeability to sand.

The NES considers that no disposal containers are defective at the time of repository closure.

Radionuclides begin to be released as soon as the disposal container loses its leaktightness:

- for the reference situation, disposal container loss of integrity is estimated at 4,300 years by taking a high corrosion rate value (10µm per year) defined in the applicable requirements, a minimum thickness value for the disposal container (53mm) and a residual thickness of 10mm (minimum thickness for preserving integrity).
- for the bounding situation, a conventional integrity period of 500 years is considered.

The spacers placed between the highly exothermic disposal packages are of the same diameter as the disposal containers. They are represented with no transport or chemical retention properties.

A schematic diagram of a HLW cell is given in Figure 2.1-9.

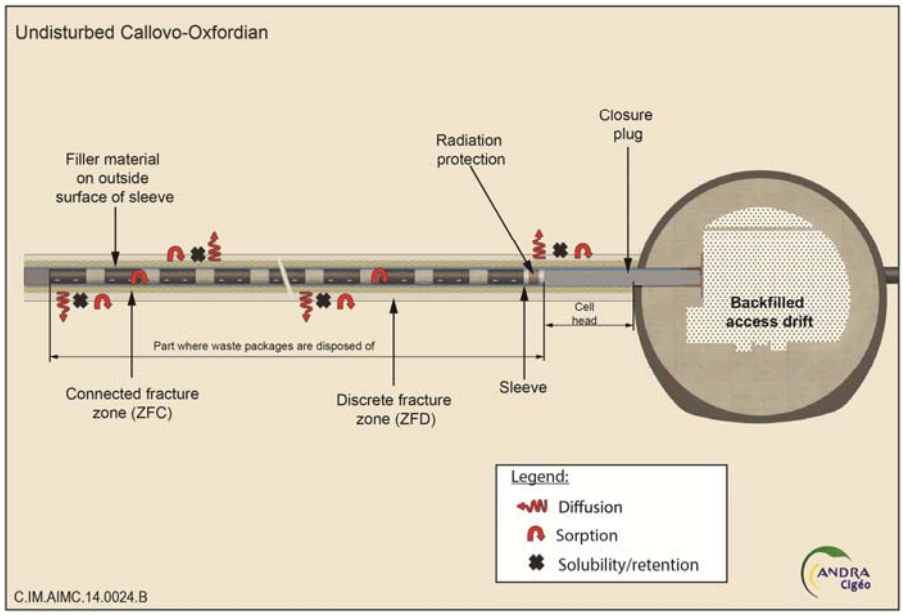


Figure 2.1-9: Schematic diagram of the HLW disposal cells for HLW waste packages with transport and retention characteristics mobilised

From a conservative perspective, the disturbance associated with the infiltration of the filler material is represented across the entire thickness of the ZFC. The ZFC is therefore represented, in both reference and bounding situations, with conservative properties equivalent to a ZFC remineralised by alkaline disturbance (permeability equivalent to sand, with no transport or retention properties).

The sleeve left in place at repository closure and the filler material for the annulus between the outside of the sleeve and the geological medium are represented in a similar way to the ZFC remineralised by alkaline disturbance.

Thermal disturbance is taken into account according to the methods presented in Chapter 2.1.8.

The values adopted for the assessments are presented in Table 2.1-11.

2.1.12 Drift closure systems

2.1.12.1 Drift seals

Drift seals comprise a 20-metre long swelling-clay central core, mechanically contained by two "low pH" concrete containment walls on each side. The interface between the seal core and the Callovo-Oxfordian clay rock is characterised by partial removal of the concrete segments (rings of liner), i.e. 4 metres removed in portions of 1 metre, and filled with the same swelling clay-based material (Figure 2.1-10).

The drift seals are represented by their hydraulic role expressed by a "full-scale" permeability equivalent to 10^{-9} m/s. Sorption in the swelling clay core is only considered in the reference situation, and not the bounding situation (see Table 2.1-9).

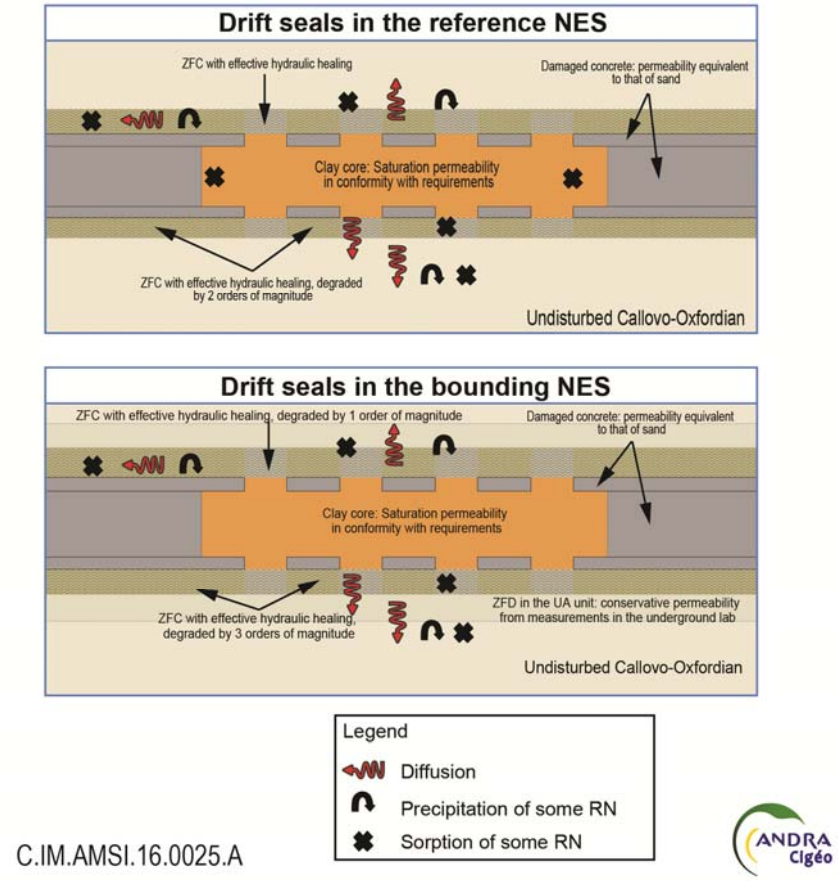


Figure 2.1-10: Schematic diagram of the representation choice for transport and retention characteristics in drift seal components

The drift seals are conceptualised as follows:

- the containment wall is grouped with the concrete segments (or concrete liner) and the compressible material injected on the outside of the concrete segments, constituting a macro-component;
- the swelling clay-based seal core is represented explicitly by an equivalent continuous porous material;
- the interface (with the partial removal zones) is represented by an equivalent permeability calculated through a harmonic mean of the permeabilities weighted by the lengths;
- at the seal, distinctions are made between (i) the localised ZFC at the concrete segments (or liners) left in place and (ii) the ZFC in direct contact with the clay core.

The ZFC is represented by an equivalent porous material with permeability calculated as the harmonic mean of the permeabilities weighted by the ZFC lengths at the removal areas.

For the bounding situation, the ZFD is represented by a porous material with conservative permeability taken from Underground Research Laboratory measurements.

The properties of the swelling clay-based clay core are presented in Table 2.1-9.

Table 2.1-9: Parameters applicable to the swelling clay -based clay core

	Reference situation	Bounding situation
Dimensions	Length of clay core for drift seals: 20 metres Length of clay core for shaft seals: 40 metres Length of clay core for ramp seals: *ramps represented by a horizontal part and a vertical part which include a 40m core*	
Total porosity ω_T	30%	
Permeability (K), in m/s	1×10^{-11} m/s	
Kinematic porosity (ω_{cin}), no units	Total porosity / 2	Total porosity / 4
Diffusion coefficient in $m^2.s^{-1}$	$Dp = D_0$ (RN)	$De = D_0$ (tracer)
Accessible porosity (ω_{acc}), no units	Anions 5% Neutrals and cations: Total porosity:	
Partition coefficient (Kd) in $L.g^{-1}$	Kdmin (bentonite) * min fraction smectites	Kd=0
Solubility limit (Csat) in $mol.L^{-1}$	Csat values in the Callovo-Oxfordian, in the bounding situation	Csat=∞

RN: radionuclide

2.1.12.2 Backfilled drifts

The backfilled drift includes (Figure 2.1-11):

- the backfill, which is not specified at this stage, but is considered to be primarily constituted of excavated clay rock reconditioned by grinding and screening;
- the concrete segments (or liners) left in place;
- the compressible material injected on the outside of the segments.

Conservative diffusion parameters (effective diffusion coefficient and accessible porosity) are used for the reference and bounding situations. Chemical retention by sorption and precipitation is not represented.

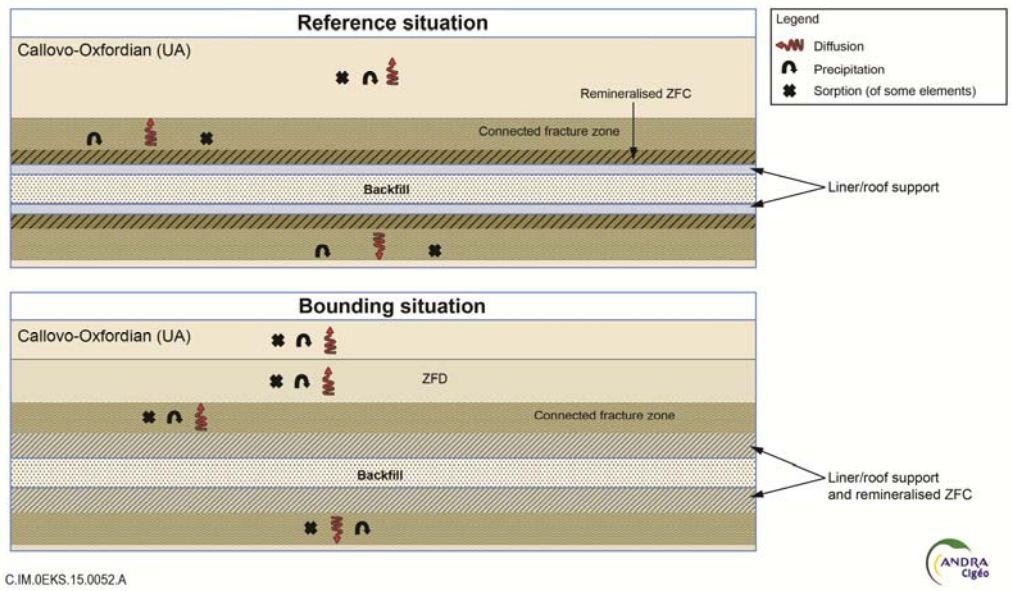


Figure 2.1-11: Schematic diagram of the components of a backfilled drift in the reference and bounding situations

For the numerical conceptualisation of the backfilled drifts, these three components are grouped into a macro-component with equivalent permeability calculated as the arithmetical mean value of permeabilities weighted by the respective cross-sections of the various components (see Table 2.1-10 and Table 2.1-11).

The conservative diffusion parameters (effective diffusion coefficient and accessible porosity) are used for the reference and bounding situations. Chemical retention by sorption and precipitation is not represented.

Table 2.1-10: Parameters applicable to backfilled drifts

	Reference situation	Bounding situation
Permeability (K), in m/s	1×10^{-08} m/s	
Kinematic porosity (ω_{cin}), no units	40%	
Diffusion coefficient in $m^2.s^{-1}$	$Dp = D_0(HTO)$	$De = D_0(HTO)$
Accessible porosity (ω_{acc}), no units	Anions 20% Neutrals and cations 40%	
Distribution factor (Kd) in $L.g^{-1}$	Kd=0	
Solubility limit (Csat) in $mol.L^{-1}$	Csat=∞	

2.1.13 Surface-bottom connection closure structures

Seals are installed in the surface-bottom connection structures at closure of the repository, in the upper part of the Callovo-Oxfordian in the units (USC and UT) where no ZFC develops. The mechanical strength of the rock means that the liner and roof support can be removed from the wall along the length of the clay core. The ZFD and the liner are therefore not represented.

Surface-to-bottom connection seals are therefore made up of:

- a central swelling clay-based core along the full height of the USC + UT horizon for the shafts, i.e. 40 metres, and a length of 100 metres for the ramps;
- "low pH" concrete containment walls on either side of the core.

Figure 2.1-12 and Figure 2.1-13 illustrate the choices made to represent the shaft seals and Figure 2.1-14 shows the ramp seals.

The surface-bottom connection seals are represented for their hydraulic role, i.e. by homogenised saturation permeability of the core and the interface with materials in contact with it. The permeability of the core is considered equal to the requirements, i.e. 10^{-11} m/s.

Conservative partition coefficients are selected for the reference situation.

The containment walls are represented with a permeability equivalent to sand (see Table 2.1-11). No diffusion transport or chemical retention properties are considered.

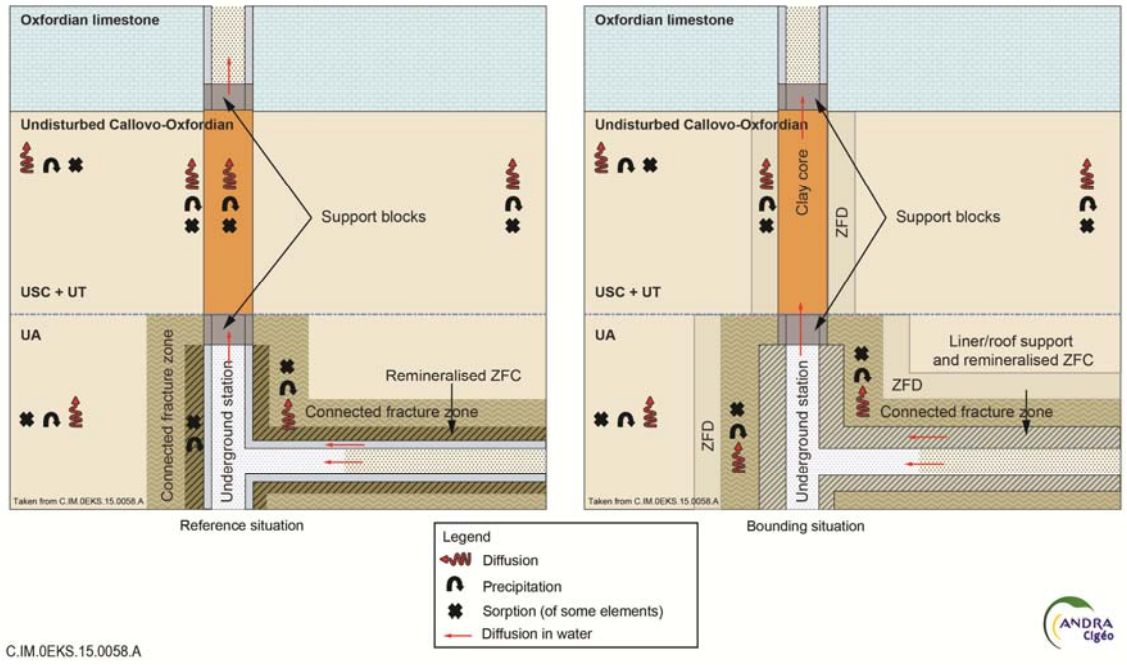


Figure 2.1-12: Schematic diagram of the representation choice for shaft seals and transport and retention characteristics (left: reference situation, right: bounding situation)

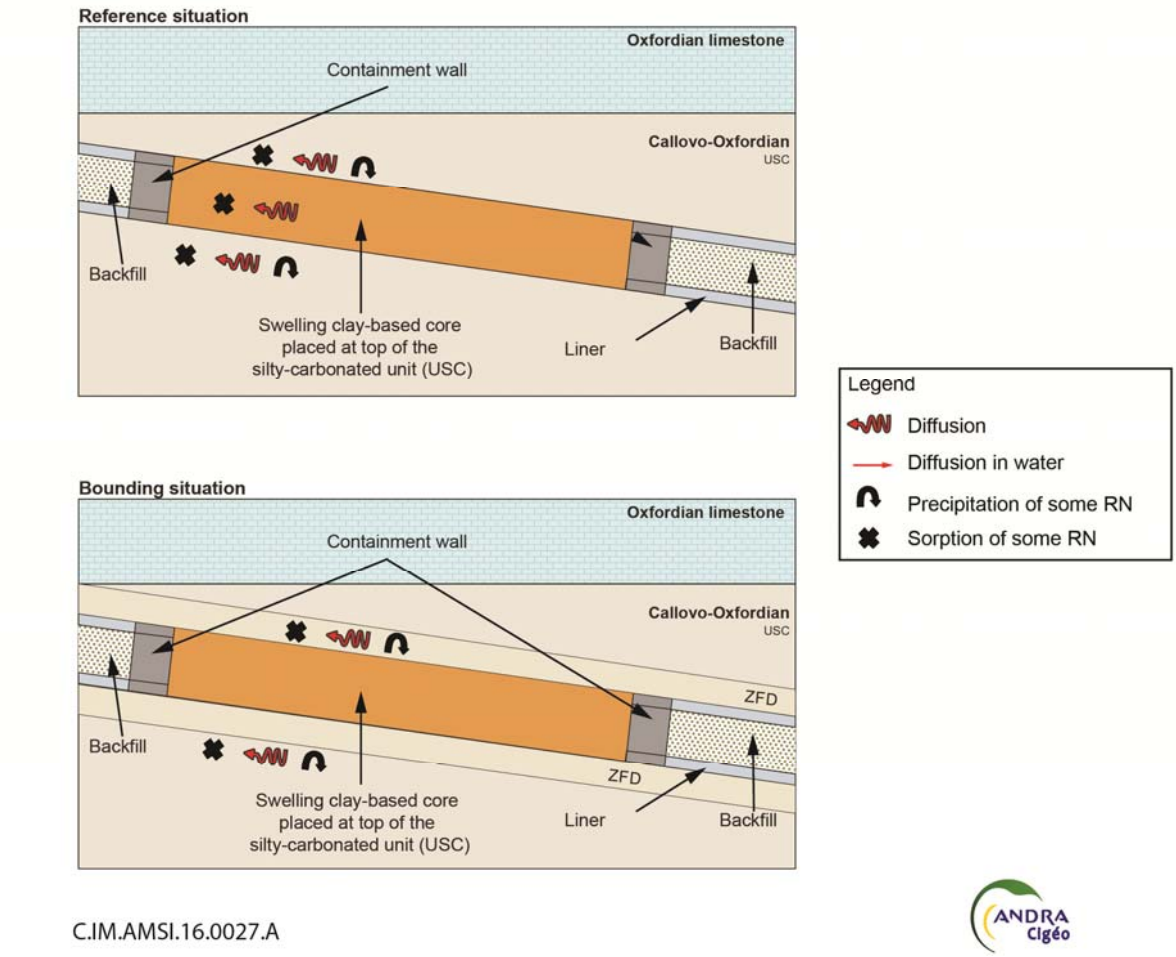


Figure 2.1-13: Schematic diagram of the representation choices for ramp seals and transport and retention characteristics (top: reference situation, below: bounding situation)

2.1.14 Backfilling the surface-bottom connection structures

Shaft station backfill is provided by a standard concrete-based incompressible material (Figure 2.1-14).

For both the reference and bounding situations, its permeability is considered equivalent to sand, conservative diffusion parameters (effective diffusion coefficient and accessible porosity) are used, and retention parameters (sorption and precipitation) are not represented (Table 2.1-12). The same characteristics are assigned to the concrete segments.

The mechanical damage to the clay rock around the structures is represented as set out in Chapter 2.1.7 and illustrated in Figure 2.1-11.

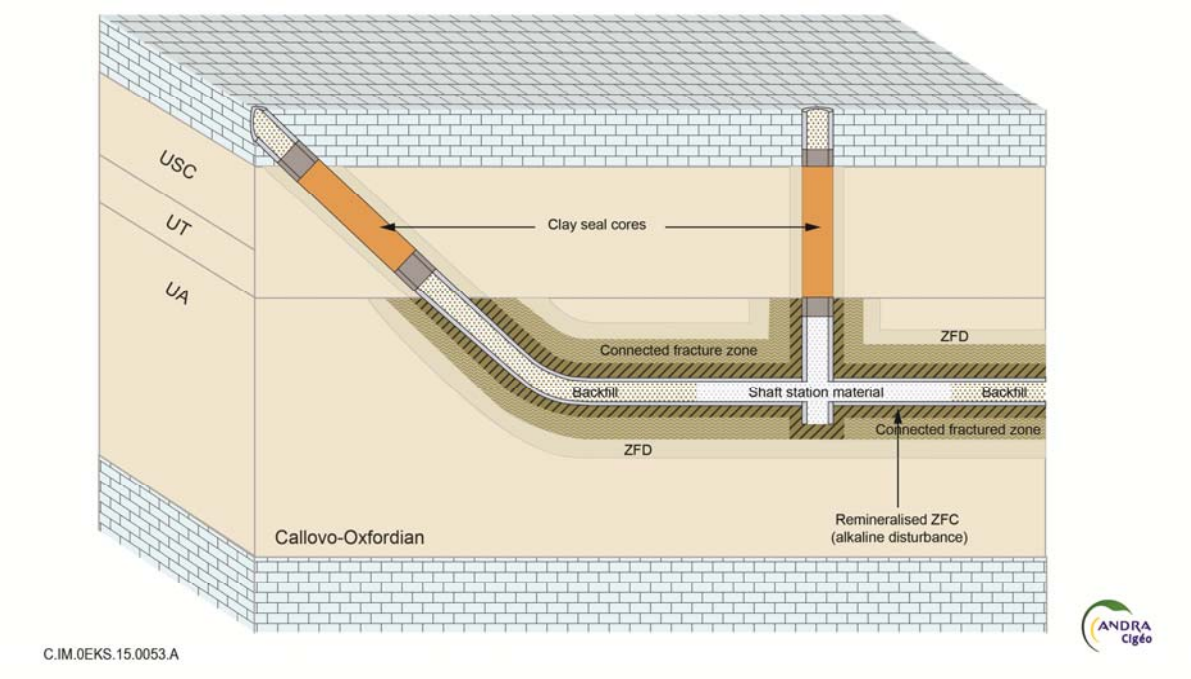


Figure 2.1-14: *Schematic diagram of surface-bottom connection structures and drifts: backfill, liner/roof support, remineralised ZFC, mechanically damaged clay rock (ZFC and ZFD in the bounding situation). Taking into account the specific properties of USC/UT and UA units.*

2.1.15 Summary of hydraulic and transfer parameters for solutes

The tables presented below summarise the hydraulic and transfer parameters for solutes of iodine-129, chlorine-36 and selenium-79 in the various components that could constitute a transfer pathway to the top and bottom of the Callovo-Oxfordian.

Table 2.1-11: Values of hydraulic and transfer parameters for solutes adopted for iodine-129, chlorine-36 and selenium-79

	Reference situation					Bounding situation				
	Permeability K (m.s^{-1})	Effective diffusion coefficient De (m².s^{-1})			Accessible porosity ω_{acc} (-)	Permeability K (m.s^{-1})	Effective diffusion coefficient De (m².s^{-1})			Accessible porosity ω_{acc} (-)
		^{129}I	^{36}Cl	^{79}Se			^{129}I	^{36}Cl	^{79}Se	
Undamaged Callovo-Oxfordien clayrock	4.10^{-14}	3.10^{-12}	5.10^{-12}	5.10^{-12}	0,07	Kv=2.10^{-13} Kh=3.10^{-13}	$6,5.10^{-12}$			0,05
Discrete fracturation zone (ZFD)	N/A					UA				
						10^{-10}	$6,5.10^{-12}$			0,05
						USC (+ UT)				
						10^{-11}	$6,5.10^{-12}$			0,05
Connected fracturation zone (ZFC)	Galleries / LL-IL vaults					Galleries / LL-IL vaults				
	10^{-9}	6.10^{-12}	10^{-11}	5.10^{-12}	0,07	10^{-8}	$1,3.10^{-11}$			0,05
	HL disposal cells					HL disposal cells				
	10^{-6}	6.10^{-12}	10^{-11}	5.10^{-12}	0,07	10^{-6}	$1,3.10^{-11}$			0,05
	horizontal sealings (galleries and LL-IL vaults)					horizontal sealings (galleries and LL-IL vaults)				
	$4,8.10^{-11}$	6.10^{-12}	10^{-11}	5.10^{-12}	0,07	$4,8.10^{-10}$	$1,3.10^{-11}$			0,05
Galleries' backfill	10^{-8}	$4,6.10^{-10}$			0,2	10^{-8}	$2,3.10^{-9}$			0,2
Concrete in coating/supporting walls and filling/suppoting blocks	10^{-6}	$4,6.10^{-10}$			0,2	10^{-6}	$2,3.10^{-9}$			0,2
Interface between clay core and clarock in sealing devices	horizontal sealings (galleries and LL-IL vaults)					horizontal sealings (galleries and LL-IL vaults)				
	5.10^{-11}	$4,6.10^{-10}$			0,2	5.10^{-11}	$2,3.10^{-9}$			0,2
	Sealings of surface-bottom links					Sealings of surface-bottom links				
	10^{-11}	10^{-10}		5.10^{-11}	0,05	10^{-11}	2.10^{-9}			0,05
Sealing's clay core	10^{-11}	10^{-10}		5.10^{-11}	0,05	10^{-11}	10^{-10}			0,05
Head of IL-LL disposal cells	10^{-6}	$6,9.10^{-10}$			0,3	10^{-6}	$2,3.10^{-9}$			0,3
Inter-package voids/apical voids	10^{-5}	$2,3.10^{-9}$			1	10^{-5}	$2,3.10^{-9}$			1
Disposal package/waste package	10^{-6}	$4,6.10^{-10}$			0,2	10^{-6}	$2,3.10^{-9}$			0,2

Table 2.1-12: Values of retention parameters adopted for iodine-129, chlorine-36 and selenium-79

	Reference situation						Bounding situation					
	Solid/solution uptake coefficient Kd (m^3.kg^{-1})			Solubility limit Csat (mol.L^{-1})			Solid/solution uptake coefficient Kd (m3.kg-1)			Solubility limit Csat (mol.L-1)		
	^{129}I	^{36}Cl	^{79}Se	^{129}I	^{36}Cl	^{79}Se	^{129}I	^{36}Cl	^{79}Se	^{129}I	^{36}Cl	^{79}Se
Undamaged Callovo-Oxfordien clayrock	0			infinite		2.10^{-9}	0			infinite		10^{-7}
Discrete fracturation zone (ZFD)	N/A			N/A			0			infinite		10^{-7}
Connected fracturation zone (ZFC)	0			infinite		10^{-7}	0			infinite		10^{-7}
Concrete in coating/supporting walls in LL-IL vaults	10^{-3}	2.10^{-2}	0	infinite		$1,5.10^{-4}$	0			infinite		5.10^{-3}
Sealing's clay core	0			infinite		10^{-7}	0			infinite		

2.1.16 Surrounding rock formations

The surrounding rock formations do not fulfil any safety function after closure. However, they are represented up to the outlets for the quantification of any potential impacts.

The main geological units of the sedimentary pile are represented:

- for the upper section:
  - ✓ the Tithonian limestone (called the Barrois limestone), outcrops of which cover the zone;
  - ✓ the Kimmeridgian marls;
  - ✓ Oxfordian limestone;
- for the lower section, the Dogger limestone formation;

These formations are represented according to their geometrical, mineralogical (marl levels, limestone levels) and hydraulic characteristics (

Table 2.1-13).

In the limestone levels, the following values are adopted for the reference situation:

- the permeabilities measured in boreholes and integrated into the hydrogeological model;
- the diffusion coefficient values measured in these limestone levels. Given the flow velocity into the aquifers, the hydrodynamic dispersion is represented;
- kinematic and accessible porosity, considered equal to total porosity;
- no chemical retention properties (partition coefficient, solubility limit) are taken into account.

In the marl levels, the following values are adopted for the reference situation:

- the permeabilities measured in the marl levels and integrated into the hydrogeological model;
- the diffusion coefficient values measured in these respective levels with reference tracers;
- the kinematic and accessible porosities, defined in accordance with total porosity;
- the retention by sorption.

In a conservative approach, retention properties in marl levels are not taken into account in the bounding situation.

Given the lack of change in the direction and intensity of horizontal flow in the Oxfordian over the next million years in the ZIRA, a horizontal hydraulic head gradient with 3.10^{-3} $m.m^{-1}$ intensity heading north is taken into account and applied in a uniform and ongoing way, in both the reference and bounding situations.

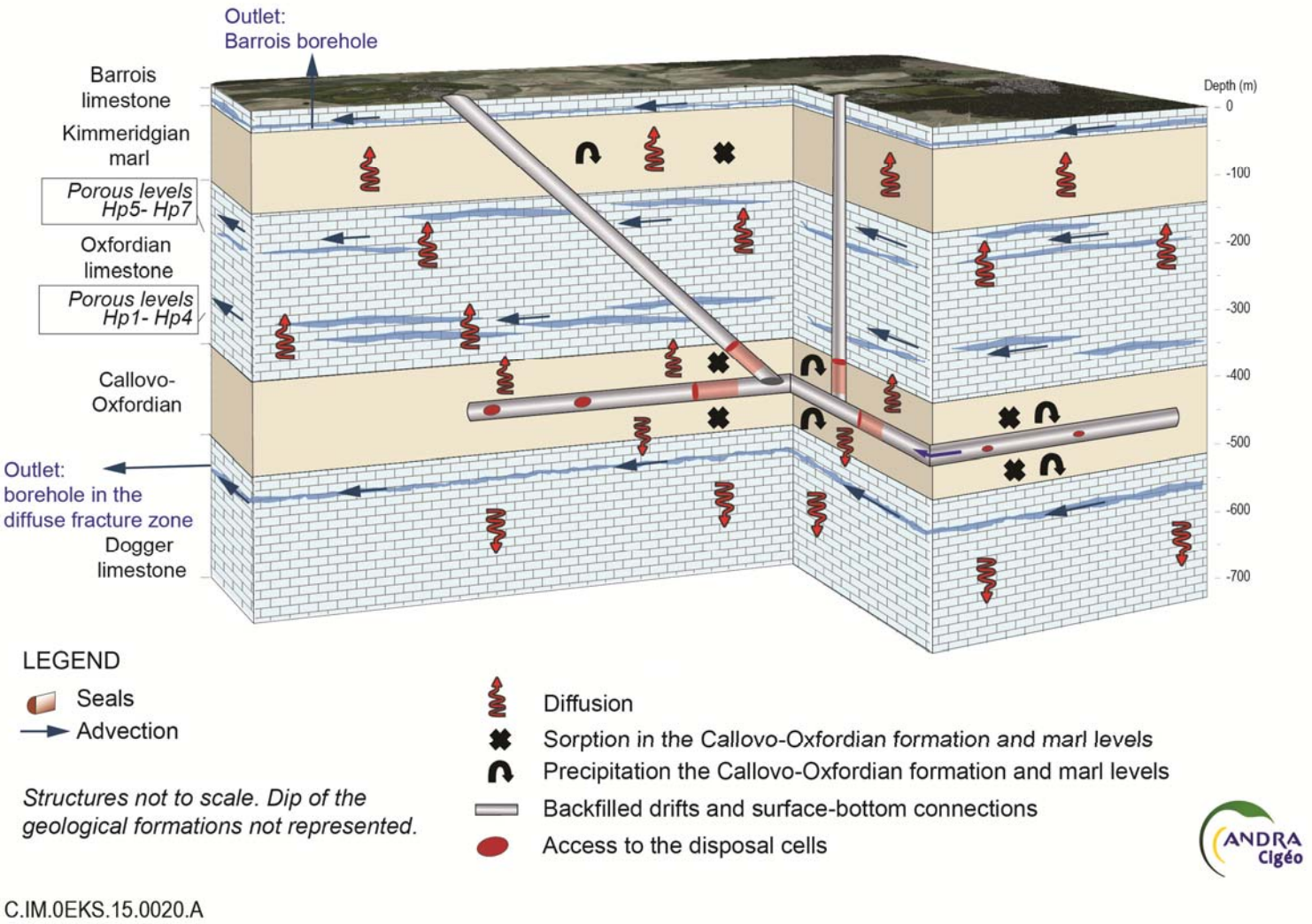


Figure 2.1-15: Schematic diagram of transfer pathways in the Callovo-Oxfordian and upper and lower surrounding rock formations

Table 2.1-13: Parameters applicable to surrounding rock formations

	Reference situation			Bounding situation (all layers)
	Marl levels	Limestone levels apart from porous horizons	Porous horizons	
Permeability (K), in m/s	Spatially variable permeability			
Kinematic porosity (ω_{cin}), no units	Total porosity / 2			Total porosity / 4
Diffusion coefficient in $m^2.s^{-1}$	De(tracer)			$Dp=D_0$(tracer)
Accessible porosity (ω_{acc}), no units	Anions: total porosity 2 Neutrals and cations:	Total porosity	Total porosity	Total porosity
Dispersivity, in m	Dogger and Oxfordian: α_T = 15m, α_L = 100m Kimmeridgian and Barrois: α_T = 0.3m, α_L = 30m			
Distribution factor (Kd) in $L.g^{-1}$	Kd=0			
Solubility limit (Csat) in $mol.L^{-1}$	Csat=∞			

2.1.17 The biosphere

The safety options for modelling the standard biospheres adopted are based on the approach described in Volume I and Appendix 5.

2.1.17.1 Standard biospheres

The assessments are presented for the temperate biosphere and hot biosphere referred to as type Cr (humid subtropical).

2.1.17.2 The outlets

The conceptualisation of the standard biospheres adopted takes into account the transfer outlets to the lower and upper surrounding rock formations. These are:

- for the transfer through the underlying rock formations: a conventional "pumping in the Dogger" outlet, east of the diffuse fracture zone, in both the reference and bounding situations;
- for the transfer through the overlying rock formations: a pumped well in the Barrois.

2.1.17.3 Hypothetical reference groups

The modelling of the transfer of radionuclides or toxic elements to humans takes into account the various potential exposure pathways (ingestion, inhalation and external exposure).

Depending on the potential of these two outlets, two hypothetical reference groups have been selected at this stage:

- for the Barrois outlet, a multi-activity hypothetical reference group with irrigation of cereal crops. The conceptual model for this group is presented in Figure 2.1-17.
- for the Dogger outlet, a multi-activity hypothetical reference group with no irrigation of cereal crops. The conceptual model for this group is presented in Figure 2.1-18.

These hypothetical groups keep a vegetable garden, farmyard animals and cattle. At the Barrois outlet, the hypothetical group also farms cereal crops. They live self-sufficiently and consume the various animal and vegetable products which they produce, and are subject to exposure pathways via inhalation and external exposure from their outdoor activities.

The biospheres are broken down into compartments, and interactions and exchanges between these compartments are identified. The transfer pathways are described via the food chain from the selected outlets.

The assessments consider a representative individual of adult age.

Consumption is based on average consumption values obtained:

- through the OPE survey performed in the Meuse/Haute-Marne region for the temperate biosphere;
- through surveys performed in Spain for a biosphere similar to the selected hot biosphere.

The transfer modelling is based on the following four models:

- for ^{36}Cl, ^{3}H, and ^{14}C, a specific transfer model based on isotopic dilution.
- for other radionuclides, a compartmental model using transfer factors between compartments at equilibrium.

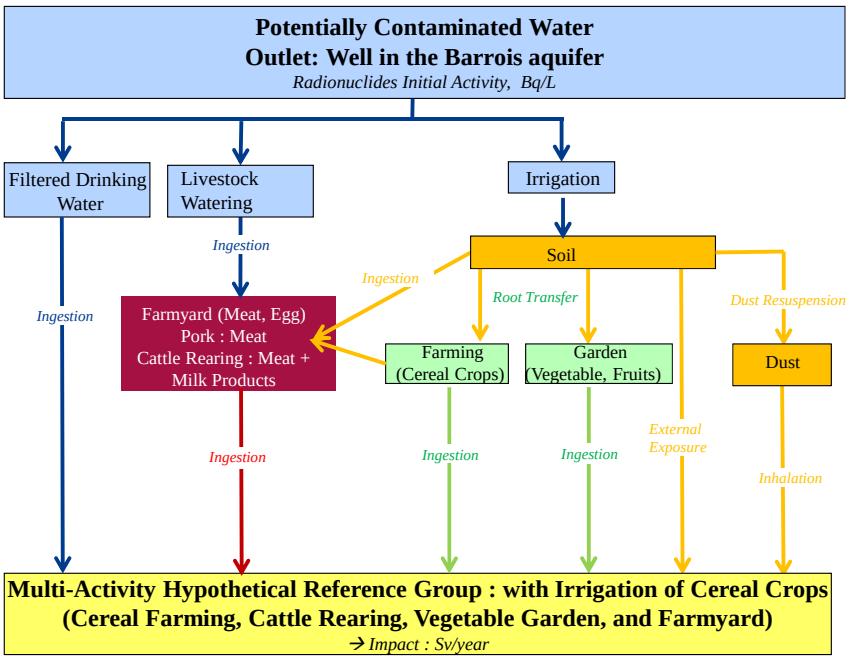


Figure 2.1-16: Conceptual diagram of radionuclide transfer pathways from potentially contaminated outlet water: wells in the Barrois aquifer to an individual representative of a multi-activity group with irrigation of cereal crops

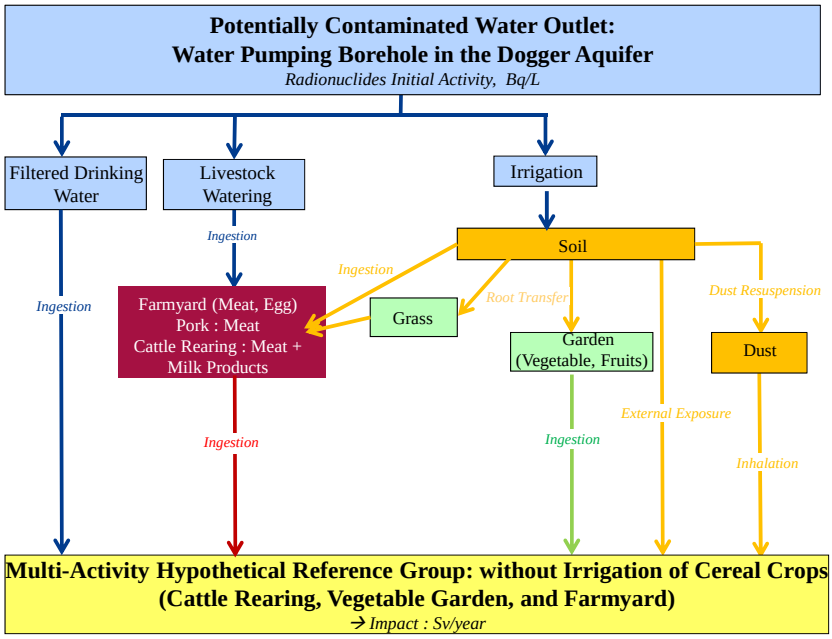


Figure 2.1-17: Conceptual diagram of radionuclide transfer pathways from potentially contaminated outlet water: well in the Dogger aquifer to an individual representative of a multi-activity group with no irrigation of cereal crops

2.2 Analysis of the NES

2.2.1 Definition of transfer pathways

The radionuclide transfer pathways from disposed packages to humans are represented in Figure 2.2-1.

Two transfer pathways are identified:

- the first corresponds to the transfer pathway that crosses the lower part of the Callovo-Oxfordian into the Dogger and the upper part of the Callovo-Oxfordian into the overlying rock formations. It is shown in red in Figure 2.2-1. It includes transfer from the packages disposed of but also radionuclide diffusion phenomena from the drifts into the clay rock;
- the second corresponds to the transfer pathway via structures. It includes:
  - ✓ the transfer pathway in the disposal cell then the backfilled drifts, the seals and the backfilled and sealed surface-bottom connection structures (in green in Figure 2.2-1),
  - ✓ the transfer pathway via the zone of mechanically damaged clay rock (in purple),
  - ✓ the transfer pathway via the concrete ILW-LL cell liner and galleries (in blue).

Transfer in the surrounding rock formations includes:

- in the underlying rock formations (Dogger), direct hydrodispersive transport to the outlet, located in the diffuse fracture zone 9km south-west of the repository footprint;
- in the overlying rock formations, hydrodispersive transport in the Oxfordian, followed by diffusive transport in the Kimmeridgian, followed by hydrodispersive transfer in the Barrois limestone.

Transfer from the outlet to humans (biosphere) includes transfer pathways via ingestion and inhalation, and exposure to ionising radiation.

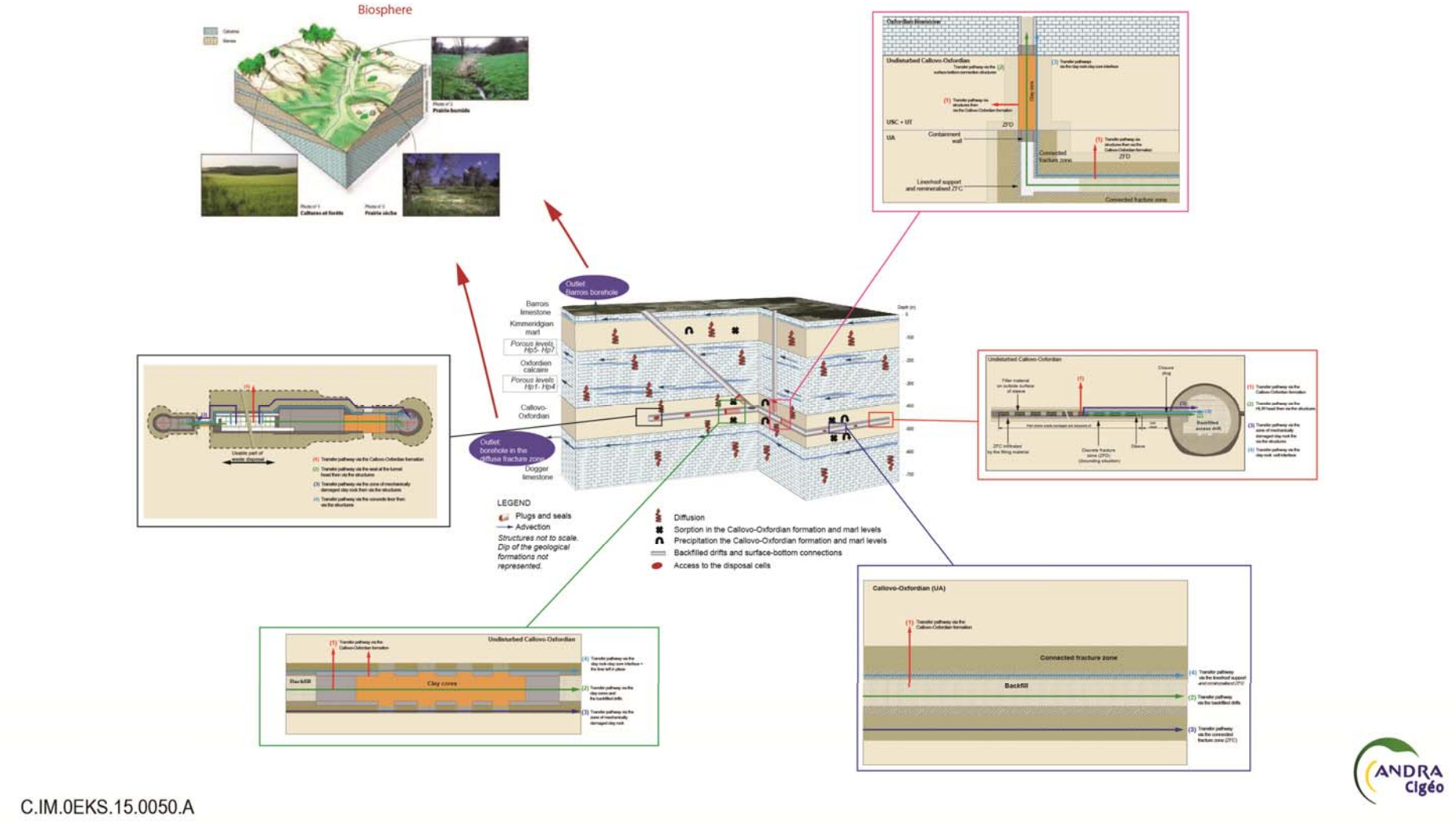


Figure 2.2-1: Schematic diagram of transfer pathways from waste packages to humans

2.2.2 Adopted indicators

As mentioned in Volume I, Andra has adopted the effective committed dose at the outlet as the main radiation protection indicator. Andra has adopted the dose constraint value of 0.25 mSv per year in the NES in accordance with the safety guidelines (1).

In order to quantify the delay and attenuation of radionuclides via transfer and retention (sorption/precipitation), dilution and radioactive decay phenomena, performance indicators are quantified in the various components for the transfer pathways via structures, the Callovo-Oxfordian and surrounding rock formations.

The main performance indicators assessed with regard to safety functions are:

- for the "resist the circulation of water" function, the water flow rates in the backfilled and sealed structures;
- for "limit the release of radionuclides and toxic elements and immobilise them in the repository" function, the peak molar flow rate of radionuclides and when they occur. These molar flow rates are normalised with regard to the total initial inventory for the radionuclide concerned (particularly as a percentage). They are calculated:
  - ✓ at different locations for the transfer pathway via the repository, in drifts and surface-bottom connections;
  - ✓ at the top and bottom of the Callovo-Oxfordian, for the transfer pathway via the Callovo-Oxfordian.
- for the "delay and attenuate radionuclide migration" function, the mapping of concentrations in solution (in the Callovo-Oxfordian and surrounding rock formations) and molar flow rates (cumulative over a million years):
  - ✓ transiting from the primary packages to the top and bottom of the Callovo-Oxfordian, distinguishing between the transfer pathway via the Callovo-Oxfordian and the transfer pathway via the structures;
  - ✓ transiting via the surrounding rock formations to the Dogger and Barrois outlets.

The results presented in the figures only cover radionuclides with a molar flow rate that exceeds 1.10^{-10} moles per year over one million years. The contribution to the impact of radionuclides below this value is negligible.

2.3 NES results

2.3.1 NES results regarding the "resist the circulation of water" function

2.3.1.1 Reference situation

The field of hydraulic heads in the Callovo-Oxfordian formation is only slightly disturbed by the hydraulic drain created by the underground facility. This is particularly due to the performance of the seals, and especially the surface-bottom connection structure seals which hydraulically "isolate" the repository from the overlying formations and the architectural design measures. Flow velocities for water in the structures are approximately 0.5mm per years in the HLW disposal section access drifts and 0.25mm per year from the ILW-LL disposal sections. The majority of water drained via the surface-bottom connection structures comes from the ILW-LL disposal section.

The water flow rate leaving all the surface-bottom connection structures is approximately 6 litres per year, distributed as follows:

- 2 litres per year in the ramps;
- 0.9 litres per year in shaft zone 1 (shafts situated near the ILW-LL zone);
- 3 litres per year in shaft zone 2 (shafts situated near the HLW zone).

The transfer conditions in the repository remain diffusive.

2.3.1.2 Bounding situation (with a hydraulic head gradient that encourages upward flow)

The hydraulic behaviour of the repository and Callovo-Oxfordian is similar to the reference situation. However, given the conservative hydraulic parameters in the bounding situation, the flow rates of water leaving the surface-bottom connection structures are higher, at around 70 litres per year, distributed as follows:

- 28 litres per year in the ramps;
- 12 litres per year in shaft zone 1 (shafts situated near the ILW-LL zone);
- 30 litres per year in shaft zone 2 (shafts situated near the HLW zone).

Nevertheless, this increase in water[103] flow rates does not modify the transfer conditions in the repository, which remain diffusive.

2.3.2 NES results regarding the "limit the release of radionuclides and toxic chemicals and immobilise them in the repository" function

2.3.2.1 Reference situation

Release of radionuclides in the ILW-LL zone

For reference, the release of radionuclides is based on the assumption of the inventory presented in Volume II, Chapter 2.2 and the safety options related to the release models presented in Volume II, Chapter 2.3.3.

The results, presented in Figure 2.3-1, show that the majority of the inventory of mobile radionuclides (96% of the total quantity of iodine-129, 80% of chlorine-36 and 98% of selenium-79) is released in a labile form.

The rest of the inventory is released progressively up to around 75,000 years (in line with the release models for metal waste):

- gradual release limited to 1000 years for bituminised sludge (integrity lifetime of disposal containers) in line with the application of the COLONBO model;
- release until around 3000 years for vitrified ILW-LL waste;
- release until around 12,500 years for zirconium hulls and chips;
- release until around 13,500 years for zirconium-niobium alloys;
- release until around 15,000 years for nickel elements.

[103] The difference with the reference situation is associated with the conservative hydraulic parameters taken into account in the bounding situation.

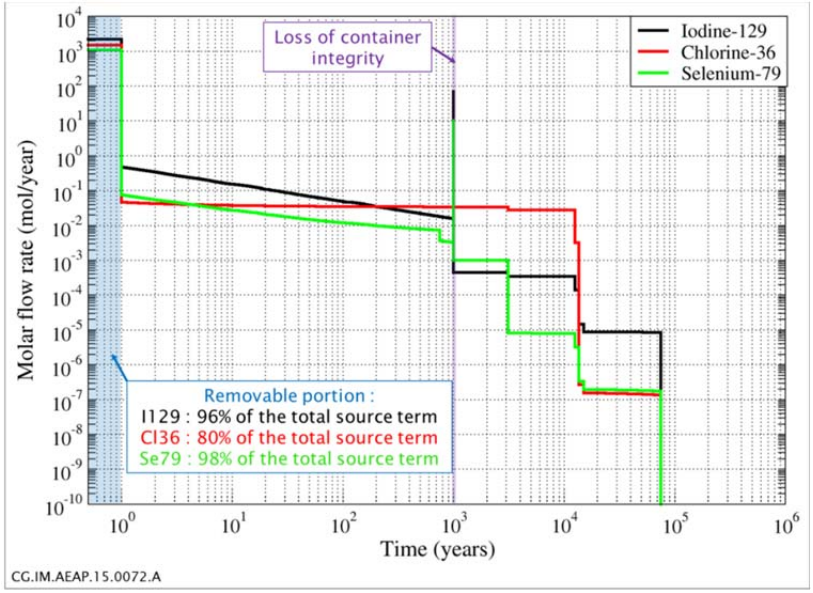


Figure 2.3-1: NES - reference situation: iodine-129, chlorine-36 and selenium-79 source terms in the ILW-LL disposal section

Release of radionuclides in the HLW zone

The evolution of the iodine-129, chlorine-36 and selenium-79 source terms in the ILW-LL disposal section (HLW1/HLW2 and HLW0 types) is presented in Figure 2.3-2. After the loss of leaktightness of the HLW[104] disposal container, application of the release model "$V_0 \rightarrow V_R$" leads to a source term period of around 300,000 years.

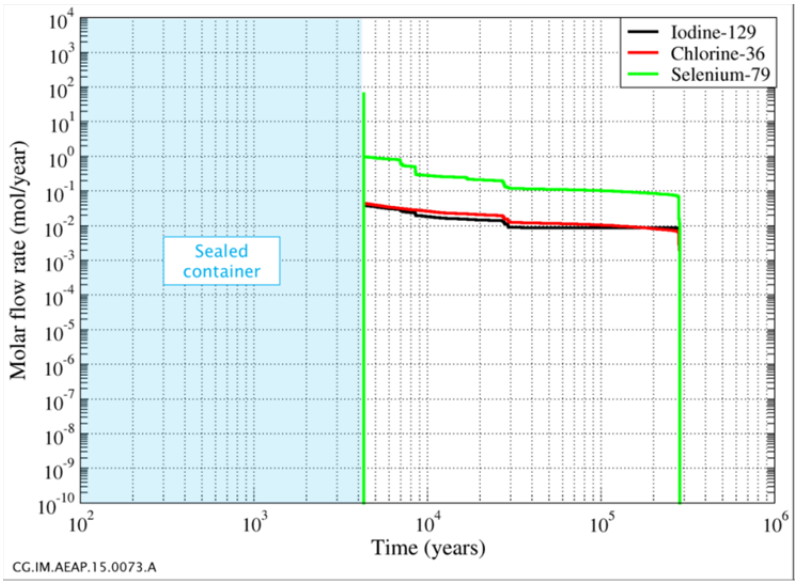


Figure 2.3-2: Normal evolution scenario – Reference situation - Iodine-129, chlorine-36 and selenium-79 source terms in the HLW disposal section

[104] Assessed at 4,300 years in accordance with the phenomenological evolution and the thickness adopted at the basic engineering design stage

2.3.2.2 Bounding situation

Release of radionuclides in the ILW-LL zone

Figure 2.3-3 presents the evolution of total iodine-129, chlorine-36 and selenium-79 source terms over time in the ILW-LL disposal section.

The majority of radionuclides (99% of the total quantity of iodine-129, 82% of chlorine-36 and 99% of selenium-79) is released in a labile form. The increase in these labile quantities compared to the reference situation is due in particular to the fact that the COLONBO model for bituminised waste is not applied.

For the rest of the radiological inventory of ILW-LL waste packages, the end of the source terms come earlier, around 15-20 years. They correspond to the end of the release of vitrified ILW-LL waste represented by a less effective V_0.S model than the reference situation.

The second step down around 15,000 years is similar to the one for the reference situation (zirconium hulls and end pieces, zirconium-niobium alloys and nickel components). Similarly, the source term ceases after 75,000 years, after the degradation of the stainless steel waste.

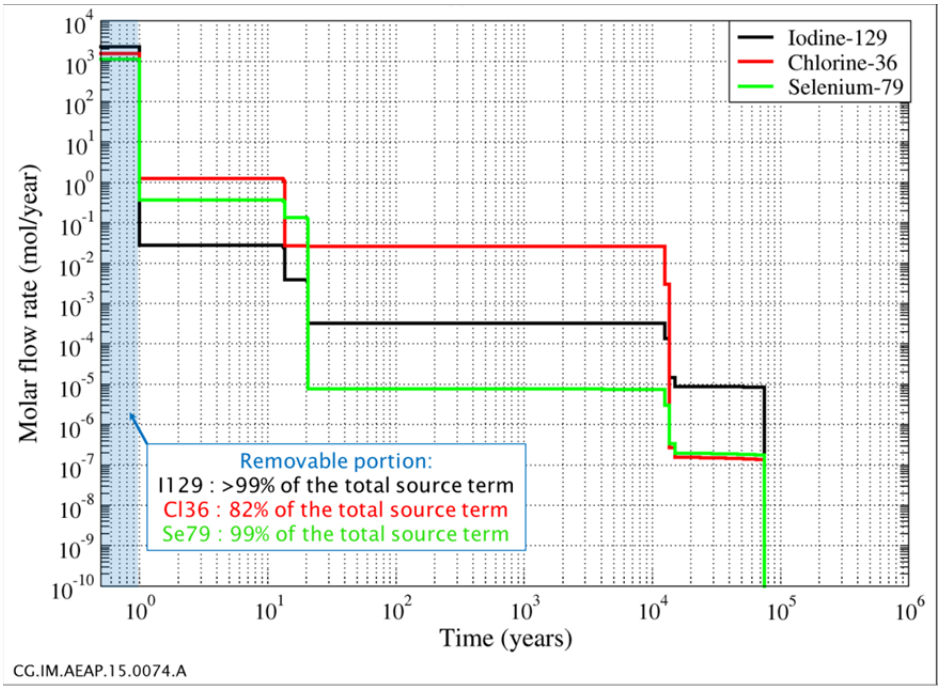


Figure 2.3-3: Normal evolution scenario – Bounding situation - Iodine-129, chlorine-36 and selenium-79 source terms in the HLW disposal section

Release of radionuclides in the HLW zone

HLW disposal containers are conventionally considered to remain leaktight for 500 years. The evolution of the iodine-129, chlorine-36 and selenium-79 source terms in the HLW disposal section (HLW1/HLW2 types and HLW0 types) is presented in Figure 2.3-4.

Application of the "V_0.S" release model, which is less effective than the "$V_0 \rightarrow V_R$" model adopted in the reference situation, gives a shorter source term half-life (of between 10,000 and 20,000 years).

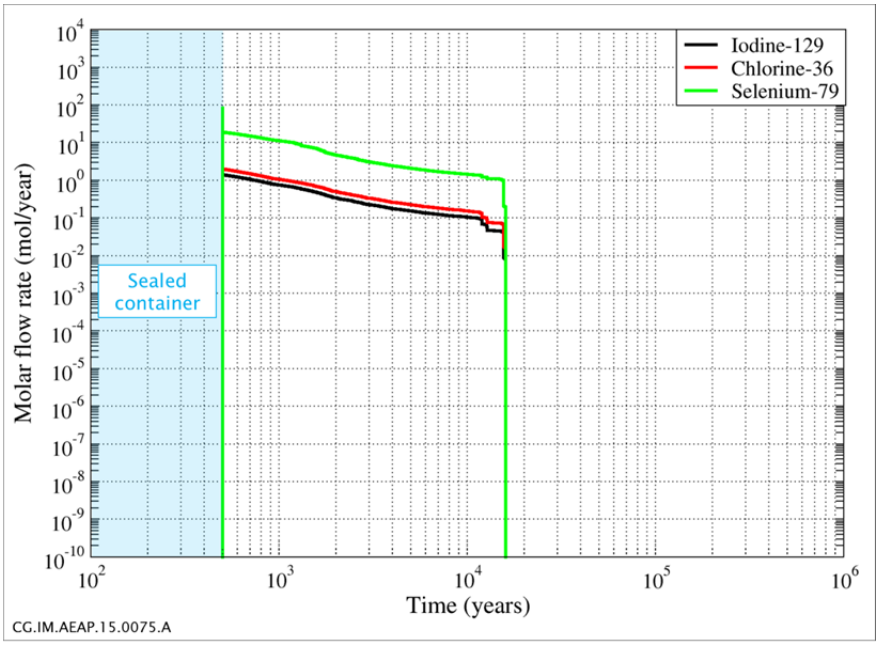


Figure 2.3-4: *Normal evolution scenario – Bounding situation - Iodine-129, chlorine-36 and selenium-79 source terms in the HLW disposal section*

2.3.3 NES results regarding the "delay and attenuate radionuclide migration" function

2.3.3.1 Reference situation

From the packages to the top and bottom of the Callovo-Oxfordian

- ***Analysis of molar flow rates for iodine-129 and chlorine-36 leaving the Callovo-Oxfordian***

Figure 2.3-5 presents the evolution of molar flow rates for iodine-129 and chlorine-36 to the top and bottom of the Callovo-Oxfordian. Table 2.3-1 presents the assessment of molar flow rates cumulative over a million years and peak molar flow rates through the Callovo-Oxfordian pathway and along the disposal structure pathway. This leads to the following observations:

- transfer by diffusion is dominant. For HLW and ILW-LL disposal sections over a period of one million years, advection transfers are of around two orders of magnitude lower than transfers by diffusion;
- molar flow rates at the top and bottom of the Callovo-Oxfordian are almost identical because the disposal structures are located in the middle of the host formation and diffusion is the dominant transfer mode;
- peak molar flow rates for iodine-129 and chlorine-36, calculated at the top and bottom of the Callovo-Oxfordian are, respectively, approximately 10^{-3} moles per year after 840,000 years and 5.10^{-4} moles per year after 440,000 years ;
- maximum iodine-129 and chlorine-36 molar flow rates to the top of the Callovo-Oxfordian through the surface-bottom connection structures are a long way below the molar flow rates reaching the top of the Callovo-Oxfordian through the host-rock itself, by a factor of around 30,000 for iodine and 1,000,000 for chlorine;
- after one million years, 22% of the initial iodine-129 and 9% of the initial chlorine-36 will have reached the upper or lower boundaries of the Callovo-Oxfordian[105]. The rest remains in the Callovo-Oxfordian or has disappeared through radioactive decay;

[105] The differences in behaviour between iodine-129 and chlorine-36 are due to the difference in mobility of these two radionuclides in the Callovo Oxfordian, the sorption of chlorine in the concrete liner of the ILW-LL cells and the half-life of chlorine-36, which provides faster radioactive decay than iodine-129.

- the peak molar flow rate for the ILW-LL disposal section occurs before that of the HLW disposal sections. Two parameters contribute to this: the release period, which is much longer for HLW waste packages than ILW-LL waste packages, and the transfer times via the Callovo-Oxfordian, which are affected by the much greater thickness around the HLW disposal sections.

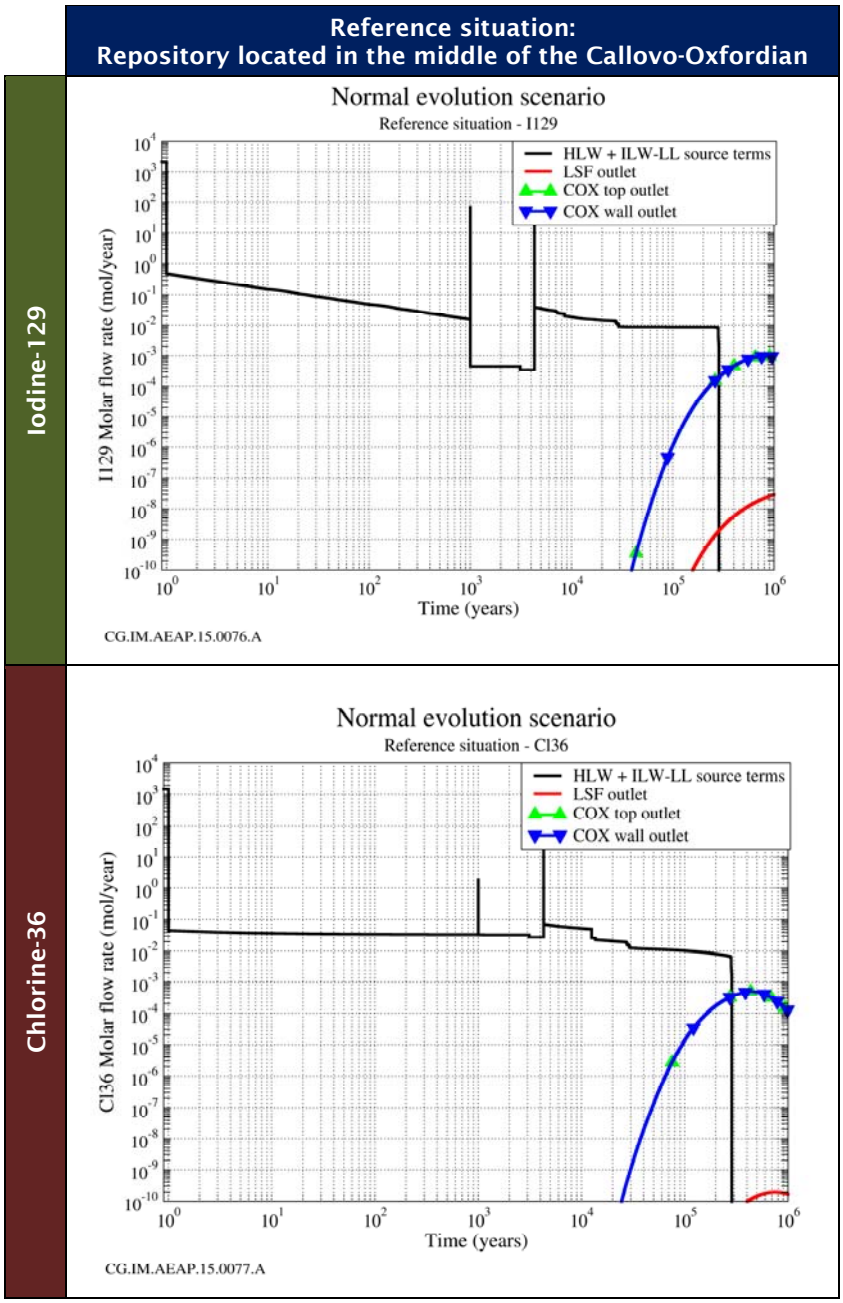


Figure 2.3-5: *Normal evolution scenario – Reference situation – Time-dependent evolution of molar flow rates for iodine-129 (top) and chlorine-36 (bottom) leaving surface-bottom connection structures and the reaching the upper and lower boundaries of the Callovo-Oxfordian.*

Table 2.3-1: *Normal evolution scenario – Reference situation – Assessment of molar flow rates cumulative over a million years and peak molar flow rates via transfer pathways through the Callovo-Oxfordian and through the access structures.*

	Iodine-129			Chlorine-36		
	% initial quantity	Peak molar flow rate (10^{-6} mol/year)	Date of peak flow rate (thousands of years)	% initial quantity	Peak molar flow rate (10^{-6} mol/year)	Date of peak flow rate (thousands of years)
Total initial inventory in moles HLW/ILW-LL	5,000 moles			5,800 moles		
Including HLW	*54%*			*68%*		
Including ILW-LL	*46%*			*32%*		
At top of Callovo-Oxfordian	11%	930	840	4.6%	490	440
Including HLW	*6.1%*	*550*	*850*	*3.9%*	*430*	*450*
Including ILW-LL	*4.9%*	*380*	*810*	*0.7%*	*70*	*340*
Via access structures	$< 10^{-3}$%	0.03	1,000	$< 10^{-5}$%	2×10^{-4}	750
Including HLW	$< 10^{-4}$%	0.002	1,000	$< 10^{-5}$%	2×10^{-4}	710
Including ILW-LL	$< 10^{-3}$%	0.03	>1,000	$< 10^{-6}$%	3×10^{-5}	> 1,000
At bottom of Callovo-Oxfordian	11%	950	840	4.6%	490	440
Including HLW	*6.1%*	*550*	*850*	*3.9%*	*430*	*450*
Including ILW-LL	*5.1%*	*400*	*810*	*0.7%*	*70*	*340*

- ***Analysis of molar flow rates leaving the Callovo-Oxfordian for other radionuclides***

Figure 2.3-6 presents the evolution of the main mobile radionuclide flows at the top of the Callovo-Oxfordian. The flows at the bottom of the Callovo-Oxfordian are almost identical, given the fact that in the reference situation, the structures are located in the middle of the Callovo-Oxfordian.

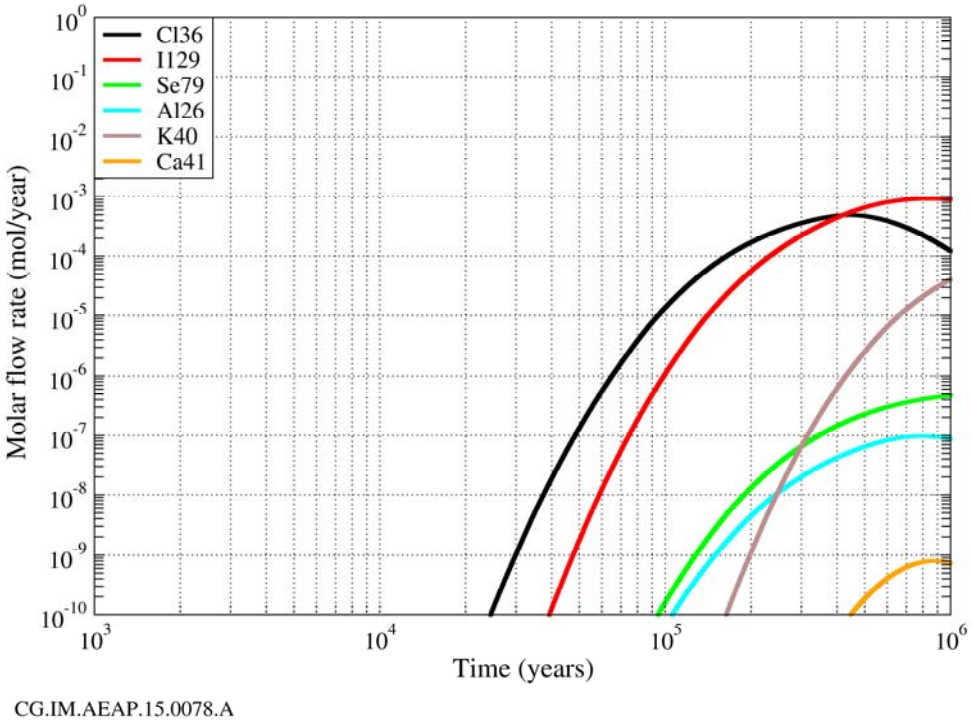


Figure 2.3-6: *Normal evolution scenario – Reference situation: Time-dependent evolution of molar flow rates at the top of the Callovo-Oxfordian (the molar flow rates are identical at the bottom of the Callovo-Oxfordian)*

The molar flow rates of mobile radionuclides leaving the Callovo-Oxfordian reach their peak after around 1 million years (except chlorine-36).

The attenuation of selenium-79, greater than iodine-129 and chlorine-36 is due to the solubility limit of selenium which tends to spread diffusion in the Callovo-Oxfordian over time.

In addition to the mobile radionuclides (iodine-129, chlorine-36 and selenium-79), other radionuclides have a molar flow rate that exceeds 10^{-10} moles per year leaving the Callovo-Oxfordian: a low inventory of aluminium-26, which is mobile and has low solubility in clay rock, and calcium-41 and potassium-40, which are weakly sorbed in cement structures and clay rock.

All other radionuclides are totally attenuated before reaching the Callovo-Oxfordian surrounding rock formations, either due to their half-life, which is significantly below the transfer time, or due to their sorption in clay rock. Figure 2.3 7 shows that the high sorption of actinides immobilises uranium-238 and neptunium-237 in the repository and in the immediate vicinity of the disposal cells within a maximum distance of around 10 m.

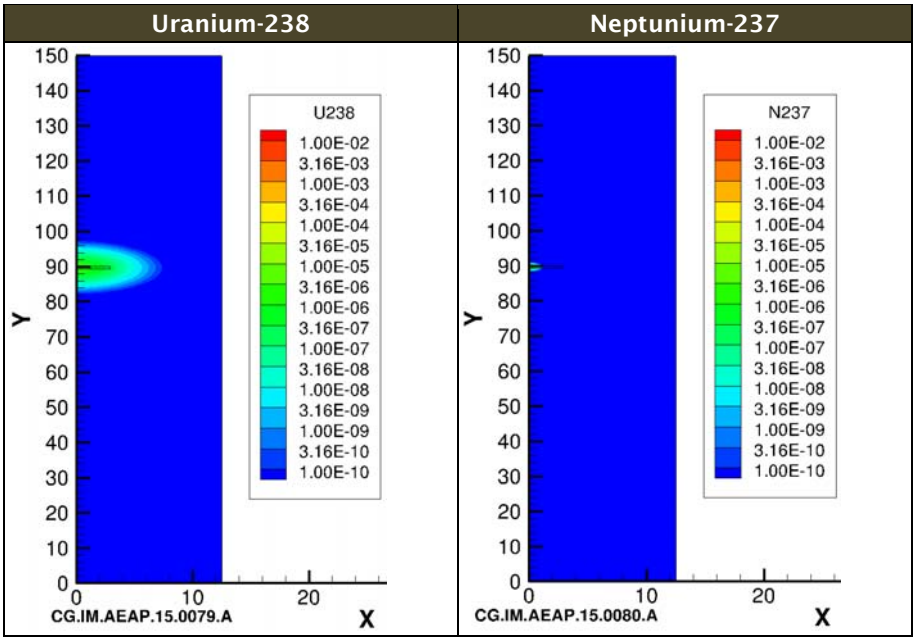


Figure 2.3-7: *Normal evolution scenario - Reference situation – Plumes of uranium-238 and neptunium-237 concentration (in moles per m³ of water) in the Callovo-Oxfordian clay rock around a HLW cell at 1 million years*

- ***Analysis of iodine-129 and chlorine-36 transfer from HLW and ILW-LL zones***

Figure 2.3-8 presents the evolution of the molar flow rates for iodine-129 and chlorine-36 released by HLW and ILW-LL waste packages migrating through the Callovo-Oxfordian and along the structures. The molar flow rates are determined at the access drifts (HLW zone), connecting drifts, the main zone and the surface-bottom connection structures at Callovo-Oxfordian upper boundary.

These graphs lead to the following conclusions:

- as mentioned in Chapter 2.3.2.1, the release of radionuclides occurs between 4300 (date of container loss of integrity) and 300,000 years for HLW waste and for around 75,000 years for ILW-LL waste;
- molar flow rates at the entrance to the drift show a limited delay with regard to the release of radionuclides. Taking into account the partition coefficient in the concrete liner of the ILW-LL disposal cells, which is higher for chlorine than for iodine, delays and spreads transfer over time, and pushes back the occurrence of the peak molar flow rate leaving the ILW-LL disposal cells by several thousand years;
- the peak molar flow rate is attenuated by around 2 orders of magnitude at the HLW disposal section outlet, 4 orders of magnitude at the HLW zone outlet and 5 orders of magnitude in the surface-bottom connection structures at the Callovo-Oxfordian upper boundary;
- the peak molar flow rate via the structure pathway is only achieved after 2 million years for iodine and 75,000 years for chlorine. These transfer times are due to the total length of the structure pathway and the very slow hydraulic system. Diffusion is dominant in the drifts and surface-bottom connections;
- molar flow rates for iodine-129 leaving the shafts and ramps essentially come from the ILW-LL disposal section. This is due to the fact that the iodine-129 inventory of the ILW-LL disposal section is primarily positioned at the entrance to the disposal section.

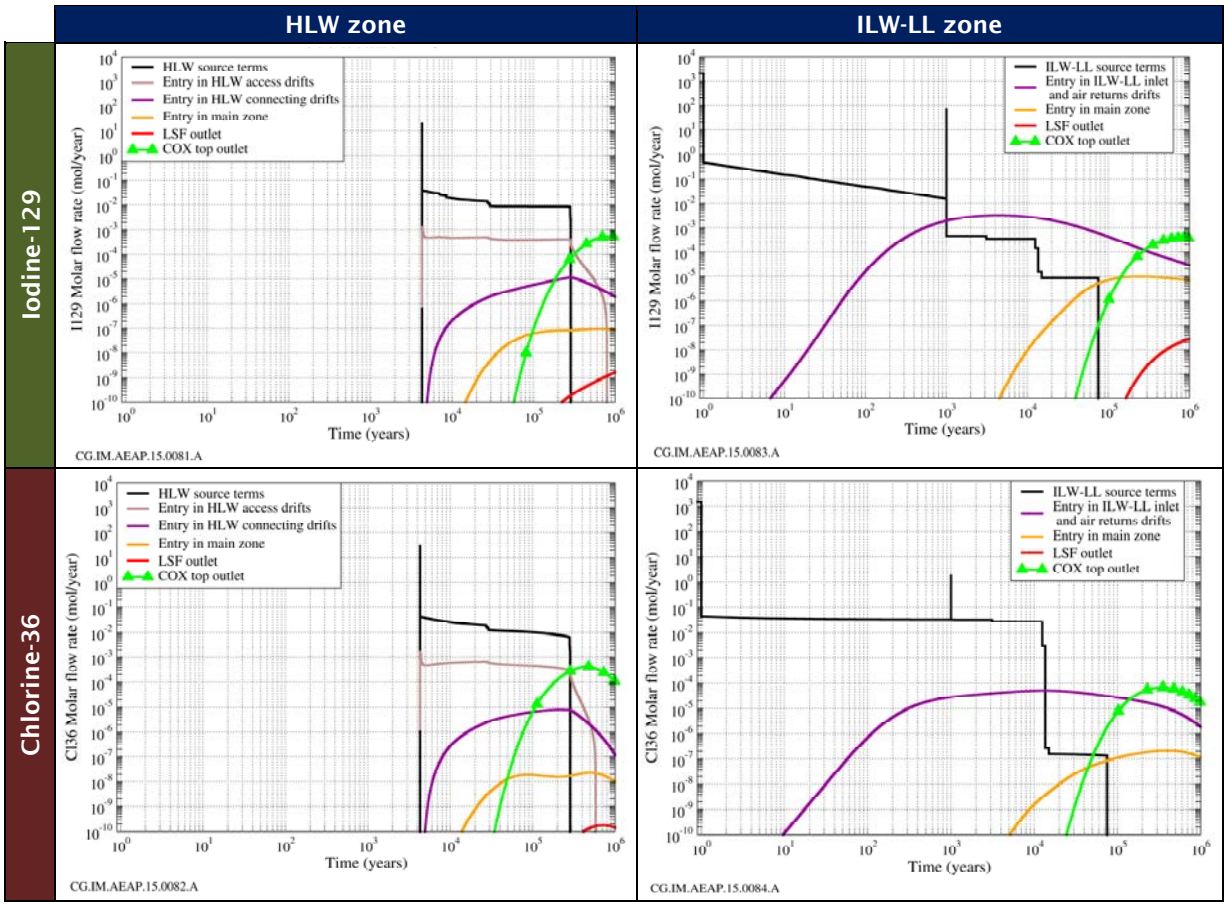


Figure 2.3-8: *Normal evolution scenario – Reference situation, HLW disposal sections (left) and ILW-LL disposal section (right). Time-dependent evolution of molar flow rates for iodine-129 (above) and chlorine-36 (below) entering access drifts (HLW only), connecting drifts and the main zone, and leaving the surface-bottom connection structures and the top of the Callovo-Oxfordian.*

Table 2.3-2 gives the assessment of molar flow rates for iodine-129 and chlorine-36 cumulative over a million years at different points along the structure pathway and leaving the top of the Callovo-Oxfordian. These molar flow rates are normalised with regard to the initial inventory in the HLW disposal sections and the ILW-LL disposal section.

These data lead to the following conclusions:

- for the HLW cell disposal sections, the main transfer pathway is the Callovo-Oxfordian, since over one million years, only 5% of the initial iodine-129 inventory (3% for chlorine-36) enters the access drifts. This is explained by the 100m length of the usable part of the HLW cells, and the lack of an efficient hydraulic drain along the drifts. Slow primarily diffusive transport combined with the length of the drifts facilitates the transfer of radionuclides from the drifts into the Callovo-Oxfordian. Therefore, only 0.2% of the initial inventory of iodine-129 (0.08% for chlorine-36) leaves the HLW disposal sections to the connecting drifts. This fraction is even lower in the surface-bottom connections at the top of the Callovo-Oxfordian for values below 0.01%;
- for the ILW-LL[106] disposal section only 8.6% of the initial inventory of iodine-129 (0.6% for chlorine-36) enters the connecting, access and air return (backfilled) drifts and the main transfer pathway remains the Callovo-Oxfordian. The transfer of radionuclides leaving the ILW-LL disposal section into the drifts and surface-bottom connections occurs in a slow hydraulic system with dominant diffusion which facilitates the transfer of radionuclides towards the Callovo-Oxfordian. Therefore, only 0.3% of the initial inventory of iodine-129 (less than 0.01% for chlorine) leaves the ILW-LL disposal via the structures. The fractions of iodine-129 and chlorine-36 leaving the surface-bottom connections are significantly below 0.001%.

Table 2.3-2: Normal evolution scenario – Reference situation: assessment of iodine-129 and chlorine-36 molar flow rates (cumulative over a million years, as a percentage of the initial inventory in the HLW disposal sections and ILW-LL disposal section) entering access drifts, connecting drifts and the main zone, and leaving surface- bottom connection structures and the top of the Callovo-Oxfordian

% of initial total inventory for HLW zone	Entering access drifts	Entering connecting drifts	Entering the main zone	Leaving the surface-bottom connections	Leaving the top of the Callovo-Oxfordian
Iodine-129	5%	0.2%	< 10^{-2}%	< 10^{-4}%	11%
Chlorine-36	3.3%	0.08%	< 10^{-3}%	< 10^{-5}%	5.8%
% of initial total inventory for ILW-LL zone	**Entering connecting/access and air return drifts**		**Entering the main zone**	**Leaving the surface-bottom connections**	**Leaving the top of the Callovo-Oxfordian**
Iodine-129	8.6%		0.3%	< 10^{-3}%	10%
Chlorine-36	0.6 %		< 10^{-2}%	< 10^{-6}%	2.1%

- ***Specific case of a configuration with lower performance closure systems for the ILW-LL cells (identified as "no ILW-LL seals" in the figures)***

Figure 2.3-9 and Table 2.3-3 show a very low difference between the molar flow rates for iodine-129 from the ILW-LL disposal section with a lower performance closure system for ILW-LL cells.

If everything else remains the same, with this lower performance system, peak molar flow rates entering the ILW-LL access and air return drifts are increased by around 20%, but this difference is reduced at the entrance to the main zone, and is no longer significant leaving the surface-bottom connections. The dates of occurrence of these peaks are not altered significantly.

[106] With a distribution of the inventory which favours maximum iodine-129 and chlorine-36 inventory near the disposal section inlet.

These results are due to the effectiveness of the seals in the surface-bottom connection structures which contribute to resisting the circulation of water and ensuring dominant diffusive transport in the repository which allows the radionuclides transferring through structures to diffuse into the Callovo-Oxfordian.

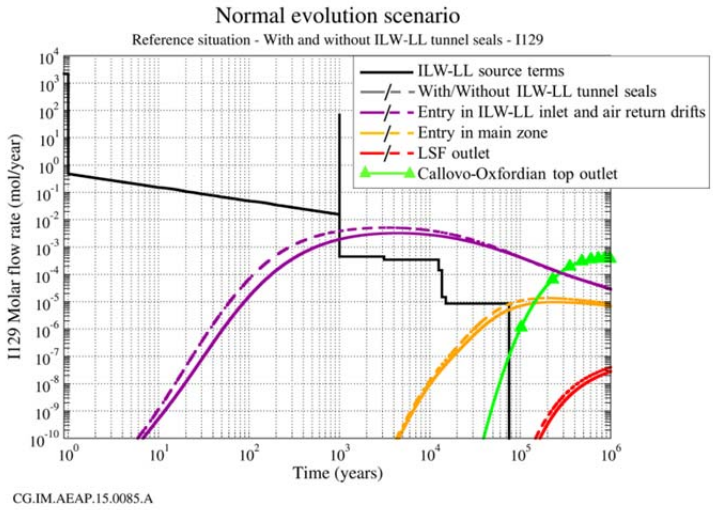


Figure 2.3-9: *Normal evolution scenario – Reference situation for ILW-LL disposal section, ILW-LL disposal cells with seal or with a closure distribution offering lower performance than a seal ("no seal"). Time-dependent evolution of molar flow rates for iodine-129 entering the access drifts (HLW only), the connecting drifts and the main zone, and leaving the surface-bottom connection structures and the Callovo-Oxfordian*

Table 2.3-3: *Normal evolution scenario – Reference situation, ILW-LL disposal section, ILW-LL disposal cells with seal and without seals: assessment of iodine-129 quantities (cumulative over a million years, normalised by the initial inventory of the total ILW-LL zone) entering connecting drifts and the main zone, and leaving surface- bottom connection structures and the top of the Callovo-Oxfordian*

	Quantity of iodine-129 (as a% of initial total inventory of the ILW-LL zone)			
	Entering connecting/ air return drifts	Entering the main zone	Leaving the surface-bottom connections	Leaving the top of the Callovo-Oxfordian
ILW-LL with seal	8.6%	0.3 %	< 10^{-3}%	10%
ILW-LL cells with no seal	10%	0.4 %	< 10^{-3}%	10 %

From the surrounding rock formations towards the outlets

Figure 2.3-10 represents the isoconcentration of iodine-129 (10^{-11} mol.L^{-1}) in the geological medium at one million years.

The radionuclides that reach the top of the Callovo-Oxfordian enter the porous horizons of the Oxfordian limestone characterised by a mean hydraulic gradient of 0.4%, pore flow rate of approximately 10 km per 100,000 years and direction towards the north-west, before reaching the base of the Kimmeridgian (green pathways). The radionuclides then migrate by diffusion in this marl formation before dispersing into the Barrois aquifer. The molar flow rates in the Oxfordian presented below are calculated at 9 km from the repository footprint.

The radionuclides that reach the bottom of the Callovo-Oxfordian enter the Dogger limestone where the flow travels north-west, with a mean speed of around 5 km per 100,000 years, before reaching the diffuse fracture zone (blue trajectories). The molar flow rates in the Dogger presented below are calculated at the diffuse fracture zone located 9 km from the repository footprint.

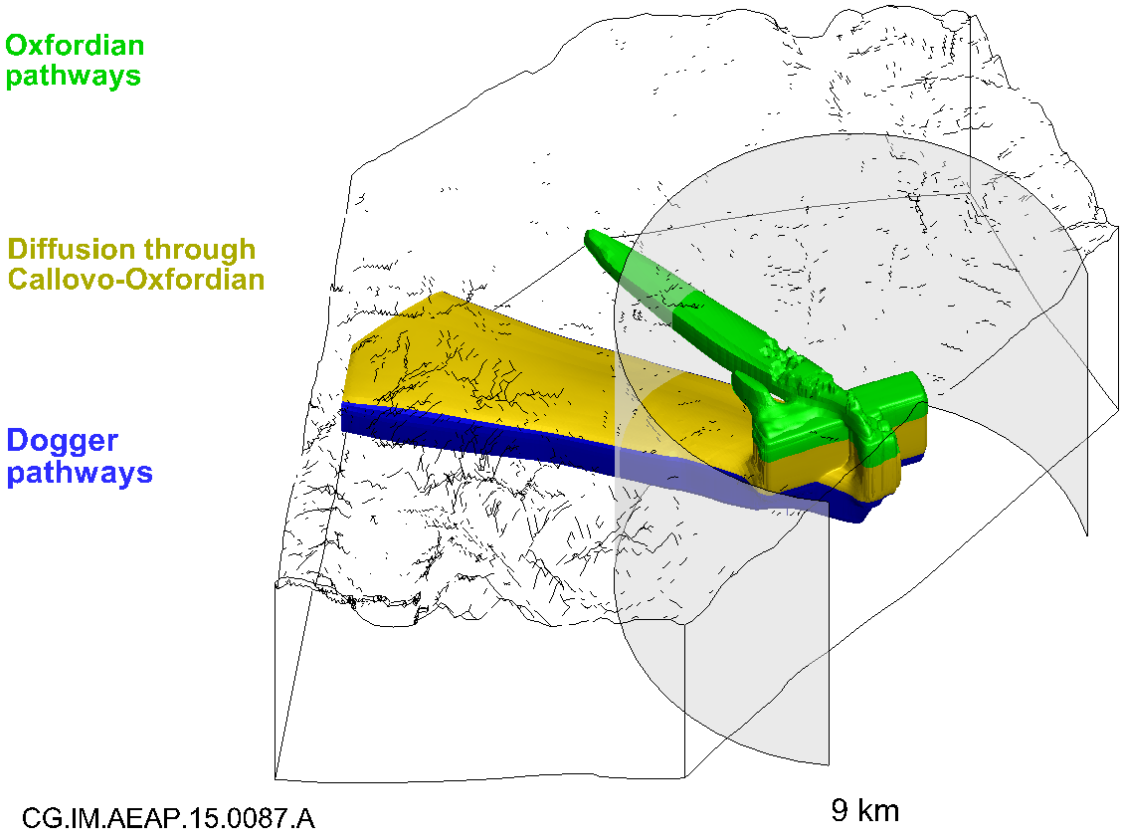


Figure 2.3-10: *Mapping of the isoconcentration of iodine-129 (10^{-11} mol.L^{-1}) in the geological medium at one million years. Blue trajectories: from the bottom of the Callovo-Oxfordian to the diffuse fracture zone; green trajectories: from the repository to the top of the Oxfordian limestone; yellow trajectories: Callovo-Oxfordian (in equilibrium with the Dogger)*

Figure 2.3-11 presents the molar flow rates for iodine-129, chlorine-36 and selenium-79 leaving the main surrounding rock formations.

Table 2.3-4 compares the molar flow rates in the surrounding rock formations with the total initial inventory. This gives the following results:

- for the transfer pathway via the Oxfordian:
  - ✓ a very low proportion of the initial iodine-129 inventory reaches the upper limits of the Oxfordian (approximately 0.006%). Transfer through the Oxfordian attenuates the iodine-129 molar flow rates by three orders of magnitude, with the peak molar flow rate occurring 150,000-years later than the date of the peak molar flow rate at the top of the Callovo-Oxfordian;
  - ✓ transfer through the Kimmeridgian attenuates by seven times more and the total quantity of iodine-129 reaching the Barrois only represents 0.0004% of the initial inventory;
  - ✓ similar observations apply for chlorine-36. Transfer through the Oxfordian leaves only 0.003% of the initial inventory reaching the upper limits of the Oxfordian and 0.0002% reaching the Barrois;

- ✓ as with iodine and chlorine-36, selenium-79 is attenuated by around 5 orders of magnitude between the top of the Callovo-Oxfordian and the top of the Kimmeridgian.

- for the transfer pathway through the Dogger:
  - ✓ flows in the Dogger to the diffuse fracture zone are faster than in the Oxfordian;
  - ✓ almost all the mobile radionuclides that reach the bottom of the Callovo-Oxfordian migrate towards the diffuse fracture zone (85% of the iodine-129, 80% of the chlorine-36 and 70% of the selenium-79), due to more limited exchanges between the Dogger and the Callovo-Oxfordian[107].

[107] Due to the relatively high migration speeds in the Dogger.

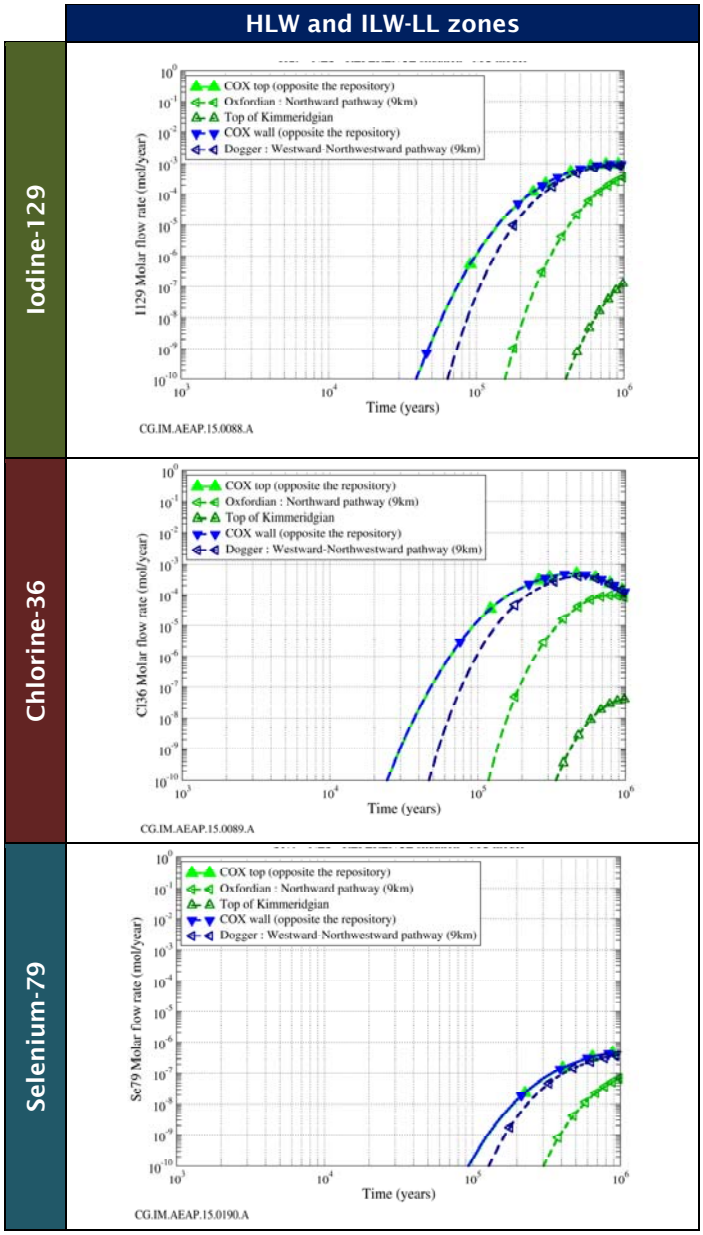


Figure 2.3-11: *Normal evolution scenario – Reference situation: Time-dependent evolution of molar flow rates for iodine-129, chlorine-36 and selenium-79 at the top and bottom of the Callovo-Oxfordian, in the Oxfordian (9km downstream of the flows), at the top of the Kimmeridgian and in the Dogger (at the diffuse fracture zone)*

Table 2.3-4: *Normal evolution scenario – Reference situation – Assessment of molar flow rates for iodine-129, chlorine-36 and selenium-79 from the Callovo-Oxfordian to the outlets, cumulative over a million years. Values normalised with regard to the total initial inventory*

		Iodine-129			Chlorine-36			Selenium-79		
		% initial quantity	Peak molar flow rate (10^{-6} mol/year)	Date of peak flow rate (thousands of years)	% initial quantity	Peak molar flow rate (10^{-6} mol/year)	Date of peak flow rate (thousands of years)	% initial quantity	Peak molar flow rate (10^{-6} mol/year)	Date of peak flow rate (thousands of years)
	Total initial inventory in moles HLW/ILW-LL	5,000 moles			5,800 moles			40,000 moles		
	Of which HLW	*54%*			*68%*			*97%*		
	Of which ILW-LL	*46%*			*32%*			*3%*		
Towards the outlet into the Barrois	At top of Callovo-Oxfordian	11%	930	840	4.6%	490	440	6×10^{-4}%	0.47	> 1,000
	Top of Oxfordian	*6×10^{-3}%*	*0.93*	> 1,000	*3×10^{-3}%*	*0.31*	*700*	*1×10^{-7}%*	*2×10^{-4}*	> 1,000
	Top of Kimmeridgian	*4×10^{-4}%*	*0.13*	> 1,000	*2×10^{-4}%*	*0.04*	> 1,000	*7×10^{-9}%*	*2×10^{-5}*	> 1,000
	Oxfordian (9km downstream) (%)	*1.8%*	*360*	> 1,000	*0.8%*	*94*	*800*	*4×10^{-5}%*	*0.07*	> 1,000
Towards the outlet into the Dogger	At bottom of Callovo-Oxfordian	11%	950	840	4.6%	49	440	6×10^{-4}%	0.48	> 1,000
	Dogger diffuse fracture zone (%)	*9.3%*	*860*	*890*	*3.7%*	*400*	*490*	*4×10^{-4}%*	*0.39*	> 1,000

Transfer into the biosphere

The biosphere model is defined in order to calculate the doses received by the hypothetical reference group selected for each of the outlets.

The results are set out in Figure 2.3-12 and Table 2.3-5:

- the "pumping in the Barrois" outlet: for both the temperate and hot standard biospheres, the radiological impacts are very low, with peaks below 1^{-6} mSv/year. The peak total dose is reached after one million years;
- the "pumping in the Dogger" outlet (diffuse fracture zone)": for both the temperate and hot biospheres, doses are primarily due to iodine-129 and chlorine-36 and remain below 0.001 mSv/year. The peak total dose is reached at around 800,000 years.

The impact at the "pumping in the Barrois" outlet is significantly lower than that of the "pumping in the Dogger" outlet[108]. This reflects additional attenuation due to the natural characteristics of the surrounding rock formations, and particularly the Oxfordian.

[108] Although, at these very low levels, the comparison is fairly irrelevant.

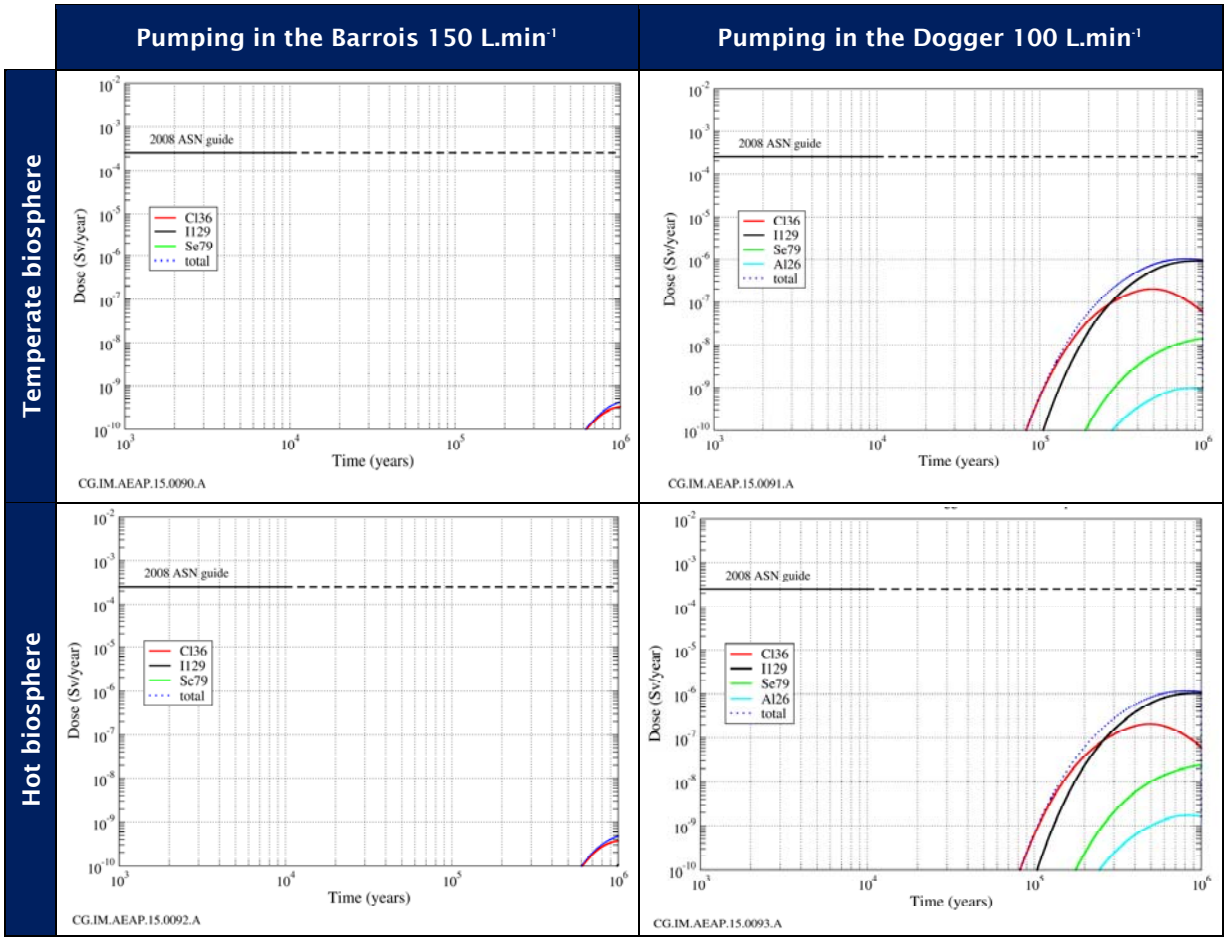


Figure 2.3-12: *Normal evolution scenario – Reference situation: Time-dependent evolution of doses at the "pumping in the Barrois" and "pumping in the Dogger (diffuse fracture zone)" outlets for the temperate and hot biospheres*

Table 2.3-5: Normal evolution scenario – Reference situation: peak doses and occurrences of peak doses at the "pumping in the Barrois" and "pumping in the Dogger (diffuse fracture zone)" outlets for temperate and hot biospheres

	Pumping in the Barrois outlet 150 L.min^{-1}				Pumping in the Dogger outlet 100 L.min^{-1}			
	Temperate biosphere		Hot biosphere		Temperate biosphere		Hot biosphere	
RN	**Peak dose (mSv/ year)**	**Date of peak dose (thousands of years)**	**Peak dose (mSv/ year)**	**Date of peak dose (thousands of years)**	**Peak dose (mSv/ year)**	**Date of peak dose (thousands of years)**	**Peak dose (mSv/ year)**	**Date of peak dose (thousands of years)**
^{36}Cl	3.2 x 10^{-07}	≥1,000	3.7 x 10^{-07}	≥1,000	2.0 x 10^{-04}	490	2.1 x 10^{-04}	490
^{129}I	9.4 x 10^{-08}	≥1,000	1.0 x 10^{-07}	≥1,000	9.2 x 10^{-04}	890	1.0 x 10^{-03}	890
^{79}Se	9.0 x 10^{-10}	≥1,000	1.9 x 10^{-10}	≥1,000	1.4 x 10^{-05}	≥1,000	2.4 x 10^{-05}	≥1,000
^{26}Al	-	-	-	-	9.7 x 10^{-07}	830	1.7 x 10^{-06}	830
Cumulative[109]	4.2 x 10^{-07}	≥1,000	4.8 x 10^{-07}	≥1,000	1.0 x 10^{-03}	800	1.1 x 10^{-03}	810

2.3.3.2 Bounding situation

For the record, the NES "bounding" situation considers two cases:

- case of the underground facility represented with a 50 metre upper undisturbed thickness of the Callovo-Oxfordian, henceforth referred to as the "high positioning repository". This situation is modelled with a hydraulic gradient of 0.1 m.m^{-1} for the entire repository footprint, which facilitates ascending advective transfer. The transfer pathways through the Callovo-Oxfordian and structures are represented;
- case of the underground facility represented with a 50 metre lower undisturbed thickness of the Callovo-Oxfordian, hereinafter referred to as the "low positioning repository". This situation is modelled with a hydraulic gradient of -0.05 m.m^{-1} for the entire repository footprint, which facilitates descending advective transfer, producing a more conservative assessment for the transfer pathways through the Dogger. Only the transfer pathway via the Callovo-Oxfordian is considered.

From the packages to the top and bottom of the Callovo-Oxfordian

- ***Analysis of molar flow rates for iodine-129 and chlorine-36 leaving the Callovo-Oxfordian***

Table 2.3-6 and Table 2.3-7 present the main indicators associated with the molar flow rates for these radionuclides. Figure 2.3-13 presents the evolution of molar flow rates for iodine-129 and chlorine-36 at the top and bottom of the Callovo-Oxfordian for the two cases quantified.

The results show that the two calculation cases are symmetrical. This leads to the following observations:

- after one million years, 80% of the initial iodine-129 and 36% of the initial chlorine-36 will have reached the edges of the Callovo-Oxfordian. The rest remains in the Callovo-Oxfordian or disappears through radioactive decay. The difference is due to the half-life of chlorine-36, which provides greater radioactive decay than iodine-129, and to the fact that it is retained in the concrete liner;

[109] The values presented in the "total" line are the peak doses and dates of occurrence which correspond to the cumulative doses for each radionuclide. These values are calculated by adding the time-dependent evolution of doses of each radionuclide, the result is marked with a blue dotted line in Figures 2.3-12 and 2.3-18. The peak doses and dates of occurrence do not necessarily coincide with those of the main radionuclides (iodine-129, chlorine-36 and selenium-79).

- the behaviours of iodine-129 and chlorine-36 are very similar. For example, the molar flow rates travelling through the Callovo-Oxfordian peak after around 100,000 years. This similarity is due to the fact that in the bounding situation, the transfer parameters for the radionuclides travelling through the Callovo-Oxfordian are similar, in particular due to the fact that no retention of chlorine-36 is accounted for in the ILW-LL cell liner;
- the peak molar flow rate for iodine transiting via structures is around 500 times lower than for iodine transiting via the Callovo-Oxfordian. For chlorine-36, it is as much as 2000 times lower. The retention of chlorine in the ILW-LL cell concrete liner contributes to reducing its molar flow rate via the structure pathway;
- when the repository is represented with an overlying 50 metres of undisturbed host-rock and a head gradient that facilitates ascending transfer ("high repository"), iodine-129 and chlorine-36 flow rates at the bottom of the Callovo-Oxfordian are lower (2.10^{-3} mol/year and 1.10^{-3} mol/year respectively) and reach their peak later (after around 250,000 years). These results are comparable to those obtained in the reference situation and are not taken into account subsequently;
- diffusion is dominant with regard to the transfer conditions in the upper and lower undisturbed thicknesses of Callovo-Oxfordian. More specifically, the ratio between the advective and diffusive flows, calculated for the upper and lower undisturbed thicknesses of Callovo-Oxfordian, is below 0.1. The difference between the molar flow rates at the top and bottom of the formation is due to the difference in thickness between the overlying and underlying undisturbed thicknesses of Callovo-Oxfordian, which are 50 metres and nearly 75 metres respectively;
- with regard to the reference situation, the cumulative quantities of mobile radionuclides that reach surrounding rock formations over 1 million years are around 5 times higher and, molar flow rates are around 10 times higher. These differences are primarily due to the difference in undisturbed thickness of host rock adopted for the bounding situation and reference situation (50 metres and 70 metres respectively).

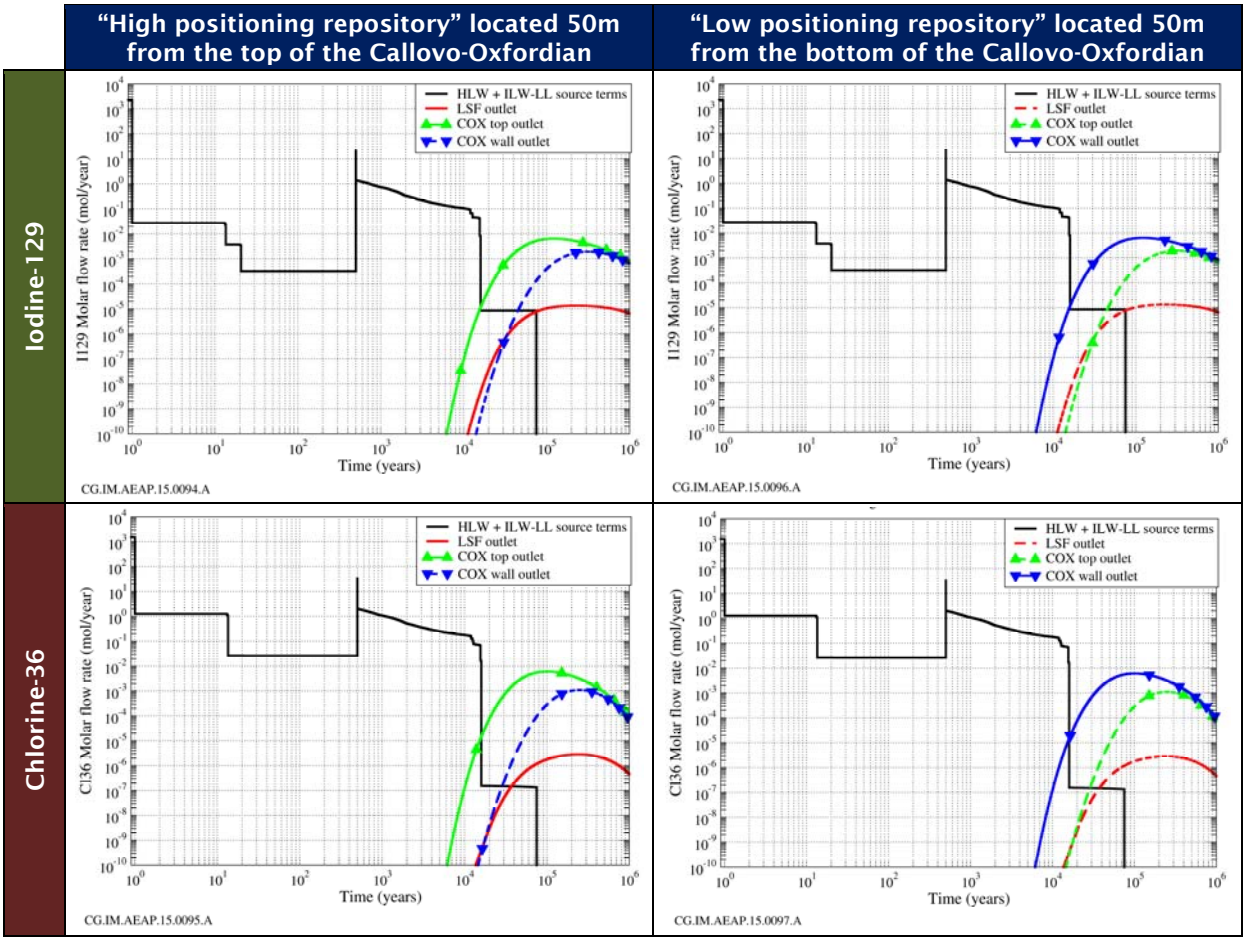


Figure 2.3-13: *Normal evolution scenario – Bounding situation – repository located 50m from top (left) or bottom (right) of the Callovo-Oxfordian: Time-dependent evolution of iodine-129 (top figures) and chlorine-36 (bottom figures) flow rates leaving the surface-bottom connection structures and the Callovo-Oxfordian*

Table 2.3-6: *Normal evolution scenario – Bounding situation ("high positioning repository") – Assessment of molar flow rates cumulative over a million years and peak molar flow rates via the Callovo-Oxfordian and structure pathway.*

	Iodine-129			Chlorine-36		
	% initial quantity	Peak molar flow rate (10^{-6} mol/year)	Date of peak flow rate (thousands of years)	% initial quantity	Peak molar flow rate (10^{-6} mol/year)	Date of peak flow rate (thousands of years)
Total initial inventory in moles	5,000 moles			5,800 moles		
Of which HLW	54%			68%		
Of which ILW-LL	46%			32%		
At top of Callovo-Oxfordian	56%	6,500	120	28%	6,100	100
Including HLW	33%	4,400	110	22%	5,100	95
Including ILW-LL	23%	2,300	160	6.1%	1,100	130
At bottom of Callovo-Oxfordian	24%	1,900	320	8.2%	1,100	230
Of which HLW	*12%*	*980*	*340*	*5.6%*	*740*	*320*
Of which ILW-LL	*12%*	*970*	*290*	*2.6%*	*370*	*210*
Via the structure pathway	0.4%	13	230	0.09%	2.8	240
Of which HLW	~10^{-3}%	0.04	260	~10^{-4}%	0.009	220
Of which ILW-LL	0.4%	13	230	0.09%	2.8	240

Table 2.3-7: *Normal evolution scenario – Bounding situation ("low positioning repository") – Assessment of molar flow rates cumulative over a million years and peak molar flow rates via the Callovo-Oxfordian and structure pathway*

	Iodine-129			Chlorine-36		
	% initial quantity	Peak molar flow rate (10^{-6} mol/year)	Date of peak flow rate (thousands of years)	% initial quantity	Peak molar flow rate (10^{-6} mol/year)	Date of peak flow rate (thousands of years)
Total initial inventory in moles	5,000 moles			5,800 moles		
Of which HLW	54%			68%		
Of which ILW-LL	46%			32%		
At top of Callovo-Oxfordian	24%	1,900	320	8.2%	1,100	230
Of which HLW	*12%*	*980*	*340*	*5.6%*	*740*	*320*
Of which ILW-LL	*12%*	*970*	*290*	*2.6%*	*370*	*210*
At bottom of Callovo-Oxfordian	56%	6,500	120	28%	6,100	100
Of which HLW	33%	4,400	110	22%	5,100	95
Of which ILW-LL	23%	2,300	160	6.1%	1,100	130

- ***Analysis of molar flow rates leaving the Callovo-Oxfordian for other radionuclides - case of a "high positioning repository" with 50 m of overlying undisturbed thickness of Callovo-Oxfordian***

Figure 2.3-14 presents the evolution of the main mobile radionuclide flow rates at the top of the Callovo-Oxfordian. These flow rates are higher than those at the bottom of the Callovo-Oxfordian, because the overlying layer of undisturbed Callovo-Oxfordian is not so thick as the underlying layer (which corresponds to the minimum defined by the specifications applicable to Cigeo). All the radionuclides with a molar flow rate of over 1.10^{-10} moles during this period are represented. This includes:

- iodine-129, chlorine-36 and selenium-79, which are all mobile radionuclides (soluble and not retained) in the Callovo-Oxfordian. The molar flow rate for selenium-79 is higher than 10^{-4} mol/year after 100,000 years;
- aluminium-26, is a mobile isotope with a long half-life; its low initial inventory leads to limited release levels, even in the "bounding situation". The molar flow rate for this isotope at the top of the Callovo-Oxfordian reaches 2.10^{-6} mol/year after 100,000 years;
- calcium-41 and potassium-40, which are weakly sorbed in concrete structures and in the Callovo-Oxfordian; their high initial inventories lead to total peak molar flow rates of over 10^{-4} mol/year, between 100,000 and 200,000 years;
- carbon-14 and molybdenum-93 which, despite their short half-life, have a high initial inventory leading to molar flow rates of over 10^{-7} mol/year. The impact of the carbon-14 should be put into perspective in the light of the very broad bounding assumptions adopted[110]. The impact of the molybdenum-93 should be put into perspective since after 50, 000 years only 10^{-3}% of its initial inventory has reached the edges of the Callovo-Oxfordian and its molar flow rate is significantly lower than the other radionuclides, given its half-life; The impact of the molybdenum-93 should be put into perspective since after 50,000 years only 10-3% of its initial inventory has reached the edges of the Callovo-Oxfordian and its molar flow rate is significantly lower than the other radionuclides, given its half-life;
- uranium-235 and uranium-238 (taking into account conservative partition coefficients in the Callovo-Oxfordian) have an inventory and half-life which lead to molar flow rates of over 10^{-10} mol/year with very late occurrence dates (peak molar flow rates leaving the Callovo-Oxfordian occurring at over 3 to 4 million years). At one million years, only 10% of the initial inventory of uranium has reached the edges of the Callovo-Oxfordian.

[110] The representation of the behaviour of carbon-14 adopted at this stage is very broad: 100% of its inventory is considered to be in organic form, with no sorption. It is considered soluble in the cement components and Callovo-Oxfordian, with a conservative diffusion coefficient.

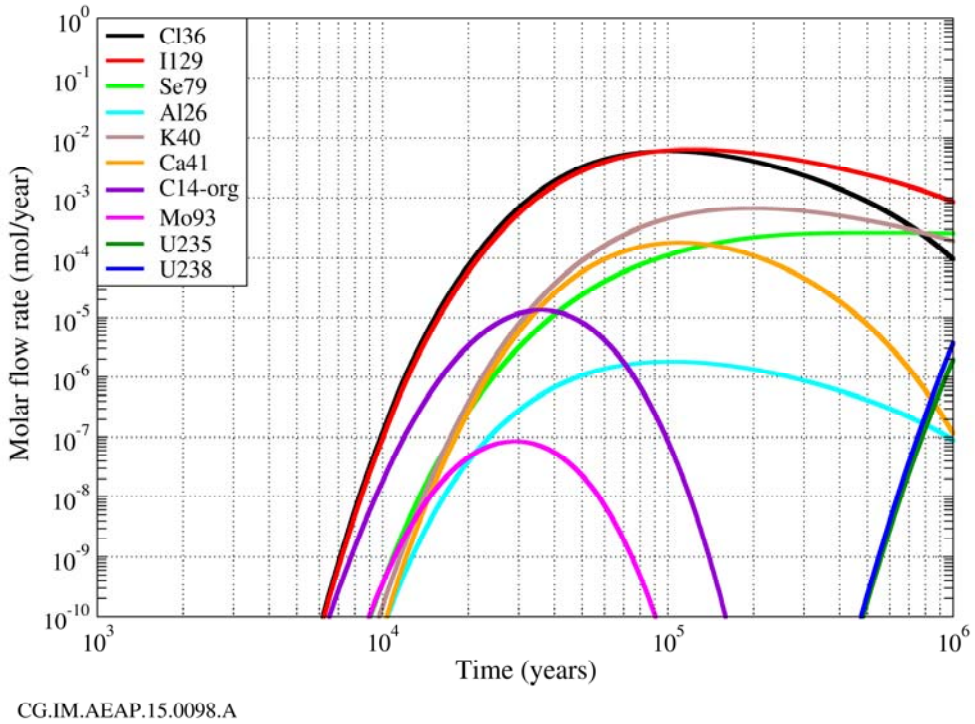


Figure 2.3-14: *Normal evolution scenario – Bounding situation: Time-dependent evolution of molar flow rates at the top of the Callovo-Oxfordian ("High positioning repository" located 50 metres from the top of the Callovo-Oxfordian)*

- ***Analysis of the transfer of iodine-129 and chlorine-36 from HLW and ILW-LL zones (case of an "high positioning repository" with 50 metre of overlying undisturbed host-rock)***

Figure 2.3-15 presents the evolution of the molar flow rates for iodine-129 and chlorine-36 released by the HLW and ILW-LL waste packages and transiting via the Callovo-Oxfordian and structures. The molar flow rates are quantified at different locations along the structures in the HLW and ILW-LL zones (access drifts (HLW zone) and connecting drifts), in the main zone and the surface-bottom connection structure outlets.

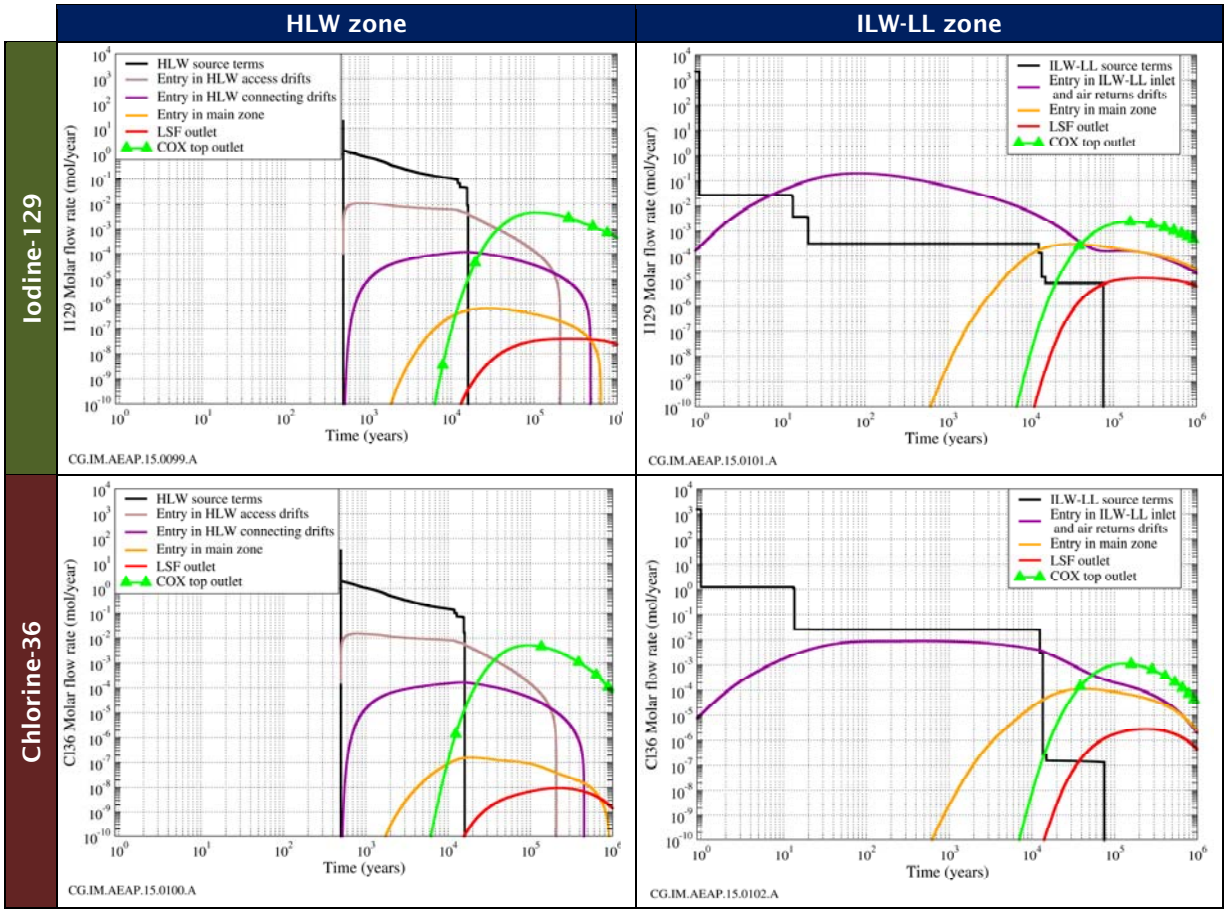


Figure 2.3-15: *Normal evolution scenario – Bounding situation – "High positioning repository" with 50 m of overlying host-rock, HLW (left) and ILW-LL (right) disposal sections: time-dependent evolution of molar flow rates for iodine-129 and chlorine-36 entering the access drifts (HLW only), the connecting drifts and the main zone, and leaving the surface-bottom connection structures and the Callovo-Oxfordian.*

The graphs for Figure 2.3-15 and Table 2.3-8 show the following points:

- in the bounding situation, the release of iodine-129 and chlorine-36 occurs earlier than in the reference situation:
  - ✓ between 500 and 20,000 years in the HLW zone;
  - ✓ before 80,000 years in the ILW-LL zone, with a higher removable fraction than in the reference situation;
- the molar flow rates for radionuclides transiting via the structure pathway are higher for the ILW-LL zone than for the HLW zone. This difference is due to the distribution of the ILW-LL inventory, which is located at the entrance to the disposal section (around 50% of the total inventory of iodine-129 and chlorine-36 is situated in the first five ILW-LL disposal cells), and the direction of the flows in the underground facility, which facilitates transfer from the ILW-LL disposal section to the main zone;
- in the HLW zone, the iodine-129 and chlorine-36 molar flow rates through the structure pathway drop suddenly, after around 200,000 years at the entrance to the access drift, 400,000 years at the entrance to the connecting drift and 600,000 years at the entrance to the main zone. This evolution is due to the slow flows towards the HLW zone. At the dates identified above, the convective flows towards the HLW zone counter-balance the diffusion flows.

Table 2.3-8 gives the assessment of molar flow rates for iodine-129 and chlorine-36 cumulative over a million years at different points along the structure pathway. These assessments are normalised with regard to the initial inventory of the HLW and ILW-LL zones, and lead to the following observations:

- in the HLW zone, less than 6% of the initial iodine-129 and chlorine-36 inventory reaches the access drifts, and the rest leaves the disposal cells radially, via the Callovo-Oxfordian. The former fraction is low because of the length of the HLW disposal cells and the slow hydraulic system. The slow transfer along the access drifts also allows the radionuclides to cross the liner and diffuse in the clay rock. Only 0.4% of the initial inventory of iodine-129 and 0.3% of chlorine-36 reach the connecting drifts. The peak molar flow rate is attenuated by two orders of magnitude. Only 0.01% of the initial inventory of iodine-129 and 0.001% of chlorine-36 reach the main zone, with further attenuation of two orders of magnitude. Ultimately, a very low fraction of the inventories of iodine-129 (approximately 0.003%) and chlorine-36 (0.0001%) leave the surface-bottom connections, with attenuation of another order of magnitude. The maximum molar flow rate is therefore 5 to 6 orders of magnitude lower than the molar flow rate for radionuclides transiting through the Callovo-Oxfordian;
- in the ILW-LL zone, 17% of the initial inventory of iodine-129 and 9% of chlorine-36 reach the connecting drifts. These proportions drop to 4.2% and 1.6% respectively at the entrance to the main zone, with the peak molar flow rate attenuated by 2 to 3 orders of magnitude. The slow kinetics of flows in the access drifts and the transfer into the Callovo-Oxfordian limit the fractions of iodine-129 and chlorine-36 leaving the surface-bottom connections to 0.4 and 0.1%, with further attenuation of the peak molar flow rates of more than one order of magnitude. The peak molar flow rate is therefore 2 to 3 orders of magnitude lower than the molar flow rate for radionuclides migrating via the Callovo-Oxfordian.

Table 2.3-8: *Normal evolution scenario – Bounding situation ("High positioning repository"): cumulative quantities of iodine-129 and chlorine-36 entering the access drifts, connecting drifts and the main zone, and leaving the surface-bottom connection structures and the Callovo-Oxfordian over a million years. Percentage of the initial inventory of HLW and ILW-LL disposal sections.*

% of initial total inventory for HLW zone	Entering access drifts	Entering connecting drifts	Entering the main zone	Leaving the surface-bottom connections	Leaving the top of the Callovo-Oxfordian
Iodine-129	5.8%	0.4%	$<10^{-2}$%	~10^{-3}%	61%
Chlorine-36	5.7%	0.3%	< 10^{-3}%	~ 10^{-4}%	32 %
% of initial total inventory for ILW-LL zone	**Entering connecting/access and air return drifts**		**Entering the main zone**	**Leaving the surface-bottom connections**	**Leaving the top of the Callovo-Oxfordian**
Iodine-129	17%		4.2%	0.4%	49%
Chlorine-36	9.3%		1.6%	0.09%	19 %

- ***Specific case of a configuration with a lower performance closure system for ILW cells***

For reasons explained above, only the configuration with an "high positioning repository" with 50 m of upper host-rock thickness is analysed.

Figure 2.3-6 and Table 2.3-9 show molar flow rates for iodine-129 from the ILW-LL zone and transiting via the Callovo-Oxfordian and the structure pathway - case with seals in the ILW-LL disposal cell and case with a lower performance closure system[111]).

With a lower performance ILW cell closure system, the cumulative molar flow rates entering the main zone and leaving the surface-bottom connections increase by around 20%, which is low considering the flows migrating via the Callovo-Oxfordian. This is due to the efficiency of the surface-bottom connection structures, which ensure that there is no significant transfer via the structure pathway. The molar flow rates at other locations are not affected.

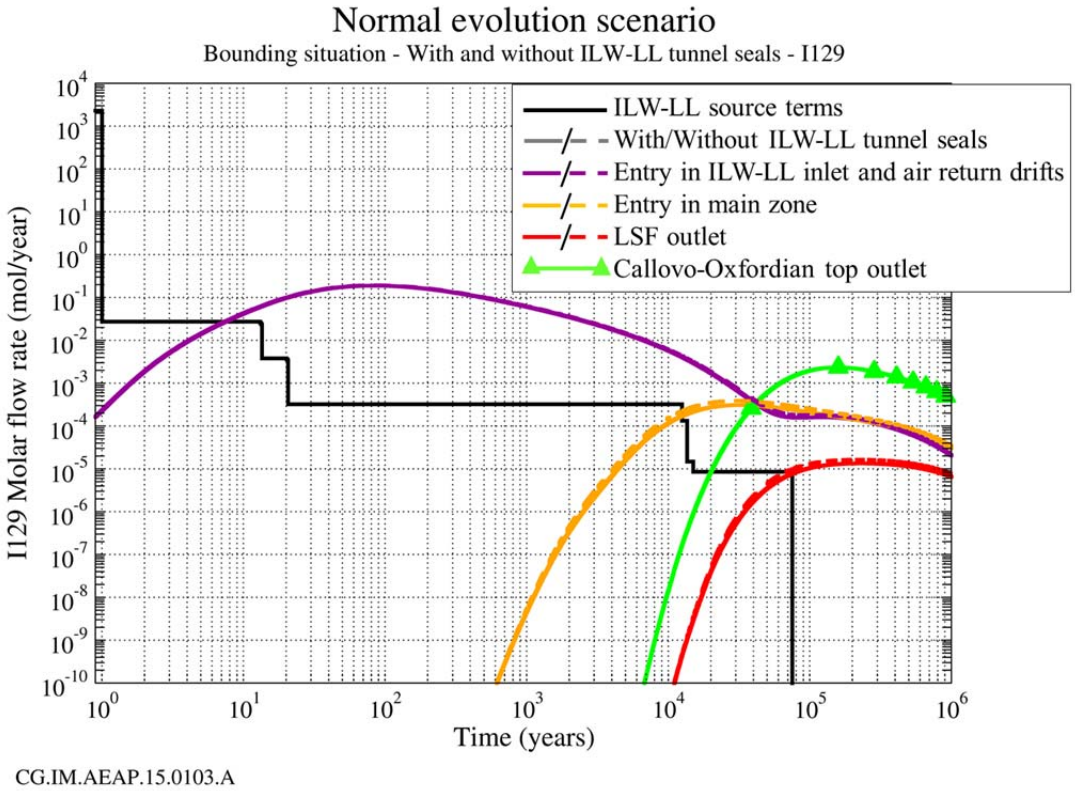


Figure 2.3-16: *Normal evolution scenario – Bounding situation ("high positioning repository"), ILW-LL disposal section, ILW-LL disposal cell with a seal or lower performance closure system: time-dependent evolution of molar flow rates for iodine-129 entering the access drifts (HLW only), the connecting drifts and the main zone, and leaving the surface-bottom connection structures and the Callovo-Oxfordian*

[111] Case identified as "no ILW-LL cell seal" in the figures and tables.

Table 2.3-9: *Normal evolution scenario – Bounding situation ("high positioning repository"), ILW-LL disposal section, ILW-LL disposal cell with seals or with lower performance closure system: assessment of iodine-129 quantities (cumulative over a million years, normalised by the initial inventory of the total ILW-LL zone) entering connecting drifts and the main zone, and leaving surface- bottom connection structures and the top of the Callovo-Oxfordian*

	Quantity of iodine-129 (as a% of total initial inventory of the ILW-LL section)			
	Entering connecting/ air return drifts	Entering the main zone	Leaving the surface-bottom connections	Leaving the top of the Callovo-Oxfordian
ILW-LL cells with seal	17%	4.2%	0.4%	49%
ILW-LL cells with lower performance closure system	18%	5.1%	0.5%	49%

From the surrounding rock formations to the outlets

Figure 2.3-17 presents the molar flow rates for iodine-129 and chlorine-36 from the top of the Callovo-Oxfordian to the Barrois outlet and from the bottom of the Callovo-Oxfordian to the Dogger outlet, in the diffuse fracture zone. Table 2.3-10 and Table 2.3-11 provide a comparison between the molar flow rates in the surrounding rock formations with the total initial inventory.

The slow flows in the Oxfordian limestone allow the radionuclides to be reduced and allow back-diffusion towards the Callovo–Oxfordian. The transfer in the Oxfordian reduces peak molar flow rates by a factor of 20 for iodine-29 and chlorine-36, compared with those at the top of the Callovo-Oxfordian, with an occurrence date for the maximum molar flow rate that falls after 250,000 years. The proportions of the initial iodine-129 and chlorine-36 inventory that reach the Barrois limestone are 3% for iodine-129 and 1% for chlorine-36. Unlike the reference situation, the attenuation obtained from transiting through Kimmeridgian is extremely limited, due to the conservative transfer parameters in the Oxfordian and the Kimmeridgian.

Flows in the Dogger towards the diffuse fracture zone are faster than in the Oxfordian limestone. Therefore, 80% of the iodine-129 and 75% of the chlorine-36 that reach the bottom of the Callovo-Oxfordian migrate towards the diffuse fracture zone, with low attenuation and a delay of approximately 30,000 years.

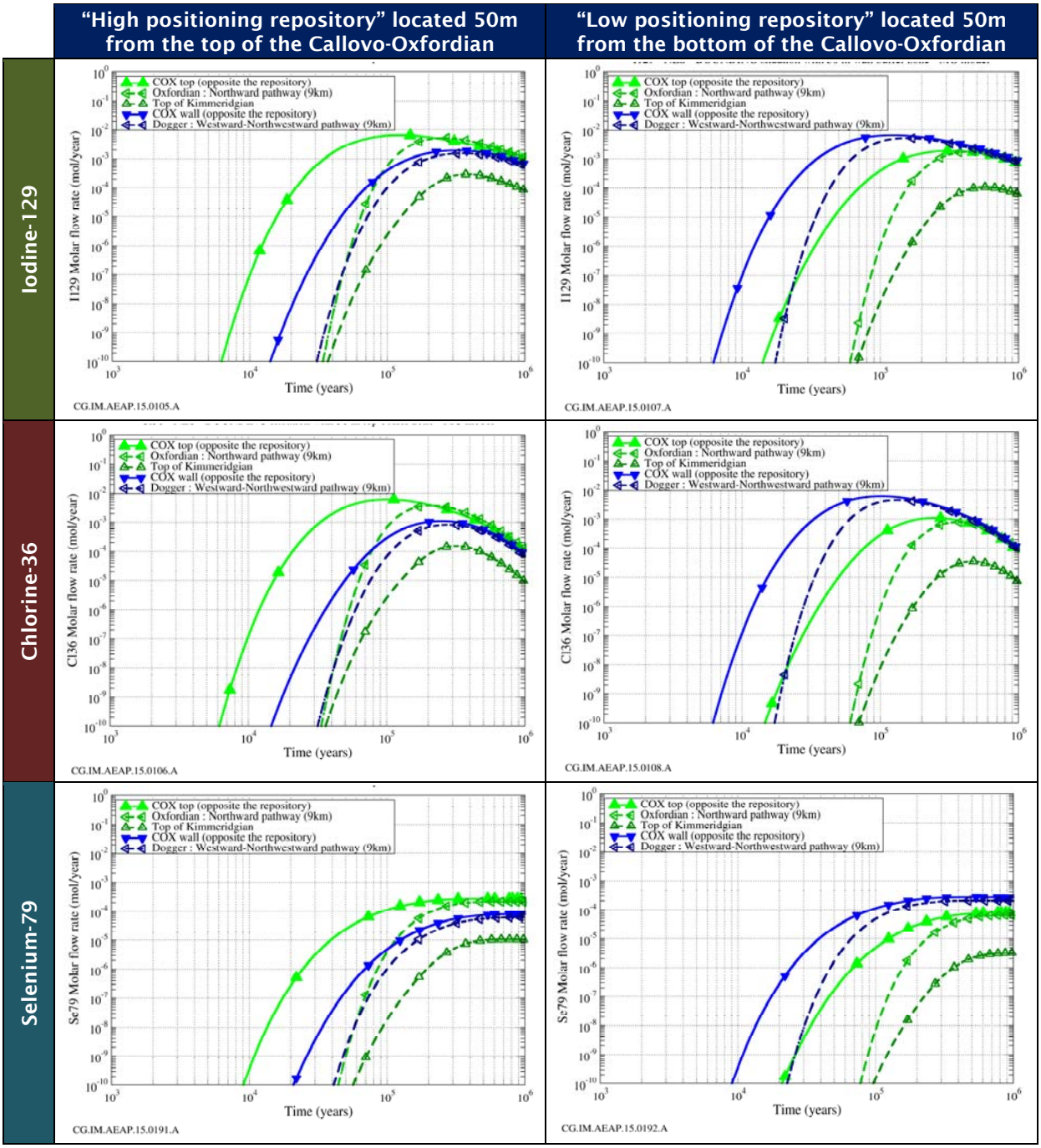


Figure 2.3-17: *Normal evolution scenario – Bounding situation, time-dependent evolution of molar flow rates for iodine-129, chlorine-36 and selenium-79 in the geological medium at the top (left) and bottom (right) of the Callovo-Oxfordian, in the Oxfordian (9km downstream of repository footprint), at the top of the Kimmeridgian and in the Dogger (at the diffuse fracture zone)*

Table 2.3-10: *Normal evolution scenario – Bounding situation – "High positioning repository" located 50m from top of the Callovo-Oxfordian: Assessment of iodine-129 and chlorine-36 molar flow rates cumulative over a million years, from the top of the Callovo-Oxfordian to the Barrois outlet. Values normalised with regard to the total initial inventory.*

	Iodine-129			Chlorine-36			Selenium-79		
	% initial quantity	Peak molar flow rate (10^{-6} mol/year)	Date of peak flow rate (thousands of years)	% initial quantity	Peak molar flow rate (10^{-6} mol/year)	Date of peak flow rate (thousands of years)	% initial quantity	Peak molar flow rate (10^{-6} mol/year)	Date of peak flow rate (thousands of years)
At top of Callovo-Oxfordian	**56%**	**6,500**	**120**	**28%**	**6,100**	**100**	**0.6%**	**270**	**540**
Top of Oxfordian	*3.2%*	*350*	*270*	*8.2%*	*240*	*230*	*0.02%*	*10*	*530*
Top of Kimmeridgian	*3.0%*	*290*	*380*	*5.6%*	*150*	*320*	*0.02%*	*10*	*730*
Oxfordian (9km downstream)	*52%*	*5,300*	*260*	*2.6%*	*3,800*	*210*	*0.4%*	*220*	*660*

Table 2.3-11: *Normal evolution scenario – Bounding situation – "Low repository" located 50m from bottom of the Callovo-Oxfordian. Assessment of iodine-129 and chlorine-36 molar flow rates cumulative over a million years, from the bottom of the Callovo-Oxfordian to the Dogger outlet. Values normalised with regard to the total initial inventory.*

	Iodine-129			Chlorine-36			Selenium-79		
	% initial quantity	Peak molar flow rate (10^{-6} mol/year)	Date of peak flow rate (thousands of years)	% initial quantity	Peak molar flow rate (10^{-6} mol/year)	Date of peak flow rate (thousands of years)	% initial quantity	Peak molar flow rate (10^{-6} mol/year)	Date of peak flow rate (thousands of years)
At bottom of Callovo-Oxfordian	**56%**	**6,500**	**120**	**28%**	**6,100**	**100**	**0.6%**	**270**	**540**
Dogger diffuse fracture zone	*44%*	*5,200*	*150*	*21%*	*4,600*	*130*	*0.4%*	*210*	*610*

Transfer into the biosphere

The results shown in Figure 2.3-18 and Table 2.3-12 present the doses received by the hypothetical reference group adopted for each of the outlets and each of the standard biospheres: temperate biosphere and hot biosphere.

The results lead to the following main elements:

- at the "pumping in the Barrois" outlet, the radiological impacts are low, at approximately 0.002 mSv/year (i.e. significantly below 0.25 mSv/year, the value fixed in the safety guidelines published by ASN in 2008 (1)) (1). The date of occurrence for the maximum total dose is at around 340,000 years for both the temperate and hot biospheres. The main contributor to this dose is the chlorine-36 for up to 600,000 years, then selenium-79;
- at the "pumping in the Dogger (diffuse fracture zone)" outlet doses are also low, at approximately 15×10^{-3} mSv/ year with the maximum dose falling around 200,000 and 250,000 years for the temperate standard biosphere and the hot standard biosphere respectively. Iodine-129 is the main contributor to the dose for up to 200,000 years, followed by selenium-79. Unlike the dose at the Barrois outlet, it is not the chlorine-36, due to the isotopic dilution model adopted, which gives a higher dilution value in the Dogger due to the salinity of its pore water (i.e. presence of stable chlorine, chlorine-35 and chlorine-37).

The difference between the reference situation and the bounding situation observed for the doses at the "pumping in the Barrois" outlet is limited by a factor of 7 for iodine-129 and 1.2 for chlorine-36. This difference reflects the fact that diffusive transport is taken into account for the marl levels of the overlying rock formations in the reference situation. These results show that the natural characteristics of the overlying rock formations can further attenuate the transfer of radionuclides into the Barrois outlet.

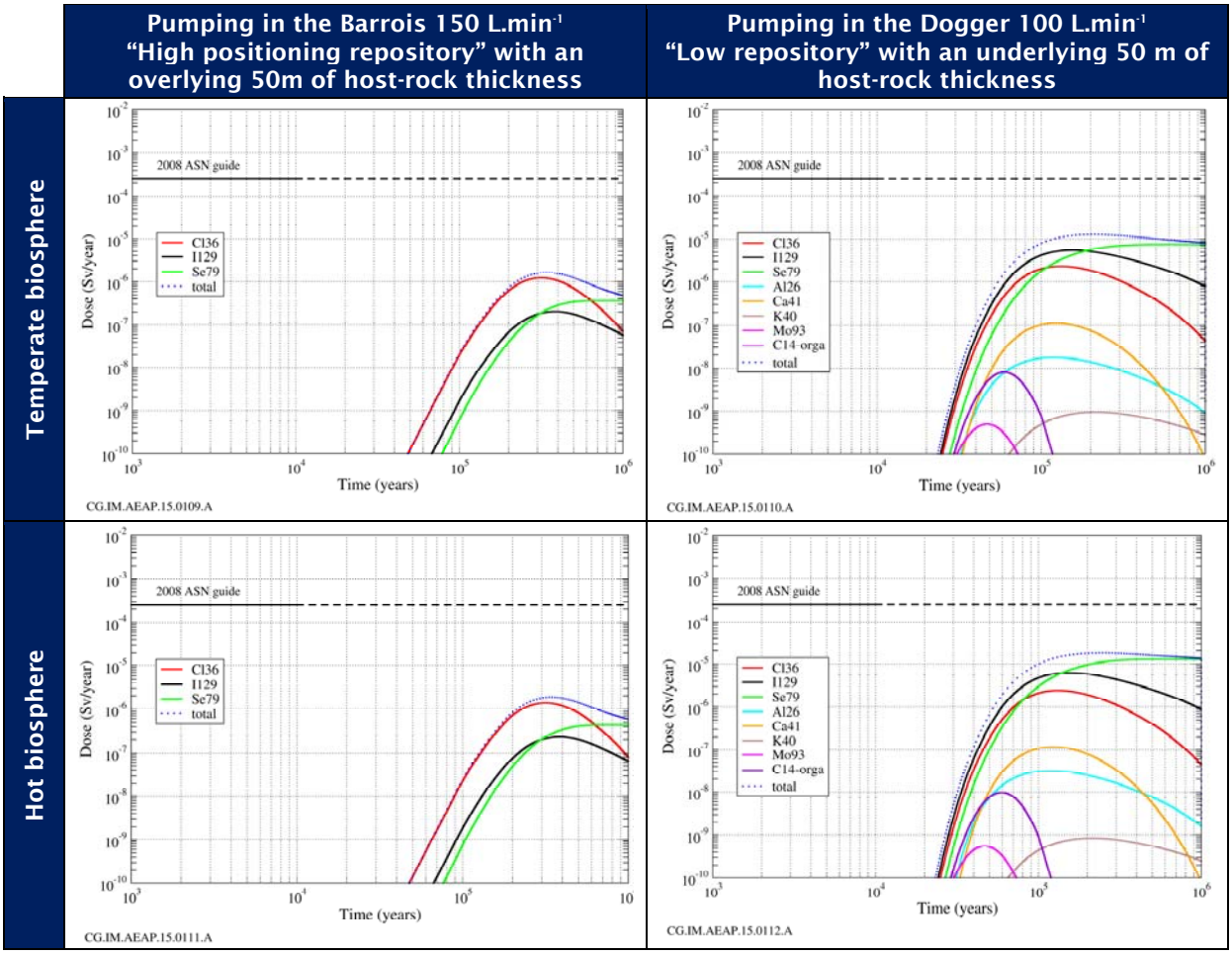


Figure 2.3-18: *Normal evolution scenario – Bounding situation: time-dependent evolution of doses at the "pumping in the Barrois" and "pumping in the Dogger (diffuse fracture zone)" outlets for the temperate and hot biospheres*

Table 2.3-12: Normal evolution scenario – Bounding situation: peak doses and occurrences of peak doses at the "pumping in the Barrois" and "pumping in the Dogger (diffuse fracture zone)" outlets for temperate and hot biospheres

	Pumping in the Barrois Repository with an overlying Host-rock thickness of 50 m				**Pumping in the Dogger (diffuse fracture zone) 100 L.min^{-1} Repository with an underlying host-rock thickness of 50 m**			
	Temperate biosphere		**Hot biosphere**		**Temperate biosphere**		**Hot biosphere**	
RN	**Peak dose (mSv/ year)**	**Date of peak dose (thousands of years)**	**Peak dose (mSv/ year)**	**Date of peak dose (thousands of years)**	**Peak dose (mSv/ year)**	**Date of peak dose (thousands of years)**	**Peak dose (mSv/year)**	**Date of peak dose (thousands of years)**
^{36}Cl	1.2×10^{-03}	320	1.4×10^{-03}	320	2.3×10^{-03}	130	2.4×10^{-03}	130
^{129}I	2.1×10^{-04}	380	2.3×10^{-04}	380	5.5×10^{-03}	150	6.2×10^{-03}	150
^{79}Se	3.7×10^{-04}	710	4.4×10^{-04}	730	7.6×10^{-03}	610	1.3×10^{-02}	610
^{26}Al					1.8×10^{-05}	120	3.1×10^{-05}	120
^{41}Ca					1.1×10^{-04}	120	1.2×10^{-04}	120
^{40}K					9.6×10^{-07}	210	8.5×10^{-07}	210
^{93}Mo					4.9×10^{-07}	47	5.5×10^{-07}	47
Organic 14C					8.1×10^{-06}	59	1.0×10^{-05}	59
Total	1.6×10^{-03}	340	1.9×10^{-03}	340	1.3×10^{-02}	210	1.8×10^{-02}	250

2.4 Lessons from the NES

Overall analysis of the results presented above provides various lessons for the two situations covered (reference and bounding) with regard to post-closure safety functions and radiological impacts.

2.4.1 Analysis of NES structuring choices

The results of the analysis of the two reference and "bounding" situations clearly show that the safety functions are ensured in the "bounding" situation (corresponding to the specified or conventional values). Taking into account the phenomenological characteristics of the Callovo-Oxfordian and its environment in which Cigeo is located makes it possible to identify a number of margins:

- the thickness of the Callovo-Oxfordian which, in the reference situation, is greater than the minimum value specified in the requirements (i.e. 50 metres), provides additional attenuation;
- the retention and transfer parameters for radionuclides in the Callovo-Oxfordian. For a molar flow rate of over 10^{-10} mol/year, the phenomenological values of the parameters taken in the reference situation provide additional attenuation of mobile anions (travelling by diffusion) and of aluminium-26, calcium-41 and potassium-40. The other radionuclides do not reach 10^{-10} mol/year;
- the difference in hydraulic head between the surrounding rock formations set in the reference situation, based on the results of hydrogeological modelling, leads to lower values than the "bounding" situation for which it was decided, by convention, to retain the maximum value. Nevertheless, diffusive transport remains dominant in the Callovo-Oxfordian and the backfilled structures for both situations;
- the surrounding rock formations have no safety function, but taking into account their natural characteristics with regard to diffusive transport through the marl levels towards outlets provides additional attenuation.

2.4.2 Analysis of post-closure safety functions

2.4.2.1 The "resist the circulation of water" function

Radionuclide transport conditions are diffusive in all repository structures, including the ILW-LL disposal cells, where the flow velocity (pore flow rate) is approximately 0.25mm per year (in the reference situation).

Dominant diffusive transport shows that the repository is working properly with regard to the "resist the circulation of water" function, due to:

- the efficiency of the seals, particularly in the surface-bottom connection structures, the favourable hydraulic properties in the Callovo-Oxfordian (low permeability) and the low vertical head gradient. Flows in the repository are very limited, both in the disposal cells and the HLW and ILW-LL disposal sections, as well as the central zone, despite the fact that this receives the contribution from all disposal sections.
- the overall architecture design measures (shafts grouped together, dead-end disposal sections).

The presence of lower performance ILW-LL cell closure systems has no significant effect on these indicators.

2.4.2.2 The "limit the release of radionuclides and toxic chemicals and immobilise them in the repository" function

Taking into account the slow release kinetics of some HLW ("$V_0 \rightarrow V_R$" model) or ILW-LL (CSD-C) packages has a limited influence on the peak molar flow rates at the top and bottom of the Callovo-Oxfordian, due to the extremely slow transfer times in the overlying and underlying undisturbed thicknesses of the Callovo-Oxfordian with regard to the release periods.

The sorption phenomena in the cement components of the ILW-LL disposal cells make a limited contribution to the total transfer time to the top and bottom of the Callovo-Oxfordian, because the performance of the Callovo-Oxfordian masks that of the structural components. In the reference situation, for chlorine-36, a mobile radionuclide that is not sorbed in the Callovo-Oxfordian, this contribution is significant in that it delays the occurrence of the peak molar flow rate by around 100,000 years, for a total transfer time of around 800,000 years.

2.4.2.3 The "delay and attenuate radionuclide migration" function

For the reference situation

- the majority of the radionuclides remain contained in the Callovo-Oxfordian after 1 million years. Only the long-lived mobile radionuclides (iodine-129, chlorine-36, selenium-79, aluminium-26, potassium-40 and calcium-41 (see Figure 2.3-6) reach molar flow rates of over 10^{-10} moles per year leaving the Callovo-Oxfordian;
- typical diffusive transport times through the Callovo-Oxfordian are approximately 450,000 years (for chlorine-36) to over 800,000 years (for iodine-129). They provide significant radioactive decay;
- taking into account the retention of some radionuclides (chlorine-36) in the concrete liner of the ILW-LL disposal cells contributes to delaying and attenuating their migration. The occurrence of the peak molar flow rates of chlorine-36 leaving the Callovo-Oxfordian is delayed by around 100,000 years;
- only the mobile radionuclides (iodine-129, chlorine-36 and selenium-79) migrate via the structure pathway from the disposals cells to the surface-bottom connection structures (ramps and shafts). This transfer occurs by dominant diffusion such that the peak molar flow rates leaving the surface-bottom connection structures at the top of the Callovo-Oxfordian are very low and significantly lower than those transiting via the Callovo-Oxfordian transfer pathway[112].

For the bounding situation:

- as with the reference situation, the majority of the radionuclides remain contained in the Callovo-Oxfordian after 1 million years.
- iodine-129 and chlorine-36 remain the main radionuclides leaving the Callovo-Oxfordian, but by taking into account a molar flow rate reference value of 10^{-10} mol/year, other radionuclides such as carbon-14, calcium-41 and molybdenum-93, appear;
- typical diffusive transport times through the Callovo-Oxfordian remain high, at over 100,000 years for iodine-129 and chlorine-36 and over 500,000 years for selenium-79.

Figure 2.4-1 shows the distribution of the transfer pathways for iodine-129 in the structural components and the geological medium from the package to the outlets. It illustrates, in particular, the low proportion of radionuclides migrating via the backfilled and sealed structures and the low quantity of radionuclides that reach the outlets.

[112] For example, the peak molar flow rate of iodine-129 via the Callovo-Oxfordian transfer pathway is 30,000 times higher than the transfer pathway via structures.

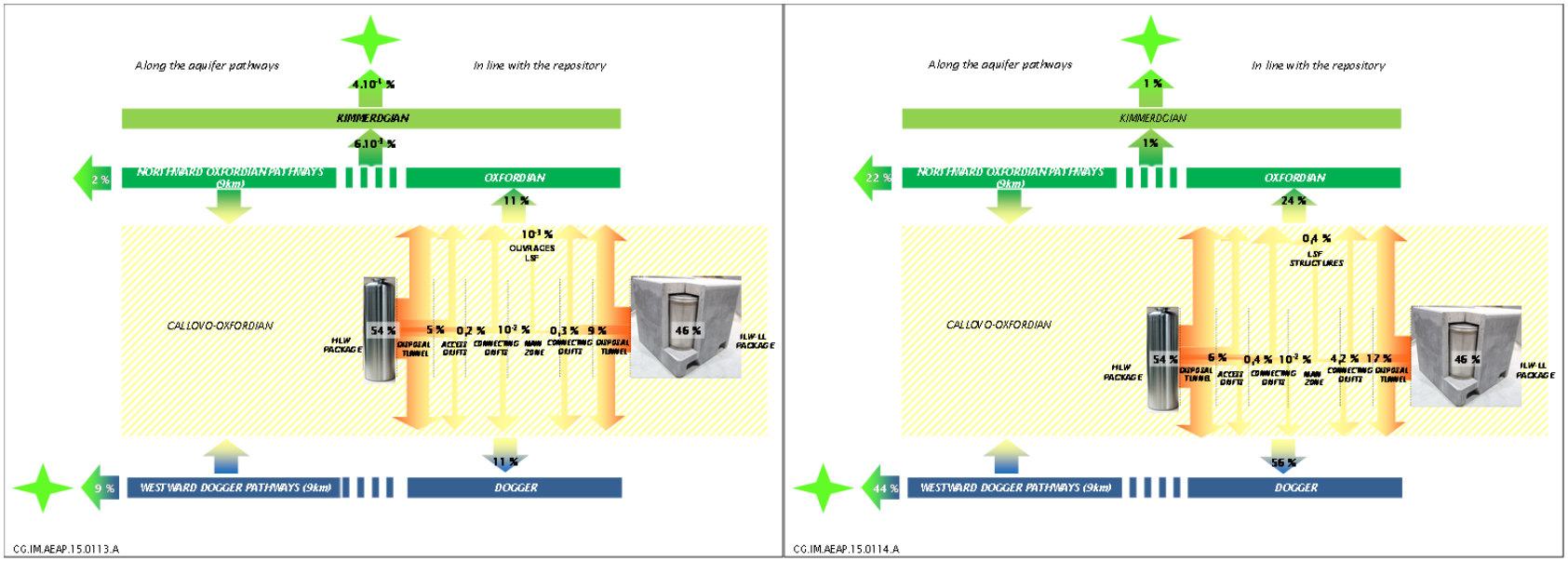


Figure 2.4-1: *Normal evolution scenario – Reference (left) and bounding (right) situations - HLW and ILW-LL disposal sections, iodine-129: summary of the distribution of the transfer pathways in the structural components and the geological medium from the package to the outlets – assessments normalised with regard to the initial inventory*

2.4.3 Analysis of radiological impacts

Table 2.4-1 gives the peak total doses (and when they occur) at the Barrois and Dogger outlets, for temperate or hot standard biospheres.

For the reference situation:

Doses at the Barrois and Dogger outlets are very low and much lower than the dose limit set in the ASN 2008 guidelines for the normal evolution scenario:

- the transfer of radionuclides is slow in the Oxfordian and diffusive in the low-permeability levels of the Oxfordian (grey sequence, C3a) and the Kimmeridgian, which provides for significant attenuation of the flow reaching the Barrois outlet as compared to the flow reaching the top of the Callovo-Oxfordian. The peak total dose is very low, below 10^{-6} mSv/year for both temperate and hot biospheres. It occurs after a million years;
- for the radionuclides that reach the Dogger, the peak total dose occurs at around 800,000 years at the outlet (diffuse fracture zone) with a value of approximately 0.0001 mSv/year for both temperate and hot biospheres.

For the bounding situation:

Doses at the Barrois and Dogger outlets are low and much lower than the dose limit of 0.25 mSv/year set in the ASN 2008 guidelines for the normal evolution scenario:

- for the repository with an overlying host-rock thickness of 50m, the peak total dose is approximately 0.001 mSv/year in the temperate and hot biospheres. It occurs at around 340,000 years;
- for the repository with an underlying host-rock thickness of 50m, the peak total dose is around 0.00001 mSv/year in the temperate and hot biospheres. It occurs between 210,000 and 250,000 years for the temperate biosphere and the hot biosphere respectively.

For the two situations (reference and bounding), the total doses (HLW + ILW-LL) are dominated by iodine-129, chlorine-36 and selenium-79.

Peak doses are not affected much by the standard biosphere which is chosen, with the peak dose obtained for the pumping in the Dogger in the hot biosphere. The peak dose is around 0.018 mSv/year, much lower than the limit of 0.25 mSv/year in the geological repository guidelines (ASN 2008) for normal evolution.

The dose at the Barrois outlet is slightly below the dose at the Dogger outlet (although the molar flow rates leaving the top and bottom of the Callovo-Oxfordian are similar).

Because of their natural characteristics, the overlying rock formations provide additional attenuation of the flow of radionuclides potentially arriving at the outlets as compared to the flows arriving at the top and bottom of the Callovo-Oxfordian.

Table 2.4-1: Normal evolution scenario: peak doses and occurrences of peak doses at the "pumping in the Barrois" and "pumping in the Dogger (diffuse fracture zone)" outlets for temperate and hot biospheres

		Temperate biosphere		Hot type biosphere	
		Peak dose (mSv/year)	**Date of peak dose (thousands of years)**	**Peak dose (mSv/year)**	**Date of peak dose (thousands of years)**
Reference situation	Pumping in the Barrois 150 $L.min^{-1}$	4.2×10^{-07}	≥1,000	4.8×10^{-07}	≥1,000
	Pumping in the Dogger (diffuse fracture zone) 100 $L.min^{-1}$	1.0×10^{-03}	800	1.1×10^{-03}	≥1,000
Bounding situation	Pumping in the Barrois 150 $L.min^{-1}$ Repository with an overlying undisturbed thickness of 50 m	1.6×10^{-03}	340	1.9×10^{-03}	340
	Pumping in the Dogger (diffuse fracture zone) 100 $L.min^{-1}$ Repository with an underlying undisturbed thickness of 50 m	1.3×10^{-02}	210	1.8×10^{-02}	250

3

Altered Evolution Scenarios (AES)

3.1 Altered evolution scenarios for seal malfunctions 305

3.2 Altered evolution scenarios for HLW disposal containers 325

3.1 Altered evolution scenarios for seal malfunctions

3.1.1 Scenarios adopted

This chapter describes the seal malfunction altered evolution scenarios (AES) for Cigeo identified in the qualitative analysis of risks and uncertainties, as per the approach detailed in Volume I.

Three AESs[113] have been identified (see Table 3.1-1):

- the "Malfunction of surface-bottom connection seals via the interface between the clay core and the Callovo-Oxfordian" scenario. Drift seals are operational;
- the "Malfunction of drift seals via the interface between the clay core and the Callovo-Oxfordian" scenario. Surface-bottom connection seals are operational;
- the "Malfunction of all (surface-bottom connection and drift) seals via the interface between the clay core and the Callovo-Oxfordian" scenario.

It should be noted that surface-bottom connection seals, and to a lesser extent drift seals, mainly contribute to the "prevent water circulation" post-closure safety function, by reducing water flows between the repository and overlying formations. These scenarios correspond to the malfunction of one or more types of these structures, which are intended to increase the hydraulic resistance of drifts and surface-bottom connections.

Table 3.1-1: Altered evolution scenarios (AES) for seal malfunctions

Seal malfunction scenarios	Types of seal			
	Shaft seals	Ramp seals	Drift seals	Option with ILW-LL cell seals
"Malfunction of surface-bottom connection seals via the interface" AES	- Core effective - Core/clay rock interface ineffective	- Core effective - Core/clay rock interface ineffective	- Core effective - Core/clay rock interface effective	- Core effective - Core/clay rock interface effective
"Malfunction of drift seals via the interface" AES	- Core effective - Core/clay rock interface effective	- Core effective - Core/clay rock interface effective	- Core effective - Core/clay rock interface ineffective	- Core effective - Core/clay rock interface ineffective
"Malfunction of all seals via the interface" AES	- Core effective - Core/clay rock interface ineffective	- Core effective - Core/clay rock interface ineffective	- Core effective - Core/clay rock interface ineffective	- Core effective - Core/clay rock interface ineffective

The results are given for the situation that considers ILW-LL closure systems that perform less well than a seal. Nevertheless, the influence of the option with ILW-LL cells seals has been studied for the "Malfunction of all seals via the interface" AES.

[113] Just as for the NES, these scenarios consider seals and their interfaces in a saturated initial state.

3.1.2 Description of the "Malfunction of seals via the interface" AESs

3.1.2.1 "Malfunction of surface-bottom connection seals via the (ZFC) interface" AES

This scenario considers malfunction of all shaft and ramp seals via the interface between the clay core and clay rock.

Based on the qualitative analysis of risks and uncertainties presented in Chapter 1, the following can be considered:

- the possible presence of a connected fractured zone (ZFC) at the clay core of the surface-bottom connection seals in the silty carbonated unit (USC) and the transition unit (UT), especially due to the time-dependent behaviour of the clay rock. Imperfect self-sealing of the ZFC in the UT would lead to a "hydraulic healing" fault.
- swelling of the clay core of the surface-bottom connection seals, attaining the target permeability;
- effective drift seals.

Given the identified causes of malfunctions, these scenarios are assumed to occur at the beginning of the post-closure phase.

Representation of surface-bottom connection seal malfunctions

Seal malfunction is represented by a degradation of the hydraulic properties resulting from the formation of a ZFC at the clay core/clay rock interface.

Figure 3.1-1 below is a schematic diagram of shaft seal malfunction. Ramp seal malfunction is represented in the same way, except for its geometry.

- ***Extension of the ZFC***

Extension of the ZFC at the clay core interface is estimated on the basis of observations made in the Meuse/Haute-Marne Underground Research Laboratory, in the niche at -445 m. Rather than a connected fractured zone (ZFC), these observations show a sparse fracturing which is probably not longitudinally connected. Nevertheless, this altered evolution scenario considers the formation of a ZFC with a similar thickness.

- ***Permeability of the ZFC***

To take into account the ineffective self-sealing in USC and UT units, the water permeability of the ZFC is considered equal to that of self-sealed clay rock in liner removal zones in the clay unit (UA), as defined for NES, bounding situation, degraded by two orders of magnitude (see Table 3.1-2). It is equivalent to "effective" hydraulic healing deteriorated by three orders of magnitude, as shown in Figure 3.1-1.

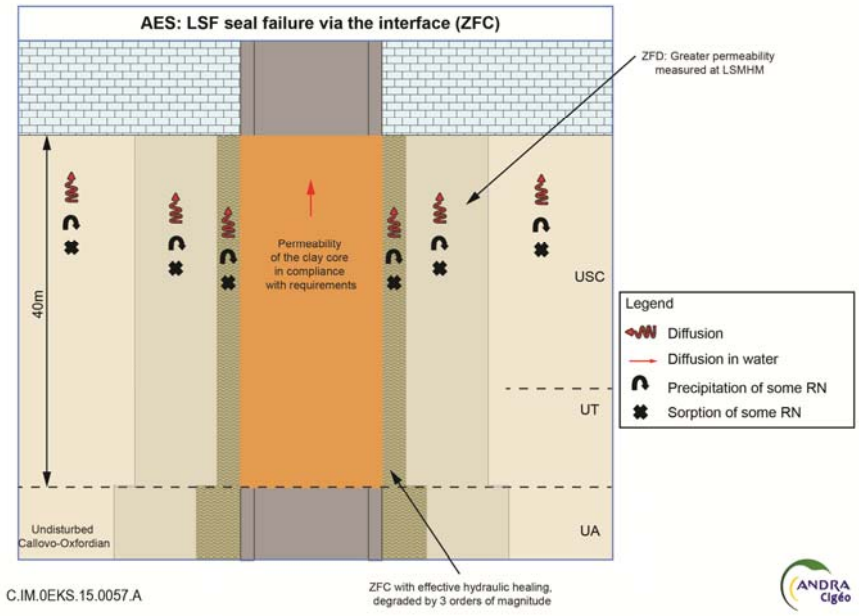


Figure 3.1-1: Schematic view of shaft seals under the "Malfunction of surface-bottom connection seals via the interface" AES (bounding situation)

Representation of structures in USC/UT units (at standard sections of ramps, excluding seals)

Damaged clay rock at standard sections of ramps in USC and UT units are represented in the same way as at interface with clay cores, with a ZFC and a ZFD as shown in Figure 3.1-1.

Representation of drift seals

In this scenario, drift seals are assumed effective. They are therefore represented in the same way as in the NES (see Chapter 2.1).

Representation of structures in the UA (excluding seals)

In the clay unit (UA), disposal cells and standard sections of drifts and surface-bottom connections are represented in the same way as in the NES.

3.1.2.2 "Malfunction of drift seals via the interface" AES

This scenario covers malfunction of all drift seals via the interface between the clay core and clay rock.

Based on the qualitative analysis presented in Chapter 1 the following can be considered:

- the malfunction of all drift seals, which results from an ineffective hydraulic healing of the ZFC at the liner removal zones, due to an unlikely combination of uncertainties;
- clay core swelling in drift seals reaches the target permeability;
- effective surface-bottom connection seals.

Given the identified causes of malfunctions, these scenarios are assumed to occur at the beginning of the post-closure phase.

Representation of drift seal malfunctions

Drift seal malfunction is represented by degradation of hydraulic properties of the damaged clay rock at its interface with the clay core.

Figure 3.1-2 below is a schematic view of malfunctioning drift seals.

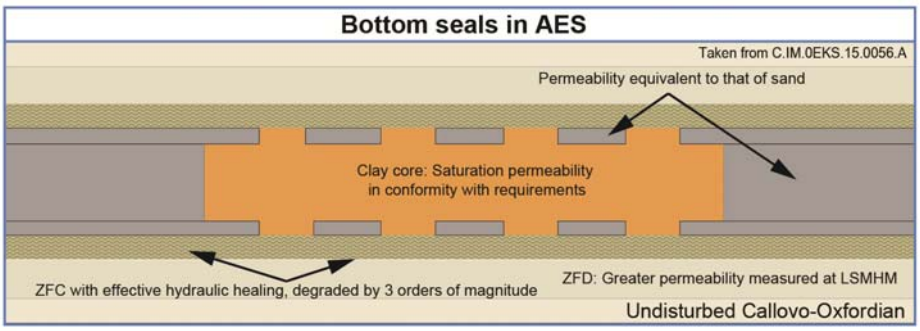


Figure 3.1-2: Schematic view of drift seals under the "Malfunction of drift seals via the interface" AES

- ***Permeability of the ZFC at the interface with the clay core:***

To take into account the ineffective hydraulic healing, the water-permeability of the ZFC at the interface with liner/support removal zones, and at the zones where it is left in place, is equivalent to that of effective hydraulic healing degraded by three orders of magnitude Table).

Representation of structures in the UA (excluding seals)

The lower efficiency of hydraulic healing is also taken into account in the ZFC and the ZFD at the interface with other structures in the clay unit (UA) (standard drift sections, surface-bottom connections, and disposal cells). This leads to:

- the water-permeability of the ZFC at the interface with these structures is equivalent to that of effective hydraulic healing degraded by three orders of magnitude;
- the ZFD is represented with conservative permeability.

Representation of structures in the USC/UT

In this scenario, surface-bottom connection seals are represented in the same way as in the NES.

3.1.2.3 "Malfunction of all seals via the interface" AES

This scenario considers the malfunction via the interface of all closing devices (drifts and surface-bottom connections) designed to increase the hydraulic resistance of repository structures. As a common cause of malfunction, it assumes the combined effects of the mechanical time-dependent behaviour of clay rock and inefficient self-sealing of the ZFC. The clay core in drift and surface-bottom connection seals reaches the target permeability.

Figure 3.1-3 provides an illustrative example. It is a schematic cross section illustrating the "Malfunction of all seals via the interface" AES with the assumptions of the NES bounding situation.

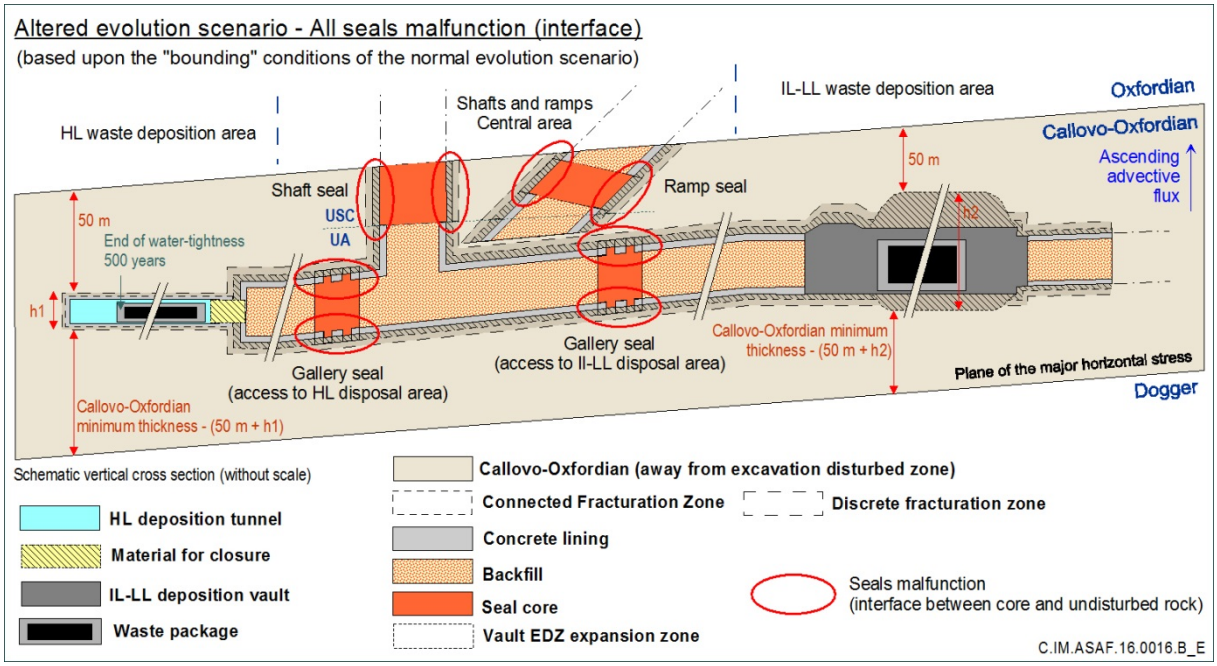


Figure 3.1-3: Schematic cross section illustrating the various repository components in the "Malfunction of all seals via the interface" AES – design with lower performance ILW-LL closing devices.

Representation of the surface-bottom connection seal malfunction

Surface-bottom connection seals are represented in the same way as in the "Malfunction of surface-bottom connection seals via the interface" AES (see Figure 3.1-1).

Representation of drift seal malfunctions

Drift seals are represented in the same way as in the "Malfunction of drift seals via the interface" AES (see Figure 3.1-2).

Representation of standard sections of ramps in USC/UT units (excluding seals)

In USC and UT units, clay rock at the interface with standard sections of ramps are represented in the same way as at the interface with clay cores, with a ZFC and a ZFD, as shown in Figure 3.1-1.

Representation of structures in the UA (excluding seals)

In the clay unit (UA), structures other than seals (standard sections of drifts and surface-bottom connections, disposal cells) are represented in the same way as in the "Malfunction of drift seals via the interface" AES:

- the water-permeability of the ZFC is equivalent to that of effective hydraulic healing increased by three orders of magnitude;
- the ZFD is represented with conservative permeability.

3.1.2.4 Conceptualisation of AESs for seal malfunctions via the interface

Physical and numerical conceptualisation of AESs for seal malfunctions is the same as for the NES (see Chapter 2.1).

Radionuclide release by disposal containers is represented in the same way as in the NES (See Volume II-Chapter 2).

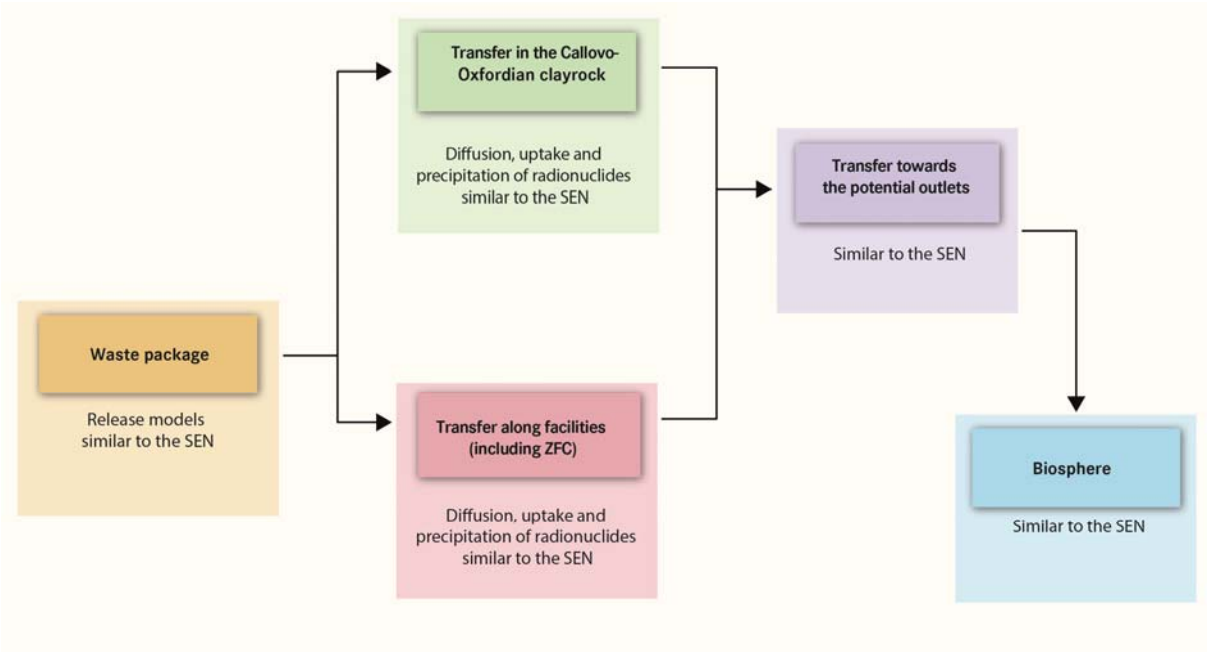
Hydraulic properties of initially fractured clay rock (ZFC and ZFD) are degraded with respect to the NES, as summarised in Table 3.1-2.

Table 3.1-2: Water permeabilities of mechanically damaged clay rock for seal malfunction via the interface AESs (values degraded under these scenarios are shaded)

Geological unit	Damaged clay rock zones	Reference situation				Bounding situation			
		NES	Surface-bottom connection seals AES	Drift seals AES	All seals AES	NES	Surface-bottom connection seals AES	Drift seals AES	All seals AES
UA	ZFC at the interface with removal zones	10^{-11}	10^{-11}	10^{-8}	10^{-8}	10^{-10}	10^{-10}	10^{-8}	10^{-8}
	ZFC at the interface with the liner	10^{-9}	10^{-9}	10^{-8}	10^{-8}	10^{-8}	10^{-8}	10^{-8}	10^{-8}
	ZFD	N/A	N/A	10^{-10}	10^{-10}	10^{-10}	10^{-10}	10^{-10}	10^{-10}
USC/UT	ZFC at the interface with the clay core	N/A	10^{-8}	N/A	10^{-8}	N/A	10^{-8}	N/A	10^{-8}
	ZFC at the interface with the liner	N/A	10^{-8}	N/A	10^{-8}	N/A	10^{-8}	N/A	10^{-8}
	ZFD	N/A	10^{-11}	10^{-11}	10^{-11}	10^{-11}	10^{-11}	10^{-11}	10^{-11}

For both reference and bounding situations, the diffusive transport and retention properties of the ZFC and ZFD are represented by the same parameters as in the NES.

Figure 3.1-4 below is a schematic diagram of transfer pathways under seal malfunction AESs.



CG.IM.ASAF.15.0027.A

Figure 3.1-4: Schematic illustration of transfers under seal malfunction AESs (release and transport pathways via the Callovo-Oxfordian and facilities)

3.1.3 Analysis of the "Malfunction of seals via the interface" AESs

Intermediate indicators are used to assess the system performance in case of closing device malfunction via the interface. The same indicators are used as for the NES (see Chapter 2.2), namely:

- transfer time and repository drainage capacity: these indicators are used to assess the time it takes for diffusive/convective transport in the Callovo-Oxfordian and along the access and connecting drifts from each disposal section. This indicator is especially useful for assessing the "prevent water circulation" function;
- amounts of radionuclides transiting along facilities and diffusing through the Callovo-Oxfordian are used to assess the "delay and lessen radionuclide migration" function.

The radiological impact is only assessed for the "Malfunction of all seals via the interface" scenario, which is considered to cover the other two.

3.1.4 Results for seal malfunction AESs

3.1.4.1 Analysis of the effects of seals malfunction via the (ZFC) interface on water flow in the repository

It should be noted that, as in the SEN, most water drained by surface-bottom connection structures comes from the ILW-LL section, this section being hydraulically upstream of the main zone, in line with the hydraulic head gradient in Oxfordian aquifers. The hydraulic contribution of HLW disposal sections, especially HLW1/HLW2, is very small.

"Malfunction of surface-bottom connection seals via the (ZFC) interface" AES

Using the assumptions of the NES reference situation, malfunction of surface-bottom connection seals via the interface (the drift seals being effective) causes greater water flow rates (several hundred litres per year) leaving the surface-bottom connection structures, mainly from the main zone rather than ILW-LL and HLW sections.

The effectiveness of drift seals in ILW-LL and HLW sections results in high head losses and thereby limits water flow rates. Flow velocities in the ILW-LL section are approximately 100 m per 100,000 years, which is of the same order of magnitude as the value assessed under the NES (with all seals effective).

Using the assumptions of the NES bounding situation, the Oxfordian hydraulic head is transmitted to the main zone. This leads to approximately 2 m3 per year water flow rates in surface-bottom connections, coming from the main zone and from a part of the ILW-LL section (see Table 3.1-3). However, the influence of the hydraulic disturbance remains limited due to the effectiveness of the drift seals (see Figure 3.1-5) which provide even greater head losses[114].

The flow velocity at the outlet of the ILW-LL disposal section is increased, up to approximately 2.5 km per 100,000 years, which is four times faster than the flow velocity assessed under the normal evolution scenario (see Table 3.1-3). This velocity, which appears intrinsically high, is nevertheless slow compared to the ability of radionuclides to diffuse from the drifts into the Callovo-Oxfordian (see *above*).

[114] Approximately 4 metres at this stage.

"Malfunction of drift seals via the interface" AES

Using the assumptions of the NES reference situation, malfunction of the drift seals only (i.e. with effective surface-bottom connection seals) leads to water flow rates leaving the surface-bottom connection structures of a few litres per year, similar to the flow rates assessed under the NES (with all seals effective). Effectiveness of the surface-bottom connection seals alone limits water flow rates in repository structures (see Table 3.1-3).

Using the assumptions of the NES bounding situation, malfunction of drift seals via the interface leads to slower flow rates leaving the surface-bottom connections than those assessed for the normal evolution situation(see Table 3.1-3). This apparent paradox is due to the fact that water circulation within the repository structures is dominated by the Oxfordian horizontal hydraulic gradient (from the ILW-LL section to the HLW sections) which cancel each other out Thus flow velocity is approximately 3 km per 100,000 years at the outlet of the ILW-LL section and 2.5 km per 100,000 years in the main connecting drifts of the HLW1/HLW2 section.

"Malfunction of all seals via the interface" AES

This scenario leads to a greater hydraulic disturbance in the repository than the other two AESs, insofar as all seals that contribute to producing hydraulic resistance in the repository (in drifts and surface-bottom connections) malfunction via the interface. Therefore, the hydraulic head of Oxfordian limestones propagates more easily from the top of the Callovo-Oxfordian into the repository.

This propagation is accentuated with the assumptions of the NES bounding situation (see Figure 3.1-5). The hydraulic head of Oxfordian limestones therefore propagates into the whole repository and causes dominant convective transport from disposal sections to surface-bottom connections: the water flow rate leaving these connections is therefore greater, up to approximately 4 m^3 per year, and comes from the whole repository (main zone and HLW and ILW-LL disposal sections) (see Table 3.1-3).

Table 3.1-3: Water flow rates leaving surface-bottom connections and flow velocities at the outlet of the ILW-LL section for the NES and for seal malfunction scenarios (using reference and bounding situation assumptions)

Scenario	Water flow rate leaving the surface-bottom connections (L/year)		Flow velocities at the outlet of the ILW-LL section (mm/year)	
	Reference situation	Bounding situation	Reference situation	Bounding situation
NES (all seals effective)	6	70	0.5	6
"Malfunction of surface-bottom connection seals via the interface" AES	250	2300	1.25	25
"Malfunction of drift seals via the interface" AES	1	50	7.5	28
"Malfunction of all seals via the interface" AES	500	3700	10	45

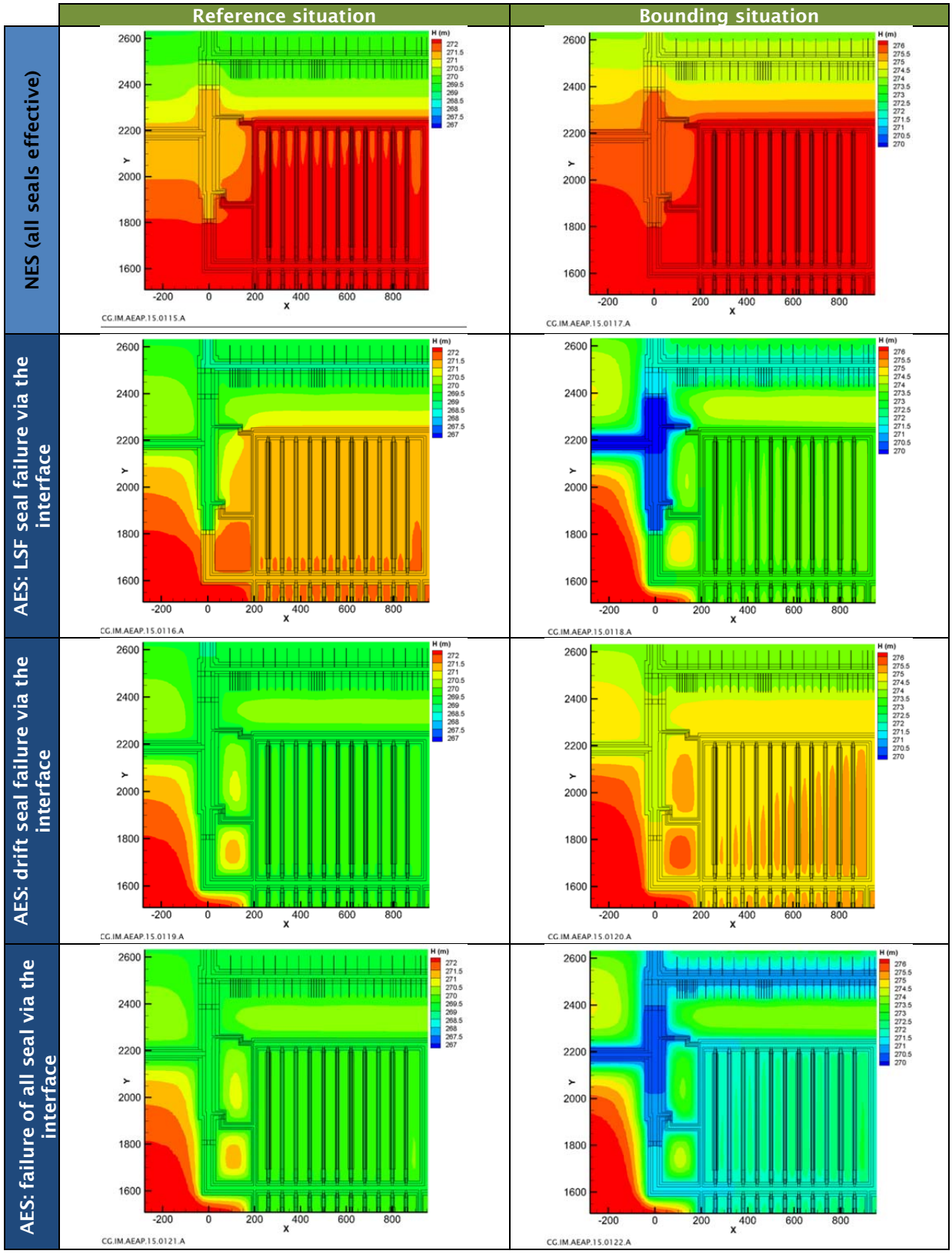


Figure 3.1 5: NES and seal malfunction AESs, using the assumptions of NES reference (right) and bounding (left) situations – Hydraulic head fields (m) in the ILW-LL section

3.1.4.2 Analysis of results with respect to radionuclide transfer

The ability of the repository and the Callovo-Oxfordian to delay and lessen radionuclide migration under the various seal malfunction scenarios is presented below for iodine-129, chlorine-36, and other radionuclides whose molar flow rate leaving the Callovo-Oxfordian is greater than 10^{-10} mol/year.

Iodine-129 transfer

For the normal evolution scenario (reference and bounding situations), diffusion is the dominant radionuclide transport process in all repository structures. Malfunction of seals via the interface causes an increase in convective transport velocities in repository structures and thereby increases transfer of radionuclides from waste packages to the top of the Callovo-Oxfordian along the structure pathway.

Using the assumptions of the NES reference situation, the dominant transport process (advection or diffusion) varies:

- in the case of malfunction of surface-bottom connection seals via the interface, advection is dominant only in surface-bottom connections and diffusion and advection are codominant in the main zone up to the HLW and ILW-LL sections;
- in the case of malfunction of drift seals via the interface, advection is dominant in both HLW and ILW-LL sections and in the main zone, and diffusion remains dominant in the surface-bottom connection structures;
- in the case of malfunction of all seals via the interface, advection becomes dominant in all repository structures.

Figure 3.1-6 shows the dominant transfer process in the main drifts, the surface-bottom connections and the Callovo-Oxfordian, for each scenario, using data from the NES reference situation.

Results for the NES bounding situation are similar, except for the "Malfunction of surface-bottom connection seals via the interface" AES, where advection is dominant in drifts.

In all seal malfunction via the interface AESs, due to the low permeability of the Callovo-Oxfordian and the low head gradients within the repository, solutes advection remains limited in structures, from cells to surface-bottom connection structures, allowing diffusive transport of radionuclides from drifts into the Callovo-Oxfordian.

The Callovo-Oxfordian therefore remains the main transport transfer pathway.

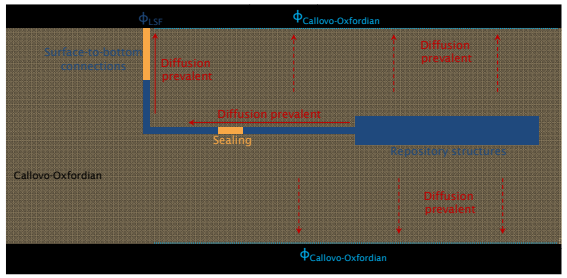
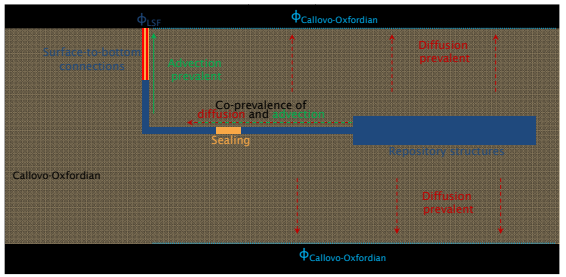
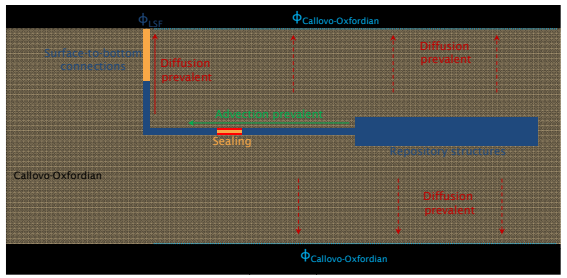
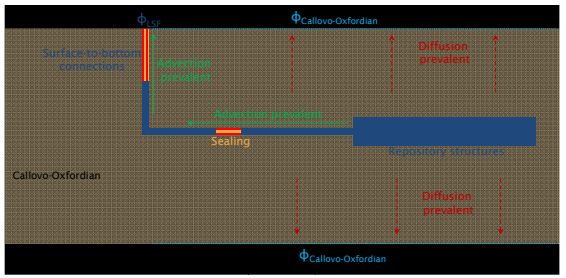
NES (all seals effective)	"Malfunction of surface-bottom connection seals via the interface" AES
	
"Malfunction of drift seals via the interface" AES	**"Malfunction of all seals via the interface" AES**
	

Figure 3.1-5: *NES and seal malfunction AESs – reference situation: schematic view of solute transfer processes in the repository and the Callovo-Oxfordian*

Malfunction of closure systems can increase and accelerate transfer along the structure pathway. To assess this effect, the fractions of iodine-129 (as a percentage of the initial inventory) transiting via the structures and Callovo-Oxfordian pathways are compared in Table 3.1-4.

For the "Malfunction of all seals via the interface" AES, Figure 3.1 7 below shows the reduction in peak molar flow rate along structures from ILW-LL cells to surface-bottom connections. It highlights the following analysis features:

- for all closure structure malfunction AESs, the cumulative quantity of iodine-129 leaving surface-bottom connections is lower than that migrating through the Callovo-Oxfordian.
- the "Malfunction of all seals via the interface" AES is the only configuration that involves a transfer along the structure pathway that temporarily exceeds the transfer across the Callovo-Oxfordian. This feature is however observed over a period of several thousand years and, moreover, with extremely low molar flow rates (lower than the peak molar flow rates across the Callovo-Oxfordian).
- nevertheless, the fraction of the initial iodine-129 inventory leaving the surface-bottom connection structures increases (to 13% compared with 1% for NES reference situation data).
- using NES reference situation data, the peak molar flow rate leaving the surface-bottom connection structures occurs around 200,000 years after closure. This is significantly earlier than for the NES which occurs after over a million years. However, as advection remains limited, the iodine-129 molar flow rate is significantly attenuated in the repository (the peak molar flow rate leaving the surface-bottom connections is 120 times lower than that entering the ILW-LL drifts);
- using NES bounding situation data, radionuclide advection velocity in the drifts is higher and limits exchanges (by diffusion) with the Callovo-Oxfordian. However, this limitation is relative as the attenuation factor is approximately 90. The peak molar flow rate occurs significantly sooner (approximately 30,000 years from closure).

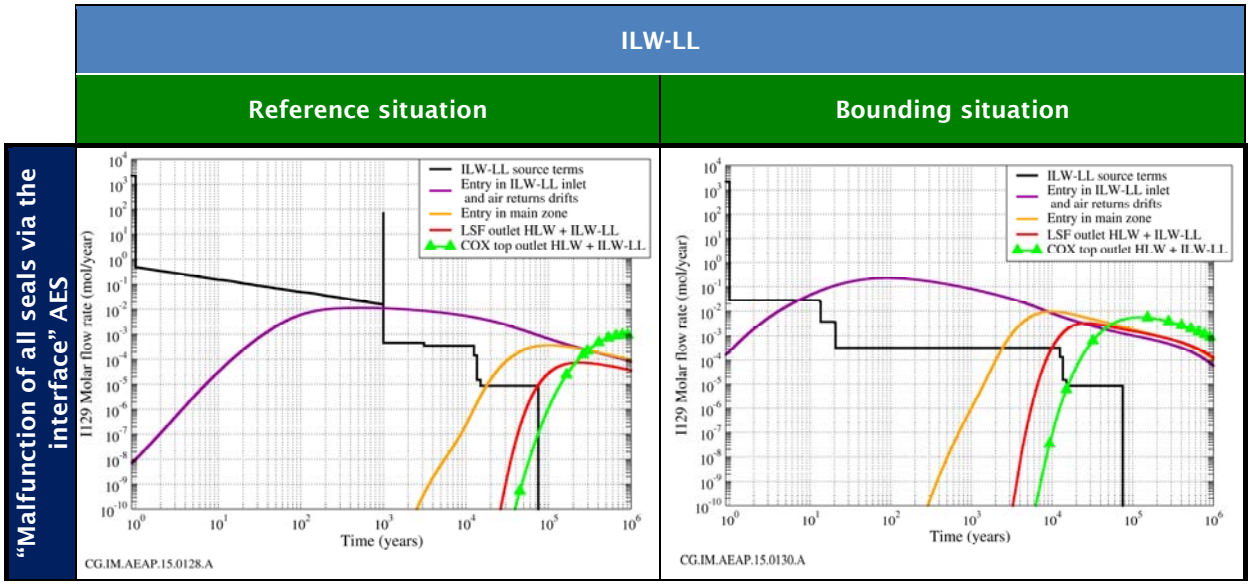


Figure 3.1-6: *"Malfunction of all seals via the interface" AES – Time-dependent evolution of iodine-129 molar flow rates entering air inlet and return drifts, entering the main zone and leaving surface-bottom connection structures and the Callovo-Oxfordian*

Table 3.1-4 shows that iodine-129 entering the main zone mainly comes from the ILW-LL section. Due to the location of iodine-129 inventory close to surface-bottom connections, the amount of iodine-129 leaving the ILW-LL cells via access drifts is very sensitive to malfunction of seals via the interface. Therefore, compared with the NES, the amount of iodine leaving the ILW-LL section and arriving in the main zone is increased by about one order of magnitude in the event of malfunction of the drift or

surface-bottom connection seals, but this amount remains limited compared with that migrating through the Callovo-Oxfordian.

Table 3.1-4: NES reference and bounding situations – Assessment of the total amount of iodine-129 (cumulated over one million years, as a percentage of the total HLW and ILW-LL inventory) entering access and connecting drifts, entering the main zone, and leaving surface-bottom connection structures and the top of the Callovo-Oxfordian

		Total amount of iodine-129 (as a% of the total initial inventory of each area)							
		Reference situation				Bounding situation			
		NES	Surface-bottom connection seals AES	Drift seals AES	All seals AES	NES	Surface-bottom connection seals AES	Drift seals AES	All seals AES
HLW	Entering access drifts	5%	6%	6.1%	6.1%	5.8%	8%	5.4%	9.1%
	Entering connecting drifts	0.2%	0.3%	0.1%	0.1%	0.4%	1.5%	< 0.1%	2.9%
	Entering the main zone	$< 10^{-2}$%	$< 10^{-2}$%	$< 10^{-4}$%	$< 10^{-3}$%	$< 10^{-2}$%	0.5 %	$< 10^{-4}$%	2.0 %
ILW-LL	Entering the connecting drifts (access / air return)	10.2%	10.4%	16.2%	17.1%	17.6%	25.1%	25.5%	34.8%
	Entering the main zone	0.4%	1.2%	6.9%	7.6%	5.1%	24.5%	17.7%	35.9%
HLW+ILW-LL	Leaving the surface-bottom connections	$< 10^{-4}$%	< 0.1%	< 0.1%	1.0%	0.2%	6.9%	0.9%	13%
	Leaving the top of the Callovo-Oxfordian	10.9%	10.9%	10.9%	10.9%	55.7%	51.9%	55.2%	48.5%

Figure 3.1-8 shows the time-dependent evolution of iodine molar flow rates leaving the surface-bottom connection structures and the top of the Callovo-Oxfordian at the repository for the NES (all seals effective) and the seal malfunction via the interface AESs. Table 3.1-5 gives cumulative quantities of iodine-129 which cross repository structures and reach the top of the Callovo-Oxfordian via the structure pathway or through the Callovo-Oxfordian over one million-year.

Assessments performed using NES reference situation data show that:

- the peak iodine-129 molar flow rate leaving the surface-bottom connection structures is much lower than that of the Callovo-Oxfordian transfer pathway, by factors of 10 (all seals malfunctioning), 400 (surface-bottom connection or drift seals malfunctioning) or 25,000 (all seals effective) respectively;
- the "malfunction of all seals via the interface" AES yields a transfer pathway along structures that exceeds that of the Callovo-Oxfordian for 20,000 years. However the peak molar flow rate along structures remains lower than that of the Callovo-Oxfordian;
- seal malfunctions have no effect on molar flow rates of the Callovo-Oxfordian transfer pathway, which highlights the fundamental role of the host rock.

Comparison of results between the drift seal malfunction configuration and surface-bottom connection seal malfunction configuration shows that these seals are somewhat redundant. When either of these seal types is effective, the peak molar flow rate leaving surface-bottom structures is attenuated by a

factor of 40 compared with the malfunction of all seals, and the transfer pathway through the Callovo-Oxfordian remains dominant.

However, the malfunction of drift seals causes dominant advection in the drifts (see Figure 3.1-8), which leads to a peak molar flow rate leaving surface-bottom connections occurring 400,000 years after closure, compared with 200,000 years in the case of all seals malfunctioning.

Assessments performed with data from the NES bounding situation lead to similar observations:

- the peak iodine-129 molar flow rates leaving the surface-bottom connection structures are lower than those crossing the Callovo-Oxfordian by factors of 1.7 (all seals malfunctioning), 7 (surface-bottom connection seals malfunctioning), 50 (drift seals malfunctioning) and 400 (all seals effective);
- the "malfunction of all seals via the interface" scenario yields a transfer pathway along the structures that exceeds that crossing the Callovo-Oxfordian, the latter being similar to that of the NES. In the case of surface-bottom connection seals malfunction (drift seals being efficient), the transfer pathway along structures exceeds that of the Callovo-Oxfordian for a short period (approximately 25,000 years).

In the "Malfunction of drift seals via the interface" AES, diffusive transfer is maintained dominant in surface-bottom connections. This enables an attenuation of the peak molar flow rate 7 times higher than under the "Malfunction of surface-bottom connection seals via the interface" AES.

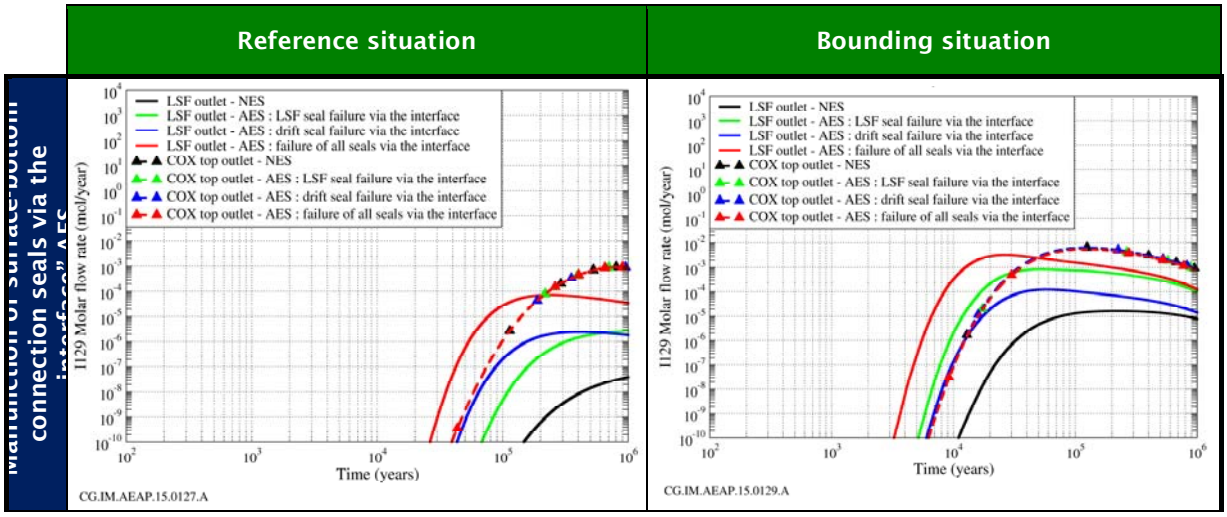


Figure 3.1-7: *NES and seal malfunction AESs – time-dependent evolution of iodine-129 molar flow rates leaving surface-bottom connection structures and the Callovo-Oxfordian*

Table 3.1-5: *"Malfunction of all seals via the interface" AES – Peak iodine-129 molar flow rates leaving the top of the Callovo-Oxfordian and surface-bottom connection outlets, occurrence dates and ratios between these peak flow rates*

		Peak iodine-129 molar flow rates							
		Reference situation				Bounding situation			
		NES	Surface - bottom connection seals AES	Drift seals AES	All seals AES	NES	Surface - bottom connection seals AES	Drift seals AES	All seals AES
Transfer across the clay rock formation	Peak molar flow rate at the top of the Callovo-Oxfordian (10^{-6} moles/year)	930	930	930	930	6500	6100	6500	5700
	Occurrence (thousands of years)	840	840	840	840	120	120	120	120
Transfer via the structure pathway	Peak molar flow rate at the top of the Callovo-Oxfordian (10^{-6} moles/year)	0.04	2.7	2.4	73	16	840	120	3,300
	Occurrence (thousands of years)	>1,000	>1,000	410	240	220	51	58	26
Ratio of peak molar flow rates via clay rock/structure pathways		23,000	340	390	13	400	7	53	1.7

- ***Sensitivity of the results to whether ILW-LL cells are sealed or not***

The option with ILW-LL cell seals has been studied with respect to iodine-129 transfer for the "Malfunction of all seals via the interface" AES. Sensitivity to the installation of ILW-LL cell seals was studied by comparing the results obtained with ILW-LL cell seals malfunctioning via the interface with those obtained without ILW-LL cell seals.

Table 3.1-6 below shows the following main information:

- using data from the NES reference situation, installation of seals at the ends of ILW-LL cells leads to molar flow rates similar to those with no seals. In the configuration with malfunction of all seals via the interface, peak iodine-129 flow rates leaving the ILW-LL cells are only reduced by 20% at most;
- using data from the NES bounding situation, installation of seals at the ends of the ILW-LL cells leads to molar flow rates fairly similar (within 10%) to those for ILW-LL cells with no seals.

Table 3.1-6: *"Malfunction of all seals" AES (reference and bounding situations). Assessment of the total amount of iodine-129 (cumulated over one million years, as a percentage of the total ILW-LL section inventory) entering connecting drifts, entering the main zone, leaving surface-bottom connection structures and leaving the top of the Callovo-Oxfordian*

	Quantity of iodine-129 (as a% of total initial inventory of the ILW-LL section)			
	"Malfunction of all seals" AES			
	Reference situation		Bounding situation	
	With no seals	With malfunctioning ILW-LL seals	With no seals	With malfunctioning ILW-LL seals
Entering access drifts (both cells ends)	17.1%	14.4%	34.8%	32.5%
Entering the main zone	7.6%	6.4%	35.9%	32.8%
Leaving surface-bottom connections	2.1%	1.7%	25.9 %	23.6 %
Leaving the top of the Callovo-Oxfordian	10.4 %	10.4 %	36.7 %	37.8 %

Chlorine-36 transfer

The behaviour of chlorine-36 in the repository system, presented in Figure 3.1-9, is similar to that of iodine-129 (Figure 3.1-8). However, the difference between the Callovo-Oxfordian and structure transfer pathways is much larger than for iodine-129. This observation, which is also true for the NES, is due to the half-life of chlorine-36 half-is shorter than the transfer time along drifts, thus providing additional radioactive decay, and to chlorine-36 sorption in the concrete of the ILW-LL cells.

The fraction of the initial chlorine-36 inventory leaving the host formation via the surface-bottom connecting structures depends on the malfunction scenario: it always remains much lower than the pathway across the Callovo-Oxfordian (by approximately 3 to 6 orders of magnitude with the reference situation assumptions, and 2 to 4 orders of magnitude with the bounding situation assumptions). Less than 0.1% of the initial inventory of chlorine-36 leaves the Callovo-Oxfordian via the surface-bottom connection structures.

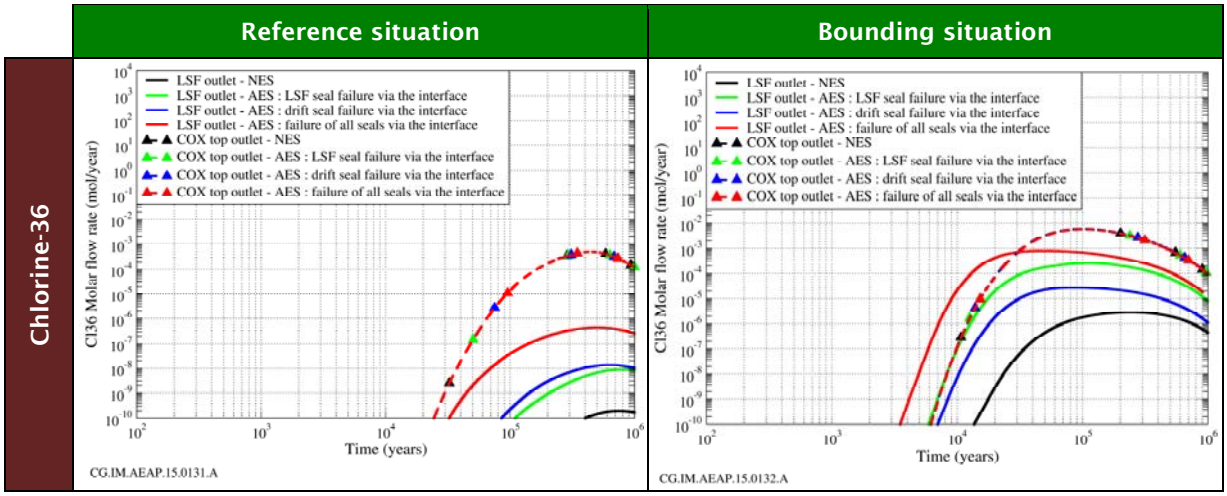


Figure 3.1-8: *NES and seal malfunction AESs (reference and bounding situations) – Time-dependent evolution of chlorine-36 molar flow rates leaving surface-bottom connecting structures and the top of the Callovo-Oxfordian*

Other radionuclides

The transfer of most other radionuclides which migrate along repository structures is completely attenuated, either due to their half-lives being shorter than the transfer time, or due to transfer from repository structures to the Callovo-Oxfordian (Callovo-Oxfordian pump effect due to its sorption capacities).

In addition to iodine-129 and chlorine-36, the radionuclides whose molar flow rate exceeds 10^{-10} moles per year in the "Malfunction of all seals via the interface" AES, (see Figure 3.1-10), are:

- using NES reference situation assumptions: selenium-79 and aluminium-26, which are mobile, relatively insoluble, and long lived isotopes, and carbon-14, which is mobile with a shorter half-life than other radionuclides that contribute to impact;
- using NES bounding situation assumptions: calcium-41 and potassium-40, weakly sorbed in cement structures and in clay rock, molybdenum-93, mobile with intermediate half-life, and uranium-235 and -238, which are less sorbed in clay rock (using bounding situation data).

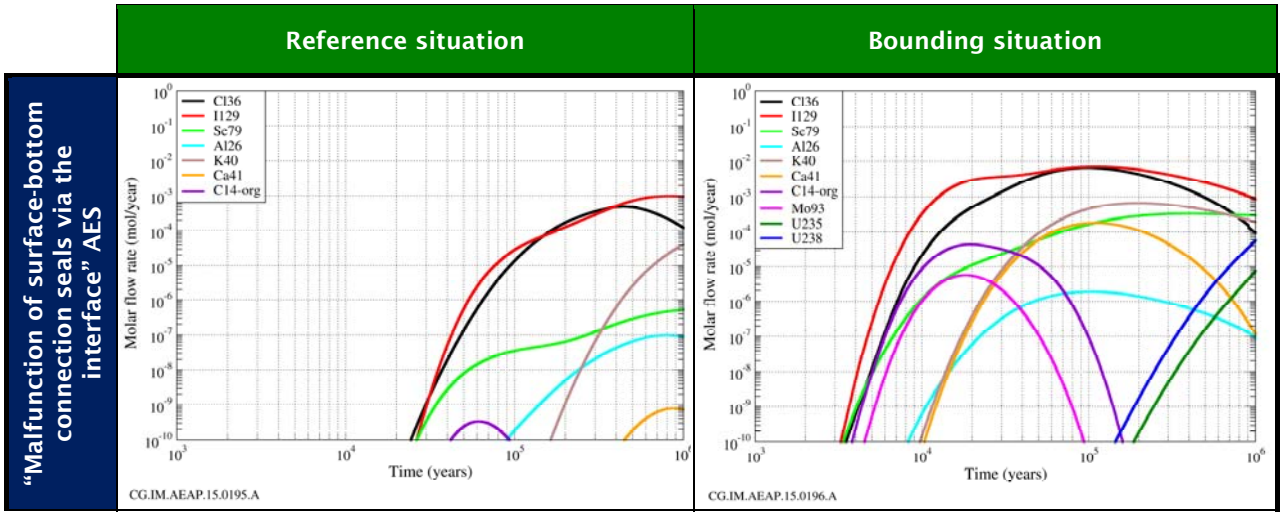


Figure 3.1-9: *"Malfunction of all seals via the interface" AES (reference and bounding situations) – Time-dependent evolution of molar flow rates of radionuclides whose total molar flow rate at the top of the Callovo-Oxfordian exceeds 10-10 moles per year*

3.1.4.3 Impact assessment

The impact for the "Malfunction of all seals via the (ZFC) interface" AES was calculated, distinguishing the following:

- the " pumping in the Barrois" outlet, for which the radionuclides transit via the Oxfordian. It results from two migration pathways:
  - ✓ the transfer pathway along structures, which is affected by seal malfunctions;
  - ✓ the transfer pathway through the Callovo-Oxfordian;
- the "pumping in the Dogger (diffuse fracture zone)" outlet, which is not affected by seal malfunctions (doses exclusively result from the Callovo-Oxfordian transfer pathway; they are therefore identical to those of the NES).

<u>On the basis of NES reference situation assumptions</u>

As analysed above, the transfer pathway through the Callovo-Oxfordian dominates the transfer pathway along structures for all radionuclides. The molar flow rates at the top of the Callovo-Oxfordian are similar to those obtained for the NES.

Molar flow rates crossing underlying and overlying formations, as well as the time-dependent evolution of doses for the "pumping in the Barrois" and "pumping in the Dogger (diffuse fracture zone)" outlets, are identical to those obtained for the NES reference situation (see Chapter 2). Compared with the NES, the only additional radionuclide is carbon-14 (which migrates along structures). However, due to its short half-life compared with transfer times in the overlying formations, carbon-14 molar flow rates are considerably lessen during transfer in these formations. The carbon-14 related dose at the outlet is negligible.

<u>On the basis of NES bounding situation assumptions</u>

Figure 3.1-11 presents the time-dependent evolution of dose at the "pumping in the Barrois" outlet for temperate and hot climate standard biospheres. Table 3.1-7 gives the peak doses and their occurrences.

The total dose is dominated by chlorine-36 and selenium-79, with a peak of approximately 0.002 millisievert at approximately 350,000 years after closure. Comparison with the NES (Table 3.1-7) does not show any significant differences, except for selenium-79, for which transfer along structures gradually increases due to its solubility. It becomes the main contributor to dose about 500,000 years after closure.

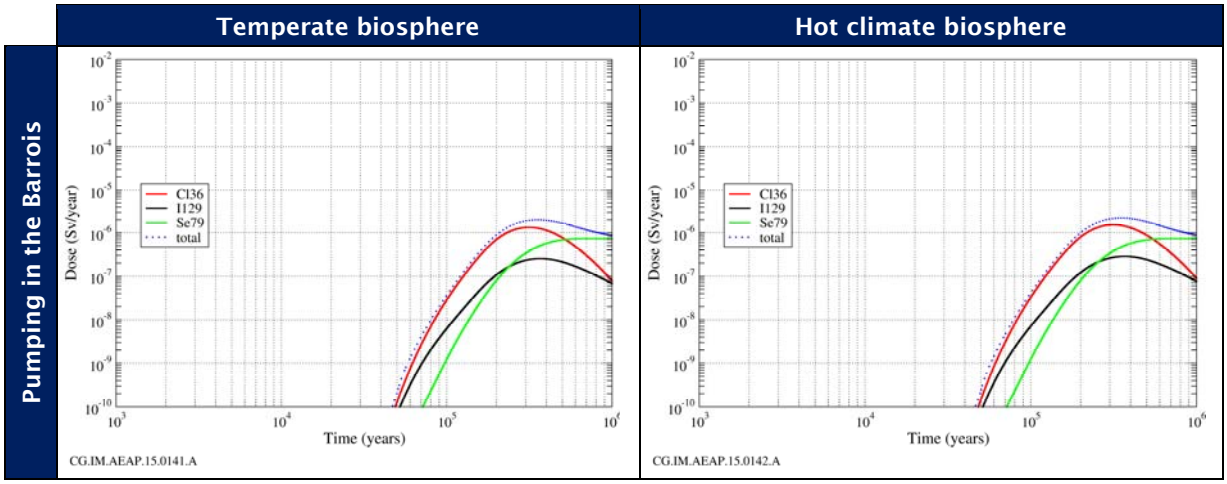


Figure 3.1-10: *Time-dependent evolution of doses for the "pumping in the Barrois" outlet for temperate and hot climate biospheres – "Malfunction of all seals via the interface" AES (bounding situation)*

Table 3.1-7: *NES and "Malfunction of all seals via the interface" AES: peak doses and occurrence dates for the "pumping in the Barrois" outlet, with temperate and hot climate biospheres (bounding situation)*

	NES (all seals effective)				"Malfunction of all seals via the interface" AES			
	Temperate climate biosphere		Hot climate biosphere		Temperate climate biosphere		Hot climate biosphere	
Radionuclide	Peak dose (mSv/year)	Date of peak dose (thousands of years)	Peak dose (mSv/year)	Date of peak dose (thousands of years)	Peak dose (mSv/year)	Date of peak dose (thousands of years)	Peak dose (mSv/year)	Date of peak dose (thousands of years)
^{36}Cl	1.2×10^{-03}	320	1.4×10^{-03}	320	1.3×10^{-03}	310	1.5×10^{-03}	310
^{129}I	2.1×10^{-04}	380	2.3×10^{-04}	380	2.3×10^{-04}	370	2.6×10^{-04}	370
^{79}Se	3.7×10^{-04}	730	4.4×10^{-04}	730	7.3×10^{-04}	730	7.3×10^{-04}	730
Total	1.6×10^{-03}	340	1.9×10^{-03}	340	2.0×10^{-03}	360	2.2×10^{-03}	350

3.1.5 Findings from the closure structure malfunction AESs

From a hydraulic behaviour standpoint, the effect of seal malfunction via the interface on the hydraulic regime in the repository structures is limited owing to the low permeability of the Callovo-Oxfordian, the performance of the seal clay cores which are not affected by the seal malfunction, and the repository architecture, in particular the use of dead-end tunnels and the grouped layout of surface-bottom connections (shafts and ramp bases) in the main zone that reduce water flow rates the repository and in the Callovo-Oxfordian:

- using NES reference situation data: flow velocities in the ILW-LL zone (which has the highest hydraulic load) are approximately 100 m per 100,000 years (malfunction of surface-bottom connection seals) to 1 km per 100,000 years (malfunction of drift seals or all seals) (see Table 3.1-3);
- using bounding situation data: flow velocities in repository structures are 25 times higher than those based on NES reference situation data. However, water flow rates in the ILW-LL zone remain very low (a little under 4 m^3 per year in the event of malfunction of all seals via the interface).

Given the large surface areas available for exchanges between the structures and the Callovo-Oxfordian, these low flow velocities in repository structures allow a significant fraction of radionuclides migrating along repository structures to migrate towards clay rock.

In the case of seal malfunction via the interface, the radionuclides that reach the top of the Callovo-Oxfordian (i.e. whose molar flow rate at the top of the formation reach 10^{-10} mol/year over a period of one million years) are the same as those for the NES, i.e. mobile radionuclides (iodine-129, chlorine-36, selenium-79 and aluminium-26), as well as potassium-40 and calcium-41, which are less mobile, and organic carbon-14. The results also show the breakthrough of molybdenum-93, uranium-235 and uranium-238, but with lower flow rates and in longer term for uranium.

The "Malfunction of all seals via the interface" AES yields an iodine-129 flow leaving surface-bottom connections greater than that leaving the Callovo-Oxfordian for 200,000 years using NES reference situation data, and approximately 50,000 years using NES bounding situation data. However the former is much lower than the peak molar flow rate through the Callovo-Oxfordian while the latter is more or less similar. This difference is explained by the fact that iodine transfer times in the Callovo-Oxfordian are lower in the bounding situation. The cumulative quantity of iodine-129 leaving the surface-bottom connections over a million-year period remains limited with respect to the total initial inventory, at barely 1% (using NES reference situation data) or 13% (using NES bounding situation data).

The repository architecture plays a significant role in the event of seal malfunction, by limiting water flow in the structures owing to its dead-end tunnels and by facilitating attenuation of molar flow rates due to the length of the structures, because radionuclides can diffuse into the Callovo-Oxfordian throughout their transfer along structures. When all seals are effective, this process allows mobile radionuclides from the ILW-LL section to benefit from an approximately 5 orders of magnitude attenuation between the entrance in drifts and the main zone outlet. This attenuation factor is reduced to 3 orders of magnitude in the event of drift or surface-bottom connection seals malfunctioning, and to 2 orders of magnitude in the event of all seals malfunctioning.

Assessments performed with NES reference situation data show that the peak iodine-129 molar flow rate reaching the top of the Callovo-Oxfordian via the structure pathway is multiplied by 40 in the event of drift or surface-bottom connection seals malfunctioning, and by 2500 in the event of all seals malfunctioning (see Figure 3.1 8). However, this molar flow rate remains 10 times lower than peak molar flow rate across the Callovo-Oxfordian.

Using NES bounding situation data, advection within structures is higher than for the reference situation. In the event of all seals malfunctioning, the iodine-129 molar flow rate leaving surface-bottom connections is multiplied by 250, without exceeding the peak flow rate through the Callovo-Oxfordian These results mean that a distinction can be made between the contributions of surface-bottom connection seals and drift seals: effective surface-bottom connection seals limit molar flow rates along structures, while effective drift seals significantly delay the peak flow rate leaving surface-bottom connections.

The assessments demonstrate the robustness of the repository in the event of seal malfunctions via the interface, in particular due to the characteristics of the Callovo-Oxfordian.

The effects of drift or surface-bottom connection seals malfunction are limited. Even in the case of all seals malfunctioning via the interface, changes in the hydraulic system are limited with respect to the normal evolution scenario, and the Callovo-Oxfordian remains the main transfer pathway.

Consequently, in terms of radiological impact (see Table 3.1-7), the dose at the Dogger outlet is unaffected by malfunction of seals via the interface.

The dose at the "pumping in the Barrois" outlet is of the same order as that obtained for the normal evolution scenario

3.2 Altered evolution scenarios for HLW disposal containers

3.2.1 Adopted scenarios

The analysis of risks and uncertainties led to the definition of two altered evolution scenarios for HLW disposal container failure (see Table 1.7-2). It thereby complies with the 2008 safety guidelines (1), which recommend: …In the "altered situations" to be studied, possible "component failures" should be taken into account, in particular "package conditioning defects could be considered, in order to take into account various uncertainties regarding the quality and ageing of packages".

The scenario of all HLW0 disposal containers failure has been adopted for quantitative assessments[115].

This chapter first gives a description and conceptualisation of the scenario then presents the results of quantitative assessments for the adopted indicators.

3.2.2 Description of the HLW disposal container failure scenario

This AES conservatively considers premature loss of integrity of all disposal containers in the HLW0 section, following oxidising corrosion due to the presence of oxygen in the HLW cell, mainly through the cell head.

Given the uncertainties concerning the oxygen concentration in the usable part of the HLW cell, it is conservatively assumed that all disposal containers in the HLW0 section are affected.

By convention and as a bounding assumption, it is considered that disposal containers lose integrity immediately upon closure of the repository, resulting in the release of radionuclides from this date.

3.2.2.1 Effects of loss of integrity on release models and on the characteristics of radionuclide transport and retention

Premature loss of integrity of HLW0 disposal containers leads the vitreous matrix to be exposed to environmental and temperature conditions that impair its confinement performance.

[115] It is considered as a bounding assumption with regard to the number of defective HLW0 disposal containers.

When the disposal container loses its integrity, it is assumed that the filler material outside the sleeve (a clay/cement material) produces a cement-based medium that affects the rate of glass alteration. By comparison with the release models adopted for the NES (clay medium), these models and parameters lead to greater release kinetics. In particular:

- taking temperature into account in the release models increases alteration kinetics given the thermal load at premature loss of disposal container integrity;
- the effect of the cement-based pH on release models is taken into account;
- the fracturing rate adopted in a cement-based medium is greater than that in a clay medium, in order to account for uncertainties regarding the risk of alteration resumption;
- attainment of a residual alteration rate V_R (model $V_0 \rightarrow V_R$) is not applicable to a cement-based medium.

Furthermore, the premature loss of disposal container integrity leads to release radionuclides in a medium that presents a temperature load greater than that of the NES, affecting radionuclide retention and transport parameters. Correction factors were applied to diffusion coefficients, partition coefficients and solubilities to take into account temperature effects in the Callovo-Oxfordian.

3.2.2.2 Conceptualisation

All other assumptions and parameters were taken as equivalent to those adopted in the NES. Thus, the physical conceptualisation of the AES is the same as that of the NES, taking into account the effects caused by the loss of disposal container integrity. A schematic diagram of the AES is given in Figure 3.2-1.

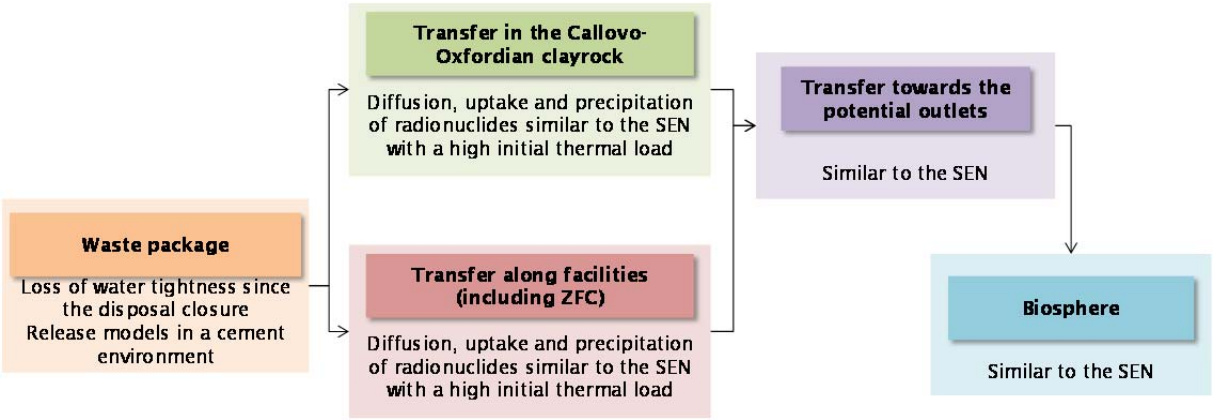


Figure 3.2-1: Schematic illustration of the HLW disposal container failure AES.

3.2.3 Analysis of the "HLW disposal container failure" AES

3.2.3.1 Indicators

As the objective was to assess the robustness of the disposal system in the event of premature loss of HLW0 disposal container integrity, only intermediate indicators were quantified, namely:

- molar flow rate entering and leaving structural components, considering the transfer pathway via structures up to the top of the Callovo-Oxfordian;
- the molar flow rate leaving the top of the Callovo-Oxfordian, following the transfer pathway through the Callovo-Oxfordian;
- the date of peak molar flow rates leaving the structures and the Callovo-Oxfordian (at top and bottom).

3.2.3.2 Radionuclides selected for the assessments

The radionuclides selected for the failure of HLW0 disposal containers AES are the same as for the NES.

3.2.4 Results of the HLW0 disposal container failure AES

3.2.4.1 Effects of premature loss of disposal container integrity on source terms

Taking a cement-based medium into account for glass dissolution leads to a release radionuclides over a one-year period[116] (see Figure 3.2-2). The source term for HLW0 waste is considered to be labile.

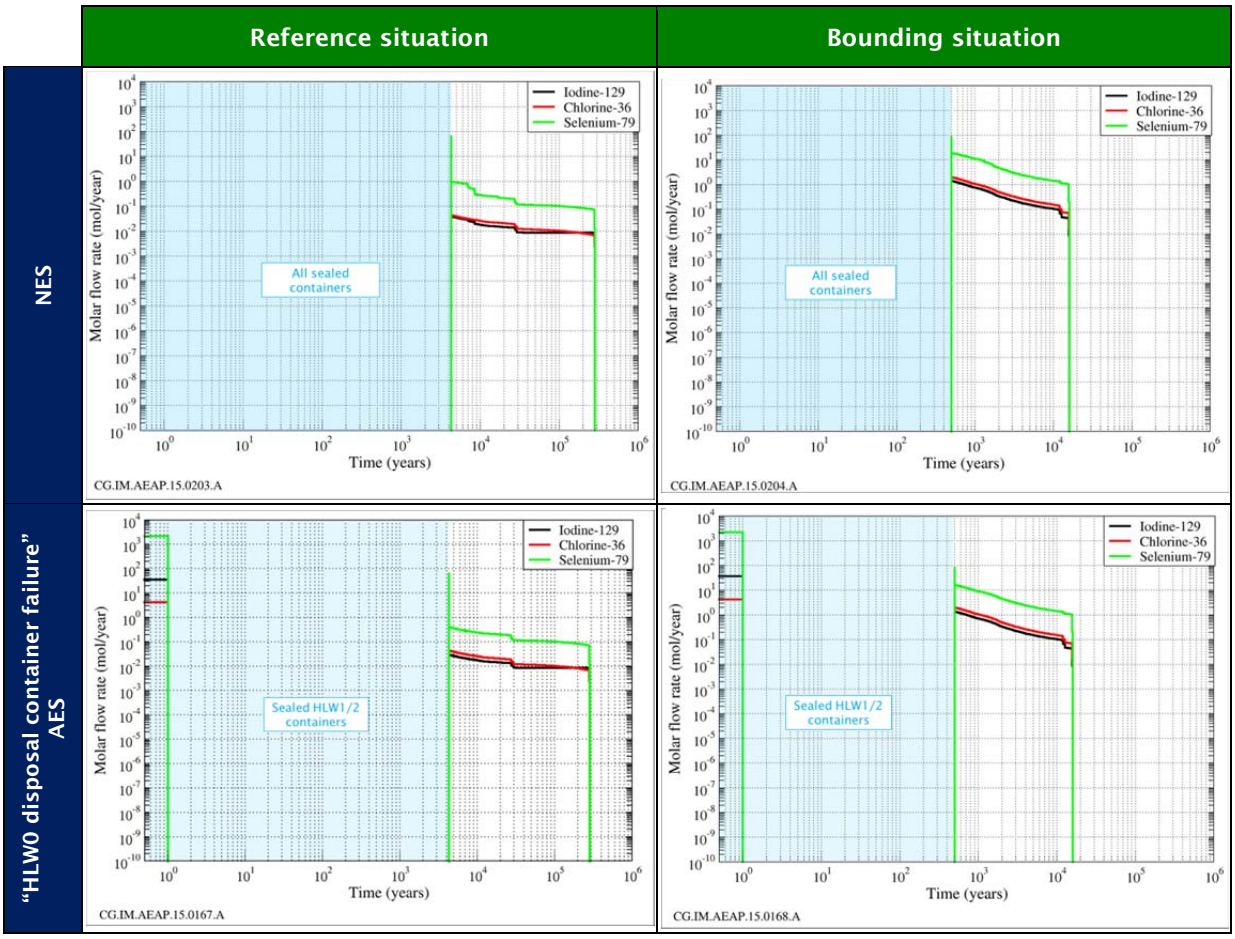


Figure 3.2-2: NES and "HLW0 disposal containers failure" AES. Assumptions of the NES reference situation (left) and the NES bounding situation (right) – Source terms for iodine-129, chlorine-36 and selenium-79

[116] For the EAS based on the NES reference situation assumptions and for the EAS based on the NES bounding situation assumptions.

3.2.4.2 Effects on hydraulic behaviour

The temporary increase in permeability due to the increased temperature does not change the hydraulic flow pattern in the structures and in the Callovo-Oxfordian. The results are identical to those of the NES for both situations (reference and bounding).

3.2.4.3 Quantitative assessments of transfers for each NES situation (reference and bounding)

Reference situation

- ***Transfer via structures (backfilled drifts and surface-bottom connections)***

As only HLW0 packages are defective, only a small fraction of the initial activity (1% of the total initial inventory of HLW packages) is released early. The molar flow rates arriving in the drifts, migrating along the structures pathway and through the Callovo-Oxfordian, are identical to those of the NES.

The thermal load in HLW0 sections is limited so the early and removable release has little effect on molar flow rates (see Figure 3.2-3 and Table for iodine-129 on the basis of the NES reference situation and Figure 3.2-3 for iodine-129 on the basis of the NES bounding situation).

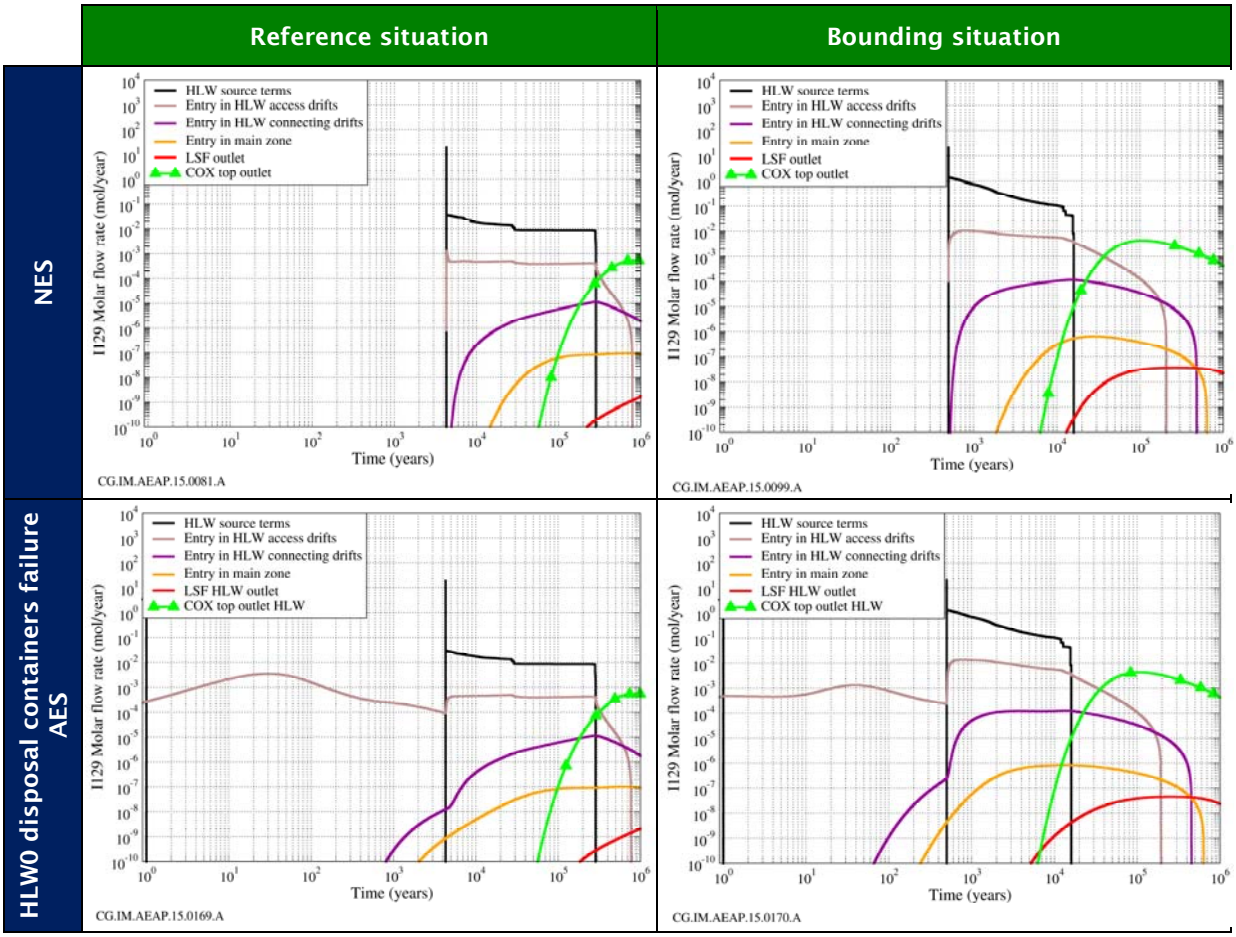


Figure 3.2-3: HLW0 section disposal container failure AES". Assumptions of the NES reference situation (left) and the NES bounding situation (right) – Time-dependent evolution for iodine-129 molar flow rate entering the drifts, in the main zone, and leaving the surface-bottom connections.

For example, the peak iodine-129 molar flow rate leaving the surface-bottom connecting structures (at the top of the Callovo-Oxfordian) is much lower (by a factor greater than 10^5) than the peak iodine-129 molar flow rate leaving the top of the Callovo-Oxfordian above the repository (see Table 3.2-1 and Figure 3.2-3).

Table 3.2-1: *"HLW0 section disposal container failure" AES - reference situation: assessment of the quantity of iodine-129 (as a percentage of the total inventory of HLW) released at 1 million years entering the drifts and the main zone, and leaving surface-bottom connection structures and the Callovo-Oxfordian*

Quantity of iodine-129 at 1 million years (% of total inventory in HLW)					
	Entering access drifts	Entering connecting drifts	Entering the main zone	Leaving via the surface-bottom connections	Leaving the top of the Callovo-Oxfordian
NES	5.0%	0.2 %	$< 10^{-2}$%	$< 10^{-4}$%	11.3 %
AES	5.0 %	0.2 %	$< 10^{-2}$%	$< 10^{-4}$%	11.5 %

Assessment of performance indicators shows that the main transfer pathway is the Callovo-Oxfordian, regardless of the component (HLW cells and all components in HLW0 section) This is explained by the lack of hydraulic drainage in the drifts due to the efficiency of the seals and therefore dominant diffusion conditions in and around the HLW cells, and by the length of HLW cells being several tens of metres long

Due to important exchanges from the drifts into the Callovo-Oxfordian, transfer in the drifts is long and limited by solute diffusion at the scale of the HLW0 section, thus allowing a gradual attenuation of radionuclides flux.

Outside the section, similar additional attenuation is obtained along the main zone drifts and the surface-bottom connections.

The transfer time in the structures masks the effects of labile release from loss of container integrity.

Identical findings apply to chlorine-36 (see Table 3.2-2 below).

Table 3.2-2: *"HLW0 section disposal container failure" AES - reference situation: assessment of the quantity of chlorine-36 (as a percentage of the total inventory of HLW) released at one million years entering the drifts and the main zone, and leaving surface-bottom connection structures and the Callovo-Oxfordian*

Quantity of chlorine-36 at 1 million years (% of the total HLW inventory)					
	Entering access drifts	Entering connecting drifts	Entering the main zone	Leaving the surface-bottom connections	Leaving the top of the Callovo-Oxfordian
NES	3.3 %	0.08 %	$< 10^{-3}$%	$< 10^{-5}$%	5.8 %
AES	4.4 %	0.1 %	$< 10^{-3}$%	$< 10^{-5}$%	5.8 %

- ***Transfer in the Callovo-Oxfordian***

The three main radionuclides contributing to dose are iodine-129, chlorine-36 and selenium-79. The results are identical to those of the NES. The inventory mobilised by failure of the HLW0 disposal containers is much lower than the total inventory of HLW and the iodine-129 molar flow rate at the top of the Callovo-Oxfordian mainly stems from the inventory of the HLW1/HLW2 sections.

Bounding situation

- ***Transfer in structures***

The results lead to the same conclusions as those given for the reference situation. The small fraction of the inventory released by the HLW0 waste packages, the molar flow rate arriving in the drifts, migrating along the structures pathway and migrating through the Callovo-Oxfordian, is essentially the same as for the NES (see Table 3.2-3).

Table 3.2-3: "HLW0 section disposal container failure" AES - bounding situation: balance of the amount of iodine-129 (as a percentage of the total HLW inventory) released at 1 million years entering the drifts and the main zone, and leaving surface-bottom connection structures and the Callovo-Oxfordian

	Quantity of iodine-129 (as a% of the total initial inventory of the HLW sections)				
	Entering access drifts	Entering connecting drifts	Entering the main zone	Leaving the surface-bottom connections	Leaving the top of the Callovo-Oxfordian
NES	5.8 %	0.4 %	$< 10^{-2}$%	$\sim 10^{-3}$%	61.1 %
AES	5.8 %	0.4 %	$< 10^{-2}$%	$\sim 10^{-3}$%	61.4 %

- ***Transfer in the Callovo-Oxfordian***

Reminder: in the bounding situation, the disposal facility is located in the Callovo-Oxfordian in order to preserve a sound 50-metre upper undisturbed thickness.

As for the reference situation, the results are identical to those of the AES. The inventory mobilised by failure of the HLW0 disposal containers is very small compared with the total inventory of HLW.

3.2.5 Findings of the "HLW0 section disposal container failure" AES

Premature failure of the HLW0 section disposal containers leading to release of radionuclides as soon as the repository is closed in a saturated medium (loss of the "Limit the release of radioactive substances" function) has no effect on repository performances.

Performance of seals and the Callovo-Oxfordian provide the lines of defence needed to fulfil the safety functions "Prevent water circulation" and "Delay and mitigate the migration of radioactive substances".

Results of the "HLW0 section disposal container failure" AES are nearly identical to those of the NES.

4

Inadvertent Human Intrusion Scenarios

4.1 Identifying inadvertent human intrusion scenarios 340
4.2 The "exploratory borehole in the Dogger" AES 340
4.3 The core sampling scenario 346
4.4 The What-if scenario for human intrusion 351

4.1 Identifying inadvertent human intrusion scenarios

4.1.1 Methodology

The only type of inadvertent intrusion considered is a borehole drilled from the surface, given the geological context of the zone of interest for detailed survey (ZIRA) and the depth at which the repository is located. The foreseeable "borehole situations" were first examined from three standpoints:

- the purpose of the borehole and the target geological formation: target depth and borehole diameters are determined by the technical objective of the borehole (for example, exploration, groundwater abstraction or geothermal energy) and the target geological formation;
- location of the borehole: the types of possible consequences in terms of deterioration of repository function and modification of the migration conditions for radionuclides and toxic elements are determined by the location of the borehole with respect to the repository architecture (disposal cells and other structures), and with respect to the hydrogeological context.
- time-based aspects: the possible types of interaction between the borehole and the repository, along with the activity levels of the radionuclides that may be mobilised, are determined by borehole life phases (drilling, use and disuse), in association with the resaturation situation and evolution of repository components.

An initial analysis led to retaining physically possible situations that could have consequences in terms of impact. These situations were qualitatively assessed for their relative likelihood and potential impacts. Ultimately, a small number of "bounding" situations were adopted for quantification.

The principle of completeness that underlies the approach outlined must be weighed against the geological and hydrogeological context of the ZIRA and the depth of the repository, which reduce the probability of deep boreholes being drilled. Furthermore, the preservation period for records of the repository, estimated at 500 years, gives time for decay of short half-life radionuclides before any such intrusion may occur.

4.1.2 Review of "borehole situations"

4.1.2.1 Purpose of boreholes and target formations

Boreholes are drilled for a specific purpose, based on the knowledge of local geology at the time the decision is made. A borehole has a target formation whose known or estimated depth, along with the ultimate purpose of the borehole, determine the drilling technique used and its planned technical cross-section (in particular, drilling diameter, tubing diameters and cementing height).

Some current knowledge regarding the ZIRA and its area may have been lost by the time a future borehole is drilled. However, it is assumed that the rationale for a drilling project will remain valid in the future. This reduces the probability of boreholes drilled with operational purposes on targets where it has already been established that they do not constitute an exceptional resource, in absolute terms, or compared with what is available elsewhere in the area.

Because of the principle of interlocked concentric drillings and tubing diameters, the final drilling diameter determines the diameter used at repository depth. On the basis of current practice, an 8"1/2 (216 mm) diameter at repository depth would be adequate for a simple geological survey in the Dogger.

A borehole for exploitation of a geothermal source at 2000m of depth would require a larger drilling diameter, of around 17"1/2 (445 mm) at 500 metres. This diameter is considered the upper limit, at repository depth, for any drilling situation.

Figure 4.1-1 shows the indicative depths of the various geological formations on the ZIRA, from the surface down to the basement (Barrois limestone dating from the Tithonian to the Stephanian).

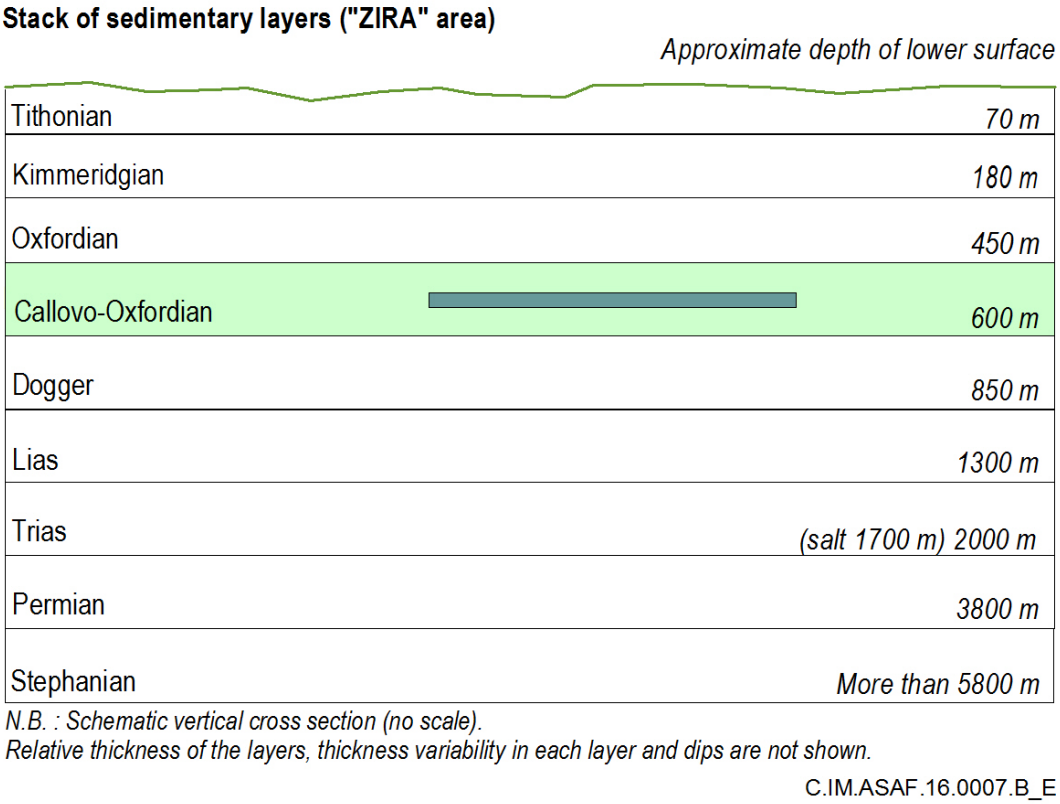


Figure 4.1-1: Schematic diagram of the depths of geological formations on the ZIRA (indicative depths for the bottom of the formations)

Drilling in the Tithonian and Oxfordian corresponds to "human actions" without intrusion. The Kimmeridgian is not considered to be a potential target. Drilling to targets in the Callovo-Oxfordian to the Stephanian could be intrusive depending on the surface position with respect to the footprint of the underground repository architecture.

Analysis of potential "targets" led to the following observations:

- the Barrois (Tithonian) limestone, permeable levels of the Oxfordian, and permeable levels of the Dogger "targets" could be prospected for water resources, or used for abstractions provided an actual water resource would be found;
- for the Callovo-Oxfordian "target" the assumed reason for drilling would be scientific research. This type of investigation involves small diameter drilling but could include core sampling;
- Permian and Stephanian "targets" would correspond to prospecting for hydrocarbon resources. Current available knowledge on the potential for conventional or non-conventional hydrocarbon resources excludes the possibility of exploitation in the ZIRA;
- Trias (partly) and Permian "targets", would correspond to the possibility of using geothermal energy (high-enthalpy geothermal resources):
  - ✓ with regard to the Trias (Bunter sandstone), the TAPPS programme deep borehole and various analyses performed by Andra and independent bodies lead to agreement on the fact that this target does not present exceptional local characteristics, in particular regarding temperature;
  - ✓ there is no precise data regarding the hydraulic and thermal characteristics of the Permian with regard to geothermal exploitation. In any case, the possible consequences of drilling to the Permian through the Cigeo repository would be comparable with those assessed for exploitation of the Trias. The same reasoning applies to possible exploitation of salt in the Upper Trias.

The aspects mentioned above make geothermal exploitation in the Trias at the ZIRA unlikely. In addition, it would require local consumption of any thermal energy produced. Situations involving drilling for geothermal exploitation have however been selected but only under the What-if category.

4.1.2.2 Borehole location in relation to the repository

Table 4.1-1 presents the various borehole locations that could disturb the repository or intercept radionuclide plumes.

Table 4.1-1: Possible locations of boreholes with respect to the repository and radionuclide plumes

Boreholes possible locations in relation with the Cigéo disposal system			
	Type of location	Description	Comment
L1	Into a waste deposition alveole : - IL-LL waste vaults - HL waste tunnels	- The borehole penetrates the deposition alveole, and possibly the waste container itself; in the latter case the extraction of cores with waste content is envisaged. - Depending on the situation, the borehole might have been driven to a greater depth through the lower Callovo-Oxfordian or stopped at the disposal depth.	"Intrusion situation" in the strict sense
L2	Into an access gallery to the waste deposition alveoles, in the HLW or ILW zones.	- The borehole hits an access gallery to the deposition alveoles. - Depending on the situation, the borehole might have been driven to a greater depth through the lower Callovo-Oxfordian or stopped at the disposal depth.	- "Intrusion situation" in the strict sense - The HLW case only is addressed; the situation of a borehole in a ILW deposition tunnel "covers" the situation of the borehole hitting an access tunnel to a ILW vault..
L3	Through the disposal architecture, without touching any structure nor the excavation damaged zone.	- The borehole is located within the disposal footprint and is deeper than the disposal. It goes through the architecture without any contact.	- The situation of a borehole hitting the EDZ is "covered" by situations L1 or L2. - The situations without any contact are only conventional. Practically they would have no negative effect on the disposal functioning.
L4	Into the migration plume coming from the disposal in the upper bounding formation (Oxfordian).	- The borehole is situated in the upper migration plume, within the disposal footprint or downstream.	- This situation belongs to the "human action" category as neither the Callovo-Oxfordian nor the disposal are hit.
L5	Into the migration plume coming from the disposal in the lower bounding formation (Dogger).	- The borehole is situated in the lower migration plume, within the disposal footprint or downstream. - The higher radionuclides concentration line starts just downstream the disposal, it continues with the Dogger flow towards the Diffuse Fracturation Zone and then changes course toward the south.	- This situation might be a "human intrusion" if the borehole is located within the the disposal footprint. - It is considered that the potential of the Dogger as a water resource is not sufficient to justify a borehole for production purposes.
L6	Into the Diffuse Fracturation Zone of the Dogger.	- The borehole is located in the Diffuse Fracturation Zone, west to south-westerly from the "ZIRA", where the hydraulic conductivity increases. - The depth is assumed sufficient to allow the withdrawal of the water contained in the permeable layers of the Dogger.	- This situation belongs to the "human action" category. - The outlet type is comparable to the one considered in the Dogger for the normal evolution scenario.
L7	Into the Marne fracturation zone (Oxfordian).	- The borehole is located in Marne valley fracturation zone which is an outlet for some of the Oxfordian water pathways.	- For the record : this outlet is not likely to be reached by the migration plume during the first million years after closure.
L8	Into, or in the vicinity of the Dogger natural outlet.	- The borehole or well is located close to the Dogger natural outlet. - Geoprospective simulations show a displacement towards East around 400 000 years.	- This situation belongs to the "human action" category. - This situation is "covered" by situation L6 which is located half way the migration streamlines.

Analysis led to adoption of the following locations:

- locations L1 and L2 correspond to actual intrusion into the repository. They could have an immediate impact in the event of waste being brought to the surface or in the case of a drilling creating a bypass in the vertical thickness of host rock, which could provide migration pathways for radionuclides;

- location L4 corresponds to possible exploitation of the most permeable levels of the Oxfordian. This is considered unlikely due to their very low productivity and is consequently considered a What-if scenario;
- location L6 corresponds to a Dogger outlet comparable to the one in the diffuse fracture zone[117] adopted in the NES.

Other locations have not been adopted:

- L3 due to the lack of consequences even though the repository footprint is crossed;
- L5 due to the salinity and depth of Dogger groundwater, which does not justify local exploitation;
- L7 due to very long pathways and adoption of L4 which is located upstream;
- L8 due to adoption of the Dogger outlet in L6.

4.1.2.3 Impact of borehole phases

Drilling phase

This is the phase during which, where applicable, repository structures would be reached and any immediate associated impacts would occur. The earliest time considered for intrusive drilling is 500 years from repository closure: this corresponds to the minimum periods for preservation of repository records indicated in the ASN Safety Guide regarding deep geological disposal (1).

In the case of intrusive drilling, it cannot be excluded that in the long term a borehole could cross the repository with no indication of its presence being detected, in particular if the target is deep and the Callovo-Oxfordian is merely a banal level to cross.

Exploitation phase (where relevant)

Borehole drilling could be followed by a pumping phase if justified by the characteristics of the geological formation.

Situations corresponding to resources too limited to allow exploitation for at least a hundred years are not taken into account in this analysis.

During exploitation, the intrusiveness or otherwise of the boreholes in the Callovo-Oxfordian is not a determining factor, as continuous tubing would isolate a borehole targeting deep aquifers (for example in the Trias) from the Callovo-Oxfordian, and therefore from the repository. Under these conditions, the only consequences of an exploitation phase would be water abstraction from formations that possibly contain radionuclides from the repository.

Borehole disuse

In all cases, boreholes are abandoned either immediately after tests or at the end of the exploitation phase. Best practices require boreholes to be sealed, in general by injecting filling grout, to prevent communication between different aquifer levels.

Conservatively, to take into account the long timescales over which the repository must function, it is assumed that any tubing corrodes rapidly and that fillers are deteriorated. The borehole diameter is assumed unchanged throughout the assessment period; the whole excavated diameter is assumed to have a permeability equivalent to that of sand.

Abandoned intrusive boreholes could therefore constitute a local bypass of the upper and lower thicknesses of undisturbed host-rock. A flow of water could occur based on the hydraulic head difference between the upper surrounding formation, the repository and the lower surrounding formation.

[117] The term “diffuse fracture zone” is used in a broad sense. It includes the Marne valley north of Joinville and the Poisson-Brouthières-Soulaincourt fracture zone.

A specific situation, in the form of an hydraulic connection between an abandoned borehole and an active borehole, is considered. In this case however, it should be borne in mind that the likelihood is lower, given the combination of events it represents (need for proximity between the two structures and relative positioning favourable to hydraulic transfer).

4.1.2.4 Repository resaturation state

During the repository resaturation transient, certain periods could correspond to the presence of gaseous phase or dissolved gases in repository structures. Arrival of a drill bit could cause various phenomena, such as loss of the drilling mud, and ejection of hydrogen and of water as liquid or aerosols. These situations will be analysed at a later stage.

Table 4.1-2 summarises the four time-based situations to be considered by combining borehole phases and the repository resaturation state.

Table 4.1-2: Borehole situations based on borehole phases and repository resaturation state.

Intrusions in terms of borehole and disposal resaturation status time frames			
Time period for the borehole		Description of the situation	Comments
P1	Drilling of the borehole during the hydro-gas resaturation process of the disposal.	- The drilling and testing of the borehole are assumed to take place 500 years after closure (duration of the preservation of the disposal records). - It is assumed that the on-going resaturation process might correspond with a gas phase and possibly high gas pressures.	- In this situation, the presence of voids, and possibly of gas pressure build-up, is likely to disturb the drilling and warn the driller (circulation fluid loss, expulsion of gas and water ...). - Once the full degassing reached, the borehole operation might continue (T2) or stop (T4).
P2	Drilling of the borehole after full resaturation of the disposal.	- The drilling and testing of the borehole are assumed to take place after full resaturation of the disposal. - For very remote drilling events, compared to the closure time, the interception of the repository might keep un-noticed.	- The more remote the drilling, the higher the possibility that the repository could be passed through without noticing it, especially if the target is deep. In this case anyway, significant part of the radiological hazard will have decayed. - On the other hand, notice of unexpected cuttings or drill string blocking are more likely for an event taking place early after the 500 years period of time.
P3	Operational phase of the borehole (if any)	- Operation phase of the borehole; at least during about one century, or conventionally assumed permanent.	- In this situation, it is assumed that the aquifer resource has been considered sufficient to motivate the pumping of the borehole during about one century at the minimum. - In the case of intrusive boreholes, operation would necessarily target the permeable layer underneath the Callovo-Oxfordian. During the operation, the disposal would be isolated from the borehole by at least one tubing and one cement completion, or possibly two of them.
P4	Abandoned borehole	- Abandoned borehole, assumed left without any attentive closure arrangement. .	- Regardless of the possible previous phases (drilling, test, operation ...) any borehole will always be considered abandoned in the long term.

4.1.3 Selection of scenarios adopted

Situations involving boreholes were examined considering a level of future technology similar to the present one as regards drilling methods and borehole equipment. Independently of the level of knowledge of local geology available at the time of drilling, it is assumed that the scientific reasoning and decision-making strategies for drilling will be the same as current ones.

Consequently:

- a small-diameter exploratory borehole will often be drilled first to check the exploitability of a poorly understood target;

- observations that have already been made (such as the low thickness of schist layers or the poor productivity of the Oxfordian limestone) will be "rediscovered" in the future, even if knowledge is lost or reduced from current levels.

Borehole situations have been classified into two categories of likelihood:

- low level of likelihood: corresponding to situations of low probability over the life of the repository. These are covered by a specific altered evolution scenario (AES);
- very low level of likelihood: corresponding to situations of very low probability or combinations of unlikely circumstances. These are covered as *What-if* scenarios to check the robustness of the repository.

Given the long operating period expected for the Cigeo repository, the question of the number of intrusive boreholes to be considered can be asked on a per drilling campaign basis, and also in terms of possible successive operations. With regard to directly exploited boreholes, or abandoned boreholes linked to an exploited borehole, the assumption of multiple boreholes does not increase the level of impact, because there would be diluted contamination due to competition between pumping operations.

At this stage, a single borehole is adopted for assessment. Taking several abandoned boreholes into account will be assessed for the construction license application (DAC).

Analysis of all situations involving boreholes has produced a limited list of six scenarios considered as "bounding" with regard to potential impacts (see Figure 4.1-2).

4.1.3.1 Situations adopted under the inadvertent human intrusion AES

Situation ① HISBor-1 (location L1) – "Exposure to core samples containing waste" scenario

The impacts considered are exclusively immediate impacts. Other possible consequences of drilling the borehole, such as those associated with local disturbance of the repository upper undisturbed thickness of host rock, are covered by other scenarios dedicated to them.

Situation ② HISBor-2c (locations L1 and L2) – Scenario involving an exploratory borehole targeting the Dogger abandoned at repository depth

The exploratory borehole is abandoned at repository depth and constitutes a bypass of the Callovo-Oxfordian upper undisturbed thickness. A hydraulic link with an exploitation borehole in the Barrois aquifer levels (same type of "Barrois" outlet as in the NES) is assumed – The requirement for a small distance between the boreholes and a favourable hydraulic link makes this situation highly unlikely.

Situation ③ HISBor-2b (locations L1 and L2) – Scenario involving an exploratory borehole targeting the Dogger abandoned at its planned depth

The exploratory borehole reaches its planned depth. It constitutes a local bypass of the Callovo-Oxfordian upper and lower undisturbed thicknesses and leads to possible migration of radionuclides into the Dogger outlets.

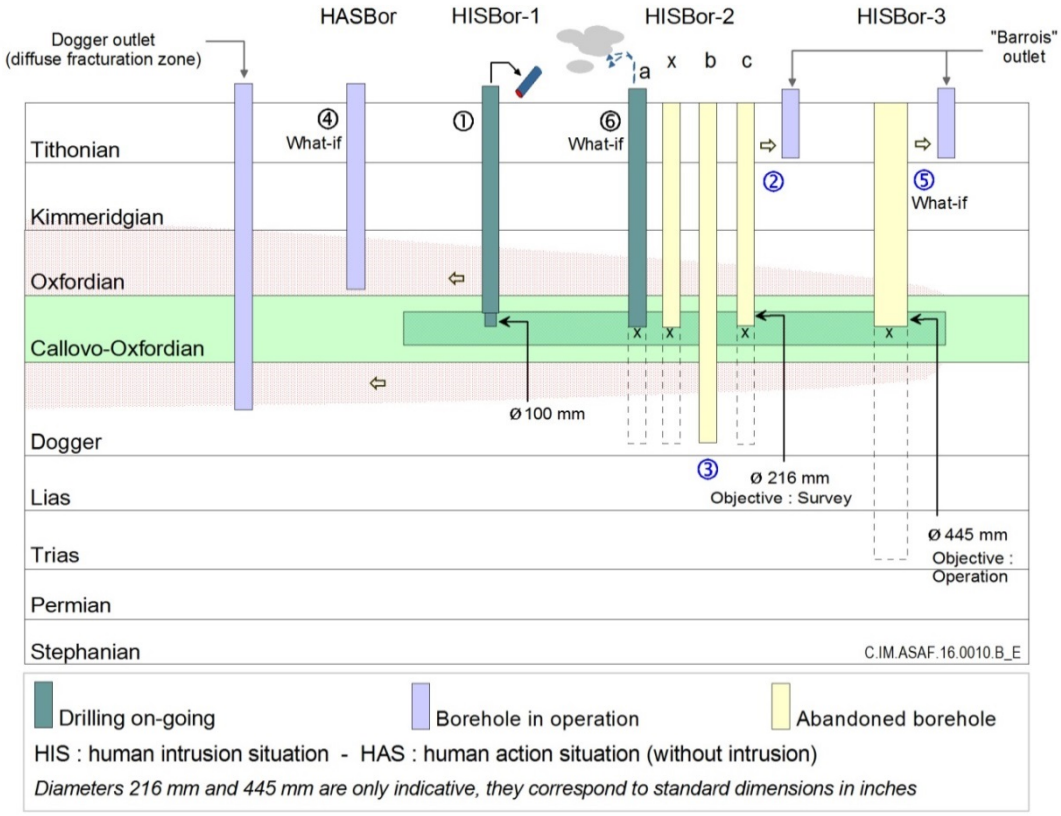


Figure 4.1-2: Schematic diagram of the "bounding" borehole situations adopted for the post-closure safety assessment.

4.1.3.2 Situations adopted as *What-if* scenarios

Situation ④ HISBor-1 (location L4) – What-if scenario involving exploitation of a non-intrusive borehole pumping from the permeable horizons of the Oxfordian limestone

The borehole is assumed to exploit the most permeable levels of the Oxfordian limestone directly above the repository. This situation is addressed under a *What-if* scenario due to the unfavourable conditions in terms of depth and available flow rate, compared with the availability of a more accessible and abundant resource in the Barrois over a long period after closure.

Situation ⑤ HISBor-3 (locations L1 and L2) – Scenario involving a geothermal exploitation borehole targeting the Trias, abandoned at repository depth

The borehole constitutes a bypass of the Callovo-Oxfordian upper undisturbed thickness. A hydraulic link operates with an exploitation borehole in the Barrois. The likelihood of geothermal exploitation in the Trias or Permian is considered "very low" due to the known geological context. The assumption of a borehole stopping at repository level is conservative in terms of hydrological consequences.

Situation ⑥ HISBor-2a (locations L1 and L2) – Scenario involving degassing of an ILW-LL cell or a HLW drift during the resaturation transient.

Depending on the circumstances, the impacts may be immediate and short-term at the moment of contact with the repository, or more long-term in the event of ejection of water containing radionuclides.

4.1.3.3 Quantifications proposed at the Safety Options Report stage

Three scenarios are covered in this report:

- The HISBor-1 (situation ①) AES involving exposure to core samples containing waste: this also assesses the residual hazardousness of repository waste;
- the HISBor-3 (situation ⑤) What-if scenario involving a geothermal exploitation borehole targeting the Trias, abandoned at repository depth: it assesses the consequences of a local bypass of the upper Callovo-Oxfordian undisturbed thickness;
- the HISBor-2b (situation ③) AES involving an exploratory borehole abandoned at its planned depth in the Dogger: it assesses the possible impacts on the "Dogger" outlet.

At this stage, the HISBor-3 (situation ⑤) What-if scenario has been preferred over the HISBor-2c (situation ②) AES due to the conservative impacts it provides, due to the borehole diameter being 445 mm instead of 216 mm.

Scenarios corresponding to situation 2 ("covered" by situation 5) and situations 4 and 6 will be assessed for the construction license application (DAC).

4.2 The "exploratory borehole in the Dogger" AES

4.2.1 Scenario analysis

Target geological horizon – Purpose and characteristics of the borehole

The HISBor-2b (situation ③) scenario is the intrusion scenario adopted for possible transfers via the Dogger aquifer levels. The outlet involved is comparable to the one adopted for the NES.

The situation described results from the drilling of an exploratory borehole to its target depth in the Dogger.. The poor characteristics of the Dogger aquifer in the ZIRA are considered to discourage any exploitation of this aquifer for drinking water or irrigation abstraction; this substantiates adoption of a diameter limited to 216 mm [118] crossing the Callovo-Oxfordian. The borehole is assumed to reach the permeable levels of the Dogger, which are in hydraulic continuity with the diffuse fracture zone located to the West of the ZIRA.

As part of using conservative values for in the context of a "bounding" assessment, a permeability of 10^{-5} m/s is used for the abandoned borehole.

[118] Indicative value resulting from conversion of the "standard" 8.5 inch diameter.

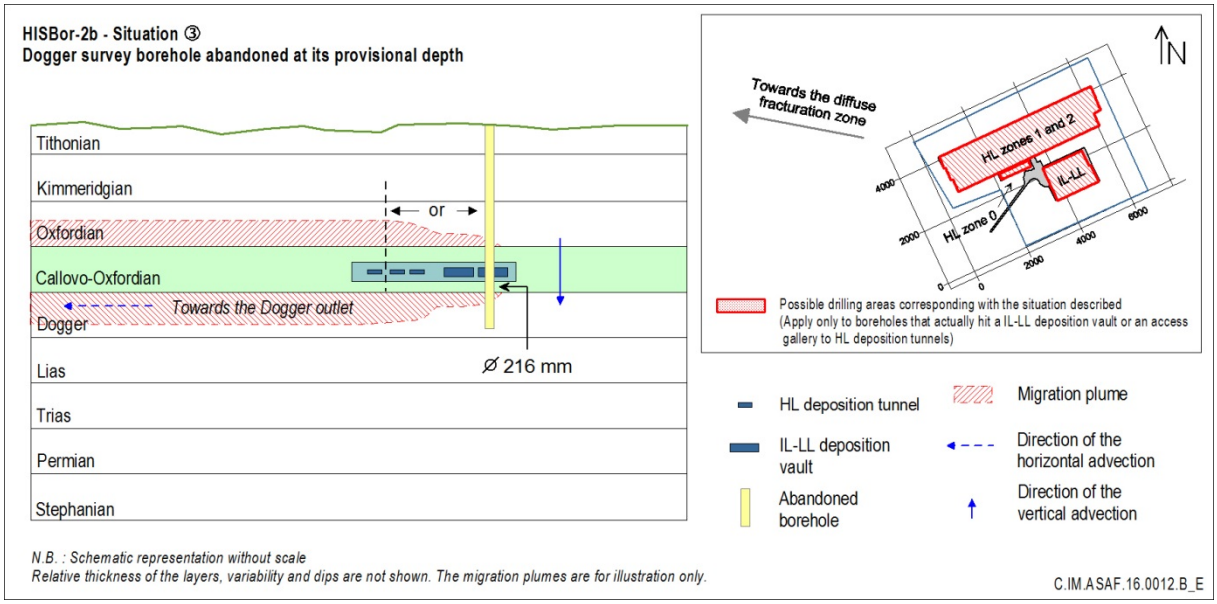


Figure 4.2-1: Schematic diagram of the HISBor-2b scenario - "Exploratory borehole in the Dogger abandoned at its planned depth ".

Borehole location in relation to repository structures

The search for "bounding" situations leads to locating the intrusive borehole at its most conservative position with respect to the location of the inventory in the repository. The cases of HLW packages and ILW-LL packages are dealt with separately.

For HLW packages, the borehole hits a cell access drift in the sector with the highest iodine-129 activity per unit of section surface, i.e. in the HLW1 section (see Figure 4.2-2). This location "covers" the cases of intrusion into the HLW2 and HLW0 sections.

For ILW-LL, the cell hit by the borehole is Number 5, consistent with the redistribution of waste package types used for the NES. Contrary to what is done for the other scenarios (redistribution "governed" by iodine-129 content alone), the activities for the intrusion scenarios are determined by considering simultaneously the redistributions "governed" by each of the 144 radionuclides, in order to reduce the number of assessments needed.

This is conservative on two levels:

- the cell containing the highest possible activity is used for each radionuclide, only taking into account the rules for physico-chemical and geometrical co-disposal of packages;
- the activities are assumed to be simultaneously present in the same cell of the ILW-LL disposal section.

Within each ILW-LL cell, the inventories of the various waste package families are assumed to be uniformly distributed for all radionuclides. Where necessary, a labile fraction and release kinetics for the fraction of activity concerned are distinguished as in the "bounding" normal evolution scenario.

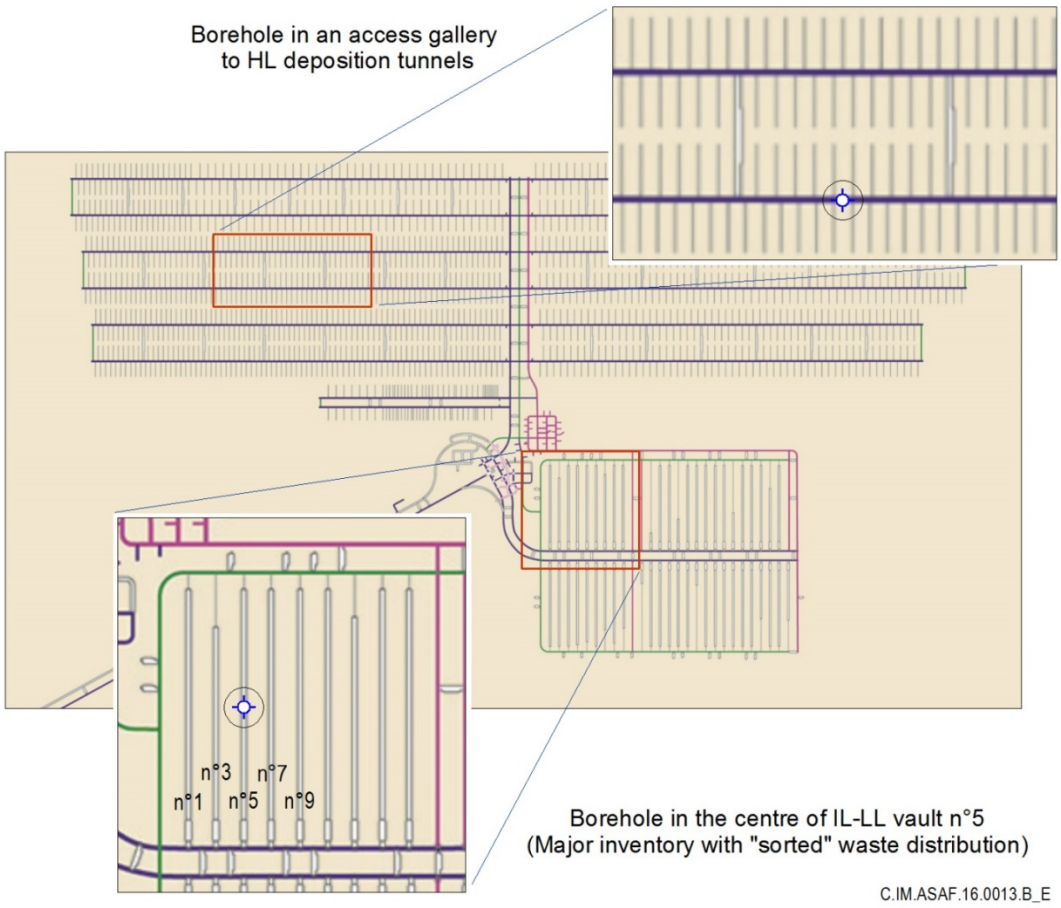


Figure 4.2-2: Location of abandoned boreholes in the ILW-LL and HLW1 sections

Two situations have been assessed to "bound" the performance range envisaged for the ILW-LL cell closure systems:

- a situation in which the access drifts to the ILW-LL cells are closed at both ends using standard backfill material;
- a situation in which ILW-LL cells are closed using with seals made of a swelling core and concrete abutments;

Date of the intrusion and taking radionuclides into account

The intrusive borehole operates from 500 years after closure, and thereafter acts as a permanent hydraulic drain between the Oxfordian, the repository and the Dogger, driven by the hydraulic head difference between the Oxfordian and the Dogger.

All radionuclides of sufficiently long half-life which may be available in the water of the cells are assumed limited by maximum concentrations at saturation. Attenuation phenomena which may occur during migration of the radionuclides to the borehole are taken into account. Appendix 12 gives the list of radionuclides adopted for the calculation.

In the case of an intrusive borehole in an ILW-LL disposal section, the water containing radionuclides is directly drawn from the affected ILW-LL cell. In the case of a borehole in the HLW disposal section, migration of radionuclides over a minimum of several tens of meters of drifts contributes to attenuating the radionuclides via transfer into the Callovo-Oxfordian, within the limits of NES bounding situation parameters.

Type of impact and hypothetical reference groups

The outlet that may be affected in this situation is a borehole into the Dogger in the diffuse fracture zone, just as for the NES. The hypothetical reference group and the ways it is reached are identical to those of the NES. The dilution flow rate taken into account at the outlet is 100 litres per minute.

Parameters - Indicators

The basic assumptions and data used (excluding those associated with the intrusion) are those of the NES bounding situation. In particular, the "lower" disposal position is considered, corresponding to the minimum of 50 metres of undisturbed host-rock under the structures.

The intrusion scenario is combined with taking into account a downward vertical hydraulic gradient in the Callovo-Oxfordian with a value of 0.05 metres per metre, which is the maximum foreseen in the ZIRA over the one million-year period. It is applied uniformly and continuously over the million-year period. The molar flows leaving the intrusive borehole are directly "injected" into the permeable levels of the Dogger.

The final indicator is the dose for each radionuclide at the "Dogger" outlet, located in the diffuse fracture zone. Intermediate indicators are assessed, such as hydraulic flow rates associated with the intrusion and the molar flow rate of radionuclides leaving the borehole.

Numerical conceptualisation

The conceptualisation differs from that of the NES, given the outlet used and the need to represent several ILW-LL and HLW cells, as the radius of influence of the borehole may be larger than a cell. A single calculation compartment is considered, at the scale of the repository. This includes the various disposal areas with all HLW1-HLW2, HLW0, and ILW-LL cells, the drift system, the drift closure structures, the surface-bottom connection structures and their closure structures the fracturing zones and the full thickness of the Callovo-Oxfordian.

The drifts and surface-bottom connection structures, the ILW-LL cells and HLW cells, and the boreholes are geometrically simplified, while maintaining the hydraulic behaviour of the system. Their volumes have been retained to maintain concentrations, and each cluster of drifts considered as a macro-drift, using the principle of equivalent hydraulic diameters to maintain water flow velocities through the repository structures. The same applies to the damaged zones of the Callovo-Oxfordian around the structures.

4.2.2 Results

4.2.2.1 Intrusion into the ILW-LL disposal section

Hydraulic behaviour

An intrusive borehole crosses the whole Callovo-Oxfordian. The hydraulic heads in the borehole at the top and bottom of the Callovo-Oxfordian are therefore identical to those in the Oxfordian and the Dogger respectively. They generate a downward flow of water in the borehole of just under 1 m^3 per year.

As the borehole is close to hydraulic equilibrium with the Callovo-Oxfordian, it does not generate significant hydraulic flows from the repository structures. The flow drained into the Dogger is mainly from the permeable levels of the Oxfordian limestone. Under these conditions, the hydraulic performances of the closure structures in the ILW-LL disposal section have little effect on the molar flow rates of radionuclides entering the borehole and, ultimately, on the dose at the outlet.

Molar flow rates leaving the Callovo-Oxfordian

The highest instantaneous molar flow rates are obtained for radionuclides characterised by low or zero retention in the Callovo-Oxfordian and the concrete, by a large initial inventory, and by a medium to

long radioactive half-life. In particular this means carbon-14[119] ($1.6x10^{-1}$ moles per year), iodine-129 ($4.5x10^{-2}$ moles per year) and chlorine-36 ($4.1x10^{-2}$ moles per year). The date of occurrence of the peak molar rates leaving the borehole at the bottom of the Callovo-Oxfordian is the same for all radionuclides, approximately 100 years after the borehole is drilled.

With regard to iodine-129, approximately 20% of the initial ILW-LL inventory migrates via the borehole over a million years. This represents approximately 55% of the inventory of the affected ILW-LL cell[120]. For chlorine-36 these values are approximately 20% and 45% respectively.

The fractions of other radionuclides leaving the borehole are below 10% of the total inventory of the disposal section and represent less than 25% of the inventory of the affected ILW-LL cell. This attenuation is facilitated by:

- radioactive decay of mobile, medium half-life radio-nuclides such as silver-108m, carbon-14 and molybdenum-93;
- precipitation of selenium-79 and technetium-99 in the undisturbed and damaged Callovo-Oxfordian around the ILW-LL cells and the borehole.
- sorption in the concrete and/or the undisturbed and damaged Callovo-Oxfordian which promotes exchanges with the Callovo-Oxfordian.

The quantities of calcium-41, potassium-40, manganese-53, iron-60, palladium-107, rubidium-87 and tin-126 leaving the borehole in 1 million years thus represent between 1 and 5% of the initial inventory of the affected ILW-LL cell. For other radionuclides, in particular lanthanides and actinides, with higher retention rates, the quantities leaving the borehole in 1 million years are less than 1% of the initial inventory of the affected ILW-LL cell.

Doses at the outlet

There is a migration distance of approximately 10 km in the permeable levels of the Dogger between the intrusive borehole location and the "Dogger" outlet in the diffuse fracture zone. For a pore flow rate of approximately 5 km per 100,000 years, the duration of transfer to the outlet means that intermediate half-life radionuclides such as silver-108m are able to decay, and there is significant transfer into the Callovo-Oxfordian, in particular for radionuclides sorbed into the Callovo-Oxfordian.

Figure 4.2-3 shows the doses at the outlet. It highlights the disappearance of silver-108m and the considerable attenuation of carbon-14. The highest dose, which corresponds to niobium-94, is less than 1 millisievert per year occurring 35,000 years after closure.

[119] In the current assessment, the whole carbon-14 inventory is assumed to be mobilisable.
[120] Note that specific redistribution of waste package types is performed for each radionuclide, with the objective of obtaining the highest possible activity in ILW-LL cell number 5, still complying with the rules for physico-chemical and geometrical co-disposal.

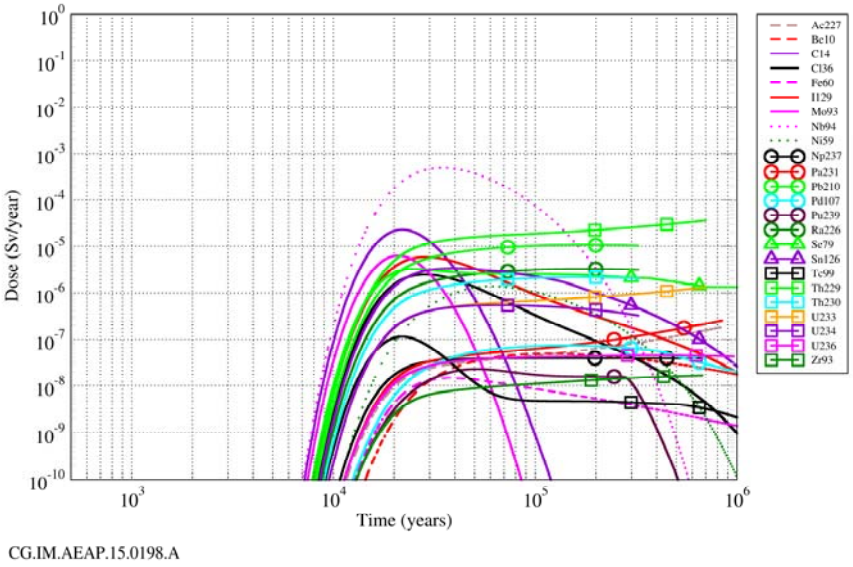


Figure 4.2-3: Human intrusion altered evolution scenario – borehole in the ILW-LL disposal section – Doses at the "Dogger" outlet for a temperate biosphere

4.2.2.2 Intrusion into the HLW disposal section

Hydraulic behaviour

As in the intrusion into the ILW-LL disposal section situation, the borehole in the HLW section is close to hydraulic equilibrium with the Callovo-Oxfordian. Under these conditions, the flow drained by the borehole, of approximately 0.7 m^3 per year, is mainly supplied by the permeable porous horizons of the Oxfordian limestone.

Molar flow rates leaving the Callovo-Oxfordian

Peak instantaneous molar flow rates of $4x10^{-5}$ moles per year and $3x10^{-5}$ moles per year are reached for chlorine-36 and iodine-129 respectively, due to their zero retention in the Callovo-Oxfordian, a large initial inventory and their long radioactive half-lives. The quantity of iodine-129 leaving the borehole in 1 million years is equivalent to the "loading" of approximately 40 HLW cells, assuming that approximately 5% of the total initial inventory enters the access drift over this period.

As in the NES bounding situation, a 500 year period of integrity has been adopted by convention for HLW disposal containers and an initial rate of glass alteration "V_0.S" for packages of the type affected by the borehole. Consistent with these assumptions, for iodine-129 and chlorine-36, the time-dependent evolution of instantaneous molar flow rates leaving the borehole at the bottom of the Callovo-Oxfordian is characterised by increasing instantaneous molar flow rate from 500 years and a peak at around 15,000 years. This shows that the borehole effect is governed by the glass release rate, as the minimum transfer time from package to access drift is around 2000 years.

For all other radionuclides covered, sorption and/or low solubility are enough to significantly attenuate transfers to the borehole by promoting diffusive transfer into the Callovo-Oxfordian from the HLW cells.

Doses at the outlet

Given the transfer time in the Dogger (see above), the peak doses obtained at the outlet are approximately 0.0003 millisieverts per year at around 600,000 years for selenium-79, 0.0001 millisieverts per year at around 40,000 years for chlorine-36 and iodine-129, and the same at around 25,000 years for niobium-94. Other radionuclides produce doses of less than 10^{-6} millisieverts per year.

4.2.3 Lessons

Given the hydraulic characteristics of the Callovo-Oxfordian, a borehole crossing an ILW-LL cell does not cause significant consequences for the hydraulic behaviour of the ILW-LL disposal section compared with that of the NES. Taking the transfer time in the Dogger into account leads to considerable attenuation of the medium half-life radionuclides which leads to a residual dose of less than 1 millisievert for all radionuclides.

The hydraulic effect of the borehole in the HLW disposal section is also moderate. The activities of iodine-129 and chlorine-36 drawn in by the borehole only represent approximately 0.2% and 0.1% respectively of the inventory of the HLW1 and HLW2 sections. The limited release rate via the vitreous matrix, combined with attenuation during migration of radionuclides in the HLW cells and the drifts, considerably reduces the activity reaching the intrusive borehole. The dose at the outlet is therefore always less than 0.001 millisievert per year.

4.3 The core sampling scenario

4.3.1 Scenario analysis

Target geological horizon – Purpose and characteristics of the borehole

The scientific objective of characterising the Callovo-Oxfordian is adopted as a possible reason for core sampling. In the case of a deeper target, core sampling would be unlikely even in the event of perceived anomalies or drill jamming on passing the repository. Under such circumstances, various unjamming operations and bit changes would be attempted to pass the obstacle. Finally, if it was not possible to cross the repository, the borehole could be filled with sealing grout over several tens of metres then drilled again at an angle, or from a different place on the surface.

The core cutter is assumed to have an internal diameter of 100[121].

It should be noted that the mechanical strength of the core samples will depend on the state of deterioration of the disposal packages crossed at the date of the intrusion. In the event of the waste having poor mechanical strength, only a fraction of the sampled length would be brought to the surface as a core sample. Friable parts of the packages and the waste contained in them would pass into the drilling fluid. In the context of a conservative approach, it is considered that the whole length of waste than could be found in a waste package will be brought to the surface in a core sample, with a maximum length set at 1 metre based on standard practices[122].

[121] This diameter corresponds to a bounding value for useful diameters and standard core sampling equipment.
[122] This length is that of standard core sample containers.

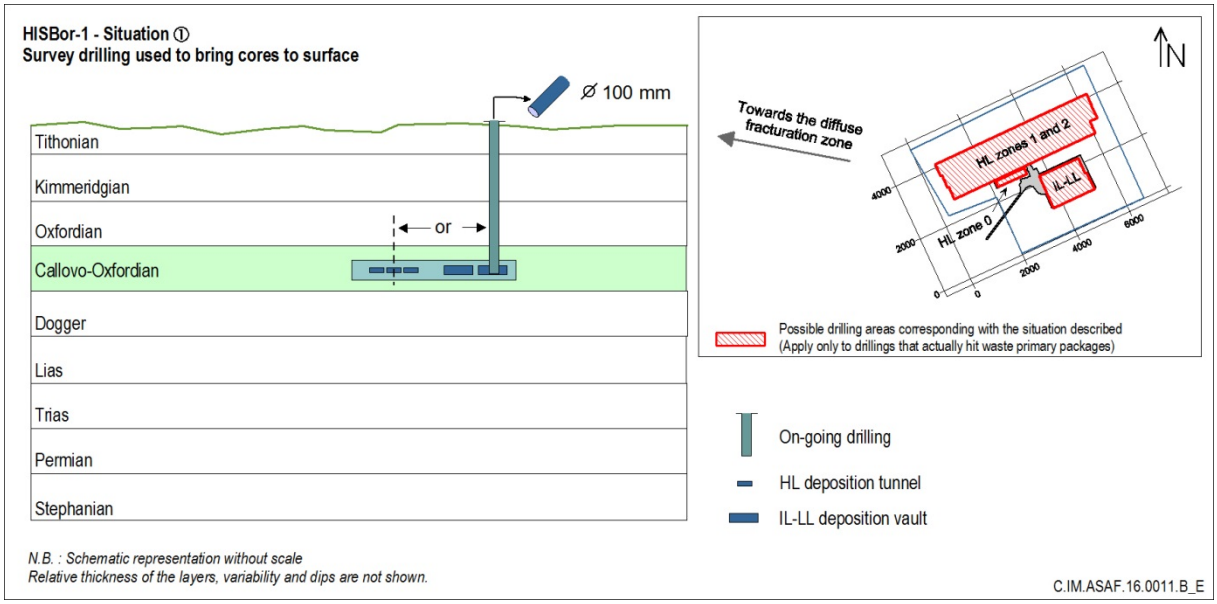


Figure 4.3-1: *Schematic diagram of the SIHFor-1 scenario – "Exploratory borehole leading to core samples containing waste being brought to the surface"*

Handling core samples

The typical maximum length of a core cutter can be up to 9m, as several elements can be assembled in series to save time in manoeuvring the drill string. When the core cutter is brought to the surface, its contents will be transferred by the drill operator into containers with a standard length of 1m. Core samples longer than this will be cut into lengths for storage.

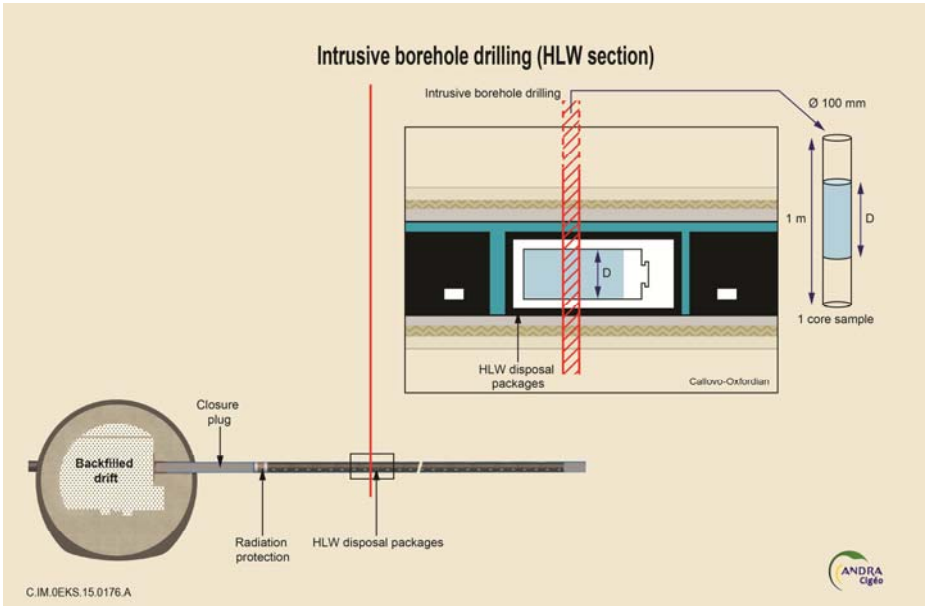


Figure 4.3-2: *Schematic diagram of core sampling in a HLW disposal section*

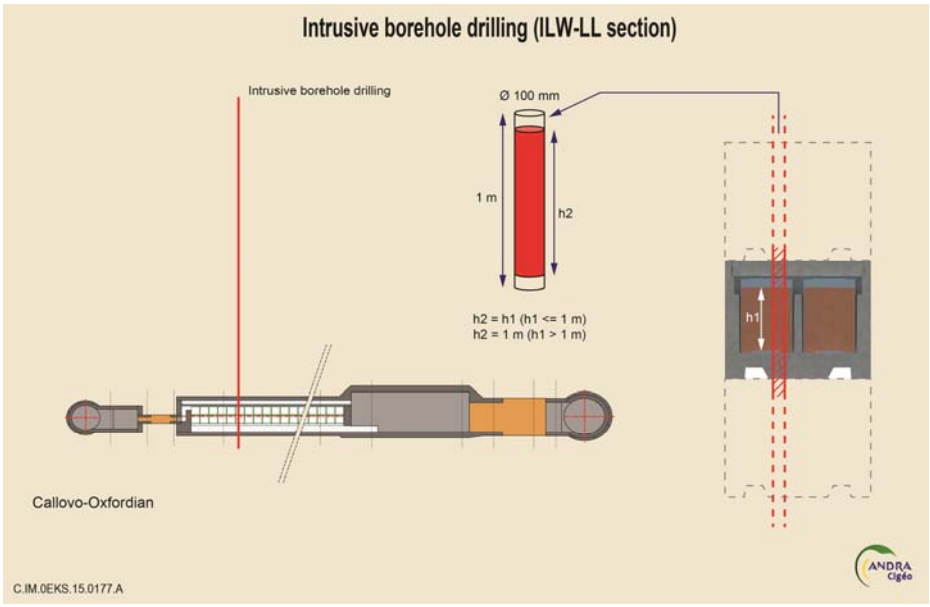


Figure 4.3-3: Schematic diagram of core sampling in an ILW-LL disposal section

The information provided by the core samples from an initial drilling is assumed adequate for protective measures to be taken in the event of further core sampling in the same campaign. Furthermore, if core-sampling investigations are pursued, the "inadvertent" nature of the intrusion could be called into question.

Borehole location in relation to package family

Doses have been calculated for each of the 98 waste package families in the industrial waste management programme (PIGD). However, it has been proposed that it be taken into account that certain families have very few packages and correspond to a very low relative probability of interception of the primary packages[123].

For waste package families with less than 10 packages, the relative probability of interception by a random borehole drilled inside the perimeter of the underground structures is less than 1/1,000,000. These have been excluded from the impact assessments for the scenario.

Hypothetical reference group affected – Assessed impact

The period of exposure of the drill operator corresponds to the time taken to extract the core sample elements from the core cutter, any cutting into pieces less than 1 m long, and installation of the core samples into their designated containers. On the basis of standard practices, these operations can last between approximately 1 and 10 minutes per metre of core sample, depending on any difficulties encountered (such as the sample jamming in the core cutter). External exposure for 10 minutes for a length of 1 metre has been adopted. Calculation of the impact considers frontal exposure at a distance of 40 cm with respect to the nearest point of the surface of the cylindrical core sample.

A dose equivalent rate is first calculated assuming uniform distribution of the activity of the extracted waste over the 1 metre core sample. The calculation takes into account the attenuation associated with the density of each type of waste. A correction factor is then applied as the waste may be concentrated on just one part of the length of the core sample. For each family of waste package, the total equivalent dose is the sum of the individual contributions of each of the 144 radionuclides present in

[123] As a guide, the probability of interception of primary packages for a randomly drilled vertical borehole within the footprint of the underground structures (approximately 1100 ha) varies from approximately 1/1,000,000 for the least numerous family and approximately 1/500 for the most numerous family given the predicted positioning of disposal packages.

the waste, on the basis of the specific activities from the reference radiological inventory of the Cigeo repository.

Time of intrusion and indicators

The core samples are assumed to be taken 500 years after closure, as soon as the specified minimum period for keeping records ends. The dose is calculated from closure to 1 million years to check that doses at 500 years are always conservative.

A combined external exposure "risk" indicator is also used to produce an ordered list of the waste package families in the PIGD, taking their size into account. This indicator is the product of dose by external exposure at 500 years for a core sample and the "relative probability" that a random borehole drilled within the footprint of the underground structures would affect this waste family in particular.

4.3.2 Results

Table 4.3-1 presents the top 5 HLW package families then the top 5 ILW-LL package families with regard to "drill operator" dose. The first HLW package family and the first ILW-LL package family correspond to a dose of around 35 millisieverts. The two right-hand columns of the table show the two main radionuclides contributing to the dose.

Table 4.3-1: Assessment of the dose received by a drill operator for external exposure to a core sample taken at 500 years, for the top 5 HLW and ILW-LL package families.

Waste family of the " PIGD"				External exposure to a 1 m core					Main contributors to the dose			
Name	Disposal area	Waste type	Number of primary packages	External exposure dose [mSv] (1)	Rank "External exposure dose"	1 / relative probability of hit (2)	Rank "relative probability"	Rank "external exposure risk" (3)	First contributor % of the total dose		Second contributor % of the total dose	
COG-830	HL	Standard container for vitrified waste of PWR/Fast breeder Reactors (SPX et PX)	1095	**36**	**1**	13600	21	3	Am241	87.2	Am243	11.4
COG-890	HL	Vitrified waste from spent fuel reprocessing CEA/DAM	80	**36**	**2**	185000	62	10	Am241	87.2	Am243	11.4
COG-880	HL	Vitrified waste from spent fuel reprocessing CEA/Civil	11	**36**	**3**	1350000	90	25	Am241	87.2	Am243	11.4
COG-900	HL	Vitrified waste from spent fuel reprocessing EL4	30	**23**	**5**	495000	78	19	Am241	86.0	Am243	12.5
COG-850	HL	Standard container of technological waste from vitrification workshops	200	**14**	**10**	52300	45	9	Nb94	100.0	Am241	0.0
EDF-120	IL-LL	Waste from AMI Chinon	100	**32**	**4**	122000	57	8	Ag108m	90.0	Ni59	8.8
COG-450	IL-LL	Standart compacted waste container with parts of PWR and Fast Breeder reactors fuel bundles	1514	**23**	**6**	67700	51	5	Nb94	100.0	Am241	0.0
COG-540	IL-LL	Compacted structural parts from spent fuel reprocessing CEA/DAM	400	**23**	**7**	256000	70	12	Nb94	100.0	Am241	0.0
COG-550	IL-LL	Compacted structural parts from spent fuel reprocessing EL4	200	**23**	**8**	513000	80	21	Nb94	100.0	Am241	0.0
COG-530	IL-LL	Compacted structural parts from spent fuel reprocessing CEA/Civil	24	**23**	**9**	4270000	100	32	Nb94	100.0	Am241	0.0

(1) 10 minutes exposure. Correction factor for cores with less than 1 m of waste
(2) "Surface area within the footprint of Cigéo" / "Projected surface area of primary packages"
(3) Rank of the multiplication "External exposure dose" x "Relative probability of hit"

The top ten families have between ten and around 1500 primary packages; the probability that a borehole hits one is therefore lower than for families with greater numbers of packages.

Table 4.3-2 gives an alternative ordered list of waste package families based on a combined "risk" indicator, which uses dose per core sample and the overall footprint of primary waste package families in disposal configuration. It therefore gives some priority to families with a large number of packages.

Table 4.3-2: Assessment of drill operator dose for external exposure to a core sample at 500 years for the top 5 HLW and ILW-LL package families in view of the "external exposure risk" combined indicator.

Waste family of the " PIGD"				External exposure to a 1 m core					Main contributors to the dose			
Name	Disposal area	Waste type	Number of primary packages	External exposure dose [mSv] (1)	Rank "External exposure dose"	1 / relative probability of hit (2)	Rank "relative probability"	Rank "external exposure risk" (3)	First contributor % of the total dose		Second contributor % of the total dose	
COG-200	HL	Standart container for UOX/URE/MOX vitrified waste	24060	**7.2**	12	617	1	**1**	Am241	87.2	Am243	11.4
COG-800	HL	Standart container for UOX vitrified waste (specification 300 AQ 060)	19010	**4.6**	14	781	2	**2**	Am241	86.0	Am243	12.5
COG-830	HL	Standard container for PWR/Fast breeder reactor (SPX et PX) virified waste	1095	**36**	1	13600	21	**3**	Am241	87.2	Am243	11.4
COG-140	HL	Standart container for UOX vitrified waste (specification 300 AQ 016)	6900	**1.9**	19	2150	7	**4**	Am241	85.5	Am243	13.3
COG-850	HL	Standard container of technological waste from vitrification workshops	200	**14**	10	52300	45	**9**	Nb94	100.0	Am241	0.0
COG-450	IL-LL	Standart compacted waste container with PWR and Fast breeder reactors fuel bundles parts	1514	**23**	6	67700	51	**5**	Nb94	100.0	Am241	0.0
COG-120	IL-LL	Standart compacted waste container with UOX/MOX/URE fuel bundles parts	22720	**1.4**	21	4510	11	**6**	Nb94	99.9	Am241	0.1
COG-110	IL-LL	Standart compacted waste container with UOX fuel bundles parts	17850	**1.8**	20	5740	13	**7**	Nb94	99.9	Am241	0.1
EDF-120	IL-LL	Waste from AMI Chinon	100	**32**	4	122000	57	**8**	Ag108m	90.0	Ni59	8.8
EDF-100	IL-LL	Waste from the dismantlIng of the existing PWR (including BCOT)	6360	**0.24**	32	1280	3	**11**	Ni59	96.7	Nb94	3.1

(1) 10 minutes exposure. Correction factor for cores with less than 1 m of waste
(2) "Surface area within the footprint of Cigéo" / "Projected surface area of primary packages"
(3) Rank of the multiplication "External exposure dose" x "Relative probability of hit"

Changes in impact over time

The dose calculation at 500 years after closure provides a conservative assessment over a million years for most waste families types. The few families for which the activity of certain radionuclides may significantly increase after 500 years all correspond to maximum doses of less than 0.005 millisieverts.

As an illustrative example, Figure 4.3-4 shows the time-dependent evolution of doses for the top 5 HLW package families and for the top 5 ILW-LL package families based on the "external exposure risk" combined indicator.

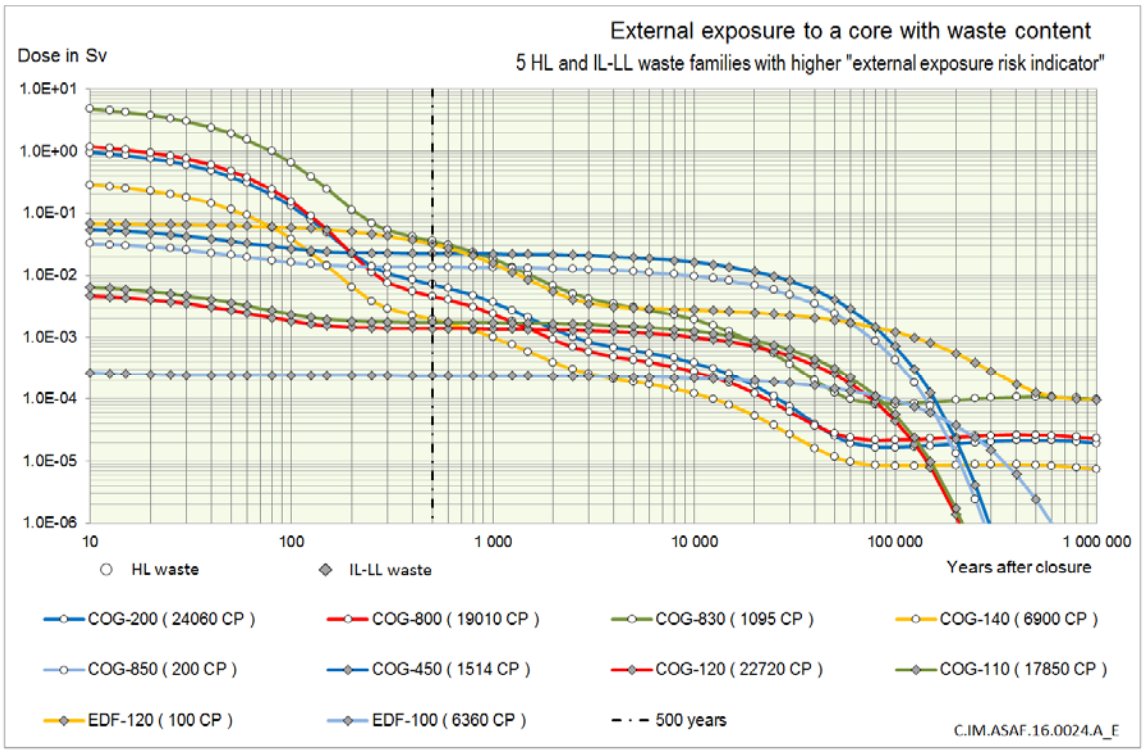


Figure 4.3-4: *Time-dependent evolution over 1 million years for the dose received by a drill operator from external exposure to a core sample taken at 500 years for the top five HLW and ILW-LL package families based on "external exposure risk".*

4.3.3 Lessons

This scenario postulates, by convention, core samples being inadvertently taken from waste packages.

The bounding radiological impacts on a drill operator at 500 years from closure are of the same order of magnitude for the HLW1/HLW2 and ILW-LL disposal sections (around forty millisieverts). The radionuclides which contribute the most to the impact are americium-241 and americium-243 for HLW packages (HLW1/HLW2), and silver-108m and nickel-59 for ILW-LL packages.

It should be noted that if only the families in each disposal sector (HLW and ILW-LL) with the largest number of packages are considered (5000 to 25,000 packages per family), the greatest impacts at 500 years are approximately 7 millisieverts for the HLW disposal sections and 2 millisieverts for the ILW-LL section.

4.4 The What-if scenario for human intrusion

4.4.1 Scenario analysis

Target geological horizon – Purpose and characteristics of the borehole

The HISBor-3 scenario (situation ⑤) is the "bounding" situation adopted for possible impacts to the NES Barrois outlet in the event of a borehole abandoned at repository depth (see Figure 4.4-1).

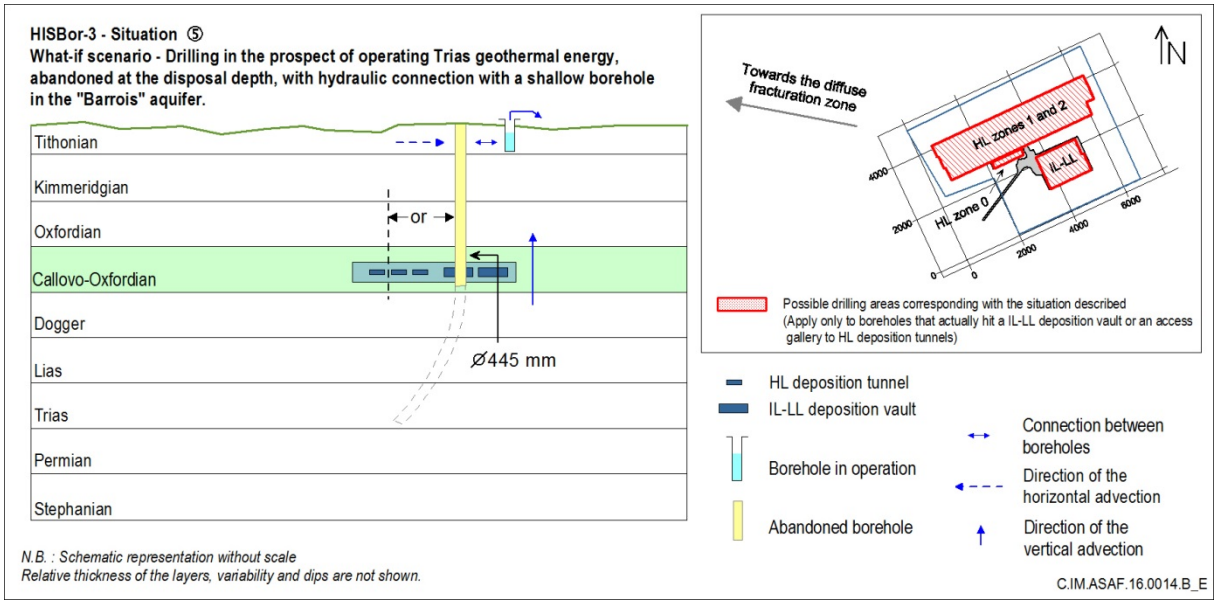


Figure 4.4-1: *Schematic diagram of the HISBor-3 'What-if' scenario - "Borehole intended for geothermal exploitation of the Trias abandoned at repository depth, linked to a Barrois (Tithonian) exploitation borehole ".*

This scenario considers that:

- the borehole is abandoned at repository depth;
- the drilling diameter at repository depth is 445 mm;
- the abandoned borehole is assumed to maintain its geometry indefinitely;
- as part of seeking conservative values for a bounding situation, the borehole is represented by a porous material with a permeability of 10-5 m/s;
- the abandoned borehole is located in a geometric arrangement such that there is a hydraulic link with an exploitation well or borehole in the Barrois (Tithonian) aquifers;
- radionuclide flows leaving the Callovo-Oxfordian via the abandoned borehole are immediately and entirely transferred into the exploitation borehole in the Barrois.

This scenario is included in the What-if category due to the low likelihood of the combination of some of these assumptions.

Type of impact and hypothetical reference groups

The outlet that could be affected by this situation is a water abstraction borehole in the Barrois (Tithonian) assumed to be hydraulically linked with the abandoned borehole. This type of outlet has already been considered in the NES; the hypothetical reference group and way it is reached are therefore identical to those of the NES.

Borehole location in relation to repository structures

The assumed location of the intrusion with respect to the disposal structures follows the same rules as for the previous scenario (see Section 4.4.1): intrusion at an access drift in the HLW1 disposal section which contains the highest surface activity densities or at ILW-LL cell number 5.

Number of boreholes considered

This scenario considers a single intrusive borehole[124].

Date of the intrusion and taking radionuclides into account

The intrusive borehole is assumed to be abandoned 500 years after closure, then to permanently act as a drain driven by the hydraulic head between the Oxfordian and the Dogger.

The list of radionuclides adopted for the impact assessment with regard to their mobility is given in Appendix 2. The release models for waste packages are identical to those of the NES bounding situation.

Parameters – Indicators

The assumptions and basic data used (other than those associated with the intrusion) are identical to those of the NES bounding situation corresponding to the upper repository location corresponding to an overlying undisturbed thickness of Callovo-Oxfordian host rock of at least 50 metres.

The largest ascending vertical hydraulic head gradient in the ZIRA over the million years, i.e. 0.1 m/m, is considered to apply uniformly and continuously over the million years. Conservatively, the intrusive borehole is assumed linked to the exploitation borehole in the Barrois aquifers. The concentration calculations take into account a dilution corresponding to an exploitation flow rate of 150 litres per minute.

The final indicator is the dose at the "Barrois borehole" outlet; intermediate indicators such as the hydraulic flow rate of the intrusive borehole and the molar flow rates of radionuclides out of the intrusive borehole are also assessed.

Numerical conceptualisation

The numerical conceptualisation follows the principles described in Section 4.2.1.

4.4.2 Results

4.4.2.1 Intrusion into the ILW-LL disposal section

Hydraulic behaviour

The presence of the borehole abandoned at repository depth leads to a hydraulic head field which creates water circulation towards the upper surrounding formation. The hydraulic flow drained by the borehole is limited by the very low permeability of the Callovo-Oxfordian.

Several aspects contribute to a hydraulic disturbance in the repository that is greater than that of the Dogger borehole AES scenario:

- the fact that the bypass only involves the upper undisturbed host-rock thickness, which precludes preferential hydraulic feed from the lower surrounding formation;
- a borehole diameter double that of an exploratory borehole;
- a greater vertical hydraulic gradient.

Figure 4.4-2 shows the hydraulic behaviours of the ILW-LL disposal section. In the "no seals" configuration inside the ILW-LL disposal section, the borehole's radius of hydraulic influence extends over the whole section and the flow rate drained is approximately 2.1 m^3 per year. Head losses in the whole section are approximately 3 metres, with a maximum of 4 metres in the affected ILW-LL cell.

In the configuration with ILW-LL cell closure using seals, head losses are less than 1.5 m in the ILW-LL disposal section as a whole but exceed 5 m in the affected ILW-LL cell. The flow rate drained is

[124] There is a low probability that two boreholes, and even less so that three successive boreholes, drilled at random within the repository footprint would hit repository structures. In any case, exploratory calculations have shown that in the hypothetical case of two simultaneous intrusive boreholes, they would not produce synergistic effects.

nevertheless limited, at approximately 0.8 m^3 per year. This flow value, which is 3 times lower than that obtained without ILW-LL seals, corresponds to an equivalent reduction of convective velocities towards the borehole.

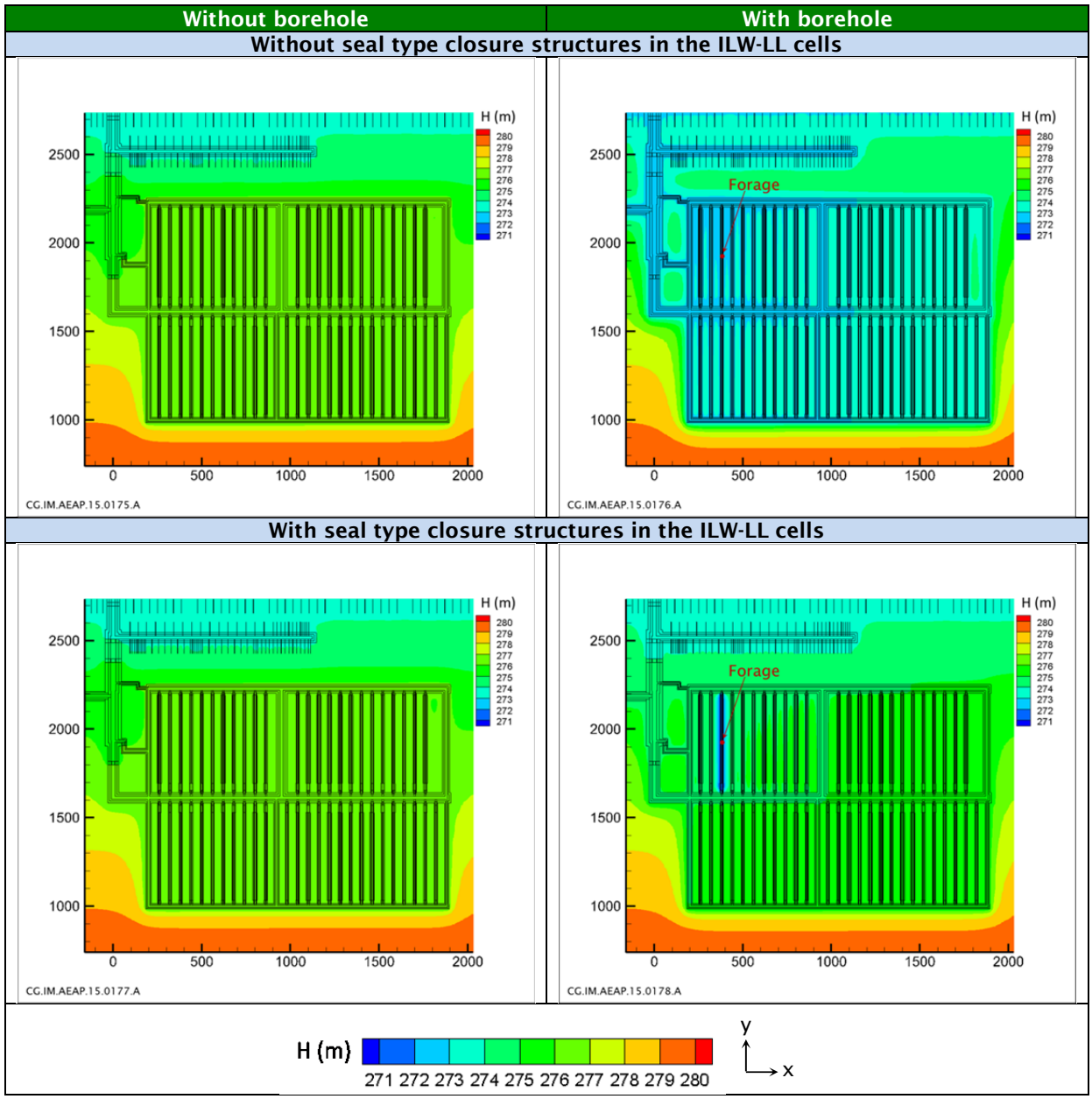


Figure 4.4-2: *Mapping of hydraulic heads in the ILW-LL disposal section (horizontal cross-section crossing the repository structure) – With and without ILW-LL cell seal type closure structures – With and without intrusive borehole*

Molar flow rates leaving the Callovo-Oxfordian

Borehole drainage leads to molar flow rates leaving the Callovo-Oxfordian that are approximately 4 times greater than those at the outlets to the Dogger in the Situation 3 human intrusion AES. The radionuclides involved are carbon-14[125] , iodine-129 and chlorine-36, with molar flow rates of between 0.1 and 1 moles per year. In this situation, the cumulative outputs of the borehole over the million-year period exceed the initial activity of the single ILW-LL cell hit by the borehole. For aluminium-26,

[125] For this assessment, the entire carbon-14 inventory is assumed to be mobilisable.

iodine-129 and chlorine-36, the cumulative outputs represent 30%, 46% and 44% respectively of their initial ILW-LL inventories, i.e. 192%, 133% and 109% of the inventory of the ILW-LL cell hit by the borehole.

Cumulative outputs over the million-year period represent approximately 30% of the total initial inventory of the ILW-LL disposal section for molybdenum-93, 12% for carbon-14 and 4% for silver-108m.

For other radionuclides, the cumulative outputs represent:

- 20% of the total initial inventory of the ILW-LL disposal section for palladium-107, characterised by intermediate retention, and for selenium-79 due to low retention in the Callovo-Oxfordian and the concrete of the ILW-LL cells.
- 1 to 5% of total initial inventory of this section for radionuclides characterised by (i) intermediate retention such as calcium-41, potassium-40, rubidium-87 and tin-106, and (ii) high retention associated with an inventory of the impacted ILW-LL cell representing over 65% of the total ILW-LL inventory, such as niobium-92 and beryllium-10;
- less than 1% for the radionuclides with high or very high retention (in the cement components and the Callovo-Oxfordian) such as actinides and lanthanides in particular.

Doses at the outlet

Figure 4.4-3 show the time-dependent evolution for doses at the " pumping in the Barrois" outlet. Peak doses remain well below deterministic effects. Peak doses at the outlet occur several tens of years after the borehole is drilled for mobile radionuclides or those with low retention in the Callovo-Oxfordian and cement components, and after several tens of thousands of years for sorbed elements (actinides and lanthanides).

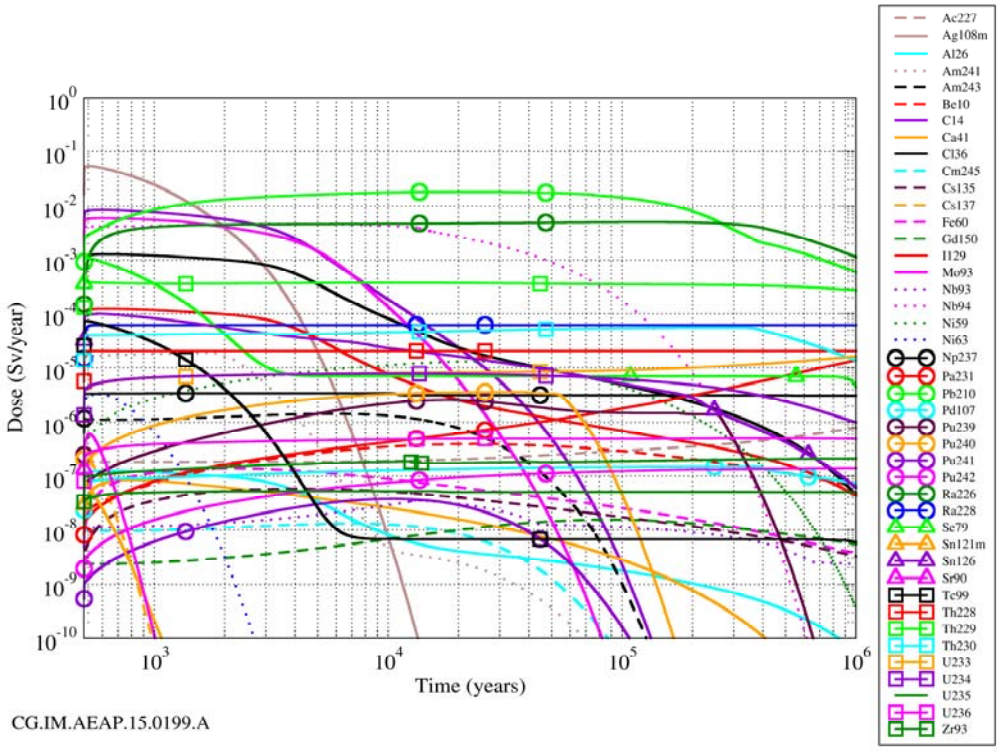


Figure 4.4-3: *Human intrusion What-if scenario – borehole in the ILW-LL disposal section (without ILW-LL cell closure structures): time-dependent evolution of doses at the "Barrois" outlet for a temperate biosphere for the 43 radionuclides whose peak dose exceeds 10^{-10} Sv/year.*

4.4.2.2 Intrusion into the HLW disposal section

Hydraulic behaviour

Under the effect of a vertical hydraulic gradient in the Callovo-Oxfordian, the abandoned intrusive borehole induces a hydraulic depression at the repository structures and causes flow into the Oxfordian limestone. The borehole drains a water flow rate of approximately 1.8 metres cube per year.

The borehole's radius of hydraulic influence at equilibrium extends over the whole division in which the cell hit by the borehole is located ($1/6^{th}$ of the HLW zone) (see Figure 4.4-4). Within the repository structures, the head loss distribution is not symmetrical on each side of the borehole due to greater water feed via the cluster of connecting drifts compared with the end of the HLW disposal section.

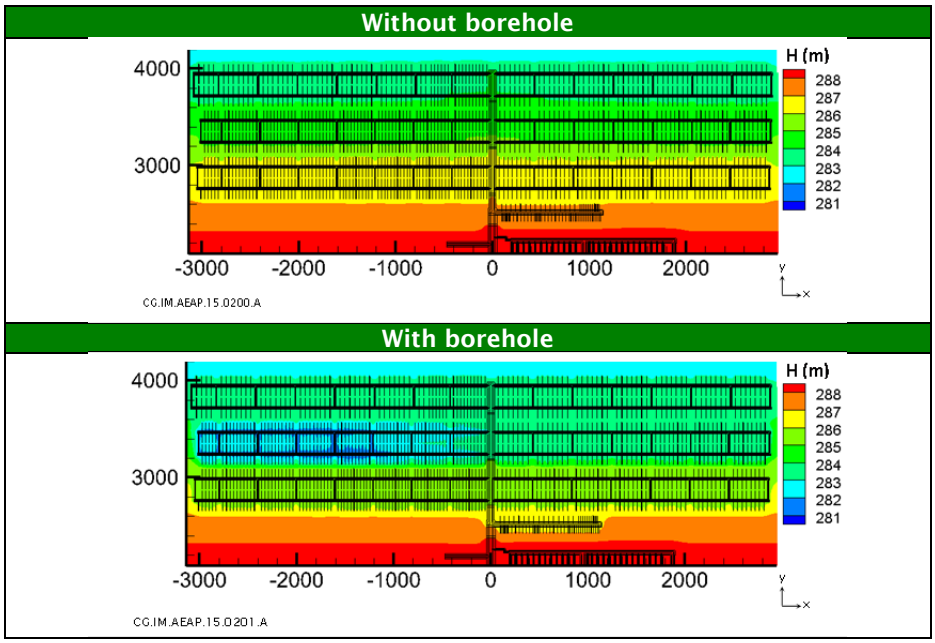


Figure 4.4-4: Mapping of hydraulic heads in the HLW1 and HLW2 disposal sections in the horizontal cross-section crossing the repository structures with and without intrusive borehole

Molar flow rate leaving the Callovo-Oxfordian

As in the case of the Dogger intrusion scenario, the highest instantaneous molar flow rates have been obtained for chlorine-36 and iodine-129, which are characterised by zero retention in the Callovo-Oxfordian, a large initial inventory and a long radioactive half-life. Due to a significant hydraulic disturbance, their peak molar flow rates are roughly 10 times greater than those obtained for the situation 3 AES, namely 3.4×10^{-4} moles per year for chlorine-36 and 2.3×10^{-4} moles per year for iodine-129.

This demonstrates an increase in the "radiological radius of influence" following from that of the hydraulic radius of influence, leading to an increase in advective transport towards the borehole and reduced exchanges by diffusion with the Callovo-Oxfordian.

Dose at the outlet

The peak doses obtained at the Barrois borehole linked with an abandoned borehole are approximately 0.003 millisieverts per year for selenium-79 and chlorine-36, 0.001 millisieverts per year for niobium-94 and 0.0002 millisieverts per year for molybdenum-93 and iodine-129. They are less than 5×10^{-5} millisieverts per year for all other radionuclides.

These “pumping in the Barrois” outlet dose peaks occur after several thousand years for medium half-life radionuclides such as niobium-94, molybdenum-92 and organic carbon-14, after around 15,000 years (end of source term) for mobile, soluble, long half-life radionuclides (iodine-129 and chlorine-36), and after several hundred thousand years for selenium-79 governed by its solubility.

4.4.3 Lessons

The inadvertent human intrusion What-if scenario combines a set of unlikely assumptions and parameters which tend to maximise impacts:

- conservative characteristics for the intrusive borehole (date of occurrence, immediate loss of integrity of any tubing, residual permeability of sand after being abandoned, large diameter, and direct hydraulic link with an exploited borehole);
- position of the borehole in the highest activity areas of the ILW-LL or HLW sections;
- assumptions regarding location of the radiological inventory in the ILW-LL disposal section.

As the drilling of such a borehole is considered much less likely than that of an exploratory borehole, this is considered a What-if scenario, used to assessing the robustness of the repository.

<u>ILW-LL disposal section</u>

- ILW-LL disposal section with ILW-LL cell closures using a material with performance characteristics equivalent to those of backfill

In this configuration, the borehole’s hydraulic radius of influence affects up to 10 ILW-LL cells for the most mobile radionuclides. The highest instantaneous dose, of approximately 55 millisieverts per year, is associated with silver-108m. The dose due to lead-210 reaches a peak of less than 20 millisieverts around 20,000 years. Up to approximately 10,000 years, the molar flows and when their peaks occur only depend on the contents of the ILW-LL impacted; in the longer term, up to 10 adjacent ILW-LL cells could be mobilised with regard to the most mobile radionuclides.

- ILW-LL disposal section with cell closure using seals

The presence of seals limits the water flow rate leaving the disposal through the borehole to approximately 0.8 cubic metres per year. On the basis of preliminary assessments for iodine-129, it seems that this limitation leads to a reduction in peak molar flow rate by a factor of approximately 5 and a delay of several thousand years compared with the case of closure using backfill. As in the previous situation, the molar flows and when the peaks occur only depend on the contents of the cell hit by the borehole up to about 10,000 years. Beyond this, the presence of seals reduces the borehole’s maximum "radiological radius" to approximately 5 cells.

<u>HLW disposal section</u>

Over one million years, the activity drained by the borehole represents approximately 3% of the iodine-129 and 2% of the chlorine-36 of the total inventories of the HLW1 and HLW2 disposal sections. The peak doses are approximately 0.003 millisieverts per year for selenium-79 and chlorine-36. They are less than 0.001 millisieverts per year for all other radionuclides.

5

What-if scenarios

5.1 What-if scenarios for malfunction of closure structures 359

5.2 What-if scenarios for disposal container failure 377

5.1 What-if scenarios for malfunction of closure structures

5.1.1 Adopted scenarios

The What-if scenarios for closure structure malfunction cover the failure of one or more types of seals designed to increase the hydraulic resistance of drifts and surface-bottom connections. These scenarios have been identified on the basis of a risks and uncertainties analysis with regard to potential causes of malfunction of closure structures, in particular seals implemented in drifts and surface-bottom connections (see Section 1.3.1 hereof).

This analysis led to definition of three What-if scenarios (see Table 1.7-3):

- a "Malfunction of surface-bottom connection seals via combined failures of the clay core and the interface between the clay core and the Callovo-Oxfordian" What-if scenario (the liner is not removed);
- a "Malfunction of drift seals via combined failures of the clay core and the interface between the clay core and the Callovo-Oxfordian" What-if scenario;
- a "Malfunction of all seals via combined failures of the clay core and the interface between the clay core and the Callovo-Oxfordian" What-if scenario.

Table 5.1-1 below summarises the list of What-if scenarios and the components involved.

Table 5.1-1: What-if scenarios for malfunction of closure structures

What-if scenarios for malfunction of closure structures	Type of closure structure			
	Shaft seals	Ramp seals	Drift seals	ILW-LL cell seals (if installed)
"Malfunction of surface-bottom connection seals" What-if scenario	- Ineffective clay core - Ineffective clay core/clay rock interface (liner not removed)	- Ineffective clay core - Ineffective clay core/clay rock interface (liner not removed)	- Effective clay core - Effective clay core/clay rock interface	- Effective clay core - Effective clay core/clay rock interface
"Malfunction of drift seals" What-if scenario	- Effective clay core - Effective clay core/clay rock interface	- Effective clay core - Effective clay core/clay rock interface	- Ineffective clay core - Ineffective clay core/clay rock interface	- Ineffective clay core - Ineffective clay core/clay rock interface
"Malfunction of all seals" What-if scenario	- Ineffective clay core - Ineffective clay core/clay rock interface (liner not removed)	- Ineffective clay core - Ineffective clay core/clay rock interface(liner not removed)	- Ineffective clay core - Ineffective clay core/clay rock interface	- Ineffective clay core - Ineffective clay core/clay rock interface

5.1.2 Description and conceptualisation of closing systems malfunction What-if scenarios

5.1.2.1 Description of the "malfunction of surface-bottom connection seals" What-if scenario

This What-if scenario considers that:

- all surface-bottom connection seals malfunction. The malfunction is represented by failed clay cores and ineffective interfaces;
- drift seals are effective.

Representation of the failed surface-bottom connection seals

The clay core of the surface-bottom connections seals is represented with hydraulic characteristics equivalent to those of backfill, as specified in the NES.

The liner left in place is represented in the same way as the liner portions in drift seals in the NES, with a water permeability equivalent to that of sand. No connected fractured zone (ZFC) is considered at the interface with clay core, but the discrete fracture zone (ZFD) is represented in reference and bounding situations.

Figure 5.1-1 below is a schematic view of the shaft seal malfunction as represented in this What-if scenario. Ineffective ramp seals are represented in the same way, except for geometry.

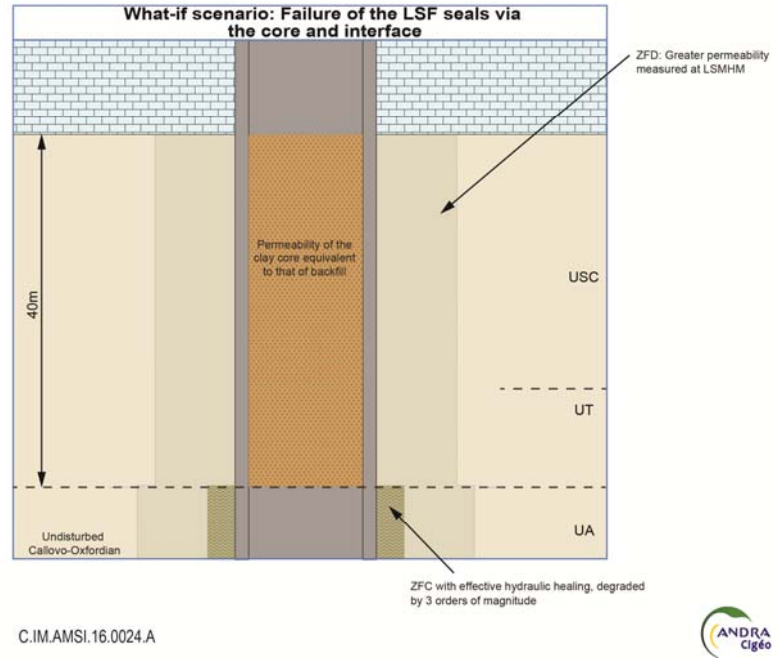


Figure 5.1-1: Schematic view of shaft seals for the "Malfunction of surface-bottom connection seals" What-if scenario" (bounding situation)

The failure is assumed to occur at the beginning of the post-closure phase[126], as in the "Malfunction of surface-bottom connection seals" altered evolution scenario.

Representation of clay rock in USC/UT units at the interface with standard sections of ramps (excluding seals)

At the interface with standard sections of ramps in the silty-carbonated unit (USC) and transition unit (UT), clay rock is represented in the same way as at the interface with clay cores, i.e. with a discrete fracture zone (ZFD) as shown in Figure 5.1-1.

[126] The seals and the repository are represented saturated from the date of closure, as for the NES.

Representation of drift seals

In this scenario, drift seals are assumed to be effective. They are represented in the same way as in the NES.

Representation of structures in the UA (excluding seals)

In the clay unit (UA), disposal cells and standard sections of drifts and surface-bottom connections are represented in the same way as in the NES.

5.1.2.2 Description of the "Malfunction of drift seals" What-if scenario

This scenario considers that:

- all drift seals malfunction. This malfunction is represented by combined failures of the clay core and the interface between the clay core and the Callovo-Oxfordian;
- surface-bottom connection seals are considered effective.

Representation of drift seals malfunction

As previously, the drift seal failure is assumed to occur at the beginning of the post-closure phase.

The malfunctioning clay core of the drift seals is represented with hydraulic characteristics equivalent to those of backfill material (see Table 5.1-2).

A continuous ZFC is considered at the interface with the clay core. Its water permeability is considered equal to that of hydraulically healed clay rock increased by two orders of magnitude.

The ZFD is not healed. It is represented using a conservative water permeability in the reference and bounding situations (see Table 5.1-2).

Figure 5.1-2 below gives a schematic view of malfunctioning drift seals as described in the What-if scenario.

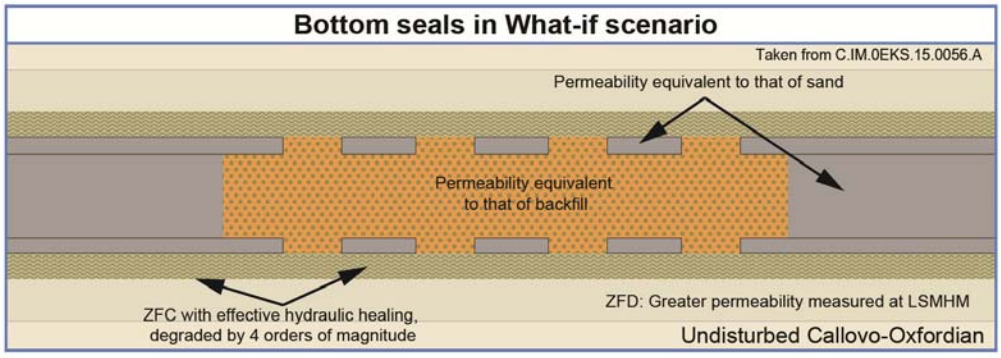


Figure 5.1-2: Schematic view of drift seals under the "Malfunction of drift seals" What-if scenario

Representation of structures in the UA (excluding seals)

In the clay unit (UA), it is assumed that the ZFD and the ZFC at the interface with the other structures (standard sections of drifts, surface-bottom connections and disposal cells) have the same characteristics as at the interface with the seals, namely (see Table 5.1-2):

- the water permeability of the ZFC is representative of an effective hydraulic healing increased by four orders of magnitude;
- the ZFD is represented with a conservative water permeability.

Representation of structures in USC/UT units

Under this scenario, the representation of surface-bottom connection seals is based on that of the NES, with an additional ZFD.

Clay rock at the interface with standard sections of ramps in the silty-carbonated unit (USC) and transition unit (UT) are represented as a ZFD in reference and bounding situations.

5.1.2.3 Description of the "Malfunction of all seals" What-if scenario

This What-if scenario considers malfunction of all seals (surface-bottom connection seals and drift seals) with combined failures of:

- the clay core;
- the interface between the clay core and the Callovo-Oxfordian:
  - ✓ for surface-bottom connection seals, by holding the liner between the clay core and the clay rock, thereby constituting an interface fault;
  - ✓ for drift seals, via a high permeability ZFC (failed hydraulic healing).

Representation of surface-bottom connection seal malfunctions

Malfunction of surface-bottom connection seals is represented in the same way as in the "Malfunction of surface-bottom connection seals" What-if scenario (see Section 0).

Representation of drift seals

Malfunction of drift seals is represented in the same way as in the "Malfunction of drift seals" What-if scenario (see Section 5.1.2.2).

Representation of structures in the USC/UT (at standard sections of ramps, excluding seals)

In USC and UT units, clay rock at the interface with standard sections of ramps is represented by a ZFD in reference and bounding situations (Table 5.1-2).

Representation of structures in the UA (excluding seals)

In the UA, structures other than seals (disposal cells and standard sections of drifts and surface-bottom connections) are represented in the same way as in the "Malfunction of the drift seals" What-if scenario (see Section 5.1.2.2), i.e.:

- the water-permeability of the ZFC is representative of effective hydraulic healing increased by four orders of magnitude;
- the ZFD is represented with conservative permeability.

5.1.2.4 Conceptualisation of What-if scenarios for seal malfunctions

Physical and numerical conceptualisation of What-if scenarios for seal malfunctions is the same as for the NES (see Section 2.1).

The list of studied radionuclides used is the same as for the NES. The release of radionuclides and their transfer from waste packages are represented in the same way as in the NES.

The retention and transfer properties of the clay core, the ZFC and the ZFD are identical to those specified for the NES, in reference and bounding situations.

The ZFC interface with HLW cells affected by the alkaline disturbance from the filler material outside the sleeve, is taken into account by considering no hydraulic healing (permeability equivalent to that of sand).

The hydraulic properties of the clay core and the initially damaged clay rock (ZFC and ZFD) are deteriorated compared to those of the NES, as summarised in Table 5.1-2.

5.1.3 Analysis of What-if scenarios for seals malfunction

The same indicators are used as for the NES, namely:

- transfer time and repository drainage capacity: these indicators are used to assess transfer times through the Callovo-Oxfordian and along structures from each disposal section. These indicators are used to assess the function "prevent water flow";
- the amounts of radionuclides migrating along the structure pathway and through the Callovo-Oxfordian. These indicators are used to assess the function "delay and lessen radionuclide migration".

The radiological impact is only assessed for the "Malfunction of all seals" What-if scenario, which is considered to cover the other two.

Table 5.1-2: What-if scenarios for malfunction of closure structures – Water permeabilities of mechanically damaged clay rock. Values deteriorated under these scenarios are shaded

Geological unit	Damaged clay rock zones	Reference situation				Bounding situation			
		NES	Surface-bottom connection seals What-if scenario	Drift seals What-if scenario	All seals What-if scenario	NES	Surface-bottom connection seals What-if scenario	Drift seals What-if scenario	All seals What-if scenario
Clay core	Drift seals	10^{-11}	10^{-11}	10^{-8}	10^{-8}	10^{-11}	10^{-11}	10^{-8}	10^{-8}
	Surface-bottom connection seals	10^{-11}	10^{-8}	10^{-11}	10^{-8}	10^{-11}	10^{-8}	10^{-11}	10^{-8}
UA	ZFC at the interface with removal zones	10^{-11}	10^{-11}	10^{-7}	10^{-7}	10^{-10}	10^{-10}	10^{-7}	10^{-7}
	ZFC at the liner	10^{-9}	10^{-9}	10^{-7}	10^{-7}	10^{-8}	10^{-8}	10^{-7}	10^{-7}
	ZFD	N/A	N/A	10^{-10}	10^{-10}	10^{-10}	10^{-10}	10^{-10}	10^{-10}
USC/UT	ZFC at the interface with clay core	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	ZFC at the interface with the liner	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	ZFD	N/A	10^{-11}	10^{-11}	10^{-11}	10^{-11}	10^{-11}	10^{-11}	10^{-11}

The ZFC at the interface with HLW cells affected by the alkaline disturbance is taken into account by considering no hydraulic healing (permeability equivalent to that of sand).

The retention and transfer properties of the clay core, the ZFC and the ZFD are identical to those specified for the NES, in the reference and bounding situations.

5.1.4 Results for seal malfunction What-if scenarios

The results are analysed with respect to those of the NES and the AES for malfunction of the same components.

5.1.4.1 Analysis of the effects on water flow in the repository

The analysis is detailed below for each scenario:

"Malfunction of surface-bottom connection seals via the core and the interface" What-if scenario

Using data from the NES reference situation, the What-if scenario for malfunction of surface-bottom connection seals via the clay core and interface leads to water flow rates leaving the surface-bottom connection structures of approximately 4 m^3 per year (see Table 5.1-3). These flow rates are 700 times

greater than those obtained under the NES reference situation and 16 times greater than those of the "Malfunction of surface-bottom connection seals via the interface" AES.

The effectiveness of the drift seals leads to significant head losses across these seals (see Figure 5.1-3), which limits the flow rates leaving the ILW-LL disposal section (increased by a factor of 1.5 compared with the AES and by a factor of 3 compared with the NES).

Using data from the SEN bounding situation, analysis of the results highlights:

- propagation of the Oxfordian limestones hydraulic head to the base of the drift seals (see Figure 5.1-3), which facilitates water flow to the main zone and leads to water flow rates of approximately 5 m3 per year leaving the surface-bottom connections;
- significant head losses (up to 4m) across the drift seals due to their effectiveness;
- water flow velocities (pore flow rate) in the drifts greater than in the reference situation, in line with the "bounding" nature of various hydraulic parameters. The pore flow rate reaches 30 mm per year at the outlet of the ILW-LL disposal section (see Table 5.1-3), which is 10 times greater than in the NES bounding situation and 20 times greater than for the What-if scenario with data from the NES reference situation. This pore velocity is almost identical to that obtained for the "Malfunction of surface-bottom connection seals via the interface" AES (see Table 5.1-3), as the hydraulic behaviour of the repository is determined by the permeability of efficient drift seals.

"Malfunction of drift seals via the core and interface" What-if scenario

Analysis of the results given in Table 5.1-3 and Figure 5.1-3 leads to the following comments:

- the assessments performed using NES reference situation data show that the effectiveness of surface-bottom connection seals is enough to lessen water flow rates leaving the repository. Water flow rates leaving the surface-bottom connection structures reach 5 litres per year, which is similar to the flow rates obtained with all seals effective (NES: 6 litres per year) and greater than those obtained for the "Malfunction of drift seals via the interface" AES (1 litre per year).
- drift seal malfunction causes hydraulic disturbance in the repository structures. The flow rate leaving the ILW-LL disposal section is the same as for the "Malfunction of drift seals via the interface" AES, but significantly greater than that obtained for the NES (by a factor of about 15);
- using NES bounding situation data, the water flow rates leaving surface-bottom connections are lower than those of the NES, due to facilitated water flow within repository structures. These flows result from the horizontal hydraulic gradient of the Oxfordian limestones (northward flow, from the ILW-LL zone to the HLW zone). Pore velocities leaving the ILW-LL disposal section are the same as those of the "Malfunction of drift seals via the interface" AES (see Table 5.1-3) and greater than those of the NES (by a factor of about 4.5).

"Malfunction of all seals via the core and interface" What-if scenario

The hydraulic head of the overlying Oxfordian propagates from the top of the Callovo-Oxfordian to the disposal sections and cells. This phenomenon is greatly accentuated in the bounding situation (see Figure 5.1-3).

Using NES reference situation data, malfunction of all seals via the clay core and the interface leads to water flow rates leaving the surface-bottom connections of approximately 6.2 m^3 per year, coming from both the main zone and the disposal sections (mainly ILW-LL sections). This flow rate is of the same order of magnitude as for the "Malfunction of surface-bottom connection seals" What-if scenario, but it is significantly greater than under the NES (by three orders of magnitude) and under the "Malfunction of all seals via the interface" AES (by a factor of about 12). This is mainly due to the permeability of the surface-bottom connection seals. Flow rates leaving the ILW-LL disposal section are doubled compared to those of the "Malfunction of drift seals" What-if scenario.

The assessments performed using NES bounding situation data show that the inefficiency of surface-bottom connections seals enables the propagation of the Oxfordian head in the whole repository and causes significant advection of radionuclides from the disposal sections to the surface-bottom connections. The water flow rates from the main zone and the HLW and ILW-LL disposal sections are approximately 8.5 m^3 per year.

These results show that, hydraulically, the repository has a substantial robustness for most What-if scenarios. Only the "Malfunction of all seals" What-if scenario based on NES bounding assumptions) produces a significant effect by propagating the hydraulic head from the overlying Oxfordian into the repository. However, the effect of this propagation remains limited with regard to the transfer of radionuclides, due to the favourable characteristics of the Callovo-Oxfordian and the dead-end architecture of the repository.

Table 5.1-3: What-if scenarios – Water flow rates leaving the surface-bottom connections and flow velocities leaving the ILW-LL disposal section (using the assumptions of NES reference and bounding situations)

Scenario	Hydraulic flow rate leaving the surface-bottom connections (L/year)		Flow velocity leaving the ILW-LL section (mm/year)	
	Reference situation	Bounding situation	Reference situation	Bounding situation
NES (all seals effective)	6	70	0.5	6
"Malfunction of surface-bottom connection seals" What-if scenario	4,200	4,900	1.5	30
"Malfunction of drift seals" What-if scenario	5	50	7.5	28
"Malfunction of all seals" What-if scenario	6,200	8,500	15	70

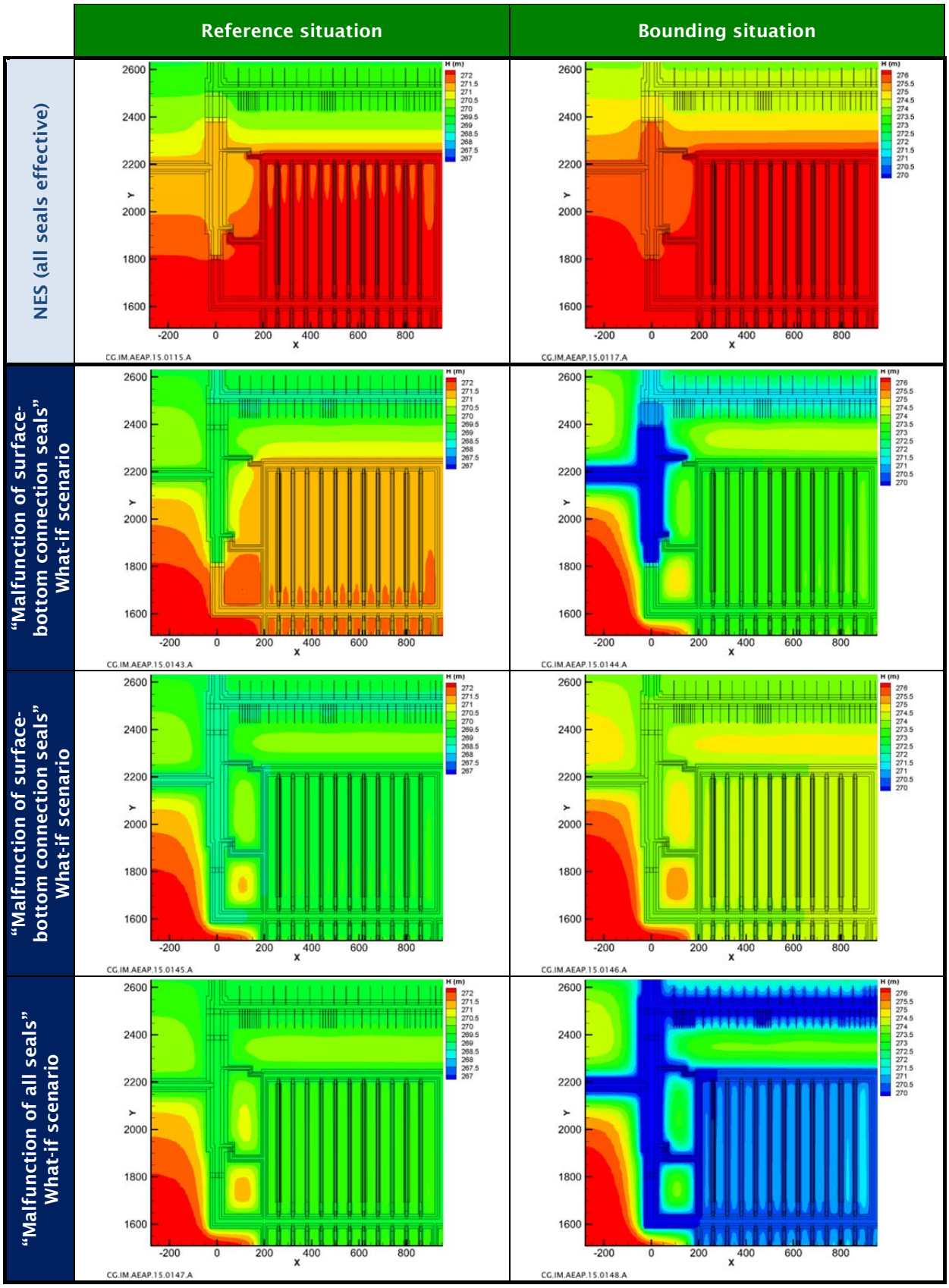


Figure 5.1-3: NES and What-if scenarios for malfunction of closure systems, for the reference situation (left) and the bounding situation (right) – Hydraulic head field (m) in the ILW-LL zone.

5.1.4.2 Analysis of What-if scenarios with regard to water flow and radionuclide transfer

Iodine-129 transfer

Figure 5.1-4 below shows the dominant transfer processes in the main drifts and surface-bottom connections and through the Callovo-Oxfordian, for the NES and for all studied What-if scenarios for malfunction of closure systems:

- in the case of malfunction of surface-bottom connection seals, advection is dominant in the surface-bottom connections and diffusion and advection are co-dominant in the drifts. Using NES bounding situation data, advection is also dominant in the drifts;
- in the case of malfunction of drift seals, advection is dominant in drifts and diffusion is dominant in surface-bottom connections.
- in the case of malfunction of all seals, advection is dominant in all structures.

Only the What-if scenario for malfunction of all seals leads to dominant advection throughout the structures transfer pathway. In this case, water circulation leads to a greater and earlier molar flow rate leaving the surface-bottom connections.

Figure 5.1-5 below shows the iodine-129 molar flow rates entering or leaving various locations along the structures transfer pathway, for the “Malfunction of all seals” What-if scenario.

The results of the “Malfunction of surface-bottom connection seals” and the “Malfunction of drift seals” What-if scenarios show that the peak molar flow rate leaving the surface-bottom connections is attenuated by a factor of 100 compared to that leaving the ILW-LL cells. This attenuation is of the same order of magnitude as for the "Malfunction of all seals via the interface” AES

Only the results for the "Malfunction of all seals” What-if scenario show less attenuation, by a factor of approximately 20 between the ILW-LL cells and the outlet of surface-bottom connections, with a peak molar flow rate that occurs about 100,000 years after closure (using NES reference situation data) or 15,000 years after closure (using NES bounding situation data).

The iodine-129 leaving the surface-bottom connections mainly comes from the ILW-LL disposal sections. The results show that the hydraulic head gradients in the repository tend to limit the advection of radionuclides from the HLW zone and to increase that of radionuclides from the ILW-LL section (for which the distribution of the iodine-129 inventory is conservatively positioned at the entrance to the section).

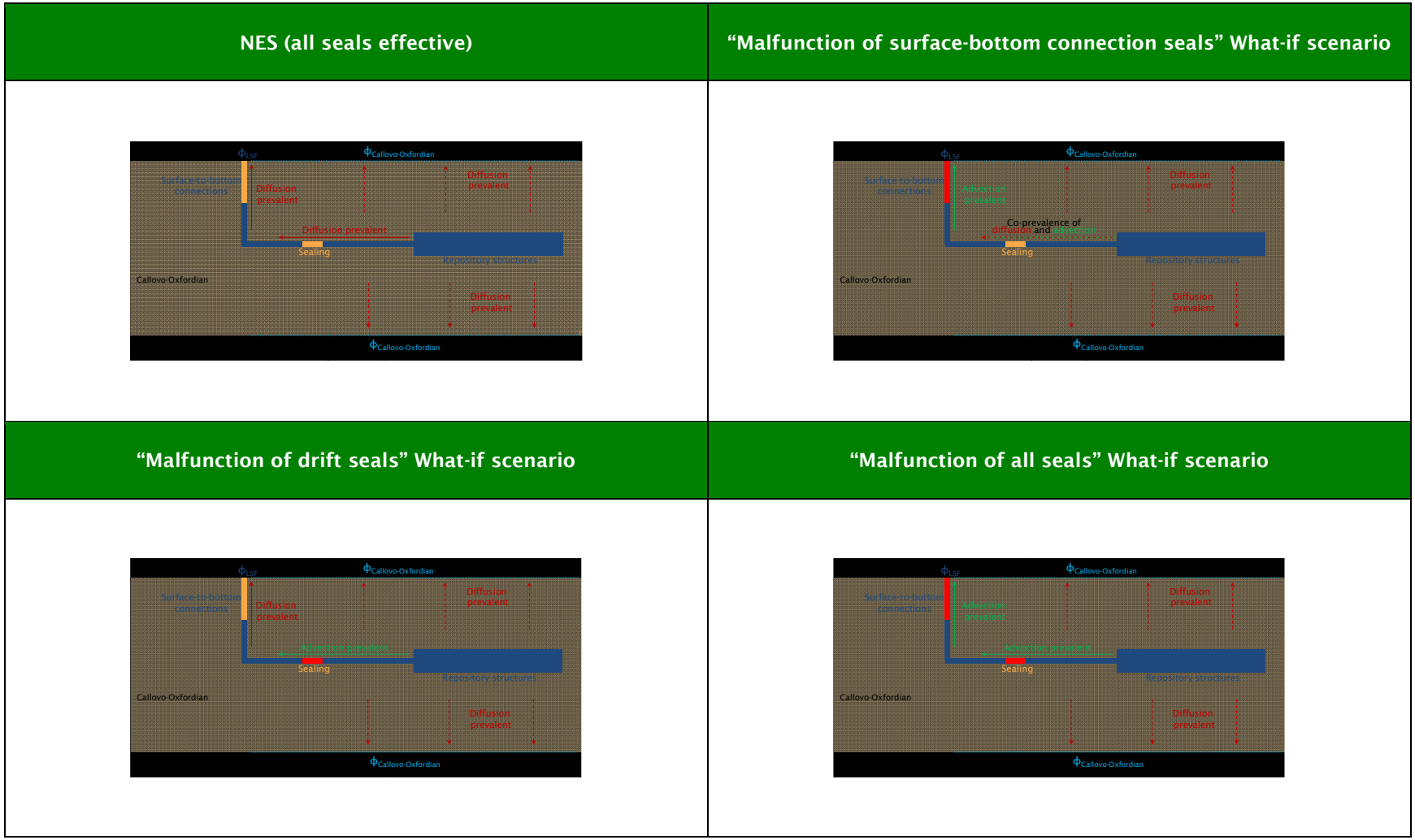


Figure 5.1-4: *NES and seal malfunction What-if scenarios (reference situation) – schematic view of solute transfer processes within structural components and across the Callovo-Oxfordian*

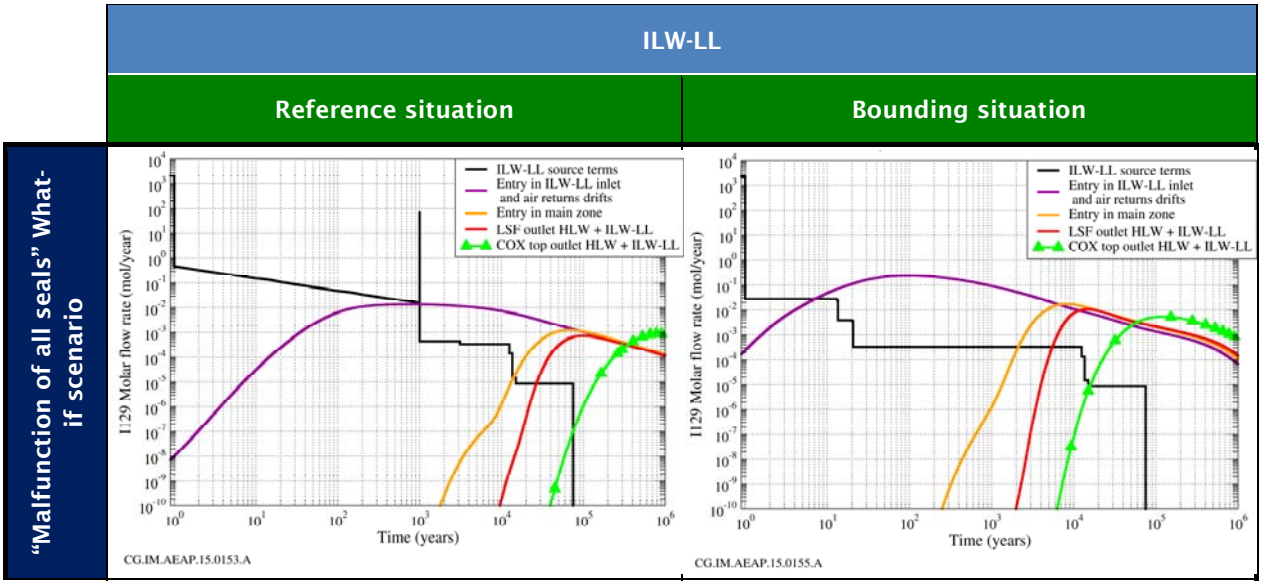


Figure 5.1-5: *"Malfunction of all seals" What-if scenario – time-dependent evolution of iodine-129 molar flow rates entering drifts and the main zone, and leaving surface-bottom connections and the Callovo-Oxfordian*

Table 5.1-4 gives the cumulative mole balance for iodine-129, normalised with respect to the initial inventory in each zone, at various places along the structures transfer pathway (cells, HLW and ILW-LL disposal sections, main zone and surface-bottom connections).

The cumulative quantity of iodine leaving the surface-bottom connections is less than that crossing the Callovo-Oxfordian for all seal malfunction What-if scenarios.

Table 5.1-4: *NES and What-if scenarios for malfunction of seals – assessment of the total amount of iodine-129 (cumulated over one million years, as a percentage of the total HLW and ILW-LL inventory) entering access and connection drifts, entering the main zone, and leaving surface-bottom connection structures and the top of the Callovo-Oxfordian.*

		Total amount of iodine-129 (as a% of the total initial inventory of each area)							
		Reference situation				Bounding situation			
		NES	Surface-bottom connection seals "What-if" scenario	Drift seals What-if scenario	All seals What-if scenario	NES	Surface-bottom connection seals What-if scenario	Drift seals What-if scenario	All seals What-if scenario
HLW	Entering access drifts	5%	5.8%	6.1%	6.1%	5.8%	8.2%	3.6%	11.3%
	Entering connecting drifts	0.2%	0.3%	< 0.1%	< 0.1%	0.4%	1.7%	< 0.1%	5.6%
	Entering the main zone	$< 10^{-2}$%	$< 10^{-2}$%	$< 10^{-4}$%	$< 10^{-5}$%	$< 10^{-2}$%	0.7%	$< 10^{-4}$%	4.8%
ILW-LL	Entering the connecting drifts (access / air return)	10%	10%	17%	25%	18%	26%	31%	43%
	Entering the main zone	0.4%	1.2%	7.8%	16%	5.1%	26%	25%	44%
HLW+ILW-LL	Leaving the surface-bottom connections	10^{-3}%	< 0.1%	< 0.1%	5.5%	0.2%	8.8%	1.0%	20%
	Leaving the top of the Callovo-Oxfordian	11%	11%	11%	10%	56%	51%	55%	45%

Figure 5.1-6 below shows the time-dependent evolution for iodine-129 flow rates leaving the surface-bottom connection structures and the Callovo-Oxfordian under the NES and the seals malfunction What-if scenarios. Table 5.1-5 gives the peak molar flow rates and when they occur.

Analysis of the results obtained with NES reference and bounding situation data leads to the following remarks:

- using NES reference situation data, iodine-129 from the HLW zones mainly migrates through the Callovo-Oxfordian, with less than 0.01% of the initial inventory reaching the main zone.
- using NES bounding situation data, malfunction of surface-bottom connection seals leads to water flows from the HLW disposal sections to the surface-bottom connections. The fraction of the initial iodine-129 HLW inventory transported by advection is 0.7% in the case of effective drift seals while it is 4.8% in the case of all failing seals;
- malfunction of all seals leads to significant iodine-129 transfer via the structures pathway: 5.5% of the initial inventory using NES reference situation data and 20% of the initial inventory using NES bounding situation data;
- the quantity of iodine-129 migrating through the Callovo-Oxfordian is little affected by seal failure in the reference situation. Using NES bounding situation data, the large amount of iodine-129 migrating along structures significantly reduces the quantity of iodine-129 migrating through the Callovo-Oxfordian, although the latter still remains the main pathway;
- transfer along the structure pathway has an earlier peak flow rate than that through the Callovo-Oxfordian (see Figure 5.1-5 and Figure 5.1-6);
- due to the Oxfordian hydraulic head gradient that causes northward water flow in the repository, the seal failure increases iodine-129 advection from the ILW-LL zone to the main zone. Meanwhile,

the amount of iodine-129 transferred along structures is increased from 0.4 to 16% (using NES reference situation data) or from 5% to 44% (using SEN bounding situation data).

The results from the NES reference situation data show that:

- the peak iodine-129 molar flow rate leaving the surface-bottom connection structures is much lower than that of the Callovo-Oxfordian transfer pathway, by a factor of over two orders of magnitude in the event of surface-bottom connection or drift seals malfunctioning.
- only the all seals malfunctioning scenario leads to a peak iodine-129 molar flow rate leaving the surface-bottom connection structures of the same order of magnitude as that leaving via the Callovo-Oxfordian transfer pathway:
  - ✓ occurring 100,000 years after closure (compared with 840,000 years for the Callovo-Oxfordian transfer pathway);
  - ✓ with molar flow rates greater than those of the Callovo-Oxfordian transfer pathway for approximately 300,000 years.

The results from the NES bounding situation data show that:

- the "Malfunction of surface-bottom connection seals" What-if scenario leads to
  - ✓ an iodine-129 molar flow rate leaving the surface-bottom connections greater than that leaving the Callovo-Oxfordian for 30,000 years;
  - ✓ a peak iodine-129 molar flow rate leaving the surface-bottom connections 5 times lower than that leaving the host formation.
- the "Malfunction of drift seals" What-if scenario leads to:
  - ✓ an iodine-129 molar flow rate leaving the surface-bottom connections greater than that leaving the Callovo-Oxfordian for 15,000 years;
  - ✓ a peak iodine-129 molar flow rate leaving the surface-bottom connections 30 times lower than that leaving the host formation.
- the "Malfunction of all seals" What-if scenario leads to:
  - ✓ an iodine-129 molar flow rate leaving the surface-bottom connections greater than that leaving the Callovo-Oxfordian for 50,000 years;
  - ✓ a peak iodine-129 molar flow rate leaving the surface-bottom connections twice that leaving the host formation.
  - ✓ this peak occurs about 15,000 years after closure;

Together, these results demonstrate the robustness of the repository in case malfunction of one set of seals (What-if scenario for malfunction of surface-bottom connections or drifts). For these two What-if scenarios, the molar flow rate migrating along the structures pathway reach the top of the host formation several thousand years earlier than that crossing the Callovo-Oxfordian. The peak molar flow rate remains lower than that leaving the Callovo-Oxfordian.

Only the "Malfunction of all seals" What-if scenario combined with the conservative assumptions of the NES bounding situation, leads to a peak molar flow rate leaving the surface-bottom connections that is slightly greater (by a factor of 2) and earlier (about 50,000 years) than that leaving the transfer pathway across the Callovo-Oxfordian.

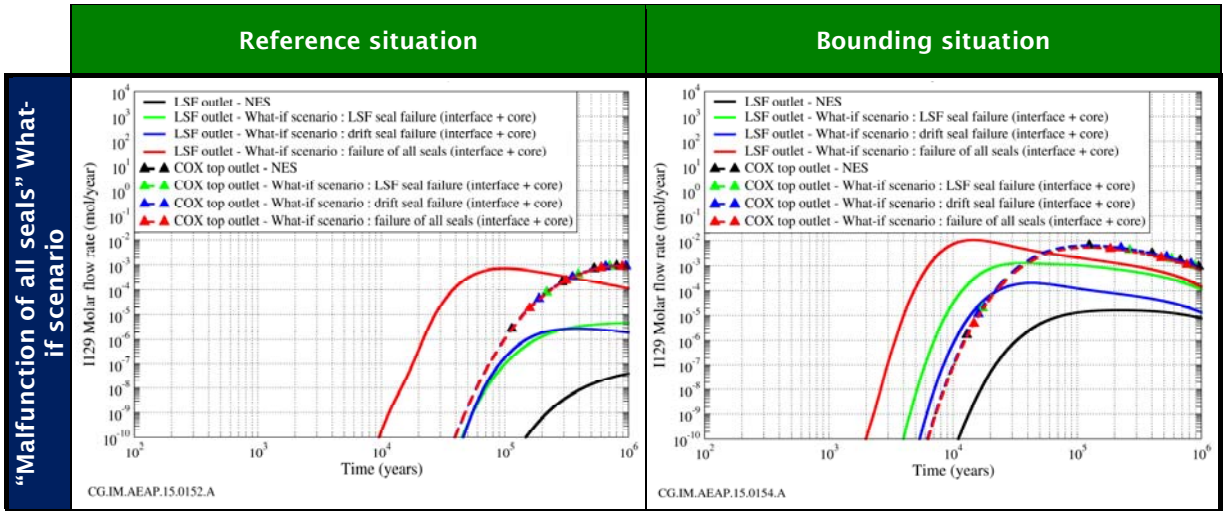


Figure 5.1-6: *What-if scenarios for seals malfunction – Time-dependent evolution of iodine-129 molar flow rates leaving surface-bottom connection structures and clay rock at the top of the Callovo-Oxfordian*

Table 5.1-5: *What-if scenarios for seals malfunction – Iodine-129 molar flow rates at the top of the Callovo-Oxfordian: Peak molar flow rates via structures and clay rock pathways, occurrence dates and ratio between peak flow rates*

		Peak iodine-129 molar flow rates							
		Reference situation				Bounding situation			
		NES	Surface-bottom connection seals What-if scenario	Drift seals What-if scenario	All seals What-if scenario	NES	Surface-bottom connection seals What-if scenario	Drift seals What-if scenario	All seals What-if scenario
Transfer across clay rock	Peak molar flow rate at the top of the Callovo-Oxfordian (10^{-6} moles/year)	930	930	930	880	6,500	6,000	6,500	5,300
	Occurrence (thousands of years)	840	840	840	840	120	120	120	120
Transfer via the structures pathway	Peak molar flow rate at the top of the Callovo-Oxfordian (10^{-6} moles/year)	0.04	4.7	2.8	740	16	1,300	210	11,000
	Occurrence (thousands of years)	>1,000	>1,000	380	100	220	36	43	15
Ratio of peak molar flow rates via clay rock/structure pathways		23,000	200	340	1.2	400	4.6	32	0.5

Chlorine-36 transfer

Figure 5.1-7 shows chlorine-36 transfer via the structures pathway and via the Callovo-Oxfordian.

Overall, the results show similar behaviour to that of iodine-129.

On the basis of the NES bounding situation data, the results of the "Malfunction of all seals" What-if scenario show:

- a chlorine-36 molar flow rate leaving surface-bottom connections greater than that leaving the Callovo-Oxfordian for approximately 40,000 years;
- a peak chlorine-36 molar flow rate leaving the surface-bottom connections that is approximately half that leaving the Callovo-Oxfordian;
- this peak occurs about 25,000 years after closure.

Despite the peak chlorine-36 molar flow rate leaving the surface-bottom connections occurs 100,000 years earlier, it remains lower than that leaving clay rock at the top of the Callovo-Oxfordian. This is the result of the radioactive half-life of chlorine-36, which is shorter than the transfer time in the whole network of drifts, enabling significant radioactive decay during its migration.

Other radionuclides

Figure 5.1-8 shows the time-dependent evolution of molar flow rates at the top of the Callovo-Oxfordian in the case of the "Malfunction of all seals" What-if scenario, using data from the NES reference and bounding situations.

For iodine-129, chlorine-36, selenium-79 and aluminium-26, the "Malfunction of all seals" What-if scenario yields greater than 10<35388>-10</35388> mol/year molar flow rates that occur earlier than for the NES, using reference situation data. However, peak molar flow rates are still governed by the Callovo-Oxfordian transfer pathway. These flow rates are similar to those of the NES.

Regarding the results obtained using NES bounding situation data, radionuclides whose molar flow rates reach 10<35389>-10</35389> mol/year are, in addition to mobile radionuclides (iodine-129 and chlorine-36), calcium-41 and potassium-40, which are weakly sorbed into the cement structures and clay rock, molybdenum-93, which is mobile and has an intermediate half-life, and uranium-235 and -238, which has low solubility in clay rock and a large inventory.

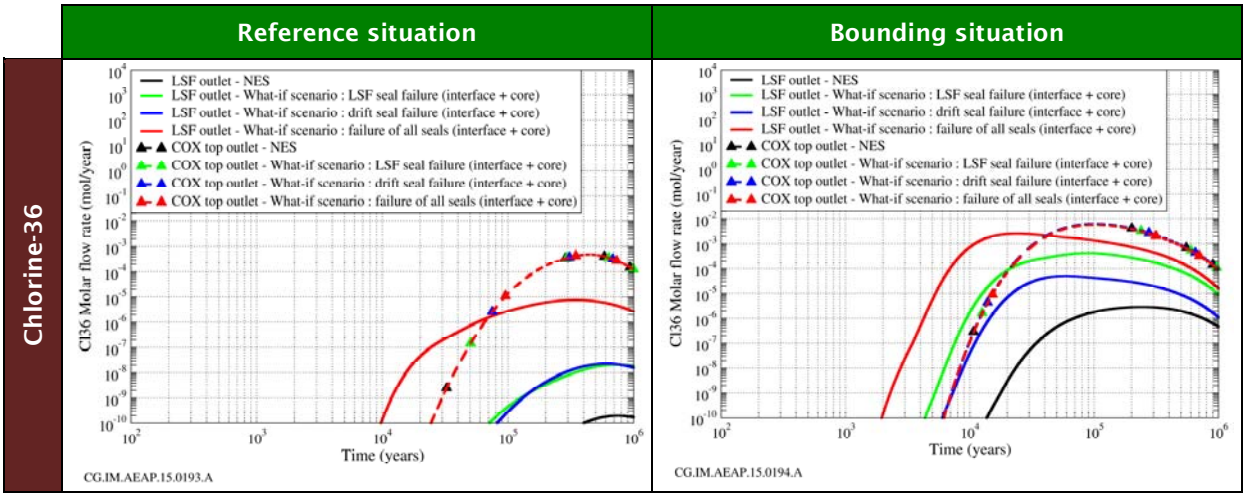


Figure 5.1-7: *NES and What-if scenarios for malfunction of seals (reference and bounding situations) – Time-dependent evolution of chlorine-36 molar flow rates leaving surface-bottom connection structures and the top of the Callovo-Oxfordian*

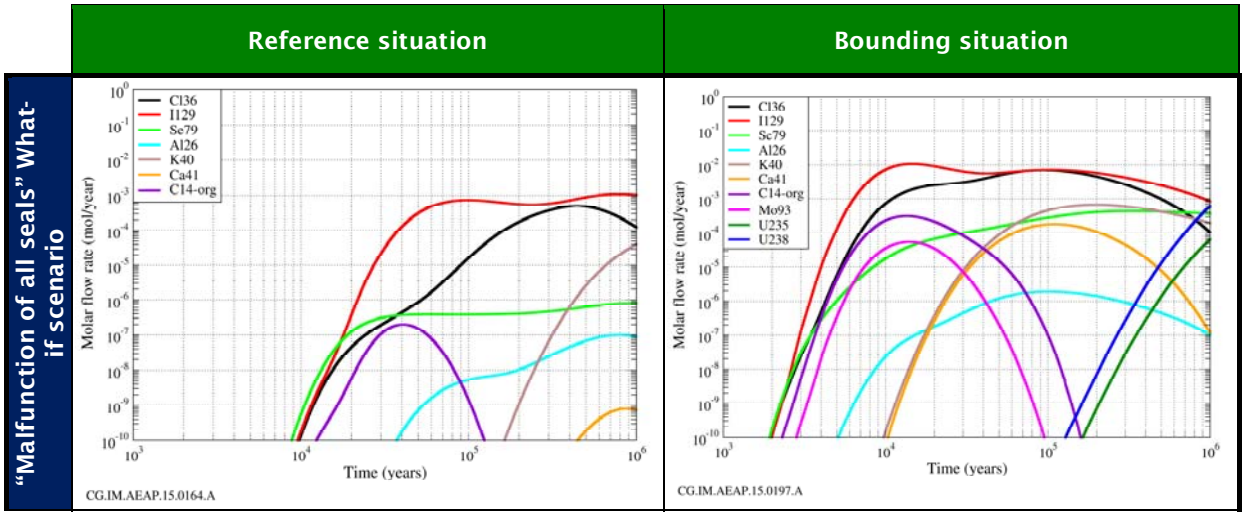


Figure 5.1-8: *"Malfunction of all seals" What-if scenario (reference and bounding situations) – Time-dependent evolution of molar flow rates for radionuclides whose molar flow rate reach 10<35568>-10</35568> moles per year at the top of the Callovo-Oxfordian*

5.1.4.3 Impact assessment for the "Malfunction of all seals via the interface and the clay core" What-if scenario

The radiological impact is assessed at the Barrois outlet using the same assumptions for transfer into the biosphere as in the NES.

Figure 5.1-9 presents the time-dependent evolution of doses at the " pumping in the Barrois" outlet for temperate and hot climate biospheres. Table 5.1-6 gives the peak doses and when their occurrences.

These results do not show any significant differences between temperate and hot biospheres.

Assessments performed using NES reference situation data show that the dose caused by the "Malfunction of all seals" What-if scenario remains of the same order of magnitude as for the NES

Assessments based on NES bounding situation data show that the impact is of the same order of magnitude as that under the NES and under the "Malfunction of seals via the interface" AES.. The peak dose is approximately 0.002 millisievert per year at around 350,000 years, which is still low. It is governed by chlorine-36, selenium-79 and iodine-129. Only selenium-79 has a significantly greater contribution to the impact than under the NES.

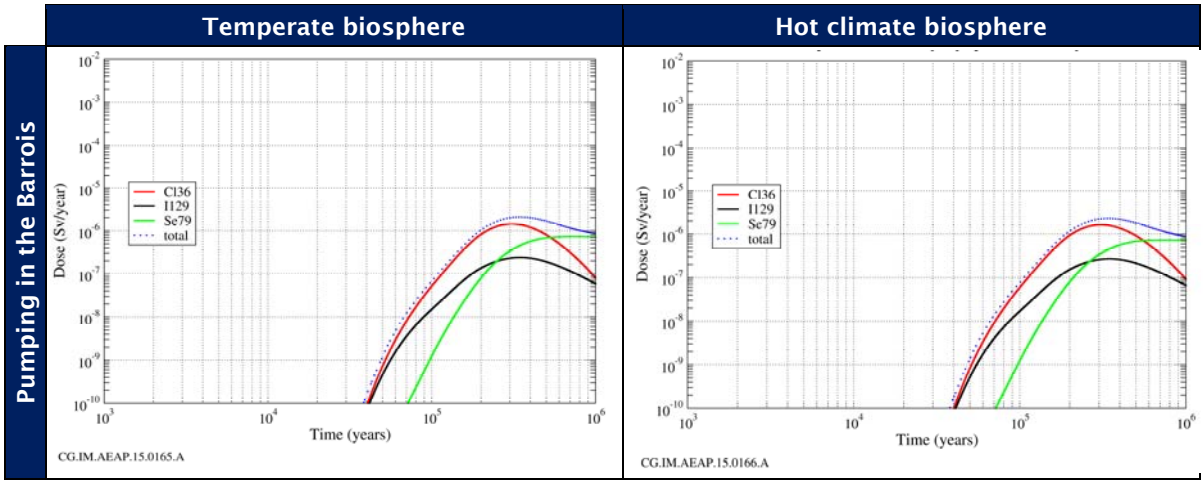


Figure 5.1-9: *"Malfunction of all seals" What-if scenario (bounding situation): time-dependent evolution of the doses at the "pumping in the Barrois" outlet for temperate and hot climate biospheres*

Table 5.1-6: *NES and "Malfunction of all seals" What-if scenario: peak doses at the "pumping in the Barrois" outlet and when they occur, for temperate and hot climate biospheres (bounding situation)*

	NES (all seals effective)				"Malfunction of all seals" What-if scenario			
	Temperate biosphere		Hot climate biosphere		Temperate biosphere		Hot climate biosphere	
Radionuclide	Peak dose (mSv/year)	Date of peak dose (thousands of years)	Peak dose (mSv/year)	Date of peak dose (thousands of years)	Peak dose (mSv/year)	Date of peak dose (thousands of years)	Peak dose (mSv/year)	Date of peak dose (thousands of years)
^{36}Cl	1.2×10^{-03}	320	1.4×10^{-03}	320	1.4×10^{-03}	310	1.6×10^{-03}	310
^{129}I	2.1×10^{-04}	380	2.3×10^{-04}	380	2.4×10^{-04}	350	2.7×10^{-04}	350
^{79}Se	3.7×10^{-04}	730	4.4×10^{-04}	730	7.3×10^{-04}	730	7.3×10^{-04}	730
Total	1.6×10^{-03}	340	1.9×10^{-03}	340	2.1×10^{-03}	350	2.3×10^{-03}	340

5.1.5 Lessons from the What-if scenarios for malfunction of closing systems

From the hydraulic behaviour standpoint, the lessons are similar to those of the altered evolution scenarios for malfunction of closure structures via the interface (Section 3.1), namely:

- limited effects in the surface—bottom connections for the scenarios that imply the efficiency of either the surface-bottom connection seals or the drift seals;
- limited effects on the hydraulic system in the What-if scenario for malfunction of all seals, due to the low permeability of the Callovo-Oxfordian and the dead-end architecture of the repository;
- slow flow in the main drifts, from the southern disposal sections (ILW-LL) towards the northern disposal sections (HLW). This flow results from the horizontal hydraulic head gradient in the Oxfordian limestones;
- using reference situation data, in the event of malfunction of all seals, water flows leaving the surface-bottom connection structures limited to about 6.2 m^3 and approximately 15 mm per year flow velocities in the ILW-LL disposal section;
- using NES bounding situation data, a hydraulic pattern that leads to greater flows in the ILW-LL disposal section, but with limited flows in the surface-bottom connections (approximately 8.5 m^3 per year in the shafts and ramps).

The robustness of the repository is highlighted by comparison of the mappings of hydraulic heads in the repository, water flows leaving the shafts and the ramps, and flow velocities leaving the ILW-LL disposal zone, for the various seal malfunction configurations studied under the altered evolution and what-if scenarios.

These results show that the efficiency of either set of seals is enough to limit radionuclide transfer via the structure pathway.

Despite the structure pathway is significant under the "Malfunction of all seals" What-if scenario, the peak molar flow rate at the surface-bottom connection outlet only occurs 100,000 years after closure, thus attenuating chlorine-36 in the reference situation structure pathway

The dead-end architecture plays a role in the event of failure of all closing systems by limiting water flows, thanks to the favourable characteristics of the Callovo-Oxfordian. In the reference situation, the length of the ILW-LL cells contributes to attenuating the main fraction of the iodine-129 inventory released by the waste packages, although this attenuation is slightly reduced in the event of drift seals malfunction. Attenuation of the iodine-129 molar flow rate between the entrance of the ILW-LL drifts and the main zone is similar to that of the altered evolution scenarios for malfunction of closure structures via the interface: approximately 3 orders of magnitude in the event of drift or surface-bottom connection seals malfunctioning and a factor of 200 in the event of all closure structures malfunctioning.

These results demonstrate the robustness of the repository, in particular the importance of the dead-end architecture and the favourable hydraulic properties of the Callovo-Oxfordian in the event of failure of all closing systems intended to increase the hydraulic resistance of drifts and surface-bottom connections.

The assessments performed with the NES reference situation data indicate that, in the event of malfunction of all closing systems, the molar flow rate along the structure pathway would be greater than that across the Callovo-Oxfordian for 300,000 years. A similar behaviour is obtained using the NES bounding situation data, but here the structures pathway dominates for approximately 50,000 years. However, the cumulated over one million years amount of iodine-129 reaching the top of the Callovo-Oxfordian via the structures is still less than 20% of the initial inventory.

The radionuclides that may reach the top of the Callovo-Oxfordian are the same as those under the AES for malfunction of closing systems via the interface. These are mobile anions (iodine-129, chlorine-36, selenium-79 and aluminium-26) and other less mobile radionuclides (potassium-40 and calcium-41) along with organic carbon-14.

The dose at the "pumping in the Barrois" outlet is approximately 0.002 millisieverts per year. This impact is similar to that of the NES (bounding situation) and much lower than deterministic effects. The dose at the outlet on the eastern limit of the diffuse fracture zone at the Dogger level is similar to that of the NES: seal malfunction has little effect on this transfer pathway.

5.2 What-if scenarios for disposal container failure

5.2.1 Reminder of adopted scenarios

The analysis of risks and uncertainties in Section 1 hereof led to specification of a What-if scenario for failure of all HLW disposal containers (HLW0, HLW1/HLW2) (see Table 1.7-2).

This section first gives a description and conceptualisation of the scenario then presents the results of quantitative assessments for the adopted indicators.

5.2.2 Description and conceptualisation of the What-if scenario for failure of all HLW disposal containers (HLW0, HLW1/HLW2)

This scenario considers premature loss of integrity for all HLW disposal containers (i.e. HLW0, HLW1/HLW2) via a process similar to that for the AES, namely oxidising corrosion associated with the presence of oxygen in the HLW cell.

It differs from the AES by the number of containers affected, using the very unlikely assumption that all containers fail as soon as the repository is closed. Release of radionuclides starts from this moment.

The induced effects of loss of integrity on the release models are the same as for the AES, namely taking a cement-based medium into account in the cell.

As these induced effects lead to a release of radionuclides into an medium with a thermal load greater than in the NES, transport and retention characteristics of the radionuclides are taken into account as done for the AES, taking into account the heat produced by HLW1 and HLW2 types[127].

Other assumptions and parameters are equivalent to those used under the normal evolution scenario. Thus, the physical conceptualisation of the What-if scenario is the same as for the NES, taking into account the effects caused by disposal container loss of integrity.

The radionuclides used for the quantitative assessment of this scenario are the same as those of the NES.

The schematic diagram of the What-if scenario is similar to that of the AES given in Figure 3.2-1.

5.2.3 Analysis of the What-if scenario for failure of HLW disposal containers

Only intermediate indicators are quantified:

- molar flow rate entering and leaving structural components, along the transfer pathway in structures up to the top of the Callovo-Oxfordian;
- the molar flow rate leaving the top of the Callovo-Oxfordian, for the transfer pathway via the Callovo-Oxfordian;
- the date of peak molar flow rates leaving the structures and the Callovo-Oxfordian (at top and bottom).

[127] For instance, on the basis of preliminary calculations, for the HLW1 and HLW2 types, after 600 years the factor applied to the effective diffusion coefficient in the Callovo-Oxfordian reaches a maximum value of 2.8 over several metres around the HLW cells

5.2.4 Results of the What-if scenario for malfunction of HLW disposal containers

5.2.4.1 Effects of premature loss of disposal container integrity on source terms and hydraulic behaviour

Consideration of a cement-based medium leads to release of radionuclides within one year for the whole inventory, whether the What-if scenario is compared to the reference situation or to the bounding situation (see Figure 5.2-1).

This release can be considered as labile for all HLW packages in this scenario.

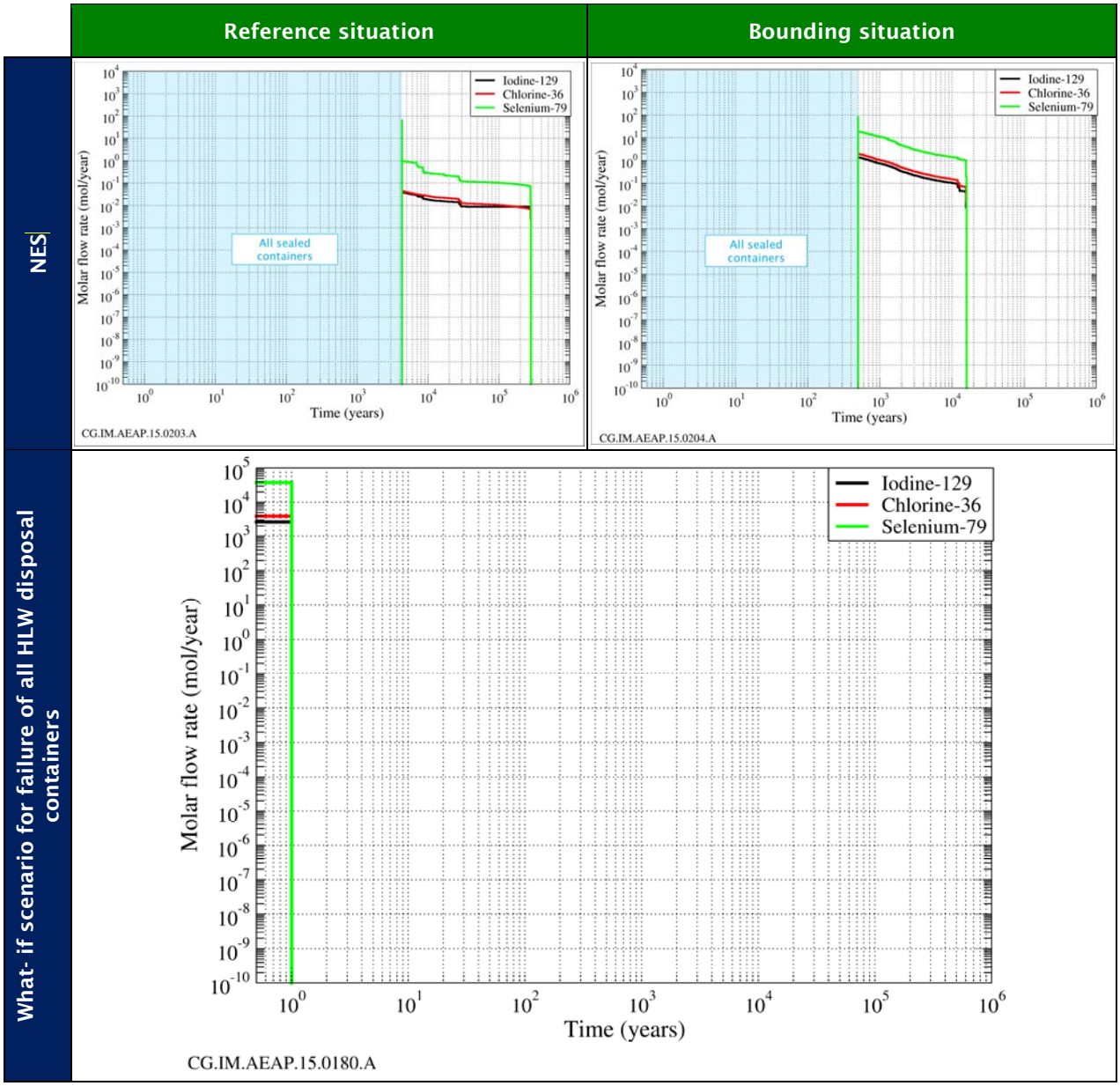


Figure 5.2-1: Reference and bounding situations of the NES and What-if scenario for failure of all HLW disposal containers – iodine-129, chlorine-36 and selenium-79 sources terms.

Under this scenario, the temporary and highly local increase in permeability due to the increased temperature does not change the hydraulic flow pattern in the structures and in the Callovo-Oxfordian.

Hydraulically, results for the what-if scenario are identical to those of the NES for both (reference and bounding) situations

5.2.4.2 Quantitative assessments of transfer

On the basis of the NES reference situation

- ***Transfer via the structures (backfilled and sealed drifts and surface-bottom connections)***

The peak molar flow rate entering the drifts is increased by a factor of approximately 10 to 100 compared with the NES and AES.

The influence of a labile source term and, to a lesser extent, heat, are masked by transfer times in drifts of several tens to several hundreds of thousands of years (see Figure 5.2-2). Consequently, the peak molar flow rates of radionuclides entering the connecting drifts are increased at most by a factor of 2 compared with those of the normal evolution scenario. Peak molar flow rates arriving in the main zone and leaving the surface-bottom connections are similar for all studied scenarios (NES, AES and What-if scenarios)

The effect of a labile source term somewhat facilitates the transfer pathway through the Callovo-Oxfordian: the amount of iodine-129 leaving this pathway is about 14% of the initial inventory compared with 11% for the normal evolution scenario, but with identical peaks occurring at the same time under all scenarios.

The consequences of the premature failure of disposal containers (labile source term and thermal transient) therefore remain negligible (Figure 5.2-2 and Table 5.2-1).

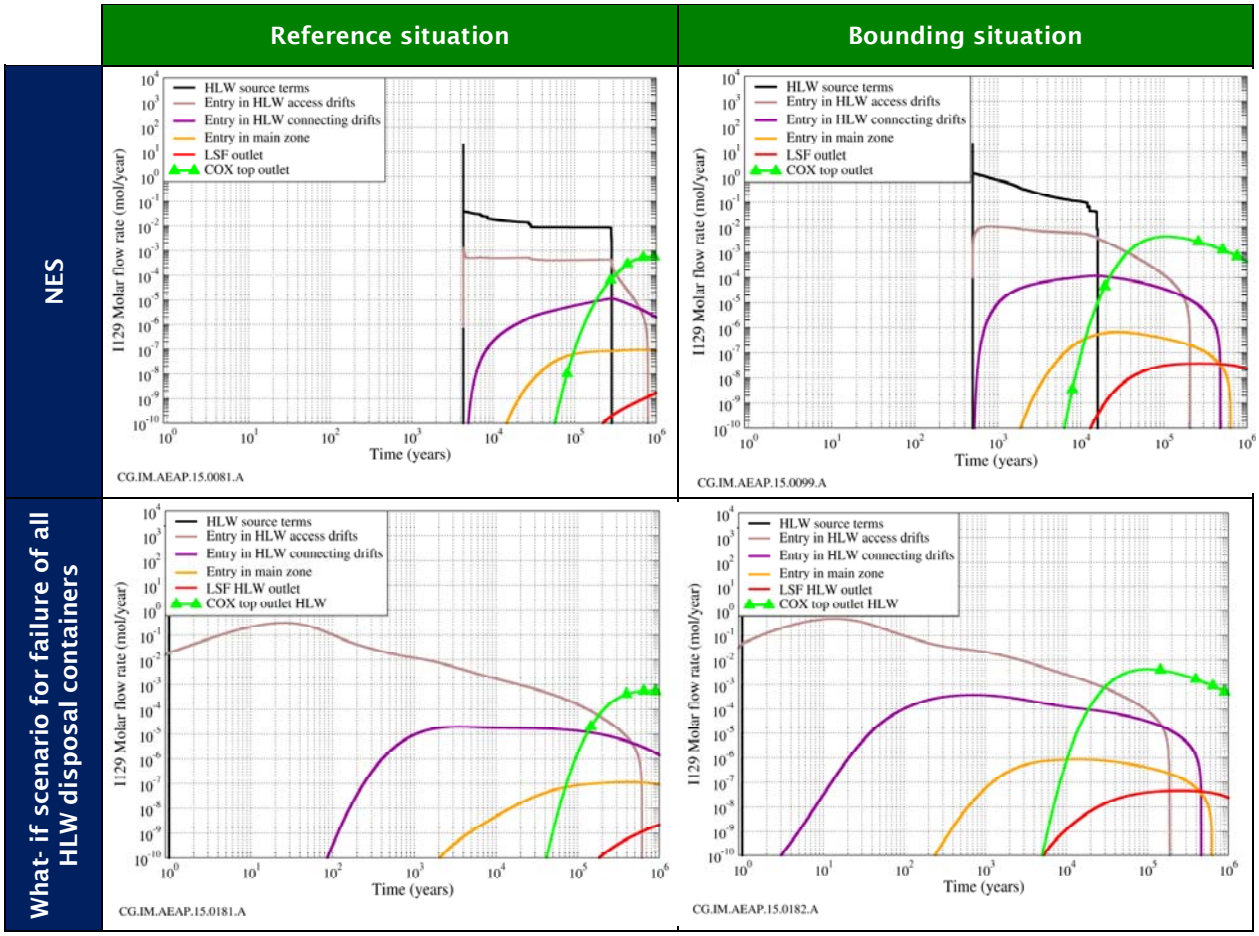


Figure 5.2-2: *What-if scenario for failure of HLW disposal containers compared with the NES: time-dependent evolution of iodine-129 molar flow rates entering drifts and the main zone, and leaving the surface-bottom connection structures.*

Table 5.2-1: *What-if scenario for failure of all HLW0 section disposal containers - reference situation: balance of the amount of iodine-129 (as a percentage of the total HLW inventory) at 1 million years entering the drifts and the main zone, and leaving via surface-bottom connection structures and the Callovo-Oxfordian*

Amount of iodine-129 at 1 million years (% of total initial inventory of each zone)					
	Entering access drifts	Entering connecting drifts	Entering the main zone	Leaving the surface-bottom connections	Leaving the top of the Callovo-Oxfordian
NES (reference)	5.0%	0.2 %	$< 10^{-2}$%	$< 10^{-4}$%	11.3 %
What-if scenario	5.1 %	0.2 %	$< 10^{-2}$%	$< 10^{-4}$%	14.2 %

The results show that the main transfer pathway remains the Callovo-Oxfordian. This is explained by the lack of hydraulic drainage in the drifts due to the efficiency of the seals and therefore dominant diffusion conditions in and around the HLW cells, and by the hundred metre length of the HLW cells.

At the scale of the disposal section, the long and limited diffusive transfer of radionuclides in the drifts enables significant mass exchange from the drifts into the Callovo-Oxfordian[128].

Outside the disposal section, additional attenuation is obtained along the main zone drifts and the surface-bottom connections. At 1 million years, only 0.00001% of the initial iodine-129 inventory (HLW) leaves the surface-bottom connections. The main contributors to the molar flow rate leaving the surface-bottom connection structures are the cells located at the edge of the HLW0 disposal section and the HLW1/HLW2 sections closest to the main zone.

The transfer time in the structures masks the effects of labile release from loss of container integrity.

Analysis of the results is identical for chlorine-36 (see Table 5.2-2 ci-below).

Table 5.2-2: *What-if scenario for failure of all HLW disposal section disposal containers – Compared with the NES reference situation: balance of the amount of chlorine-36 (as a percentage of the total HLW inventory at 1 million years entering the drifts and the main zone, and leaving via surface-bottom connection structures and the Callovo-Oxfordian*

Quantity of chlorine-36 at 1 million years (% of total initial inventory of each zone)					
	Entering access drifts	Entering connecting drifts	Entering the main zone	Leaving the surface-bottom connections	Leaving the top of the Callovo-Oxfordian
NES (reference)	3.3 %	0.08 %	$< 10^{-3}$%	$< 10^{-5}$%	5.8 %
What-if scenario	4.5 %	0.1 %	$< 10^{-3}$%	$< 10^{-5}$%	8.1 %

[128] At 1 million years, only 0.2% of the initial iodine-129 inventory has left the HLW disposal sections towards the connecting drifts, with attenuation of the peak molar flow rate by approximately 2 orders of magnitude compared with the molar flow rate leaving the cells.

- ***Transfer in the Callovo-Oxfordian***

The three main radionuclides contributing to dose are iodine-129, chlorine-36 and selenium-79.

In this What-if scenario, the entire HLW inventory is affected by failure of all HLW disposal containers, and due to a pseudo-labile source term in this case, the following observations can be made:

- for iodine-129, peak molar flow rates at the top of the Callovo-Oxfordian and occurrence dates are essentially the same as those of the NES and AES. However, the release leaving the Callovo-Oxfordian starts approximately 20,000 years earlier;
- For the What-if scenario, the peak chlorine-36 molar flow rate at the top of the Callovo-Oxfordian occurs 150,000 years earlier than for the NES and the AES, because under the What-if scenario, the duration of the source term is much shorter than its half-life;
- for selenium-79, the peak molar flow rate is identical for all studied scenarios, due to its release governed by solubility in clay rock.

Bounding situation

- ***Transfer in structures***

The results lead to the same conclusions as those given for the reference situation:

- the main transfer pathway remains the Callovo-Oxfordian. This is explained by the lack of hydraulic drainage in the drifts due to the efficiency of the seals and therefore dominant diffusion conditions in and around the HLW cells, and by the hundred metre length of the HLW cells.
- at the scale of the disposal section, the long and limited diffusive transfer of radionuclides in the drifts enables significant mass exchange from the drifts into the Callovo-Oxfordian;
- additional attenuation is obtained along the main zone drifts and the surface-bottom connections.

Table 5.2-3: What-if scenario for failure of all HLW section disposal containers - bounding situation: balance of the amount of iodine-129 (as a percentage of the total HLW inventory) at 1 million years entering the drifts and the main zone, and leaving via surface- bottom connection structures and the Callovo-Oxfordian

	Quantity of iodine-129 at 1 million years (% of total initial inventory of HLW disposal sections)				
	Entering access drifts	Entering connecting drifts	Entering the main zone	Leaving the surface-bottom connections	Leaving the top of the Callovo-Oxfordian
NES	5.8 %	0.4 %	$< 10^{-2}$%	$\sim 10^{-3}$%	61.1 %
What-if	5.8 %	0.4 %	$< 10^{-2}$%	~10^{-3}%	61.5%

- ***Transfer in the Callovo-Oxfordian***

As a result of the labile source term that concerns the entire HLW inventory due to failure of all HLW disposal containers:

- for iodine-129 and chlorine-36, peak molar flow rates at the top of the Callovo-Oxfordian and their occurrence date are essentially the same as those of the NES and EAS (see Figure 5.2-3). Release leaving the Callovo-Oxfordian starts approximately 1000 years earlier;
- for selenium-79, the peak molar flow rate is identical for all studied scenarios, due to its release governed by solubility in clay rock.

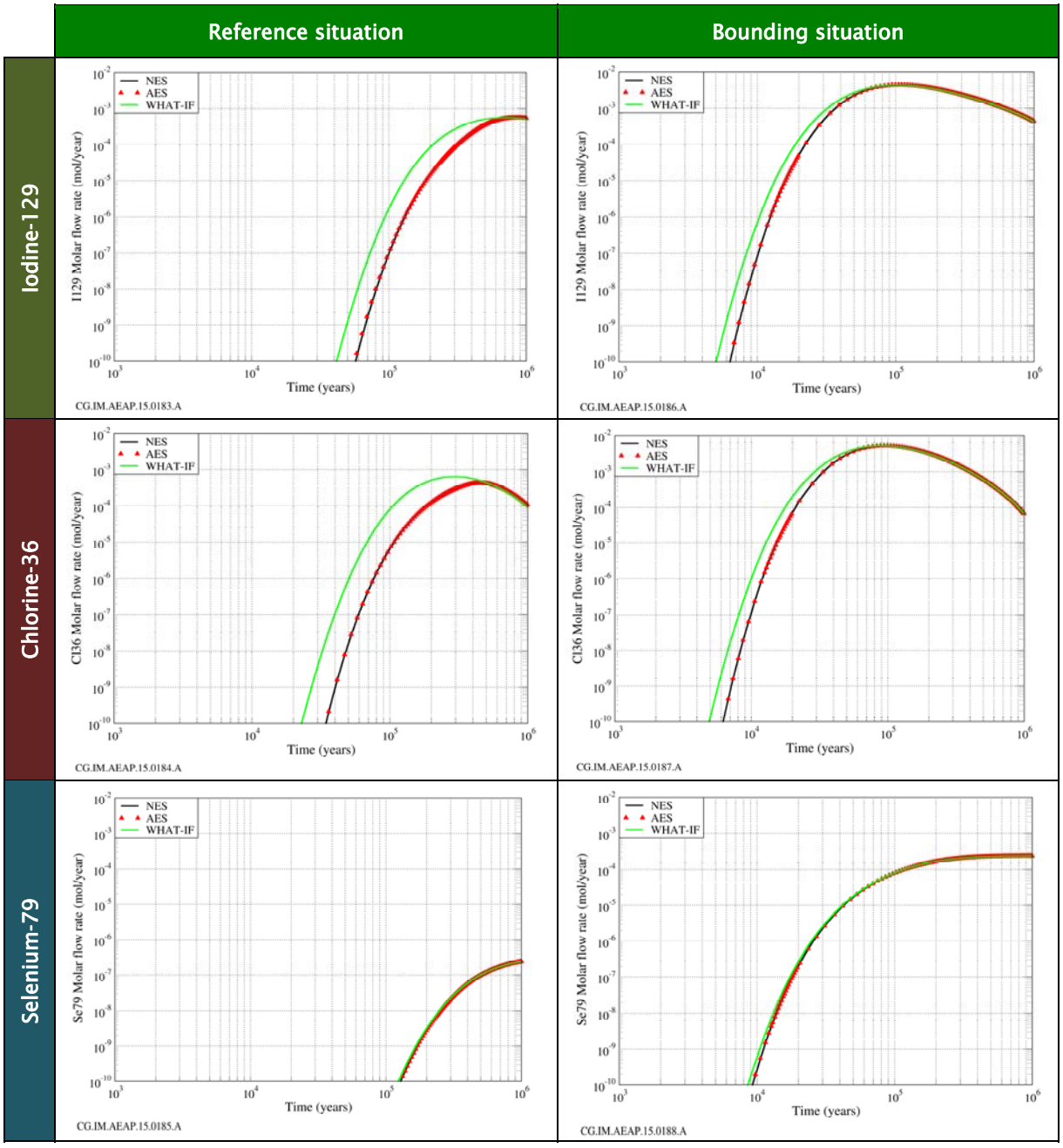


Figure 5.2-3: What-if scenario, failure of all HLW disposal containers: time-dependent evolution of iodine-129, chlorine-36 and selenium-79 at the top of the Callovo-Oxfordian.

5.2.5 Lessons

Overall analysis of the results presented above leads to several lessons, in terms of the influence of failure of HLW0 disposal containers (AES) and all HLW disposal containers (What-if scenario) on the source term and on transfer of radionuclides within the HLW disposal sections and up to the top of the Callovo-Oxfordian:

- failure of HLW0 disposal containers (AES) has no influence on transfer along structures or through the Callovo-Oxfordian, due to its low inventory in mobile radionuclides;
- transfer conditions in the repository and in the Callovo-Oxfordian are not affected by temperature, so dominant diffusion conditions remain. Hydraulically, the results are identical to the NES;
- taking into account the influence of temperature and the cement-based conditions (due to the filler material outside the sleeve) leads to use a "V0.S" model and therefore an instant (or "labile") release;
- the start of molar flow rates are 10,000 to 20,000 years earlier due to faster release of radionuclides. The low solubility of selenium-79 limits this effect for this radionuclide;
- at the scale of HLW cells, the main transfer pathway is the Callovo-Oxfordian. Over a million years, only 5% of the initial iodine-129 inventory enters the access drifts (and the mechanically damaged clay rock surrounding them). This dominance of the Callovo-Oxfordian transfer pathway is explained by the lack of hydraulic drainage in the drifts and by the hundred metre length of the HLW cells;
- molar flow rates of mobile radionuclides entering the drifts are increased compared with the NES, due to the effect of temperature and labile release. However, the transfer times in the Callovo-Oxfordian and via the structures are sufficiently long to mask this effect. No significant effect is observed at the top of the Callovo-Oxfordian;
- slow and limited diffusive transfer in the drifts enables radionuclides that migrate in these structures to diffuse into the Callovo-Oxfordian. Thus, the molar flow rates of these radionuclides are attenuated by two orders of magnitude by the time they enter the main zone and an additional attenuation of one order of magnitude is observed along the surface-bottom connections;
- the molar flow rate of iodine-129 leaving the surface-bottom connection structures remains several order of magnitude lower than that of the Callovo-Oxfordian transfer pathway. After a million years, the total amount of iodine-129 leaving the surface-bottom connection structures corresponds to about 00001% (reference situation) to 0.0001% (bounding situation) of the total initial inventory, i.e. about 5 orders of magnitude less than for the Callovo-Oxfordian transfer pathway;
- The main contributors to the molar flow rate leaving the surface-bottom connection structures are the cells located at the edge of the HLW0 disposal section and the HLW1/HLW2 sections closest to the main zone.

VOLUME IV – TEACHINGS – IMPORTANT COMPONENTS – ACTIVITIES IMPLEMENTED RIGHT FROM THE DESIGN PHASE

1

Teachings at the basic engineering design stage and forthcoming safety iterations

1.1 Components important to the post-closure robustness of the repository as of the basic engineering design stage 387

1.2 The robustness of the repository following its closure is an important element of the adaptability of the Cigeo project 392

1.3 The challenges of the forthcoming post-closure safety iteration during the detailed engineering design submitted with the construction licence application 392

1.4 Gradual integration of design changes and avenues of optimisation into the development of the Cigeo project 393

1.1 Components important to the post-closure robustness of the repository as of the basic engineering design stage

Due to its intrinsic geometric and physicochemical characteristics (more than 300 m deep, more than 130 m thick, low permeability, high retention capacity, low diffusion coefficients, etc.), the Callovo-Oxfordian formation in which Cigeo will be built is the chief component that will ensure post-closure passive safety and for a very long time after.

Added to this are the favourable geological characteristics of the future Cigeo facility, which include (a) its location in a geological environment of very low seismic activity and where the internal geodynamic evolution is limited across a millennium; (b) the absence of major discontinuities and of low vertical hydraulic gradients in the Callovo-Oxfordian formation, and the absence of rare resources.

The adopted design measures, in particular in terms of Cigeo's general architecture, leverage the favourable characteristics of the Callovo-Oxfordian formation:

- Its dead-end architecture that restricts flows within the repository by preferably utilising the low flows in the Callovo-Oxfordian formation.
- Substantially long cells that favour the transfer pathway preferred by the Callovo-Oxfordian formation.
- A plane repository that favours the large undisturbed thicknesses of the Callovo-Oxfordian formation. etc.

The adopted design measures also preserve the favourable characteristics of the Callovo-Oxfordian formation:

- Temperatures limited to 100°C maximum (margin taken at 90°C).
- Reduction of voids within the repository to limit long-term extension of the damaged area and thereby keep large undisturbed thicknesses of the Callovo-Oxfordian formation unaltered particularly around the disposal cells, etc.

Compared with the Callovo-Oxfordian formation, the direct role played by the engineered components is more limited. Nevertheless, they contribute to the robustness of the repository by limiting the release of radionuclides and toxic chemical and/or their migration out of the disposal cells, particularly along the transfer pathway formed by the structures and in situations where the Callovo-Oxfordian formation is 'short-circuited'. This is specifically the case of HLW disposal containers and HLW glass matrices (because of the high activity of the waste) and of the seals on the surface-to-bottom connections (because of their position at the repository outlet).

Although the characteristics of the components important to the safety of the repository are necessary after Cigeo's final closure[129], specific requirements , inspection and monitoring of the key parameters of these components are implemented once the site is selected (via siting criteria), during the design stage (via defined requirements and R&D studies), during the construction and operation phases, and, where appropriate, during the post-closure monitoring phase[130]. These activities are presented in Chapter 2 herein on a preliminary basis. The final activities will be included in the construction licence application.

[129] At final closure, the last shafts in Cigeo's logistics support zone will be backfilled and its shafts and ramps will be sealed and backfilled. The surface facilities will be dismantled. The 2006 Planning Act states that Cigeo's final closure may be authorised through only one act. According to the current schedule, Cigeo will probably be closed definitively around 2150.

[130] The exact objectives and duration of the post-closure monitoring phase are yet to be defined.

1.1.1 The Callovo-Oxfordian formation — the pillar of the repository's post-closure safety

More than 20 years of knowledge acquired at various characterisation scales confirm that the Callovo-Oxfordian formation is the pillar of Cigeo's safety on more than one account:

- ***The Callovo-Oxfordian formation protects waste packages from natural external hazards and everyday human activities by keeping them away from the surface.***

The survey work conducted on the geological medium — and the Callovo-Oxfordian formation in particular — both at surface level and within the underground research laboratory have made it possible determine the medium's intrinsic characteristics and verify their suitability for geological disposal of high-level and intermediate-level long-lived waste. As Dossier 2005 had established the fundamental feasibility of the repository in this zone and Dossier 2009 has specified the zone of interest for detailed reconnaissance (ZIRA), this verification was conducted throughout the transposition zone. The Callovo-Oxfordian formation in which Cigeo's underground facility will be built thus fulfils the technical site criteria in ASN's 2008 safety guide on deep geological disposal (1).

The depth of the Callovo-Oxfordian formation (and thus of Cigeo's underground facility, which is well more than 200 m deep), the lack of earthquakes in the Paris basin, and the limited and uniform internal geodynamic evolution at the future site will protect Cigeo from erosion phenomena for a millennium as well as from earthquakes and "normal" unintended human intrusion. Furthermore, the future site is located far from major geological features that may be hydraulically active and no fault throws greater than 5 m in the Callovo-Oxfordian formation have been found in the transposition zone.

- ***The intrinsic characteristics of the Callovo-Oxfordian formation — such as its permeability, thickness, and vertical hydraulic gradient — make it possible to contain the radionuclides and toxic elements into the waste packages.***

Due to its very low permeability and low hydraulic gradients, the Callovo-Oxfordian formation limits in the influx of water for the transfer pathway via the repository structures both under normal changes and in the event of failure of all or a portion of the seals or unintended human intrusion.

The low influx of water and the geometric and physicochemical characteristics of the Callovo-Oxfordian formation (large thickness, reducing water chemistry, high retention capacity, etc.) are favourable to:

- Mitigating degradation of waste packages, particularly the HLW glass matrix, and thus mitigating the release of radionuclides and toxic elements.
- Poor solubility of most radionuclides and toxic elements released by the waste packages .
- Preferred transfer of radionuclides and toxic elements released by the waste packages via the Callovo-Oxfordian formation and to slow transfer by diffusion.

Most radionuclides and toxic elements will thus remain confined to the repository and in the near field. Only soluble non-sorbed long-lived radionuclides, such as chlorine-36, migrate through the Callovo-Oxfordian formation, but in a delayed and attenuated manner.

For example, in a normal evolution scenario, out of 144 radionuclides contained in the waste packages, only iodine-129 and chlorine-36 (and selenium-79 to a lesser extent) are able to leach out of the Callovo-Oxfordian formation in very low levels and at peak flow occurrence dates far into the future (well beyond 300,000 years). The residual impact in terms of annual dose based on bounding assumptions is thus well below the 0.25 mSv/year dose constraint set by the 2008 ASN guide.

1.1.2 The architectural measures and engineered components that play an additional role

While the Callovo-Oxfordian formation is pivotal to post-closure safety, the design measures and engineered components play an additional three-pronged role:

- Leveraging the favourable characteristics of the Callovo-Oxfordian formation.
- Maintaining these favourable characteristics.
- Utilising these favourable characteristics following the release of radionuclides and toxic elements only under controlled physicochemical conditions or slowly over time (case of HLW waste packages).

1.1.2.1 General architectural measures that leverage the favourable characteristics of the Callovo-Oxfordian formation

These measures are *ultimately* intended to favour the durability of waste packages and drive the transfer pathway of radionuclides and toxic elements potentially released by the disposal packages via the Callovo-Oxfordian formation.

<u>The dead-end architecture in general and in the waste sections</u>

This measure limits the flow of water in the repository by utilising the low flows of water in the Callovo-Oxfordian formation, particularly in the event of failure of all the closure structures ("what-if" scenario).

This leads to (i) favouring low, slow degradation of the waste packages, (ii) limiting the transfer of radionuclides and toxic elements released via the repository structures to the top of the Callovo-Oxfordian formation by the surface-bottom connection structures, and (iii) favouring the (slow) transfer pathway via the Callovo-Oxfordian formation for radionuclides and toxic elements.

Thus, in the event of failure of all the seals, the radionuclides liable to reach to the top and wall of the Callovo-Oxfordian formation are few in number (iodine-129, chlorine-36, selenium-79, aluminium-26, potassium-40, calcium-41, and organic carbon-14) and are at low peak flows such that their residual dose impact levels are similar to those in the normal evolution scenario (bounding case).

<u>Overall horizontal structure of the repository and dimensions of the repository structures as limited as reasonably possible</u>

This relates in particular to HLW disposal cells measuring around 0.7 m in diameter on account of their high activity.

These measures maintain substantial thicknesses of the Callovo-Oxfordian formation between the repository and the surrounding rock formations (Oxfordian limestone and Dogger), which help to delay and limit the transfer of radionuclides and toxic elements.

<u>Grouping of the shafts and ramp bottoms in the same zone of limited footprint</u>

This measure makes it possible to limit the "hydraulic drivers" between the surface-bottom connection structures from the Oxfordian limestone, which could increase the circulation of water within the repository part of site[131].

The (very) low vertical hydraulic gradients in the Callovo-Oxfordian formation across the ZIRA, where the shafts will be located, help to limit the potential circulation of water within the repository between these structures.

In this overall context, locating all the HLW1/HLW2 sections downstream of the shafts and the bottom of the ramps in relation to the direction of flows in the Oxfordian limestone also helps to limit flows of water, and thus migration of radionuclides and toxic elements, from these sections to the shafts and ramps.

[131] Preferential flow path between the surface-bottom connection structures.

The extremely long disposal cells (several tens of metres for the HLW disposal cells and several hundreds of metres for the ILW-LL disposal cells)

This measure promotes the preferred transfer of the radionuclides and toxic elements from the disposal cells to the Callovo-Oxfordian formation.

As for radionuclides and toxic elements that nevertheless may spread from the disposal cells to the drifts, specifically in the event of failure of the seals, the lengths of the disposal sections and drifts also promote this preferred transfer to the Callovo-Oxfordian formation, thereby helping to limit flows of radionuclides and toxic elements that could rise to the surface-bottom connection structures via the repository structures.

1.1.2.2 Architectural measures and requirements maintaining the favourable characteristics of the Callovo-Oxfordian formation

Other measures for maintaining the favourable characteristics of the Callovo-Oxfordian formation have been adopted in addition to those listed above:

- Directing the disposal cells, connecting drifts, and disposal sections intended to receive seals according to the major horizontal stress. This measure limits vertical extension of damage to the clay rock along their edges and thus keeps the thicknesses of the Callovo-Oxfordian formation on either side as unaltered as possible.
- Limiting the temperatures for exothermic waste in the Callovo-Oxfordian formation and the architectural measures and requirements. These are intended to maintain the properties of the engineered components, particularly those of the waste packages.
- Arranging the HLW waste packages and ILW-LL waste packages in separate sections located several hundred of metres apart from one another, locating the ILW-LL disposal cells several tens of metres apart from one another, and placing ILW-LL waste packages that may interact with one another into separate cells. This set of measures makes it possible to limit the physicochemical interactions (thermal, hydraulic, mechanical, chemical) between different types of waste package, and thus maintain their performance. This entails, for example, centre-to-centre distance values between ILW-LL cells and identifying ILW-LL package families that are or are not suitable for co-disposal.
- Limiting temperatures in the Callovo-Oxfordian formation. The maximum transient temperatures in the Callovo-Oxfordian formation, which are related to exothermic waste (primarily HLW), are defined (100°C) to limit any mineralogical changes that could affect the favourable characteristics of the Callovo-Oxfordian formation. Furthermore, a check is subsequently made to ensure that the favourable characteristics of the Callovo-Oxfordian formation are not altered by its thermo-hydro-mechanical response.

1.1.2.3 Surface-to-bottom connection seals that block the flow of water[132] via the underground structures

Due to their specific position at the repository outlet, the seals on the surface-bottom connection structures play, along with the Callovo-Oxfordian formation, the most important role in the long-term post-closure safety of the repository. This role complies with the 2008 ASN safety guide (1), which states: "The surface-to-bottom connections and possibly some drifts and certain structures within the repository will require seals to ensure water-tightness to a specified quality level. This concern must be included from the design phase".

These seals leverage the absence of connected damaged zones in the lithostratigraphic silty-carbonated unit at the top of the Callovo-Oxfordian layer that can create zones of high permeability. The use of a swelling clay-based core of (very) low permeability in this unit in direct contact with the clay rock with the removal of liners/roof supports thus makes it possible to design seals with a low overall saturation permeability (currently approx. 10^{-11} m/s).

[132] Due to their position at the repository outlet, the seals on the surface-to-bottom connections play the most important role of all the seals by contributing to the limitation of flows of water between the underground facility and the overlying formations. The seals in the drifts increase their hydraulic resistance and help slow down the flow of water in the facility. The seals on the ILW-LL disposal cells help to ensure containment as close to the waste packages as possible.

1.1.2.4 HLW disposal packages that prevent then limit the release of radionuclides

Taking account of scientific uncertainties, technological limits, and economic factors, Andra designs HLW disposal containers that are as leaktight as possible so that the favourable characteristics of the Callovo-Oxfordian formation are utilised only after the radioactivity contained in the waste has sufficiently decayed. This also corresponds to a return to a temperature that is sufficiently low to control the behaviour of the radionuclides and toxic elements in the Callovo-Oxfordian formation and the low dissolution of the glass matrix due to the presence of water.

The HLW disposal containers are designed at the same time as the cells, which impose their environmental conditions on the containers. At this stage, Andra makes sure the leaktightness of the HLW disposal containers is maintained at least as long as the core temperature of the glass is greater than 50°C in the case of moderately-exothermic HLW0 waste delivered before 2075, and greater than 70°C in the case of highly-exothermic HLW1/HLW2 waste delivered after 2075. With the architecture selected for the underground facility, these limits correspond to a period of less than 500 years after the closure of Cigeo.

Once the disposal containers have corroded and are no longer leaktight due to their slow dissolution, the glass efficiently contains the fission products, activation products, and minor actinides embedded within it.

1.1.3 Engineered components that play a more limited role in the operations of the repository

- Bottom seals (horizontal seals)

In the event of loss of hydraulic function of the vertical or inclined seals, the horizontal seals limit the flow of water and the flow of radionuclides carried in solution along the drifts to the bottom of the surface-bottom connections.

However, these are major-failure situations that make it possible to more accurately characterise and quantify the role of these seals. For instance, this limitation of the flow of water, and thus the limitation of the flow of radionuclides (mobile) exiting via the "disposal" transfer pathway are observed specifically in bounding situations for both AES scenarios and *what-if scenarios*. In this bounding situation, the selected hydraulic performance of the Callovo-Oxfordian formation is lower than the reference situation by a factor of 25, which utilises more water within the repository. Furthermore, for these configurations and in relation to the scenario involving failure of all the seals, the role of the bottom seals is (a) to mitigate down to one order of magnitude the maximum flows of the radionuclides exiting via the "disposal" transfer pathway and (b) promote the dominance of the transfer pathway via the Callovo-Oxfordian;.

Furthermore, the scenario of intrusion (borehole) in an ILW-LL cell shows the extremely limited role of the ILW-LL cell seals. The maximum flow of radionuclides collected by the borehole is, at most, increased by a factor of three between cell seals with high hydraulic performance (low permeability) and cell seals of lower hydraulic performance (permeability increased by more than two orders of magnitude).

- Backfill

The use of backfill to fill in the entrances to the HLW disposal cells helps to locally maintain the favourable characteristics of the Callovo-Oxfordian clay rock by reducing compressible voids that may be filled during rupture of the cell entrances and the drift roof supports. They thus limit excess damage to the clay rock. They are currently made up of excavated clay rock stored in muck piles and potentially supplemented by additives.

- Concrete in ILW-LL disposal cells

The concretes in the ILW-LL disposal cells help to maintain within the cells a pH range compatible with the longevity of some types of ILW-LL waste (bituminised sludge, metal waste) and the low solubility (thus mobility in a solution) of most radioactive and toxic elements, particularly actinides. The concrete used to make the ILW-LL disposal containers provides a supplemental amount of concrete.

A table summarising the post-closure safety functions, their correspondences with the main components of the repository, and the associated characteristics are presented is Appendix 3 herein.

1.2 The robustness of the repository following its closure is an important element of the adaptability of the Cigeo project

The repository is able to adapt to changes in the radiological inventory and the delivery schedules. In the engineering design phase, the safety assessment takes account of uncertainties in knowledge of the radiological inventory of waste packages and thus suggests a "margined" inventory.

Following delivery-schedule-independent safety assessments for the ILW-LL disposal section, Andra developed a method for the redistribution of waste package families by decreasing level of linear activity starting at the section access points (in accordance with physicochemical and geometric co-disposal rules). This method of placement of the inventory thus makes it possible to free the post-closure safety assessment from the dictates of waste generators' package delivery schedules throughout the facility's operation.

Lastly, the organisation of Cigeo's architecture keeps underground spaces free for additional cells in the ILW-LL cells, in particular for the disposal of LLW-LL reserves from the PIGD, or sections within the ZIRA[133]. The application of the aforementioned key principles and design requirements to these cells (and any new sections) will ensure zero impact on post-closure safety for the selected scenarios.

1.3 The challenges of the forthcoming post-closure safety iteration during the detailed engineering design submitted with the construction licence application

The properties of the Callovo-Oxfordian formation are well known thanks to an extensive characterisation programme conducted in the boreholes and the underground research laboratory.

The aim of the forthcoming iteration will be to consolidate the teachings of the safety analysis and, more specifically, to rank the key parameters and set out the design of some engineered components.

It will integrate the design of the components at the detailed engineering design stage as well as the supplementary R&D studies, presented in Cigeo's study and testing development plan (PDD) (28) and scheduled for 2015-2017, which complement the data already obtained. This is particularly the case of the studies on the HLW disposal containers, the behaviour of the HLW and ILW-LL cells, the bottom seals, the hydraulic-gas transient, and associated simulations. The findings will be integrated into the qualitative the quantitative safety analyses and will be presented in the safety analysis report filed with Cigeo's construction licence application.

The safety iteration will therefore verify the margins used in the safety options report. In the light of the teachings of the safety assessments conducted for the safety options report, extra attention will be given to adequately defining the hydraulic performance levels required for the bottom closure structures, particularly those of the ILW-LL cells, in relation with the design studies.

[133] Zone of interest for detailed reconnaissance. This zone is compatible with potential siting of the ramp access point at the boundary between the Meuse and Haute-Marne departments. It covers a surface area of approximately 30 km^2. This zone does not prejudge the possibility of building portions of the repository elsewhere as demonstrated in Dossier 2005, which established the fundamental feasibility of the deep geological repository in the Callovo-Oxfordian formation across the transposition zone (which encompasses the ZIRA).

The phenomenological analysis of the disposal situations during Cigeo's operation[134] and after its final closure, which will in particular integrate the facility's detailed description (detailed engineering design phase), will make it possible to consolidate the findings of the basic engineering design. This phenomenological analysis will in particular take into account all the engineered components that may be left in place after during Cigeo's final closure in order to verify the low disturbance of these components on the Callovo-Oxfordian formation.

1.4 Gradual integration of design changes and avenues of optimisation into the development of the Cigeo project

Due to the gradual deployment of the Cigeo facility and the continuous increase in knowledge, the project's development will exceed the scope of the detailed engineering design and continue for several decades. This means that, in relation to a basic engineering design configuration, a portfolio of opportunities for optimisation and technical variations must be continuously taken into consideration.

At each stage of the project's development, the progress on the studies of these various optimisations and the analysis of their intersecting impacts in terms of safety and technical execution and cost challenges make it possible to define which of these variants can be integrated into a proposed construction configuration and which must continue to be studied concomitantly and by which deadline.

At the construction licence application deadline, project reference will comprise the entire set of (i) the robust, demonstrated solution for the construction phase (T1) and for the subsequent construction phases (TU) proposed at that time and proposed as constructed for the T1 phase, (ii) the design changes envisaged for the subsequent TU phases in the light of their completion deadlines, and (iii) the method and the estimated schedule for their demonstration and gradual integration into Cigeo's construction. This approach will include the necessity to implement over time the best available techniques within a process of continuous improvement of safety and technical and economic optimisation.

The main technical variants identified, at the basic engineering design stage, that may impact post-closure safety are as follows:

[134] Conditions of closure of the cells during operation in particular.

Table 1.4-1: The main optimisation opportunities and technical variants identified, at the basic engineering design stage, that may impact post-closure safety.

Optimisation opportunities and technical variants	Technical or technical and economic benefit	Post-closure safety verification planned between now or after the construction licence application
Direct disposal of ILW-LL waste packages	Reduction in the number of ILW-LL disposal cells and thus in the drift length in the ILW-LL sections Note: May facilitate construction, operation and closure of the ILW-LL section.	Impact of scenarios of unintended human intrusion in the disposal cell and failure of the closure structures
Closure structures in the ILW-LL section (backfill)	Optimise the number of seals *(performance, position, number)* Note: May make construction of the seals in the ILW-LL section easier.	Impact during an intrusion AES Impact for the selected safety scenarios, particularly failure of the seals on the surface-to-bottom connections Note: the seals on the surface-to-bottom connections are, with the Callovo-Oxfordian formation, items important to long-term safety. The closure system that will be implemented in the ILW-LL drifts and disposal cells combining backfill and seals and which will be clarified during the detailed engineering design, will provide additional margins.
ILW-LL cells of greater cross-section	Correlated reductions in the number of disposal cells and the lengths of the drifts in the ILW-LL section via the increase in the number of packages per disposal cell.	After the T1 phase, the impact of the heightened activity in the ILW-LL disposal cell and the ILW-LL section for all the selected safety scenarios.
ILW-LL drift and cell roof support: use of compressible segments	Correlated reductions of the excavated cross-section and thickness of the concrete Mechanised placement technique that may improve worksite safety Note: increase in control of the stability of the structures throughout Cigeo's operating period	Potential impact across the damaged zone during excavation work and its changes over time Potential impact of the limitation in the amount of concrete in the ILW-LL disposal cells on the containment performance of the ILW-LL waste packages and the containment of radionuclides and toxic elements released within the disposal cells Where appropriate, the potential impact for all the selected safety scenarios

Optimisation opportunities and technical variants	Technical or technical and economic benefit	Post-closure safety verification planned between now or after the construction licence application
Less conservative design of all the supports-liners based on specified constitutive equation	Correlated reduction of the excavated cross-section and thickness of the concrete	Potential impact across the damaged zone during excavation work and its changes over time. Potential impact of the limitation in the amount of concrete in the ILW-LL disposal cells on the containment performance of the ILW-LL waste packages and the containment of radionuclides and toxic elements released within the disposal cells. Where appropriate, the potential impact for all the selected safety scenarios.
Longer HLW1/HLW2 cell (150 m)	Reduction in the number of HLW1/HLW2 disposal cells and in the drifts lengths in the HLW1/HLW2 sections Note: increase in the ease of construction, operation, and closure of the HLW1/HLW2 sections	Impact of the heightened activity in the HLW1/HLW2 sections for all the selected safety scenarios Note: longer cells help even more to promote the transfer of radionuclides released by the HLW packages toward the Callovo-Oxfordian formation and, at the same time, limit their transfer to the drifts.
Thermal design of the HLW1/HLW2 sections based on changes in the criterion of argillite rupture under thermo-hydro-mechanical loading (less conservative criterion)	Decrease in the length of the drifts in the HLW1/HLW2 sections, in particular by potentially reducing the centre-to-centre distances between the disposal cells Note: see link with the increase in the length of the HLW disposal cells	Potential impact for all the selected safety scenarios due to the heightened activity in the HLW1/HLW2 sections Note: by design, compliance with the thermal (T<90°C) and THM (unchanged criterion) criteria
Placement of the vitrified ILW-LL waste packages in between the HLW1/HLW2 waste packages	Reduction in the number of ILW-LL disposal cells and thus in the drift lengths in the ILW-LL section	Impact for all the selected safety scenarios after the T1 phase: • Note: heightened activity in the applicable HLW1/HLW2 disposal cells and HLW1/HLW2 sections • ILW-LL disposal cells: reduction in the drift length in the ILW-LL section

The study of these technical variants is included in the rationale behind the progression of the detailed engineering design in order to specify, at the construction licence application deadline, which ones may be presented in the construction solution in TI and which ones will have to be studied further before being integrated in the TU.

2

Important activities for the design and closure of the repository

2.1 Inspection and monitoring activities during construction and up to the start of the industrial pilot phase 397
2.2 Activities during the industrial pilot phase and then during routine operation 398
2.3 Post-closure inspection and monitoring 403
2.4 Observation — a supplemental means of monitoring 403

The fundamental feasibility of the disposal of high-level and intermediate-level long-lived waste in the Callovo-Oxfordian geological formation in Meuse/Haute-Marne was established in 2005 both in terms of safety — and post-closure safety in particular — as well as construction, operation, and closure of the facility.

Since 2005, scientific and technological studies have been conducted in the lead-up to the licence application to build Cigeo. The repository's industrial feasibility was confirmed during the 2013 critical feasibility review, which enabled Andra to start work on the engineering design phase.

Andra used the international TRL (Technology Readiness Level) scale[135] to gauge the maturity of the advancement of the development of Cigeo's engineered components, specifically those important to post-closure safety (seals on the surface-to-bottom connection structures, HLW containers, general architecture, etc.). This scale, presented in the figure in Appendix 1, is described in ISO standard 16290:2013, which Andra has transposed into its Project Development Plan (PDD) (28).

In order to ensure that post-closure passive safeguards are protected and maintained, an appropriate level of control and monitoring is implemented at Cigeo from the start of its construction and then during its operation when required. This ensures that the components in the safety system will fulfil their post-closure safety functions when Cigeo is finally closed.

During the basic engineering design stage, Andra has established a preliminary list of the components and key characteristics at Cigeo based on the information provided in volumes II and III. This list will be confirmed in the safety analysis report that will be filed with the construction licence application.

Furthermore, in pursuance of Chapter V of the Order of 7 February 2012 (15), although Cigeo's final closure will occur in a relatively far-off future, measures will be taken during the facility's design and operation to guarantee that the post-closure safety functions to be performed by the safety-important components may be fulfilled and that any imperative corrective actions may be conducted. In particular, this means setting up studies and demonstrators sufficiently ahead of time and inspecting and monitoring the characteristics of the items during the construction and operation of the facility.

An initial list of the activities that have been or will be implemented is given in the following sections. In particular, more details on the inspection and monitoring plan will be provided in the safety case that will be filed with the licence application.

2.1 Inspection and monitoring activities during construction and up to the start of the industrial pilot phase

The initial construction phase plays a vital role in Cigeo's reference progression. The first components that will be built and commissioned for the receipt and emplacement of waste packages include the ramps, shafts and the first phase of ILW-LL disposal cells. The facility structures will also help in conducting tests (demonstrators, operation, monitoring) necessary to properly start up Cigeo and gradually take it forward to full operation during the industrial pilot phase.

[135] The conditions in which the components will fulfil their functions are particular. To ensure that the fundamental objective of post-closure passive safety is achieved, the functions of some items shall be maintained after closure of the repository and under changing conditions (absence, the presence, of water; change in redox conditions, etc.). The use of the TRL scale to assess the level of technology maturity of Cigeo and its component items takes account of this specific functional environment. The tests that will be conducted on these items in order to assess their performance will integrate these specific features. Tests and simulations will be conducted to specifically assess the robustness and durability of the items in the series of conditions that will be encountered by the packages.

The list of parameters to be inspected and monitored will be consolidated by the time the construction licence application. The first items related to the monitoring to be implemented are presented as follows at this stage.

In conjunction with the post-closure safety functions to be ensured by the Callovo-Oxfordian formation

- Condition (fracture, oxidation, saturation state, etc.) of the clay rock along on the walls of each surface-bottom connection at the interface with the Callovo-Oxfordian USC, the ILW-LL disposal cells, and the drift portions to be sealed.
- Geometry of the disposal cells.
- Geometric position of the disposal cells and drift portions to be sealed in relation to the top and wall of the Callovo-Oxfordian formation
- Geometric and physicochemical characteristics of the liners and sleeves in the seal zones, ILW-LL disposal cells, and access drifts.
- Geometric and physicochemical characteristics of the materials brought in and which will be left in place once the repository is closed.

In conjunction with the post-closure safety functions to be ensured by the seals

- Specific structures are chosen among the ramp and shaft sections in which vertical and inclined seals are to be made during final closure of the repository.
- Specific structures are chosen among the connecting drifts in which horizontal seals are to be made during final closure of the section.

2.2 Activities during the industrial pilot phase and then during routine operation

2.2.1 General process

Incremental development of the project requires confirmation of design assumptions within the actual operational environment. The industrial pilot phase[136] is part of this process and makes it possible to confirm predicted changes to the repository. It includes the implementation of demonstrators (closure structures, “test cells”, etc.) to ensure:

- Performance of the components.
- Ability to close off and seal drifts ramps.
- Ability to monitor the disposal structures.

The principles and objectives of the test programme to be conducted within Cigeo during the industrial pilot phase and in relation to post-closure safety are summarised in the Operations Master Plan (PDE) (8).

At this stage, a report on the industrial pilot phase will be published around ten years after its start.

This report will include a report on the initial test/demonstrator/monitoring findings in relation to post-closure safety.

The monitoring activities will continue during the period of routine operation. In accordance with regulations, a feedback report on the operation and monitoring of the repository will be proposed at each safety review. During the industrial pilot phase and routine operation, the monitoring programme will in particular cover parameters related to the design and behaviour of the structures during Cigeo's century-long service life. For example, the verification of the important characteristics of the Callovo-Oxfordian formation, specifically those immediately adjacent to the repository and used as input data for the post-closure safety assessment (permeability, mechanical behaviour, etc.), will be integrated into the monitoring programme conducted during the industrial pilot phase.

[136] The industrial pilot phase is a period of the Cigeo project, not a "purpose" as such. Its objective will be to conduct all the testing operations, all the operations for setting up the demonstrators (e.g. for the sealing of cells), and all the operation and monitoring operations that will be necessary to successfully commission Cigeo and take it forward to full operation.

Some of the structures built during the initial construction phase — such as the ramps, shafts and logistics support zone ("operation" and "construction" portions) — will be used throughout Cigeo's operation. They will therefore be sized to facilitate the development and construction of all the subsequent phases.

Throughout Cigeo's operating period, and specifically during periodic safety reviews, an analysis — informed by the latest available knowledge, and in particular experience feedback relating to the facility's operation and monitoring — will be performed, to ensure that the closure steps in the baseline scenario are compatible with the objectives and enable the post-closure safety functions to be maintained.

Specific studies will be conducted on some avenues of optimisation during the industrial pilot phase. In this regard, and as indicated in the Operations Master Plan (PDE) (8), Andra has already planned to build a large inactive disposal cell demonstrator in order to study the possibility of widening the diameter of the ILW-LL disposal cells. If the results of the measurements tests to be conducted on this demonstrator are satisfactory, disposal cells of this size will, provided that licensing is obtained, be built for some package families during the subsequent phases. Implementation of other avenues of optimisation, such as for extending the HLW1/HLW2 cells (construction is currently scheduled to start around 2068[137]) and direct disposal of ILW-LL packages[138] (handling and emplacement tests), may also be studied in suitable inactive demonstrators at the start of the industrial pilot phase.

Specific studies will be conducted on some avenues of optimisation during the industrial pilot phase.

2.2.2 Closure structure demonstrators

Regarding the closure structures, which are among the items important to Cigeo's post-closure safety, Andra plans to build seal demonstrators within Cigeo and specifically at that start of the industrial pilot phase. The demonstrators proposed at this stage (see Volume II herein) are:

- A ramp sealing demonstrator.
- A reference drift sealing demonstrator.
- A "hydraulic cut-off" sealing demonstrator (currently selected as a variant).

These structures will be built in a dedicated zone located at the bottom of the ramps. This zone's location may change over the course of the design studies in order to limit constraints related to construction and operation of the repository and have a greater plan area for its potential development (excluding the ramp sealing demonstrator, which, in accordance with its specifications, would be located on top of the Callovo-Oxfordian formation).

These demonstrators located within Cigeo will not be used in the repository's operation. Their role is to demonstrate, at the industrial scale, the maturity and effectiveness of the proposed technical solutions that will be implemented during the subsequent phases of development of the underground facility. The demonstration data they will provide on certain structures will make it possible to achieve the levels de technology maturity required for their licensing. This step will make it possible to prepare for the placement of the first actual drift seals by 2040, if such a choice is made. As for the shaft seals, the prospect of ultimately closing the underground research laboratory offers the possibility to build, within the URL, a representative shaft sealing demonstrator that will have been operated and observed over several decades and to monitor changes in the sealed structure over time.

[137] According to the current Operations Master Plan (PDE).
[138] Disposal of ILW-LL waste packages received from a waste generator without first being placed in a disposal container.

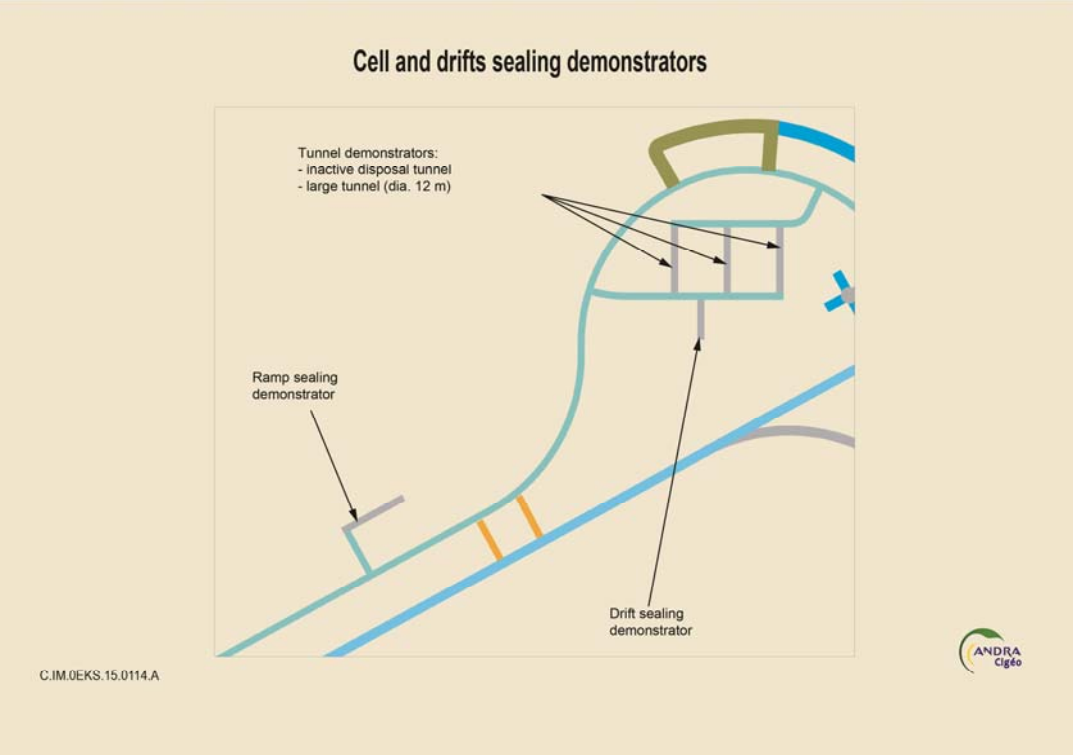


Figure 2.2-1 : *Diagram showing the locations of the demonstrators at the basic engineering design phase (HLW cell and hydraulic cut-off demonstrators not shown). The location of the zone within the underground facility may change with design studies.*

Specific monitoring measures may be implemented in some portions of the underground facility (HLW and ILW-LL disposal cells, ramp and shaft sections, drift sections or intersections). Their roles and the functions of the specific measurements that they house will be defined in the construction licence application file.

As for the seals, there also are plans to build drift observation sections that will be representative of the various types of section to be sealed. These drift observation sections will themselves not *ultimately* be sealed. These observation sections would be located near main level's air inlet and air return, respectively, in order to cover the entire range of the thermal and moisture loads in the sections to be sealed. They will make it possible to closely monitor the near-field clay rock (deformations, fractures, desaturation, etc.) without having to worry about the instrumentation's compatibility with the subsequent sealing requirements.

2.2.3 Reference disposal cells

All the disposal cells will in principle be equipped with monitoring devices. These cells, referred to as "reference cells", will be fitted with specific monitoring devices that will provide data in addition to those provided by the monitoring devices in all the cells and valid for a set of similar cells not equipped with such devices. Two of the first ILW-LL cells built during the industrial pilot phase will be reference cells. In addition, a so-called "inactive" ILW-LL cell containing only dummy packages and representative of the first cells filled with packages, will be built during the industrial pilot phase specifically to monitor changes in loads exerted on the liner-roof support, the mechanical behaviour of the liner-roof support, the mechanical behaviour of the near-field clay rock, and their potential damage throughout the operation of the ILW-LL section.

In addition to monitoring of the building of the structures, which will provide an initial picture, monitoring implemented during the construction phase will be continued through each phase of the Cigeo project.

More particularly, the inactive reference ILW-LL disposal cell will make it possible to indirectly monitor the preservation of undisturbed clay rock during Cigeo's operation. The retention of the undisturbed host rock zones will be indirectly monitored in the ILW-LL disposal cells by verifying the compliance of the initial void fraction in the disposal chamber. This verification involves inspecting initial geometry of the disposal chamber and the position of the packages during emplacement. This verification will also use data on the monitoring of the clearances within the reference ILW-LL disposal cells.

2.2.4 Inspection and monitoring of the architecture

The monitoring programme will relate in particular to the key parameters of the architecture's design that will be defined at the forthcoming stage corresponding to the detailed engineering design phase of the project.

Some portions of the underground facility (HLW and ILW-LL disposal cells, ramp and shaft sections, gallery sections or intersections) selected for their representativeness of a set of structures or for their specific position (e.g. at the location of a future seal) will be the subject of specific monitoring measures. Their roles and the functions of the specific measurements that they house will be defined in the construction licence application file.

In addition, Andra will conduct an observation programme as part of the project's incremental development. This programme will not be regulatory in nature. It will be conducted to continuously improve knowledge about Cigeo and particularly to optimise the facility.

2.2.5 Inspection and monitoring of packages

Requirements of a qualitative, quantitative or declarative nature are contained within the package acceptance specifications referred to in article L.542-12 of the French Environmental Code.

The requirements are specified for the primary waste packages and result from the consideration of the safety of Cigeo during its operation and after closure, as well as the operational, safety, health and environmental protection requirements. They form part of Cigeo's operating reference document.

Andra and the generators have already begin joint discussions to define the package quality control strategy which will be adopted at the end of the detailed engineering design stage, as well as the technical and organisational measures which will be taken to apply this strategy. This joint elaboration should ensure that the rules so defined are objective and shared.

Due to the importance of the HLW disposal containers, inspections will be conducted within Cigeo during the containerisation of the HLW primary packages and during and after welding of the lids onto the container bodies to ensure compliance with the defined requirements. The selected fabrication process will be based on procurement and construction procedures as well as codified and standardised inspections. Tests will be conducted in the factory as well as in Cigeo to minimise the risk of fabrication defects and detect potential deviations. The following inspections will be conducted on all welded parts to ensure their conformity.

Proven methods of inspecting the various operations in the fabrication of HLW packages — such as visual inspection, dimensional inspection, ultrasonic examination and eddy current testing — are available.

2.2.6 Preliminary report

The following table lists the operational monitoring requirements specific to post-closure safety in conjunction with post-closure safety functions and identified at this stage.

This list of parameters may change depending on the studies currently being conducted for the purposes of the construction licence application.

Table 2.2-1 Preliminary list of the estimated monitoring requirements for to post-closure safety

Post-closure safety functions	Underground facility component examined	Potential monitoring requirements over time
Block the circulation of water	Sections of surface-to-bottom connections in surrounding rock formations intended to be sealed	Hydraulic head fields in porous horizons of Oxfordian limestone and in the Barrois layers
	Sections of surface-to-bottom connections in the Callovo-Oxfordian formation intended to be sealed	Characteristics of the near-field clay rock, in particular the damaged clay rock (permeability, porosity, fracture, spatial extension, deformation, desaturation) Forces exerted on the liner-roof support and deformations of the liner-roof support
	Drift sections intended to be sealed	
	Ramp and drift seal demonstrators	Characteristics of the near-field clay rock, in particular the damaged clay rock (permeability, porosity, fracture, spatial extension, deformation, desaturation) before, during, and after removal of the liner Concrete setting, fractures, stresses, and deformations of the concrete mechanical containment walls Resaturation of the core and clay (water content, interstitial pressure, stresses, deformations) Stresses and/or deformations between the clay core, the near-field clay rock, and the concrete mechanical containment walls Stresses and deformations in the clay core Flow of water (flow rate) in the seals and at the interfaces
Restrict the release of radionuclides and toxic elements and immobilise them in the repository	ILW-LL disposal cell	Environmental conditions within the cell: temperature, humidity, and the presence of liquid water Deformations, movements, and the physicochemical state of the packages Disposal cell deformations
	HLW disposal cell and HLW disposal waste packages	Environmental conditions within the cell: temperature, humidity, presence of liquid water, presence of O2 and of H2 Chemical composition of the liquid water collected at the disposal cell head Water ingress of traces of humidity at the drift around the HLW disposal cell, particularly at the interface between the disposal cell and the clay rock Deformations of the sleeves and waste packages State of corrosion of the containers, in particular the presence of zone of localised corrosion
Delay and mitigate the migration of radioactive substances and toxic elements	Underground facility, Callovo-Oxfordian formation	Characteristics of the near-field clay rock, in particular the damaged clay rock (permeability, porosity, fracture, spatial extension, deformation, desaturation) Presence of radionuclides and toxic elements from the waste in the Oxfordian limestone layer Hydraulic head fields in the Oxfordian limestone layer (porous horizons)
Protect the favourable	ILW-LL drifts and disposal cells	Characteristics of the near-field clay rock, in particular the damaged clay rock (permeability, porosity, fracture, spatial extension,

Post-closure safety functions	Underground facility component examined	Potential monitoring requirements over time
characteristics of the clay rock	HLW disposal cells	deformation, desaturation, oxidation, temperatures, interstitial pressures and total stresses)
	Geological medium	Hydraulic head fields in the Oxfordian limestone layer and around the surface-bottom connection structures and at the repository Temperature in the Oxfordian limestone, particularly opposite the exothermic waste sections Interstitial pressure fields in the Callovo-Oxfordian formation near the surface-bottom connection structures and the underground facility structures Temperature fields in the Callovo-Oxfordian formation near the HLW section structures

2.3 Post-closure inspection and monitoring

Any monitoring devices left in use after the closure of the facility will be limited and should not disturb the disposal facility or the Callovo-Oxfordian formation in order to ensure passive safety

At this stage, Andra plans to primarily use non-intrusive surface-based techniques (geophysics, etc.) for the underground facility. Measurements within the disposal structures may be transmitted wirelessly through the soil from the bottom to the surface. The monitoring of hydraulic loads in the Oxfordian limestone may make it possible to indirectly verify the proper operation of the seals on the surface-bottom connection structures.

Post-closure monitoring devices will be set up during the operational phase to allow cross-checking with data obtained by the operational phase monitoring devices.

2.4 Observation — a supplemental means of monitoring

Andra will conduct an observation programme as part of the project's incremental development. This programme will not be regulatory in nature. It will be conducted to continuously improve scientific and technological knowledge particularly to optimise Cigeo.

Observation consists in investigating facts and processes in order to better understand them, particularly by identifying their origin. It forms part of a continuous improvement process ("responsible operator" process complying with Art. 2.7.2 of the Order of 7 February 2012 on basic nuclear installations.

These in-situ observations will supplement the data already obtained from the design and R&D studies conducted before and during the repository's construction. Their purpose is to:

- Inform decision-making during the development of the underground facility and its stepwise closure.
- Monitor phenomenological processes in order to confirm their initial stages of change and increase confidence in the knowledge applied to assess the long-term safety.
- Better gauge design margins in order to optimise the design of future phases.

APPENDICES

APPENDICES TO VOLUME I

Appendix 1 : Memory management

The safety guidelines for disposal in a deep geological formation published by the French Nuclear Safety Authority (ASN) (1) state that:

"The post-closure safety of the disposal facility should be guaranteed passively in order to protect humans and the environment, and should not depend on institutional monitoring or control, as there is no certainty that this can be maintained for more than a limited period";

"The memory of the disposal facility's existence depends on the durability of the measures taken during archiving and on the institutional documents produced to comply with regulations; on these conditions, it would be reasonable to expect that the memory of the disposal facility's existence would not be lost for at least 500 years".

In the long-term, once the underground disposal facilities are closed, their safety relies on the rock's capacity to contain the radioelements passively over a very long period of time, in all situations that can be envisaged.

Preserving the memory post-closure would delay the occurrence of any human intrusion as a result of the existence of the disposal facility being forgotten. The chosen memory management principle is based on two requirements:

- research into technical solutions to preserve the memory for as long as possible and for at least 500 years after closure;
- account being taken in the safety assessment of the possibility of the memory being lost after 500 years, in compliance with the safety guidelines (1), and unintentional human intrusion occurring as a result after that.

Through its experience with surface facilities, particularly its CSM waste disposal facility, Andra has developed a memory-keeping system that should be robust enough to last for at least six centuries. This is referred to as the "reference solution".

▪ ***Presentation of the reference solution***

The problem of preserving a memory of disposal facilities was first considered in the 1980s in relation to the CSM waste disposal facility. To address the problem, a permanent paper archiving solution was defined in 1995. In 1996 the Turpin Commission approved the methods chosen by Andra and recommended some further developments. Andra's reference solution for keeping a long-term memory of its disposal facilities, which stems from these early ideas, currently consists of:

- ·three "passive memory" techniques:
  - ✓ a detailed record consisting of all the technical documentation necessary for monitoring, understanding and modifying a waste disposal facility. This detailed record is compiled by selecting and creating a hierarchy of information on the basis of possible evolution scenarios identified in accordance with the long-term approach to safety. A set of research tools (inventories, glossary, index, abstracts) is provided to ensure accessibility and ease of understanding. The durability of the documents relies on the appropriate selection of ink and archival paper, and two copies are kept at separate sites, the disposal facility site and the National Archives. Lastly, the detailed record is kept valid and up-to-date through the addition of further documents every 5 years until the end of the monitoring phase;
  - ✓ the précis is a single document providing a summary of the technical and historical information, intended for decision-makers and the public. Updates are produced after each revision of the safety analysis reports. The final version's informative power will depend on it

being distributed widely, to town halls, notaries, associations, the local district council, the prefecture, ministries, national and international institutions, etc.;
  - ✓ an entry in the register of public service easements provides administrative signposting of the site, warning of the potential risk of doing work on the site;
- two "active memory" techniques:
  - ✓ the development of communication with the public through the organisation of open days, talks, exhibitions and interviews, and also through the distribution of memory-specific communication tools, brochures and the website;
  - ✓ a strengthened role for the local information commissions (CLI), the discussion topics of which include memory, and which should keep the memory alive locally.

Analysis of this system, particularly in view of experience of the durability of other historical memory-keeping systems, leads to the conclusion that there is a good level of confidence in its ability to last for several centuries.

To improve the system's robustness as regards the needs of future generations, which are difficult to conceive of in the long term, Andra has the system appraised every ten years by French and international experts, so that its ability to meet the needs of these future generations can be constantly re-evaluated.

In terms of its implementation, all documents in the reference solution are printed on archival paper, the specification for which is defined by two international standards (ISO 9706 as regards permanence and ISO 11108 as regards durability). The specific characteristics of this paper (slightly alkaline, low lignin content, high tear strength) make it more durable than ordinary paper. Studies commissioned by Andra between 2007 and 2009 showed that, with natural ageing, it should last between six and ten centuries, including the inks used. This covers the regulatory period defined at present for all current and future disposal facilities.

- ***Andra's memory programme***

However, the reference solution cannot be considered the best available solution without more detailed examination. Furthermore, it has certain weaknesses: it is very focused on document conservation and does not give sufficient consideration to other media. Its suitability to meet the potential needs of future generations has not been sufficiently reviewed (only one ten-yearly assessment had been carried out by the end of 2015). Lastly, guaranteeing preservation of the memory for "only" a few centuries after the closure of the disposal facility is thought to be too short by some of the stakeholders in the facility, including its future neighbours.

Consequently, in 2010 Andra decided to launch a memory programme aiming at two results: to make the reference solution more robust and to pursue discussion and research on preserving the memory for several millennia.

The memory programme includes work aimed partly at continuing to compile and improve the memory of the facilities, and partly at carrying out scientific research in two areas: material ageing and the human and social sciences.

The following work has already begun on compiling and improving the memory of the facilities:

- the relevance of the CSM memory-keeping system to the needs of future generations is analysed every ten years by bringing together a group of international stakeholders to assess on a regular basis its suitability and completeness;
- preparation of the Cigeo memory has begun: the detailed memory of the Meuse/Haute-Marne Centre is being compiled, along with other supporting documents, ahead of the creation of Cigeo (selecting what should be preserved of the information used for deciding to create Cigeo, from everything produced since the start of the 1980s);
- the "technical" usefulness of the memory must be explained so that the benefits for long-term safety of preserving the memory are clear;

- Andra is running discussion groups near its sites to arouse interest among local communities in the issue, but also to gather their ideas on how they could appropriate it locally, with the ultimate aim that associations could be formed to preserve the heritage left behind by Andra;
- collaborations have been established with a number of French and international artists in various artistic fields, to seek their vision of the problem of preserving the memory of the disposal facilities through their art;
- Andra is involved in international work on memory as part of the NEA/RWMC/RK&M (long-term memory) and RepMet (metadata preservation) working groups: benchmarking practices in the various participating countries, establishing common definitions and a common bibliography, and developing recommendations;
- the creation of spaces dedicated to memory in Andra's visitor centres;
- investigating the possibility of setting up a historical archive and memory centre, with a delegation from Archives de France.

Scientific studies of the ageing of materials began with testing of the ink/paper combination using standardised tests. Research on the durability of other media in the longer term is currently being defined. It will look at non-paper-based media for writing and engraving, particularly studies of surface markers to be installed on the disposal facility caps and the production of sapphire discs as demonstrators for memory media that can last for up to a million years.

As regards the human and social sciences, a laboratories grouping has been formed to study the perception of very long time scales. For the other subjects (archiving, linguistics, semiology, museology, the archaeology of technologies and landscapes, etc.), a three-stage approach is being adopted: a concise bibliography is being compiled to see whether research already exists and is adequate; if not, a more detailed bibliography will be produced with the help of academics, to determine what research, if any, should be added to the research programme. The research will cover the following subjects:

- the durability:
  - ✓ of languages and symbols to determine the reasonable length of time during which current or dead languages might be known, and what communication methods could be used when these languages are no longer known;
  - ✓ of the institutional conservation of written records, sounds, images, objects, etc. by specialist French organisations but also by international bodies, to examine the preventive measures taken to limit deterioration over time and foster appropriation and transmission by future generations;
  - ✓ of long-term digital archiving, particularly by organising a watch in this emerging field, which could, within a few decades, open up new long-term horizons;
- temporality and remains:
  - ✓ archaeology of technologies and landscapes, including evolution caused by humans and by geodynamics, and the memory-keeping potential of human creations (use of the backfilling of surface-to-bottom connections as a memory tool);
  - ✓ the memory of "historic" disposal facilities not managed by Andra, in different parts of France (uranium mines, nuclear tests, etc.);

- the societal dimension of the problem:
  - ✓ public perception of very long time scales (several millennia or more), in the context of a group of human and social sciences laboratories,
  - ✓ society's potential evolutions in science, technology, humanities, etc. broken down into three major orientations (regression, stagnation and progression);
  - ✓ including preservation of the memory of waste disposal facilities in educational syllabuses on nuclear, heritage and memory;
  - ✓ intergenerational transmission of memory via Internet-based social networks to share the memory of the waste disposal facilities worldwide.

The memory programme will be run in step with the decision-making milestones of the Cigeo project. It will be extended in order to support the development of the disposal facility and its gradual closure.

Appendix 2 : Applicable General Regulations

Table 2.4-1: Regulatory texts

Topic	Text	Reference
Nuclear	Environment Code- Legislative Part, Book I: Common provisions, Title II: Public information and participation, Chapter V: Other information methods – section 1: Provisions on activities other than nuclear activities (L 125 et seq.)	(30)
Nuclear	Environment Code- Legislative Part, Book V: Prevention of pollution, risks and hazards, Title IV: Waste, Chapter II: Specific provisions on the sustainable management of radioactive materials and waste (L 542 et seq.)	(31)
Nuclear	Environment Code- Legislative Part, Book V: Prevention of pollution, risks and hazards, Title IX: Nuclear safety and basic nuclear installations – Chapter I: General provisions on nuclear safety (L 591 et seq.)	(32)
Nuclear	Environment Code- Legislative Part, Book V: Prevention of pollution, risks and hazards, Title IX: Nuclear safety and basic nuclear installations – Chapter III: Basic nuclear installations (L 593 et seq.)	(33)
Nuclear	Decree No 2007-1557 on basic nuclear installations and controlling the carriage of radioactive substances as regards nuclear safety	(34)
Nuclear	Order of 7 February 2012 laying down the general rules on basic nuclear installations	(15)
Protection against ionising radiation	Order of 1 September 2003 defining the methods for calculating effective doses and equivalent doses resulting from human exposure to ionising radiation	(35)
Environmental impact	Order of 9 August 2013 approving Nuclear Safety Authority Decision No 2013-DC-0360 on controlling hazards and the health and environmental impact of basic nuclear installations	(36)

Appendix 3 : International standards and texts

Table 2.4-2: International standards

Source	Publication date	Reference	Title
WENRA[139]	2014	(37)	Radioactive waste disposal facilities Safety reference levels
IAEA	2006	(38)	SF-1: Fundamental Safety Principles
	2011	(39)	SSR-5: Disposal of Radioactive Waste
	2006	(40)	GS-R-3 The management system for Facilities and Activities

Table 2.4-3: International best practices

Source	Publication date	Reference	Title
NEA	2012		Methods for Safety Assessment of Geological Disposal Facilities for Radioactive Waste ISBN: 978-92-64-99190-3
	2009		Considering Timescales in the Post-closure Safety of Geological Disposal of Radioactive Waste ISBN: 978-92-64-06058-6
	2009		International Experiences in Safety Cases for Geological Repositories (INTESC). Outcomes of the INTESC ISBN: 978-92-64-99103-3
	2004		ISBN: 92-64-02075-6
IAEA	2009		GSR Part 4 Safety Assessment for Facilities and Activities
	2009		GSG-1 Classification of radioactive waste
	2014	(41)	SSG-31 Monitoring and Surveillance of Radioactive Waste Disposal Facilities
	2012	(42)	SSG-23 The Safety Case and Safety Assessment for the Disposal of Radioactive Waste
	2011	(43)	SSG-14 Geological Disposal Facilities for Radioactive Waste
	2008	(44)	GS-G-3.4 The Management System for the Disposal of Radioactive

[139] Western European Nuclear Regulators Association

Source	Publication date	Reference	Title
	1996	(45)	INSAG-10: Defence in Depth in Nuclear Safety

Table 2.4-4: List of ICRP publications

Source	Publication date	Reference	Title
ICRP	2013	(46)	ICRP Publication 122 – Radiological Protection in Geological Disposal of Long-lived Solid Radioactive Waste
	2007	(47)	ICRP Publication 103 – The 2007 Recommendations of the International Commission on Radiological Protection
	2007	(48)	ICRP Publication 101 – Assessing Dose of the Representative Person for the Purpose of Radiation Protection of the Public and the Optimization of Radiological Protection

Appendix 4 : Modelling tools

1. The "package/cell"-scale compartment: this consists of all the constituent components of the HLW cell or ILW-LL cell (containers, overpacks, functional clearances, concrete liner/roof support) and the near-field environment of the cells: discrete and connected fracture zones, thermally (HLW) and chemically (ILW-LL) disturbed zones, and the complete thickness of undisturbed Callovo-Oxfordian.

This cell-scale modelling can be used to quantify the molar flow rates of solutes (i) entering and remaining in the Callovo-Oxfordian, and (ii) entering and remaining in the access drift for the HLW cell and in the connecting and air return drifts for the ILW-LL cell (Figure 2.4-1).

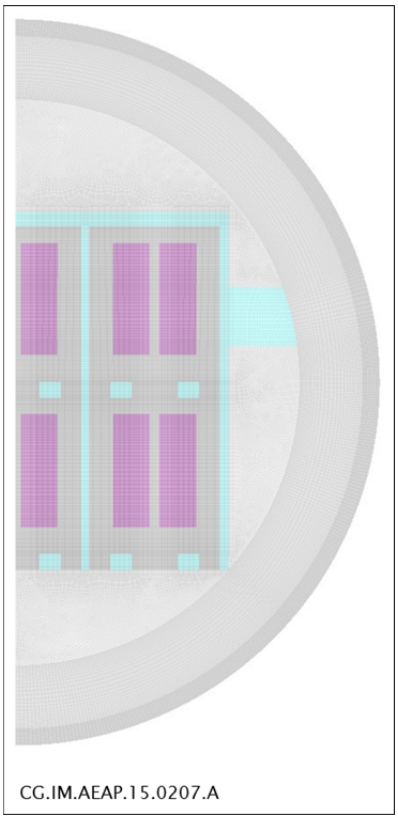


Figure 2.4-1: "Package/cell"-scale compartment: representation of an ILW-LL half-cell including the disposal packages and primary packages

2. The "disposal facility"-scale compartment: this includes the different disposal sections with all the cells, the system of drifts and their closure structures, the system of surface-to-bottom connecting structures and their closure structures, the different (disturbed) Callovo-Oxfordian zones and the complete thickness of Callovo-Oxfordian. Each cell is represented in a simplified way so that the amount of water drained from the geological medium can be taken into account and the kinetics of the solute convection in the engineered components can be reproduced as accurately as possible. The molar flow rates entering the drifts, obtained using the "package-cell"-scale model, are applied directly to the corresponding drifts as volumetric source terms in the "disposal " compartment.

   Quantifications for the two transfer pathways, namely (i) the geological medium transfer pathway and (ii) the disposal facility structure transfer pathway, are also performed at this scale.

3. The "geographical medium"-scale compartment: the model includes the repository zone, the Callovo-Oxfordian and its surrounding rock formations (above and below) as far as the outlets (Figure 2.4-2). The geometry of each disposal section is treated, on a macroscopic level, as a parallelepiped-shaped disposal box enveloping the cells it contains. The molar flow rates out of the surface-to-bottom connecting structures (on top of the Callovo-Oxfordian) determined at "disposal facility"-scale are applied direct to the same place in the multilayer geological medium in the form of a volumetric source term.

At this scale, the molar flow rates of solutes leaving the different outlets are identified, with the aim of subsequently quantifying the radiological impact (biosphere model).

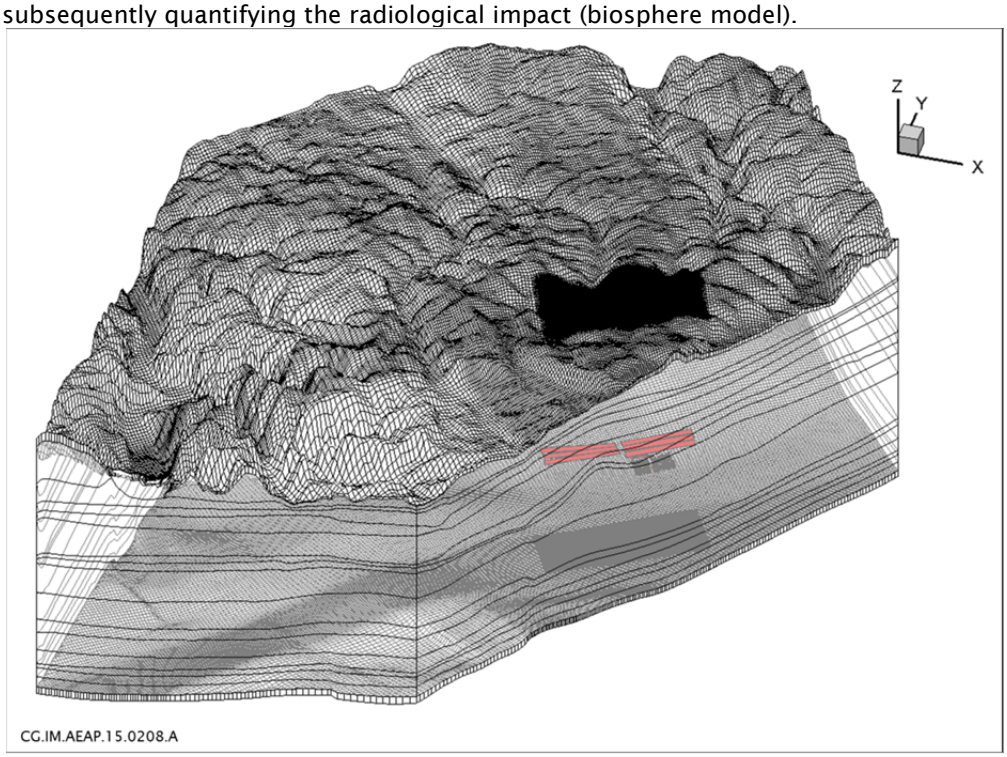


Figure 2.4-2: "Geological medium"-scale compartment representing the multilayer geological medium and the Cigeo geological disposal facility

Appendix 5 : The "biosphere" approach taken by Andra

As shown in Figure 5.7.2 of Volume I, the "biosphere" approach is broken down into the following stages:

- ***Definition of the assessment framework***

This consists of defining the basic elements of the assessments to be conducted, which can influence the choices to be made as regards the biosphere: the time scales of each phase in the disposal facility's life, the applicable standards, the site, the objectives of the assessment, and the safety and impact indicators chosen.

- ***Selection of standard biosphere(s)***

This process leads to the identification, using conventional methods, of:

- the operation and monitoring phases (short-term, i.e. a few hundred years), for which a temperate biosphere that can be considered constant for the period in question can be used;
- the post-closure phase, for which the time scales are longer (between several hundred years and a millennium). Over time periods of this length, one or more standard biosphere(s) have to be chosen on the basis of modelling results taking account of overall climate changes and their impact on the surface environment.

Once the list of plausible standard biospheres has been drawn up, the possible standard biospheres for the durations and future dates in question are chosen for the assessment, in view of their relevance to the assessment framework and particularly to the safety scenario being considered. The standard biospheres likely to exist during the period covered by the assessment need to be considered individually, regardless of their sequence over time.

These biospheres are treated as having an equal probability of occurrence. The approach leads to the definition of a conceptual model for each of the standard biospheres selected.

Once the standard biospheres to be used for the assessment have been chosen, phenomenological descriptions of the biospheres are produced. From these, the components of the standard biosphere (climate, vegetation, fauna, soil, geomorphology, geology, hydrology and hydrogeology, and human activity) are described so that the all likely characteristics of each of these components can be tracked and the potential exposure pathways of individuals can be taken into account.

- **Identification and justification of the compartments of the conceptual model**, i.e. description of the reference biosphere for each standard biosphere to be used for the assessments. This stage leads to the selection of all the components to be introduced into the model, taking account of the assessment framework.

  This involves:

  - ✓ **Selection of outlets**. This process results in:
    - the selection of the outlet(s) and their locations on the basis of hydrogeological and radionuclide transport models where the installation site or region is known and data are available. The outlet(s) supplying the current or hypothetical reference group(s) are then chosen from among the outlets identified in the present or predicted for the future on the basis of the models;
    - the selection using conventional methods, where appropriate, of one or more outlet(s), the location of which depends on the situations to be considered and the activities of these current or hypothetical reference group(s).

- ✓ **Selection of hypothetical reference groups**. The procedure for this is based on a pre-selection strategy that consists of:
  - pre-selecting several potential exposed groups whose behaviour is representative of the biosphere's habits and resources in the region or site, where this is defined (e.g. groups of fishermen, farmers, villagers), as an indicator of maximum potential exposure;
    - then describing an individual representative of each of these pre-selected groups in terms of age group, exposure pathways and food consumption behaviour, distinguishing between:
      - a group or individual potentially subject to a particular exposure pathway because of their specific activity. Higher consumption of a product of their activity leads a particular diet being adopted. However, the approach does not consider extreme behaviour defined for unrealistic behaviours (high consumption of more than 3 food types according to the BIOMASS method);
      - a group or individual potentially subject to all the exposure pathways due to multiple activities (vegetable plot, poultry yard, livestock holding, etc.). These activities lead to the ingestion exposure pathway through the consumption of home-produced animal and vegetable products, and to the inhalation and external exposure pathways due to their outdoor activities. In this case, Andra will look at average behaviour.

For the post-closure phase (from a few hundred years to a millennium), the hypothetical reference group(s) is/are defined on the basis of observation of biospheres representative of the chosen standard biospheres.

- ***Selection of other biosphere components*** *(atmosphere, soil, animals and plants).* The approach taken to selecting these components distinguishes between the different phases in the life of the current or future facility, i.e.:
  - ✓ the operation and monitoring phase (a few hundred years), using the characteristics of the biosphere components that represent the transfer pathways observed at present in the region concerned, taking account of the outlet location and potential exposure associated with human activity;
  - ✓ the post-closure phase (from a few hundred years to a millennium), for which components are chosen that allow exploration of all the transfer pathways in the region "representative" of the standard biosphere being considered by the assessment, and its potential taking account of the location of the outlet and the potential exposure associated with human activity.
- ***Modelling of transfers of radionuclides or toxic elements to humans***

This procedure consists of describing the transfer pathways associated with a "defined" outlet, i.e. an outlet located and characterised using the approach defined earlier. It means that the consequences associated with each of the potential outlets are studied separately, particularly in view of the specific activities of the reference group (in the short term) or the hypothetical group(s) (in the long term). This approach allows the exploration, for example, of specific transfer pathways to humans from potentially contaminated water.

If the possibility emerges of a current or hypothetical reference group using several types of outlet simultaneously, the approach will involve:

- ✓ examining the likelihood of a scenario involving different outlet types simultaneously and, where appropriate, specifying the choices that might conventionally be made;
- ✓ maintaining a certain amount of realism as regards the characteristics (Time/Space/Usage/Flow rates) of the outlets and the activities of the current or hypothetical reference groups, particularly by taking into account the results of the hydrogeological modelling, the modelling of radionuclide transfer, and changes in the concentration over time.

- ***Building of computer models based on the quantifications***

  This includes choosing the models, some of which may be specific to certain radionuclides. In terms of modelling transfers in the biosphere, Andra uses:

  - ✓ for all radionuclides except chlorine-36, tritium and carbon-14, a compartmental model using transfer factors between compartments in equilibrium;
  - ✓ for chlorine-36, tritium and carbon-14, a special transfer model based on isotope dilution.

APPENDICES TO VOLUME II

Appendix 1 : List of the ILW-LL waste families

Saline waste with bitumen matrix (bituminised sludge)

Bituminised waste from La Hague (COG-020, COG-420)

The COG-020 family is treated sludge conditioned by embedding it in bitumen, at La Hague effluent treatment station 3 (STE3).

The COG-420 family corresponds to the bituminised fraction of the sludge from effluent treatment at STE2 stored in silo 550-14 at La Hague.

Bituminous waste from Marcoule produced before 1995 (CEA-1020, CEA-1021)

These families contain all the packages of bituminised sludge produced at the liquid effluent treatment station at Marcoule between 1966 and the introduction of "product quality monitoring" in 1995. These packages are conditioned in non-alloy steel drums. A number of packages have already undergone recovery operations consisting in placing them in EIP overpack drums: these new packages are stored at the EIP.

Bituminous waste from Marcoule produced after 1995 (CEA-1000, CEA-1010)

These families contain all the packages of bituminised sludge produced since the introduction of "product quality monitoring" in 1995. Some of these packages are conditioned in non-alloy steel drums (CEA-1010), and the rest (since 1996) in stainless steel drums (CEA-1000).

Non-bituminised saline waste (non-bituminised sludge)

Dried STE2 sludge, compacted and immobilised in a metal container, from La Hague (COG-430)

"STE2" sludge is the precipitates immobilising the activity contained in low-level and intermediate-level secondary effluents from the La Hague plant. It is mainly from the operation of the UP2-400 plant between 1966 and 1997 and is stored in 7 silos numbered 550-10 to 550-15 and 550-17 at the former effluent treatment station (STE2). The process currently used to condition this waste is drying prior to compacting the sludge in the form of pellets, which will then be conditioned in stainless steel drums.

Compacted metal waste

Compacted waste from the HAO silo at La Hague (COG-070)

The COG-070 family contains the packages from the compacting of waste stored in the silo of the HAO (High Activity Oxide) unit.

Standard packages of compacted waste from La Hague (COG-100, COG-110)

In the Areva NC plant at La Hague, compacting is the process currently used for conditioning the structural waste from fuel assemblies and some metal technological waste. This is done in the hull compacting facility (ACC). The CSD-C canisters that can be considered for disposal at Cigeo from 2025 by the industrial waste management programme (PIGD) are:

- in the case of the COG-100 family, those currently being produced in accordance with the specification 300 AQ 055 that come from the reprocessing of UOX fuels;
- in the case of the COG-110, those expected to be produced from 2014 that come from the reprocessing of UOX fuels and that include the current and new types of cladding.

Compacted metal structural waste from La Hague (COG-120, COG-450, COG-530, COG-540, COG-550)

These packages come from the compacting of structural waste produced as a result of the future reprocessing of mixed UOX, ERU and MOX fuels (COG-120), fuels from the Phenix and Superphenix fast neutron reactors (COG-450), fuels from the CEA (COG-530 for CEA/Civil and COG-540 for CEA/DAM) and those from the EL4 reactor at Brennilis (COG-550).

Metal waste with cement matrix

Packages of cemented hulls and nozzles from La Hague (CEC, COG-040)

During the 1990-1995 period, structural waste was cemented into stainless steel drums in compliance with the specification 300 AQ 25; this practice was replaced from 2002 by the compacting described above.

Cemented metal structural waste from Marcoule (CEA-1050)

This family contains the metal structural waste from fuels, apart from those from the GCR reactors (Phenix fuels, OSIRIS fuels, etc.), reprocessed at the UP1 plant (Marcoule); they are made from different materials: aluminium, stainless steel, nickel alloy, zirconium-tin alloy, etc. depending on the type of fuel. This waste will be recovered as it is, placed in 380-litre drums, then immobilised by a cement matrix.

Magnesium structural waste from Marcoule (CEA-1060)

Magnesium structural waste consists of the cladding and plugs (or tips) of GCR reactor fuels reprocessed at the Marcoule site. It contains magnesium but also aluminium. This waste should be recovered, conditioned, then immobilised in 223-litre stainless steel drums according to the hypothesis currently applied by the CEA. The material to be used for the immobilisation of this waste is currently being defined.

Activated waste (EDF-080, EDF-090)

These families contain miscellaneous components exposed to the neutron flux while they were in a reactor. They include activated operating waste from pressurised water reactors (PWRs) currently in operation (EDF-080) and activated dismantling waste from first-generation reactors and non-sodium-bearing dismantling waste from the Superphenix fast neutron reactor (EDF-090).

Vitrified intermediate-level long-lived waste

Vitrified rinse effluents (COG-470, CEA-1120)

The conditioning used for certain intermediate-level effluents produced during rinsing operations performed as part of the final shutdown of plant UP2-400 (COG-470) and of the vitrification facility at Marcoule (CEA-1120) is vitrification and conditioning in identical containers to those used for vitrified high-level waste on the corresponding sites.

Vitrified americium-bearing effluents (CEA-340)

The reprocessing of recyclable products containing plutonium produces effluents containing americium, plutonium and uranium. These effluents are currently stored on the Valduc site. The hypothesis applied for their conditioning is vitrification at a facility to be built on the Valduc site, followed by conditioning in a standard container of the type used on the La Hague site. The thermicity of the vitrified waste produced in this way will be low, enabling it to be assigned to the ILW-LL category.

Other intermediate-level long-lived waste

Packages of cemented technological waste from La Hague (COG-030 and COG-050)

The COG-050 family corresponds to packages produced between 1990 and 1994 of technological waste embedded in cement in asbestos-cement containers, and not suitable for surface disposal.

These containers have subsequently been replaced by fibre-reinforced concrete containers (CBF-C'2) (COG-030). The majority of the solid technological waste from the La Hague plant affected by contamination making it unsuitable for surface disposal, is conditioned in CBF-C'2 containers. This waste is made up of metal or organic materials. It is collected in metal canisters or drums or in polyethylene bins, which are then immobilised inside the CBF-C'2 containers using fibre-reinforced concrete.

Alpha waste from Melox and La Hague (COG-400)

This family contains packages of solid waste contaminated mainly with plutonium during MOX fuel fabrication (MELOX plant and fuel fabrication facility at Cadarache) or fuel reprocessing (La Hague plants). It consists of miscellaneous metal waste (tools, cables, etc.) and organic waste (gloves, extraction hoses, etc.). Waste packages from operations prior to the final shutdown and dismantling of facilities at the UP2-400 plant at La Hague are also assigned to this family. The conditioning hypothesis previously applied by AREVA was compacting. At the ASN's request, AREVA is currently researching an alternative conditioning method to direct compacting, which will be an incineration/melting/vitrification process. The corresponding package is the PIVIC package, which is used as the reference in the detailed engineering design studies.

Metal and organic waste immobilised in a cementitious material (CEA-050, CEA-060, CEA-090, CEA-270, CEA-330, CEA-1100)

This family contains packages of solid waste from operation, maintenance and dismantling by the CEA that are heavily contaminated with alpha emitters, conditioned in non-alloy steel containers. This waste mainly consists of metals and plastics. The primary waste comes from the Cadarache centre and other CEA centres. It may or may not be compacted before being immobilised in a cementitious material in containers.

Alpha waste from Marcoule in 200-litre drums (CEA-1180)

This is solid technological waste produced by the UP1 facility and contaminated with pure alpha emitters. The waste is wrapped in a double thickness of vinyl, conditioned in 100-litre or 118-litre drums, then compacted into pucks. The pucks are conditioned in 200-litre carbon steel or stainless steel drums and then immobilised in gravel and mortar.

Cemented waste from the HAO silo at La Hague (COG-440)

The COG-440 family contains the packages produced by the conditioning of small particle-size process waste (fines from dissolution/clarification, resins and some fines from shearing) stored in the silo of the HAO (High Activity Oxide) unit. The current conditioning hypothesis applied by AREVA is cementation of the waste in stainless steel drums.

Compacted waste (COG-460)

The compacting process used at La Hague for conditioning the structural waste from spent fuels will also be used in the coming years for conditioning certain operating and dismantling waste from the UP2-400 plant in CSD-C packages: these packages are grouped together in the COG-460 family.

Waste immobilised in a cement-bitumen matrix from Cadarache (CEA-080, CEA-110, CEA-300)

This family contains packages of slightly irradiating solid waste from operation, maintenance and dismantling by the CEA, conditioned in non-alloy steel containers and immobilised in a cement- and bitumen-based material. Their production ended in 1990.

Waste immobilised in a cementitious material (CEA-120, CEA-290, CEA-440, CEA-480, CEA-1090)

This family consists of packages of moderately irradiating solid waste from operation, maintenance, cleanup or dismantling by the CEA. This waste is conditioned in metal drums and comes from different CEA centres (Fontenay-aux-Roses, Saclay, Cadarache, Valduc, Marcoule, etc.); it consists mainly of metals, cellulose or plastics, rubber, plaster, paint and glassware.

Waste immobilised in a cementitious material from La Hague (COG-480)

This family contains the waste from the dismantling of the former irradiated fuel reprocessing plant, UP2-400, at La Hague, which will be conditioned in fibre-reinforced concrete containers and immobilised in cement in the next few years.

Irradiating waste to be reconditioned from CEA (CEA-400, CEA-410, CEA-420)

These families consist of irradiating waste that is being or will be produced by the operation, cleanup and dismantling of certain CEA facilities. This waste will be placed in Diadem storage containers and stored at the future Diadem facility. The reconditioning of waste in Diadem containers for disposal has not yet been determined.

Sludge or evaporation concentrates embedded in a cementitious material (CEA-070, CEA-100, CEA-140, CEA-150, CEA-280, CEA-310, CEA-320, CEA-1040, CEA-1140)

In the case of the packages already produced, this waste comes from the conditioning of filtration sludge or evaporation concentrates from effluent treatment stations at the Cadarache, Fontenay-aux-Roses and Valduc facilities. The sludge has been treated chemically, mixed with cement, then conditioned in metal drums made from non-alloy steel. The concentrates have been embedded in a cement-based matrix and conditioned in metal drums. Some of these packages have been placed in concrete hulls or steel containers, either permanently or not.

In the case of the packages yet to be produced, the waste is:

- partly process waste from different sources linked to the operation of plant UP1 at Marcoule and to the final shutdown and dismantling of the plant; the conditioning applied by the CEA at this stage is to embed the waste in a cement matrix and put it into stainless steel drums;
- partly co-precipitation sludge from effluent treatment on the Marcoule site, which is currently bituminised but in future will be immobilised in cement and conditioned in stainless steel drums.

PWR dismantling waste (EDF-100)

This is waste that will be produced when the PWRs are dismantled. The current scenario adopted by EDF is to put it in optimised metal containers. The facility to be used for conditioning this waste will be defined in liaison with the dismantling of the first PWR units.

Waste from end-of-operation and dismantling operations at the UP2-400, UP2-800 and UP3 plants compacted in CSD-C canisters (COG-490)

The compacting process used at La Hague for conditioning the structural waste from spent fuel will also be used in the coming years for conditioning certain dismantling waste from the UP2-400, UP2-800 and UP3 plants in CSD-C packages.

Waste from the dismantling of laboratories and plants, immobilised in a cementitious material (CEA-460, COG-500, COG-510, COG-520)

Waste from the dismantling of the UP2-400, UP2-800 and UP3 plants at La Hague and waste linked to the dismantling of facilities at the Valduc site will be immobilised by a cementitious material inside a fibre-reinforced concrete or metal container.

Activated waste (CEA-360)

This family contains the non-sodium-bearing activated dismantling waste from the Phenix fast neutron reactor.

Used sealed sources (CEA-450, CEA-1510, EDF-110)

These families contain the different types of used sealed source (neutron sources, sources containing natural uranium, radium, plutonium or americium) from various origins: the CEA (which, as supplier, has recovered a large number of used sources), EDF (primary and secondary source rods from PWRs, etc.). Some of these are already conditioned in concrete or metal containers.

Sodium-bearing waste (EDF-250, CEA-380)

This consists of boron carbide (B4C) pins from the control rod assemblies of the Superphenix (EDF-250) and Phenix and Rapsodie (CEA-380) fast neutron reactors. These pins are likely to contain sodium residues that were not removed when the control rods were washed.

Drums of radium-bearing lead sulphates from the Le Bouchet plant (CEA-231, CEA-232)

The CEA's plant in Le Bouchet (Essonne), which from 1958 to 1970 processed an imported ore, uranothorianite, to extract uranium and thorium, produced radioactive residues: radium-bearing lead sulphates from decontamination of the bases of the ore extraction tower. These residues were conditioned on site in metal drums, and since then have undergone a series of reconditioning operations.

Miscellaneous mainly metal waste to be conditioned or reconditioned (CEA-370, CEA-430, CEA-1110, CEA-1151, CEA-1152, CEA-1200, EDF-120)

These CEA families consist of irradiating waste that has been, is being or will be produced by the operation, cleanup and dismantling of certain CEA facilities. The plan is to put most of it into Diadem storage containers and store it at the future Diadem facility. The conditioning of the waste in Diadem containers for disposal has not yet been determined. For the other waste, the conditioning also remains to be decided.

The EDF-120 family contains the waste stored in shafts at the Irradiated Materials Workshop (AMI) in Chinon. It mainly comes from assessment activities. It consists of a wide variety of waste types from the PWR and GCR series. The conditioning methods for this waste have not yet been determined.

Miscellaneous waste produced during the operation, maintenance and dismantling phases of the ITER reactor (ITER-010)

ITER waste will be produced by the replacement of components during operation and by their removal after final shutdown. This waste will be characterised by its tritium and activation products content and by the nature of some of the waste.

Waste collected by Andra conditioned in 870-litre containers (AND-000)

Waste collected by Andra includes:

- radium-bearing items for medical use (AND-050) consisting of needles and very small metal tubes, each containing a few milligrams of radium. The radium is in a solid and insoluble chemical form (sulphate or chloride). Andra envisages conditioning this radium-bearing medical waste in 870-litre containers;
- sources from smoke detectors, for which the conditioning hypothesis adopted at this stage is 870-litre drums;
- sources from lightning conductors, containing americium or radium, conditioned in 870-litre containers;
- used sealed sources collected by Andra, particularly as part of its public service role. They will also be conditioned in 870-litre containers;
- four 200-litre drums of silicon contaminated with carbon-14 from the company Isotopchim, which is also to be reconditioned in 870-litre drums.

Long-term management solutions for waste collected by Andra that is not suitable for surface disposal are currently being studied. At this stage, the estimated volume of this waste destined for Cigeo is 18 m³, which corresponds to nineteen 870-litre packages.

The summary table below gives the IDs of the ILW-LL families and shows their correspondence with the National Inventory (2012 version), as well as the number of packages in each family.

Type ID	Type title	Identifier of the 2012 Edition of the IN	Number of packages
AND-000	Waste collected by Andra conditioned in 870-litre containers	S01	19
CEA-050	870-litre non-alloy steel containers produced in accordance with a quality assurance specification (from 01/01/94) and containing miscellaneous waste (mainly alpha Pu) immobilised in a cementitious material	F2-5-04	3 550
CEA-060	500-litre steel containers produced since 1994 in accordance with a quality assurance specification and containing miscellaneous waste immobilised in a cementitious material	F2-5-05	1 250
CEA-070	500-litre concrete containers containing drums of filtration sludge embedded in a cementitious material, produced in accordance with a quality assurance specification	F2-5-02	43
CEA-080	870-litre carbon steel containers produced from 1972 to 1990 containing diverse waste in a cement-bitumen matrix	F2-5-04	2 188
CEA-090	870-litre non-alloy steel containers produced from 1990 to 1993 containing miscellaneous waste (mainly alpha Pu) immobilised in a cementitious material	F2-5-04	562
CEA-100	870-litre non-alloy steel containers containing 700-litre drums of 800 g/l concentrates embedded in a cementitious material	F2-5-03	40
CEA-110	500-litre carbon steel containers produced from 1970 to 1990 containing miscellaneous waste in a cement-bitumen matrix	F2-5-05	427
CEA-120	500-litre non-alloy steel containers produced from 1990 to 1994 containing miscellaneous waste immobilised in a cementitious material	F2-5-05	210
CEA-140	500-litre concrete containers produced before 1994 containing drums of filtration sludge bituminised in a cementitious material	F2-5-02	2 297
CEA-150	500-litre concrete containers containing drums of evaporation concentrates embedded in a cementitious material	F2-5-02	381
CEA-231	Drums of radium-bearing lead sulphates from the Le Bouchet plant conditioned in 5 m³ concrete containers	F2-5-01	19
CEA-232	Drums of radium-bearing lead sulphates from the Le Bouchet plant conditioned in EIP containers		952
CEA-270	870-litre non-alloy steel containers containing miscellaneous waste immobilised in a cementitious material (CEA/DAM Valduc)	F2-5-04	415
CEA-280	223-litre non-alloy steel drums containing filtration sludge embedded in a cementitious material (CEA/DAMValduc)	F2-5-02	2 149
CEA-290	Non-alloy steel containers from the reconditioning of 1800-litre concrete containers containing miscellaneous waste immobilised in a cementitious material	F2-5-06	169
CEA-300	Non-alloy steel containers from the reconditioning of 1800-litre concrete containers containing miscellaneous waste immobilised in a cement-bitumen matrix	F2-5-06	11
CEA-310	Non-alloy steel containers produced from the reconditioning of 1000-litre concrete containers containing miscellaneous waste immobilised in a cement-bitumen matrix or a sludge/cement mixture	F2-5-06	88
CEA-320	Steel drums containing sludges or concentrates or a mixture of cemented sludges and concentrates	F2-6-02	360
CEA-330	870-litre non-alloy steel containers containing metal and organic waste from "Pegase"	F2-5-04	619
CEA-340	Standard waste canister (CSD) containing vitrified americium-bearing effluents (Valduc ILW-LL glass packages)	F 2-6-03	300
CEA-360	Waste from the dismantling of Phenix core objects	F2-4-12	781
CEA-370	Toxic objects from Phenix	F2-4-12	8
CEA-380	Miscellaneous waste containing B4C from the operation and dismantling phases of the Rapsodie and Phenix FNR reactors	F2-4-15	3
CEA-400	Irradiating waste from the dismantling of Rapsodie, cleanup of the pits at Cadarache and the operation and dismantling of the JHR	-	200
CEA-410	Irradiating waste from the operation and dismantling of various facilities at Saclay	-	300
CEA-420	Irradiating waste from the operation and dismantling of various facilities at Fontenay-aux-Roses	-	230
CEA-430	Miscellaneous waste from the operation, cleanup and dismantling phases of various facilities at the Grenoble Centre	DIV 2	40
CEA-440	500-litre stainless steel containers containing miscellaneous non-compactable waste immobilised in a cementitious material (operation of CABRI, dismantling of Rapsodie, pits at CAD, CENG)	F2-5-05	2 000
CEA-450	Non-alloy steel containers from the reconditioning of concrete containers known as "source assemblies"	F2-9-01	41
CEA-460	Waste from the dismantling of CEA's Valduc facilities	-	40
CEA-480	Non-standard pre-concreted 223-litre packages	DIV 2	50
CEA-1000	Stainless steel overdrums containing stainless steel drums of bituminised waste produced in accordance with a quality assurance specification (from October 1996)	F2-4-03	2 700
CEA-1010	Stainless steel overdrums containing non-alloy steel drums of bituminised waste produced in accordance with a quality assurance specification (from 1995 to 1996)	F2-4-03	1 709
CEA-1020	Stainless steel overdrums containing non-alloy steel drums of bituminised waste produced before 1995, transported in primary packages	F2-4-04	12 955
CEA-1021	Stainless steel overdrums containing non-alloy steel drums of bituminised waste produced before 1995, transported in disposal packages		11 467
CEA-1040	Stainless steel drums containing cemented process wastes	F2-4-10	3 013
CEA-1050	Stainless steel drums containing cemented metal structural waste (including from the dismantling of the Celestin reactors)	F2-4-07	1 320
CEA-1060	Stainless steel drums containing magnesium structural waste immobilised in a cementitious material	F2-4-09	7 464
CEA-1090	Stainless steel drums containing metal and organic technological waste immobilised in a cementitious material	F2-4-11	1 353
CEA-1100	870-litre non-alloy steel containers containing metal and organic technological waste immobilised in a cementitious material (alpha waste from Marcoule)	F2-5-04	410
CEA-1110	Technological waste from AVM	F2-4-05	188
CEA-1120	AVL-type stainless steel containers containing vitrified waste from Marcoule UP1 rinse effluents (ILW-LL glass packages)	F2-4-13	147

Type ID	Type title	Identifier of the 2012 Edition of the IN	Number of packages
CEA-1140	Stainless steel drums containing cemented filtration sludge from the STEMA facility	F2-4-10	120
CEA-1151	Structural waste, miscellaneous metal waste and waste from the dismantling of the TOP and TOR lines, to be reconditioned in EIP drums	F2-4-14	60
CEA-1152	Structural waste, miscellaneous metal waste and waste from the dismantling of the TOP and TOR lines		450
CEA-1180	200-litre alpha drums stored in building 99 in the north sector of CDS, to be placed temporarily in a 500-litre reversible hull	CEA-1180	183
CEA-1200	Miscellaneous waste stored in buildings 211 and 213 (excluding containers of PIVER vitrified waste and other HLW glass packages)	DIV 2	50
CEA-1510	Radioactive sources (alpha, neutron and other)	S01	60
COG-020	Drums of bitumen STE3 produced according to the specification 300 AQ 027	F2-3-04	11 900
COG-030	Packages of cemented solid operating waste produced after 1994 in accordance with specification 300 AQ 044	F2-3-08	8 292
COG-040	Drums of cemented hulls and nozzles produced in accordance with the specification 300 AQ 025	F2-3-01	1 517
COG-050	Packages of cemented solid operating waste produced before 1994 in accordance with specification 300 AQ 038	F2-3-07	324
COG-070	Standard canisters for compacted waste (CSD-C) containing hulls and nozzles from the high activity oxide (HAO) silo	F2-3-02	1 527
COG-100	Standard canisters for compacted waste/CSD-C produced in accordance with the specification 300 AQ 055 (including hulls and nozzles from ECE drums and from pools S1, S2 and S3)	F2-3-02	6 675
COG-110	Standard canisters for compacted waste (CSD-C) containing hulls and nozzles from UOX fuel assemblies	F2-3-02	17 850
COG-120	Standard canisters for compacted waste (CSD-C) containing hulls and nozzles from UOX/ERU/MOX fuel assemblies	F2-3-02	22 720
COG-400	Alpha waste from Melox and LHA	F2-3-10	4 400
COG-420	Drums of bituminised STE2 waste (partial recovery from silo 50-14)	F2-3-05	340
COG-430	Dried STE2 sludge, compacted and immobilised in a metal container	F2-3-12	14 429
COG-440	Cemented ECE drums containing fines and resins from the HAO silo	F2-3-13	121
COG-450	Standard canisters for compacted waste (CSD-C) containing structural waste from PWR and FNR fuel assemblies (Superphenix and Phenix)	F2-3-02	1 514
COG-460	Standard canisters for compacted waste (CSD-C) containing metal and organic technological waste and dismantling waste	F2-3-02	500
COG-470	CSD-B packages containing vitrified medium-level effluents (final shutdown of UP2-400, UP2-800 and UP3)	F2-3-1 1	900
COG-480	CBF-C'2 containers containing operating and dismantling waste (ATTILA pit bins)	F2-3-08	18
COG-490	Waste from end-of-operation and dismantling operations at the UP2-400, UP2-800 and UP3 plants compacted in CSD-C canisters	F2-3-02	4 450
COG-500	Waste from end-of-operation and dismantling operations at the UP2-400, UP2-800 and UP3 plants compacted in CBF-C'2 containers	F2-3-08	1 051
COG-510	Waste from end-of-operation and dismantling operations at the MELOX plant conditioned in CBF-C'2 containers	F2-3-08	352
COG-520	Waste from end-of-operation and dismantling operations at the Cadarache CFCa facilities conditioned in CBF-C'2 containers	F2-3-08	25
COG-530	Packages of compacted structural waste from CEA/Civil SF reprocessing	F2-3-02	24
COG-540	Packages of compacted structural waste from CEA/DAM SF reprocessing	F2-3-02	400
COC-550	Packages of compacted structural waste from EL4 SF reprocessing	F2 3-02	200
EDF-080	C1PG containers of PWR activated operating waste	F2-2-03	1 200
EDF-090	C1PG containers of first train activated dismantling waste excluding sodium-bearing waste from Superphenix	F2-2-03	700
EDF-100	Activated dismantling waste from PWRs in the current fleet (including BCOT)	-	6 360
EDF-110	PWR primary and secondary source rods and other miscellaneous sealed sources	S01	20
EDF-120	Waste from AMI at Chinon	DIV 2	100
EDF-250	Miscellaneous waste containing B4C from the operation and dismantling phases of the Superphenix FNR reactor	F2-4-15	5
ITER-010	Miscellaneous waste produced during the operation, maintenance and dismantling phases of the ITER reactor	-	4 676

Appendix 2 : List of HLW families under consideration for Cigeo

Vitrified waste

CSD-V vitrified waste packages from AREVA/La Hague (COG-140, COG-200, COG-800, COG-810, COG-820, COG-830, COG-880, COG-890 and COG-900)

These packages are standard canisters for vitrified waste (CSD-V) made from stainless steel in which solutions of fission products and minor actinides, calcined and incorporated into a glass matrix, are conditioned in the R7 and T7 vitrification facilities at La Hague. The fission product solutions come from the reprocessing of UOX fuels (COG-140 and COG-800 for fuels with higher burnup rates), from the reprocessing of spent fuels from the CEA and from the Brennilis EL4 reactor (COG-880 for CEA/Civil, COG-890 for CEA/DAM and COG-900 for EL4), from the reprocessing of spent MOX fuels mixed with spent UOX and ERU fuels (COG-200), and from the reprocessing of spent fuels from the Phenix and Superphenix fast neutron reactors mixed with UOX fuels (COG-830).

Vitrified waste packages are also produced when the vitrification furnace is purged (COG-810) and from calcines from calciner cleaning operations (COG-820).

Packages of vitrified fission product molybdenum-rich solutions from La Hague (COG-150)

These packages come from the vitrification of molybdenum-rich fission product solutions using a similar process to the one used today for producing vitrified waste packages, but using a "cold crucible" technology combined with a new glass formulation. These solutions, stored on the La Hague site, come from the reprocessing of spent fuels known as "UMo" (consisting of a uranium-molybdenum alloy) used in gas-cooled (graphite-moderated) reactors (GCRs) now shut down.

Vitrified waste packages from the Marcoule vitrification facility (CEA-1070 and CEA-1080)

These packages come from vitrification campaigns at the Marcoule vitrification facility (AVM), which began in 1978. Production in compliance with a quality assurance specification began in March 1995 and corresponds to the CEA-1070 family. Production prior to 1995 corresponds to the CEA-1080 family.

PIVER vitrified waste packages from the CEA/Marcoule (CEA-200 and CEA-1190)

The development and refinement of the waste vitrification process were undertaken by the CEA at several facilities in the Marcoule pilot facility (APM) from the early 1960s. These studies led to the construction of the first industrial pilot facility for the vitrification of spent fuel dissolution solutions (PIVER).

The fission product solutions vitrified at this facility came partly from the reprocessing of Sicral-type spent fuels (Si Cr Al: a uranium, silicon, chromium and aluminium alloy) used in GCRs (gas-cooled reactors), and partly from the reprocessing of UO_2-based fuels irradiated in the Phenix fast neutron reactor. These packages (CEA-200) were produced between 1969 and 1973 in the case of the Sicral vitrified waste packages (94% of the total) and between 1979 and 1980 in the case of the Phenix vitrified waste packages.

Research led in parallel to the production of vitrified waste samples conditioned in stainless steel containers of different geometries, which are now stored in building 213 of the APM (CEA-1190).

Atalante vitrified waste packages from the CEA/Marcoule (CEA-350)

Research conducted in Atalante on UOX and MOX fuels generates radioactive effluents, which have to be vitrified in an Atalante shielded process line. The conditioning process envisaged by the CEA consists of waste vitrification in metal pots, grouping and immobilising the pots in a basket with glass frit, then loading into a stainless steel AVM-type container. Production of these packages should begin by 2030.

Other high-level waste (used sealed sources, technological waste, etc.)

Technological waste packages from the AREVA/La Hague vitrification facilities (COG-850)

In the first few years of operation of the R7 vitrification facility in La Hague, technological waste from the facility's operation was conditioned in standard stainless steel canisters of identical external geometry to that of the vitrified waste packages from La Hague. The same conditioning is envisaged for baskets of technological waste such as pieces of glass and cut up equipment from the R7 and T7 facilities.

Waste from the Elan IIB elution columns conditioned in standard canisters from AREVA/La Hague (COG-860)

The Elan IIB facility, located in La Hague, was a pilot for producing sealed sources of caesium-137 and strontium-90. The caesium was transported from CEA/Marcoule in elution columns on a mineral exchanger then eluted, concentrated and calcined. The caesium oxide powder was then sintered and conditioned in two thicknesses of metal. Four elution columns are currently stored at La Hague. The conditioning process for the mineral exchanger of these elution columns has not been decided. At this stage, conditioning in a standard stainless steel canister is the chosen solution.

Packages of strontium titanate capsules from AREVA/La Hague (COG-870)

The Elan IIB facility, located in La Hague, was a pilot for producing sealed sources of caesium-137 and strontium-90. The strontium arrived at the Elan IIB facility conditioned in metal cases (capsules) and was separated, compacted and conditioned in two thicknesses of metal. This facility, operated by the CEA, went into operation in 1970. Production was shut down from 1973. Fifteen strontium titanate capsules are currently stored at La Hague. The process envisaged at present for the conditioning of these capsules is to immobilise them in a standard stainless steel canister. The choice of immobilisation matrix is currently being studied.

Used sealed sources (caesium-137, strontium-90, plutonium-238) from the CEA (CEA-1500)

These are highly radioactive sources containing caesium and strontium, some of which come from isotope generators, along with a batch of sources from cardiac pacemakers (plutonium-238). These sources will be conditioned in a package of identical external geometry to the AVM glass package.

The following table summarises the families and number of packages of high-level waste.

Type ID	Type title	Identifier of the 2012 Edition of the IN	Number of packages
CEA-200	Piver containers produced between 1969 and 1981 and containing solutions of Sioral and Phénix fission products in a glass matrix	F1-5-01	88
CEA-350	Stainless steel containers containing vitrified Atalante waste	-	5
CEA-1070	Containers with vitrified AVM waste produced in accordance with a QA specification since March 1995	F1-4-01	865
CEA-1080	Containers of vitrified AVM waste produced before 1995	F1-4-01	2 294
CEA-1190	Miscellaneous vitrified waste (laboratory glassware) stored in APM building 213 (excluding Piver)	F1-5-01	8
CEA-1500	HLW radioactive sources (137 Cs, 90 Sr, 238 Pu)	S01	7
COG-140	Standard vitrified waste containers/CSD-V: UOX glass produced according to specification 300 AQ 016	F1-3-01	6 900
COG-150	Standard vitrified waste containers/CSD-V: UMo glass produced according to specification 300 AQ 059	F1-3-02	1 000
COG-200	Standard vitrified waste containers/CSD-V: UOX/URE/MOX glass	F1-3-01	24 060
COG-800	Standard vitrified waste containers/CSD-V: UOX glass produced according to specification 300 AQ 060	F1-3-01	19 010
COG-810	Standard vitrified waste containers/CSD-V: R7/T7 purge glass	F1-3-01	250
COG-820	Standard vitrified waste containers/CSD-V: calcine glass	F1-3-01	75
COG-830	Standard vitrified waste containers/CSD-V: REP/RNR glass (Superphenix and Phenix)	F1-3-01	1 095
COG-850	Technological waste from vitrification facilities and conditioned in standard containers	F1-3-03	200
COG-860	Waste from ELAN IIB elution columns conditioned into standard containers	F1-3-05	52
COG-870	Strontium titanate capsules conditioned in standard containers	F1-3-04	3
COG-880	Packages of vitrified waste from CEA/Civil SF reprocessing	F1-3-01	11
COG-890	Packages of vitrified waste from CEA/DAM SF reprocessing	F1-3-01	80
COG-900	Packages of vitrified waste from EL4 reprocessing	F1-3-01	30

Appendix 3 : Reference radiological inventory of families of HLW0, HLW1 and HLW2 and ILW-LL packages.

Change in activity for radionuclides with a maximum activity greater than 10^{12} Bq during a period of one million years after closure

HL waste (moderate heat content) - Total inventory (4147 primary waste packages)

Radionuclides sorted according to maximum activity over 1 My n° 1 to 42 - (t0 : 2140)

42 radionuclides activity (4.4E-01 < half-life < 5.0E+10 year and maximum activity > 1E+12 Bq) (After Darwin Pepin - Jeff 3.1.1.)

[Moteur - CIMASAF160022-23-25_E_AGIR-v44a_TCI-Cigéo-v24e_do141112-maR3-v5SF3_Pour-icono-DOSAF.xlsm]

n°	RN	Half-life [year]	Activity t0 = 2140 [Bq]	Activity t0=100 Y [Bq]	Activity t0+200 y [Bq]	Activity t0+500 y [Bq]	Activity t0+1000 y [Bq]	Activity t0+2000 y [Bq]	Activity t0+5000 y [Bq]	Activity t0+10000 y [Bq]	Activity t0+20000 y [Bq]	Activity t0+50000 y [Bq]	Activity t0+100000 y [Bq]	**Activity max over 1My [Bq**	Time for max over 1My [Y]
1	**Cs-137**	3.00E+01	7.28E+17	7.25E+16	7.21E+15	7.11E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	7.28E+17	t0
2	**Sr-90**	2.88E+01	4.20E+17	3.78E+16	3.41E+15	2.49E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	4.20E+17	t0
3	**Am-241**	4.33E+02	9.80E+16	8.35E+16	7.12E+16	4.40E+16	1.98E+16	3.98E+15	3.30E+13	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	9.80E+16	t0
4	**Sm-151**	9.00E+01	7.15E+16	3.31E+16	1.53E+16	1.52E+15	3.23E+13	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	7.15E+16	t0
5	**Tc-99**	2.14E+05	3.37E+15	3.36E+15	3.36E+15	3.36E+15	3.35E+15	3.34E+15	3.31E+15	3.26E+15	3.15E+15	2.86E+15	2.43E+15	3.37E+15	t0
6	**Pu-238**	8.77E+01	1.39E+15	7.16E+14	3.76E+14	6.19E+13	4.20E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	1.39E+15	t0
7	**Pu-239**	2.41E+04	5.14E+14	5.13E+14	5.12E+14	5.10E+14	5.06E+14	4.97E+14	4.70E+14	4.23E+14	3.32E+14	1.46E+14	3.49E+13	5.14E+14	1.00E-01
8	**Pu-240**	6.56E+03	4.79E+14	4.74E+14	4.69E+14	4.54E+14	4.31E+14	3.88E+14	2.83E+14	1.67E+14	5.79E+13	2.44E+12	< 1.E+12	4.79E+14	2.00E-02
9	**Nb-93m**	1.61E+01	4.78E+14	4.78E+14	4.77E+14	4.74E+14	4.70E+14	4.62E+14	4.46E+14	4.31E+14	4.22E+14	4.14E+14	4.05E+14	4.78E+14	3.00E+01
10	**Zr-93**	1.53E+06	4.35E+14	4.35E+14	4.35E+14	4.34E+14	4.34E+14	4.34E+14	4.34E+14	4.33E+14	4.31E+14	4.25E+14	4.15E+14	4.35E+14	t0
11	**Np-237**	2.14E+06	2.33E+14	2.36E+14	2.39E+14	2.44E+14	2.49E+14	2.52E+14	2.53E+14	2.52E+14	2.52E+14	2.49E+14	2.45E+14	2.53E+14	4.00E+03
12	**Am-242m**	1.41E+02	2.39E+14	1.46E+14	8.96E+13	2.05E+13	1.75E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	2.39E+14	t0
13	**Am-243**	7.36E+03	2.38E+14	2.36E+14	2.33E+14	2.27E+14	2.16E+14	1.97E+14	1.49E+14	9.28E+13	3.62E+13	2.15E+12	< 1.E+12	2.38E+14	5.00E-02
14	**Th-229**	7.34E+03	2.21E+14	2.20E+14	2.20E+14	2.19E+14	2.17E+14	2.14E+14	2.07E+14	1.99E+14	1.93E+14	1.95E+14	2.05E+14	2.25E+14	4.00E+05
15	**U-233**	1.59E+05	1.84E+14	1.84E+14	1.84E+14	1.84E+14	1.84E+14	1.85E+14	1.85E+14	1.87E+14	1.90E+14	1.97E+14	2.07E+14	2.25E+14	4.00E+05
16	**Ni-63**	1.01E+02	2.12E+14	1.06E+14	5.34E+13	6.76E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	2.12E+14	t0
17	**Cm-242**	4.46E-01	1.99E+14	1.22E+14	7.44E+13	1.70E+13	1.46E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	1.99E+14	t0
18	**Th-230**	7.54E+04	1.96E+14	1.96E+14	1.96E+14	1.96E+14	1.96E+14	1.96E+14	1.95E+14	1.95E+14	1.93E+14	1.86E+14	1.72E+14	1.96E+14	5.00E-01
19	**Ra-226**	1.60E+03	1.82E+14	1.83E+14	1.83E+14	1.85E+14	1.87E+14	1.90E+14	1.94E+14	1.95E+14	1.93E+14	1.87E+14	1.73E+14	1.95E+14	8.00E+03
20	**Pb-210**	2.22E+01	1.82E+14	1.83E+14	1.83E+14	1.85E+14	1.87E+14	1.90E+14	1.94E+14	1.95E+14	1.93E+14	1.87E+14	1.73E+14	1.95E+14	8.00E+03
21	**U-234**	2.46E+05	1.83E+14	1.83E+14	1.83E+14	1.83E+14	1.83E+14	1.82E+14	1.81E+14	1.78E+14	1.73E+14	1.59E+14	1.38E+14	1.83E+14	3.00E+02
22	**Cm-244**	1.80E+01	1.72E+14	3.66E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	1.72E+14	t0
23	**Cs-135**	2.30E+06	1.67E+14	1.67E+14	1.67E+14	1.67E+14	1.67E+14	1.67E+14	1.67E+14	1.67E+14	1.66E+14	1.65E+14	1.62E+14	1.67E+14	t0
24	**Sn-126**	2.30E+05	1.26E+14	1.26E+14	1.26E+14	1.26E+14	1.26E+14	1.26E+14	1.24E+14	1.23E+14	1.19E+14	1.09E+14	9.35E+13	1.26E+14	t0
25	**Se-79**	3.77E+05	7.80E+13	7.80E+13	7.80E+13	7.79E+13	7.78E+13	7.77E+13	7.73E+13	7.66E+13	7.52E+13	7.11E+13	6.49E+13	7.80E+13	t0
26	**Mo-93**	4.00E+03	6.23E+13	6.12E+13	6.01E+13	5.71E+13	5.23E+13	4.40E+13	2.62E+13	1.10E+13	1.95E+12	< 1.E+12	< 1.E+12	6.23E+13	t0
27	**Pu-241**	1.43E+01	3.88E+13	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	3.88E+13	t0
28	**Cm-243**	3.00E+01	1.82E+13	1.81E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	1.82E+13	t0
29	**Pd-107**	6.50E+06	1.59E+13	1.59E+13	1.59E+13	1.59E+13	1.59E+13	1.59E+13	1.59E+13	1.59E+13	1.59E+13	1.58E+13	1.58E+13	1.59E+13	t0
30	**U-236**	2.37E+07	1.30E+13	1.30E+13	1.30E+13	1.30E+13	1.30E+13	1.30E+13	1.31E+13	1.31E+13	1.31E+13	1.31E+13	1.31E+13	1.31E+13	3.00E+04
31	**Th-228**	1.91E+00	1.30E+13	1.30E+13	1.30E+13	1.30E+13	1.30E+13	1.30E+13	1.30E+13	1.30E+13	1.30E+13	1.30E+13	1.30E+13	1.30E+13	1.25E+01
32	**Th-232**	1.41E+10	1.30E+13	1.30E+13	1.30E+13	1.30E+13	1.30E+13	1.30E+13	1.30E+13	1.30E+13	1.30E+13	1.30E+13	1.30E+13	1.30E+13	1.00E+05
33	**Ra-228**	5.75E+00	1.30E+13	1.30E+13	1.30E+13	1.30E+13	1.30E+13	1.30E+13	1.30E+13	1.30E+13	1.30E+13	1.30E+13	1.30E+13	1.30E+13	1.00E+05
34	**Nb-91**	6.80E+02	9.08E+12	8.20E+12	7.41E+12	5.46E+12	3.28E+12	1.18E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	9.08E+12	t0
35	**Ni-59**	7.60E+04	4.61E+12	4.61E+12	4.60E+12	4.59E+12	4.57E+12	4.53E+12	4.41E+12	4.21E+12	3.84E+12	2.92E+12	1.85E+12	4.61E+12	t0
36	**Eu-152**	1.35E+01	4.61E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	4.61E+12	t0
37	**U-235**	7.04E+08	3.78E+12	3.78E+12	3.78E+12	3.78E+12	3.78E+12	3.78E+12	3.78E+12	3.79E+12	3.79E+12	3.80E+12	3.80E+12	3.80E+12	2.00E+05
38	**Ac-227**	2.18E+01	3.77E+12	3.77E+12	3.77E+12	3.77E+12	3.77E+12	3.77E+12	3.77E+12	3.77E+12	3.77E+12	3.78E+12	3.79E+12	3.80E+12	3.00E+05
39	**Pa-231**	3.28E+04	3.77E+12	3.77E+12	3.77E+12	3.77E+12	3.77E+12	3.77E+12	3.77E+12	3.77E+12	3.77E+12	3.78E+12	3.79E+12	3.80E+12	3.00E+05
40	**Cd-113m**	1.41E+01	3.25E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	3.25E+12	t0
41	**Eu-154**	8.59E+00	2.99E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	2.99E+12	t0
42	**Sn-121m**	5.50E+01	1.94E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	1.94E+12	t0
*		Color pattern - Minimum values : 1.00E+12 Bq							Maximum values : 7.28E+17 Bq						

HL waste (high heat content) - Total inventory (51886 primary waste packages)

Radionuclides sorted according to maximum activity over 1 My n° 1 to 53 - (t0 : 2140)

53 radionuclides activity (4.4E-01 < half-life < 5.0E+10 year and maximum activity > 1E+12 Bq) (After Darwin Pepin - Jeff 3.1.1.)

[Moteur - CIMASAF160022-23-25_E_AGIR-v44a__TCI-Cigéo-v24e_do141112-maR3-v5SF3_Pour-icono-DOSAF.xlsm]

n°	RN	Half-life [year]	Activity t0 = 2140 [Bq]	Activity t0=100 Y [Bq]	Activity t0+200 y [Bq]	Activity t0+500 y [Bq]	Activity t0+1000 y [Bq]	Activity t0+2000 y [Bq]	Activity t0+5000 y [Bq]	Activity t0+10000 y [Bq]	Activity t0+20000 y [Bq]	Activity t0+50000 y [Bq]	Activity t0+100000 y [Bq]	**Activity max over 1My [Bq**	Time for max over 1My [Y]
1	**Cs-137**	3.00E+01	6.19E+19	6.16E+18	6.13E+17	6.05E+14	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	6.19E+19	t0
2	**Sr-90**	2.88E+01	3.59E+19	3.24E+18	2.91E+17	2.13E+14	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	3.59E+19	t0
3	**Am-241**	4.33E+02	1.62E+19	1.38E+19	1.18E+19	7.30E+18	3.28E+18	6.70E+17	1.31E+16	5.10E+15	2.26E+15	1.95E+14	3.31E+12	1.62E+19	t0
4	**Sm-151**	9.00E+01	1.06E+18	4.90E+17	2.27E+17	2.25E+16	4.79E+14	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	1.06E+18	t0
5	**Cm-244**	1.80E+01	9.84E+17	2.09E+16	4.45E+14	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	9.84E+17	t0
6	**Am-243**	7.36E+03	3.37E+17	3.34E+17	3.31E+17	3.21E+17	3.07E+17	2.79E+17	2.10E+17	1.31E+17	5.13E+16	3.05E+15	2.76E+13	3.37E+17	5.00E-02
7	**Pu-240**	6.56E+03	1.24E+17	1.26E+17	1.24E+17	1.20E+17	1.14E+17	1.03E+17	7.48E+16	4.41E+16	1.54E+16	6.46E+14	3.29E+12	1.26E+17	5.00E+01
8	**Tc-99**	2.14E+05	9.46E+16	9.46E+16	9.46E+16	9.45E+16	9.43E+16	9.40E+16	9.31E+16	9.16E+16	8.87E+16	8.05E+16	6.85E+16	9.46E+16	t0
9	**Pu-238**	8.77E+01	6.92E+16	3.82E+16	2.15E+16	4.17E+15	3.23E+14	2.30E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	6.92E+16	t0
10	**Pu-239**	2.41E+04	7.96E+15	8.94E+15	9.87E+15	1.26E+16	1.69E+16	2.47E+16	4.27E+16	5.93E+16	6.53E+16	3.58E+16	8.80E+15	6.53E+16	1.50E+04
11	**Ni-63**	1.01E+02	5.45E+16	2.74E+16	1.37E+16	1.74E+15	5.55E+13	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	5.45E+16	t0
12	**Pu-241**	1.43E+01	3.11E+16	1.10E+16	1.08E+16	1.05E+16	1.01E+16	9.29E+15	7.28E+15	4.84E+15	2.14E+15	1.85E+14	3.14E+12	3.11E+16	t0
13	**Cm-243**	3.00E+01	2.94E+16	2.92E+15	2.90E+14	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	2.94E+16	t0
14	**Am-242m**	1.41E+02	1.94E+16	1.18E+16	7.24E+15	1.66E+15	1.42E+14	1.04E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	1.94E+16	t0
15	**Cm-242**	4.46E-01	1.61E+16	9.84E+15	6.02E+15	1.38E+15	1.18E+14	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	1.61E+16	t0
16	**Zr-93**	1.53E+06	1.22E+16	1.22E+16	1.22E+16	1.22E+16	1.22E+16	1.22E+16	1.21E+16	1.21E+16	1.21E+16	1.19E+16	1.16E+16	1.22E+16	t0
17	**Nb-93m**	1.61E+01	1.19E+16	1.21E+16	1.21E+16	1.21E+16	1.21E+16	1.20E+16	1.19E+16	1.19E+16	1.18E+16	1.16E+16	1.13E+16	1.21E+16	1.25E+02
18	**Eu-154**	8.59E+00	1.18E+16	3.70E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	1.18E+16	t0
19	**Cm-245**	8.50E+03	1.09E+16	1.08E+16	1.07E+16	1.05E+16	1.01E+16	9.28E+15	7.26E+15	4.83E+15	2.14E+15	1.85E+14	3.14E+12	1.09E+16	5.00E-02
20	**Np-237**	2.14E+06	3.85E+15	4.34E+15	4.75E+15	5.66E+15	6.48E+15	7.00E+15	7.14E+15	7.14E+15	7.13E+15	7.07E+15	6.95E+15	7.14E+15	6.00E+03
21	**Sn-121m**	5.50E+01	6.11E+15	1.73E+15	4.92E+14	1.12E+13	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	6.11E+15	t0
22	**U-233**	1.59E+05	1.53E+12	3.31E+12	5.29E+12	1.21E+13	2.54E+13	5.49E+13	1.46E+14	2.97E+14	5.88E+14	1.38E+15	2.48E+15	5.82E+15	6.00E+05
23	**Th-229**	7.34E+03	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	1.16E+12	4.68E+12	2.89E+13	1.04E+14	3.25E+14	1.11E+15	2.27E+15	5.81E+15	6.00E+05
24	**Cs-135**	2.30E+06	3.53E+15	3.53E+15	3.53E+15	3.53E+15	3.53E+15	3.53E+15	3.52E+15	3.52E+15	3.51E+15	3.48E+15	3.42E+15	3.53E+15	t0
25	**Sn-126**	2.30E+05	3.37E+15	3.37E+15	3.37E+15	3.36E+15	3.36E+15	3.35E+15	3.32E+15	3.27E+15	3.17E+15	2.90E+15	2.49E+15	3.37E+15	t0
26	**Cm-246**	4.73E+03	2.38E+15	2.34E+15	2.31E+15	2.21E+15	2.05E+15	1.77E+15	1.14E+15	5.49E+14	1.27E+14	1.56E+12	< 1.E+12	2.38E+15	2.00E-02
27	**Se-79**	3.77E+05	1.28E+15	1.28E+15	1.28E+15	1.28E+15	1.28E+15	1.28E+15	1.27E+15	1.26E+15	1.24E+15	1.17E+15	1.07E+15	1.28E+15	t0
28	**Nb-94**	2.00E+04	1.18E+15	1.18E+15	1.17E+15	1.16E+15	1.14E+15	1.10E+15	9.92E+14	8.34E+14	5.89E+14	2.08E+14	3.68E+13	1.18E+15	t0
29	**Cd-113m**	1.41E+01	1.02E+15	7.50E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	1.02E+15	t0
30	**Pd-107**	6.50E+06	1.01E+15	1.01E+15	1.01E+15	1.01E+15	1.01E+15	1.01E+15	1.01E+15	1.01E+15	1.01E+15	1.00E+15	9.97E+14	1.01E+15	t0
31	**Ni-59**	7.60E+04	9.16E+14	9.15E+14	9.14E+14	9.12E+14	9.08E+14	8.99E+14	8.75E+14	8.36E+14	7.63E+14	5.80E+14	3.68E+14	9.16E+14	t0
32	**C-14**	5.70E+03	3.41E+14	3.37E+14	3.32E+14	3.21E+14	3.02E+14	2.67E+14	1.85E+14	1.01E+14	2.99E+13	< 1.E+12	< 1.E+12	3.41E+14	t0
33	**Eu-152**	1.35E+01	2.86E+14	1.70E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	2.86E+14	t0
34	**Mo-93**	4.00E+03	2.75E+14	2.70E+14	2.66E+14	2.52E+14	2.31E+14	1.94E+14	1.16E+14	4.86E+13	8.59E+12	< 1.E+12	< 1.E+12	2.75E+14	t0
35	**H-3**	1.23E+01	2.63E+14	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	2.63E+14	t0
36	**Cl-36**	3.01E+05	1.72E+14	1.72E+14	1.72E+14	1.72E+14	1.72E+14	1.71E+14	1.70E+14	1.68E+14	1.64E+14	1.53E+14	1.37E+14	1.72E+14	t0
37	**Pu-242**	3.74E+05	7.99E+13	8.08E+13	8.15E+13	8.31E+13	8.51E+13	8.85E+13	9.60E+13	1.03E+14	1.06E+14	1.02E+14	9.27E+13	1.06E+14	2.00E+04
38	**Ca-41**	1.03E+05	7.25E+13	7.24E+13	7.24E+13	7.22E+13	7.20E+13	7.15E+13	7.01E+13	6.78E+13	6.33E+13	5.18E+13	3.70E+13	7.25E+13	t0
39	**U-234**	2.46E+05	3.31E+13	4.78E+13	5.60E+13	6.48E+13	6.68E+13	6.68E+13	6.62E+13	6.54E+13	6.36E+13	5.86E+13	5.12E+13	6.69E+13	1.25E+03
40	**Ho-166m**	1.20E+03	4.43E+13	4.18E+13	3.94E+13	3.32E+13	2.48E+13	1.39E+13	2.46E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	4.43E+13	t0
41	**Pb-210**	2.22E+01	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	2.30E+12	5.08E+12	1.03E+13	2.26E+13	3.45E+13	4.04E+13	2.00E+05
42	**Ra-226**	1.60E+03	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	2.31E+12	5.10E+12	1.03E+13	2.26E+13	3.45E+13	4.04E+13	2.00E+05
43	**Th-230**	7.54E+04	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	1.22E+12	1.82E+12	3.58E+12	6.37E+12	1.15E+13	2.34E+13	3.49E+13	4.04E+13	2.00E+05
44	**U-236**	2.37E+07	2.73E+12	3.09E+12	3.46E+12	4.53E+12	6.25E+12	9.42E+12	1.71E+13	2.56E+13	3.36E+13	3.76E+13	3.78E+13	3.78E+13	8.00E+04
45	**Ag-108m**	4.18E+02	1.02E+13	8.65E+12	7.33E+12	4.46E+12	1.95E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	1.02E+13	t0
46	**Eu-155**	4.75E+00	7.26E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	7.26E+12	t0
47	**Kr-85**	1.08E+01	6.36E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	6.36E+12	t0
48	**Co-60**	5.27E+00	4.69E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	4.69E+12	t0
49	**U-235**	7.04E+08	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	1.14E+12	2.65E+12	3.61E+12	3.91E+12	4.00E+05
50	**Ac-227**	2.18E+01	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	1.11E+12	2.55E+12	3.91E+12	5.00E+05
51	**Pa-231**	3.28E+04	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	1.11E+12	2.55E+12	3.91E+12	5.00E+05
52	**U-238**	4.47E+09	2.22E+12	2.22E+12	2.22E+12	2.22E+12	2.22E+12	2.22E+12	2.22E+12	2.22E+12	2.22E+12	2.22E+12	2.23E+12	2.23E+12	1.00E+06
53	**I-129**	1.61E+07	2.15E+12	2.15E+12	2.15E+12	2.15E+12	2.15E+12	2.15E+12	2.15E+12	2.15E+12	2.15E+12	2.15E+12	2.15E+12	2.15E+12	t0
*		Color pattern - Minimum values : 1.00E+12 Bq						Maximum values : 6.19E+19 Bq							

IL-LL waste - Total inventory (175981 primary waste packages)

Radionuclides sorted according to maximum activity over 1 My n° 1 to 62 - (t0 : 2140)

62 radionuclides activity (4.4E-01 < half-life < 5.0E+10 year and maximum activity > 1E+12 Bq) (After Darwin Pepin - Jeff 3.1.1.)

[Moteur - CIMASAF160022-23-25_E_AGIR-v44a__TCI-Cigéo-v24e_do141112-maR3-v5SF3_Pour-icono-DOSAF.xlsm]

n°	RN	Half-life [year]	Activity t0 = 2140 [Bq]	Activity t0=100 Y [Bq]	Activity t0+200 y [Bq]	Activity t0+500 y [Bq]	Activity t0+1000 y [Bq]	Activity t0+2000 y [Bq]	Activity t0+5000 y [Bq]	Activity t0+10000 y [Bq]	Activity t0+20000 y [Bq]	Activity t0+50000 y [Bq]	Activity t0+100000 y [Bq]	**Activity max over 1My [Bq**	Time for max over 1My [Y]
1	**Ni-63**	1.01E+02	6.94E+18	3.49E+18	1.75E+18	2.22E+17	7.07E+15	7.19E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	6.94E+18	t0
2	**Cs-137**	3.00E+01	1.03E+18	1.02E+17	1.02E+16	1.00E+13	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	1.03E+18	t0
3	**Am-241**	4.33E+02	3.29E+17	2.81E+17	2.39E+17	1.48E+17	6.65E+16	1.34E+16	1.14E+14	2.75E+12	1.20E+12	< 1.E+12	< 1.E+12	3.29E+17	t0
4	**Sr-90**	2.88E+01	2.40E+17	2.16E+16	1.95E+15	1.42E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	2.40E+17	t0
5	**Pu-238**	8.77E+01	9.26E+16	4.20E+16	1.91E+16	1.78E+15	3.47E+13	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	9.26E+16	t0
6	**Ni-59**	7.60E+04	7.50E+16	7.49E+16	7.49E+16	7.47E+16	7.43E+16	7.37E+16	7.17E+16	6.85E+16	6.25E+16	4.75E+16	3.01E+16	7.50E+16	t0
7	**Pu-240**	6.56E+03	3.77E+16	3.74E+16	3.70E+16	3.58E+16	3.40E+16	3.06E+16	2.23E+16	1.31E+16	4.57E+15	1.92E+14	1.08E+12	3.77E+16	2.00E-02
8	**Pu-239**	2.41E+04	3.49E+16	3.48E+16	3.47E+16	3.44E+16	3.40E+16	3.30E+16	3.03E+16	2.63E+16	1.97E+16	8.35E+15	1.98E+15	3.49E+16	1.00E-01
9	**C-14**	5.70E+03	3.49E+16	3.45E+16	3.41E+16	3.29E+16	3.09E+16	2.74E+16	1.90E+16	1.04E+16	3.07E+15	7.99E+13	< 1.E+12	3.49E+16	t0
10	**Nb-94**	2.00E+04	3.11E+16	3.10E+16	3.09E+16	3.06E+16	3.00E+16	2.90E+16	2.61E+16	2.20E+16	1.55E+16	5.49E+15	9.69E+14	3.11E+16	t0
11	**Pu-241**	1.43E+01	2.59E+16	2.11E+14	7.35E+12	5.58E+12	5.36E+12	4.94E+12	3.87E+12	2.57E+12	1.14E+12	< 1.E+12	< 1.E+12	2.59E+16	t0
12	**H-3**	1.23E+01	1.86E+16	6.73E+13	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	1.86E+16	t0
13	**Sm-151**	9.00E+01	5.84E+15	2.70E+15	1.25E+15	1.24E+14	2.64E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	5.84E+15	t0
14	**Ra-226**	1.60E+03	5.70E+15	5.50E+15	5.31E+15	4.79E+15	4.05E+15	2.98E+15	1.54E+15	1.07E+15	1.02E+15	1.02E+15	9.85E+14	5.70E+15	1.00E-02
15	**Pb-210**	2.22E+01	5.70E+15	5.56E+15	5.37E+15	4.84E+15	4.09E+15	3.01E+15	1.55E+15	1.07E+15	1.02E+15	1.02E+15	9.85E+14	5.70E+15	t0
16	**Tc-99**	2.14E+05	4.97E+15	4.97E+15	4.97E+15	4.96E+15	4.96E+15	4.94E+15	4.89E+15	4.81E+15	4.66E+15	4.23E+15	3.60E+15	4.97E+15	t0
17	**Nb-93m**	1.61E+01	2.68E+15	2.70E+15	2.68E+15	2.61E+15	2.52E+15	2.35E+15	1.98E+15	1.67E+15	1.48E+15	1.42E+15	1.39E+15	2.71E+15	5.00E+01
18	**Ag-108m**	4.18E+02	2.32E+15	1.96E+15	1.66E+15	1.01E+15	4.41E+14	8.41E+13	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	2.32E+15	t0
19	**Zr-93**	1.53E+06	1.49E+15	1.49E+15	1.49E+15	1.49E+15	1.49E+15	1.49E+15	1.48E+15	1.48E+15	1.47E+15	1.45E+15	1.42E+15	1.49E+15	t0
20	**Mo-93**	4.00E+03	1.44E+15	1.41E+15	1.39E+15	1.32E+15	1.21E+15	1.02E+15	6.05E+14	2.54E+14	4.50E+13	< 1.E+12	< 1.E+12	1.44E+15	t0
21	**Pd-107**	6.50E+06	1.19E+15	1.19E+15	1.19E+15	1.19E+15	1.19E+15	1.19E+15	1.19E+15	1.19E+15	1.19E+15	1.18E+15	1.18E+15	1.19E+15	t0
22	**Np-237**	2.14E+06	1.06E+15	1.07E+15	1.08E+15	1.10E+15	1.12E+15	1.13E+15	1.13E+15	1.13E+15	1.12E+15	1.11E+15	1.09E+15	1.13E+15	4.00E+03
23	**U-234**	2.46E+05	1.09E+15	1.11E+15	1.12E+15	1.12E+15	1.12E+15	1.12E+15	1.11E+15	1.10E+15	1.07E+15	9.88E+14	8.67E+14	1.12E+15	6.00E+02
24	**U-233**	1.59E+05	1.06E+15	1.06E+15	1.06E+15	1.06E+15	1.06E+15	1.06E+15	1.06E+15	1.06E+15	1.07E+15	1.07E+15	1.08E+15	1.08E+15	1.50E+05
25	**Th-229**	7.34E+03	1.03E+15	1.03E+15	1.03E+15	1.03E+15	1.03E+15	1.04E+15	1.04E+15	1.05E+15	1.06E+15	1.07E+15	1.08E+15	1.08E+15	1.50E+05
26	**Th-230**	7.54E+04	1.00E+15	1.00E+15	1.00E+15	1.00E+15	1.00E+15	1.00E+15	1.01E+15	1.01E+15	1.02E+15	1.02E+15	9.83E+14	1.02E+15	4.00E+04
27	**Co-60**	5.27E+00	9.17E+14	4.38E+14	4.38E+14	4.38E+14	4.38E+14	4.38E+14	4.37E+14	4.36E+14	4.34E+14	4.28E+14	4.18E+14	9.17E+14	t0
28	**Cm-244**	1.80E+01	7.57E+14	1.61E+13	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	7.57E+14	t0
29	**Sn-121m**	5.50E+01	6.16E+14	1.75E+14	4.95E+13	1.13E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	6.16E+14	t0
30	**Am-243**	7.36E+03	4.99E+14	4.94E+14	4.90E+14	4.76E+14	4.54E+14	4.13E+14	3.12E+14	1.95E+14	7.60E+13	4.54E+12	< 1.E+12	4.99E+14	5.00E-02
31	**Fe-60**	1.50E+06	4.39E+14	4.39E+14	4.39E+14	4.39E+14	4.39E+14	4.39E+14	4.38E+14	4.37E+14	4.35E+14	4.29E+14	4.20E+14	4.39E+14	t0
32	**Nb-91**	6.80E+02	3.36E+14	3.03E+14	2.74E+14	2.02E+14	1.21E+14	4.37E+13	2.06E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	3.36E+14	t0
33	**Be-10**	1.60E+06	2.89E+14	2.89E+14	2.89E+14	2.89E+14	2.89E+14	2.89E+14	2.88E+14	2.88E+14	2.86E+14	2.83E+14	2.77E+14	2.89E+14	t0
34	**Kr-85**	1.08E+01	2.62E+14	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	2.62E+14	t0
35	**Pu-242**	3.74E+05	1.68E+14	1.68E+14	1.68E+14	1.68E+14	1.68E+14	1.67E+14	1.66E+14	1.65E+14	1.62E+14	1.53E+14	1.39E+14	1.68E+14	2.50E+00
36	**U-236**	2.37E+07	7.31E+13	7.32E+13	7.33E+13	7.37E+13	7.42E+13	7.51E+13	7.74E+13	7.99E+13	8.23E+13	8.34E+13	8.33E+13	8.34E+13	6.00E+04
37	**Cm-243**	3.00E+01	8.31E+13	8.25E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	8.31E+13	t0
38	**Cl-36**	3.01E+05	8.25E+13	8.24E+13	8.24E+13	8.24E+13	8.23E+13	8.21E+13	8.15E+13	8.06E+13	7.87E+13	7.35E+13	6.55E+13	8.25E+13	t0
39	**Sn-126**	2.30E+05	7.50E+13	7.50E+13	7.49E+13	7.49E+13	7.47E+13	7.45E+13	7.39E+13	7.27E+13	7.06E+13	6.45E+13	5.55E+13	7.50E+13	t0
40	**U-238**	4.47E+09	7.19E+13	7.19E+13	7.19E+13	7.19E+13	7.19E+13	7.19E+13	7.19E+13	7.19E+13	7.19E+13	7.19E+13	7.19E+13	7.19E+13	4.00E+05
41	**Th-228**	1.91E+00	7.13E+13	7.12E+13	7.11E+13	7.11E+13	7.11E+13	7.11E+13	7.11E+13	7.11E+13	7.11E+13	7.11E+13	7.11E+13	7.13E+13	3.00E+00
42	**Th-232**	1.41E+10	7.11E+13	7.11E+13	7.11E+13	7.11E+13	7.11E+13	7.11E+13	7.11E+13	7.11E+13	7.11E+13	7.11E+13	7.11E+13	7.11E+13	5.00E+05
43	**Ra-228**	5.75E+00	7.11E+13	7.11E+13	7.11E+13	7.11E+13	7.11E+13	7.11E+13	7.11E+13	7.11E+13	7.11E+13	7.11E+13	7.11E+13	7.11E+13	5.00E+05
44	**Pt-193**	5.00E+01	6.70E+13	1.67E+13	4.18E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	6.70E+13	t0
45	**Eu-154**	8.59E+00	6.46E+13	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	6.46E+13	t0
46	**U-235**	7.04E+08	4.23E+13	4.23E+13	4.23E+13	4.24E+13	4.24E+13	4.24E+13	4.25E+13	4.26E+13	4.29E+13	4.33E+13	4.35E+13	4.35E+13	2.50E+05
47	**Ac-227**	2.18E+01	3.11E+13	3.12E+13	3.12E+13	3.12E+13	3.14E+13	3.16E+13	3.23E+13	3.33E+13	3.51E+13	3.89E+13	4.18E+13	4.35E+13	4.00E+05
48	**Pa-231**	3.28E+04	3.11E+13	3.12E+13	3.12E+13	3.13E+13	3.14E+13	3.16E+13	3.23E+13	3.33E+13	3.51E+13	3.89E+13	4.18E+13	4.35E+13	4.00E+05
49	**Se-79**	3.77E+05	3.94E+13	3.94E+13	3.94E+13	3.94E+13	3.94E+13	3.93E+13	3.91E+13	3.87E+13	3.80E+13	3.60E+13	3.28E+13	3.94E+13	t0
*		Color pattern - Minimum values : 1.00E+12 Bq						Maximum values : 6.94E+18 Bq							

IL-LL waste - Total inventory (175981 primary waste packages)

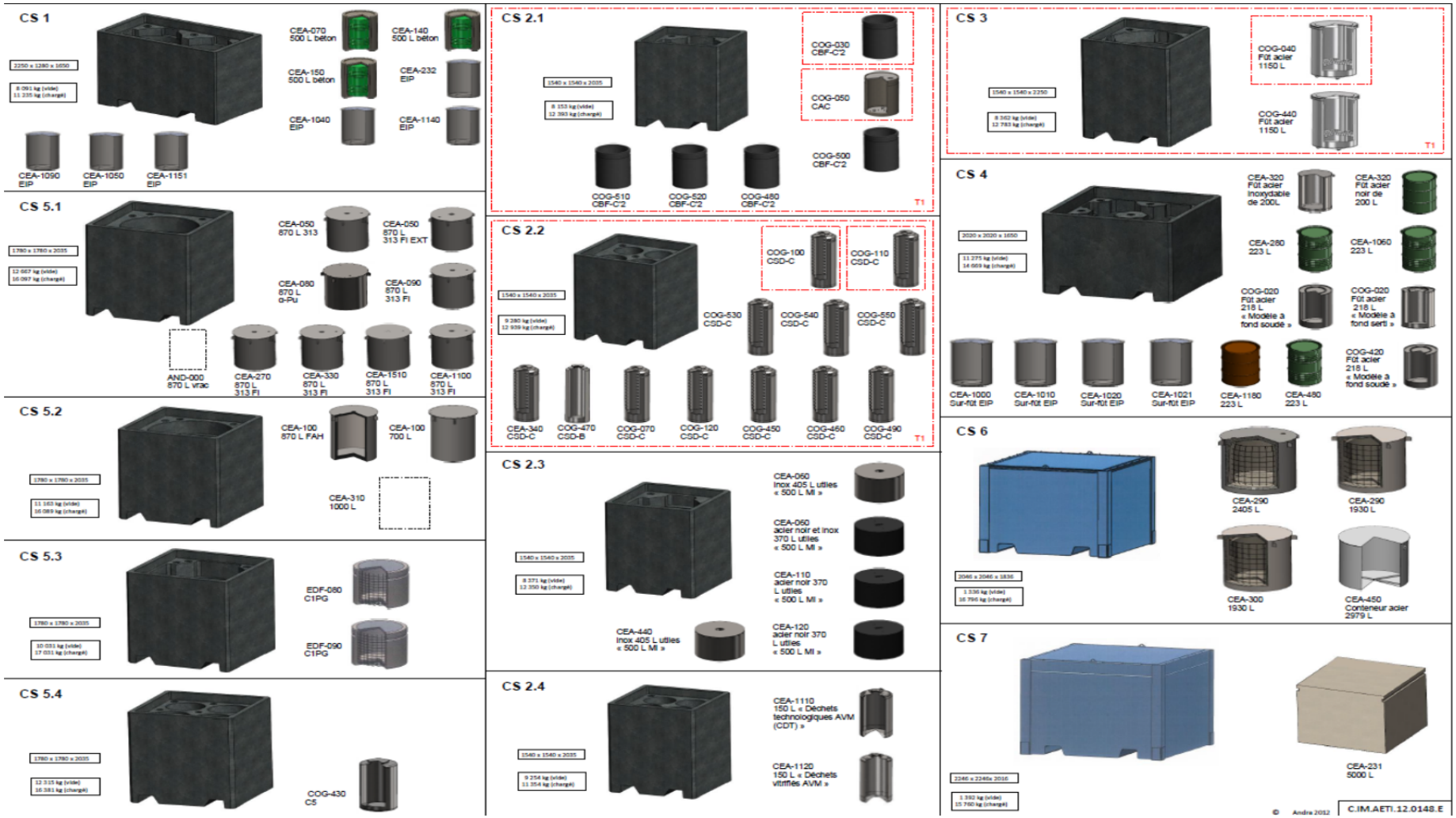
Radionuclides sorted according to maximum activity over 1 My n° 1 to 62 - (t0 : 2140)

62 radionuclides activity (4.4E-01 < half-life < 5.0E+10 year and maximum activity > 1E+12 Bq) (After Darwin Pepin - Jeff 3.1.1.)

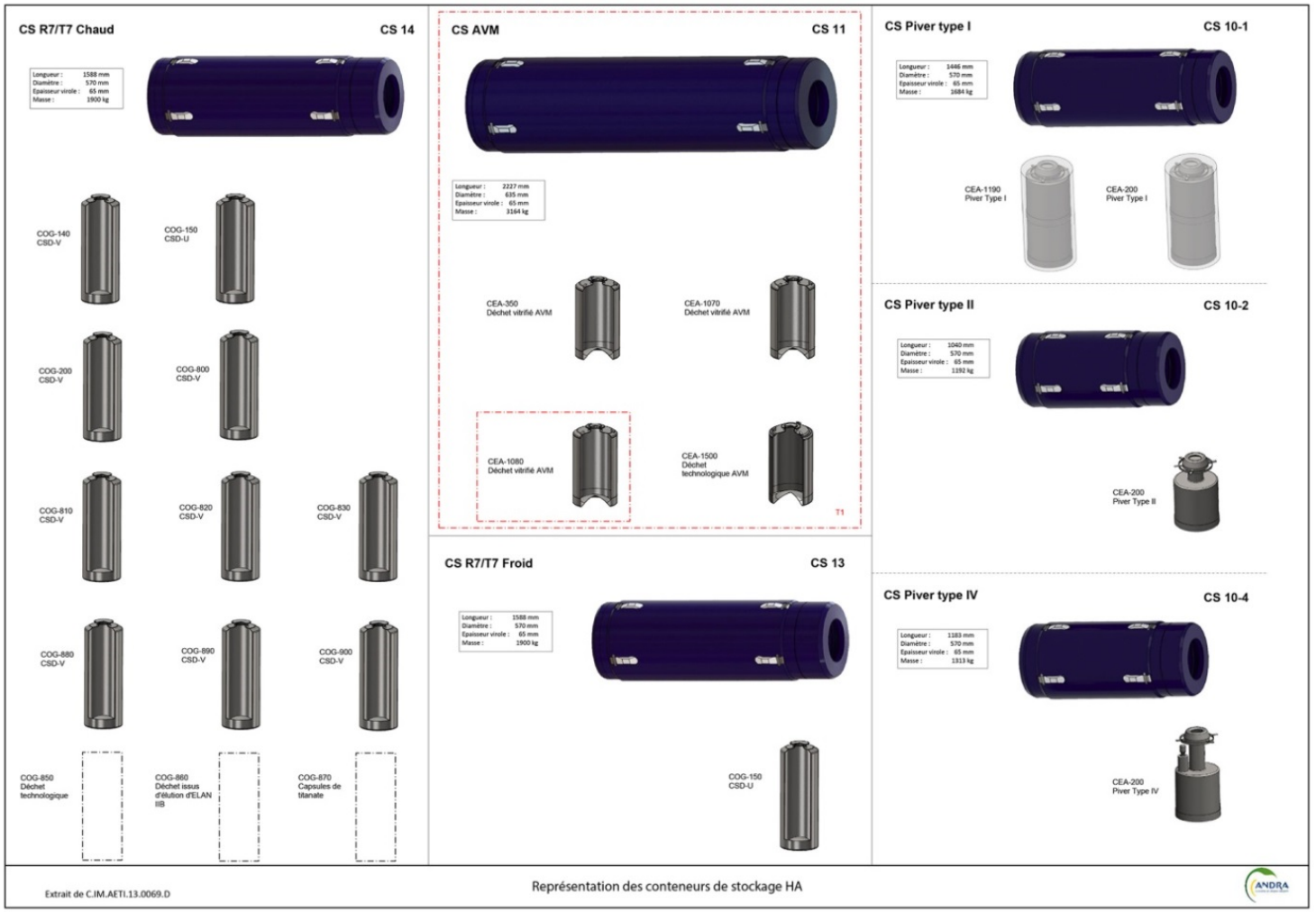
[Moteur - CIMASAF160022-23-25_E_AGIR-v44a__TCI-Cigéo-v24e_do141112-maR3-v5SF3_Pour-icono-DOSAF.xlsm]

n°	RN	Half-life [year]	Activity t0 = 2140 [Bq]	Activity t0=100 Y [Bq]	Activity t0+200 y [Bq]	Activity t0+500 y [Bq]	Activity t0+1000 y [Bq]	Activity t0+2000 y [Bq]	Activity t0+5000 y [Bq]	Activity t0+10000 y [Bq]	Activity t0+20000 y [Bq]	Activity t0+50000 y [Bq]	Activity t0+100000 y [Bq]	**Activity max over 1My [Bq**	Time for max over 1My [Y]
50	**Ar-39**	2.69E+02	3.18E+13	2.46E+13	1.90E+13	8.77E+12	2.42E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	3.18E+13	t0
51	**Am-242m**	1.41E+02	2.89E+13	1.77E+13	1.08E+13	2.47E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	2.89E+13	t0
52	**Cs-135**	2.30E+06	2.44E+13	2.44E+13	2.44E+13	2.44E+13	2.44E+13	2.44E+13	2.43E+13	2.43E+13	2.42E+13	2.40E+13	2.37E+13	2.44E+13	t0
53	**Cm-242**	4.46E-01	2.39E+13	1.47E+13	8.98E+12	2.05E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	2.39E+13	t0
54	**Nb-92**	3.50E+07	1.52E+13	1.52E+13	1.52E+13	1.52E+13	1.52E+13	1.52E+13	1.52E+13	1.52E+13	1.52E+13	1.52E+13	1.52E+13	1.52E+13	t0
55	**Cd-113m**	1.41E+01	1.24E+13	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	1.24E+13	t0
56	**Ca-41**	1.03E+05	9.30E+12	9.29E+12	9.29E+12	9.27E+12	9.24E+12	9.18E+12	8.99E+12	8.69E+12	8.13E+12	6.64E+12	4.74E+12	9.30E+12	t0
57	**Cm-245**	8.50E+03	5.81E+12	5.76E+12	5.71E+12	5.58E+12	5.35E+12	4.93E+12	3.86E+12	2.57E+12	1.14E+12	< 1.E+12	< 1.E+12	5.81E+12	5.00E-02
58	**Sm-146**	1.00E+08	4.31E+12	4.31E+12	4.31E+12	4.31E+12	4.31E+12	4.31E+12	4.31E+12	4.31E+12	4.31E+12	4.31E+12	4.31E+12	4.31E+12	6.00E+02
59	**Gd-150**	1.82E+06	3.43E+12	3.43E+12	3.43E+12	3.43E+12	3.43E+12	3.42E+12	3.42E+12	3.41E+12	3.40E+12	3.36E+12	3.30E+12	3.43E+12	1.25E+01
60	**Eu-152**	1.35E+01	2.34E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	2.34E+12	t0
61	**I-129**	1.61E+07	1.90E+12	1.90E+12	1.90E+12	1.90E+12	1.90E+12	1.90E+12	1.90E+12	1.90E+12	1.90E+12	1.90E+12	1.89E+12	1.90E+12	t0
62	**Cm-246**	4.73E+03	1.58E+12	1.56E+12	1.54E+12	1.47E+12	1.37E+12	1.18E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	< 1.E+12	1.58E+12	2.00E-02
*		Color pattern - Minimum values : 1.00E+12 Bq						Maximum values : 6.94E+18 Bq							

Appendix 4 : ILW-LL disposal package models at the basic engineering design stage



Appendix 5 : HLW disposal package models at the basic engineering design stage



Appendix 6 : Extract from the ASN's 2008 safety guide onsite technical criteria

"The key criteria for the choice of site are as follows:

- *Stability*

The stability of the geological medium should be such that any changes in the initial conditions, due to natural phenomena (e.g. glaciation, seismic activity, neotectonic movements), shall remain acceptable from the repository safety point of view. It is recommended that the choice of site and the design of the disposal facility are such that any changes in the disposal system can be determined over a period of time allowing substantial decay of the radioactivity of the radionuclides in the waste package inventory. In particular, the stability of the geological medium (which should allow for limited, predictable changes) must be demonstrated for a period of at least 10,000 years.

- *Hydrogeology*

The site's hydrogeology should be characterised by very low permeability of the host formation and a low hydraulic head gradient. A low regional hydraulic head gradient shall also be sought for the formations surrounding the host rock.

Hydrogeological measurements should be made over a much wider zone than that of the site in order to build flow models that take into consideration flows from the source zones to the outlets. These regional models should allow simulation of the speed and direction of underground circulation.

Water-conducting discontinuities and heterogeneities should be identified, characterised and taken into account where the nature and geometry of these could reduce the capacity of the host rock locally to participate in the safety functions.

- *Minimum depth*

The site should be chosen such that the chosen depth of the waste disposal structures covered by this rule can guarantee that the repository's safety will not be significantly affected by erosion phenomena (particularly as a result of glaciation), by the effects of an earthquake, or by the consequences of a "minor" human intrusion.

The thickness of the surface zone that could be disturbed in this way is around 200 metres.

- *No sterilisation of extractable underground resources*

The site should be chosen so as to avoid areas that could be of exceptional interest in terms of underground resources".

Appendix 7 : Performance of vitrified high-level waste (HLW)

A distinction is made between AREVA's CSD-V vitrified waste and other vitrified waste.

AREVA's CSD-V vitrified waste

This section concerns vitrified waste of the COG-140 and COG-800 families, with which there is a large amount of past experience.

- ***Knowledge of behaviour based on more than 30 years' R&D***

R&D conducted for over 30 years on vitrified waste has determined the evolution of the glass' alteration over time (see Figure 2.4-3), and this is now the subject of an international consensus. To begin with, the glass alters at initial rate V_0, then at residual rate V_R, which is much lower than the initial rate V_0 (around 4 times lower at 50°C). Between these two rates, there is a transitional alteration rate known as the "rate drop".

The alteration of the glass at the initial rate is mainly driven by the hydrolysis of the silicate network. The initial alteration rate increases as the pH and temperature increase. The requirements of a pH close to neutral and restriction of the temperature to 70°C when the disposal container breaks will limit the initial release rate of the vitrified waste. The variability of the initial alteration rate of R7/T7 glasses in the R7/T7 composition range as specified by AREVA is low (around a factor of 4). Furthermore, studies have determined the initial alteration rate of R7/T7 glasses in a clayey synthetic water representative of expected repository conditions: it is approximately 5 times higher than the rate measured in deionised water due to its alkaline and alkaline earth ion concentrations and to a lesser extent its pH.

The transitional rate drop is a consequence of the reduction in glass dissolution affinity and in the formation of a passivating gel, which acts as a diffusion barrier to the chemical species, particularly the silicon. In the absence of environmental materials, the quantity of glass altered during this stage is low compared with the other two stages (initial and residual alteration rates).

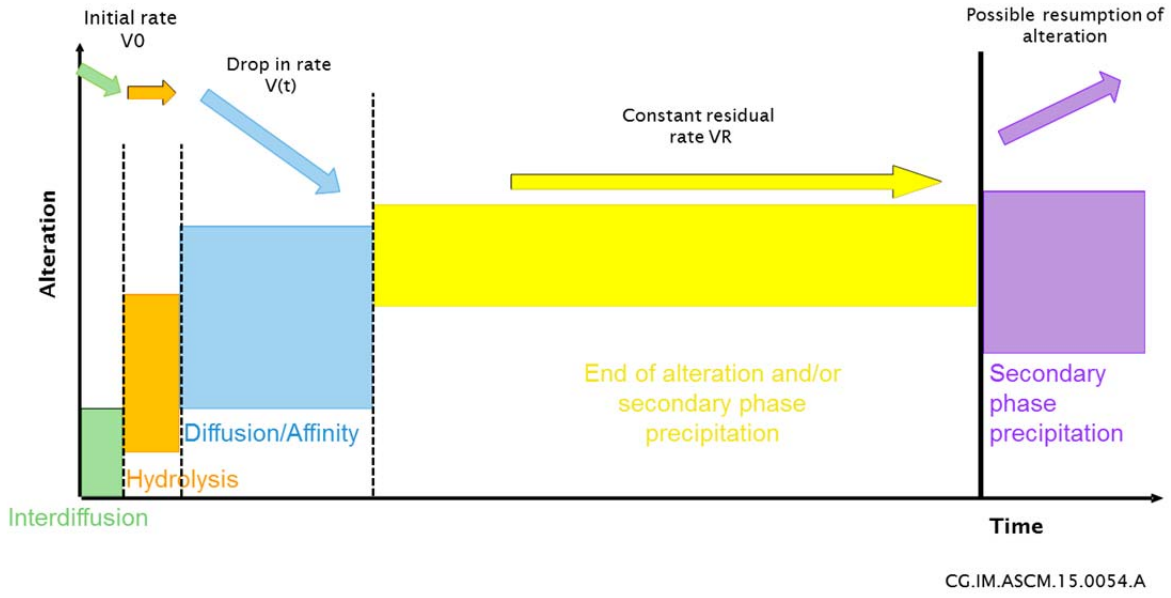


Figure 2.4-3: Evolution of the quantity of glass altered associated with different alteration rates as a function of time

The residual alteration rate is due to an equilibrium being reached between, on the one hand, limitation of the reaction affinity and of migration within the glass alteration film and, on the other hand, the precipitation of more or less crystallised secondary phases such as phyllosilicates, which keep the alteration of the glass going by consuming silicon. The residual rate increases when the temperature increases. It varies as a function of pH depending on the alteration conditions and the glass composition. The variability of the residual alteration rate of R7/T7 glasses in the R7/T7 composition range as specified by AREVA is low (around a factor of 10). Furthermore, studies have determined the residual alteration rate of R7/T7 glasses in the presence of a clayey synthetic water representative of expected repository conditions. It is heavily dependent on whether or not magnesium silicate phases could precipitate, which leads experimentally to residual rates approximately 5 times higher than those measured in deionised water under more conservative water renewal conditions than those expected in repository. The precipitation of these phases is only possible in the presence of magnesium and only above a threshold pH. If there is no magnesium renewal or if the pH drops, the residual rate measured is then similar to that measured in deionised water.

The transition from the initial rate to a residual rate is quick in deionised water and static conditions (the larger the surface area of the glass, the quicker) but in repository it will depend on the environmental conditions. This time period is directly linked to the interactions between silicon (released by the glass), iron (sleeve, disposal container) and corrosion products. These interactions are governed in the short term by silicon sorption and in the medium and long term by co-precipitation of silicon with iron, leading to the formation of iron silicates. Numerous experiments have been carried out in surface and underground laboratories in order to determine the nature of corrosion products and the results are consistent with results from the examination of archaeological analogues.

The resumption of glass alteration can lead to an increase in the alteration rate to values nearly but not quite as high as the initial rate. It is caused by the precipitation of secondary phases (mainly zeolites), which have only been observed experimentally at temperatures above 90°C and pH values above 10.5 at ambient temperature. The requirements of a pH close to neutral and restriction of the temperature to 70°C when the disposal container breaks prevent this risk.

Once the disposal container has broken, the alteration of vitrified waste can begin in water (saturated conditions) or in water vapour (non-saturated conditions caused in particular by hydrogen production linked to the corrosion of the metal sleeve and disposal container). Studies conducted in the last five years or so show that the alteration rate of glass at 90°C (known as the hydration rate or V_{hydr}) is higher by approximately one order of magnitude than the residual leaching rate measured in pure water at the same temperature. This is probably an overestimate because the only long-term experiment shows a reduction in the alteration rate over time. Furthermore, the hydration rate increases as the relative humidity and temperature increase. It is always well below the initial alteration rate. When glass is weathered, no radionuclides are released.

The quantity of altered glass depends on the alteration rate and the reactive surface area of the glass. As with the alteration rate, the apparent reactive surface area is unique to each alteration rate. It is equal to the total surface area of the glass (i.e. approximately 40 times the external surface area of the glass block if fracturing is included) for the residual rate and around 5 times higher than the external surface area for the initial rate. The reactive surface area during glass weathering is unknown but is likely to be somewhere between the two values given above. The glass fracturing measurements have been confirmed by numerical simulations. The models developed show (i) that there is less fracturing with glasses produced in a cold crucible than with glasses produced in a melting pot and (ii) that the risk of excessive fracturing in the waste repository due to overburden pressure can be ruled out.

Most of the R&D was carried out on inactive SON68 reference glass but experiments on active glasses have also been performed to check that they behave in a similar way. Studies of self-irradiation effects (up to cumulative doses of at least 10^{19} α/g) do not show any modification of the microstructure and show an increase in resistance to cracking. Above a cumulative dose of $4x10^{18}$ α/g, the physicochemical properties stabilise (equilibrium between damage being caused and restoration of the structure). Helium production linked to α decays has no impact on the mechanical behaviour of the glass up to a content of $8x10^{19}$ He/g (corresponding to several million years). Studies of leaching of

active glasses show no significant differences compared with those on inactive glasses, at both the initial alteration rate and the residual alteration rate.

If a filling material is put on the sleeve extrados, its impact must be assessed as regards the alteration of vitrified waste. The requirements indicate on the one hand that the filling material formulation should limit as much as possible any chemical disturbances to the vitrified waste and to the mobility of dissolved radionuclides, and on the other hand that it should lead to a favourable physicochemical environment for the protection of vitrified waste, it means in particularly that the cell should have a pH close to neutral. The R&D programme launched in 2015 is designed to check that these requirements have been met with regard to (i) the initial and residual alteration rates of the glass, which will depend mainly on the pH in the immediate vicinity of glass when the water comes in, and (ii) the transition time necessary to reach the residual rate, which is strongly linked to the nature of corrosion products of sleeve and disposal container.

- ***Conservative alteration models based on phenomenological knowledge***

The alteration model developed by Andra, the CEA and producers is described by Figure 2.4-4. It identifies 4 phases:

4. as long as the primary container remains sealed, there is no glass alteration;
5. once the container breaks, the glass is weathered. In the absence of liquid water, no radionuclides are released;
6. once the clearances within the container have become saturated with water, the glass leaching begin at the initial rate. The release of radionuclides is then congruent with glass alteration. When resaturation occurs, radionuclides within earlier weathered glass are released immediately. This is a very conservative approach, but it is based on experience showing that tracer elements are rapidly released from previously weathered glass when it is subsequently leached by water;
7. once the metal components have completely corroded and the corrosion products have become saturated with silicon, the glass leaching goes on at residual rate V_R. The hypotheses adopted at this stage to assess the duration of the transition phase to reach the residual rate are very conservative . It will also be necessary to evaluate the effect of the sleeve extrados filling material on the nature of corrosion products and therefore on the duration of the transition phase to reach the residual rate.

The lifetime of vitrified waste packages therefore depends on parameters intrinsic to the glass (alteration rates, reactive surface areas, etc.) but also on parameters specific to metal components (corrosion rates, nature and properties of corrosion products) and on the physicochemical conditions in the HLW cell (evolution of resaturation, pH, temperature). Depending on the environmental conditions, it could be as much as several thousand years.

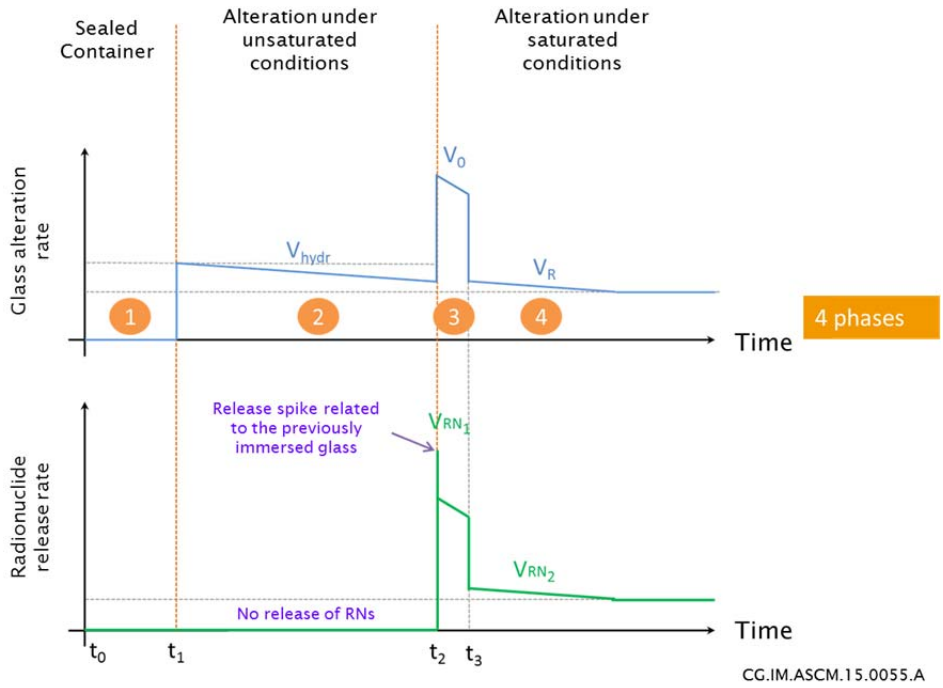


Figure 2.4-4: Evolution of glass alteration rate and radionuclide release rate as a function of time for the different glass alteration phases

This model is applicable only for homogeneous glass (in particular without crystallisation). The production specifications, glass composition, cooling scenario and maximum temperature of glass during storage (temperature below 510°C at the core of the glass) and disposal (temperature below 450°C required at the core of the glass under permanent conditions and of 500°C under transitional conditions for 24 hours at most, in particular due to the stress relieving treatment of the disposal container) guarantee the stability of the glass matrix and the maintenance of its containment properties.

Other vitrified waste

The phenomenology described above for R7/T7 glasses can be transposed to other borosilicate glasses with specific sets of parameters, but the level of knowledge for these different glasses (variability of composition, long-term behaviour) means that the same alteration model cannot be used in all cases.

For glasses in the R7/T7 glass composition range, the model set out above can be applied. This is the case in particular for the vitrified waste from Atalante (CEA-350) and for some of the vitrified purge glasses (COG-810) and calcine glasses (COG-820), the PWR/FNR glasses (COG-830), glasses resulting from the reprocessing of MOX fuels mixed with spent UOX and ERU fuels (COG-200), glasses resulting from the reprocessing of the CEA's spent fuel (COG-880 and COG-890) and glasses resulting from the treatment of the EL4 reactor at Brennilis (COG-900).

For the AVM glasses produced in accordance with quality assurance specifications (CEA-1070) and the AVM glasses not produced in accordance with quality assurance specifications but the composition of which is in the composition range of glasses produced in accordance with quality assurance specifications (some of the CEA-1080 glasses), the model proposed above is applicable with a specific set of parameters. In the absence of any hydration rate measurements, the hydration rate is conservatively considered to be the same as the initial alteration rate. Research in progress aims to confirm that this model would apply to these AVM glasses by studying more specifically the transition phase from the initial rate to the residual rate.

For other AVM glasses (some of the CEA-1080 glasses), the PIVER glasses (CEA-200) and the UMo glasses (COG-150), the model proposed is a simplified version of the previous model, which does not consider the residual alteration rate because of a lack of data. Furthermore, because the hydration rate is not known, it is assumed to be the same as the initial alteration rate. This results in an alteration model that is very conservative as regards radionuclide release and leads to life times of several thousands of years (several tens of thousands of years for UMo glasses).

For less than a dozen AVM glasses of atypical composition, the proposed model conservatively leads to a very rapid glass alteration.

For glasses of atypical composition making any transposition from known borosilicate glasses impossible and for which the parameters (surface area, initial leaching rate, etc.) are unknown, no model can be proposed. This is the case in particular with the VULCAIN and GULIVER glasses (CEA-1190), the purge glasses and calcine glasses produced with CE22 glass frit (some of COG-810 and COG-820). This affects a very small number of packages.

Appendix 8 : Performance of intermediate-level long-lived waste (ILW-LL)

Vitrified ILW-LL

The purpose of the glass matrix of vitrified ILW-LL is to "limit the release of radionuclides and immobilise them in the waste repository" through its resistance to leaching. The performance of these packages depends on the environmental conditions and therefore on the chosen disposal option, but in all cases the diagram in Figure 2.4-3 applies. The chosen disposal option has no impact on the hydration rate (no interaction with surrounding materials): where this rate is unknown (AVM glasses and Valduc glasses) it is assumed to be the same as the initial alteration rate. The initial and residual rates do, however, depend on the chosen disposal option.

- ***Disposal in a HLW cell: similar behaviour to vitrified HLW***

The behaviour of vitrified ILW-LL disposed of in a HLW cell is identical to that of vitrified HLW. Because the composition of AVM glasses (CEA-1120 except those containing beryllium) is in the composition range of the AVM glasses produced in accordance with quality assurance specifications (CEA-1070), a similar release model including the residual rate is proposed.

For other AVM glasses (CEA-1120), the ILW-LL glasses from Valduc (CEA-340) and the CSD-B glasses (COG-340), the model proposed is a simplified version of the model for the R7/T7 glasses, which does not consider the residual alteration rate because of a lack of data. This results in an alteration model that is very conservative as regards radionuclide releases.

- ***Disposal in an ILW-LL cell: different behaviours depending on the type of concrete***

Where vitrified ILW-LL waste is disposed of in an ILW-LL cell, the glass matrix will be leached by cementitious water. The phenomenology is identical to that for vitrified HLW (Figure 2.4-3) but it is no longer possible to rule out the risk of alteration resumption due to an alkaline pH. Moreover, this alteration resumption has been observed in certain experiments (at 300 and 700 days for experiments performed at pH 13.2 and 50°C). On the other hand, experiments conducted in water at equilibrium with a low-pH concrete show a more marked rate drop (3 orders of magnitude rather than 2 for standard concretes) and no alteration resumption. However, there is not enough knowledge to demonstrate that there is no risk of alteration resumption or to configure a model that includes a residual rate. Consequently, the release model proposed for disposal options with standard concrete and low-pH concrete is a simplified, conservative model that does not take account of a residual rate being reached. In view of these hypotheses, the lifetime of vitrified ILW-LL waste is therefore between a few hundred and a few thousand years.

Activated metal waste

The processes used and the associated parameters depend on where in the waste the radionuclides are located:

- the release of activated radionuclides in different alloys depends on the following processes and parameters:
  - ✓ the metal oxidation process (corrosion of the metal); the associated parameters are the corrosion rate and the thickness of the piece of metal containing the activation products;
  - ✓ the formation and dissolution of an oxide layer on the metal's surface, and the possible migration of the radionuclides within this oxide layer; the parameters associated with these processes of oxide dissolution and radionuclide migration within the oxide are unknown at this stage of the research;
- the radionuclides within the zirconium oxide (in the case of zirconium alloys) are released either through dissolution of the zirconium oxide or through migration within the zirconium oxide. At this stage, no release model has been proposed for the inventory in the zirconium oxide;
- the radionuclides on the surface of the various materials are released instantaneously when the water arrives.

The corrosion rates of the stainless steels, nickel alloys and zirconium alloys have been measured experimentally and compared with data in the literature. The rates used are by preference those from long-term tests performed under experimental conditions similar to those expected in the waste repository: a pH of between 9 (long term) and 12.5/13.5 (short term), anoxic conditions, a temperature of between 25°C and 50°C, presence of chlorides, etc.). The corrosion rates are scarcely or not at all affected by the effects of irradiation or by changes in temperature and pH over time. They lead to the release of all the activation products at between 10,000 and 100,000 years.

Saline waste with a bitumen matrix

The presence of water in contact with bituminised waste leads to the release of salts and radionuclides in accordance with the process described in Figure 2.4-5.

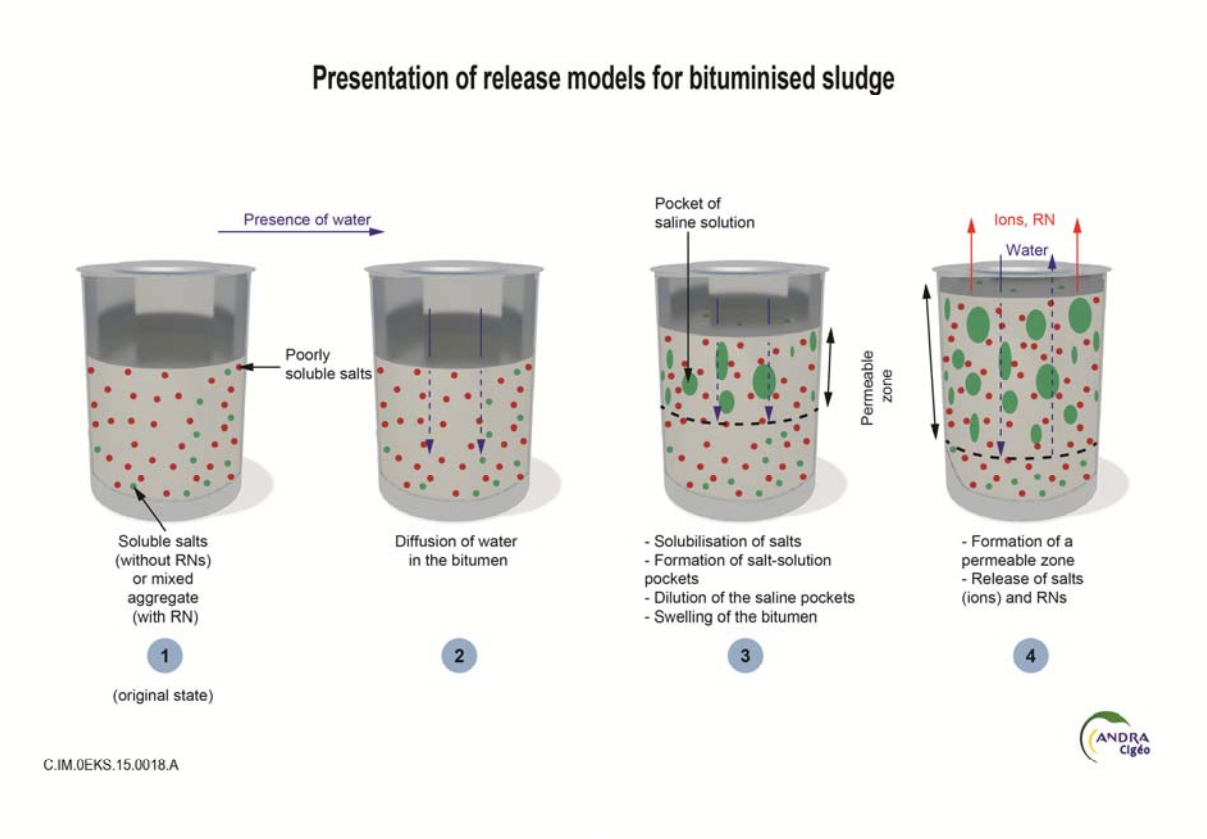


Figure 2.4-5: Release of salts and radionuclides as a result of water entering bituminised waste

This process of releasing radionuclides and salts was the subject of a model known as COLONBO, the validity domain of which is based in particular on the following hypotheses:

- a mass concentration of soluble salts in the embedded waste of between 2% and 22%, which applies to most packages except some of the legacy drums at STEL;
- a temperature of between 20°C and 30°C: this criterion is covered by the requirement to place cells of bituminised sludge far enough away from other cells that a temperature of 30°C is not exceeded within the waste;
- a pH of between 7 and 12.5: the choice of cementitious material used for the container packages and/or liners helps to keep within this pH range;
- maintenance of geometry: because the model is based on water and salt diffusion, the package performance is closely linked to the geometry (thickness) of the embedded waste. This geometry is maintained as long as the disposal package remains intact, i.e. for at least 1000 years. Once the disposal package ruptures, the geometry can no longer be maintained so the model no longer applies.

A very conservative simplified model has been developed: this model is based on the solubility of the salts and does not take account of the bitumen matrix. If this model is used, it must be coupled with calculations of the solubility of the salts in the cell in a cementitious environment.

Non-bituminised saline waste

For saline waste that does not include a bitumen matrix, only the model based on the solubility of the salts is applicable

Appendix 9 : Families suitable for co-disposal from a physicochemical point of view

Elementary family ID	Elementary family title	Category
CEA-070	500-litre concrete containers containing drums of filtration sludge embedded in a cementitious material, produced in accordance with a quality assurance specification	ILW-LL1
CEA-100	870-litre non-alloy steel containers containing 700-litre drums of 800 g/l concentrates embedded in a cementitious material	ILW-LL1
CEA-140	500-litre concrete containers produced before 1994 containing drums of filtration sludge embedded in a cementitious material	ILW-LL1
CEA-150	500-litre concrete containers containing drums of evaporation concentrates embedded in a cementitious material	ILW-LL1
CEA-231	Drums of radium-bearing lead sulphates from the Le Bouchet plant conditioned in 5 m³ concrete containers	ILW-LL1
CEA-232	Drums of radium-bearing lead sulphates from the Le Bouchet plant conditioned in EIP containers	ILW-LL1
CEA-280	223-litre non-alloy steel drums containing filtration sludge embedded in a cementitious material (including drums produced in accordance with a quality assurance specification)	ILW-LL1
CEA-310	Non-alloy steel containers produced from the reconditioning of 1000-litre concrete containers containing miscellaneous waste immobilised in a cement-bitumen matrix or a sludge/cement mixture	ILW-LL1
CEA-320	Steel drums containing sludges or concentrates or a mixture of cemented sludges and concentrates	ILW-LL1
CEA-1140	Stainless steel drums containing cemented filtration sludge from the STEMA facility	ILW-LL1
COG-430	Dried STE2 sludge, compacted and immobilised in a metal container	ILW-LL1
CEA-1000	Stainless steel overdrums containing stainless steel drums of bituminised waste produced in accordance with a quality assurance specification (from October 1996)	ILW-LL2
CEA-1010	Stainless steel overdrums containing non-alloy steel drums of bituminised waste produced in accordance with a quality assurance specification (from 1995 to 1996)	ILW-LL2
CEA-1020	Stainless steel overdrums containing non-alloy steel drums of bituminised waste produced before 1995, transported in primary packages	ILW-LL2
CEA-1021	Stainless steel overdrums containing non-alloy steel drums of bituminised waste produced before 1995, transported in disposal packages	ILW-LL2
COG-020	Drums of bitumen STE3 produced according to the specification 300 AQ 027	ILW-LL2
COG-420	Drums of bituminised STE2 waste (partial recovery from silo 550-14)	ILW-LL2
CEA-370	Exotic objects from Phenix	ILW-LL3
CEA-420	Waste from the operation and dismantling of various facilities at FONTENAY-aux-ROSES	ILW-LL3
CEA-1040	Stainless steel drums containing cemented process wastes	ILW-LL3
COG-040	Drums of cemented hulls and nozzles produced in accordance with the specification 300 AQ 025	ILW-LL3
COG-070	Standard canisters for compacted waste/CSD-C containing hulls and nozzles from the HAO silo	ILW-LL3
COG-440	Cemented ECE drum containing fines and resins from the HAO silo	ILW-LL3
AND-000	Waste collected by Andra conditioned in 870-litre containers (used sealed sources, etc.)	ILW-LL3
CEA-050	870-litre non-alloy steel containers produced in accordance with a quality assurance specification (from 01/01/94) containing miscellaneous waste (mainly alpha Pu) immobilised in a cementitious material	ILW-LL3

Elementary family ID	Elementary family title	Category
CEA-060	500-litre steel containers produced since 1994 in accordance with a quality assurance specification, containing miscellaneous waste immobilised in a cementitious material	ILW-LL3
CEA-080	870-litre carbon steel containers produced from 1972 to 1990 containing diverse waste in a cement-bitumen matrix	ILW-LL3
CEA-090	870-litre non-alloy steel containers produced from 1990 to the end of 1993 containing miscellaneous waste (mainly alpha Pu) immobilised in a cementitious material	ILW-LL3
CEA-110	500-litre carbon steel containers produced from 1970 to 1990 containing diverse waste in a cement-bitumen matrix	ILW-LL3
CEA-120	500-litre non-alloy steel containers produced from 1990 to 1994 containing miscellaneous waste immobilised in a cementitious material	ILW-LL3
CEA-270	870-litre non-alloy steel containers containing miscellaneous waste immobilised in a cementitious material (CEA/DAM Valduc)	ILW-LL3
CEA-290	Non-alloy steel containers from the reconditioning of 1800-litre concrete containers containing miscellaneous waste immobilised in a cementitious material	ILW-LL3
CEA-300	Non-alloy steel containers from the reconditioning of 1800-litre concrete containers containing miscellaneous waste immobilised in a cement-bitumen matrix	ILW-LL3
CEA-330	870-litre non-alloy steel containers containing metal and organic waste from "Pegase"	ILW-LL3
CEA-400	Irradiating waste from the dismantling of Rapsodie, the cleanup of the pits at CADARACHE and the operation and dismantling of the JHR	ILW-LL3
CEA-410	Irradiating waste from the operation and dismantling of various facilities at SACLAY	ILW-LL3
CEA-440	500-litre stainless steel containers containing miscellaneous non-compactable waste immobilised in a cementitious material (operation of CABRI, dismantling of Rapsodie, pits at CAD, CENG)	ILW-LL3
CEA-450	Non-alloy steel containers from the reconditioning of concrete containers known as "source assemblies"	ILW-LL3
CEA-460	Waste from the dismantling of facilities at the CEA Valduc centre	ILW-LL3
CEA-480	Non-standard pre-concreted 223-litre packages	ILW-LL3
CEA-1090	Stainless steel drums containing metal and organic technological waste immobilised in a cementitious material	ILW-LL3
CEA-1100	870-litre non-alloy steel containers containing metal and organic technological waste immobilised in a cementitious material (alpha waste from MARCOULE)	ILW-LL3
CEA-1110	Technological waste from AVM	ILW-LL3
CEA-1151	Structural waste, miscellaneous metal waste and waste from the dismantling of the TOP and TOR lines, to be reconditioned in EIP drums	ILW-LL3
CEA-1152	Structural waste, miscellaneous metal waste and waste from the dismantling of the TOP and TOR lines	ILW-LL3
CEA-1180	200-litre alpha drums stored in building 99 in the north sector of CDS, to be placed temporarily in a 500-litre reversible hull	ILW-LL3
CEA-1510	Radioactive sources (alpha, neutron and other)	ILW-LL3
COG-030	Packages of cemented solid operating waste produced after 1994 in accordance with the specification 300 AQ 044	ILW-LL3
COG-050	Packages of cemented solid operating waste produced before 1994 in accordance with the specification 300 AQ 038	ILW-LL3
COG-400[140]	Alpha waste from Melox and LHA	ILW-LL3
COG-460	Standard canisters for compacted waste/CSD-C containing metal and organic technological waste and dismantling waste	ILW-LL3

[140] This family could eventually be part of the ILW-LL6 category depending on its conditioning

Elementary family ID	Elementary family title	Category
COG-480	CBF-C'2 containers containing operating and dismantling waste (ATTILA pit bins)	ILW-LL3
COG-490	Waste from end-of-operation and dismantling operations at the UP2-400, UP2-800 and UP3 plants compacted in CSD-C canisters	ILW-LL3
COG-500	Waste from end-of-operation and dismantling operations at the UP2-400, UP2-800 and UP3 plants conditioned in CBF-C'2 containers	ILW-LL3
COG-510	Waste from end-of-operation and dismantling operations at the MELOX plant conditioned in CBF-C'2 containers	ILW-LL3
COG-520	Waste from end-of-operation and dismantling operations at the CADARACHE CFCa facilities conditioned in CBF-C'2 containers	ILW-LL3
EDF-120	Waste from AMI at Chinon	ILW-LL3
CEA-1050	Stainless steel drums containing cemented metal structural waste (including from the dismantling of the Celestin reactors)	ILW-LL4
CEA-1060	Stainless steel drums containing magnesium structural waste immobilised in a cementitious material	ILW-LL4
EDF-080	C1PG containers of PWR activated operating waste	ILW-LL4
EDF-090	C1PG containers of 1st train activated dismantling waste excluding sodium-bearing waste from Superphenix	ILW-LL4
EDF-100	Activated dismantling waste from PWRs in the current fleet (including BCOT)	ILW-LL4
ITER-010	Miscellaneous waste produced during the operation, maintenance and dismantling phases of the ITER reactor	ILW-LL4
CEA-360	Waste from the dismantling of Phenix core objects	ILW-LL5
CEA-430	Miscellaneous waste from the operation, cleanup and dismantling phases of various facilities at the GRENOBLE Centre	ILW-LL5
CEA-1200	Miscellaneous waste stored in buildings 211 and 213 (excluding containers of vitrified waste from PIVER and other HLW glass packages)	ILW-LL5
COG-100	Standard canisters for compacted waste/CSD-C produced in accordance with the specification 300 AQ 055 (including hulls and nozzles from ECE drums and from pools S1, S2 and S3)	ILW-LL5
COG-110	Standard canisters for compacted waste/CSD-C containing hulls and nozzles from UOX fuel assemblies	ILW-LL5
COG-120	Standard canisters for compacted waste/CSD-C containing hulls and nozzles from UOX/ERU/MOX fuel assemblies	ILW-LL5
COG-450	Standard canisters for compacted Waste/CSD-C containing structural waste from PWR and FNR fuel assemblies (Superphenix and Phenix)	ILW-LL5
COG-550	Packages of compacted structural waste from EL4 SF reprocessing	ILW-LL5
EDF-110	PWR primary and secondary source rods and other miscellaneous sealed sources	ILW-LL5
COG-530	Packages of compacted structural waste from CEA/Civil SF reprocessing	ILW-LL5
COG-540	Packages of compacted structural waste from CEA/DAM SF reprocessing	ILW-LL5
CEA-340	Standard canister (CSD) containing vitrified americium-bearing effluents (Valduc ILW-LL glass packages)	ILW-LL6
CEA-1120	AVM-type stainless steel containers containing vitrified waste from MARCOULE UP1 rinse effluents (ILW-LL glass packages)	ILW-LL6
COG-470	CSD-B packages containing vitrified medium-level effluents (final shutdown of UP2-400, UP2-800 and UP3)	ILW-LL6
CEA-380	Miscellaneous waste containing B4C from the operation and dismantling phases of the Rapsodie and Phenix FNR reactors	ILW-LL7
EDF-250	Miscellaneous waste containing B4C from the operation and dismantling phases of the Superphenix FNR reactor	ILW-LL7

APPENDICES TO VOLUME III

Appendix 1 : Summary tables of the constructive choices as regards representation of the characteristics of the waste disposal system components

- ***Choice of hypothetical reference groups***

Table 2.4-5: Hypothetical reference groups identified for a temperate standard biosphere

Hypothetical reference groups	Activities leading to potential exposure	Temperate standard biosphere			
		Outlet: Wells in the Barrois limestone Possible operating flow rates: 150 L.min^{-1}		**Outlet: Borehole in the Dogger in the discrete fracture zone** Possible operating flow rate: 100 L.min^{-1}	
		Choice	Justification	Choice	Justification
Multi-activity	Includes intensive cereal-growing, livestock-rearing, vegetable garden, farmyard animals Diet: average behaviour based on survey (OPE)	• Multi-activity hypothetical reference group with irrigation of cereal crops: ✓ Irrigated cereal crops ✓ Cattle farming ✓ Vegetable garden ✓ Farmyard animals • Quantification for the Safety Options Report	• Currently observed activities. • Irrigation not currently observed but potential activity with range of evaluated flow rates • Used to explore all transfer pathways associated with a well in the Barrois limestone	• Multi-activity hypothetical reference group without irrigation of cereal crops: ✓ Cattle farming ✓ Vegetable garden ✓ Farmyard animals • Quantification for the Safety Options Report	• Currently observed activities. • Irrigation not currently observed. No potential with the range of evaluated flow rates. Non-retained activity. • Used to explore the transfer pathways associated with operation of a borehole in the Dogger without irrigation of cereal crops

Hypothetical reference groups	Activities leading to potential exposure	Temperate standard biosphere			
		Outlet: Wells in the Barrois limestone Possible operating flow rates: 150 L.min^{-1}		**Outlet: Borehole in the Dogger in the discrete fracture zone** Possible operating flow rate: 100 L.min^{-1}	
		Choice	Justification	Choice	Justification
Arable farmer	Specific activity: Large crops (cereals, etc.) Appropriate diet (heavy consumption of the products of cereal-growing)	• Hypothetical reference group of farmer engaging in intensive cereal-growing with irrigation (without cattle farming): ✓ Irrigated cereal crops ✓ Vegetable garden ✓ Farmyard animals • Evaluation for the construction licence application taking into account an appropriate diet	• Currently observed activity. • Irrigation not currently observed but potential activity with range of evaluated flow rates • Used to explore a specific exposure pathway associated with cereal-growing	• Intensive cereal-growing with irrigation not retained.	• No potential with the range of evaluated flow rates.
Livestock farmer	Specific activity: All livestock-rearing (cattle, sheep, goats, pigs, reindeer, horses, ostriches, etc.) Appropriate diet (heavy consumption of farm-raised animal products)	• Cattle and sheep farmer hypothetical reference group: ✓ Cattle farming ✓ Vegetable garden ✓ Farmyard animals • Evaluation for the construction licence application taking into account an appropriate diet	• Cattle farming observed • Used to explore a specific exposure pathway associated with the consumption of farm-raised animal products	• Cattle farmer hypothetical reference group: ✓ Cattle farming ✓ Vegetable garden ✓ Farmyard animals • Evaluation for the construction licence application taking into account an appropriate diet	• Cattle and sheep farming observed • Used to explore a specific exposure pathway associated with the consumption of farm-raised animal products

Hypothetical reference groups	Activities leading to potential exposure	Temperate standard biosphere			
		Outlet: Wells in the Barrois limestone Possible operating flow rates: 150 L.min^{-1}		**Outlet: Borehole in the Dogger in the discrete fracture zone** Possible operating flow rate: 100 L.min^{-1}	
		Choice	Justification	Choice	Justification
Villager	Specific activity: Vegetable garden, Farmyard animals, Dwelling Appropriate diet (consumption of plant and animal products from the vegetable garden and farmyard)	• Villager hypothetical reference group: ✓ Vegetable garden ✓ Farmyard animals • Evaluation for the construction licence application taking into account an appropriate diet	• Currently observed • Used to explore the specific exposure pathways associated with the consumption of home-produced products from the garden and farmyard	• Same as for Barrois • Villager hypothetical reference group: ✓ Vegetable garden ✓ Farmyard animals • Evaluation for the construction licence application taking into account an appropriate diet	• Same as for Barrois
Angler	Specific activity: Fishing for fish (freshwater or other types), crustaceans, shellfish	• Non-retained activity	• No river outlet	• Non-retained activity	• No river outlet
Hunter	Game	• Non-retained activity	• No river outlet	• Non-retained activity	• No river outlet
Forager	Mushrooms, berries	• Non-retained activity	• No river outlet	• Non-retained activity	• No river outlet
Tourist	Occasional (bathing, walks, picnics)	• Non-retained activity	• No potentially contaminated body of water	• Non-retained activity	• No potentially contaminated body of water
Specific activity	Vineyards, sawmills, quarries on the basis of local observation	• Non-retained activity	• Not observed in the ZIRA	• Non-retained activity	• Not observed in the ZIRA

Table 2.4-6: Hypothetical reference groups identified for a temperate standard biosphere

Potentially exposed groups	**Breakdown of activities leading to potential exposure**	**Hot damp tropical type Cr biosphere**			
		Outlet: Wells in the Barrois limestone Possible operating flow rates: 150 L.min^{-1}		**Outlet: Borehole in the Dogger in the discrete fracture zone** Possible operating flow rate: 100 L.min^{-1}	
		Choice	Justification	Choice	Justification
Multi-activity	Includes arable farming, livestock-rearing, vegetable garden and farmyard animals, hunting, angling, leisure activities Diet: average behaviour based on survey (OPE)	• Multi-activity hypothetical reference group with irrigation of cereal crops: ✓ Irrigated cereal crops ✓ Cattle farming ✓ Vegetable garden ✓ Farmyard animals • Quantification for the Safety Options Report	• Currently observed activities. • Irrigation not currently observed but potential activity with range of evaluated flow rates • Used to explore all transfer pathways associated with a well in the Barrois limestone	• Multi-activity hypothetical reference group **without** irrigation of cereal crops: ✓ Cattle farming ✓ Vegetable garden ✓ Farmyard animals • Quantification for the Safety Options Report	• Currently observed activities. • Irrigation not currently observed. No potential with the range of evaluated flow rates. Non-retained activity. • Used to explore the transfer pathways associated with operation of a borehole in the Dogger without irrigation of cereal crops
Arable farmer	Specific activity: Large crops (cereals, etc.) Appropriate diet (heavy consumption of the products of cereal-growing)	• Hypothetical reference group of farmer engaging in intensive cereal-growing with irrigation (without cattle farming): ✓ Irrigated cereal crops ✓ Vegetable garden ✓ Farmyard animals • Evaluation for the construction licence application taking into account an appropriate diet	• Currently observed activity. • Irrigation not currently observed but potential activity with range of evaluated flow rates • Used to explore a specific exposure pathway associated with cereal-growing	• Intensive cereal-growing with irrigation not retained.	• No potential with the range of evaluated flow rates.

Potentially exposed groups	Breakdown of activities leading to potential exposure	Hot damp tropical type Cr biosphere			
		Outlet: Wells in the Barrois limestone Possible operating flow rates: 150 L.min^{-1}		**Outlet: Borehole in the Dogger in the discrete fracture zone** Possible operating flow rate: 100 L.min^{-1}	
		Choice	Justification	Choice	Justification
Livestock farmer	Specific activity: All livestock-rearing (cattle, sheep, goats, pigs, reindeer, horses, ostriches, etc.) Appropriate diet (heavy consumption of farm-raised animal products)	• Cattle/sheep farmer hypothetical reference group: ✓ Cattle/sheep farming ✓ Vegetable garden ✓ Farmyard animals • Evaluation for the construction licence application taking into account an appropriate diet	• Cattle farming observed • Used to explore a specific exposure pathway associated with the consumption of farm-raised animal products	• Cattle and sheep farmer hypothetical reference group: ✓ Cattle farming ✓ Vegetable garden ✓ Farmyard animals • Evaluation for the construction licence application taking into account an appropriate diet	• Cattle and sheep farming observed • Used to explore a specific exposure pathway associated with the consumption of farm-raised animal products
Villager	Specific activity: Vegetable garden, Farmyard animals, Dwelling Appropriate diet (consumption of plant and animal products from the vegetable garden and farmyard)	• Villager hypothetical reference group • Evaluation for the construction licence application taking into account an appropriate diet	• Currently observed • Used to explore the specific exposure pathways associated with the consumption of home-produced products from the garden and farmyard	• Same as for Barrois • Villager hypothetical reference group: ✓ Vegetable garden ✓ Farmyard animals • Evaluation for the construction licence application taking into account an appropriate diet	• Same as for Barrois
Angler	Specific activity: Fishing for fish (freshwater or other types), crustaceans, shellfish	• Non-retained activity	• No river outlet	• Non-retained activity	• No river outlet
Hunter	Game	• Non-retained activity	• No river outlet	• Non-retained activity	• No river outlet
Forager	Mushrooms, berries	• Non-retained activity	• No river outlet	• Non-retained activity	• No river outlet

Potentially exposed groups	**Breakdown of activities leading to potential exposure**	**Hot damp tropical type Cr biosphere**			
		Outlet: Wells in the Barrois limestone Possible operating flow rates: 150 L.min^{-1}		**Outlet: Borehole in the Dogger in the discrete fracture zone** Possible operating flow rate: 100 L.min^{-1}	
		Choice	Justification	Choice	Justification
Tourist	Occasional (bathing, walks, picnics)	• Non-retained activity	• No potentially contaminated body of water	• Non-retained activity	• No potentially contaminated body of water
Specific activity	Vineyards, sawmills, quarries on the basis of local observation	• Fruit-growing hypothetical reference group	• Potential activity	• Fruit-growing hypothetical reference group	• Potential activity

- ***Structural choices for representing mechanically damaged clay rock***

Table 2.4-7: Transfer and retention characteristics of connected fracture zones and discrete fracture zones

Characteristics or processes	Normal evolution scenario situation	Structural choice of connected fracture zone representation	Structural choice of discrete fracture zone representation
Permeability	Reference	• Outside the liner removal zone: value corresponding to effective hydraulic healing downgraded by two orders of magnitude • Directly above the removal zones (seals): phenomenological values taking into account effective hydraulic healing (self-sealing and closure of the fractures).	Not represented
	Bounding situation	• Outside the liner removal zone: value used as reference downgraded by one order of magnitude. • Directly above the removal zones (seals): effective hydraulic healing degraded by one order of magnitude	Conservative value resulting from measurements made in this zone at the Meuse/Haute-Marne Centre (Underground Research Laboratory), after excavation.
Diffusion coefficients	Reference and bounding	Correction factors increasing diffusion compared with undisturbed Callovo-Oxfordian.	Values measured in undisturbed Callovo-Oxfordian.
Accessible porosities	Reference and bounding	Correction factors decreasing the accessible porosity	Values measured in undisturbed Callovo-Oxfordian.
Diffusion coefficients (Kd)	Reference and bounding	Conservative values (min Kd).	Values measured in undisturbed Callovo-Oxfordian.
Solubility limit (Csat)	Reference and bounding	Conservative values (max Csat)	Values measured in undisturbed Callovo-Oxfordian.

- ***Constructive choices as for representation of alkaline disturbance***

Tableau 2.4-8: Transfer and retention characteristics retained for fractured clay rock (connected fracture zone) under the influence of alkaline disturbance

		Connected fracture zone remineralised in contact with standard concrete	Connected fracture zone affected by an alkaline plume without remineralisation (standard or low-pH concrete)
Extension	Criteria	Corresponds to the transformation of all the smectite ([smectite]=0)	Ionic strength (I > 0.2M), [K] >10^{-2} mol.L^{-1}
	On contact with low-pH concrete	Not represented	Not represented
	Directly above the backfilled drifts	CCC cm Integrated into liner	Represented Thickness < mm cm
	Directly above the usable part of the ILW-LL cells	Represented Thickness DDD cm	Represented Thickness < mm cm
	Directly above the HLW cells	Represented over the whole thickness of the connected fracture zone (XXX cm)	Represented Thickness < mm cm
Permeability		Pessimistic permeability equivalent to that of sand	No effect
Transfer and retention characteristics: Reference situation	Anions (Chlorine-36, iodine-129, aluminium-26, selenium-79)	Pessimistic De and accessible porosity (D_0 in porosity) Pessimistic Csat*	De and accessible porosity increased in line with ionic strength (I) Pessimistic Csat*
	Alkalines, alkaline earths	Pessimistic De (D_0 in porosity) Corrective factors applied to conservative Kd (in line with ionic strength and [K]) Pessimistic Csat*	Corrective factors applied to conservative Kd (in line with ionic strength and [K]) Pessimistic Csat*
	Other radionuclides	Pessimistic De (D_0 in porosity) Kd, Csat: no impact (conservative values applied to connected fracture zone) Pessimistic Csat*	No impact (conservative values applied to connected fracture zone) Pessimistic Csat*
Transfer and retention characteristics: Bounding situation	All radionuclides	Pessimistic permeability values equivalent to those of sand Pessimistic De and accessible porosity (diffusion in water D_0) Kd, Csat not represented (Kd=0, Csat=∞)	Same treatment as in reference situation

* For an ionic strength of more than 4 times the ionic strength of the water in the undisturbed Callovo-Oxfordian

- ***Structural choices for representing retention characteristics potentially influenced by a plume of organic substances or saline***

Table 2.4-9: Chemical retention characteristics in the (undisturbed or damaged) clay rock affected by the plume of complexing organic substances

Radionuclides	In the undisturbed Callovo-Oxfordian, in the connected fracture zone and the discrete fracture zone	
	Effect if: [ISA] >1.10^{-4} mol · L^{-1} (or [L]* > 1.10^{-3} mol · L^{-1})	Effect if: [ISA] >1.10^{-3} mol · L^{-1} (or [L]* > 1.10^{-2} mol · L^{-1})
Chlorine-36, iodine-129, aluminium-26, selenium-79	Kd: no effect (Kd=0) Csat: no effect	Kd: no effect (Kd=0) Csat: no effect
Alkalines	No effect	No effect
Actinides and lanthanides	Pessimistic Kd (factor 0.1) Pessimistic Csat (factor)	Pessimistic Kd (factor 0.01) Pessimistic Csat (factor)
Other radionuclides		

* [L]: complexing organic substances in the waste except ISA, excluding cement admixtures and non-complexing organic substances

Table 2.4-10: Chemical retention characteristics in the cementitious materials affected by the plume of complexing organic substances

Radionuclides	Effect linked to the presence of ligands (except ISA)	Effect linked to the presence of ISA (cumulatively with the effect linked to [L])		
		[ISA] = 1.10^{-4} mol.L^{-1}	[ISA] = 1.10^{-3} mol.L^{-1}	
	Effect if: [L]* > 1.10^{-3} mol.L^{-1}	Effect if: 1.10^{-5} ≤ [ISA] < 1.10^{-4} mol.L^{-1}	Effect if: 1.10^{-4} mol.L^{-1} ≤ [ISA] < 1.10^{-3} mol.L^{-1}	Effect if: 10^{-3} mol.L^{-1}≤ [ISA]
Chlorine-36, iodine-129, aluminium-26, selenium-79	Conservative Kd Conservative Csat	No effect	Conservative Kd Conservative Csat	Pessimistic Kd (conservative * 0.1) Pessimistic Csat (conservative*factor)
Alkalines	No effect	No effect	No effect	No effect
Actinides and lanthanides	Conservative Kd Conservative Csat	Conservative Kd Csat: no effect	Pessimistic Kd (conservative * 0.1) Pessimistic Csat (conservative*factor)	Pessimistic Kd (conservative * 0.01) Pessimistic Csat (conservative*factor)
Other radionuclides	Conservative Kd Conservative Csat	No effect	No effect	Pessimistic Kd (conservative * 0.1) Pessimistic Csat (conservative*factor)

* [L]: complexing organic substances in the waste except ISA, excluding cement admixtures and non-complexing organic substances

Table 2.4-11: Transfer and retention characteristics retained for materials affected by the saline plume

Radionuclides	Undisturbed and mechanically damaged clay rock	Standard concrete (if I>1M)	Clay cores
Chlorine-36, iodine-129, aluminium-26, selenium-79	De increased in line with ionic strength Kd: no effect Pessimistic Csat*	Pessimistic Kd Pessimistic Csat	Not represented: covered by the conservatism of the parameters for retention and transfer in the clay core
Alkalines, alkaline earths	Kd reduced in line with the ionic strength and concentration of [K] Pessimistic Csat*	Pessimistic Kd Pessimistic Csat	
Other radionuclides	Kd: no effect Pessimistic Csat*	Pessimistic Kd Pessimistic Csat	

* if the ionic strength is 4 times greater than the ionic strength of the water in the undisturbed Callovo-Oxfordian

Table 2.4-12: Transfer and retention characteristics retained for the clay core

		Reference clay core representation	Representation of clay core in the bounding situation
Extension		Uniform properties throughout the clay core	
Permeability		Permeability defined by the requirements	
Diffusion		Conservative values, consistent with required permeability	Pessimistic values.
Retention	Anions (Chlorine-36, iodine-129, aluminium-26, selenium-79)	Retention not represented (Kd=0, Csat=∞)	Retention not represented (Kd=0, Csat=∞)
	Alkalines, alkaline earths	Retention parameters defined in line with the minimum smectite content, which covers cumulative uncertainty	
	Other radionuclides	Retention parameters defined in line with the minimum smectite content	

Appendix 2 : Human intrusions Recommendations in the safety guide for the geological repository and international practices Human intrusion Recommendations in the safety guide for the geological repository and international practices

Recommendations in the ASN's 2008 safety guide on intrusion scenarios

The ASN safety guide for the final disposal of radioactive waste in a deep geological formation (1) states that 200 m is the minimum depth to guarantee that "*[...] the repository's safety will not be significantly affected by erosion phenomena (particularly as a result of glaciation), by the effects of an earthquake, or by the consequences of a "minor" human intrusion.* "

Furthermore, it requires that the site be selected "*so as to steer clear of areas that could be of exceptional interest in terms of underground resources*" with the aim of avoiding any impact on "*extractable underground resources*". This measure also helps to reduce the likelihood of surveying work or operations occurring. Both constraints are met within the ZIRA.

The guide then specifies the types of situation to be examined as part of the safety analyses: "[...] *"altered" situations corresponding to the occurrence of uncertain but plausible events, either natural or linked to human activity, which are superimposed upon the reference situation and could lead to acceleration of the migration of radioactive substances between the disposal structures and the biosphere.* "

Appendix 2 of the safety guide (1) explains the different situations and hypotheses to consider for human intrusions:

- in terms of date of occurrence: "*it would be reasonable to expect that the memory of the disposal facility's existence would not be lost for at least 500 years. This value of 500 years will be used as the earliest date of occurrence of a human intrusion;*"
- and in terms of the characteristics of the human intrusion situations retained, which must be based on pessimistic hypotheses:
  - ✓ "*the existence of the waste disposal facility and its location are forgotten*;"
  - ✓ "*the level of technology is the same as today.* "

The situations to be considered as human intrusion in the context of a clay formation are, as a minimum, the following:

- "*Exploratory borehole penetrating a disposal structure. A situation involving a borehole penetrating the disposal facility with the extraction of core samples must be retained. The use of core samples consisting of high-level waste leads to external exposure which will be assessed in line with the types of analysis performed on these core samples*";
- "*Abandoned and inadequately sealed exploratory borehole penetrating a disposal structure. For sedimentary sites, the consequences of linking together aquifers or an aquifer and the disposal structures must be examined*";
- "*Exploratory borehole for water for human consumption or agricultural use in a deep aquifer. The plausibility of water being pumped out for human consumption or agricultural use from a deep aquifer shall be specified in line with water resources. The effect of the pumping on the flows will be assessed as regards individual exposure.* "

Human intrusion according to international organisations

According to the OECD-NEA [Future Human Actions at Disposal Sites - Safety Assessment of Radioactive Waste Repositories - OECD - NEA - 1995 (ISBN 92-64-14372-6 (66 95 04 1) NC)], "future human actions" refers to actions carried out after the closure of the disposal facility that have the potential to disturb or significantly alter the capabilities of natural or engineered barriers contributing to the containment of the radioactive waste. According to the IAEA [IAEA Safety Glossary - Terminology used in nuclear safety and radiation protection - IAEA - 2007 Edition], only human actions with a direct impact on the disposal facility should be considered as human intrusions.

As to whether the intrusion is deliberate or not, the OECD-NEA makes a distinction between:

- inadvertent intrusions in which the repository and/or the associated barrier system are accidentally penetrated because their location is unknown, their role is forgotten or the consequences of the intrusion are poorly understood;
- deliberate intrusions in which the persons responsible for the intrusion are aware of the presence of the waste or of the possible impact of the disturbance on the operation of the repository.

The IAEA's current HIDRA working group (Human Intrusion in the context of Disposal of Radioactive waste) provides an opportunity to focus on the distinction between "human intrusions" and "human actions". The need for discussions of human intrusion scenarios to be accompanied by detailed explanations concerning the potential accumulation of unlikely events, used as the basis for some scenarios, has also been emphasised. Finally, it should be pointed out that an inevitable consequence of the principle of concentrating and isolating waste, which underpins and justifies deep geological repository projects, is the risk of major exposure when contact with this waste occurs. Depth and geological context are key factors in reducing the likelihood of such events occurring.

In accordance with the 2008 ASN guide, these considerations do not mean that there is no need to evaluate inadvertent human intrusion situations. Instead they make it necessary to distinguish between the immediate effect on the operators responsible for the intrusion (impact on the borehole driller), and the consequences for operation of the repository and likely long-term impact (abandoned borehole).

Appendix 3 : List of radionuclides retained for intrusion scenario calculations (half-life more than 20 years)

RN	Half-life (years)
Be10	1,60E+06
C14	5,70E+03
Al26	7,17E+05
Si32	1,32E+02
Cl36	3,01E+05
Ca41	1,03E+05
Ti44	6,00E+01
Mn53	3,68E+06
Fe60	1,50E+06
Ni59	7,60E+04
Ni63	1,01E+02
Se79	3,77E+05
Kr81	2,10E+05
Rb87	4,81E+10
Sr90	2,88E+01
Zr93	1,53E+06
Nb91	6,80E+02
Nb92	3,50E+07
Nb94	2,00E+04
Mo93	4,00E+03
Tc97	2,60E+06
Tc98	4,20E+06
Tc99	2,14E+05
Pd107	6,50E+06
Ag108m	4,18E+02
Sn121m	5,50E+01
Sn126	2,30E+05
I129	1,61E+07

RN	Half-life (years)
Cs135	2,30E+06
Cs137	3,00E+01
La137	6,00E+04
Sm146	1,00E+08
Sm151	9,00E+01
Eu150	3,64E+01
Gd148	7,46E+01
Gd150	1,82E+06
Tb157	9,90E+01
Tb158	1,80E+02
Dy154	3,00E+06
Ho163	4,57E+03
Ho166m	1,20E+03
Lu176	4,00E+10
Hf178n	3,10E+01
Hf182	9,00E+06
Re186m	1,90E+05
Ir192n	2,41E+02
Pt193	5,00E+01
Hg194	4,44E+02
Pb202	5,30E+04
Pb205	1,53E+07
Bi207	3,18E+01
Bi208	3,68E+05
Bi210m	3,00E+06
Po209	1,02E+02
Ra226	1,60E+03
Th229	7,34E+03

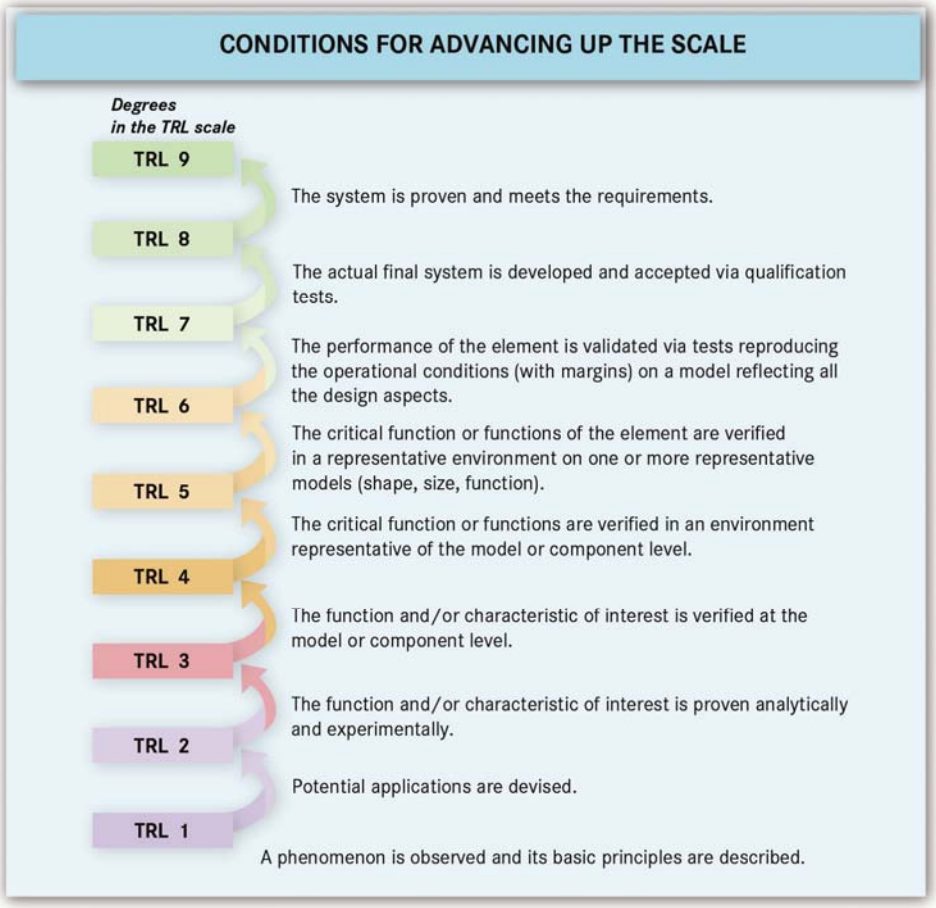
RN	Half-life (years)
Th230	7,54E+04
Th232	1,41E+10
Pa231	3,28E+04
U232	6,98E+01
U233	1,59E+05
U234	2,46E+05
U235	7,04E+08
U236	2,37E+07
U238	4,47E+09
Np236	1,52E+05
Np237	2,14E+06
Pu238	8,77E+01
Pu239	2,41E+04
Pu240	6,56E+03
Pu242	3,74E+05
Pu244	8,00E+07
Am241	4,33E+02
Am242m	1,41E+02
Am243	7,36E+03
Cm243	3,00E+01
Cm245	8,50E+03
Cm246	4,73E+03
Cm247	1,60E+07
Cm248	3,40E+05
Cm250	8,00E+03
Bk247	1,38E+03
Cf249	3,51E+02
Cf251	8,98E+02

Decay chains considered

Zr93→Nb93m,
4N (Cm244→Pu240→U236→Th232→Th228→Ra228),
4N+1 (Cm245→Pu241→Am241→Np237→U233→Th229),
4N+2 (Cm246→Pu242→U238→U234→Th230→Ra226→Pb210)
4N+3 (Am243→Pu239→U235→Pa231→Ac227).

APPENDICES TO VOLUME IV

Appendix 1 : TRL (Technological Readiness Level) scale for assessing the technological readiness level of an element



Appendix 2 : Example of application to the HLW disposal container

TRL scale applied to Cigeo: HLW disposal containers *(critical functions: "delaying ingress of water to waste"* *and "capability for horizontal handling")*	
After achieving TRL 9	Cigeo is in full industrial operation. The industrial HLW containers are received, welded to form the disposal packages and emplaced in the repository at the nominal rate. Operating reports are published regularly.
After achieving TRL 8 and to reach TRL 9	Cigeo is in industrial pilot phase. The first real waste packages are received. The operator conducts tests to verify operating procedures under active conditions. The industrial HLW disposal containers are received and welded by the industrial unit to make active disposal packages, which are emplaced in the repository. Compliance with the specified technical requirements is verified.
After achieving TRL 7 and to reach TRL 8	Following construction, the facility is now in industrial pilot phase. The operator is conducting tests to verify operating procedures under inactive conditions. The first industrial HLW containers are received and welded by the industrial unit to make inactive disposal packages, which are emplaced in the repository.
After achieving TRL 6 and to reach TRL 7	The Cigeo geological disposal facility has not yet been built. Several identical examples of a HLW disposal container model with the same characteristics as the planned industrial HLW disposal container (material type(s), size, mass, thickness, shape, presence of an object simulating a glass container, etc.) are manufactured, assembled and welded using processes identical to the future industrial processes (same material, same welding technology, etc.); the future industrial manufacturing conditions are reproduced or taken into account as far as possible (temperature, irradiation, etc.). The HLW disposal packages manufactured are put through characterisation testing (non-destructive and destructive analysis) and strength/durability testing (drop, fire, corrosion, etc.), reproducing and sometimes exceeding the operational conditions envisaged during operation and for several centuries after closure, with a view to validating their performance. Modelling is carried out in parallel to check the models' capacity to reproduce the observed behaviour and to assess behaviour in other conditions, particularly so as to define an operating range with limits.
After achieving TRL 5 and to reach TRL 6 *Current phase of Cigeo project*	Several examples, potentially of various HLW disposal container models with characteristics representative of the planned industrial HLW disposal containers (shape, size, function, material) are manufactured, assembled and welded. These models are characterised (non-destructive and destructive analysis), tested and simulated to assess their critical functions in environmental conditions representative of the repository (temperature, clay or cement environment, mechanical stress, redox conditions, etc.).
After achieving TRL 4 and to reach TRL 5	Models of HLW disposal containers (not necessarily “life size” or fully functional, but as representative of the planned industrial HLW disposal containers as necessary) or HLW disposal container components (specimens, whole or parts of lids, bodies, weld zones, runners, etc.) are used to assess the critical functions of industrial HLW disposal containers in environmental conditions representative of repository conditions. These models or components are put through characterisation testing (non-destructive and destructive analysis) and strength/durability testing. Modelling is carried out in parallel to check the models' capacity to reproduce the observed behaviour and to assess the behaviour in other conditions, particularly so as to define an operating range with limits.
After achieving TRL 3 and to reach TRL 4	One or more models of HLW disposal containers or HLW disposal container components are manufactured to establish basic performance. Verification is limited to laboratory conditions and simulation and is scarcely representative.

Appendix 3 : Correspondence table: post-closure safety functions/disposal system components

Post-closure safety functions \ Disposal system components		Host formation	Architecture			HLW engineered components			ILW-LL engineered components			Seals	
		Callovo-Oxfordian	Surface-bottom connections (ISC)	Section(s)	g drifts between sections	HLW cell	HLW primary package	HLW disposal container	ILW-LL disposal cell	ILW-LL primary package	ILW-LL disposal container	LSF seals	Bottom seals
Isolating waste from surface phenomena and human actions		(1)											
Preventing the circulation of water													
	Limiting the flow of water from the overlying formations that the surface-bottom connections pass through and from the Callovo-Oxfordian											(22)	
	Limiting the flow of water between the repository and the overlying formations (via the surface-bottom connections)	(2)	(6)									(22)	(23)
	Limiting the speed of water circulation within the repository	(2)	(6)	(7)	(12)							(22)	(23)
Restricting the release of radionuclides and immobilising them in the repository													
	Protecting the waste from water							(19)		(20)			
	Restricting radionuclide dissolution	(3)		(7) (8)		(15)	(18)	(19)	(15)	(20) (15)	(21)		
	Restricting radionuclide mobility	(3) (4)				(16)			(13)	(20)			
Delaying and attenuating radionuclide migration													
	Delaying and attenuating longitudinal radionuclide flows in the structures				(13)	(13) (15)			(13) (15)				(24)
	Delaying and attenuating radionuclide migration in the Callovo-Oxfordian	(3) (4) (5)	(6)	(9) (14)	(14)	(9)			(15)				
	Preserving the surrounding formations' natural capacity for dispersion and dilution											(22)	
Preserving the favourable properties of the Callovo-Oxfordian													
	Keeping the temperature within the repository and the Callovo-Oxfordian within a controlled range from a phenomenological point of view			(10)		(16)							
	Limiting (the extent of) damage to the clay rock around the repository over time				(11) (14)	(17)			(17)			(22)	(23)
	Preserving sufficiently large thicknesses of undisturbed Callovo-Oxfordian			(11) (14)	(11) (14)	(11) (14)			(11) (14)				

(1) Low, uniform geodynamic depth
(2) Very low permeability and low vertical hydraulic gradients
(3) Chemical properties of Callovo-Oxfordian waters
(4) Retention capacity, dominant transfer by diffusion
(5) Dominant transfer by diffusion and associated thickness
(6) Consolidation of the surface-bottom connections
(7) Dead-end section(s)
(8) Distance between exothermic sections isolated from other sections
(9) "Planar" architecture of the sections
(10) Centre-to-centre distance between cells
(11) Backfilling to limit volume of residual void spaces
(12) Backfilling and length
(13) Length
(14) Location in the Callovo-Oxfordian
(15) Chemical environment
(16) Spacers between packages where appropriate for HLW1/HLW2 cells
(17) Limitation of residual void spaces
(18) Vitrification
(19) Thickness and nature of material
(20) Matrix dependent on families
(21) Geometry of bituminised waste maintained for a limited period
(22) Swelling clay core and no connected fracture zone
(23) Clay core and healed connected fracture zone
(24) Orientation in accordance with main horizontal stress

BIBLIOGRAPHIC REFERENCES

1 Guide de sûreté relatif au stockage définitif des déchets radioactifs en formation géologique profonde. Autorité de sûreté nucléaire. (2008). Guide de l'ASN. 32 p.

2 Act 91-1381 of 30 December 1991 on radioactive waste management research. (1992). Official Journal of the French Republic Acts and Decrees No. 1, 10 p

3 RFS n°III.2.f du 10 juin 1991 - Définition des objectifs à retenir dans les phases d'études et de travaux pour le stockage définitif des déchets radioactifs en formation géologique profonde afin d'assurer la sûreté après la période d'exploitation du stockage. (1991). Autorité de Sûreté Nucléaire. RFS III.2.f.

4 Dossier 2005. Andra research on the geological disposal of high-level and long-lived radioactive waste Results and outlook. Andra. (2005). Andra. Reports No. 265. Report DCOM/13-0225. 40 p.

5 Act 2006-739 of 28 June 2006 on the sustainable management of radioactive material and waste. (2006). Official Journal of the French Republic. Acts and Decrees No. 93, 9,721 p.

6 Délibération du conseil d'administration de l'Agence nationale pour la gestion des déchets radioactifs du 5 mai 2014 relative aux suites à donner au débat public sur le projet Cigéo. Ministère de l'écologie, du développement durable et de l'énergie (2014). Journal Officiel. Lois et décrets, n°108, pp.7851-7854.

7 Dossier d'options de sûreté - Partie exploitation (DOS-Expl). Andra. (2015). Note technique n° CGTEDNTEAMOASR10000150060.

8 Proposition de plan directeur pour l'exploitation (PDE). Andra. (2015). Note technique n° CGTEDNTEAMOASDR0000150063.

9 Dossier d'options techniques de récupérabilité (DORec). Andra. (2015). Note technique n° CGTEDNTEAMOARV00000150059.

10 Adaptabilité de Cigéo au stockage éventuel de combustibles Andra. (2012). Note technique n° CGTEFNTEAMOAMT07000120116.

11 Adaptabilité de Cigéo pour le stockage des déchets en "réserves". Andra. (2015). Note technique n° CGNTADPG150006.

12 Esquisse de la notice des capacités techniques de l'exploitant. Andra. (2015). Note technique n° CGTEDNTEAMOASYN0000150064.

13 Avis n° 2010-AV-0084 du 5 janvier 2010 de l'ASN sur le dossier de l'agence nationale de gestion des déchets radioactifs (ANDRA) relatif à la proposition d'une zone d'intérêt pour la reconnaissance approfondie et de scénarios d'implantation en surface pour un stockage réversible en formation géologique profonde. Autorité de Sûreté Nucléaire (ASN) (2010).

14 Act No. 2006-686 of 13 June 2006, as amended, on transparency and security in the nuclear field. Consolidated version dated 12 July 2014. (2006).

15 Order of 7 February 2012 laying down the general rules on basic nuclear installations Consolidated version dated 05 July 2013. (2012).

16 Biosphère. Démarche de choix et de description d'une ou plusieurs biosphère(s). Andra. (2009). Transparent n° SURTRASSN090025.

17 NEA IGSC Scenario Development Workshop, 1-3 June 2015, Issy-les-Moulineaux, France (En cours de publication). (2016). OCDE.

18 Dossier ""projet de stockage de déchets radioactifs en couche géologique profonde -maîtrise des risques en exploitation au niveau esquisse du projet Cigéo". Niel, J.C. Autorité de Sûreté Nucléaire. (2015). Lettre de l'ASN du 7 avril n°CODEP-DRC-2015-004834.

19 Référentiel du site Meuse/Haute-Marne - Présentation générale. Andra. (2012). Rapport n° DRPASMG120032.

20 Référentiel du site Meuse/Haute-Marne. Tome 1. Le site de Meuse/Haute-Marne: histoire géologique et état actuel. Andra. (2012). Rapport n° DRPASMG120032.

21 Référentiel du site Meuse/Haute-Marne. Tome 2: L'évolution naturelle du site de Meuse/Haute-Marne. Andra. (2012). Rapport n° DRPASMG120032.

22 L'aléa sismique pour un stockage géologique implanté sur la ZIRA, Site de Meuse / Haute-Marne. Bruhlet, J., Dubreuilh, P., Ego, F.,Lebon, P. Andra. (2013). Note technique n° CGNTASMG120018.

23 Comportement des déchets en stockage. Modèles de relâchement des radionucléides pour les différentes familles de colis. Schumacher, S., Deydier, V., Martin, C.,Ricard, D. Andra. (2013). Note technique n° CGNTASCM130021.

24 Modèles de relâchement retenus pour les déchets HA et MA-VL vitrifiés pour les évaluations de sûreté après fermeture de Cigéo. Andra. (2014). Note technique n° SURNTASAF140024.

25 Modèles de relâchement retenus pour l'évaluation de sûreté après fermeture. Andra. (2014). Note technique n° SURNTASAF140003.

26 Arrêté du 29 septembre 2005 relatif l'évaluation et à la prise en compte de la probabilité d'occurrence, de la cinétique, de l'intensité des effets et de la gravité des conséquences des accidents potentiels dans les études de dangers des installations classées soumises à autorisation.Version consolidée au 28 octobre 2015. (2015).

27 Conception des bétons pour une durée de vie donnée des ouvrages. Maîtrise de la durabilité vis-à-vis de la corrosion des armatures et de l'alcali-réaction. Etat de l'art et guide pour la mise en oeuvre d'une approche performantielle et prédictive sur la base des indicateurs de durabilité. (2004). Association Française de Génie Civil, Documents scientifiques et techniques. 252 p.

28 Plan de développement des composants du projet Cigéo - Déclinaison suivant l'échelle TRL (ISO 16290:2013). Andra. (2014). Plan de Déroulement, de Développement n° CGPDDADPG140031.

29 Exigences applicables - Projet Cigéo. Andra. (2014). Spécifications n° CIGEOSPADPG110020.

30 Code l'environnement. Partie législative. Livre Ier: Dispositions communes. Titre II: Information et participation des citoyens. Chapitre V: Autres modes d'information. Section 1: Dispositions relatives aux activités autres que les activités nucléaires. (article L125-1 à L125-9). (2015). Code l'environnement,

31 Code l'environnement. Partie législative. Livre V: Prévention des pollutions, des risques et des nuisances. Titre IV: Déchets. Chapitre II: Dispositions particulières à la gestion durable des matières et des déchets radioactifs (Article L542-1 à L542-14). (2015).

32 Code l'environnement. Partie législative. Livre V: Prévention des pollutions, des risques et des nuisances. Titre IX: La sécurité nucléaire et les installations nucléaires de base. Chapitre Ier: Dispositions générales relatives à la sécurité nucléaire (Articles L591-1 à 591-5). (2015).

33 Code l'environnement. Partie législative. Livre V: Prévention des pollutions, des risques et des nuisances. Titre IX: La sécurité nucléaire et les installations nucléaires de base. Chapitre III: Installations nucléaires de base (Articles L593-1 à L593-38). (2015).

34 Decree 2007-1557 of 2 November 2007 concerning basic nuclear installations and the supervision of the transport of nuclear materials with respect to nuclear safety. Consolidated version dated 27 February 2014. (2007).

35 Arrêté du 1er septembre 2003 définissant les modalités de calcul des doses efficaces et des doses équivalentes résultant de l'exposition des personnes aux rayonnements ionisants. Ministère de la santé, de la famille et des personnes handicapées (2013). Journal Officiel de la République Française, n°262, pp.58003-58068.

36 Arrêté du 9 août 2013 portant homologation de la décision n° 2013-DC-0360 de l'Autorité de sûreté nucléaire du 16 juillet 2013 relative à la maîtrise des nuisances et de l'impact sur la santé et l'environnement des installations nucléaires de base. Ministère de l'Écologie, du développement durable et de l'énergie (2013). Journal Officiel de République Française, n°193, pp.14278.

37 Radioactive Waste Disposal Facilities Safety Reference Levels v2.2. (Wgwd), W.G.O.W.a.D. Western European Nuclear Regulators Association (WENRA). (2014). 81 p.

38 Fundamental safety principles. Safety fundamentals. IAEA. (2006). IAEA safety standards series n°SF-1. 37 p.

39 Disposal of Radioactive Waste. Specific Safety Requirements. IAEA. (2011). IAEA Safety Standards Series n°SSR 5. 62 p.

40 The management system for facilities and activities. Safety Requirements. IAEA. (2006). IAEA Safety Standards Series n°GS-R-3. 27 p.

41 Monitoring and Surveillance of Radioactive Waste Disposal Facilities. Specific Safety Guide. IAEA. (2014). IAEA Safety Standards Series n°SSG-31. 96 p.

42 The Safety Case and Safety Assessment for the Disposal of Radioactive Waste. Specific safety guide. IAEA. (2012). IAEA Safety Standards Series n°SSG-23. 140 p.

43 Geological Disposal Facilities for Radioactive Waste. Specific Safety Guide. IAEA. (2011). IAEA Safety Standards Series n°SSG 14. 104 p.

44 The management system for the disposal of radioactive waste. Safety guide. IAEA. (2008). IAEA safety standards series n°GS-G-3.4. 85 p.

45 Defence in depth in nuclear safety: INSAG-10. A report by the International Nuclear Safety Advisory Group. International Atomic Energy Agency. (1996). IAEA. INSAG series n°10. n° STI/PUB/1013. 37 p.

46 ICRP Publication 122: Radiological Protection in Geological Disposal of Long-lived Solid Radioactive Waste (2013) 42,

47 ICRP publication 103: The 2007 recommendations of the International Commission on Radiological Protection (2008) *Annals of the ICRP,* 37**,** (2-4), 330 p.

48 ICRP Report 101: Assessing Dose of the Representative Person for the Purpose of Radiation Protection of the Public and The Optimisation of Radiological Protection: Broadening the Process (2006) *Annals of th ICRP,* 36**,** (3), 104 p.