Report Series

Dossier 2005 Argile

SYNTHESIS

Evaluation of the feasibility of a geological repository in an argillaceous formation

Meuse/Haute-Marne site

December 2005

ANDRA
Agence nationale
pour la gestion des déchets radioactifs

The present English version is a translation of the original “*Dossier 2005 Argile*“ documentation written in French, which remains ultimately the reference documentation.

In order to be consistent through the various documents, while the word ''storage'' (''*entreposage*'' in French) refers only to temporary management (in terms of concept and facility), ''disposal'' (in term of concept) and ''repository'' (in terms of facility or installation) refers to long term management of high level long lived radioactive waste (''*stockage*'' in French for these words).

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Introduction

I. Assessment of the feasibility of a geological high-level, long-lived waste repository: the Andra research framework

I.1 The law of 30 december 1991

By the Law of 30 December 1991 on the management of high-level, long-lived waste, referred to in article L542 of the Environment Code, the National Radioactive Waste Management Agency (Andra) was conferred the mission of assessing the feasibility of deep geological disposal of high level long lived radioactive waste (HLLL, HAVL in French) and, in particular, through the construction and operation of underground laboratories (2nd avenue of the Law). Later the government requested Andra to carry out its work with a rationale of reversibility. On the other hand, the Atomic Energy Commission (CEA) is the steering body in charge of research on the separation and transmutation of the HLLL waste (1rst avenue of the Law), as well as their storage and conditioning (3rd avenue).

Within this framework, the research was conducted, with tools and at different levels of maturity, on two types of geological media: clay and granite. The present report is a synthesis of work performed by Andra for the study of a geological repository in a clay formation. Another report presents the detailed knowledge acquired in the field of granite media.

The Law of December 1991 institutes a National Review Board (CNE), an independent commission of French and foreign scientific experts, in order to carry out a continuous assessment of the research conducted by the CEA and Andra and publish a yearly evaluation report. The Law stipulates that the government will address to the Parliament a global research assessment report, prepared by the CNE, as input to the 2006 parliamentary debate.
Since 1996, the Ministry of Research has been coordinating the elaboration, implementation and follow-up of the strategy and the research programmes carried out by Andra and the CEA. The Nuclear Safety Authority and its technical support, the Institution of Radioprotection and Nuclear Safety (IRSN), have also examined the research results from a safety viewpoint.

The Law of 1991 states the main principles to be taken into account in the research initiative and, in particular, the necessity of working "*by respecting the protection of the nature, environment and health*" and "*taking into consideration the right of future generations*". In particular, a problem should not be bequeathed to them without a solution, while they should be allowed to retain control over the committed process.

Andra has the following mission:

- acting as *a global programme agency*, which orients the research and animates the scientific and technical community interacting in this field;
- assessing the feasibility of a possible deep geological repository with a rationale of reversibility, notably through *research conducted in underground laboratory*. As far as the granite medium is concerned, so far no underground laboratory is available in France, but Andra is benefiting from knowledge acquired in foreign laboratories (Äspö in Sweden, Grimsel in Switzerland) and is pursuing its work in order to assess French granite assets. For the clay medium, the Meuse/Haute-Marne underground laboratory created by the Decree of August 1999 is available to Andra as well as foreign underground laboratories.

I.2 The basic safety rule RFS III.2.f

The Nuclear Safety Authority issued in 1991 a basic safety rule (RSF III.2.f), which provides a framework for long-term safety expectations with respect to disposal design principles, favourable geological media choice criteria and study modalities.

It presents the basic objectives which must serve as guidelines for the work on geological disposal : protection of man and the environment against possible consequences of radioactive waste, limitation of the radiological impact of a repository to a level as low as reasonably achievable, and specifies the *necessity of a multi-barrier disposal concept*, namely the packages containing the waste, the engineered barrier (components and materials between the package and the geological medium), the geological medium itself.

The RFS indicates the major expectations with respect to a potential site : long-term geodynamic stability (in particular, no significant earthquake risk), no important water circulation in the geological medium, adequate mechanical properties of the rocks to allow excavating underground installations, confinement properties of the geological medium with respect to the radionuclides, a sufficient depth to protect the waste from various aggressions, no exploitable outstanding natural resources in the vicinity.

II. The Andra research programme on disposal in a clay formation

II.1 Knowledge acquisition on the geological medium

Since 1991, Andra has launched a major research programme on the study of disposal in a clay formation ; a key element is the study, in eastern France (the Meuse/Haute-Marne site), of a stiff clay rock (argillite) approximately 155 million years old, the Callovo-Oxfordian, found at a depth from 400 to 600 metres.

The work on the site and in the Meuse Haute-Marne laboratory sector has allowed collecting much scientific information and acquiring an in-depth understanding of this site's geological environment to ensure that the clay layer of the Callovo-Oxfordian provides the expected favourable properties and to assess its long-term behaviour, notably by taking in account the waste repository impact. The purpose of the approach was not to determine a specific site for a possible repository; the issue of where to locate a repository seems, in fact, to be premature at this stage. Therefore, Andra objective was to assess only the transposability of the results obtained on the laboratory site to a larger zone. Through this transposability approach, the results will not depend on the specificities of any particular location.

Therefore 27 deep bore-holes have been drilled since 1994 and 2300 m of argillite core samples extracted (from 4200 m of cored samples). Andra has taken over 30 000 samples (including 7300 fluid samples) and analysed 5300 rock samples. Direct survey of the Callovo-Oxfordian host formation started in the shafts in March 2004. Furthermore scientific activity has been going on in 40 m of drifts at a depth of 445 m since November 2004; over 300 m of drifts have been excavated at a depth of 490 m, of which some 120 m are dedicated to scientific experiments. In all, over 1000 sensors have been installed for measurement in the rock and in situ observation of its behaviour.

Data are also acquired from many additional studies conducted in surface laboratories in France or abroad, or in underground research laboratories such as Mont Terri (Switzerland), where the argillaceous rock presents similar characteristics to that of Bure, or as well Mol (Belgium).

Aerial view of the Meuse/Haute-Marne Underground Research Laboratory

II.2 Four research avenues

In addition to the work aimed at characterising the geological medium, studies and research are carried out in four additional fields:

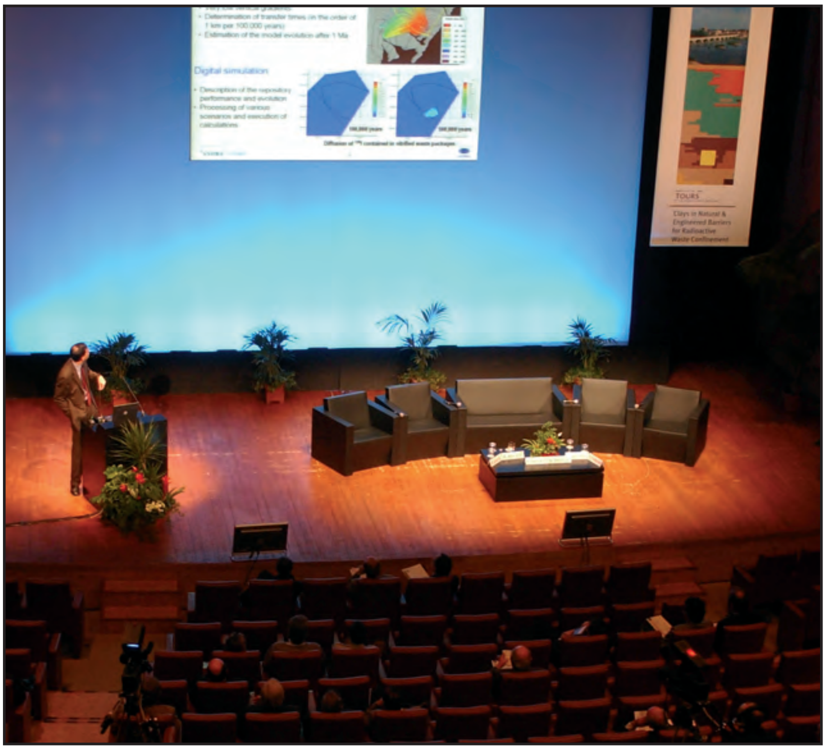
- *data acquisition*: waste packages, behaviour of the materials (waste over-packing, engineered barriers, ground supports, etc.). The objective is to understand the physical and chemical phenomena which would govern the repository and its environment over very long periods,
- *repository design*: waste conditioning, architecture and integration of the repository in a geological environment, construction and operation modes, waste package management, possibilities of repository closure, etc. The objective is to propose a repository architecture taking into account reversibility while being robust in terms of safety,
- *behaviour of the repository and its evolution* under the effect of the interaction of its components. The objective is to acquire an in-depth understanding of the thermal, mechanical, chemical and hydraulic phenomena, then describe them with modelling and finally simulate them with digital codes,
- *long-term safety analyses in order to assess the performances* of the repository with respect to the objective of ensuring the protection of man and his environment. The purpose is to assess the possible impact of a repository and appraise the robustness of its design.

II.3 An important mobilisation of the french and international scientific community

For its studies and research on disposal, Andra developed many scientific collaborations with French partners (Atomic Energy Commission CEA, National Geological Survey BRGM, National Center for Scientific Research CNRS, National Polytechnique Institute of Lorraine INPL, French Petroleum Institute IFP, School of Mines of Paris EMP, National Research Institute on Industrial Risks INERIS, etc.) and international partners, as well as exchanges with foreign counterpart agencies or organisations: Nagra (Switzerland), Enresa (Spain), BGR (Germany), Ondraf (Belgium). About some hundred laboratories were regularly associated with this research programme and 7 laboratory consortiums were formed by Andra around the following topics: corrosion of metals, clay, concrete, thermo-hydromechanical coupled phenomena, radionuclides, geomechanics and bio-geoprospective.

In addition, three research consortiums (GDR) associate Andra with the Nuclear Cycle Backend Programme (PACE programme) conducted by the CNRS: FORPRO, which groups together some 40 laboratories of the CNRS for the geological medium study, MOMAS for digital simulation and PRACTIS/PARIS for the physico-chemistry of actinides.

Andra participates also actively in the projects of the V^{th} and VI^{th} Framework Programme of the European Union (Clipex, Ecoclay, Reseal III, Febex, Crop, SFS, Modex Rep, Bioclim, Esdred, etc.).



Presentation of results about clays in natural and engineered barriers for radioactive waste confinement at the Tours-2005 International Meeting

Andra scientific policy and role

To conduct its research, Andra calls on multi-disciplinary scientific competences, notably in the fields of earth sciences, materials, environment, computing and modelling, measurement and monitoring. To do this, the Agency identifies the major scientific issues related to radioactive waste management, assesses the main stakes, elaborates the necessary research programmes by extensively associating all the competent scientific partners and by allowing them to hierarchise priorities in terms of research on waste management. Andra arouses, sets up and sustains networks of scientific partners, bringing together the skills needed, developing relationships and partnerships with industry, the academic world, and major research bodies. The importance of the partnership with the CNRS should be particularly underlined within the framework of the research consortiums (GDR) under the Nuclear Cycle Backend Programme (PACE). In addition, a support policy for doctorate and post-doctorate theses has been implemented. As a programme agency, Andra unifies the scientific community efforts, mobilises this community and promotes relevant research topics. The 15 year period since 1991 has been marked by an ongoing investment by the scientific community around Andra key issues. This has also stimulated a very productive intellectual openness in terms of innovation and interchange of competences.

II.4 The Dossier 2005 architecture

The feasibility study of a repository is intended to assess the conditions under which it would be possible to construct, operate, manage with a rationale of reversibility, close and monitor a repository and then let it evolve without any human intervention and without human safety and environmental protection being at stake at any moment.

To assess this feasibility, it is necessary to thoroughly understand the properties and evolutions of the repository's various components up to very long time scales: packages, structures, geological medium. Such knowledge allows founding on sound scientific bases, an assessment on the repository feasibility with respect to the objectives of reversibility and safety assigned to it.

• Five "knowledge reference documents"

Andra structured knowledge acquisition around five reference documents:

- "Meuse/Haute-Marne site" reference document, which covers the data related to the geological medium and the biosphere (host formation and its environment, circulation or transfer pathways of the radionuclides in the environment, studies on the current and future biospheres, etc.),
- "materials of a HLLL waste repository" reference document, grouping the data related to the behaviour of the materials used for the construction of the architecture (steel, concrete, clay and backfill material),
- "radionuclides and toxico-chemical elements behaviour" reference document, which covers the data related to the physical and chemical behaviour of the radionuclides,
- "source terms modelling of HLLL waste packages" reference document, which summarises the knowledge and models on waste behaviour in the repository environment,
- "characteristics and inventory model of the HLLL waste packages" reference document, which lists all the high-level and long-lived waste yet produced and to be produced by the existing nuclear facilities.

• Three "tomes"

Andra structured the synthesis of the results obtained around three tomes, with each referring to one of the aspects of the analysis process.

- *Architecture and management of a geological repository*

Andra proposes a repository architecture which is both possible with respect to expectations and realistic from an industrial viewpoint. Based on available knowledge and technology, the studied technical options, selected as simple and as robust as possible, show that solutions do exist. At the feasibility study phase, these options are not to be considered as optimised: they are likely to evolve, would the current work be pursued beyond 2006.
This architecture serves as a base on which the repository safety was analysed and, in particular, the repository behaviour and its evolution at various time scales.

- *Phenomenological evolution of a geological repository*

The design and assessment of a repository safety is based on the understanding of the processes taking place within the latter and its environment. This should allow to know about the evolution of the repository components at the various time scales and then, *in fine*, the possible release and migration of the radionuclides in the environment at the scale of the million years.

- *Safety evaluation of a geological repository*

It aims at examining whether the studied repository concepts comply with the protection objectives for man and the environment by assessing the repository behaviour over time. In particular, long-term safety analysis consists of:

- Defining and representing the most likely evolution of the repository,
- Examining the risks of dysfunction, their causes and their effects,
- Selecting the repository situations and phenomena which are important with respect to safety, translating them with normal or altered evolution scenarios,
- Quantifying these scenarios by simplified modelling, but still representative of the phenomena,
- Assessing the consequences and impact of these scenarios,

-.Identifying the design factors or provisions liable to make the disposal concept more robust.

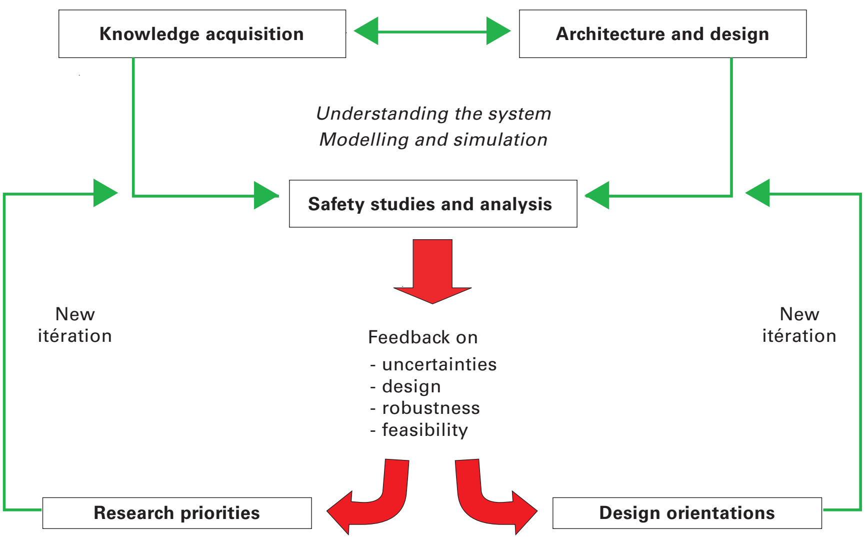
The iterative development of the project allows performing work regarding safety in each phase with a feedback to the design studies and knowledge acquisition needs.

II.5 An iterative approach

In accordance with the RFS III.2.f, which stipulates that "*the quantitative objectives for the confinement performances of the various barriers may only be truly set at the end of an iterative process, integrating the experience acquired during the safety study of the repositories*", Andra conducted its studies following an iterative approach as the knowledge about and the architecture of the repository were specified.
This approach, which integrates safety right from the farthest upstream phases of the design, allows progressively orienting the choices toward solutions offering the greatest robustness with respect to knowledge uncertainties, and introducing prevention and protection measures against the identified risks.

Each iteration is characterised by knowledge acquisitions and by the study of architecture designs in consistency with this knowledge. The available knowledge allows learning about the behaviour of the concepts studied through modelling.

These elements constitute the base of a safety analysis for the repository long-term specific functions and its operational safety. What is learned from the safety analysis then becomes input data for the next iteration: knowledge uncertainties which should be reduced in priority, orientations in terms of design.



Three iterations of this kind were carried out between 1994 and 2005 (construction and operation licence application of the underground research laboratory in 1996, Dossier 2001, Dossier 2005).

Chronological milestones

1992 *Repository design work* and highlighting of the main basic data: system elements, necessary performances, knowledge to be acquired.

1994-96 *Geological survey on two clay sites*: one at the limit of the Meuse and Haute-Marne, the other in the Gard. On the Meuse/Haute-Marne site, 3 bore-holes were drilled together with 2D geophysical campaign and geological mapping.

1997 *Initial selection of repository concepts ("initial design options")* taking into account the configuration of each of the two sites.

1998 Study of the selected repository concepts to answer the questions resulting from the initial safety analyses. These studies lead to *the selection of preliminary concepts* proposing a very large range of technical solutions.

December 1998 *Government's decision to select the Meuse/Haute-Marne site for the installation of the first laboratory*. Definition of this laboratory experimentation programme.

1999-2001 *In-depth study of the Callovovo-Oxfordian* on the Meuse/Maute-Marne site (3D geophysical campaign, bore-holes, seismic logging, etc.) and *start of sinking operations* of the laboratory main and auxiliary shafts.

Year-end 2001 *The Dossier 2001 Argile presents the acquired knowledge, tests the methods implemented and, provides a first safety check of the preliminary repository concepts also analysed from the viewpoint of reversibility rationale.*

2002 Starting from the Dossier 2001 Argile:

- *elaboration of the revised scientific programme HAVL Argile 2002-2005,*
- *selection of the repository concepts (packages and disposal cells)*, which includes basic data for the engineering, behaviour and safety studies carried out from 2002 to 2005.

2003-2004 *Deep and sometimes deviated bore-hole programmes* on and around the site of the Meuse/Haute-Marne Laboratory (FRF and FSP drilling programmes)

October 2004 Auxiliary shaft reached TD (total depth) at - 490 metres.

November 2004 *Experimental drift available at - 445 metres* in the main shaft.

Since February 2005 *Drifts have been excavated at a depth of 490 metres at the bottom of the auxiliary shaft (experimental drifts, interconnecting drifts between the shafts and technical drifts for laboratory operations).*

April - September 2005 *The various experimental drifts (depth of 490 metres) were commissioned.*

Dossier 2005 Argile

1

Design approach for a safe and reversible disposal system

Design approach for a safe and reversible disposal system

The basic objective of long-term management of high-level and long-lived waste (HLLLW) is to protect for a very long period man and the environment against the risks associated with these waste. The response offered by a repository consists of confining these waste in a deep geological formation in order to prevent the dissemination of the radionuclides contained in them. This confinement is passively ensured over long time scales (up to several hundreds of thousands of years), that is, without requiring for a very long time maintenance or monitoring as stated by the basic safety rule RFS III-2-f.

The purpose of the feasibility study of a HLLLW repository in a deep geological formation conducted by Andra and based on the Meuse/Haute-Marne site characteristics was to assess the conditions under which a disposal facility may be constructed, operated, managed with a reversibility rationale, closed and monitored, and then let evolve without any human intervention and without the safety of the workers and the public, and the protection of the environment being at stake at any moment. *Safety is thus the key issue of the repository design approach*.

HLLL waste and spent fuel

• The two main types of waste

There are two types of waste:

- high-level waste, also called C waste. These waste are reprocessing residues of spent fuel unloaded from the nuclear power plants. These residues are embedded in a melting glass matrix (hence the name vitrified waste). They mean a very small volume, but 96 % of the residual radioactivity after reprocessing is concentrated in them. They are stored on the Marcoule and The Hague sites;

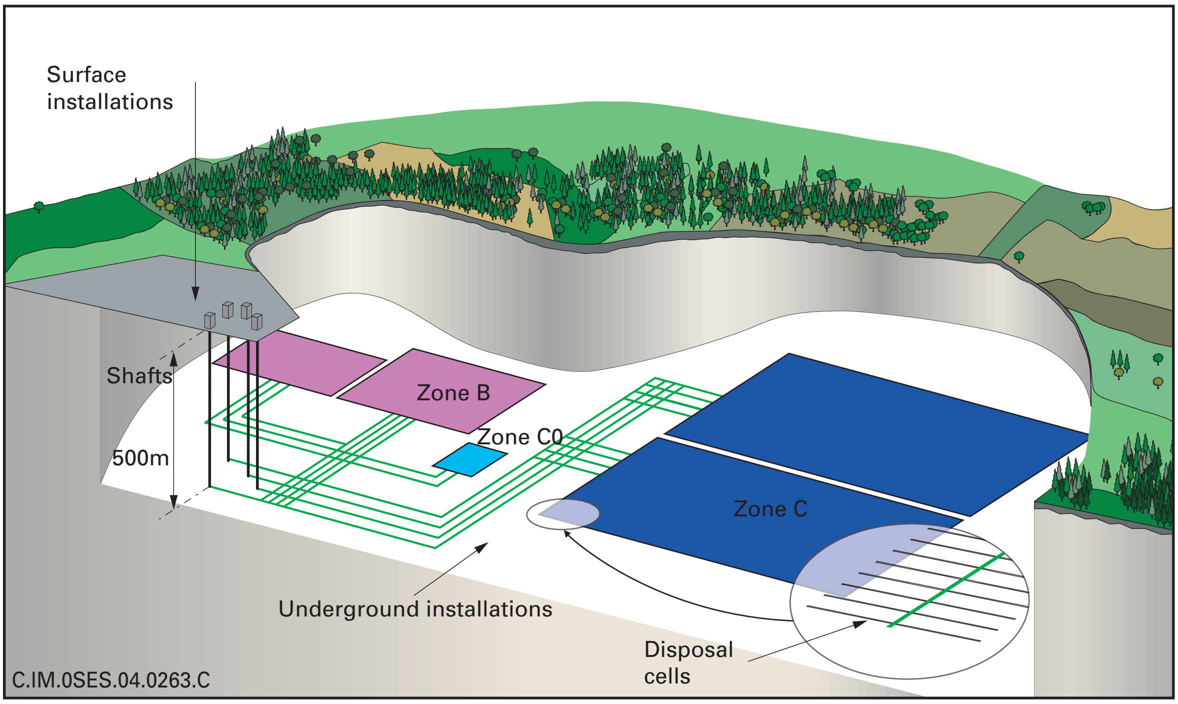
- medium-level waste, also called B waste. This waste is, first of all, the technological waste originating from the reprocessing process of spent fuel. It includes also the waste originating from research activities or, in very small quantity, naturally high radioactive objects (radium). It comes in a wide variety of forms (conditioning in concrete, bitumen, or in metal form). It represents the major part of the volume, but a minor part in terms of radioactivity. Is is mainly stored on The Hague, Marcoule and Cadarache sites.

• The special case of spent fuel

The spent fuels unloaded from the nuclear power plants are not classified as waste. In fact, the Nuclear Cycle Backend strategy defined by the French utility, EDF, provides for their recycling in the COGEMA plant at The Hague. However, to cover possible evolutions in the fuel cycle, Andra was asked to also take into account in its studies, as it is done in several other countries, the possibility of direct disposal of spent fuel (also called SF, CU in French). This explains why specific concepts were developed for these materials. A distinction is made between two main types of fuels: those composed of uranium oxide (called UOX), and those based on a mix of uranium oxide and plutonium (called MOX), which recycle the plutonium originating from the reprocessing of the spent fuel (UOX).

The disposal process

The primary waste packages are made up of a metal or concrete container. Many types exist depending on the waste's nature.
The primary packages are transported in shipping casks by rail and/or road from the production centres of these packages (fuel reprocessing plants, nuclear power plants or research laboratories) up to the disposal facility.
At the disposal facility, the packages are removed from the shipping casks and put in disposal packages which contain in their concrete or metal envelope one or several primary packages of the same type.
The disposal package enclosed in a metal biological shielding cask is lowered through a dedicated shaft and transported through the drift network to the specific repository zone. In this zone, the package is removed out from the cask and emplaced in a disposal cell.
In a reversible disposal system, the packages can be managed as simply as in a storage. If this choice is made, the repository can be closed by stages, the first one being the disposal cell sealing.
Little by little the cells and the drifts of the repository zone and then the repository would be closed following a progressive, controlled and reversible process. The closure does not prevent package retrieval, but complexity grows with the evolution of the reversibility level.



Basic diagram of a repository layout during operation: disposal cells are excavated underground in the host formation and are grouped in modules. These modules are integrated in a drift network linked to surface by access shafts. Waste package management such as reception and conditionning is performed in surface installations.

Deciding on the feasibility of a possible repository refers to a conviction regarding a specific site according to the following:

- *there are technologies available to carry out all the repository phases,*
- *their implementation remains accessible* (in particular, cost or development needs are not prohibitive),
- *the selected geological medium has favourable characteristics* to contribute to a safe management,
- the technologies allow constructing, operating, closing and letting evolve the repository *under safe conditions over time scales varying up to several hundreds of thousands of years,*
- the short- and long-term *safety assessment* of these concepts *can be conducted with sufficient confidence.*

In addition to operating and long-term safety, the repository design must satisfy the reversibility requirement tightly linked to the application of the precaution principle stipulated by the Law of 30 December 1991. Reversibility refers to a "cautious" management in successive stages of a repository, leaving the choices open for the next generations. Its study requires a good scientific and technical understanding of how a repository evolves and describing the means of action needed to preserve the possibilities of a choice. The reversibility requirement is also at the core of thinking about studying a possible repository and completes the orientations of the basic safety rule (RFS III.2.f).

RFS III.2.f "The protection of man and the environment in the short- and long-term is the basic objective assigned to a deep geological repository"

It must be ensured "without depending on an institutional control on which we cannot rely with certainty beyond a limited period" (500 years).

Repository in its various phases

- *Preparatory phase for packages emplacement*: construction of the surface installations, the connecting structures between the surface and the underground installations, the first repository modules.
- *Operation and observation phase*: the main function of the repository is to accommodate the packages in the host formation. In a reversibility rationale, the operation takes place in stages, preserving at each stage the freedom of choice for the management of the waste and the installations : package reception and emplacement, construction of new repository modules, observation and monitoring of the installations and their evolution, progressive closure of the underground structures (by backfill and sealing), possibility of going backwards. No duration was set *a priori* for this phase: the time scale is a hundred years to several hundred years.
- *Post-closure phase*: the main function of the repository is to protect *man and the biosphere from the dissemination of radionuclides contained in the waste*. This phase consists *of mainly backfilling and sealing the underground installations* and corresponds to the lowest reversibility level. Then for a duration ranging up to several hundreds of thousands of years, the post-closure phase is characterised *by the total absence of human action* (maintenance, for example) in the underground installations.

1. The safety approach

The safety approach to assess a geological high-level and long-lived waste repository has several specificities:

- the necessity of dealing in a coordinated way with the repository management *in the operating phase as well as in the post-closure phase, where safety must be ensured without requiring any particular intervention (passivity)*, in accordance with the Basic Safety Rule,
- the consideration of *extremely long time scales*,
- *the very tight link between design, knowledge acquisition and safety assessment*, from a viewpoint of feasibility assessment,
- *the key issue of the notion of uncertainty management*, and, in particular, for the post-closure phase.

These peculiarities result as much from the studied topic specificity (the geological repository) as from the issue raised (that of feasibility). They require calling on many disciplines (mining and nuclear engineering, safety, earth sciences, material sciences, etc.) and implementing specific methods at the interface of these disciplines.

1

Open and not optimised solutions at the feasibility assessment stage

Although the Dossier 2005 Argile is based on observations and results from experiments carried out on the Bure site (Meuse/Haute-Marne Laboratory), the safety approach is not a "conventional" and regulatory safety approach of an application for the construction and operation licence of a basic nuclear installation, at least under three aspects:

- *the purpose of the feasibility is to demonstrate the existence of technical solutions which are not definitively frozen*. The concepts may evolve along the stages, which could lead to the opening of a repository. Thus, when several technological solutions can be proposed for an issue, as for instance an operating one, the feasibility assessment is based on one of the best known technologies, but the possibility to resort to another one still remains,

- *the proposed technological solutions do not pretend to be optimised*, particularly in terms of operating safety. It would be too early within the context of feasibility to implement in all its completeness an ALARA radiological protection optimisation approach (as low as reasonably achievable) leading to the optimisation of the repository design regarding the operating safety criteria (radiological impact on workers, the public, etc.). Nonetheless, the designer must still bring elements demonstrating that the proposed concepts respond to the operating safety objectives,

- *the purpose of the approach is not to position the repository on a particular site in order to apply for a construction and operation licence, but to assess its feasibility in a particular geological formation by resorting to a determined location and by ensuring the transposability of the results to a larger zone*. This transposability approach means that the results obtained are not dependent on the specificities of a small-scale zone, which would leave no flexibility for a possible siting of the repository.

1.1 General principles of the safety approach

1.1.1 Robustness and demonstrability

The safety assessment is based on the repository concepts, which are described down to the necessary level of detail adapted to the assessment exercise. *These concepts must allow the operation of the repository, and then the control of evolution over the long term, while ensuring safety for the public and workers. In particular, safety in the post-closure phase must be ensured without any particular intervention being needed* in accordance with the RFS. They are defined with respect to two principles.

- *Robustness*: the elements of the repository must guarantee the maintenance of their function(s) when faced with reasonably conceivable demands and despite residual uncertainties. The concepts generally adopt the most robust solutions possible with regards to external disturbances and uncertainties. *The safety analysis provides an overview of the robustness of the concepts proposed.*

- *Demonstrability*: the reliability of the selected concepts must be easy to check by the studies without calling on complex demonstrations subject to caution. Demonstrability is a relative notion and the simplicity of a check is not a goal in itself: *the dossier must make the best possible use of multiple lines of evidence* (safety assessment by calculation, qualitative reasoning or calling on natural analogues, experimentations or technological demonstrators).

1.1.2 Operating safety and long-term safety: specific approaches

In accordance with the RFS, two principles provide guidelines to the repository design:

- the protection of man and the environment against possible consequences related to the radioactive waste,
- the limitation of the possible radiological impact to a level as low as reasonably achievable (ALARA radio-protection optimisation principle).

The Dossier 2005 is concentrated on the radiological risk, but without overlooking the other possible impacts of a repository. The solutions to the problems raised by the radionuclides include, in fact, a great part of the difficulties raised by chemical toxics, since the problematics are of the same kind (prevent and delay the transfer of toxic elements to the environment). At the feasibility stage, the chemical impact of the repository is studied in general and concentrates for the quantitative assessments on a few of the most penalising toxics. Likewise, the environmental impacts (landscape, noise, etc.) comparable to those of other industries do not constitute a particular topic of study in a feasibility phase. Other possible consequences for the environment and, in particular, the degradation of natural resources (access to an ore deposit underlying the repository, heating of an aquifer) are taken into account in accordance with the RFS, which imposes discarding any site with outstanding resource.

Andra developed two different safety approaches according to the repository phases:

- *The first one concerns operating safety, which is close to a conventional approach. It concentrates on the specific issues of the repository,* and does not exhaustively consider the safety provisions already well known in another context, for example, the surface installations. The dangerous situations and potential risks related to the repository particular context were identified, and then protection and prevention measures were proposed in order to control them and satisfy the protection objectives with respect to the radiological risk and other ones (fire, crushing, etc.). The analysis of operating safety took into account the main specific risks (exposure of the personnel to radiation, contamination during a falling of package, traffic accident involving physical injury, fire, etc.). The residual risk which would persist despite the implementation of the prevention and protection measures was also characterised.
- *The other one concerns the assessment of long-term safety in the post-closure phase in order to evaluate the repository robustness versus the objective of long-term confinement of the radioactive waste with respect to the biosphere.* Emphasis is placed on the integration of scientific knowledge and the management of uncertainties.

1.2 Long-term safety

1.2.1 The safety assessment phases

1.2.1.1 Functional analysis: safety as input to design

The protection of man and the environment against the dissemination of radionuclides is the basic function of the repository, without excluding other functions, such as the accommodation of the packages.

The basic safety rule identifies confinement "barriers" : waste packages, engineered barriers (materials placed between the packages and the rock), *the host formation*, which protect the waste against water circulation and intrusive human actions, and limit and delay the transfer of radionuclides in the geological medium and the biosphere.

In an iterative approach between design and safety, *Andra assigned safety functions to all the components of the repository having a significant role (host formation, waste packages, architecture elements) and this functional analysis defines then the technical specification in term of requirement for each component to be designed.* These component characteristics (for example, materials and thickness of the disposal packages, cell dimensions, etc.) were determined with respect to safety by taking into account the interactions with the environment and the possible uncertainties. They were then integrated in the repository evolution scenarios and assessed with more or less penalising calculation values.

The design of a "multi-function" system completes the notion of a "multi-barrier" system. Some components contribute to fulfilling the same function (complementarity) or maintaining the function in case one of them fails (redundancy).

Functions and barriers

The repository is expected to:

- prevent water circulation: the geological medium contributes to this, as well as the design of the repository structures,
- immobilise the radionuclides within the package: the waste contribute to this objective, as well as the containers and the chemical conditions in the disposal cells,
- and delay and attenuate the migration of the radionuclides which would have been released outside of the disposal cells.

These functions are ensured over time by several different and independent (up to a certain limit) components.

1.2.1.2 Synthesis of knowledge, management of uncertainties

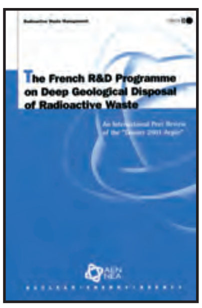
The assessment of a repository feasibility assumes that a sufficient knowledge of the behaviour of the repository components has been acquired, in particular, thanks to the composition of a large corpus of scientific knowledge and the development of a repository architecture down to a sufficient level of detail, and taking into account unavoidable uncertainties when considering evolution over hundreds of thousands of years. Over such time scales, no feedback is available other than by means of natural and archaeological analogues. This does not mean, however, that these residual uncertainties related to the long durations, specific to the dossier, cannot be managed with a sufficient degree of confidence:

- *provisions are taken with regards to the repository conditions which would allow overcoming uncertainty consequences* : choice of a very stable geological medium hardly affected since its deposition (155 million years ago), compartmentalisation of the repository into zones to prevent interactions between various kinds of waste, use of simple materials whose behaviour is well-known (for example, unalloyed steel, concrete), etc.
- *in addition, safety is integrated upstream from the design* in order to orient the choices toward the most robust solutions with respect to a possible lack of knowledge,
- *finally, uncertainties are systematically investigated and their potential effects examined*, particularly in qualitative safety analyses, *and taken into account in the safety assessment.*

The repository architecture proposed by the Dossier 2005:

- is the result of an interactive work carried out between on one hand the engineering department and the research programme department, and on the other hand the department in charge of the safety assessment, which steers far upstream the research programmes and the design work,
- integrates the knowledge acquired on site and the lessons learned from the safety assessment carried out in 2001 for the geological disposal in clay.

Dossier 2001 Argile : a few lessons learnt



The safety assessments conducted in 2001 by Andra identified the repository elements and natural phenomena on which specific efforts were needed: for example, a more detailed characterisation of the geological medium, study of the sealing at the level of repository access structures as shaft, etc.
The Dossier 2001 also included detailed examinations by Andra evaluators (Directorate of Nuclear Safety and Radiological Protection, National Review Board) and a peer review under OECD/AEN aegis, which confirmed or specified the orientations for the next research programme. This feedback helped Andra to strengthen the interfaces between engineering and safety, on the one hand, and research and safety, on the other hand.

Andra implemented three complementary approaches to synthesise the knowledge, describe the repository evolution and manage the uncertainties.

- *Knowledge reference documents were made up* in order to provide a complete view of the elements available on the studied components: geological medium, materials, packages, etc. They describe the state of knowledge, correlatively identify the lack of knowledge and thus contribute in determining the sources of uncertainty and orienting the actions to reduce them.

- Once a good level of knowledge is reached on each of the components and the repository global architecture is defined, *it is necessary to describe as finely as possible its evolution over space and time : this is the purpose of PARS* (phenomenological analysis of repository situations), which describes the phenomena (thermal, mechanical, hydraulic, chemical, radiological) and their couplings throughout the repository evolution and specifies the phases of this evolution from its construction up to 1 million years. The system has to be broken down into simple subsystems in order to analyse it: PARS splits the repository evolution into a set of situations, each corresponding to a specific part of the repository and a specific time period, as well as a homogeneous phenomenological state. The phenomena and their couplings, as well as the associated models, are assessed for each situation: this assessment underlines the limits of knowledge or understanding and determines the uncertainties. *The systematic work accomplished with PARS led to a list of uncertainties*. This approach is completed by a more transversal view of the main processes governing the repository evolution.

- *Finally, in a conventional way, the calculation parameters, models or data are systematically listed in order to ensure their traceability* and to progressively update them through knowledge acquisitions, for the safety calculations.

Uncertainties and time scale

The uncertainties are not of the same kind depending on the time periods, components or parts of the repository and its environment. For example:

- the uncertainties *on the behaviour of the materials and the packages* (metals, cements, glasses, etc.) and their degradation increase over time up to a phase where their behaviour is no longer foreseeable and the materials are no longer able to play a favourable role for safety. Nonetheless, if the environmental conditions are controlled, the favourable properties of these materials can be mobilised over very long periods,

- the uncertainty *on the geological medium* and its behaviour is rather decreasing when the thermal, mechanical and hydrological processes due to the disturbance of the repository dwindle or reach an equilibrium. The time to reach equilibrium and the nature of the equilibrium can involve uncertainties,

- the uncertainty *on the surface environment* increases because of major climatic evolutions, such as the periodic glaciations.

The various time scales considered are integrated in the safety analysis within the scope of the safety functions, the performance assessment and the analysis of the uncertainties.

1.2.1.3 A normal evolution scenario: complying with the objectives

The confrontation of the functional analysis and the PARS (phenomenological analysis of the repository situations) allows describing the normal evolution situations of the repository in the post-closure phase, that is, those situations in which the components fulfil the expected functions and which appear to be the most likely. Although the repository does not undergo a unique evolution because uncertainties remain (for example, the lifetime of each container can vary beyond the minimum limit set by the design, etc.), the situations are similar in the way they progress and allow defining a normal evolution scenario (SEN) associated to alternative situations or models, and sensitivity analyses.

Once the normal evolution is described, scientists propose, according to the context set by safety, the models and parameter representing it.

The calculations confirm that the proposed concepts effectively fulfil the safety functions which are assigned to them and that the individual radiological exposures are acceptable under normal evolution.

The radiological and chemical impact is conventionally evaluated in agreement with the RFS by calculating the committed individual exposure dose.

• *For the repository operating situations*, Andra set the same objectives as for its current operating facilities:

  - for the public, a maximum allowable dose of 0.25 milliSievert per year (mSv/year) in a normal situation, in consistency with the objective imposed by the RFS for the long term. This value corresponds to a fraction of the public individual exposure limit (1 mSv/year) adopted by the International Commission of Radiological Protection and the Euratom 96/29 directive, excluding individual exposure to natural radioactivity (2.4 mSv/year on the average in France) and for medical purposes,

  - for the "exposed" workers (working in the repository controlled areas and with regular medical check-up), a maximum allowable dose of 5 mSv/year in a normal situation, that is, a quarter of the current regulatory value.

• *For the long term, the main safety indicator remains the committed dose at the outlet within the context of a reference group and a biosphere. It must, in accordance with the RFS, remain lower than 0.25 mSv/year in a normal situation.*

Although the calculation of this dose for periods close to our own is a well-known exercise in the field of impact assessment, this case presents specific problems when it is carried out over a million years. At this scale, it is not realistic to pretend to be able to make an assessment on the lifestyles of the populations in the considered sector. The environment conditions and, in particular, the climatic conditions will also undergo major variations; their main characteristics are predictable, but it will be difficult to accurately describe them at a local level. Also, the model used for the impact calculation does not pretend to have a predictive character with respect to the transfer times and pathways of the radionuclides to the biosphere. It pretends only to overestimate the repository impact from a "cautious" viewpoint without being excessively pessimistic. The long-term calculated dose is an indicator of the impact and not a prediction of this impact.

Other indicators are proposed by Andra to characterise the safety level of the concepts. In particular, radionuclide concentration flows as assessed at various locations (typically at the host formation interface) allow refining the judgement on the repository safety and overcoming some of the uncertainties. They cannot be compared, however, to the regulatory thresholds.

Calculation of the impact of chemical toxics

The selected methodology consists of calculating the concentrations of toxics at the outlet and/or the doses liable to be received by the reference group and comparing them according to what seems most relevant:

- in priority, to the reference toxicological values according to the methodology recommended for the impact assessment of classified industrial installations, when these values are available,
- otherwise, to the maximum concentrations in the environment set by the regulations on the quality of waters or to reference values adopted internationally, such as those defined by the World Health Organisation for certain toxics.

1.2.1.4 Managing uncertainties: a qualitative analysis of safety and altered evolution scenarios

A qualitative safety analysis determines and assesses, component by component and with respect to the safety functions assigned to each, *the uncertainties in order to ensure that:*

- *these uncertainties are taken in account by the design choices, which reduce their effects* (for example, use of over-packs to prevent the migration of radionuclides in a hot environment),
- *they are considered in the normal evolution scenario (SEN) and, in particular, through sensitivity analyses.*

This analysis can reveal residual uncertainties still not taken into account. Then, it will be necessary to ensure that their effects are minima or their occurrence very unlikely… The qualitative safety analysis results will lead to the definition of altered evolution scenarios (SEA). In order to ensure their completeness, they will be compared to international expert databases describing the processes to be taken into account and, in particular, the FEPs ("features, events and processes") of the OECD/NEA.

Andra defined and studied these scenarios corresponding to highly unlikely events or to dysfunction of safety functions:

- "*package failure*" altered scenario where a series of packages would not fulfil the expected functions, along with several variants in terms of container types or number of packages,
- *scenario where all or a part of the sealing system has failed*,
- *scenario where an unintentional human intrusion disturbs the repository*: considering the repository depth, this intrusion means a bore-hole intercepting a drift or a module.

These scenarios include also a phenomenological description (PARS in altered situations) and a modelling. By assuming that a barrier or a safety function fail, they allow appraising the system overall robustness by comparing it with the SEN.

International data providing guidelines to the analysis

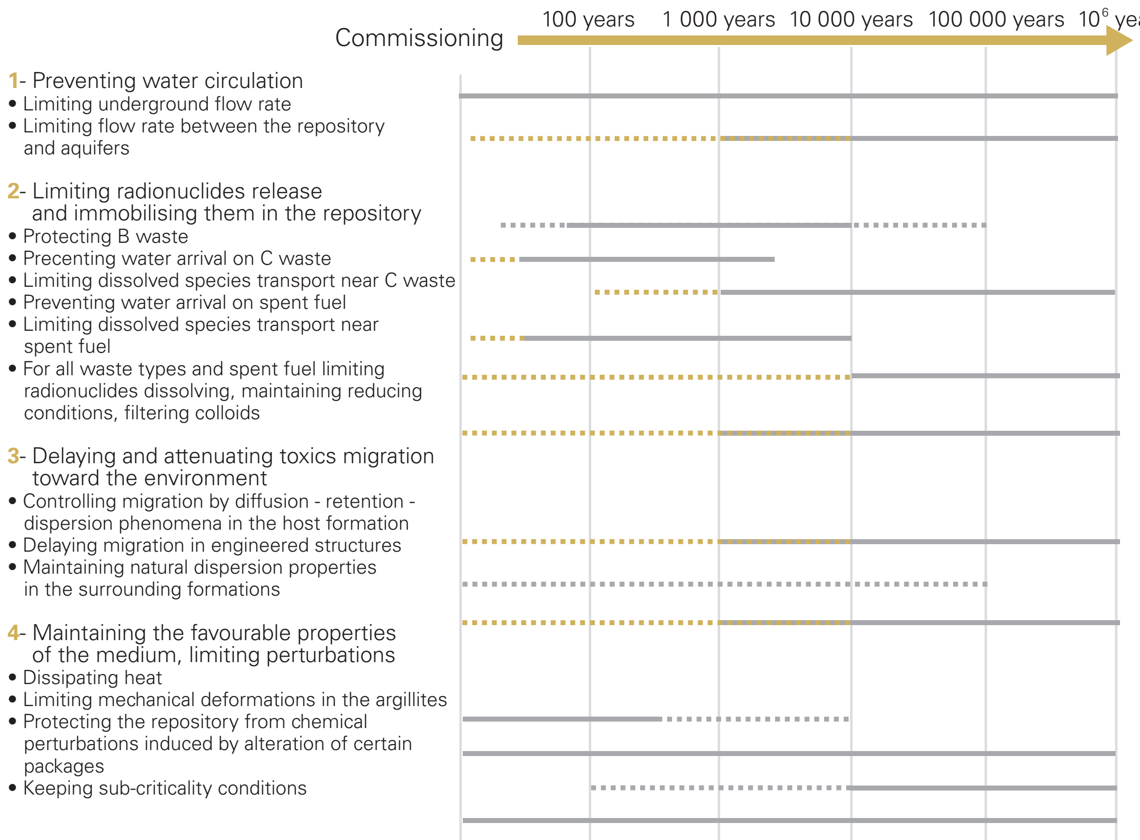
In addition to the RFS recommendations, Andra took into account a number of principles elaborated by the organisations (IAEA, OECD/NEA, ICPR), which organise debates within the international community, by establishing common references. Three examples:

- the NEA recommends *carefully defining "the assessment basis"* (to put it plainly, it means the scientific and technical knowledge supporting the safety assessment, the modelling tools, the database) and discussing its quality and credibility. The assessment basis is composed, first of all, by the 3 tomes of the Dossier 2005 (Architecture and management of a geological repository, Phenomenological evolution of a geological repository, Safety assessment of a geological repository), which describe, respectively, the selected concepts and their justification, the acquired knowledge base and the associated conceptual models, the highlighting of these elements and their discussion to ensure the safety evaluation;
- the NEA recommends also recourse to "multiple lines of evidence", that is, going beyond simply the performance calculations, the qualitative arguments and the various indicators in order to increase the credibility and the soundness of the analyses. Due to the importance given to the most extensive use of scientific data and qualitative safety analysis, the Dossier 2005 adheres to this approach;
- the NEA expects from a safety evaluation document, clearness, transparency and traceability in order to find the source of any statement, data, assumption, through a clear presentation, the use of references, reporting and discussion of uncertainties, open questions or any element liable to compromise the repository safety (openness), the organisation of internal and external peer reviews. With this goal in mind and to prepare its dossier, Andra created external groups in charge of reviewing most of the Dossier 2005 documents.

1.2.2 Long-term safety functions of the repository

Multiple safety functions are assigned to the installation in response to the aim of establishing a geological repository capable of *protecting man and the environment against the risks associated with HLLL waste over a very long period by containing it in a deep formation to prevent dissemination of the radionuclides contained in the waste.* These safety functions complement each other to enhance the system overall performance. By providing some degree of redundancy, they enable the system to more successfully withstand a failure or external aggression.

First and foremost, deep geological disposal protects waste against erosion and the main human activities, which, on a timescale of hundreds of thousands years, only impact a superficial layer a few tens of metres thick.



In this context, controlling dissemination of the radionuclides contained in waste depends on three major functions that must be performed by the repository:

- *preventing water circulation,*

- *limiting radionuclide release and immobilising radionuclides inside the repository,*

- *delaying and reducing the migration of any radionuclides released by waste.*

Ultimately, it must be possible for these three functions to be performed passively (i.e. with no need for human intervention). Some are only needed at a late stage. For example, the repository ability to limit radionuclide migration does not become operational until the waste packages begin to release radionuclides. Such functions are said to be latent during the period when they are already available, but not yet operative.

In order to implement these functions:

- *maximum advantage must be taken of the favourable properties of the Callovo-Oxfordian argillites* (i.e. low permeability, retention capacity, geochemical properties and hydrogeological environment – cf chapter 3). The formation age, its tectonic stability and the repository depth make reasonable arguments that these favourable properties will remain very stable over the studied timescale (i.e. between one thousand and several hundred thousand years),
- *the repository architecture was designed in such a way, notably in order to preserve the favourable properties of the geological environment*, in particular by minimising disturbance caused by excavating the underground structures, the materials introduced and the presence of waste, notably with regard to their heat release.

1.2.2.1 Preventing water circulation in the repository

The aim is to contain the radioactivity present in the packages, by keeping it immobilised in them. The repository role is to:

- *limit water circulation around the packages*, which is the main factor liable to alter waste container,

- prevent advection of radionuclides, precisely in order to limit their means of migration through diffusion mode only, a very slow phenomenon, by limiting both the flow rate of water reaching the repository and the velocity at which it circulates through the repository and on to the surrounding formations.

The low permeability of the Callovo-Oxfordian argillites, combined with architectural and sealing designs, limit water flows in the repository.

Hydraulic regime in the repository

In its natural state, the host formation is saturated with water; *water can drain vertically through it*, following the direction of the gradient imposed by the difference in hydraulic head (pressure) between the overlying and underlying geological formations, which are more permeable than the Callovo-Oxfordian argillites, although this occurs very slowly, due to the very low permeability of argillites (approximately a few centimetres per hundred thousand years).

These conditions are only changed by the repository:

- during its operational phase, as excavating and ventilating the structure desaturate the argillites in contact with air,
- and during a transient period, once the underground facility is closed, characterised by a gradual return to a state of saturation of the geological environment and repository materials, in which the various flows converge toward the structures. This resaturation period, estimated at one hundred thousand years, depends on the permeability of the environment (very low in the case of Callovo-Oxfordian argillites) and structures (design, dimensions, materials, etc.), and the effects of gas (particularly hydrogen generated by corrosion) which delay the end of the resaturation period, etc.

When the underground facility and its environment are saturated, the hydraulic heads are back at equilibrium and the water flow in the Callovo-Oxfordian argillites is again a single-directional vertical one.

1.2.2.2 Limiting radionuclide release and immobilising the radionuclides inside the repository

The possibility of water reaching waste packages in the long term cannot be ruled out. *In such conditions, the repository function is to limit the release of radionuclides into the water, and to "immobilise" them in the waste or as close to it as possible. There are twin objectives:*

- *Limiting alteration caused by water to waste containers, or to the glass, bitumen or cement matrices that contain the radionuclides inside* the containers, *by creating favourable physical and chemical environmental conditions,*
- Once waste packages have begun to be altered by water, *limiting the mobility of any radionuclides liable to dissolve in the water by creating favourable geochemical conditions* (reducing and controlled-pH conditions) so that such elements are maintained in, or precipitated into a solid state (very few radionuclides such as iodine129 and chlorine36 are unaffected by such geochemical conditions) *and by relying on the favourable properties of the geological environment* (such as the low porosity of the rock and the retention capacity of the argillaceous minerals that behave as physical filters to further reduce the migration of such elements).

Limiting package alteration caused by water: different scenarios for different waste products

- With B waste packages, the aim is to protect the metal parts that they contain from corrosion by creating a favourable chemical environment (with reducing potential and a pH of 10 to 12.5) and, in the specific case of bituminous waste, *relying durably on the containment properties of bitumen* by maintaining the disposal cell at a temperature between 20 and 30°C and controlling the pH of any water that reaches the bitumen (pH 10 to 12.5).
- With vitrified C waste packages, *the aim is to prevent any water from coming into contact with the glass for several thousand years. Doing so would maintain the glass durability over a period much longer than the thermal phase* during which the glass temperature remains high and radionuclide release phenomena are relatively unpredictable on the basis of current knowledge. *After the thermal phase, the objective is to limit the alteration of the glass*, both by limiting the possibility for dissolved elements to migrate within the close environment, and by controlling the pH at the interface between the glass and its environment (pH between 7 and 9), as glass is sensitive to this parameter.
- With spent fuel, one of the repository functions is *to prevent any water from reaching the assemblies for approximately 10,000 years, again a period far outlasting the thermal phase. After that time* and in order to limit fuel dissolution, the objective is *to control both the transport of dissolved elements near the assemblies and the water chemistry* (neutral to alkaline pH and reducing conditions).

1.2.2.3 Delaying and reducing the migration of radionuclides into the environment

The surrounding geological formations

Although they are not part of the "containment system" as such, the surrounding geological formations (above and below the host formation) are also being studied.

The aim is to understand how any radioactivity released by the repository beyond the host formation could reach the biosphere.

One of the repository functions is to *delay and limit, in both space and time, the migration of radionuclides* released by waste and once dissolved in water.
This is achieved by relying on the favourable properties of the host formation, that means in the case of the Callovo-Oxfordian argillites : low permeability, a low diffusion coefficient and a high radionuclide retention capacity.
Additionally, radionuclides can be trapped within some repository components (disposal cells, swelling clay buffer engineered barriers, bentonite seals, etc.) thereby retarding their migration.

1.2.2.4 Preserving the environment favourable properties and limiting disturbances induced by the repository

Repository architecture and construction techniques are designed in order to take advantage of the geological environment favourable properties and to limit the disturbances caused by the facility.

A first expected function is the ability to dissipate the heat produced by waste radioactivity. The goal is to maintain a temperature below 100°C at the skin of the packages, and below 90°C in the rock, so as to remain within temperature domains covered by current knowledge and by the ability to understand phenomena and their couplings. This function is particularly important for vitrified C waste (and if applicable, spent fuel).

Furthermore, to avoid irreversible mineralogical transformations, it is important to limit the amount of energy transferred to the rock. The period during which the argillites in contact with the waste disposal cells is above 70°C, must not exceed one thousand years.

A second function is to control disturbances in the host formation.

- Excavating underground cavities in an environment subject to natural mechanical stresses generated by the pressure of the overburden formations will lead to *deformations in the argillites*. Moreover, the heat released by spent fuel and C waste packages will expand materials and induce deformations. In parallel with the aforementioned safety functions (preventing water flow, delaying and reducing radionuclide migration), it is important to minimise local rock damage caused by mechanical strain.
- It is also important to check that hydric disturbance (desaturation during construction and operation) and chemical disturbance (due to the introduction of oxygen and external materials) of the geological environment, possibly coupled with mechanical disturbance, do not damage the geological environment.
- Lastly, due to the presence of fissile materials in some waste packages, one must ensure that the repository remains in a *sub-critical configuration* (to ensure that an uncontrolled nuclear chain reaction cannot spontaneously begin in the waste), taking in account possible movements and long-term evolution of such materials.

1.2.3 Repository architecture - Addressing long-term safety requirements

Several structuring architectural features have been designed in order to limit water circulation, radionuclides release and migration into the environment and disturbances caused by the repository.

1.2.3.1 A repository located in the centre of a geological formation

To maximise the argillites thickness above and below the repository that constitutes a first barrier to water circulation and radionuclide migration (and therefore in order to maintain a maximum buffer of sound host formation above and below), Andra adopted *a low-ceilinged design for the underground facility, with a single level lay-out in the middle of the Callovo-Oxfordian layer* (to provide equal buffer thickness with respect to the overlying and underlying geological formations). A minimum buffer thickness of sound formation was set as 50 m; as the studied formation is at least 130 m thick, the underground facility is located in a 30 m thick band centred at mid-height within the formation.

1.2.3.2 Repository compartmentalisation

The various repository zones are compartmentalised to reduce the quantity of waste and radionuclide affected in the event of failure or intrusion. *Each compartment is separated from the others by a large thickness of argillite* (250 m in between zones and 50 m in between modules) and by seals closing the access drifts.

Separating the spent fuel, B and C waste into distinct, phenomenologicaly-independent zones eliminates the inherent complexity involved with interactions between various waste types. This also simplifies the task of understanding the phenomena and in particular, makes the various repository zones, thermally independent.

1.2.3.3 Structures designed to limit mechanical disturbance of the geological environment

Structures have a simple, typically close to circular profile, which, for an underground structure, means the most stable configuration, causing least disturbance and their size is kept as small as possible. The underground structures have *a lining that provides ground support for at least a century*. For enhanced stability, *the distance between adjacent disposal cells is at least five times the cell diameter.*

To prevent mechanical damage propagating to the argillites once the lining becomes degraded (cf. chapter 6), *the residual clearance around the packages in the disposal cells is limited by design, and some underground structures (as drifts and shafts) are backfilled when the decision is taken to close them as part of the reversible repository management.*

1.2.3.4 Design limiting thermal disturbance

The number of disposal packages per C waste (or spent fuel) disposal cell, and the distance between adjacent cells are determined so as to limit temperature and therefore prevent any alteration of the argillites (at first temperature <90°C in the argillites, then <70°C after 1,000 years). The hottest packages may require a relatively long interim storage before emplacement in the repository. Furthermore, to preserve the containment properties of bitumen, which according to current models requires a temperature below 30°C, bituminised B waste packages are kept away from other waste packages, which are hotter.

1.2.3.5 Underground facilities with multiple seals and a dead-end architecture to prevent water circulation

When the decision to close the repository is made and progressively implemented, the disposal cells, access drifts and shafts are sealed with low permeability swelling clay plugs.

The seals prevent water circulation (which is a factor in package alteration and radionuclides release) *and help to control radionuclide migration.*
Specific measures have been studied and tested with a view to maintaining a continuous leak-tightness between the disposal cell seals and the Callovo-Oxfordian argillites, and cut off the potentially-fractured argillite zone in the immediate vicinity of the excavated structure.

Additionally, to reduce any extension of the damaged zone around seals, the seals and drift sections that are to be sealed, run parallel to the main geomechanical stress and their cross-section at the seal level is kept to a minimum (<7 m).

Structures are organised in a dead-end arrangement to limit water circulation:

- the disposal cells are dead-end tunnels,
- the disposal cell groups and subgroups have a dead-end architecture. Disposal cell groups are accessed via a limited number of drifts, which are close to each other and run in parallel,
- The repository lay-out itself also has a global dead-end architecture: all the shafts are grouped together in the same zone, virtually cancelling out any hydraulic head gradient between them.

1.2.3.6 A favourable physico-chemical environment for waste packages

The design of the disposal cells, and particularly the choice of their materials, provides a favourable physico-chemical environment for waste and waste packages. *The aim is to postpone their alteration in order to limit any early release of radionuclides.*

- *The choice of concrete for the B waste cells* contributes to the physico-chemical protection of the waste and helps to retain certain radionuclides, while inducing only limited chemical disturbance in the environment.
- *With the vitrified C waste, however*, use of concrete near the packages cannot be considered because the alkaline conditions that it would create could accelerate the glass alteration process. *Only metallic materials will be used.*

Disposal package: steel or concrete

Concrete is well-suited for to manufacture the containers for B waste disposal packages, because it is adapted to large-scale use, its moderate density limits the weight of the packages being handled, and it can be a particularly durable material in disposal cells that are ventilated during the operational phase.
Metallic containers appear to be a more appropriate choice for the containers of spent fuel and C waste packages. Steel offers superior heat resistance and, in the absence of oxygen, can act as a reliable watertight barrier for long periods. Concrete would be a less suitable long-term choice, with respect to the ability of glass or spent fuel pellets to durably confine the long-lived radionuclides and would create alkaline conditions with detrimental effect with respect to glass.

Functions

Protect man and the environment from the dissemination of radioactive elements

- by taking in account likely natural events and hypothetical situations
- by protecting the environment from other (chemical) impacts

Functions	Period	Disposal package	Repository modules	Shafts and connecting drifts	Cell seals	Shaft and connecting drift seals	Backfill	Surface installations	Construction, operation and management resources	Geological environment	Primary packages
		Main engineered components									
Isolating waste from surface erosion phenomena and normal human activities	After closure		■							○	
Preventing water circulation Limit water flows and circulation	After closure		■	■	■	X				◄	
Limiting the release of toxic elements and immobilising them in the repository											
B waste: Protecting metallic waste against corrosion	After closure	■	■							○	□
B waste: Protecting bitumen matrix (with bituminised waste): temperature, deformation, pH	Any	■	■							○	□
Vitrified C waste: Preventing water from reaching the glass during the thermal period	Thermal period	X								○	□
Vitrified C waste: Limiting glass aqueous alteration, local transport of dissolved species, pH	After closure		■		■					○	□
Spent fuel: Preventing water from reaching CU assemblies	Thermal period	X								○	□
Spent fuel: Limiting aqueous alteration of the ceramic and restricting local transport of dissolved species	After closure		■		■					○	□
Limiting the dissolution of toxic elements and implement reducing chemical conditions	After closure	■	■		■					◄	
Filtering colloids	After closure		■		■					◄	
Delaying and reducing the migration of toxic elements into the environment											
Controlling diffusion migration, retention and dispersion into the host formation	After closure		■	■	■					◄	
Delaying the migration of toxic elements in engineered components	Any	■	■		■					○	
Preserving the natural dispersion capacity in the surrounding geological formations	After closure									○	
Preserving the geological environment favourable properties											
Limiting mechanical deformation in the Callovo-Oxfordian argillites	Any	■	■	■	■	■	X			○	□
Dissipating heat (primarily in C waste and spent fuel)	Any	■	■							○	□
Protecting the disposal modules against chemical disturbance induced by the alteration of certain packages	Any		■		■	■				○	□
Maintaining a sub-critical state (spent fuel, type C4 vitrified C waste, type B3/4/5 B waste)	Any	■	■								□
Compartmentalising the repository	Any		■			■					□

■ Contribution of an engineered component to a function
X Main function of a component
○ Characteristic of the geological environment involved in performing a function
◄ Function relying on a favourable property of the geological environment
□ Characteristic of primary packages involved in performing a function

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1.3 Operational safety

As in any industrial installation, the construction and operation of the repository means risk for man and the environment: radiological risks, but also conventional risks common to non-nuclear industrial activities (fire, explosion, gas releases, electrical hazards, dust emission, falling blocks, etc.). Operational safety controls these risks that are taken into account in the installation design. It aims at confining the radioactive materials in order to prevent any dissemination, protecting workers and general public against irradiation, avoiding a criticality accident, removing out gas produced by the packages to limit the formation of explosive atmospheres, evacuating the heat generated by some packages and anticipating conventional accidental risks.

Based on industrial experiences of operating nuclear facilities, Andra has identified and listed in order of importance the potentially hazardous situations during repository operation (risk analysis): the likelihood of their occurrence and the severity of their consequences have been assessed qualitatively and preventive and protective measures proposed. *Some risks specific to a geological repository, associated to an accident situation (fire, falling packages, falling cage in the shaft) have been studied in detail (cf chapter 5)*.

Risk analysis

This analysis aims at identifing the risks of the repository activities, from construction to closure, at characterising them and suggesting ways of mitigating them.
It starts by identifying the potential risks from standard hazard lists and feedback from similar installations. The analysis is based on the subdivision of the installation and the functions to be maintained for a given time.
Once identified, each risk is characterised and preventive (preventing hazard occurrence) and protective (limiting its effects if it occurs) measures are proposed, for example: biological shielding to deal with irradiation, ventilation to dilute gas and heat, pessimistic calculations on all situations in the lifetime of disposal packages with respect to the risk of criticality, etc.
This analysis is completed by *a final assessment of the remaining risk* despite mitigation measures, that is to say the likelihood of its occurrence and its potential consequences on man and the environment.

1.3.1 Conventional risks

• Repository construction
It generates risks similar to those encountered during the construction of manufacturing or mining facilities, and underground tunnels: basically, falling objects during handling operations or blocks in underground work, traffic accidents, electrical accidents, etc., plus risks inherent to the working environment: confined areas, noise, dust, machine exhaust, etc.
These risks may be prevented by means of physical protection and instructions, the availability of intervention resources, training and awareness-raising of teams.

• While operating the repository
Some of these conventional risks remain once the repository construction is over, but to a lesser degree.
In the surface and underground installations, the work must be organised around inspections, procedures and authorisations as required in a basic nuclear facility.
Andra has paid particular attention to the risk of fire, given the potential aggravating circumstance of the underground context. Prevention includes the control and restriction of inflammable products, the use of electric machines, the planning of maintenance and inspection procedures and staff training. Detection, extinction and smoke extraction network systems should also be installed and emergency exits indicated.

1.3.2 Radiological risks and protection systems as in the nuclear industry

The waste packages contain radioactive materials that present external (irradiation) and internal (inhalation, ingestion) risks for humans. *Controlling the radiological risk is based on current systems in the nuclear industry to limit the exposure of humans to the objective fixed by Andra:*

Smear-testing the absence of contamination

- *with respect to the risk of external exposure (irradiation*): packages conditioned in shielded cells with remote-controlled operation, transport of disposal packages in biological protection casks, area zoning according to their irradiation levels to limit staff presence near the packages, offset of the operator machine control panel with respect to the radioactive source, etc.
- *with respect to the risk of internal irradiation* (by ingestion of radioactive particles on the surface of the transport package, the package itself or the transfer cask): checks for absence of surface contamination of outer packaging (which under current transport regulations must be less than 4 Becquerel/cm^2 for β, emitters and 0.4 Becquerel/cm^2 for α emitters), primary package, disposal package, transfer cask, depressurisation of shielded cell and possible filtration system, etc.

The radiological risk from the natural presence of radon gas in the underground medium is low in an argillaceous medium and is kept negligible by the permanent ventilation in the drifts.

Sufficiently thick shielding

External exposure is controlled by the thickness of radiological protection shielding between the radioactive sources and man.

- *For fixed installations* (doors, walls, disposal cell gates and shutters, etc.), this thickness is calculated so that under normal operating conditions, any operator remaining permanently near the area containing radioactive sources will not be exposed to a dose rate of more than 5 mSv/year.
- *For mobile sources*, particularly package transfer shielding casks, the maximum dose rates envisaged also respect the 5 mSv/year, as no permanent work station is planned in the immediate proximity during their transfer.

1.3.3 Risk of criticality

The risk of criticality relates to an uncontrolled nuclear chain reaction. In practical terms, this only involves the spent fuel packages, as the B and C packages do not contain sufficient quantities (*"critical mass"*) of fissile materials required for the reaction.

To avoid this risk, the arrangement of the assemblies in the packages is checked for sub-critical geometry and water ingress is limited along the various operations as water that would favour a fission reaction.

While operating the repository, the events likely to cause a risk of criticality correspond to the conjunction of extreme accidental damage to the spent fuel packages after a fall and a water ingress. *Limiting handling heights and reducing the size of both packaging and transfer cask* (designed then to withstand falling heights greater than the physically possible one) reduces the risk and consequences of an accidental fall, as well as the absence of package stacking. The particular case of a package falling in the shaft has been studied specifically (cf chapter 5).

1.3.4 Risks linked to the external repository environment

1.3.4.1 Earthquakes

Site seismicity is an important parameter. Zones with low seismicity are favoured. The probability of such a phenomenon occurring in the sector of the Meuse/Haute Marne underground laboratory is extremely low. Moreover, underground engineered structures usually withstand quite well seismic stress, particularly because movements are attenuated with increasing depth.

To prevent the loss of safety functions (radiological protection, non-dispersion of radioactive materials), *equipment and surface buildings enclosing radioactive waste are dimensioned for a Safety Margin Computed Earthquake* (equivalent to the safety NPP shut-down earthquake SMS, defined in Basic Safety Rule no. 2001-01). *For underground installation, the studies have confirmed that the Maximum Physically Possible Earthquake (SMPP) more penalizing than the SMS has no effect on the engineered structures.*

1.3.4.2 Meteorological risks

The main risks (exceptional rainfall, extreme temperatures, lightning, very strong winds, etc.) are currently taken into account in the design of the surface installations and have no impact on underground activities.

1.3.4.3 Falling aircraft

A falling aircraft will only have an impact on the surface installations. A basic rule of the safety authority sets out recommendations for assessing this risk and taking it into account, if necessary, in the installations design. Here again the objective is to deal with a loss of containment of the radioactive materials stored in the installations. Such a study should come under a more advanced stage of the project and will be conducted at this appropriate moment.

1.3.4.4 Loss of power and utilities

This does not put personnel in immediate danger, but causes difficulties by shutting down the various systems (ventilation, transfer in the shafts, lighting, etc.). Several solutions may be studied: redundancy, emergency power supply, batteries, etc.

2. Reversibility

2.1 The requirement for reversibility

The study on the reversibility of the disposal system is prescribed under the 1991 Law. In June 1998, the National Review Board (CNE) submitted a report on reversibility to the government. In December 1998, the government made public a declaration recalling that research must be pursued with a rationale of reversibility. Andra work incorporates this requirement in the repository design. Such a requirement implies a human presence, monitoring and maintenance operations over time and without long-term safety at stake, the primordial objective of the repository. On the contrary, with a cautious and stepwise management of the disposal process, reversibility may contribute to confidence building in long-term safety.

2.1.1 Motivations

The notion of reversibility is closely linked to the application of the principle of precaution. Maintaining reversibility means a "cautious" approach in the long-term management of radioactive waste: it leads to preferring decisions that leave options open, to a stepwise repository management, flexible solutions and reversible choices rather than a technical approach engraved forever.

It also acknowledges the right of future generations and the respect of their freedom of choice: future generations could favour other waste management choices, such as retrieving the radioactive materials out of the repository for new processing. Reversibility leaves the options open and allows future generations to keep control of the environmental or technological processes, without nevertheless leaving them issues without outline of solution or tools to deal with them. The respect of possible choices requires flexibility in designing the repository, with gradual and evolving options.

It also refers to an attitude of modesty and humility: given the very long timescales considered for the repository study, a cautious approach is preferred with respect to scientific knowledge available at a given moment and the various factors of uncertainty.

Accordingly, reversibility cannot be taken as an "all or nothing" notion that assumes a first phase with a "fully" reversible repository management, followed by a second phase where it would be "fully" irreversible. On the contrary, Andra has examined a gradual evolution of the degree of reversibility during the repository process, thereby addressing reversibility in terms of levels.

2.1.2 The approach adopted by Andra

2.1.2.1 Reversibility levels and stages

Beyond the ability of removing already emplaced packages ("retrievability"), Andra concept of reversibility means:
- *the possibility of gradual and "flexible" operation of the repository process,* leaving future generations the freedom of decision about the repository process,
- *the ability to make evolving the repository design during the repository process.*

Reversibility means firstly, therefore, similar flexibility in managing packages as in an interim storage. The waste package must be as easy to retrieve as it was to emplace, without damage to the installation or the package itself. Studies show that this possibility remains open for one or several centuries at least, without intervention apart from current maintenance and follow up. Unlike storage, however, a repository may also be closed to guarantee long-term passive protection for man and the environment. In this context, the option left open for future generations is a stepwise closure, which if so wished, can reduce the reversibility gradually as and when the choices are made. The gradual construction of the repository also means some flexibility in the development of the installation. It provides the opportunity for it to evolve in order to take account of the experience acquired.

This approach represents the main choices that future generations will be faced with: envisaging other waste management or recycling solutions, taking the evolution of technical, economic and social requirements into account, acquiring additional elements on possible choices to take an important decision, making the most of knowledge improvement.

Accordingly, the repository process is broken down into successive stages by allowing for an observation period, before deciding to keep the installation as it is, to go ahead on to the next stage or backwards to the previous stage. Moving from one stage to the next is not a definitive choice - turning the page - but a reasoned choice, in full knowledge of scientific, technical, economic, social and environmental parameters.

It is always possible to go backwards at any stage, but this will vary in terms of technical complexity, costs of implementing these choices and consequences induced in terms of human intervention. Whereas it is conceivable that, as data acquisition progresses, the move to a lesser reversibility level could be planned, the elements motivating this step must be well understood as well as the necessary resources for going backwards, if appropriate, and the conditions for this return.

Reversibility: several management stages in the possible closure of a repository

Several stages are possible in a repository management scheme that may lead to its closure

- access to the packages in the disposal cell remains possible
- sealing the repository cell and continued access to the drifts serving the cell
- backfilling the access drifts to the disposal cells, then to the repository modules
- etc. until shaft sealing

Simply put, the first level of reversibility can be assimilated with an interim storage management and the final level corresponds to closure (cf chapter 6). It is possible to retrieve the package at each stage, with varying degree of complexity.

2.1.2.2 Reversibility and duration: several levels

The notion of reversibility is linked to time. *Andra has decided not to set a preconceived duration for reversibility, but to consider levels of reversibility* associated with closure stages.

To consider all the waste packages in reasonable technical and economic conditions, the repository must be operated for at least several decades up to the order of a century. This evaluation of the operation duration, based on the inventory of the French waste packages, is of the same order of magnitude in the other European countries.

The actual operation duration does not, however, represent an intangible value and may well vary according to decisions to be taken throughout operation. These decisions may result in waiting periods, firstly to produce and review the licence application for the repository or its partial closure and secondly, for economic, political or social reasons. This duration of the order of a century nevertheless provides a first order of magnitude to assess the duration of the processes in question. In itself it represents a reversibility parameter, as it allows for adaptation and evolution over a long period.

All the *stages in the reversible management of the repository is based on a milestone linked to a decision*. These *"decision-making milestones"*, which include analyses, reviews and assessments based on acquired data, must be scheduled. The decisions to be taken at each milestone are mainly:

- to go backwards by demolishing part or all of the closure engineered structures already built, until all or some of the waste packages are retrieved,
- to wait before moving onto the next stage to take full advantage of an observation and/or monitoring additional time,
- to move on to the next stage.

In fact, there is a greater number of possible choices that may differ according to the type of waste: it could be decided, for example, to retrieve some waste packages simultaneously and to wait before moving on to the following stage for the other waste packages.

In addition, the opening time of the engineered structures varies from one to the other; first built and last closed, the connecting engineered structures (the shafts in particular) should remain open the longest.

However, given the possible frequency of the decision-making milestones and time constants of the phenomena, a period of reversibility for the repository of several hundred years could be forecast, without drastic modification to the selected concepts. This duration allows introduction of new technologies over time and itself take part in reversibility by not setting technical solutions engraved forever.

2.2 Taking reversibility into account in the repository design

2.2.1 Repository architectures integrating and favouring reversibility

Simplicity and robustness of the concepts, durability of materials, modularity: the repository architectures proposed by Andra integrate the requirement for reversibility and make it easier to implement.

2.2.1.1 Simple, robust repository concepts

The engineering studies aimed to propose simple, robust repository concepts. Simplicity is linked to a concern for both technical feasibility and behaviour control. The options proposed by Andra provide an easier description of the evolution of these concepts over time and their modelling.

2.2.1.2 Durable materials and systems to facilitate a possible package retrieval

The concern to facilitate package retrievability by future generations led Andra to *favour durable materials for the packages and engineered structures* (concrete, stainless steel, etc.), as maintaining them in good condition is a basic condition of reversibility. Their durability in a repository environment may be estimated at several centuries.

In addition, several systems converge on facilitating the reversible management of the repository and the eventual retrievability of the packages: for example, grouping packages in standardised containers, identical handling systems for both emplacing and retrieving the packages, etc.

2.2.1.3 Modularity of underground installations for flexible management and design evolution

Modular architecture is proposed, thus providing *flexible management of the repository, for example stage-by-stage construction and operation, which also facilitates feedbacks integration*.

Each category of waste packages is emplaced in a dedicated repository zone, built, operated and closed independently. Each repository zone is designed to be built and operated gradually as *successive disposal cell sub-assemblies. As for operation, closure is designed gradually and is organised over several stages*: closure of disposal cell sub-assemblies, that may be conducted at the same time as the construction of new sub-assemblies, closure of access to these sub-assemblies, then to the repository installations concerning this waste category and finally to the whole installation.

As the repository is developed stage by stage, new engineered structures may be designed (or redesigned) to take full advantage of experience and knowledge acquired during the operation and observation of previous engineered structures, society expectations and technical progress made elsewhere. It is therefore possible to incorporate data from the social, technical and scientific environment.

2.2.2 The technical feasibility of going backwards

Andra has studied the technical feasibility of reversing the process for the various repository stages: technological resources, operating conditions and necessary precautions.

The repository is therefore designed to allow packages to be retrieved in the first stage by simply reversing the process of their emplacement in the disposal cell (as in an interim storage facility). For subsequent stages, Andra has made provision for re-opening the closed installations and installing the equipment required to retrieve the packages, if so decided. It has examined the various processes in going backwards. This is possible at each stage, with varying ease depending on the stage. In any case, the study of reversibility implies the availability, at each stage, of tools for reversing the process, before moving on to a new stage.

1

2.2.3 An observation programme in support of reversible repository management

Keeping the options open during the repository process implies knowledge of its evolution and situation at all times, therefore observing it and setting up the necessary measurement resources and systems. Andra has studied the possibility of incorporating measurement sensors into the engineered structures without disturbing operation or safety.

Beyond these surveillance measures relating to operational safety, this monitoring programme aims to check that the repository is operating as forecast, to suggest actions to maintain the management choice and to use this feedback to improve the repository design and management. The acquired data thus contributes to improving modelling and increasing reliability of forecast phenomena.

Various technologies have been reviewed based on the parameters to be measured. Feedback from the surveillance of other engineered structures provides a range of solutions guaranteeing the measurement of the main properties over timescales that are compatible with the need for reversibility and surveillance.

International consensus on step-wise approach

Concerted action within the European Union has shown the relevance of sub-dividing the repository process into stages to understand reversibility and provide a gradual framework for decision taking.
The OECD's Nuclear Energy Agency views the step-wise approach to reversibility under a careful, flexible process as reflecting "good practices". NEA insists on the need to introduce institutional, organisational, regulatory, political and financial provisions in addition to technical solutions to ensure package retrievability and repository management reversibility.
The step-wise approach presented by the National Research Council (NRC) in the United States provides the decision-makers with a wide range of options at all stages and may be compared with the approach suggested by Andra. NRC emphasises the technical as well as the social, political and economic advantages of this approach compared with a “linear” one.

Dossier 2005 Argile

2

Packages

Packages

The feasibility study of a high-level long-lived waste repository, its design and safety assessment relies on the knowledge of packages:

- quantity, types and characteristics of current and future packages,
- long-term phenomenological behaviour in a repository situation, particularly the possible release of radionuclides.

1. High-level and long-lived waste

1.1 Radioactive waste

In France, radioactive waste is classified according to its level (very low, low, intermediate, high), i.e. the intensity of emitted radiation, and *its half-life* (short- or intermediate-lived on the one hand, long-lived on the other hand) of the main radionuclides they enclose. These two characteristics allow to define how long they will remain potentially harmful. Waste management methods must be adapted to this potential harm.

Activity \ Period	Short-lived (SL) < 30 years	Long-lived (LL) > 30 years
Very low-level waste (VLLW)	The VLLW disposal facility in the Aube district (excluding mining residues stored on site)	
Low-level waste (LLW)	The LILW disposal facility in the Aube district	Installation project for a radium/graphite disposal facility
Intermediate-level waste (ILW)		
High-level waste (HLW)	Research carried out under the Law of 30 December 1991	

Classification of radioactive waste

The ionising radiations emitted by the short-(or intermediate-)lived radionuclides are principally formed of β particles and γ photons, whereas ionising radiations emitted by long-lived radionuclides notably include α particles.

To protect humans from high activity of short-lived radionuclides, a sufficiently thick protection screen acts as a barrier against the β and particularly the γ radiation (a few metre thick concrete shield for waste with the highest level of activity); the radionuclides must also be contained for a time matching their radioactive lifetime.

The long-lived radionuclides issues concern limiting their dissemination, mainly to prevent ingestion or inhalation that would expose the organism to α radiation. When waste activity is significant, their confinement must last over very long periods.

Radioactive decay and half-life – radiation type

A radioactive isotope of an element is physically unstable due to an excess of protons or neutrons in its nucleus. The nucleus may be transformed spontaneously into another stable or still radioactive nucleus: this irreversible transformation, or disintegration, is accompanied by the emission of an alpha (helium nucleus made up of two protons and two neutrons) or beta (electron or positron) particle and a gamma photon. Radioactive disintegration of a given nucleus is a random phenomenon over time. It is however possible to define a period (or half-life) for each radioactive isotope, which is the time taken by 50% of the initial quantity to disintegrate. Thus, the radioactive half-life of carbon isotope 14 (^{14}C) is 5,730 years. As disintegration occurs, a progressively lesser quantity of the radioactive isotope remains. This gradual reduction in radioactivity is called radioactive decay. After a period of n half-lives of a radioactive isotope, this will decrease by $½^n$ compared with the initial inventory; thus, after ten half-lives, only a thousandth of the initial radioactive material will remain approximately.

Three types of radiation

Alpha (α): emission of particles made up of helium atom nuclei with little penetration (diffusion in the air only on a few centimetres). These particles can be stopped by a sheet of paper.

Beta (β): electrons that penetrate several metres in air. A sheet of aluminium or a pane of glass can stop them.

Gamma(γ): electromagnetic radiation with far greater penetration, similar to X-rays. Several centimetres of lead or several tens of centimetres of concrete are needed to stop them.

2

1.2 High-level and long-lived waste

1.2.1 Type and source

High-level and long-lived waste accounts for about 5% of the volume of radioactive waste produced in France. It contains large quantities of short- or intermediate-lived radionuclides (producing a high activity level) and moderate to very large quantities of long-lived radionuclides.

C waste storage facility

The main sectors of activity contributing to the production of this waste are the electro-nuclear industry (EDF nuclear power plant reactors, Cogema fuel reprocessing plants at La Hague and Marcoule) and research and national defence activities (CEA centres). Apart from spent fuel reprocessing residues, must be taken in account waste produced by operation and maintenance in reprocessing and nuclear power plants.

Spent fuels unloaded from the EdF reactors are reprocessed in Cogema plant at La Hague. The aim of reprocessing is to separate the uranium and plutonium, themselves not considered as waste, from the waste itself: fission products, activation products, minor actinides conditioned in La Hague plant . Added to these high-level residues are essentially metallic materials from fuel assemblies and intermediate-level operating and maintenance waste from reprocessing plant (liquid effluents, etc.). The recovered uranium and plutonium are used in manufacturing MOX (uranium oxide and plutonium) and URE (reprocessed uranium) fuels. After use in the reactors, they are stored temporarily whilst awaiting reprocessing according to EDF industrial strategy for managing the fuel cycle backend.

Nuclear reactor operations also generate intermediate-level waste: this involves systems for starting up and operating the reactors which, after some time in service, are replaced and therefore become waste. This waste is currently stored on the nuclear power plant sites.

The long-lived waste produced by sectors other than electro-nuclear production (research, defence) is usually intermediate-level technological waste: replaced or obsolete parts, contaminated by processed materials and radioactive waste, etc. Note also the existence of a small quantity of spent fuel produced by research or defence reactors, for which disposal possibilities are being studied.

1.2.2 Two categories of waste

1.2.2.1 High-level waste (or vitrified waste), also known as C waste

It accounts for 1% of the volume of radioactive waste and relates to unrecoverable material contained in solutions from spent fuel reprocessing in the Cogema plants: fission products, minor actinides, activation products.
Its high $\beta-\gamma$ level generates *considerable heat* which decreases over time, principally with the radioactive decay of the fission products with average half-lives (Caesium^{137}, strontium^{90}).
Nowadays it is incorporated in a borosilicate glass matrix (R7T7 glass), with a particularly high and long-lasting containment capacity (several hundreds of thousands of years) under favourable physico-chemical environment conditions. The radionuclides are thus spread uniformly in the glass matrix. This vitrified waste is poured into stainless steel drums, to make up vitrified C waste primary packages.

Standard container for vitrified waste (CSD-V)

[1] The UP2-400 La Hague and UP1 Marcoule plants, now decommissioned, processed fuels from the graphite-gas and fast neutron reactors. Fission product solutions were conditioned by vitrification; on the other hand, effluent sludges were embedded in bitumen at Marcoule plant.

There are three types of radionuclides produced in a reactor:

- *fission products* are produced directly from the fission of the uranium and plutonium atoms: caesium, strontium, iodine, technetium, etc. or through fission fragment disintegration. *Caesium^{137} (and its daughter product barium^{137}) and strontium^{90} (and its daughter product yttrium^{90}) cause most of the radiation and heat release of the HLLL waste, that are very high during the first 300 years* given their half-life of thirty years.
- *actinides* are natural or artificial elements with a nucleus counting a proton quantity higher than or equal to 89. Four actinides exist in the natural state: actinium, thorium, protactinium and uranium. Minor actinides (mainly americium, curium and neptunium) are formed in a reactor by successive neutron captures from fuel nuclei. *Their radioactivity and heat rating decrease slowly.* After decay of the fission products with average half-lives, the waste generates residual heat from the α activity of americium^{241}, which in turn decreases gradually.
- *activation products* are formed by the capture of neutrons mainly in fuel cladding and structure materials. They have considerably less radioactivity than fission products and minor actinides, but must be taken into account as some of these radionuclides have a long radioactive half-life.

1.2.2.2 Intermediate-level, long-lived waste, also known as B waste

This comes mainly from nuclear fuel manufacturing and processing plants, and research centres. It therefore includes a large variety of items such as structural elements from fuel assemblies (cladding from the fuel rods called "hulls", end pieces called "end caps" and assembly spacer grids, etc.), sludge from effluent treatment, miscellaneous equipment (filters, pumps, etc.). This is basically metal but organic and inorganic components such as plastics and cellulose may also be included.

Standard container for compacted waste (CSD-C)

Concrete fiber-reinforced container (technological waste)

Its $\beta-\gamma$ level is low or intermediate and it therefore generates little or no heat. However, the quantity of long-lived elements that it contains justifies a very long-term confinement, like that for C waste.

Depending on type, it is *conditioned in bitumen* (sludge from effluent treatment), *in concrete or by compacting* (hulls and end pieces, technological waste). The conditioned waste is then placed in concrete or steel drums. These drums make up the B waste primary packages which are both more numerous and more diverse through their conditioning.

Heat release from waste packages

The radionuclides contained in the waste emit β, γ and α radiations which are partially or totally slowed down within the waste and/or its conditioning matrices, particularly glass. It therefore loses all or part of its kinetic energy which is then transformed into heat.
The amount of heat released by the waste and the waste packages over time therefore depends mainly on the type and quantity of radionuclides they contain and it decreases in proportion to the radioactive decay of these radionuclides.
The heat effect mainly corresponds to short-lived (cobalt^{60}) up to intermediate-lived (caesium^{137}, with a half-life of 30 years) radionuclides. Thus, the heat released by the waste packages is above all significant during the first tens to a few hundreds years maximum after package manufacturing. Beyond this period, there are fewer β-γ emitters; the heat released by the packages is then mainly caused by the α emitters, but less heat is emitted.

2. The inventory model

2.1 1 Surveying the existing and future production of waste by the current power plants

2.1.1 An inventory model of current and future waste for repository studies

As input to the repository feasibility study, Andra, in close collaboration with the waste producers has drawn up an inventory model of HL-LL waste. This inventory model allows for both *the waste already produced*, that is stored in conditioned and unconditioned form on the production sites and *the waste that will be produced in the future by the current nuclear power plants.* This dimensioning inventory model (MID) provides an envelope of volume and nature of the waste likely to be considered, in order to assess its geological disposal feasibility with dimensioning margins

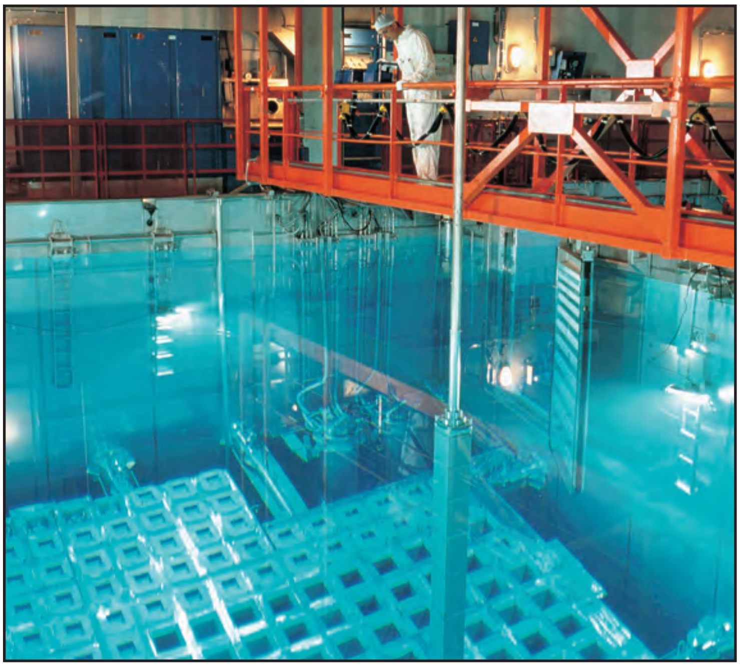
It refers to *conditioned waste*. That entails knowledge or formulation of hypotheses on the nature and conditioning methods of as yet unconditioned existing and future waste. The selected hypotheses are based on the industrial processes currently used by the producers: vitrification, compaction, cementation and bituminisation.

The inventory of existing waste is based on the knowledge of the processes that generate radioactive waste and effluents, the waste production balance figures that each installation regularly issues, the identification of the storage locations for the produced waste and the control of their contents.

The inventory model *for future productions* is based on waste production and conditioning hypotheses, primarily nuclear power plant management scenarios worked out with the waste producers (EDF, CEA, COGEMA).

2.1.2 –Making allowance for spent fuel (CU)

Spent fuel is not considered as waste. Nevertheless in order to assess the specific management issues of dealing with spent fuel in a geological repository, various study scenarios include spent fuel from EDF or CEA nuclear reactors in the event that it is not to be reprocessed. The spent fuel contains radionuclides involved in fission reactions (plutonium, minor actinides and fission products) and presents high-level activity that is notably exothermic. This heat release is due to their medium-lived fission product content, plutonium and americium (principally released by plutonium decay); these last two elements lead to slower decay over time Other spent fuel characteristics are: their large dimensions and higher fissile matter content (uranium and plutonium) that constitutes a criticality risk.



Spent fuel cooling pool

Spent fuel assembly

It comprises zircaloy rods containing either uranium oxide fuel pellets (UO_2) or mixed uranium-plutonium oxide fuel pellets (UO_2-Pu), depending on whether it is UOX or MOX fuel. The ends of these 4-5 metres long rods are sealed by two welded plugs. Each stack of pellets is kept axially in place by a helical spring located in the upper part. The rods are kept in place by sets of metallic grids and a mechanical handling device is placed at the top of the assembly.

2.1.3 Four scenarios to provide the orders of magnitude

Four study scenarios have been defined in collaboration with the producers to provide orders of magnitude of HLLL waste that will be produced in the future by the current EDF nuclear power plant fleet. They are based on three common hypotheses applied across the board to the current nuclear power plants (58 reactors): total electricity production of 16,000 terawatt-hours (TWh), mean reactor service life of 40 years, average burn-up of unloaded fuel[2]. These hypotheses, for the current EDF nuclear power plant fleet, mean a total quantity of 45,000 metric tons of heavy metal (MTHM).

These scenarios aim to examine how repository architecture could adapt to the various management processes for the electro-nuclear fuel cycle back-end and do not to predict an industrial blueprint. The principle that has been adopted is to outline possible industrial strategies without favouring one over another.

2 The mean burn-up values are as follows: URE 45 GWj/MTHM, UOX1 33 GWj/MTHM, UOX2 45 GWj/MTHM, UOX3 55 GWj/MTHM, MOX 48 GWj/MTHM.

Four scenarios

- **Scenario S1a** *assumes that all the spent fuel unloaded by EDF power plants currently operating will be reprocessed* (45000 MTHM, comprising 8000 MTHM of UOX1, 20500 MTHM of UOX2, 13000 MTHM of UOX3, 800 MTHM of URE and 2700 MTHM of MOX).
- **In scenarios S1b and S1c**, the 42300 MTHM of UOX/URE are reprocessed. However it is assumed that the MOX spent fuel (2700 MTHM) will not be reprocessed and this hypothesis entails the feasibility of their direct disposal. In scenario S1b, the vitrified waste packages are assigned a higher heat rating than current waste packages, in scenario S1c, their heat rating is equivalent.
- **Scenario S2** *has been introduced to analyse the feasibility of direct disposal of UOX and MOX spent fuels*. It considers the partial reprocessing of the UOX spent fuel until 2010 (8000 MTHM of UOX1 and 8000 MTHM of UOX2), then direct disposal of 29000 MTHM with 12500 MTHM of UOX2, 14000 MTHM of UOX3, 500 MTHM of URE and 2000 MTHM of MOX.

2.2 The inventory model reference packages

2.2.1 Allowance made for the diversity of current and future waste packages in standardised disposal options

The waste inventory and definition of appropriate conditioning methods has led to a wide variety of primary waste package families (61 in all) that differ in their radiological content, heat release, the physical and chemical nature of their waste or conditioning materials, dimensions and quantities.

The inventory model groups the families together into a lower number of representative reference packages covering all these HLLL waste package families, so that:

- the scientific and technical studies can be developed further by limiting the number of cases to be dealt with specifically yet without overlooking the diverse nature of the waste packages,
- standardised structures and resources can be designed for implementation in a repository facility.

This approach has led to a disposal concept for each of the listed waste packages.

Each inventory model reference package corresponds to the characteristics of various primary packages from different families, which makes the studies easier.

Legend of the classification (next page)

- **At level 1**, the main reference packages are differentiated by:

- the nature of their content (reactor operating waste, effluent treatment sludge, technological waste, fuel assembly cladding waste, sources, radium-bearing waste, high-level spent fuel reprocessing waste, spent fuel as appropriate).
- their heat release level (B waste, C waste and CU),
- their conditioning methods (compacting, bituminisation, cementation, vitrification, containerisation). Several vitrified C waste reference packages are defined to separate past productions of vitrified waste (C0), from current productions (C1) and potential future productions (C2, C3 and C4). This distinction primarily relates to the variation in the chemical composition of the glass, the heat rating and waste package dimensions.

- **At levels 2 and 3**, the reference packages describe the variability of the waste packages in more detail, for the purposes of detailed studies: chemical composition of the waste, presence of organic matter, production of gas, nature and dimensions of the container…

List of inventory model reference packages covering all the listed waste package families by group

Reference packages	Cat.	Level 1	Level 2	Level 3	Description of waste grouped in reference packages
Activation product waste	B	B1			Standardised containers (CSD-C) of compacted activation product waste from PWR and Fast Neutrons Reactors
Bituminised waste		B2	B2.1		Waste embedded in bitumen - 238 and 245-litre drums
			B2.2		Waste embedded in bitumen - 428-litre drums
Technological and miscellaneous cemented or compacted waste		B3	B3.1	B3.1.1	1000-litre concrete containers reconditioned or not in metallic containers
				B3.1.2	Concrete containers (CAC and CBF-C'2) containing miscellaneous technological waste
				B3.1.3	1800-litre concrete containers containing miscellaneous waste
			B3.2	B3.2.1	500-litre concrete containers containing sludge & concentrates
				B3.2.2	1200-litre concrete containers (CBF-C'2) containing CEDRA and AGATE waste
			B3.3	B3.3.1	Standardised containers for compacted waste (CSD-C) containing alpha waste
				B3.3.2	Multipurpose storage (EIP) drums containing pulverulent cemented waste
				B3.3.3	500-litre steel containers containing miscellaneous waste
				B3.3.4	870-litre steel containers containing miscellaneous waste
Cemented cladding waste		B4			Drums of cemented cladding hulls and end caps
Compacted cladding waste with or without technological waste		B5	B5.1		Standardised containers (CSD-C) containing a mixture of hulls and end caps and technological waste (including organic waste)
			B5.2		CSD-C containing a mixture of hulls and end caps and metallic technological waste
			B5.3		CSD-C containing PWR fuel cladding waste (HAO), with no technological waste
			B5.4		CSD-C containing magnesium cladding waste
Cladding and structural waste put in drums		B6	B6.1		180-litre steel containers containing operating waste from the Marcoule vitrification shop (AVM)
			B6.2		Multipurpose storage drums containing metallic cladding waste
			B6.3		Multipurpose storage drums containing magnesium cladding waste
			B6.4		Multipurpose storage drums containing technological and organic waste
			B6.5		Multipurpose storage drums containing metallic technological waste
Sources		B7	B7.1		"Source" reference packages (including existing source blocks)
			B7.2		CSD-C with rods from primary and secondary sources (PWR reactor)
			B7.3		Multipurpose storage drums with sealed sources
Radium and americium bearing waste		B8	B8.1		Multipurpose storage drums with radium-bearing lead sulphates
			B8.2		870-litre steel drums with radium and americium-bearing lightning rods
			B8.3		Multipurpose storage drums with ORUM
Vitrified waste	C	C0	C0.1		Vitrified PIVER waste
			C0.2		Vitrified UMo waste
			C0.3		Vitrified AVM waste
		C1			Vitrified "current thermal" UOX/URE waste
		C2			Vitrified "future thermal" UOX/URE waste
		C3			UOX/MOX vitrified waste
		C4			UOX + Pu vitrified waste
EDF PWR spent fuel (as appropriate)	CU	CU1			PWR UOX and URE spent fuel
		CU2			PWR MOX spent fuel
CEA spent fuel (as appropriate)		CU3	CU3.1		UNGG and EL4 spent fuel
			CU3.2		Spent fuel from Celestin reactor
			CU3.3		Spent fuel from nuclear propulsion reactors

2.2.2 Some general characteristics of reference packages

2.2.2.1 B waste packages

B waste extends to several different reference packages

245-litre steel drum for waste embedded in bitumen

- *Reference packages B2, that on their own account for almost half the inventory model volume for B waste packages*, contain waste embedded in bitumen matrices. *This type of waste does not give off heat*. The radiolysis of the constituent organic matter in the bitumen leads to *hydrogen production*.
- *Reference packages B5* consist of cladding waste from fuel assemblies compacted then conditioned in standardised containers for compacted waste (CSD-C). Most of these *release little heat* (mainly attributable to cobalt-60) that rapidly drops (30 watts at the time of waste package production, 10 watts after 15 year cooling). Some B5 waste packages contain technological and organic waste and may produce hydrogen as a result of organic matter radiolysis.
- *Reference packages B1* (operating waste from EDF pressurised water reactor fleet[3] and deconstruction waste from the Superphenix fast neutron reactor[4]) present *low heat rating* (20 watts at the time of the waste package production, 3-4 watts after 15 year cooling) and are the B waste with the highest irradiation level (equivalent dose rate of the order of 50 Sv/hr a few centimetres from the package at the time of production, 15 Sv/hr after 10 year cooling).

- *For their part, the other reference packages, B3 (technological and miscellaneous cemented waste), B4 (cemented hulls and end caps), B6 (miscellaneous technological waste), present a wide variety of waste types and conditioning methods.*

Gas release by waste packages

Various primary B waste packages, notably when embedded in bitumen or including organic matter (cellulose, PVC, ..) produce gases such as hydrogen (1 to 10 litres per annum at atmospheric pressure per waste package) and also carbon dioxide gas and methane, resulting from the radiolysis of their constituents. For safety reasons, industrial facilities (nuclear as non-nuclear ones) evacuate gas by ventilation. Feasibility studies have checked the possibility of implementing current industrial methods for the repository operating phase. Once the repository is closed (through the decision-making process of a reversible management), radiolysis gas diffuse, in gaseous form and dissolved in water, through the close environment and the structures,. It has been verified that they will not, in time, create overpressure likely to irreversibly alter the confinement of the waste.
Some waste packages may also contain traces of gaseous radionuclides; their release is very limited and can only lead to very low-level radiological exposure. However, this type of gas is confined as much as possible in the waste packages to protect man and the environment; would a small part be released, it would be caught by the ventilation system during the repository operating phase.

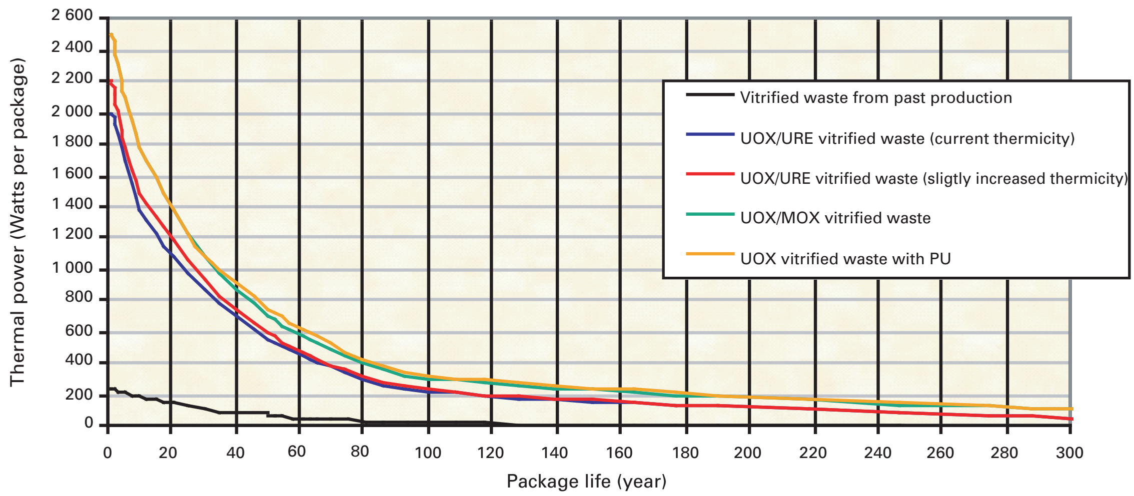
[3] *called PWR.*
[4] *called FNR.*

2

2.2.2.2 C waste packages

Five reference packages C cover the existing and forecast vitrified waste package families.

- *Reference package C0* covers *the legacy waste, that presents medium-level heat release:* legacy waste packages manufactured in the PIVER experimental facility at Marcoule; "UMo" waste left from reprocessing former Natural Uranium Graphite Gas (UNGG) reactor technology fuel, currently stored at La Hague and planned for vitrification; vitrified waste packages produced in the Marcoule vitrification plant, mainly from UNGG fuel.
- The other C packages are *highly exothermic*. *Reference packages C1 and C2* include the vitrified waste from UOX/URE spent fuel reprocessing currently in production (C1) or that is planned for reprocessing in the short term (C2). There are two further reference packages (C3/C4) that do not correspond to current reprocessing practices, but aim to explore alternative conceivable processes: the waste packages include more actinides (americium, curium, even plutonium on an exploratory basis) and primarily relate to of MOX fuel reprocessing waste, once combined with UOX fuel reprocessing waste (at the ratio of 15% MOX: 85% UOX). The radiation level varies with the type of waste package and its age. It is of the order of 250 Sv/hr after 60 year cooling for the most highly irradiating C waste packages.



> ***Primary C waste packages***
>
> The vitrified waste is conditioned *in identical (materials, geometry) stainless steel CSD-V containers for all C0.2, and C1 - C4 waste packages* (height 1340 mm, diameter 430 mm)
> The container used at the Marcoule vitrification shop (AVM, reference package C0.3) differs from the CSD-V in diameter (500 mm) and height (1015 mm).
> The PIVER vitrified waste stainless steel containers (reference package C0.1) are of the same diameter but are of variable height (575-875 mm) and the waste package weight is <130 kg. The other C waste package weight is about 500 kg.

2.2.2.3 Spent fuel (CU)

Spent fuel (CU) is not considered as waste; nonetheless it has been studied.

- *Fuel from* EDF *PWR reactor fleet* is divided into two groups: *CU1 for UOX/URE fuel and CU2 for MOX fuel*, with a different geometry, notably their length. They do not exceed 800 kg in mass. This type of waste, like C waste, *releases significant amounts of heat*. The large contribution of plutonium and americium to this heat release results in *slower decay over time*. Two situations are included for conditioning: either the spent fuel could be delivered directly to a workshop where it would be directly conditioned in disposal packages; or it could arrive already placed in over-pack, an option being considered by the CEA in the long-term storage study.
- *Spent fuel from research and national defence activities is grouped in reference package CU3: they are small dimension packages and their heat rating is moderate or low (<200 watts).*

2.2.3 Quantitative inventories according to scenarios

In the above scenarios, quantification of the number of reference packages is based on the inventory and waste production forecast as indicated up by producers. Generally high and encompassing estimates have been adopted. Dimensioning margins have been added to allow for uncertainties. Furthermore, in a cautious approach, no allowance has been made for future management possibilities for existing or future waste (particularly part of the bituminised waste) in the event of other disposal solutions.

Number and volume of primary waste packages, for B waste reference packages

Reference	Scenario S1a		Scenario S1b		Scenario S1c		Scenario S2	
package	Number	Volume (m^3)	Number	Volume (m^3)	Number	Volume (m^3)	Number	Volume (m^3)
B1	2 560	470	2 560	470	2 560	470	2 560	470
B2	105 010	36 060	105 010	36 060	105 010	36 060	105 010	36 060
B3	32 940	27 260	32 940	27 260	32 940	27 260	30 390	24 540
B4	1 520	2 730	1 520	2 730	1 520	2 730	1 520	2 730
B5	42 600	7 790	39 900	7 300	39 900	7 300	13 600	2 490
B6	10 810	4 580	10 810	4 580	10 810	4 580	10 810	4 580
B7	3 045	1 440	3 045	1 440	3 045	1 440	3 045	1 440
B8	1 345	775	1 345	775	1 345	775	1 345	775
Total	**199 835**	**81 105**	**197 135**	**80 615**	**197 135**	**80 615**	**168 285**	**73 085**

Numbers and volumes of primary waste packages, for C waste reference packages

Reference	Scenario S1a		Scenario S1b		Scenario S1c		Scenario S2	
package	Number	Volume (m^3)	Number	Volume (m^3)	Number	Volume (m^3)	Number	Volume (m^3)
C0	4 120	700	4 120	700	4 120	700	4 120	700
C1	4 640	810	4 640	810	38 350	6 710	4 640	810
C2	990	170	27 460	4 810	0	0	5 920	1 040
C3	13 320	2 330	0	0	0	0	0	0
C4	13 250	2 320	0	0	0	0	0	0
Total	**36 320**	**6 330**	**36 220**	**6 320**	**42 470**	**7 410**	**14 680**	**2 550**

Number of spent fuel assemblies, if appropriate

	Scenario S1a	Scenario S1b	Scenario S1c	Scenario S2
CU1 reference UOX assemblies	0	0	0	54 000
CU1 reference MOX assemblies	0	5 400	5 400	4 000

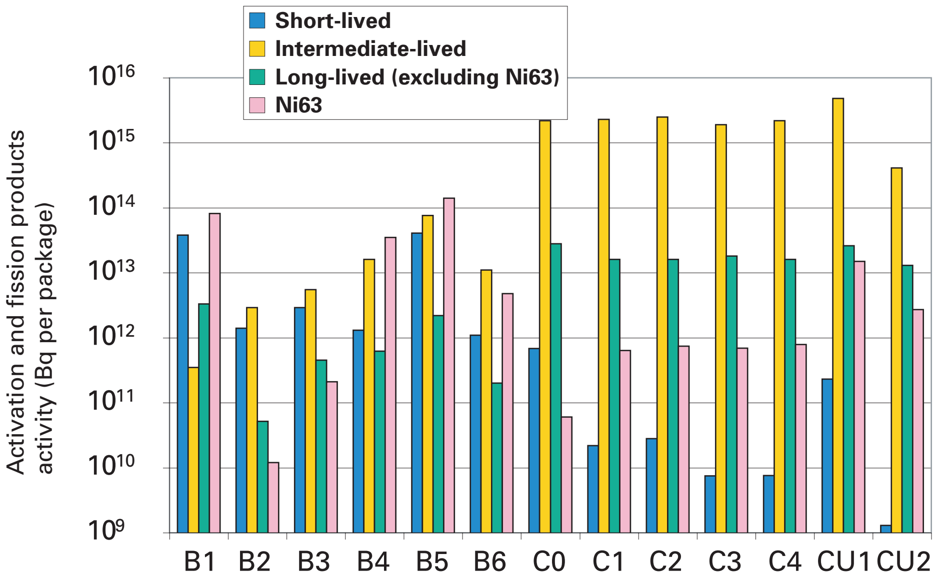
2.2.4 Radiological inventory

The radiological inventory of the waste packages concerns the presence of fission or activation products and as well actinides in the waste.

- **Fission and activation products (FP – AP)**

A very large proportion of the fission and activation product activity is accounted for by short-lived (<6 years), primarily *cobalt-60*, and *medium-lived radionuclides* (6-30 years), primarily *caesium-137 and strontium-90. Most of the medium-lived activity is found in C waste*; with regards to B waste, activity is much lower, at least by two orders of magnitude. It concerns reference packages containing fuel assembly cladding waste (B5.1/B5.2, B5.3, B4 and B6.3).

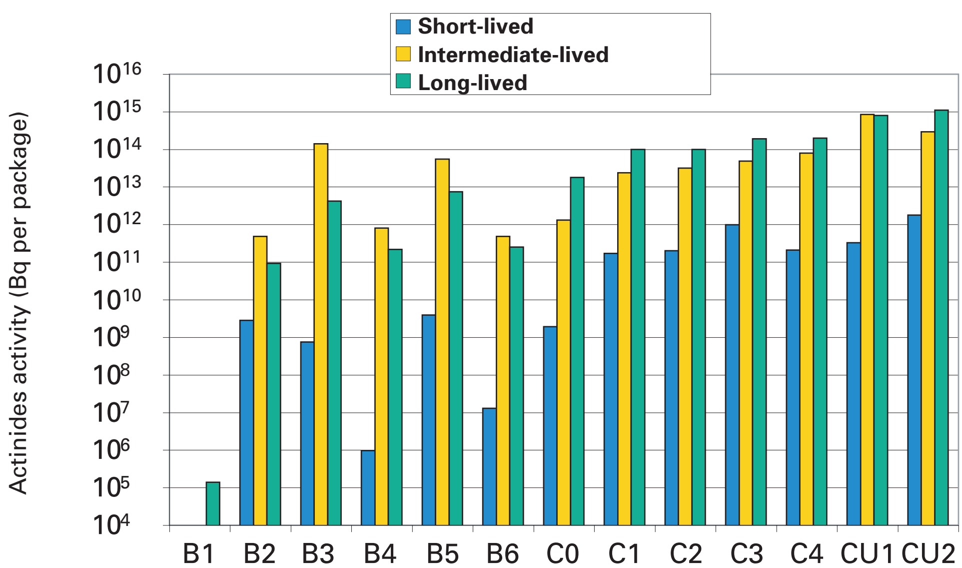
The long-lived fission and activation products (excluding nickel-63) present, on the other hand, much lower activity levels and are mainly concentrated in C waste packages. B waste packages contain these products too, but at activity levels that are two to three orders of magnitude lower. *Nickel-63* is a special case with an intermediate radioactive half-life (100 years). It is present at a relatively high activity level in many waste packages. *Its activity is significant in B waste packages*, particularly reference packages B1, B4 and B5.



AP/FP activity by reference package

• Actinides

The reference packages also contain variable quantities of actinides: *most of the actinide inventory* initially contained in the fuel (excluding uranium and plutonium extracted during reprocessing and present as traces) *is concentrated in C waste packages*. However the actinide content of B waste reference packages is not negligible: indeed, reference packages B3 and B5 present a similar activity of medium-lived actinides to those found in vitrified C1-C4 waste reference packages. The proportion of long-lived actinides is also higher in B3 and B5 waste packages than in the other B waste packages and is similar to the long-lived actinide activity level in reference package C0.



Actinide activity by reference package

The total activity level of all the inventory model waste *in the case of long-lived radionuclides* is 6.10^{+17} Bq for activation and fission products (excluding ^{63}Ni) and 6.10^{+18} Bq for actinides (applicable to scenario S1a: total reprocessing of EDF fuel[5]). *Long-lived activity is for the most part concentrated in C waste:* 91% of the long-lived activity in activation and fission products is found there in addition to 97% of the long-lived activity in actinides. *In the B waste category, B5 reference packages account for most of the inventory of long-lived radionuclides*, with about 75% of the activation and fission products and 67% of the actinides respectively.

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[5] *Scenario S2 has similar orders of magnitude: 7.10^{+17} Bq for activation and fission products (excluding ^{63}Ni) and $1.7.10^{19}$ Bq for actinides.*

Chemical inventory of primary waste packages

The chemical composition of primary waste packages is highly diverse. The packages can contain metals (such as stainless steels, zircaloys), organic matter (mainly the bitumen of B2 reference packages) or glass (C waste).
The stainless steels and some of the alloys contain nickel and chrome. B waste, and to a lesser extent C waste, can also contain aluminium or magnesium.
One constituent of the glass matrix of the C waste glasses is boron, a chemical element that is toxic when not immobilised.
Some B waste also contain materials, such as lead or cadmium that are chemically toxic when released into the environment.

3. The long-term behaviour of the waste packages

Andra, the waste producers (EDF, COGEMA, CEA) and CEA research laboratories, have studied long-term waste package behaviour to assess radionuclides release when disposed of in a geological repository. After identification of the phenomena likely to first alter the matrices and waste in the presence of water and then to release the radionuclides into the solution, key phenomena are selected and their modelling provides a quantitative evaluation. The uncertainties and limits of complex interactions inevitably lead to simplifications: as a general rule modelling adopts conservative hypotheses which overestimate the release.

3.1 - C waste packages (Reference packages C0, C1 to C4)

The issue is to model the behaviour of the glass matrix when water comes into contact with it, that is once the waste package is no longer watertight. Thus the phenomenon involved is slow dissolution of the constituents of the glass - mainly the silica. Several parameters govern this solution process. Some of them relate to the chemical and physical properties of the glass, primarily its fracturing rate which determines the amount of reactive surface area between the glass and the water. Other parameters relate to the waste package environment such as temperature and pH, which influence silica solubility. The chemical equilibrium between the glass, silica in solution and the other solid phases in the vicinity come into play through the processes of dissolved silica precipitation and the sorption of this silica (primarily on the corrosion products of the metallic container).
Study of these mechanisms has led to the adoption of two behaviour models for glass:

- The "$V_0 \rightarrow Vr$" model is applicable to the glasses produced by the COGEMA La Hague plant (R7T7) since the 1980s and the glasses to be produced by similar methods in the future (C1-C4 reference packages). This model fits with experimental observations, firstly of an initial dissolution rate (V_0), not controlled by the silica concentration in water (because of interactions with the surrounding materials), then the deceleration of this rate to a residual rate (once the surrounding materials have been saturated in silica). This model leads to *glass matrix lifetimes of at least several hundreds of millennia*.

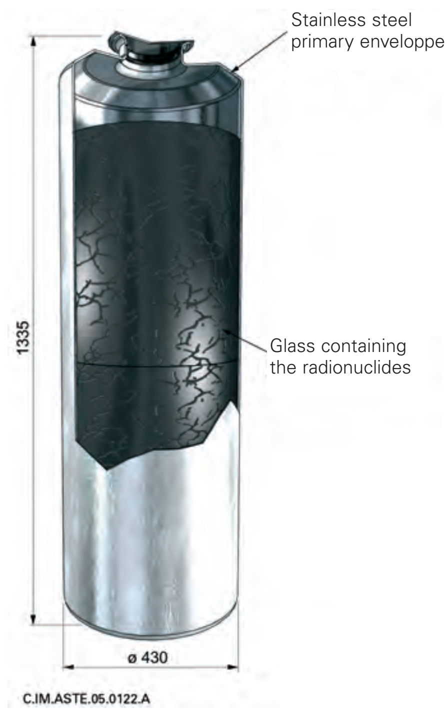


Diagram of an R7T7 vitrified C waste primary package

- The "V_0.S" model is for reference packages C0, that contain legacy waste primarily produced at Marcoule in the 1960s-1970s. This penalising model does not allow for a second phase with deceleration of the initial rate and leads *to glass matrix lifetimes at the scale of one to a few millennia. Because of the lack of available data at this stage, this model has been adopted.*

Using a cautious approach, modelling considers that the radionuclides embedded in the glass matrix dissolve congruently (that is at the same rate) to the other constituents of the glass. Thus no allowance is made for their possible retention in the altered phase of the glass.

In order to improve the glass matrix durability, the environmental parameters that have an influence on glass dissolution have been pinpointed and taken into account for the repository architectures (temperature, pH,…).

3.2 Bituminised packages (reference packages B2)

The radionuclides in these waste packages are in the form of dry salts embedded in bitumen. When water comes into contact with the embedding material, it slowly diffuses to reach the salts (first of all those that are closest to the waste package walls) that gradually absorb it. Through this action over time, the radionuclides contained in the salts dissolve and the bitumen material, whose overall permeability level increases mechanically, swells. The released radionuclides can then migrate through the more permeable bitumen zone towards the outside of the waste package.

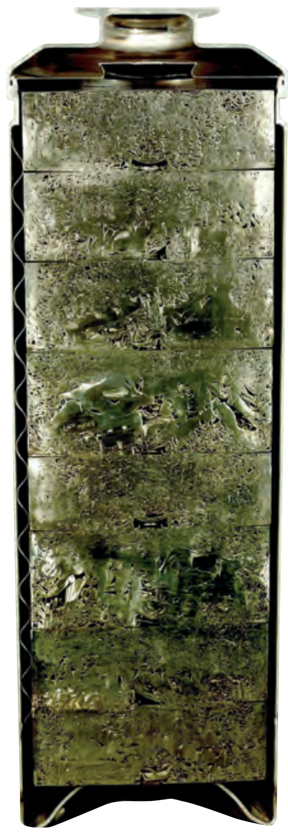
The proposed release model incorporates the slow transfer of water into the embedding material and the gradual formation of a permeable zone. It results in a gradual radionuclide release over a period lasting from 10,000 years to several tens of thousands years. *Andra has adopted 10,000 years to be on the safe side.*

3.3 Hulls and end caps from spent fuel reprocessing (reference packages B4 and B5)

The major constituents of these waste are cladding waste from fuel assemblies: cladding sections made from zircaloy or magnesium (hulls), stainless steel end caps, miscellaneous stainless steel or nickel alloy elements (grids, springs…) together with technological waste.
The radionuclides contained by these waste are found:
- at the surface of the waste,
- inside the metallic materials (zirconia, zirconium or magnesium alloy, steel); these are essentially activation products.

These two categories differ in the way radionuclide release occurs when water comes into contact with the waste.
The radionuclides located on the surface may dissolve as soon as the water comes into contact with them (they are described as "labile"), as they are immediately accessible to the water. Their retention may depend mainly on the properties of the environment provided by the repository: a reducing medium limiting the solubility of most of the radionuclides, retention by the structure materials and in the geological formation.

The radionuclides located inside the metallic materials, particularly the hulls, are released with these materials once altered by corrosion. The corrosion rates of the materials containing activation products (stainless steel, zirconium and nickel alloys) thus lead to:
- gradual release staggered over *100,000 years* for the *activation products contained in the zirconium alloys*;
- gradual release over periods from *10,000 to 100,000 years* for the *activation products contained in the stainless steels and nickel alloys*.



Cut-away model of a CSD-C container, showing the stack of wafers

3.4 The other B waste packages (reference packages B1, B3 and B6)

The radioactivity in B1 waste packages essentially originates from the activation products formed while the materials contained in the waste are inside the reactor. The radionuclides are thus mainly located inside these materials and are released as the materials gradually corrode.

The radionuclides in the other B waste packages (except B1) are generally located at the surface of the waste. Therefore an immediate release model is adopted, similar to the model described for radionuclides located at the surface of reference packages B4 or B5.

3.5 Spent fuel (reference packages CU1 and CU2)

Research has concerned the behaviour of spent fuel once the waste packaging is no longer leak-tight. Spent fuel is made up of diverse materials and its physical and chemical state is heterogeneous when removed from the reactors. The location of the radionuclides also differs and schematically are inside and at the surface of the structure elements (claddings, end caps, grids…), in the uranium oxide or mixed uranium and plutonium oxide pellets (that contain the majority of the radionuclides) and in the clearance between the pellets inside the claddings (in which case they are gaseous or volatile radionuclides).

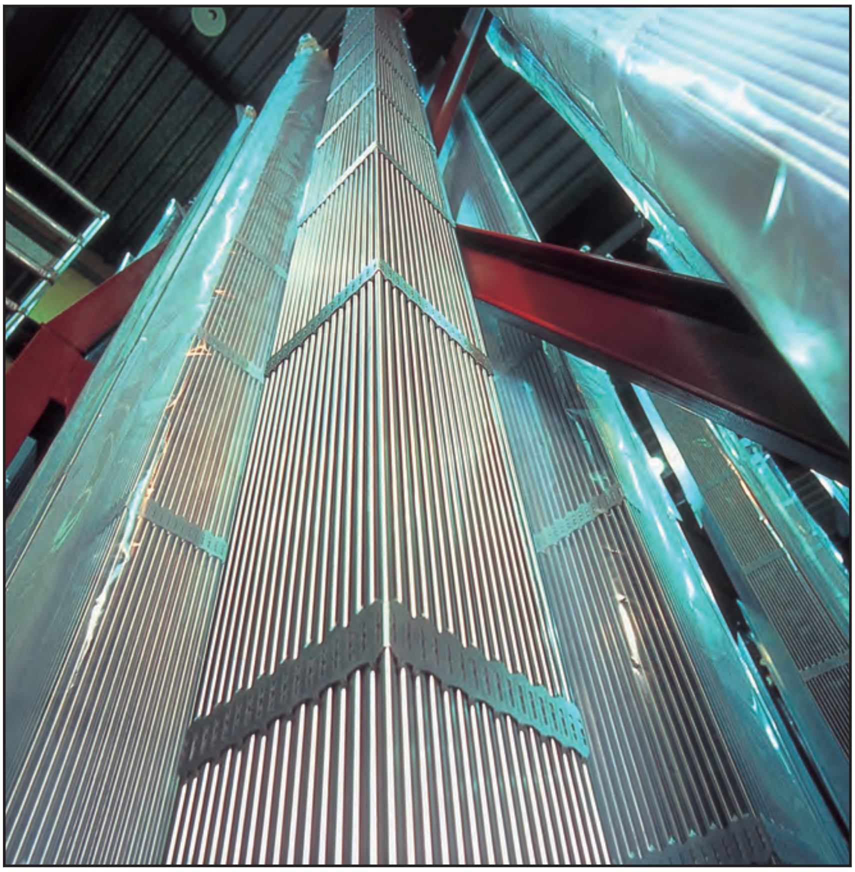
In the case of structure elements, the radionuclide release process is governed by corrosion phenomena, although the specific environmental conditions created by water radiolysis need to be considered. Then the analysis is similar to the one developed for hulls and end caps, because the size and distribution of the structure elements are similar.

Radionuclides located in the pellets are gradually released as the uranium oxide matrix dissolves, which is primarily governed by uranium solubility. Uranium has particularly low solubility in an environment such as an underground repository (a chemically reducing medium). However, water radiolysis may, initially induce the presence of oxidising water very locally and increase uranium solubility. As a cautious approach, a radiolytic dissolution model for the fuel pellets has been adopted at this stage, although this is internationally deemed to be pessimistic.

Furthermore the pellets are not homogeneous. They present joints in between the grains and an altered zone at the surface (rim). Thus control of radionuclide release by matrix alteration is only adopted for the portion of radionuclides located inside the pellets and that are neither in the grain joints nor in the rim. The latter are considered as labile and the same goes for the radionuclides in the clearance between pellets.

In the case of spent fuel, these various element lead to adopting:

- a *labile fraction* (that is released as soon as the water arrives) in the range *10-35% of the radioactive inventory* of the spent fuel, depending on the assembly types (UOX or MOX);
- *a release rate* that decreases over time for the pellets, *that results in release staggered over 50,000 to 100,000 years according to the burn-up (in principle a penalising value);*
- a release of *activation products located in the structure elements over a period of about 20,000 years*.



Fuel assemblies

Dossier 2005 Argile

The geological medium: the Meuse/Haute-Marne site

3

The geological medium: the Meuse / Haute-Marne site

The deep underground disposal concept is based upon the idea that there are geological formations capable of confining the disposal packages that are emplaced within them, for very long periods of time, until they reach a negligible level of radioactivity. The geological medium (clay, granite, salt, etc.) and the repository architectures must, in the very long term, ensure the confinement of the long-lived radionuclides which could be released into the biosphere, in order to protect man and the environment. This geological medium is therefore the key part of the disposal system.

The research work undertaken by Andra on clay aims at designing a deep repository:

- which protects the disposal packages from phenomena such as erosion and the main human activities by emplacing them away from the surface,
- which mobilises the properties, particularly in terms of confinement, of the geological medium chosen as a barrier preventing the dissemination of radionuclides contained in the waste, or slowing it down to a minimum (no water flow, reducing environment). These properties must be appraised accurately and guaranteed over very long time scales (from one thousand years to several hundred thousand years),
- which preserves the favourable properties of the geological medium over very long periods of time despite disturbances (thermal, chemical and mechanical) imposed on the medium both by the waste packages which may give off heat, by the repository construction and operation and by long term deterioration of the repository components (packages, cells, drifts).

RFS III.2.f *More generally, the system of confinement is made up of equipments or systems preventing or mitigating to a specified level, the transfer of radioactive material into the biosphere.*

In the case of a deep geological repository, the confinement system is made up of the three following barriers:

- the waste package,

- the engineered barrier,

- the geological barrier, meaning the site geological formations.

While the barriers in the confinement system play complementary roles, the geological barrier is assigned an essential role especially in the long term.

1. The expected functions of the geological medium

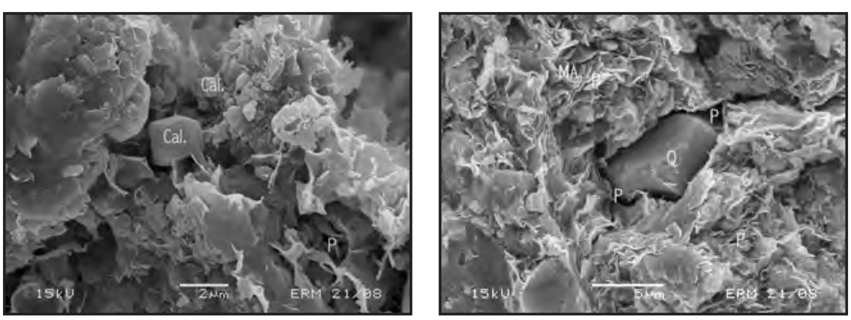
By the type and layout of their minerals and by their compactness and low permeability, deep argillaceous formations, such as the Callovo-Oxfordian formation of the Meuse/Haute-Marne site which is approximately 155 million years old, have intrinsic properties which are valuable for the study of a geological repository of HLLL radioactive waste:

- *water circulation*, which is the main factor leading to package deterioration, radionuclides dissolution and transport in the repository, *is very low*,
- *the chemistry of the medium remains stable* over time no matter what disturbances occur due to the deterioration of the materials used for the installations, and this does guarantee preservation of the argillites confinement properties,
- *the mechanical behaviour of these formations* limits disturbances (micro-fissuring, fracturing) due to excavation of underground installations and likely to increase permeability in the immediate vicinity of the drifts.

From a macroscopic viewpoint, this geological medium provides:

- *long term geological stability*, ensured by a very low-activity geodynamic context (low seismicity in particular) and by the depth of the layer (500m) which protects it from any impact of the surface processes (erosion and climatic changes),
- *the homogeneity of the argillaceous strata* related to a uniform deposit environment and a geological history relatively undisturbed by tectonic movements and interactions between fluids and rocks.

1.1 The argillite: properties for the disposal of radioactive waste packages

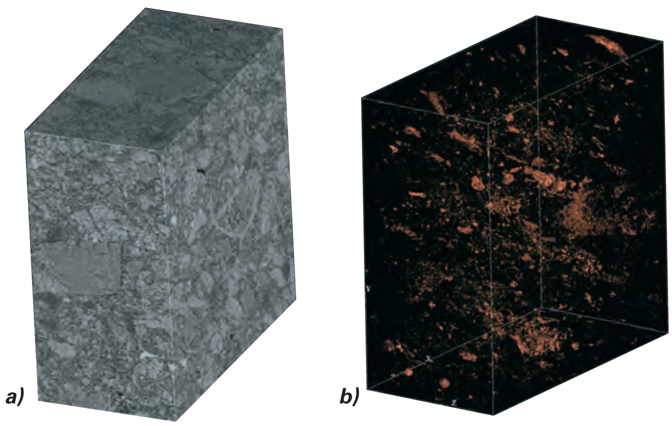


Argillite observed with a scanning electron microscope. In the argillaceous matrix can be seen: the macroporosity (P), quartz grains (Q), and calcite grains (Cal).

The properties of the argillite, as a rock, are a consequence of its mineralogical arrangement. It is made up as follows:

- *clay minerals* composed of microscopic crystals in the form of sheets, whose main components are silica and alumina between which the water molecules are trapped. The surface of these sheets is electrically charged, and this allows them to retain various chemical elements (magnesium, sodium, calcium, caesium, strontium) that can be found in the waste. *Argillite has retention properties;*
- *carbonates*, the main constituents of limestone rock, which are in chemical equilibrium with the carbon dioxide dissolved in the water. These carbonates regulate the pH in the medium. The large amount of carbonate in the argillite (25% of volume) allows the medium to maintain a constant level of acidity (pH). *The chemical medium is stable;*
- *quartz*, a mineral with good mechanical properties and a good heat conductor. *The rock is strong and has the capacity to transfer heat in line with the thermal power of radioactive waste.*

1.1.1 Very low permeability



The spaces in between the solid particles of argillite, are called pores, filled up with interstitial fluids, i.e. water in small quantities. *The porosity (percentage of voids in relation to the total volume of the rock) is low (between 10 and 18 %) and the pore radius is very small* (lower than 1/10th of a micron): half the water molecules are trapped along the pore walls. The special geometry of the porosity of argillite explains why water circulation is extremely limited: *argillite is said to have very low permeability*.

3D reconstruction of an argillite sample (approximatly 1 cubic millimeter volume) from tomography imaging:
a) Volume restitution of the sample and its various minerals.
b) Macroporosity visualization (from Sammartino, 2005).

1.1.2 A diffusive means of transport of the radionuclides dissolved in the water and the ability to delay their migration into the environment

In argillite, the chemical elements, whether they are radioactive or not, dissolved in water, move mainly by *diffusion* (that is, as a result of their own movement) and not by advection (driven along by water in movement). Advection is very low in the argillite layer due to its low permeability and the absence of an effective hydraulic drive which would need significant differences in hydraulic heads at the layer boundaries. Diffusion, which is a slow migration mode requiring several thousand years for a transfer to the environment to occur, is therefore dominant.

In the argillite pores, the radionuclides dissolved in water in the form of ions (that is, electrically charged) move and enter into contact with the argillaceous minerals which present large contact surfaces:

- those that are positively charged (cations) can be fixed at these surfaces or between the clay mineral surfaces, and are therefore retained (this is known as *sorption or retention*),
- those that are negatively charged (anions) are, due to the narrowness of the argillite pores, repelled by these surfaces, and this slows down their migration (this is known as *anionic exclusion*).

1.1.3 The capacity to absorb chemical disturbances ("buffer effect")

The construction and operation of a possible repository will mean the presence of external components inside the argillite: the introduction of air into the rock brings about oxidation of some its constituents, in particular pyrite (natural iron sulphide) and organic matter. *Also, certain elements are produced by the degradation of the repository materials*, especially concrete and cement: thus, the degradation of concrete releases alkaline elements which will increase the pH of the water, leading to the dissolution of quartz and clay minerals and the precipitation of calcite and other silicated minerals such as zeolite. However, the mass ratio between host formation minerals and engineered elements migrating inside the host formation is so high that *the chemical disturbances brought about by the repository are limited in extension to a few decimetres* (this is known as the *buffer effect of argillite).*

1.1.4 Sufficient mechanical strength and thermal conductivity

Geologists in the Meuse/Haute-Marne Laboratory main shaft

The geotechnical quality of the rock must be appraised in order to design the underground structures, verify the feasibility of their excavation and above all check that the construction of structures does not cause fracturing in the immediate vicinity which may facilitate water circulation and thus reduce some of the initial confinement properties of the geological medium.
In general, the clay formations are not reputed for the mechanical strength or their capacity to evacuate heat. However, due to their mineralogical composition and their compactness, some argillites, such as the Callovo-Oxfordian ones, have more favourable characteristics.

3

The high proportion of carbonates and their distribution in the rock give *good mechanical strength* to Callovo-Oxfordian argillites and allow them to withstand the damage brought about by the construction of underground installations. Furthermore, the presence of smectite clay minerals provides, through their swelling properties, *a certain degree of deformability (which facilitates in particular healing of the damaged zone) and an ability to creep*, which is the capacity to gradually accommodate deformation over time (viscosity).

The presence of quartz confers *an acceptable level of thermal conductivity, which is sufficient to dissipate the heat* produced by the radioactivity of the waste without any detrimental effect on their short-term mechanical strength and deformation.

1.2 The argillaceous host formation: physical characteristics required for deep disposal over very long time periods

Apart from the qualities linked to the type of argillite, the host formation must have certain physical characteristics favourable to the lay-out and operation of a repository over very long time periods.

1.2.1 Ability to accommodate a repository

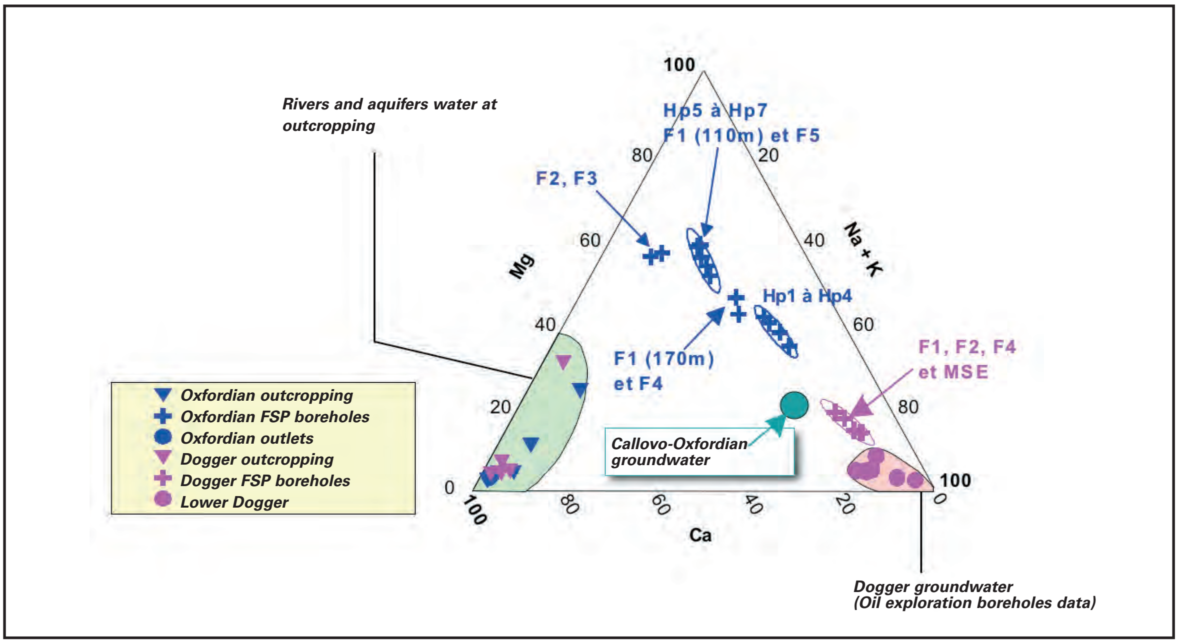
The host formation must be able to ensure confinement over the whole surface area of the repository. It must therefore be:
- *sufficiently thick over the whole of this area* in order to isolate the waste from water ingress from the overlying and underlying strata and in this way retain the radionuclides,
- *sufficiently homogeneous and with very little or no physical discontinuities (no fractures) and no mineralogical discontinuities (compositional homogeneity)*. The simpler the geological formation (for example superposed horizontal layers), the easier its characterisation.

It must be as well possible to build the underground installations under satisfactory safety conditions and at a reasonable cost without reducing the initial confinement properties. The deeper the host formation, the higher the overburden pressure and the more cautious the repository excavation and ground support.

1.2.2 Ensuring long-term radionuclide retention capacity in order to slow down dispersion

Knowledge of the mechanisms of geological formations deposition and their subsequent transformations is important for the study of the feasibility of the repository. It allows for past geological stability (over several million years), while at the same time considering possible future stability conditions. It also provides modelling for the long term evolution of these formations.

Deep argillaceous formations are stable over time and often perform the role of a permeability barrier. They behave in the same way as "closed systems" and exchanges with the surrounding geological formations are very slight. This is the case especially for oil geological configurations in which the clay layers act as barrier preventing migration of hydrocarbons that have accumulated in the underlying reservoir layers.



Concentration in major cations of Callovo-Oxfordian, Dogger and Oxfordian grounwater. Their differences mean that water exchanges in between these formations are very limited.

1.2.3 The stability of the geological structure in the long term

The reconstruction of the movements that the geological structure has undergone throughout its history and of their resulting deformations enables us to assess the dynamic of the region and monitor the different tectonic episodes that have affected the continental crust at the local level. On theses bases, it is necessary to ensure that the site under consideration is far enough away from zones that have undergone tectonic deformation (in France, the Rhine graben and the Alps in particular).

The tectonic activity in the region of the Meuse/Haute-Marne site is very low (low seismic activity, little crust displacement, perennial orientation of stresses) and the geological structure is stable, as evidenced by the absence of quaternary indices of tectonic activity on the faults surrounding the study area. In these conditions, the possible tectonic movements are limited to very low recurrence of pre-existing faults structuring the basement.

The topography will be affected in the long term (geomorphologic evolution) by processes of erosion or backfilling depending on upwards movement (uplift) or subsidence. The reconstruction of the paleosurfaces in the Paris basin enables us to specify the erosion velocity and assess regional and temporal stability. In a little active or inactive tectonic context, the uplift velocity will remain low and constant for the next few million years.

1.2.4 The existence of low local hydraulic head gradients, vertical ones in the host formation and horizontal ones in the surrounding water-bearing formations

The lower the gradients, the slower the water circulation. Knowledge of the gradients can only be measured by characterising the permeability and the hydraulic head (pressure) of the host formation and the surrounding formations (underlying and overlying formations). It is also necessary to identify the pathways along which the radionuclides are likely to be dispersed and may then migrate to the biosphere, and to check that the water circulation will not be modified by climatic and topographic changes in the periods considered.

The properties of the medium needed for the safety functions

Functions		Period	Needed properties
1 - Preventing water circulation		Post-closure	Low permeability
2 - Limiting radionuclide release and immobilizing them in the repository			
• B waste	Protecting metallic waste from corrosion	Post-closure	Low permeability
	Protecting the embedding bitumen (bitumised waste): temperature, deformations, pH	Any	Low permeability, capacity for buffering disturbance
• Vitrified C waste	Prohibiting water ingress in the assemblies during the thermal phase	Thermal phase	Low permeability
	Limiting the transport of dissolved species to the glass neighbouring area	Post-closure	Low-velocity diffusion of dissolved elements
• Spent fuel	Prohibiting water ingress in the assemblies during the thermal phase	Thermal phase	Low permeability
	Limiting the transport of dissolved species to the neighbouring area	Post-closure	Low-velocity diffusion of dissolved elements
Limiting radionuclide dissolution, ensure reducing chemical conditions		Post-closure	Low permeability, capacity for buffering disturbance
Filtering the colloids		Post-closure	Small pores
3 - Delaying and reducing radionuclide migration			
Controling migration by diffusion, retention, dispersion in the host formation		Post-closure	Low-velocity diffusion of dissolved elements

2. The characteristics of the Meuse/ Haute-Marne site: collecting data – the main stages

Acquiring knowledge of the geological medium in the Meuse/Haute-Marne sector (Callovo-Oxfordian host formation and Dogger, Oxfordian and Kimmeridgien surrounding formations) was organised by pursuing several complementary strategies:
- drilling 27 bore-holes several hundred metres deep, carrying out 2D (1994-1996) and 3D (end of 1999-beginning of 2000) seismic campaigns on the site, geological surveying to observe the outcropping formations both at local and regional scales, ascertaining the main features of the geological environment and taking samples,
- laboratory analyses and experiments, in Mol (Belgium) and in Mont Terri (Switzerland) in particular, to test methods and tools and to validate modelling,
- shaft sinking starting in 2000 with *in situ* survey of the medium and full-scale appraisal of its behaviour,
- excavating experimental drifts at "-445 metres level" from 2004 and at "-490 metres level" from 2005 with their related experimentations.

These works aimed at obtaining a detailed understanding of the Meuse/Haute-Marne site geological environment in order to:

- *ensure that this geological configuration, and in particular the Callovo-Oxfordian argillaceous layer, presents the expected properties,*
- *assess its long term behaviour*, and especially the effect of the disturbances that repository structures installation would imply.

The surveys, measurements and analyses of the current state of the site and of the properties of the Callovo-Oxfordian argillaceous layer have enabled us *to produce an image of the site* (commonly referred to as a *conceptual model)* providing us with a reconstruction of its geological history and presenting its future evolution. This image, consistent with the sedimentological, structural, hydrogeological, geomechanical and geochemical data acquired, *serves as a basis for simulations allowing us to assess the repository performance.*

2.1 1994-1996: understanding the main features of the Meuse/Haute-Marne site geological environment

This first stage enabled Andra:

- *to confirm the value of the Callovo-Oxfordian argillites level and their geological context in a zone of several hundred square kilometres*, which straddles the south of Meuse district and the north of Haute-Marne district,

- *then to select a study site for the underground research laboratory.*

2.1.1 Checking the arrangement of the geological layers

In 1994, Andra collected and processed a large amount of geological and hydrogeological data: surface geological mapping, hydrogeological data of boreholes and springs and moreover geophysical seismic surveys obtained during oil exploration campaigns in the Meuse district and in the north of Haute-Marne district. *1,300 kilometres of seismic profiles have been obtained and studied with the data input of 68 regional oil exploration bore-holes.*

After this inventory, the north of Haute-Marne and the south of Meuse appeared as a *simple geological area* of the Paris basin:

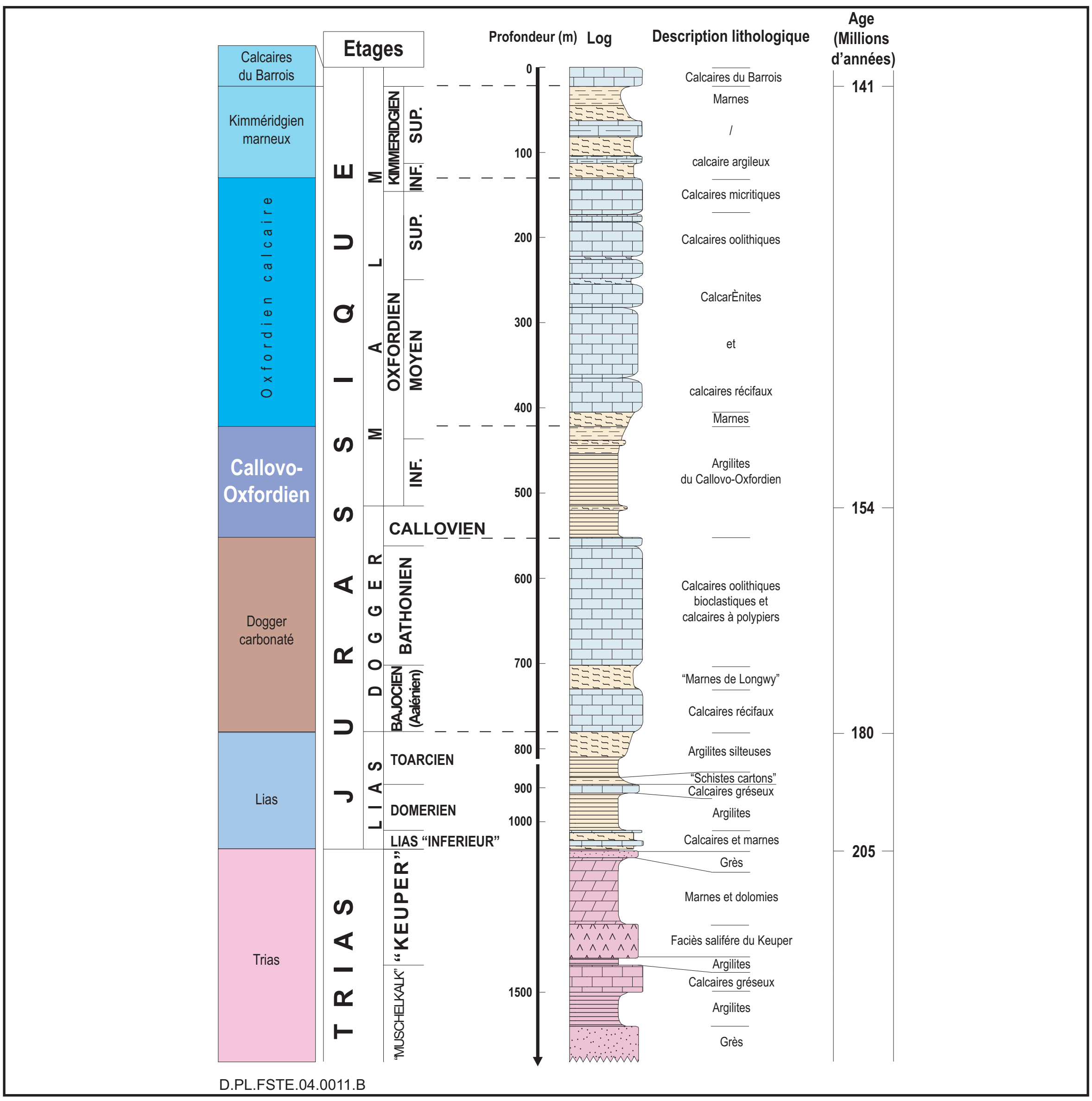
- *there is a succession of practically horizontal layers*: limestone, marls, and clay formations which were deposited in ancient oceans;
- *the layer selected for the study is a clay formation at least 130 m thick dated to 155 million years and located at a depth of between 400 and 600 m: the Callovo-Oxfordian argillites.*

Geological map of the Meuse/Haute-Marne sector

Succession of layers starting at the surface in the study area

Geologically the south of the Meuse district and the north of the Haute-Marne district belong to the eastern edge of the Parisian basin. This basin is shaped like a bowl filled with a succession of sedimentary layers the oldest of which are located on the edges and the bottom of the bowl, and the most recent at the centre.

Formation	Age	Thickness right below the URL site	Characteristics
Barrois Limestones Marls	Thitonian 140 million years Kimmeridgian 145 million years	±25 m 100 m	Surface Aquifer Impermeable
Oxfordian limestone	Upper to medium Oxfordian 150 million years	300 m	Low permeability
Callovo-Oxfordian argillites	**Lower Oxfordien - Upper and medium Callovian 155 million years**	**130 m**	**Selected host layer**
Dogger limestone	Lower Callovian - Dogger 165 million years	250 m	Low permeability



Geological cross-section at the Meuse/Haute-Marne Laboratory site

The Andra research area is bounded by:

- in the south east, the Gondrecourt-le-Château graben with a north east/south west direction,
- in the south west, the Marne graben oriented north/north west. It extends south along the Poisson fault which is parallel to this graben
- to the north, the Aulnois-Saint-Amand structure which presents slightly dipping layers.

The Callovo-Oxfordian formation is composed of clay formations, argillites, which thickness varies from 130 to 160 metres in the study area. All the layers making up the Callovo-Oxfordian and the surrounding formations *are practically horizontal, with a slight dip from 1° to 1.5° towards the west and the centre of the Parisian basin.*

2.1.2 Obtaining the first data to characterise the Callovo-Oxfordian clay formation

The objective in 1994 was to carry out an initial characterisation of the properties of the different formations, and specifically the Callovo-Oxfordian one, at large mesh and based on cored bore-holes. Surface geological mapping improved the precision of the existing maps. Two deep cored bore-holes, HTM 102 (-1,100 m) in Haute-Marne and MSE 101 (-920 m) in Meuse, 15 kms apart, confirmed the simple geological arrangement in the study area. Using logging equipment developed for the oil exploration industry, Andra made continuous recordings, from total depth to surface, of parameters (electrical resistivity, sonic velocity, porosity, density…), took core samples (cylindrical samples of rock) to conduct laboratory analysis and tests, and perform hydrogeological measurements.

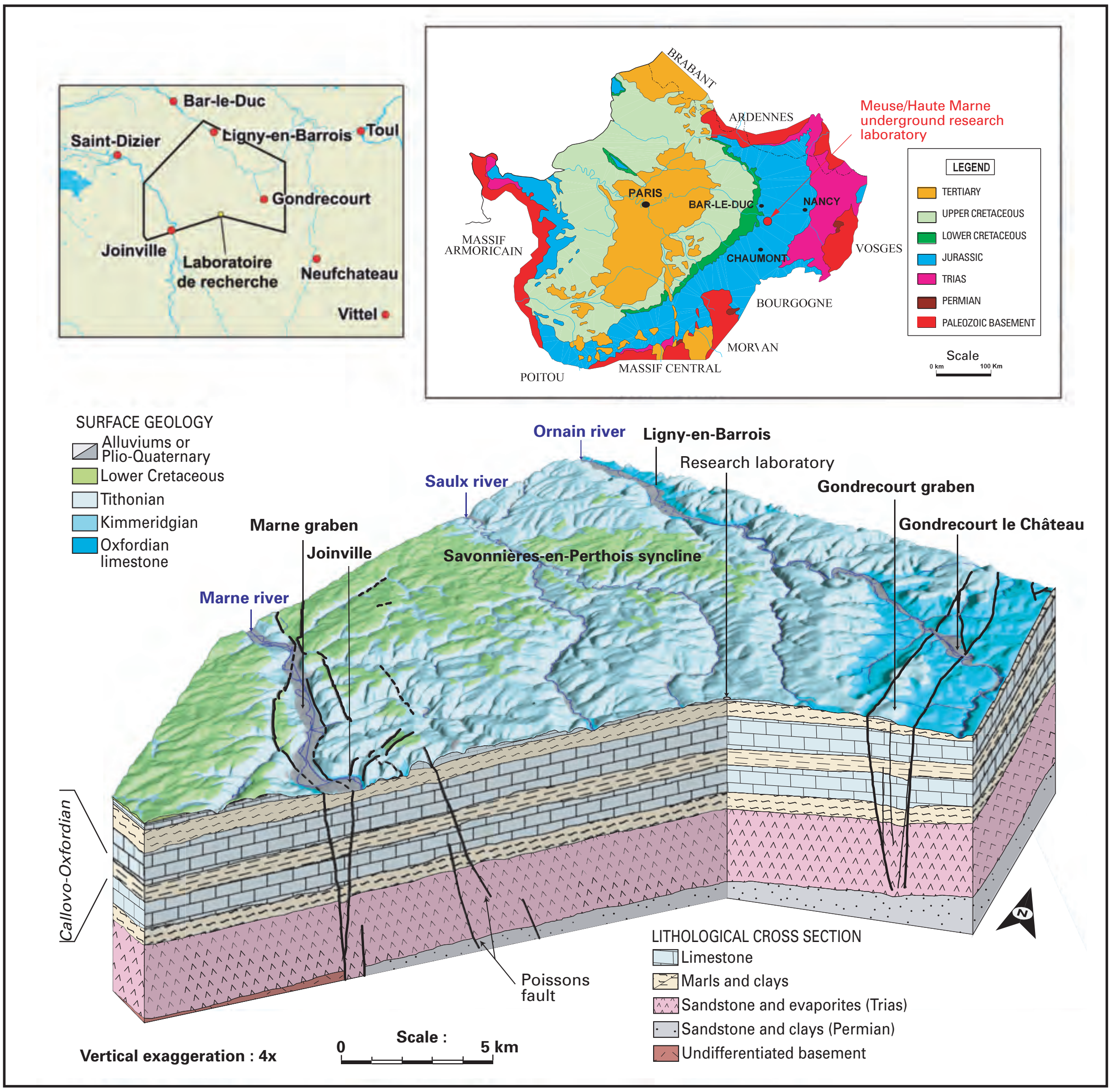
These analyses, measurements and tests:

- *provided preliminary results of the geomechanical, thermal, geochemical and hydrogeological properties of the rock,*
- *confirmed the rock low permeability,*
- *showed that the properties of the clay formation did not rule out a repository feasibility study* and that at this large scale, they only varied very slightly,
- *highlighted the absence of significant water resources in the limestone formations surrounding the Callovo-Oxfordian clay layer* (flow rate inadequate to justify drilling any water producing well). This result is important as it is evidence of a favourable hydrogeological context in the geological layers which may happen to be water bearing in other areas of the Paris basin.

All these works lead us to select the Bure site for the installation of the underground research laboratory, the preliminary study of mechanical properties of the argillaceous formation having shown the feasibility of excavating the structures necessary for the laboratory (shafts and drifts).

The different study scales

Different terms are used to refer to the study domain scale or the geographical extensions of the surveys.
The Paris basin, sedimentary system extending from east to west from Lorraine to Normandy and, from south to north, from Poitou to northern France.
We also refer to the regional scale to describe a zone approximately 10,000 square kilometres large, corresponding to the eastern part of the Paris basin where the study area is located.
The Meuse/Haute-Marne sector corresponds to a zone 40 km from east to west and 60 km from north to south approximately centred on the laboratory site. The sector is limited to the east, south and west by the Gondrecourt graben and the Marne faults. The detailed geological studies were performed in this sector as were the bore-holes drilled by Andra.
The Laboratory site, corresponding to an extension of the detailed investigations conducted on the Meuse/Haute-Marne underground Laboratory, meaning a few square kilometres.
Finally, the **transposition zone** is defined as the surface area upon which the Callovo-Oxfordian properties and the geology of the surrounding formations are similar to those determined at the Meuse/Haute-Marne underground Laboratory site in (see paragraph IV of this chapter). It represents an extension of the order of 200 square kilometres.



3D geological block diagram of the Meuse/Haute-Marne sector

2.1.3 Specifying the characteristics of a possible research Laboratory site

The work carried out in 1995-1996 provided data enabling an experimental programme to be defined for the underground Laboratory and to design its architecture.

• **A high-resolution geophysical seismic survey (2D seismic survey)** detailed the arrangement of geological layers. Three seismic profiles, 15 km long in total, completed the configuration of previous oil exploration profiles available at a smaller mesh of 2 km around the planned Laboratory site.

• **Three cored bore-holes** with specific objectives completed the survey.

. The EST103 bore-hole (- 523 m) specified the lithological, mineralogical and geochemical nature of the Callovo-Oxfordian argillites. Hydrogeological equipment was installed to perform continuous measurements of the hydraulic head in the overlying Oxfordian limestones: the work confirmed the absence of water resources in these upper levels. Moreover, seismic logging carried out in this bore-hole was coupled with the profiles obtained by the 2D geophysical survey in order to specify the representation of the different layers.

. The EST104 bore-hole (- 530 m) specified the vertical distribution of the geomechanical and geochemical properties of the Callovo-Oxfordian argillaceous formation.

. Bore-hole EST106 (-150 m) allowed to survey the geomechanical properties of the ground close to the surface (calcaires du Barrois and Kimméridgien marls) to determine the methods both for sinking the underground laboratory access shafts and for the construction of the Laboratory surface buildings.

• **In an additional bore-hole,** EST107 (-425m drilled from the HTM102 bore-hole platform), a hydraulic pressure measuring device (EPG electromagnetic pressure gauge) was installed in the centre of the Callovo-Oxfordian layer, transmitting data to the surface by electromagnetic wave. It has been monitoring the pressure in the layer continuously since 1996.

The work carried out in 1995-1996 has provided the site preliminary geological characterisation in preparation for the possible construction of an underground Laboratory.

2.2 1996-2004: the work carried out at the Mont Terri (Switzerland) underground Laboratory

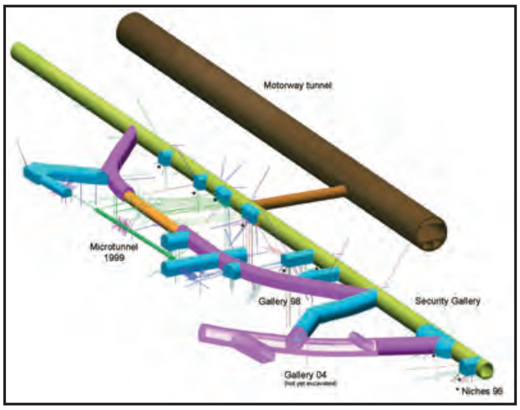
From 1996, Andra prepared the experimental programme for the Meuse/Haute-Marne Laboratory to be carried out, would a construction and operating license be granted, as previous experiments at the Mol (Belgium) laboratory had shown that developing special equipment and experimental protocols was time consuming.

Andra joined an international consortium project set up to conduct in situ experimentation in the Mont Terri road tunnel (Jura Canton and Republic - Switzerland): the planned timetable was compatible with Andra's one, the range of experiments proposed suited largely to Andra experimental programme and the characteristics of the Mont Terri argillites (known as Opalinus clay) to be studied in the experiments were similar to the Callovo-Oxfordian ones. The experiments are being carried out by several partners, thus facilitating sharing the work, exchanging ideas, synthesising knowledge and saving time in the experiments preparation.

• **The initial activities (1996-1997)** enabled to test instrumentation and method: sampling of interstitial water from Opalinus clay *in situ* by means of bore-holes, measurement of the interstitial pressure and the natural stresses in the formation, optimisation of drilling methods, etc.

• **Since 1998**, the cooperation, extended to eight partners from seven countries, has focussed on experiments designed to collect scientific data on the process governing the clay behaviour: chemical element diffusion experiment in the rock, etc.

• **Since 2002**, a programme aims at full-scale model validation, on the basis of data collected by the Meuse/Haute-Marne underground Laboratory: experiments on diffusion, gas characterisation, geochemistry, heating to assess the mechanical behaviour of the rock. It also includes full-scale engineering tests: drift excavation and ventilation, engineering barrier emplacement, groove to cut off the excavation damaged zone and to restore the geological medium continuity.



Mont Terri Laboratory

Experimentation carried out at Mont Terri met two necessities:

- *preparing the experiments in the Meuse/Haute-Marne underground Laboratory in the best possible conditions, if licensed.* Part of the equipment developed for Mont Terri was re-used in the Meuse/Haute-Marne Laboratory and the feedback from Mont Terri experimental programme saved time in developing experimental protocols;
- *full-scale validation of modelling developped on small scale* for the Callovo-Oxfordian taking account of the transposition limits (materials similar from a mineralogical and physical viewpoint, but with different contexts and geological histories). *At the end of the day, the aim was to ensure that the Callovo-Oxfordian modelling was valid at full-scale.*

Opalinus clay from Mont Terri and Bure argillites: similarities

The Opalinus clay is the geological formation studied by Nagra on the Mont Terri site and in north Switzerland (Zürcher Weinland). Slightly older (180 million years), it nevertheless has comparable characteristics to the Callovo-Oxfordian. The clay formation has a similar mineralogical composition (clay, quartz and carbonates) to that of the median part of the Callovo-Oxfordian although it is slightly less carbonated. Like the Callovo-Oxfordian argillites, the Opalinus clay is a reducing medium, with low permeability and small pore size. Their transfer properties are similar (diffusion is preponderant), as are their mechanical properties. Although influenced by alpine tectonics in the Mont Terri sector, the Opalinus clay history (burying, diagenesis) shows no significant difference with the Callovo-Oxfordian one.
This formation is thus a relevant basis for comparison with that studied on the Meuse/Haute-Marne site. Specifically, the feedback from almost ten years scientific work at Mont Terri has shown that the observations and analyses carried out on samples were confirmed by in situ experiments. It was therefore possible to transpose the models developed for Opalinus clay to the Callovo-Oxfordian, for example in order to determine pore water chemistry or to validate diffusion coefficients.

3

2.3 1999-2005: experimental programme of the Meuse/Haute Marne Laboratory

View of the Meuse/Haute-Marne Laboratory main shaft

The publication of the ministerial order granting a license to the Meuse/Haute-Marne underground Laboratory in Bure in August 1999 was the starting point for a new stage in the research programme after several years of regional survey works and studies at the Mont Terri laboratory.

The purpose of this programme is to provide the data, with supporting evidence, required for the modelling of phenomena identified as important for the design and safety assessment of a possible repository: checking the favourable properties of the formation (extension of disturbances due to a repository, confinement capacity and radionuclides transfer processes in the Callovo-Oxfordian), constructability of a repository and ability to take in account rock excavation damage.

Apart from full scale experiments and direct measurements on the argillites in the Laboratory drifts starting in 2004 (drift at a depth of -445 m excavated from the main shaft) and in 2005 (drifts at a depth of -490 m excavated from the auxiliary shaft), the excavation and construction of the two shafts between 2000 and 2005 were accompanied by numerous scientific works aimed at carrying out *in situ* detailed observation of the geology in the Oxfordian and the Callovo-Oxfordian, monitoring the hydraulic and mechanical disturbances and appraising the extent of rock damage.

The research programme also includes drilling bore-holes and seismic surveys designed to increase knowledge of the host layer and the surrounding formations at the scale of both the site and the sector.

The underground research Laboratory

is the most effective means of:

- confirming geological knowledge regarding Callovo-Oxfordian argillites, assessing their confinement capability, and defining the repository architecture,
- performing *in situ* measurements directly on the argillites, or taking sample, to specify precisely their confinement properties,
- carrying out larger scale experimentations to determine the possibilities of repository construction by integrating the disturbances caused by the construction works.

The study programme also includes other means: additional survey works (drilling bore-holes and seismic reflection, tests and analyses on samples in surface laboratories).

Objectives of the underground laboratory **RFS III.2.f.**

The objectives of the underground laboratory must notably be:

- carrying out measurements on the rock or fluids which have been subject to as little disturbance as possible from the conditions of the experiment, in order to improve knowledge of the parameters already assessed partly during the survey programme carried out from the surface;
- determining, by means of larger scale experimentation, the behaviour of the different rocks and fluids, while taking into account the natural phenomena and the modifications brought about by the repository operations;
- surveying the medium, and in particular its variability in space, to assess the capability of the site and then the possible location of the drifts and future repository structures;
- determining the methods of excavating, plugging and sealing cavities.

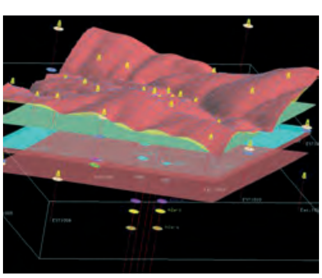
Measurements in situ and on samples:

Measurements must be carried out in the laboratory, to confirm or refine the values of parameters and to appraise anisotropy, spatial distribution, and scale effects. Among the investigations that must be carried out:

- assessing the average bulk permeability of the medium;
- specifying, through measurement in the underground part of the laboratory, the hydraulic role of the aquifer faults or fractures which may be encountered;
- determining and monitor over time the geochemical properties of water and gas encountered while excavating drifts and drilling bore-holes in the underground part of the laboratory, in order to ascertain connections between the more or less permeable intercepted zones;
- assessing the initial stress tensor;
- appraising, on the basis of the cavities excavation in the underground laboratory, the feasibility of rock excavation and also its behaviour at the walls (risk of scaling of hard rock, convergence for plastic rock);
- measuring the deferred mechanical effects (relaxation, creep);
- specifying with greater detail the geochemical properties which may affect the migration of radionuclides and especially refining the determination of water-rock exchange coefficients measured on cores.

2.3.1 Improve knowledge of the host formation and its surrounding formations: seismic surveys, bore-holes and samples testing

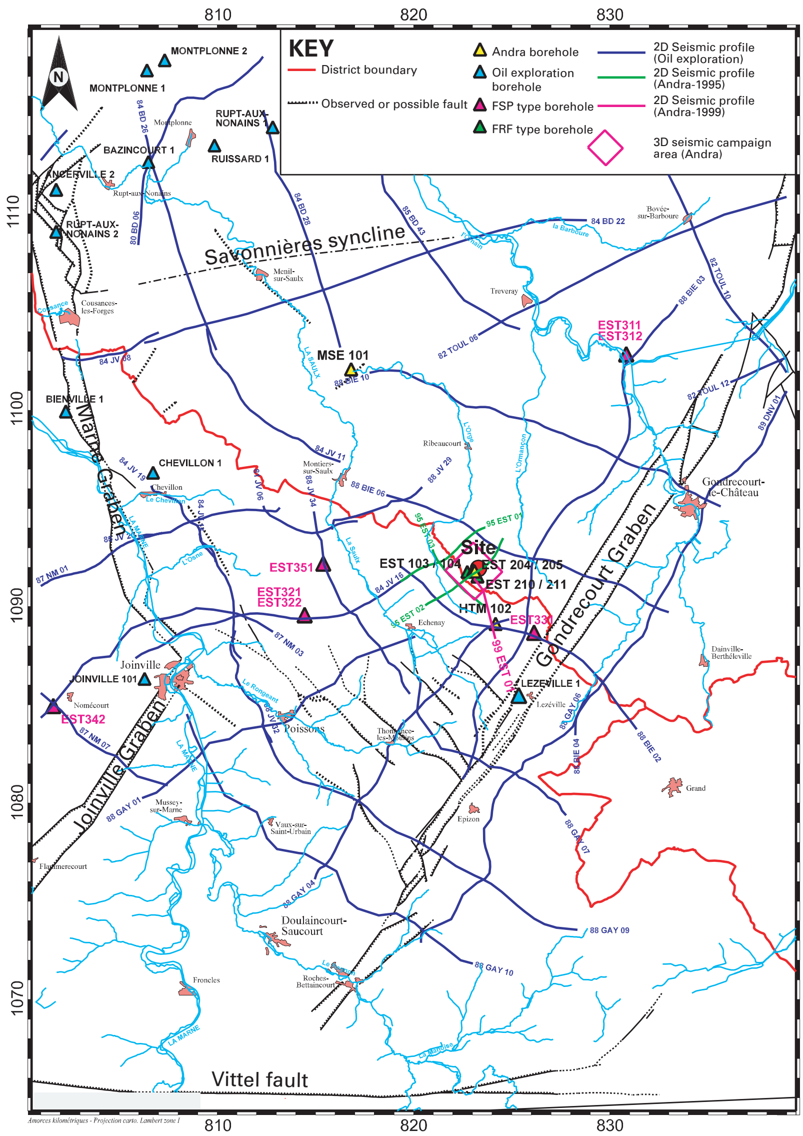
• **At the scale of the laboratory site,** *the 3D Seismic survey (1999-2000) covering 4 square kilometres and the cored bore-holes EST204 and 205 drilled along the two shafts axis provided greater precision of the geometry of the layers making up the underground part of the site.*



3D construction of the geological model

The 3D seismic surveys provided an image of the volume of the laboratory site with a greater level of detail. It confirmed the fact that Callovo-Oxfordian argillaceous layer is regular with a thickness over 130m and a consistent geometry with the history of deposits which succeeded the Callovo-Oxfordian. There have been no disruptive phenomena in the laboratory zone since the formation of the Callovo-Oxfordian (great stability).

It revealed no faults with vertical throw in the Callovo-Oxfordian layer, nor in the overlying Oxfordian limestone. In lower levels of the Dogger underlying layer, subvertical WNW-ESE structures with small throw (2.50 m at most) have been detected but it was not possible to ascertain their exact nature at the time (fracturing or specific geological structure). This uncertainty was resolved at a later stage.



Location of the boreholes drilled by ANDRA and seismic profiles

• **On the laboratory site, 4 hydrogeological and geochemical bore-holes** *(EST201, EST202, EST203 and EST206) were drilled in 2000 to various depths around the location of the two shafts and completed with measuring equipment to monitor the hydraulic heads.*

Consequently, it was possible to determine the hydraulic gradients in the three formations overlying the Callovo-Oxfordian (calcaires du Barrois, Kimméridgien marls, Oxfordian) and to specify their hydrodynamic characteristics in order to define the initial state before undertaking the construction of the laboratory. On the basis of hydraulic tests in bore-holes and geochemical analyses conducted on water samples, Andra has established a detailed description of the permeable and impermeable levels over the whole site, identified the most porous levels in the Oxfordian limestone, measured their permeability and characterised their hydraulic relationships.

• **The extensive programme of mechanical tests** carried out with the EST205 bore-hole cores enabled to improve the knowledge of the geomechanical behaviour of the argillites and to create behaviour models to forecast rock damage according to the type of construction of the underground installations. This programme has been complemented by geomechanical measurements in bore-hole EST204 drilled out along the main shaft axis.

Borehole EST 205 has, for the first time on the site, enabled measurements of the initial state of the ground pressures in the geological formations.

Bore-hole EST205

It was drilled according to a different method from the previous ones, using an oil-based mud to ensure perfect stability in the bore-hole walls and samples of excellent quality (cores used for the purposes of geomechanical studies).

Borehole EST 205 has, for the first time on the site, enabled measurements of the initial state of the stress field in the geological formations.

• **At the sector scale,** *eight bore-holes reaching different depths and at 5 different locations spread over the whole sector (FSP programme) allowed , in 2003, an assessment of the hydraulic head in the Oxfordian* (EST311, EST313, EST321, EST331, EST351) and in the upper levels of the Dogger (EST312, EST322, EST342) over a large area around the laboratory.

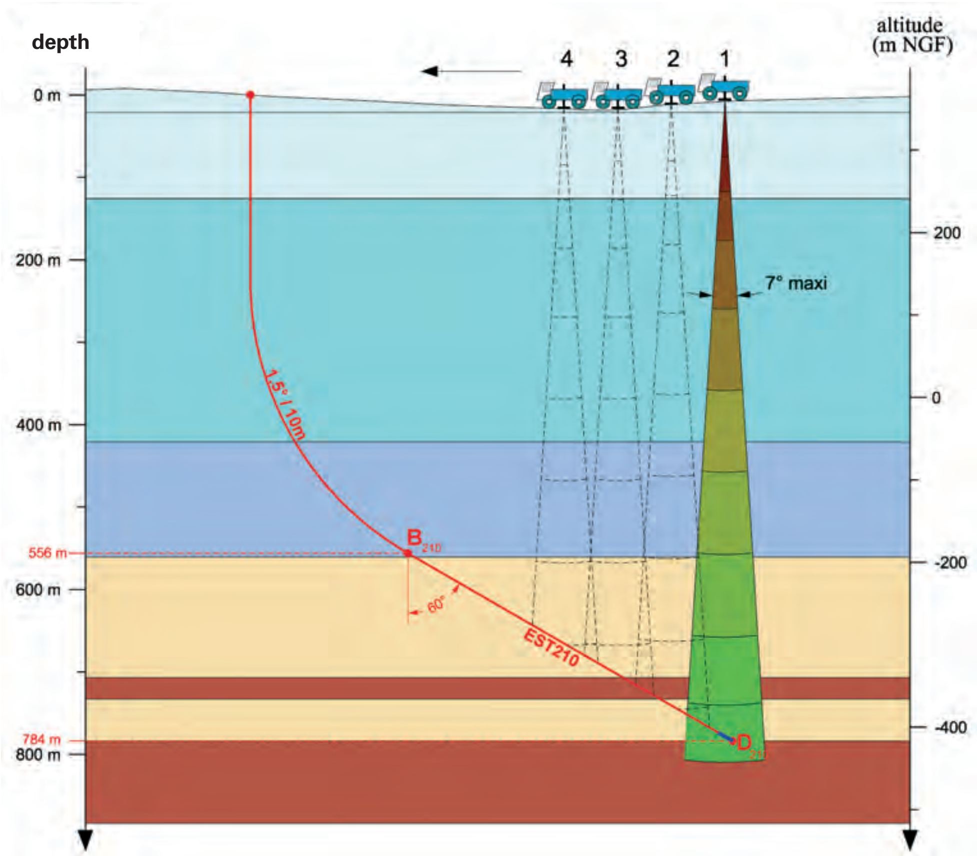
The locations chosen for these bore-holes are in an orthogonal transect to the three bore-holes drilled before 1996 (HTM102, EST103, MSE101), at a few kilometres away from each of them, in order to fit modelling at best.

The permeability of the limestone formations was measured in these bore-holes to assess water flow velocity. Water samples were taken to analyse certain radionuclides naturally present in this water (krypton-81 and chlorine-36) and to determine the time since they had infiltrated the rock. Moreover, the geological observations made in these bore-holes and the core samples allowed new data to be collected, over a sector of ten kilometres around the site, thus consolidating the geological model.

• **In 2003-2004, the formation survey programme** *comprised 8 bore-holes (FRF programme).*

Drilling platform

- *Four directional deviated bore-holes (EST209, EST211, EST361 in the Callovo-Oxfordian, EST210 in the Dogger) confirmed the homogeneity of the host formation and the absence of faults.* More than 1,300 metres cores have been obtained in the Callovo-Oxfordian formation and 300 metres in the Dogger formation.
- The first objective was to survey the type of structures identified in 2000 in the Dogger limestones by 3D seismic surveys: the EST210 directional bore-hole in the Dogger showed that they did not correspond to faults, but had geometric and sedimentological characteristics of fossil coral massifs also observed on regional outcrops. The seismic measurements carried out in this bore-hole in order to obtain a clearer image of the Dogger at this point, confirmed this interpretation. At the level of these structures, the permeability of the upper part of the Dogger far from being affected, on the contrary is very low. This work enabled to rule out the possible presence of tectonic structures in the Dogger at the site scale.
- Directional deviated bore-hole EST211 cored the Callovo-Oxfordian formation over more than 400 metres above the structures observed in the Dogger where no discontinuities were intercepted and only few microfissures were noted.
- Two other directional deviated bore-holes intercepted the argillites over a great length within the Callovo-Oxfordian: bore-hole EST361 almost completely horizontal with the same direction West SouthWest - East NorthEast along more than 800 m (cored over 650 m) and bore-hole EST209 drilled the North-South direction along 300 m.



Geological survey with deviated boreholes and seismic measurements

These last three bore-holes surveyed the host formation along 1500m and allowed a comparison of the sedimentological and petrophysical characteristics at laboratory footprint scale with the data from the site 3D seismic survey. It showed that there were no fractures and *very few microfissures in the Callovo-Oxfordian on the laboratory site and that these microfissures were plugged. They are, moreover, located generally at the top and bottom of the layer. They are located one or several meters apart from each other with a metric extension.* In situ *measurements confirmed the very low permeability of the argillites.*

Bore-holes EST361 and EST209 were used as well to carry out *in situ* stress measurements to specify the natural stress field in the Callovo-Oxfordian.

Argillite cores

- *Four vertical bore-holes allowed important safety parameters to be measured* (EST207, EST208, EST212 and EST363)

In view of the limited capacity of gas to disperse through analogous low permeable formations examined abroad, Andra attempted to assess the conditions of gas migration, which could be produced as a result of the deterioration of repository components (mainly hydrogen from the corrosion of metallic components). Completed in 2004, the gas injection tests carried out in bore-hole EST363 (-540 m) drilled on the Saudron platform allowed to determine air inlet and fracturing pressures in the argillites and to appraise the water/gas flow parameters, and in particular to specify the pressure above which the transfer of gas into the Callovo-Oxfordian argillites occurs either when combined with water flow or by the opening up of fractures in the sound formation. In this latter case it was noted that fractures close up again and rock permeability is not modified after gas migration.

Completed in June 2004, the pressure measurements and the sampling of fluids from bore-hole EST207 (-560 m) made it possible *to obtain the hydraulic pressure profile over the whole Callovo-Oxfordian and at the interfaces with the surrounding formations.*

This data was complemented by *continuous pressure measurements* obtained by means of EPG pressure measuring equipment (similar to that installed in 1996 in bore-hole EST107) located in the Callovo-Oxfordian argillites (bore-holes EST211, EST212 and EST363).

In bore-hole *EST208*, a diffusion test has been carried out, from the surface, at a depth of 500 m similar to those conducted from the experimental underground drifts (DIR experimentation described hereafter).

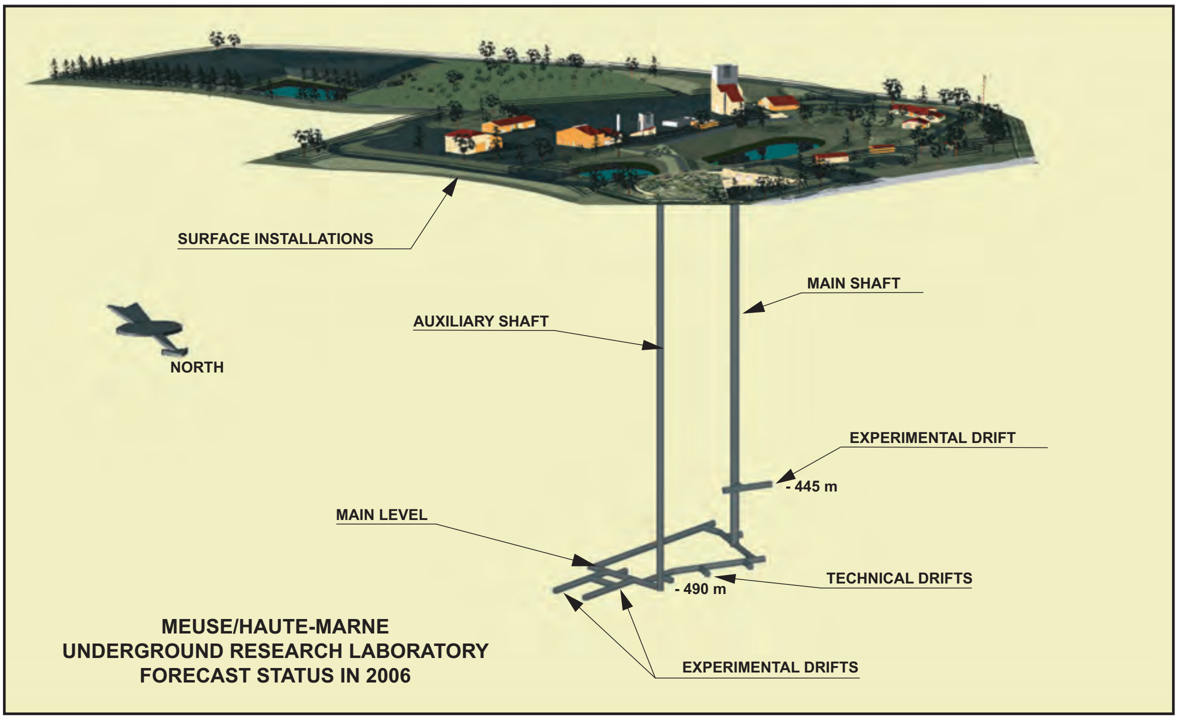
Meuse/Haute-Marne Laboratory core library

2.3.2. The experimental programme at the Meuse/Haute Marne laboratory: validating knowledge *in situ*

The purpose of the research programmes is to provide the data and supporting evidence required for the modelling of phenomena identified as important for the design and safety assessment of a possible repository.

It is divided into two major parts:

- validating the constructability of a repository, and the capacity to manage rock damage brought about by excavation and to seal the structures,
- confirming the favourable properties of the formation (geochemical composition, confinement capacity).



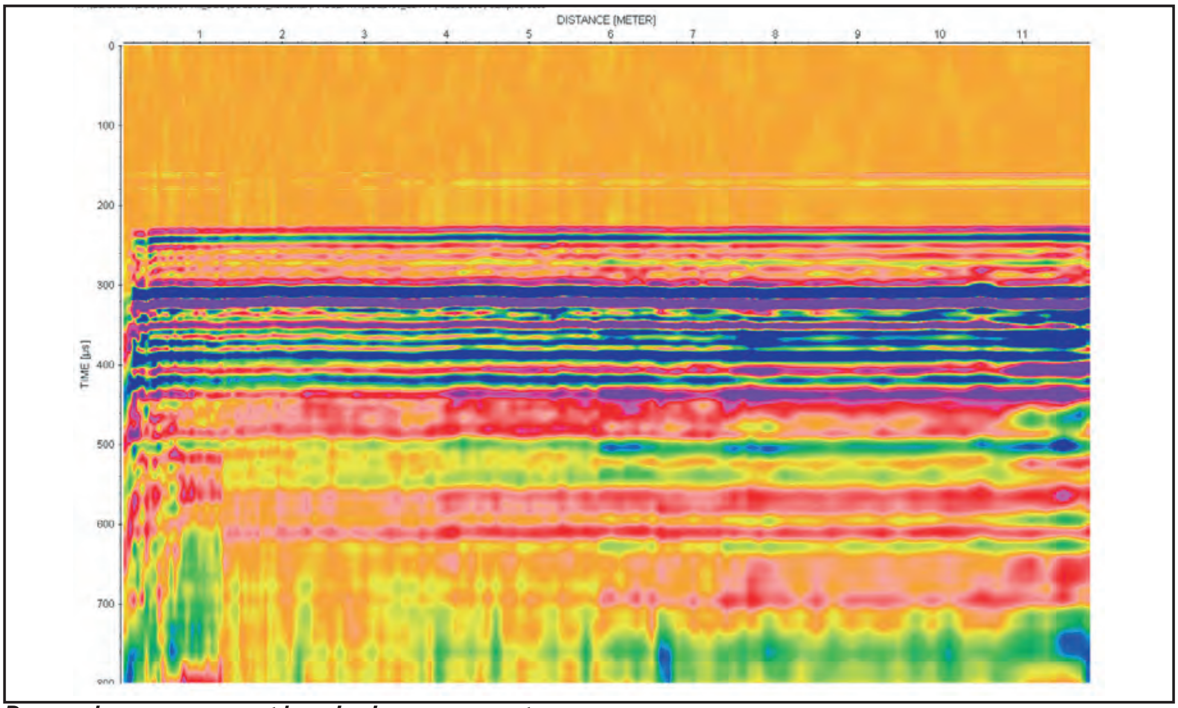
2.3.2.1 1 Experiments in the shafts (main and auxiliary) while sinking

The works related to three scientific objectives.

• **Supporting the geological model** with further sedimentological and microstructural data. *During shaft sinking since August 2000, scientists carried out continuous measurements of the formations crossed and established a detailed geological map all along the wall of the two shafts.* The objectives of *this geological survey* were to assess the lithological variability of the layers at the decametric scale, to observe their nature in the different directions, to characterise their natural fracturing and micro-fracturing and assess their impact on fluid circulation. The observations made since the start of shaft sinking confirm the sedimentary and tectonic data already obtained in bore-holes and supply precise quantified structural data which support the geological model.

• **Specifying the hydrogeological properties** *of limestone formations overlying the Callovo-Oxfordian. Hydrogeological monitoring* of these formations focuses on the observation of possible water ingress at the wall and its measurement using metering equipment installed in the shafts. While sinking, bore-holes have been drilled to sample undisturbed fluids and carry out hydrogeological tests. The hydrogeological disturbances caused by shaft sinking in the overlying formations are monitored continuously by the measuring network installed in the course of 2000 in the bore-holes drilled close to the shafts.

• **Characterising the damage** c*aused in the Callovo-Oxfordian by shaft sinking. Mechanical disturbance monitoring* consists in observing the shaft walls in order to describe the effects of excavation and natural loss of rock confinement in the formations crossed and quantifying deformation by measurements all along shafts until the concrete lining installation phase (which means after around three weeks).



Damaged zone assessment by seismic measurements

In the Callovo-Oxfordian argillites, Andra also measured the deformations and displacement in the rock, as well as the stresses (and/or deformations) in the shaft lining to understand the deferred behaviour of the massif and the lining. By means of radial bore-holes, seismic and permeability measurements were made to characterise the disturbances in the zone affected by shaft sinking. The monitoring of all these deformation can be carried out for several years.

Geologists surveying a drift wall

To this monitoring programme, is associated systematic wall sampling for analysis in other laboratories (petrography, mineralogy, hydrogeochemistry, geomechanics) or to be kept as control samples, and also *topographical measurements and photographs*. All the data are integrated into Andra's data base in real time.

The international modelling programme associated with the REP experimentation

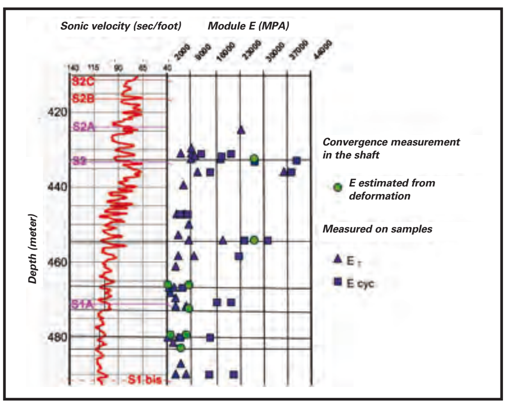
The Modex-REP (V^{th} and then VI^{th} European framework programme for research and development) brings together European Andra counterparts (Belgian, German, Spanish, Swiss) together with French and European research partners. The aim is to test the capacity of rheological models to predict the response of argillite to shaft sinking.

The REP experimentation, which started in the 2^{nd} quarter of 2005, provides observations of the damage caused to argillites in the shaft walls and a first large scale verification of the various argillite mechanical behaviour simulation models.

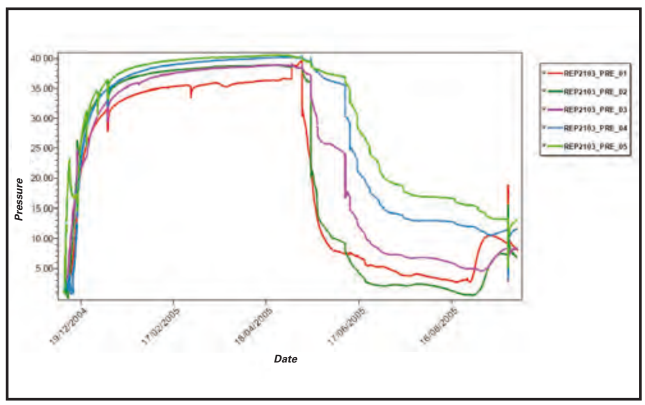
About fifteen bore-holes drilled from the experimental drift located at -445 m (45 m above the main underground laboratory level drifts) are directed towards a main shaft section situated 20 m lower (between -465 and -470 m), oriented in the directions chosen according to the natural stresses around the shaft and spaced 0.5 m to 5 m away from the shaft wall. Once main shaft sinking was resumed in March 2005 (halted from August 2004 while the drift was being constructed at -445 m), the sensors that were already emplaced in these bore-holes monitored in real time the approach of the excavation work face which passed at the level of the instrumented zone at the beginning of May 2005, and then the deferred effects on the argillites as the work face moved away deeper. These sensors measured deformation, pressure, permeability and seismic velocity variations through geophysical methods. These measurements provided a detailed characterisation of the Callovo-Oxfordian geomechanical behaviour.

This experimentation has confirmed the mechanical parameters of the rock and demonstrated the absence of any fractured zone around the structure. It has also revealed that rock density evolution around the excavation sunk is very slight (very slight evolution measured by a reduction of less than 2% in seismic wave propagation velocities). This modification is perceptible up to 1-1.5 metres from the shaft wall (microfissured zone). Beyond that distance, the properties of the massif do not show any change. As for the hydraulic properties, the excavation work induces a hydraulic head loss in the massif for a distance of about ten metres. The permeability in the vicinity of the shaft wall (up to two metres away) is hardly modified, in any case less than 10^{-11} m/s, and unchanged beyond that distance.

Experimentation entered a new observation phase of long duration in the third quarter of 2005, when the final shaft lining was installed to stop argillite deformation. Hence monitoring pressure and stress measurements around the she shaft is planned to last several years.



REP experiment: initial state measurements confirm hydromechanical parameters values



REP experiment: pressure monitoring around the shaft while sinking

2.3.2.2 The experimental programme in the Meuse/Haute Marne Laboratory drifts

The Meuse/Haute-Marne Laboratory drifts have accommodated experimentations aiming to validate *in situ* the knowledge gained from smaller scale tests at Mont Terri or in surface laboratories, since 2004 at a depth of -445 m (from the main shaft) and since the second quarter of 2005 at a depth of -490 m (from the auxiliary shaft). Theses experimentations focus essentially on monitoring mechanical rock damage while excavating, geochemical data, water and radionuclide diffusion measurements through tracers.

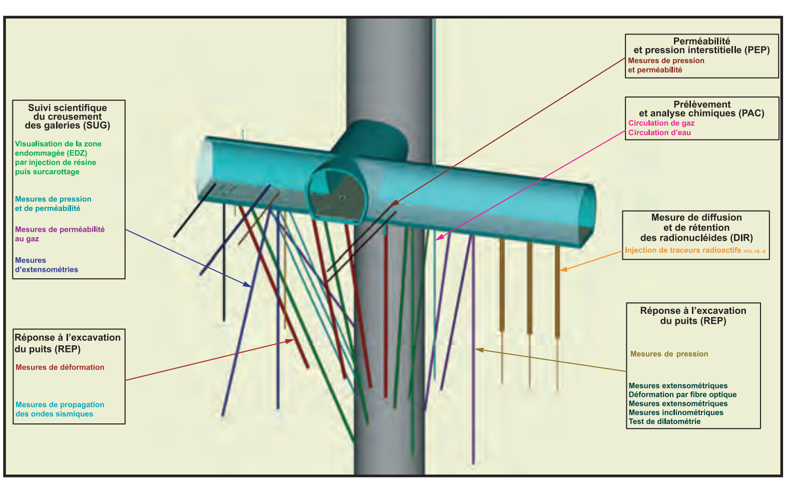
• The experimental drift at -445 m

Operational in November 2004, this drift, located in the main shaft at the -445 m level, accommodates, in addition to the REP experimentation equipment which measures deformations in the argillite of the main shaft while sinking, a large scale geomechanical, hydrogeological and geochemical experimental programme (PEP, PAC, DIR, and SMR experimental programmes).

Experiment drift of the Meuse/Haute-Marne Laboratory (-445m level)

The experiments carried out in this drift are designed to *collect in situ data concerning the damage to argillite during excavation works and fluid/rock transfers and interactions in the Callovo-Oxfordian argillites:*

- *Slanted (oblique) bore-holes* were drilled at the intersection between the shaft and the drift roof. Sonic wave velocity measurements were also carried out before and after excavation. They showed that damage was limited to a thickness of 20 to 40 centimetres in the walls where the argillite is microfissured, but not fractured.
- During the excavation, an *extensometer* was installed in the drift axis, in order to monitor deformations. A measurement section (SMR) transversal to the experimental drift was installed after excavation: force and deformation sensors were emplaced on ground support and deformation sensors in the argillite. Bore-holes drilled in different directions in the wall of the drift were injected with resin, then over-cored in order to detect by means of fluorescence technique, any fracture which may have been induced by the excavation. No fractures were detected.
- *Two bore-holes* have been equipped to *sample water and gases dissolved* in the argillite (PAC experiments) in order to make *in situ* measurements of certain chemical parameters and specify interstitial water chemical composition. Two methods have been implemented: the first one is based on gas circulation in a bore-hole to sample and analyse the gases dissolved in the interstitial fluids; the other one is based on water circulation in a bore-hole to monitor how its composition evolves as it reaches equilibrium with the interstitial water. From these experiments, the nature of the dissolved gases (CO2, alcanes…) and the composition of the water after reaching chemical equilibrium with the argillite have been determined. The acquired findings corroborate the chemical composition of pore water obtained by modelling and specify one of the model's parameters (the exchange coefficient between sodium and potassium).



General layout of the experiments in the -445 meters drift

- *Two horizontal bore-holes (PEP experiment) and a vertical one (associated with REP experiment) were equipped to complete argillites permeability data.* Acquired data confirmed the very low rock permeability measured otherwise.

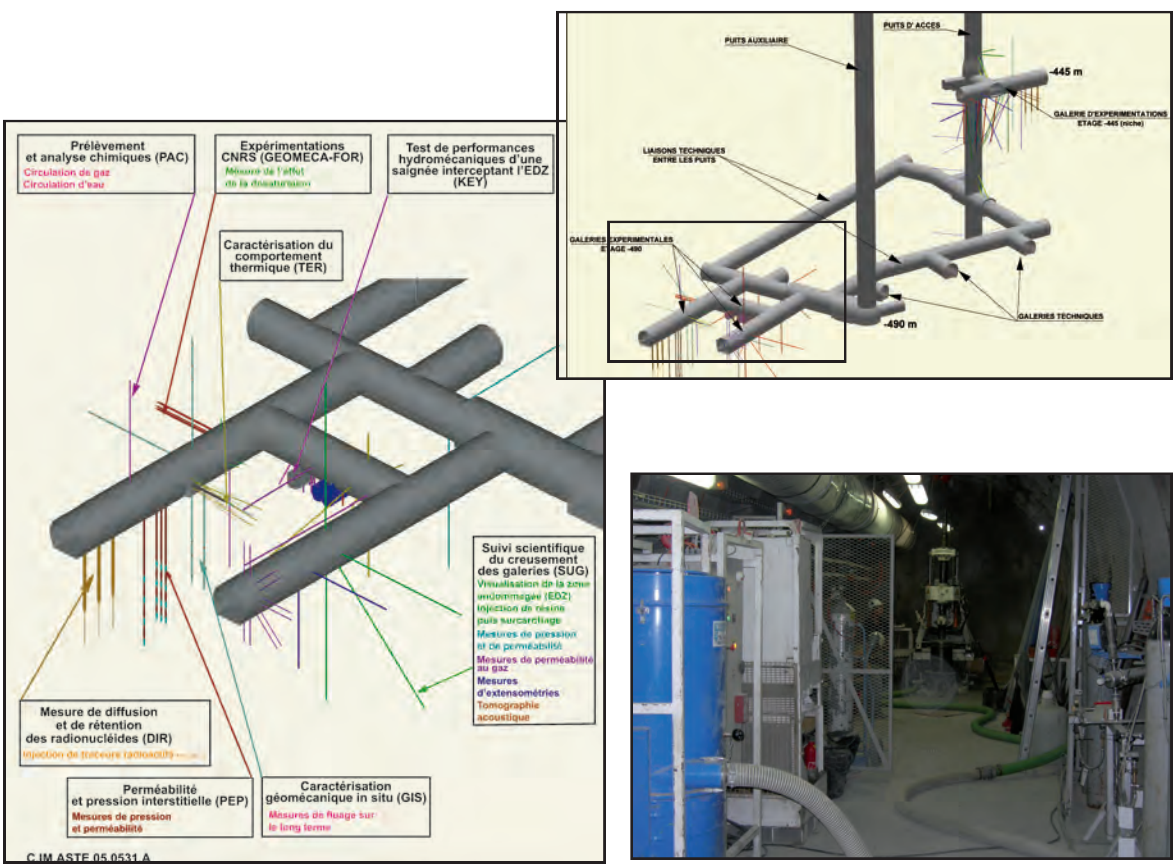
Relevé de données dans la galerie expérimentale à - 445 m

Three bore-holes were equipped to carry out DIR experiments that compare the *in situ* diffusion experiment results with those of the digital models built from work on core samples using the same tracers. The aim of the DIR is to measure the diffusion velocity of the water (molecules containing tritium) and of specific radioactive elements present in the waste or that present similar behaviour (iodine-125, chlorine-36, sodium-22, caesium-134). Monitoring these *in situ* diffusion tests (monitoring the tracer concentration decay in the solution injected into the test chambers) during over 6 months shows that the rock appears to display a diffusive behaviour in line with the diffusion parameters established in the laboratory from samples for tritiated water, anionic (chorine-36 and iodine-135) and cationic (sodium-22) species. Ultimately (2006) coring will be carried out in the area of the rock where the tracers will have diffused.

3

• Experimental drifts at -490 m

Late in 2004 excavation of experimental drifts on the main level (-490 m) began from the bottom of the auxiliary shaft. It was completed in September 2005



General layout of experimentations at the -445 m level drift

Two experiments were conducted in dedicated experimental drifts during this excavation work:

- *damage characterisation in the experimental drifts where specific measurement (SMR)* sections were conducted with similar experimental devices to those installed in the drift at -445 m. Thus the mechanical behaviour of two argillite horizons with different mechanical characteristics (at level -445 m the argillites are stiffer and with a higher carbonate content than at level -490 m) could be compared and feedback obtained from the two excavation techniques used, the traditional drilling/blasting method at level -445 m and mechanical method (hydraulic rock-breaker) at level -490 m,
- adapted from the EZ-A test conducted in the Mont Terri laboratory between 2003 and 2004, *the KEY experiment carried out in the third quarter of 2005 aims to test the possibility of cutting off any circulations in the fractured zone*, parallel to the drift axes, using grooves about two metres deep filled with bentonite (swelling clay). During the construction phase, some ten instrumentation bore-holes monitor the argillite behaviour and the obtained performance is measured. The configuration of the drift hosting the experiment is conducive to the expression of fracturing (close to the auxiliary shaft and other experimental drifts). The experiment comprised three phases. The *first one* consisted of characterising the damaged zone around the drift using geological observations, geophysical measurements (sonic velocity in bore-holes) and permeability measurements. It revealed the overall presence of fractures under the drift that enabled the test to be carried out. During the *second phase*, three grooves were created using a purpose-designed and manufactured saw on the basis of feedback from the EZ-A experiment. The feasibility of groove excavation and the saw's good performance were demonstrated together with a good behaviour of the argillite during the sawing operations (quality and stability of vertical walls obtained).

Key experiment: cutting a groove in the wall of the experimental drift using a saw

The purpose of the *third phase* was to check both the hydraulic performance of the groove system by filling two grooves with waterproof resin to simulate the hydraulic characteristics of hydrated bentonite, and its mechanical performance, by simulating hydrated bentonite swelling in a groove using hydraulic jacks. The tests showed that the grooves effectively interrupted the circulations in the fractures and that pressurizing the groove was well reflected in the argillite. The jacks were then removed and the groove filled with compacted bentonite bricks. A hydration system was then installed. The effects of hydratation on re-pressurizing are observed throughout, with various sensors. It is planned to monitor the measurements for several years.

In another experimental drift excavated at -490 m permeability (PEP), diffusion (DIR), hydro-geochemistry (PAC), thermal (TER) experiments and mechanical *in situ* creep (GIS) measurements are being conducted:

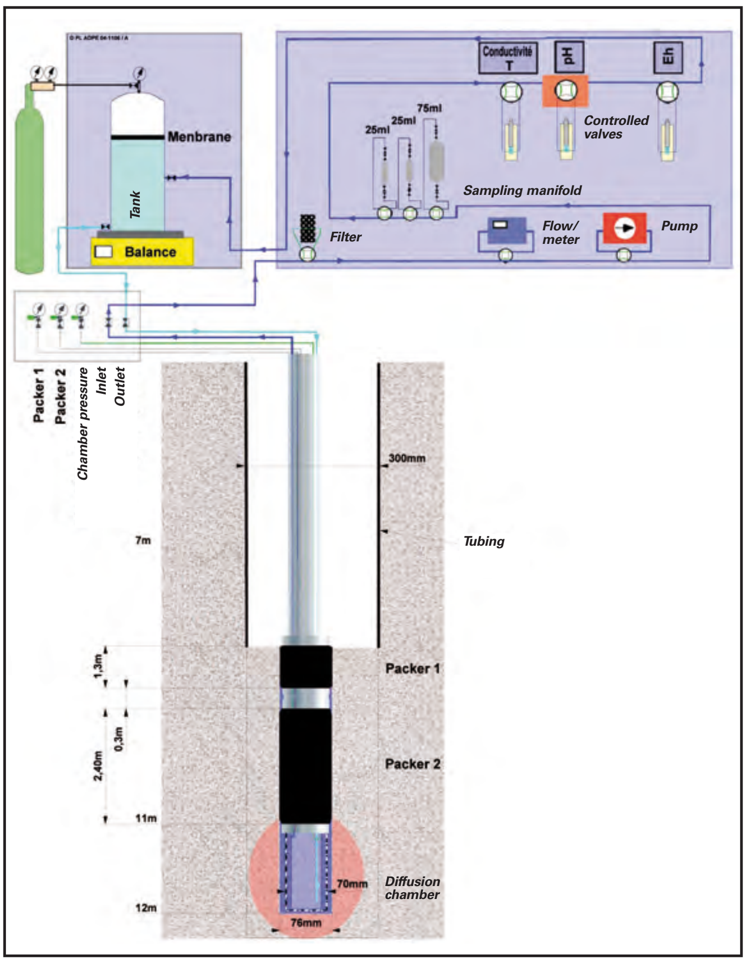
- Beyond *permeability and interstitial pressure* measurements (data already acquired at this level of the formation using other instrumentation), the PEP experiment aims at carrying out a long-term study of both hydromechanical coupling, by installing a strain gauge close to a test bore-hole and the effect of water salinity on pressure in the measuring chamber, in order to investigate the osmotic phenomena that may occur on a large scale.

- The PAC and DIR experiments already conducted at -445 m are repeated at level -490 m to supplement the measurements. These new diffusion measurements will back up as well the earlier findings obtained for this same level of argillite in the diffusion test carried out in a bore-hole (EST 208). The follow-up of this latter test confirms the expected diffusive behaviour in the rock and the diffusion parameters for the various tracers used.

- *argillite creep measurement* is carried out in bore-holes drilled from the drift, using instruments (called dilatometers) monitoring the pressure at the bore-hole wall and deformation (GIS experiment). This experiment could be conducted for several years.

- in order to measure the thermal conductivity (TER experiment), a heating appliance of the same type as that used in the Mont Terri laboratory has been installed in a bore-hole. Pore pressure, temperature and displacement sensors measure the thermal conductivity parameters of the argillite around this bore-hole and also provide data on the thermo-hydro-mechanical effects in the rock. This experiment was set up at the beginning of the last quarter of 2005 and will be continued with different heating cycles throughout 2006.

DIR- Diffusion and retention: a proven test method



Basic layout of DIR experiment

Already used at Mont-Terri, the method consists in maintaining a solution containing a mixture of tracers in contact with the argillite in an injection chamber located at the end of a bore-hole. At close intervals, samples of this solution are taken, then analysed in laboratory and, from the decay of the tracer concentration, the diffusion coefficient (or velocity) is calculated almost in real time. After one or two years, sampling the rock around the test bore-hole will allow to analyse in greater detail the tracer concentration profiles.

Circulation, sampling and parameters recording panels

At the end of 2005 all the experiments were running: that means that their results when set-up and from initial measurements have already acquired. They will be followed up throughout 2006 and may even be extended beyond that date as all the experiments support further data recording. Thus today data could be supplemented, the uncertainties reduced and records acquired over longer periods.

Interdisciplinary observation of the damaged zone: scientific co-operation in the underground Laboratory

Experimental areas in laboratory drifts (located at -490 meters) are assigned to the "Interdisciplinary observatory of the damaged zone", a CNRS research programme (FORPRO research group) for several years. It groups all the experimentations relating to the effects of desaturation on the mechanical behaviour of argillites and also the observation of mechanical, physico-chemical processes (development of micro-fissuring, evolution of the structure and chemistry of argillites). It includes notably an experiment, GEOMECA-FOR, aiming at surveying mechanical processes while the rock is desaturating.

Meuse/Haute/Marne underground Laboratory: the main construction stages

Construction phase:	**Completion date**
Start of main shaft sinking	August 2000
Start of auxiliary shaft sinking	November 2000
Sinking is suspended due to a serious accident	May 2002 - April 2003
Main shaft reaching the Callovo-Oxfordian at-420 metres	May 2004
Auxiliary shaft reaching -490 metres	October 2004
Commissioning of an experimental drift in the main shaft (-445 metres)	November 2004
Resumption of main shaft sinking	March 2005
Experimental drift excavation begins at the bottom of the auxiliary shaft	February 2005
Commissioning of the first experimental zone at -490 m (SMR experiment)	April 2005
Level -490 reached via the main shaft – end of REP experiment	September 2005
KEY experiment conducted at -490 m	August 2005
Commissioning of the experimental drift (PAC, DIR, PEP, GIS, TER) at -490 m	September 2005
Experimental set-ups are completed, initial measurements are recorded and long-term measurement follow-up starts	December 2005

Meuse/Haute-Marne underground Laboratory: the main experiments

	Experiments	Type of scientific work	Chronology
Shaft sinking	**Geological observations**	Description of intercepted layers; survey of fractures and geological objects encountered	Observations made while sinking since August 2000
Shaft sinking	**Measurement of exhaure water flow rates in the shafts**	Collection of the water flowing from the shaft walls at each producing level in the Oxfordian and measurement of flow rates	Measurement carried out in the Oxfordian limestones since February 2002
Shaft sinking	**Geotechnical measurements**	Measurements of deformation in shaft walls and argillite, characterisation of the damaged zone in 4 instrumented zones (SMGR) between -450 and -500m	Measurements carried out at regular intervals, while sinking from August 2001 up to the first half of 2005
Shaft sinking	**REP** (Response of the rock to shaft sinking))	Instrumentation of a volume of rock intercepted by the main shaft to measure the state of the rock before sinking, then the disturbances during and after	Instrumentation installed at the end of 2004 – beginning of 2005, continuous monitoring of sinking and deferred effects since the 2nd quarter of 2005
Drift -445meters	**Geotechnical measurements**	Measurement of deformation (SMC) of drift walls and in the argillite, characterisation of the excavation damaged zone EDZ	Measurements carried out while excavating the drifts (4th quarter of 2004) and monitoring since then
Drift -445meters	**PEP** (Permeability and Pressure)	Measurements to confirm the permeability of the argillite and additional hydraulic head measurement	Measurement made in the 1rst quarter 2005
Drift -445meters	**PAC** (Samples for chemical analysis)	Geochemical analyses and partial gas pressure measurement (pCO2) to obtain the chemical components of argillite water	Instrumentation installed at the end of 2004 – beginning of 2005, Then regular sampling to carry out chemical analyses and tracer monitoring
Drift -445meters	**DIR** (Diffusion and Retention)	Diffusion measurement (different tracers) in the argillite	
Drifts –490 meters	**Geotechnical measurements**	Same as for drift at -445 m	Measurements carried out during excavation work (2nd & 3rd quarter) and monitoring after that
Drifts –490 meters	**KEY**	Full-scale test to create cut off grooves in the damaged zone, fill them with swelling clay then measure their performance levels	Technological test carried out in summer 2005 and measurements of the bentonite until September. Hydration and performance monitoring since September 2005
Drifts –490 meters	**PEP**	Same as for the shift at -445 m and measuring the effects of hydro-mechanical and osmotic couplings	Equipping with instrumentation and measurements in October 2005 followed by continuous monitoring
Drifts –490 meters	**PAC**	Same as for drift at -445 m	Installation in October, followed by an equilibration phase and the injection of tracers at the end of 2005, then continuous monitoring
Drifts –490 meters	**DIR**	Creep measurements with a dilatometer	
Drifts –490 meters	**GIS** (Geomechanical *in situ*)	Creep measurements with a dilatometer	Measurements made in October then continuous monitoring
	TER	Thermal conductivity measurement of the argillite	Instrumentation installed in October and November 2005, followed by continuous monitoring

3. Knowledge acquired

3.1 In-depth understanding of the geological environment

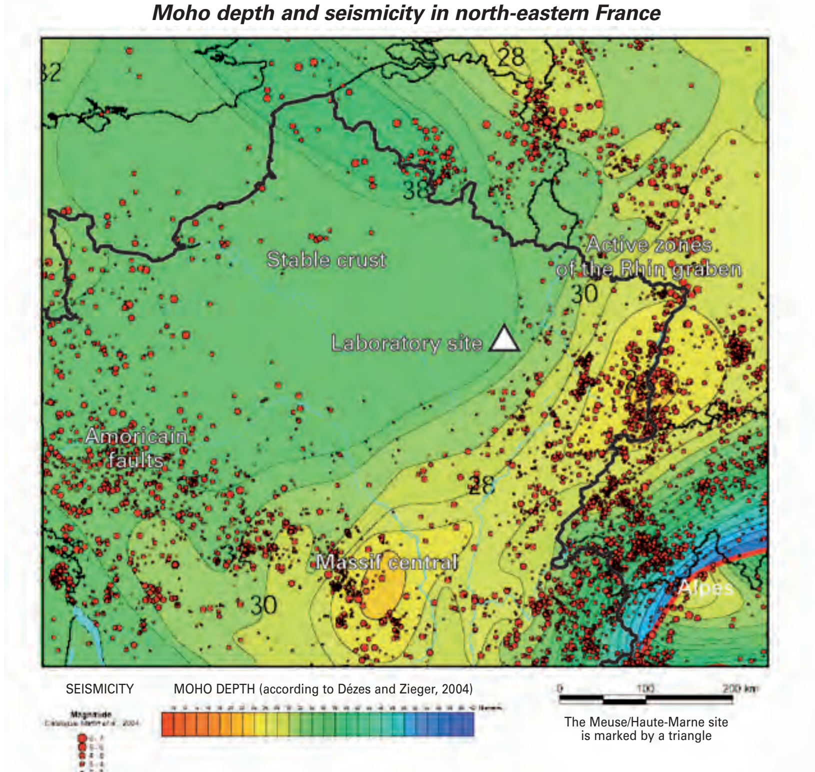
3.1.1 Layers with simple, regular geometry

The detailed examination of 350 km of seismic profiles in the study sector *shows that the tectonic deformations that have affected the region in the last 150 million years are slight* and limited essentially to the Gondrecourt and Marne grabens, at the edges of the study sector. *Between these faults, the Callovo-Oxfordian layer is regular and practically flat, which facilitates the design of the repository architecture.*

3.1.2 A geologically stable environment

France belongs to the domain known as the "west European" plate. It is an upward movement from Africa towards the north, which started over 100 million years ago, and its collision with Eurasia 50 million years ago which caused the formation of the Alps. The convergence velocity of these plates is very low. It is estimated at less than 1 cm per year. This movement is absorbed essentially by deformations which occur in mountain ranges. The remaining movement is absorbed by slipping along the main faults which surround the plate. In western Europe, it is the case for the zone known as "*the west European rift*" which corresponds to sedimentary graben such as Alsace, characterised by significant seismicity and by deformations known to be of tectonic origin. The slipping rate along the most active faults is of the order of 0.01 to 0.1 mm/year in the Rhine graben. Outside these zones, the possible movements are of even lower and are divided in between the regional faults which affect the basement. The possible slipping rate values are of the order of 0.001 to 0.0001 mm/year.

Moho depth and seismicity in north-eastern France



Seismicity of the Paris basin and its surrounding

Located in this intra-plate context, away from the active tectonic regions, the Paris basin remained particularly little affected by tectonics during the last 65 million years. This is a remarkable zone of the west European plate, where the lithosphere has a stable uniform thickness and stands out due to its practically non-seismic characteristic.

The Meuse/Haute-Marne site has therefore kept a stable geological environment: the slow displacement of the plates making up the earth crust and the location of this part of the Paris basin more than 350 km apart from the alpine collision front explains why it has undergone only slight deformation.

The available seismicity data confirms that the region is remarkably non-seismogenic. A network of earthquake recording stations has been set up within a 30 km radius from the underground Laboratory and completes the national seismic monitoring stations network already in place. It recorded the recent earthquakes in Saint-Dié and Besançon, highlighting their very low effect on the sector, and also earthquakes up to 10,000 times weaker or very far away such the earthquake in Sumatra in December 2004 and all the movements related to local human activity such as quarry blasting.

However, the risk of earthquakes near the site cannot be totally excluded on a scale of several hundred thousand years. To estimate the seismic risk over long periods of time, the faults near to the site are assumed as active and *maximum physically possible earthquakes (SMPP)* values are considered, despite the absence of seismicity and recent tectonic deformations. The very penalizing hypothesis, with a hypothetical earthquake of magnitude 6.1±0.4, is postulated as occurring 6 km from the site. *Then, to be on the safe side, we check that the repository structure can withstand such an earthquake.*

3.1.3 The absence of exploitable natural resources

Research was carried out between 1903 and 1945 for coal, and between 1978 and 1988 for hydrocarbons. According to known deposits in Lorraine, two levels of the Permian were capable of providing resources: The Westphalian, main hydrocarbon souce-rock and the richest coal formationl in the Lorraine basin, is absent directly below the site and the Stephanian, which has a very low coal potential, is located at a great depth (3,800m) according to seismic profiles and boreholes.

As regards a possible geothermal resource, data from oil exploration and Andra boreholes show that in the sector under study:

- the geothermal gradient measured (2.6°C for 100 m in depth, to be added to the average ground surface temperature of 10°C) is lower than average, and consequently the temperature in the aquifer sandstone of the lower Trias is relatively low at a depth of 1,300 m (45°C at most),
- water productivity of triassic sandstone in this sector is very low or even inexistent.

Therefore there are no outstanding natural resources in the study sector.

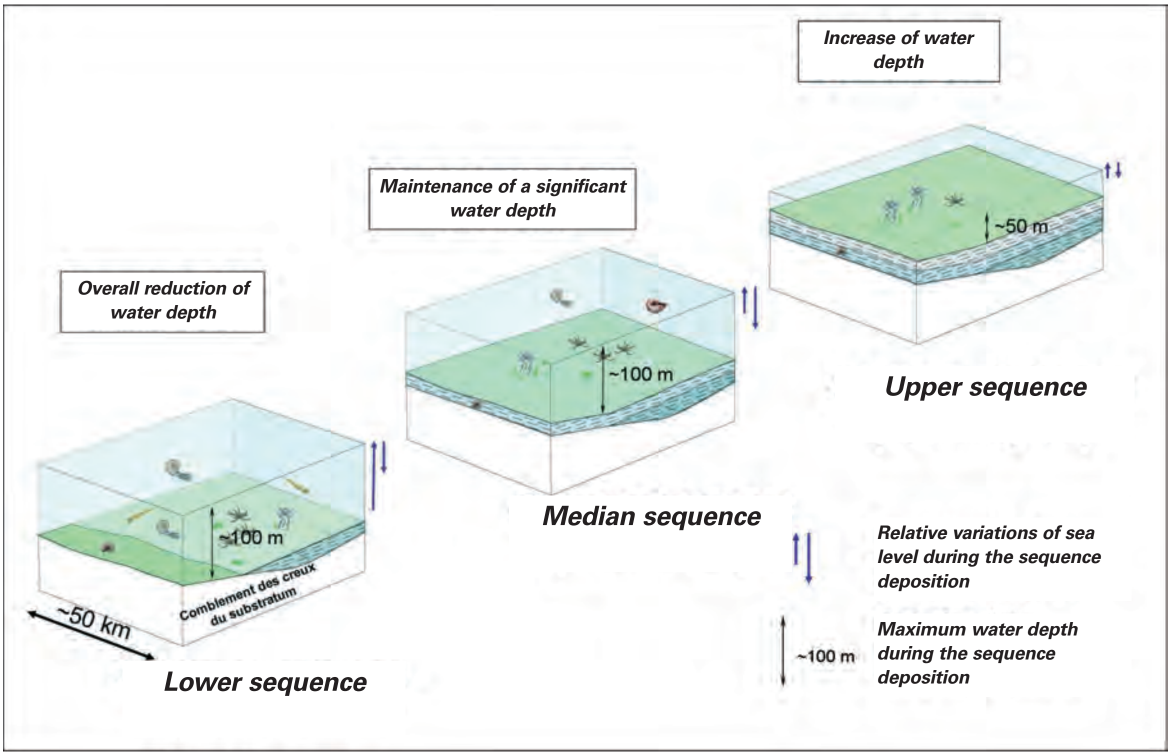
> **RFS III.2.f.** “Absence of sterilisation of underground resources.
> With respect to underground management, the site should be chosen so as to avoid zones with known or suspected asset of outstanding character”

3.2 The favourable properties of the argillaceous layer

3.2.1 A homogeneous argillaceous layer over a large surface area

The Callovo-Oxfordian argillites form a uniform clay dominant layer between 422 and 552 m in depth directly below the underground laboratory site. Due to layers dipping north-west, this depth increases progressively to reach more than 600 m, fifteen kilometres or so towards north. In the same way, the layer thickness varies from approximately 130 to 160 m from south to north-west. The layer thickness guarantees a better confinement (the thicker the layer, the better the protection). Seismic data and the correlations between bore-holes show that this thickness variation is progressive at the sector scale, and consistent with the initial topography, rather even, which determined the sedimentation of this formation.

The layer homogeneity has been observed on several scales: from the sector to the sample and in the horizontal and vertical directions.



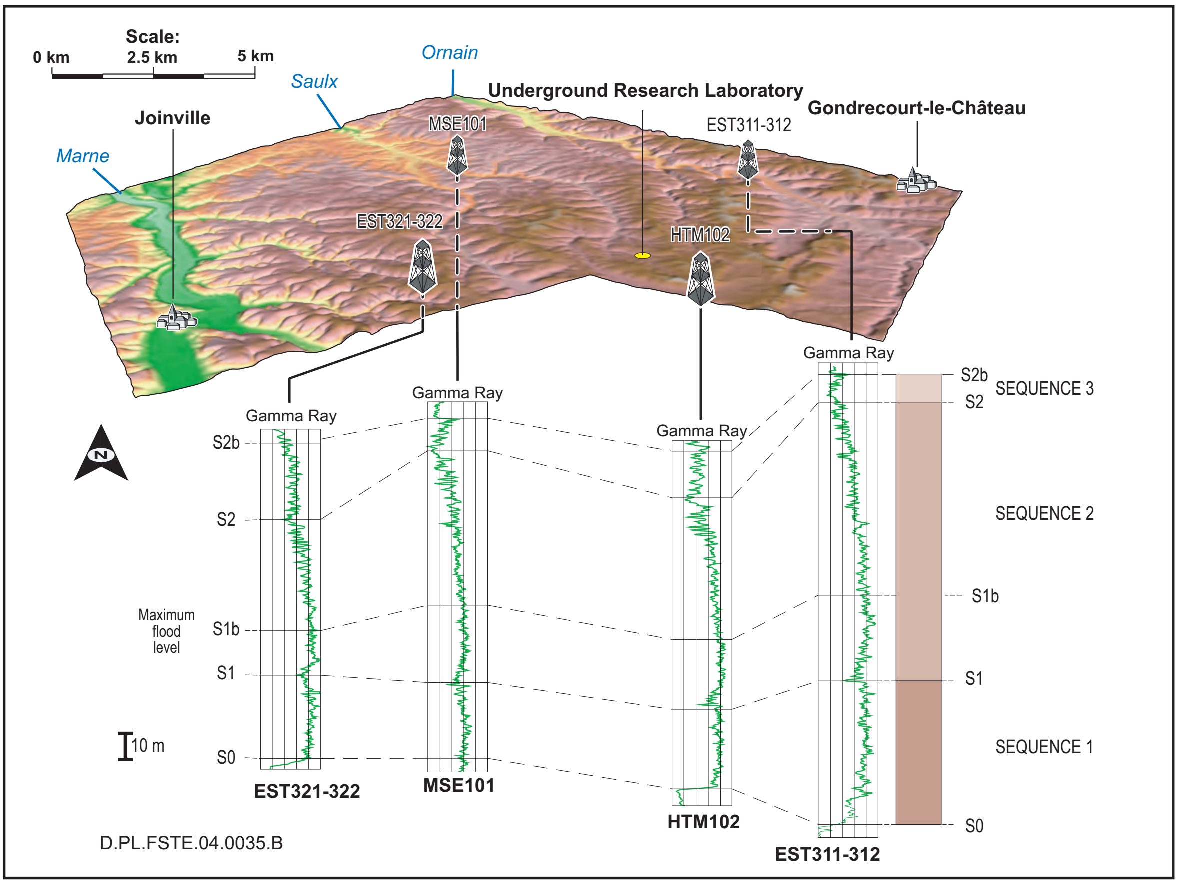
The variation of sea level during deposition means a variation of sedimentary layers: the higher the sea level (maximum flood), the more the clay layers ; the lower the sea level, the more the carbonate layers.

• **Vertically**, the measurement always show the same *low variation in the mineralogical composition* (content and type of clay, carbonates, quartz and pyrite) of the rock: this proves that sediments were deposited at the same time (around 155 million years ago), in the same type of environment and with the same intensity. The small variations in the proportions of the main mineralogical phases (clay, carbonates, quartz and feldspar) are organised into three continuous sedimentary levels (or sequences). They translate the low cyclical variations of the sea level at the time the layer was deposited (between -158 million and -152 million years approx.). The thicknesses of these three sequences are respectively 18 m (lower sequence), 80 m (median sequence) and 34 m (upper sequence) at the underground laboratory site. It is in the median sequence, approximately in the centre of the layer and corresponding to the level studied for a possible repository (-490 m directly below the laboratory site), that the highest proportion of clay minerals can be found (up to 60%). Within this sequence, the change in the mineralogy of the clays occurs over a few metres and indicates a displacement of the sources of sediments linked to high sea level conditions prevailing during the deposit. The upper sequence shows a higher carbonate content. The carbonates are evidenced in the form of nodules and small carbonated levels (decimetric to metric).

Average composition of the three sequences of the argillite layer [6]

	Upper sequence	Median sequence	Lower sequence
Carbonates	42 %	23 %	28 %
Clays	25 %	55 %	41 %
Quartz and feldspars	31 %	20 %	29 %

[6] These are the three major components. There is also a small amount (2 to 3 %) of pyrite and organic material.



Logs showing the lateral homogeneity of the Callovo-Oxfordian formation (Meuse/Haute-Marne sector)

• **Laterally**, this argillaceous layer has the same organisation over a zone of more than 350 square kilometres over the whole sector studied: it appears to be practically identical in all the bore-holes drilled within 15 km from the underground laboratory, according to the continuous measurements carried out along the bore-holes (logs) and the analyses of its minerals. In particular, logging enables to correlate, over distances of 20 to 30 km, the different levels of the Callovo-Oxfordian identified by means of detailed sedimentological and stratigraphical analyses. Thus, the only clear trend identified is a very slight enrichment in quartz (5 to 10 %) when moving fifteen kilometres northwards from the laboratory site. The same is true for the variations in thickness of each of the sequences, which are very gradual (a few metres). Only the lower sequence, controlled by the topography of the underlying formation, shows slightly more significant variations in thickness (of the order of twenty metres in the sector considered). The constancy of these sequences is evidence of tectonic and sedimentary stability which characterises the deposit period. This is a favourable criterion which provides some flexibility for siting a possible repository.

The Callovo-Oxfordian sediments were, de facto, produced in a continuous manner and in very calm deposition conditions. The reconstruction of the deposition conditions of the formation also shows that the origin of the sediments has not changed significantly throughout the deposition period (dismantling of the Brabant massif and the Armorican massif both emerged at this time) and that the sedimentation occurred far from the coast and in uniform condition for the whole of the zone.

This context excludes:
- the presence of sedimentation gaps large enough to disturb the layer continuity,
- the existence of sand lenses, especially since the sediment supply sources (unflooded zones) are far away, particularly in high sea level periods.

Thus, geological reconstructions and bore-holes surveys have not shown up significant sedimentary discontinuities which may modify, at the sector scale, the geochemical and geomechanical properties of argillites, and therefore their retention capacity or their suitability for excavating underground structures.

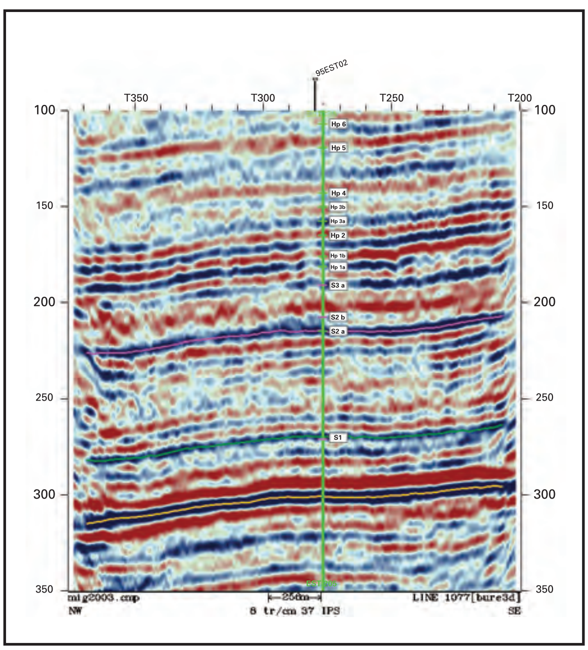
• **At sample level,** analyses enabling us to determine the distribution of molecular fossils (organic molecules typical of living organisms present at the time of Callovo-Oxfordian sedimentation) underline the low variability (horizontal and vertical) which is once again evidence of a very stable deposition environment and a paleoenvironment during this period in the studied zone.

3.2.2 Absence of faults

Faults and cracks might affect the continuity of the Callovo-Oxfordian, i.e. its *confinement capacity*. Therefore, this type of discontinuity should be detected, and its origins and changes over time should be known, particularly by interpreting the geological and tectonic history of the east of the Paris basin in reference to events such as the opening of the North Sea (170 million years ago) and of the Bay of Biscay (130 million years), the Pyrenean uplift (50 million years) and Alpine uplift (30 million years). The orientation of the regional stresses has remained stable since that last tectonic episode.

To date, no fault has been identified in the Callovo-Oxfordian and its surrounding formations over an area of 250 km² towards north and north-west of the laboratory. The only known faults are located outside of that area, the Marne faults (NNW direction) and the Gondrecourt graben (NE direction) which form the sector boundaries towards west, south and east.

The presence of vertical faults with a throw greater than a few metres has been ruled out as a result of geological mapping and seismic-reflection campaigns (2-metre detection threshold using 3D seismic imaging fine processing techniques). Smaller faults, referred to as secondary ones, where they exist, are limited in terms of extension (a few hundred metres extension maximum).



3D seismic section after interpretation

Field reconnaissance work by directional deviated drilling have supplemented the previous investigations and looked for secondary fracturing, if any:

- *in the Callovo-Oxfordian, no Andra borehole, either vertical or deviated (i.e. 2,500 m in cumulated cored length) has intercepted any secondary fault*. A few microstructures were found. They were all clogged and do not affect the confinement properties of the Callovo-Oxfordian. The permeability measurements carried out in the deviated boreholes at these microstructure levels are similar to the ones recorded in the Callovo-Oxfordian, which indicates they play no particular hydraulic role. Additionally, the filling mineralogical content (e.g. celestine crystals) shows that they formed shortly after the layer deposition under sediment compaction and that they were subsequently unaffected by fluid circulations. Lastly no fault has been observed either at the work face or at the walls throughout the drift excavation works at -445 m and -490 m (that is for over 300 metres in length);

- *in the lower levels of the underlying layer (Dogger)*, a directional deviated borehole went through the area where 3D seismic imaging detected sub-vertical WNW-ESE structures. Borehole surveys and tests demonstrated that these were not faults. The highly detailed geophysical image shows a structure of the same size as coral reefs and on the same stratigraphic level as observed at the outcropping. At the same time, core observation from that borehole shows characteristic reef facies. Lastly, the measurements carried out indicate that this zone has very low permeability.

Geological structures

Geologically speaking, there are different types of structures which may affect a formation, depending on its origin and whether a displacement occurred or not.

Structures with displacement

Fault: break with relative displacement (throw) of both resulting compartments. In practice, a fault is a vertical or near-vertical accident. Its dimensions are variable: from a few hundred metres to several hundred kilometres horizontally, and from a few tens of metres to several thousand metres vertically. The origin of a fault is always tectonic.

Secondary fault: the notion of "secondary fault" is relative to the size of the object, smaller than a "major fault" or a "regional fault". Also added is the notion of slight vertical throw (from a few decimetres to a few metres). Oil companies use the term "sub-seismic fault" for faults having vertical throws too small to be detected by seismic-reflection survey.

Structures without displacement

Joint: break in the rock resulting from stress relaxation, presumably tectonic, without displacement of the two separated parts (both compartments are in connection). Joints vary in extension from a few decimetres to a few hectometres.

Diaclase: any plane (or sub-plane) discontinuity without relative displacement of the compartments, but both limits are not necessarily in connection; the resulting voids may be filled with minerals (carbonates, clays, quartz, etc.). Diaclases may be tectonic or sedimentary.

Tension gash or crack: break of a few centimetres to a few decimetres in length and a few millimetres to a few centimetres in width resulting from stress.

Microfissure: any break in the rock, without prejudging its genesis, a few millimetres thick and with a maximum extension of a few decimetres.

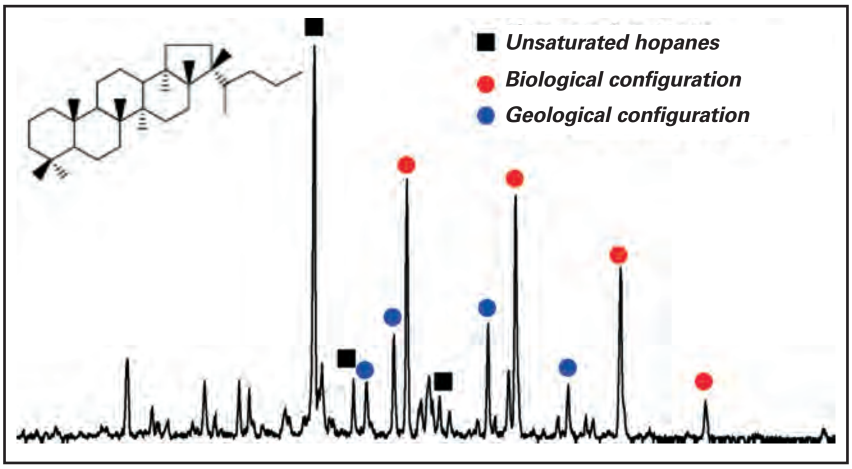
Microstructures: when the extension of the object cannot be assessed (e.g. core sample) and, as a result, its mode of genesis cannot be determined, joints, diaclases and gashes are termed "microstructures".

3.2.3 A clay with very low permeability and high confinement capability

The Callovo-Oxfordian geological formation has very low permeability, *which greatly reduces water flow through the layer and prevents possible radionuclide transportation by advection*, i.e. conveyed by flowing water.

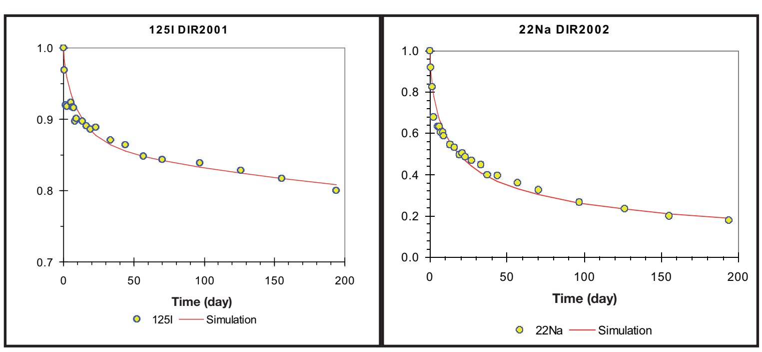
The measurements made in deep bore-holes drilled from surface and on samples, have indicated that the layer permeability varies in the range 10^{-12} to 10^{-14} m/s, most of the measurements being concentrated between 5.10^{-13} and 5.10^{-14} m/s. These figures have been confirmed by measurements made in the experimental drift at -445 m, and by bore-hole measurements drilled from the experimental drifts at -490 m. Indirect permeability assessments also produce the same range of values. This very low permeability is explained by the argillaceous nature, the thin and very small radius rock pores (less than 1/10 of a micron). These permeability measurements are similar to the ones whether obtained from samples at the pluri-centrimetric scale or in the bore-hole at the decametric scale. Given the diversity of the methods and means used to obtain the rock permeability value in surface laboratory and in situ, the proposed value range appears to be particularly robust. This tends to strongly confirm the layer's homogeneity and constancy of its properties.

Studies have highlighted that diagenesis occurred very early on during burying compaction and was moderate (argillite temperature did not exceed 40°C while it is currently 23°C). The current Callovo-Oxfordian formation characteristics were primarily acquired over the first few millions of years of the history of the layer. The initial phases, particularly clay minerals, were unaffected by major changes to their crystal chemistry and texture. The isotopic analyses carried out on the carbonated phase (especially from strontium and carbon isotopes) clearly show that the limited diagenesis processes helped retain the original marine signature of carbonated cements. *Broadly speaking, the diagenesis phenomena recorded by the Callovo-Oxfordian are very discreet, regional in extension and consistent with geological temperatures not exceeding 40°C. Therefore, they are not likely to have caused heterogeneities at the transposition zone scale.*



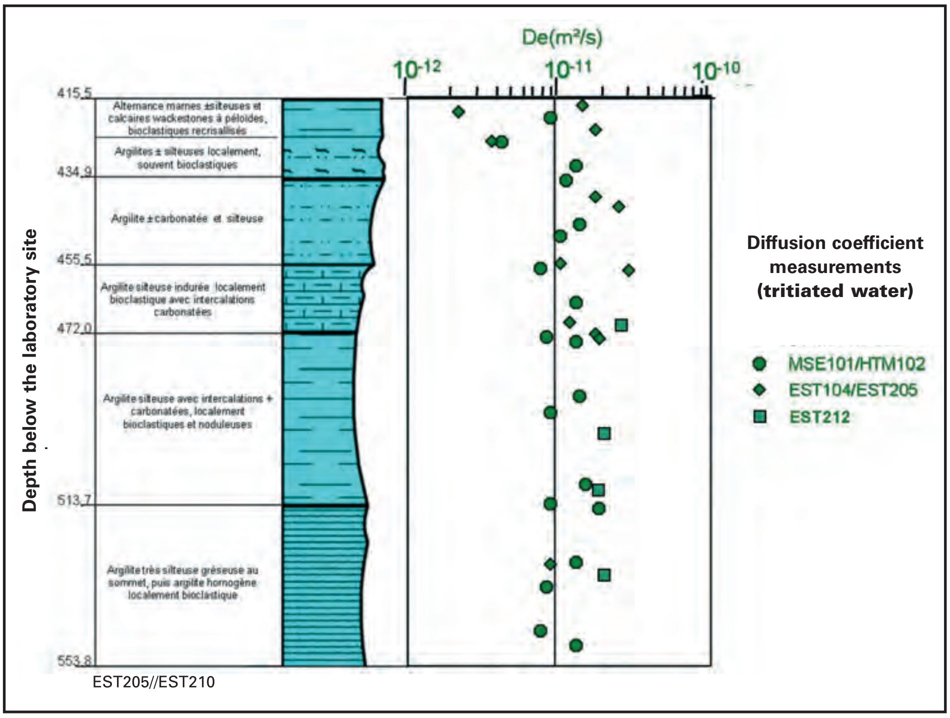
Mass spectrometry of hopanes (organic elements derivative of bacteria) showing the preservation in the Callovo-Oxfordian formation, of typical structures of living organisms (biological configuration in red points), meaning a moderate thermal diagenesis.

Analysis of the distribution of certain chemical elements and their isotopes in the different rock minerals and the interstitial water confirms that exchanges have been very limited in the layer for 150 million years. The distribution of the more mobile elements such as chlorine or helium proves that they move by diffusion from the Dogger towards the Oxfordian limestone while migrating through the Callovo-Oxfordian, rather than by advection. It confirms that the chemical elements are transported very slowly (a few hundred millennia to migrate through the layer). These diffusive transport timescales are consistent with the ones estimated by modelling on the basis of the diffusion tests conducted on samples or *in situ*. Indeed, the interpretation of the follow-up of the diffusion tests carried out in the experimental drift at -445 m (three diffusion tests) and in the EST208 bore-hole drilled from the surface, leads to very low vertical diffusion coefficient values, consistent with the values obtained by measuring argillite samples. The following diffusion coefficient reference values will be retained: $2.5.10^{-11}$ m2/s for the tritiated water and 5.10^{-12} m2/s for the anionic species (primarily iodine and chlorine).



Experimental results and modelling: the model provides a representation of the diffusive behaviour of tracers in the Callovo-Oxfordian argillites (example of iodine 125 anion and sodium 22 cation)

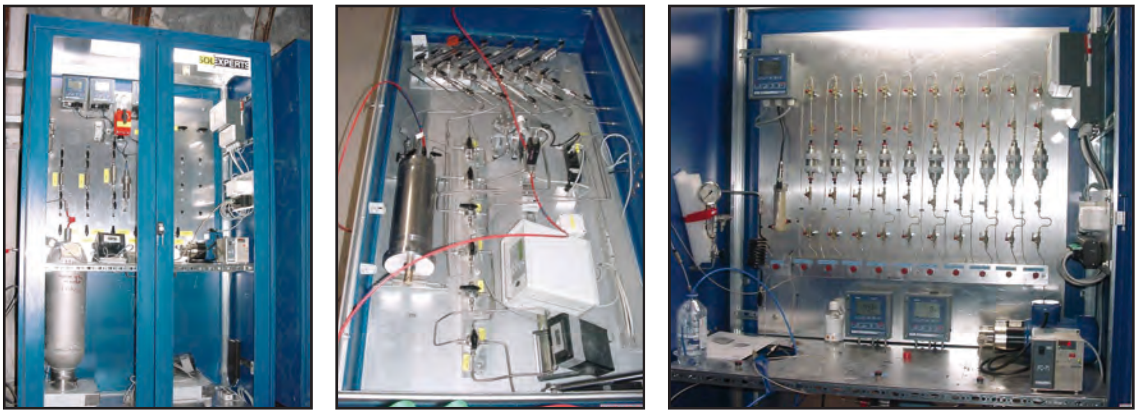
All the diffusion parameter values obtained to date are highly consistent, on one hand at the different scales of the investigations (either on centimetric samples or in diffusion chambers at the scale of one metre) and ,on the other hand, in the levels of argillite with distinct mineralogy. This demonstrates that this factor varies very slightly over the height of the formation.



Diffusion coefficient along the Callovo-Oxfordian layer

In addition to its permeability, the confinement capabilities of the Callovo-Oxfordian stem from its mineralogical composition: X-ray diagrams and chemical analyses show that the most abundant clay minerals are of the “illite-smectite interstratified“ type, that have the specificity, especially smectite, of being made up of stacked sheets (like the “mille feuille” puff pastry). *In between these sheets, a great quantity of the elements in solution in water, primarily radionuclides, can fix*. The *in situ* diffusion tests on cationic species (caesium) measured in the laboratory by bringing argillite into contact with water that contains a dissolved radionuclide have also confirmed this. The main radionuclides studied, some of which are also chemically toxic, are iodine, technetium, caesium, selenium, boron, chromium, nickel, zirconium, niobium, molybdenum, pewter, lead, uranium, neptunium and plutonium. *This fixing capability is also confirmed by the in situ diffusion tests on cationic species (caesium). It means an additional delay in the migration of elements in the Callovo-Oxfordian and has been tested in many experimental configurations (water chemistry, element concentration in solution).*

Finally, the chemical composition of the interstitial water of the rock (only the small quantity of water trapped in the rock pores) appears to be in equilibrium with the rock in line with various elements of the geological and hydro-geological context. As direct knowledge of the Callovo-Oxfordian pore water composition presents inherent difficulties because of the rock’s properties (low water content in the formation, 7 to 8% in mass percentage, very low permeability), the mineral phases, chemical reactions and parameters governing this equilibrium were identified from measurements and tests on bore-hole cores. These data were then input into a geochemical model to calculate the chemical composition of the pore water. The approach has been successfully tested and implemented in the Mont Terri laboratory. The PAC experiment carried out in the Meuse/Haute-Marne Laboratory has verified the model’s validity for the Callovo-Oxfordian argillites: the analyses of the samples from the gas and synthetic water circulation bore-holes in the drift at -445 m confirm the hypotheses about the reactions governing the chemical composition of the pore water and the model’s main parameters. The chemical composition obtained by modelling is thus confirmed: it reveals neutral pH and is reducing as expected given the presence of pyrite and organic matter. It is considered to be homogenous throughout the thickness of the formation, which is consistent with the latter’s overall lithological homogeneity.



PAC experiment panels: gas and water pipes

Under these circumstances, many radionuclides such as those of the uranium family (actinides) have a very low solubility in water and precipitate in solid (and microscopic) form, which prevents their transfer through rock.

3.2.4 A layer suitable for mining excavation

The geomechanical tests and measurements on the samples collected in boreholes demonstrated that these *argillites are stiff, become little and slowly deformed, which allows consideration for current mining methods.*

The mineralogical composition and density of the Callovo-Oxfordian argillites mean a relatively high resistance for an argillaceous rock. Their resistance to single-axis compression is greater than 25 MPa on average in carbonated levels and approximately 20 MPa on average in argillaceous levels in the middle of the formation.

The study of the mechanical behaviour of the argillites used different types of three-axis loading tests varying the stresses applied and application time. Test results suggest that *the argillites are little deformable*. For comparison purposes, their mechanical characteristics are equivalent to those of the argillaceous formation crossed by the La Chamoise highway tunnel (south-eastern France) at a depth of about 400 m.

Excavating operations in the Meuse/Haute-Marne underground Laboratory

Hydraulic rock hammer in an experimental drift at -490 meters

The mechanical resistance of the rock (compared to the overburden pressure 500 m deep, i.e. approx. 12 MPa) and its low deformability allows excavating drifts using current methods. As shown during the Meuse/Haute Marne Laboratory construction, we can consider for excavating drift, mechanical equipment, for example hydraulic rock breakers as in the drifts at -490 m, or explosives (the conventional drill and blast method) as in the drift at -445 m. Other conventional mining methods (road header) can also be considered. As for drift ground support, it can be provided by sliding metal arches and/or bolting inserted as the excavation progresses, combined with shotcreting.

3.2.5 Characteristics consistent with reversibility

While Callovo-Oxfordian argillites have a low deformability, they can however evolve over time on account of the clay minerals they contain (this is termed "creep"). When subjected to anisotropic stress conditions, argillites become deformed gradually, which tends to make them more isotropic. *This deferred behavioural mechanism is slow*. Its characterization required long and very accurate measurements on samples, by checking test conditions for several months (several years for some samples). Creep velocity measured after 3 years corresponds at best to displacements of a few microns per year (hardly detectable with current measuring instruments). By comparison, creep velocity measured is 1,000 times lower than the Boom clay one, studied in the Mol underground laboratory (Belgium).

The measurements obtained at the scale of a structure in the Meuse/Haute-Marne Underground Laboratory indicate a deformation amplitude of a few centimetres after six months, which corresponds to deformation rates approaching those measured in the short-term tests (over 100 days) on the samples taken from the levels with the highest clay content.

After two to three years, the deformation rate should reduce by at least a factor of 10, which is confirmed by the example of road tunnels constructed some decades ago in similar formations. Continuous deformation measurement in the Meuse/Haute-Marne Underground Laboratory is planned for several years, primarily in the instrumented sections at the main level located at -490 m. They will enable to verify these orders of magnitudes.

For periods over a few decades, the deformation rate assessment is based on other investigation methods: study of mineral deformation mechanisms and geological layer deformations since their emplacement. The values obtained by modelling for long periods reveal that argillites have some capacity for deformation, but the proportions are such that they do not put at stake the stability of the underground structures. The wall displacement rate should thus continue to diminish: it should be 100 times lower after 100 years and 1000 times lower after 1000 years.

Deferred deformation of the argillites results in gradual loading of underground structures. Underground excavation lining and, over the longer term, backfilling materials, allow taking up the stresses.

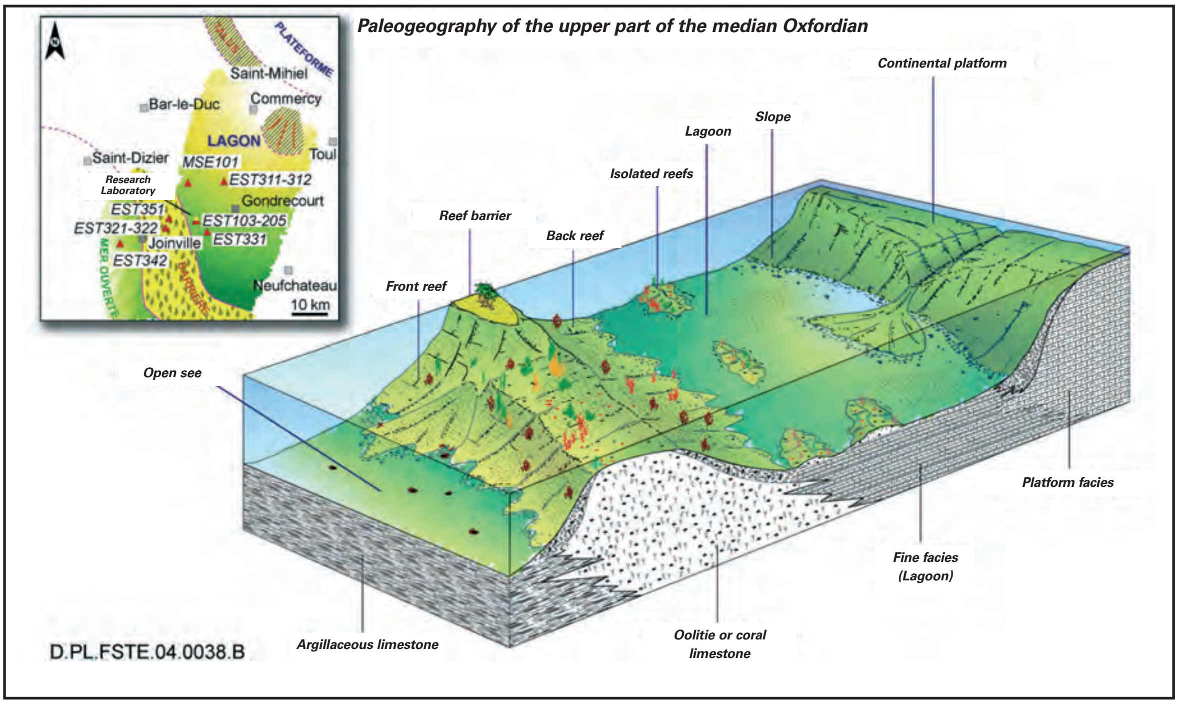
3.3 A favourable hydro-geological context

Understanding the geological medium entails as well acquiring an overall knowledge of the formations surrounding the Callovo-Oxfordian argillites.

3.3.1 Low permeability of the formations surrounding the Callovo-Oxfordian argillites and slow circulations

The borehole measurements in the study sector highlighted *the low matrix permeability of the formations surrounding the Callovo-Oxfordian argillites*, particularly the Oxfordian (from 10^{-9} to 10^{-7} m/s) and Dogger (from 10^{-10} to 10^{-8} m/s) calcareous formations, deemed to be water-bearing[7] in other parts of the Paris basin. For example, water flow rate measured in the shafts of the Underground Laboratory when intercepting the Oxfordian limestones is less than 10 litres per minute. This is explained by the high level of recrystallization of these limestones which has plugged the pores of the rock during major diagenetic processes expressed regionally on the eastern edge of the Paris basin.

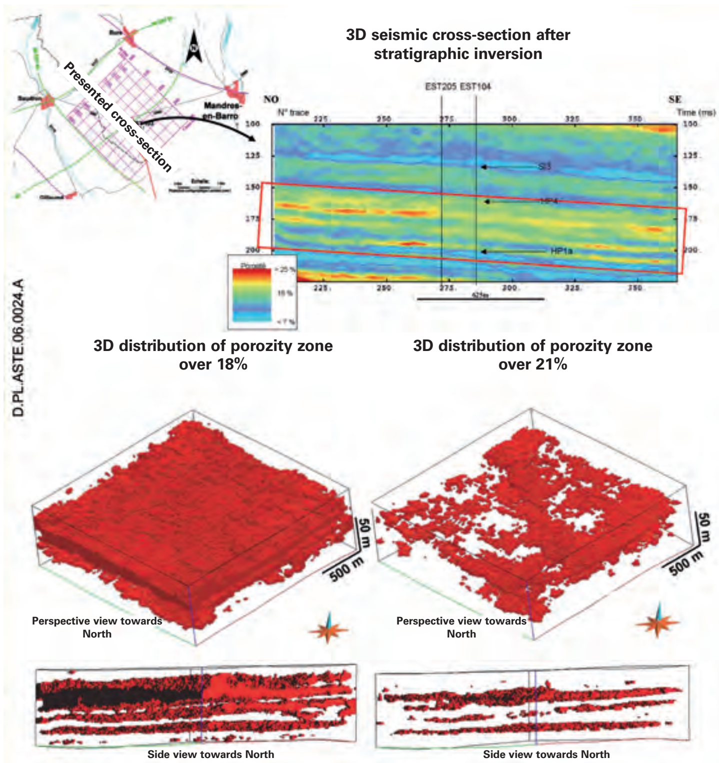
[7] - *A geological formation is qualified as water bearing or aquifer when its permeability is over 10^{-6}m/s.*



Oxfordian paleo-environment reconstruction

These processes are linked to the circulation of fluids of meteoric origin, in limestones such as those of the Oxfordian or Dogger formations, that have gradually replaced the original seawater. They are characterized by dissolution near outcropping zones, and precipitation when the formation is overlaid. These diagenetic processes are responsible for the low porosity (6 to 10 %) and for the overall lower permeability of the Dogger and Oxfordian formations in the area (by 1 to 2 orders of magnitude) than the measured one at the centre of the Paris basin. These phenomena do not affect the more impervious carbonated cements of the Callovo-Oxfordian argillites, which retain their original marine signature. The petro-physical characteristics (porosity, permeability) of the surrounding formations, resulting from these processes, have been acquired in the transposition zone at least 30 million years ago, as indicated by the absence of $^{234}U/^{238}U$ imbalance in the carbonated matrices.

Certain levels of the carbonated Oxfordian have a higher porosity than the rest of the formation. Their organisation appears directly linked to the initial sedimentation conditions. That explains their overall geometry organized according to their stratification as shown by the 3D seismic data recorded on site. Underground water circulation occurs mainly in these levels, also more permeable (up to 10^{-7} m/s).



Reconstruction of the Oxfordian porous layer morphology on the basis of 3D seismic data

Due to the low permeabilities of the Oxfordian and Dogger formations, flow is very slow: hydro-geological modelling shows that, in the transposition zone, velocity is in the order of a kilometer per hundred thousand years in the Oxfordian, and even slower in the Dogger. These velocities are consistent with the results of analyses of chlorine^{36} and carbon^{14} isotopes. *The mean age of the water in the Oxfordian and Dogger formations is approximately 400 000 years and 1 million years respectively.*

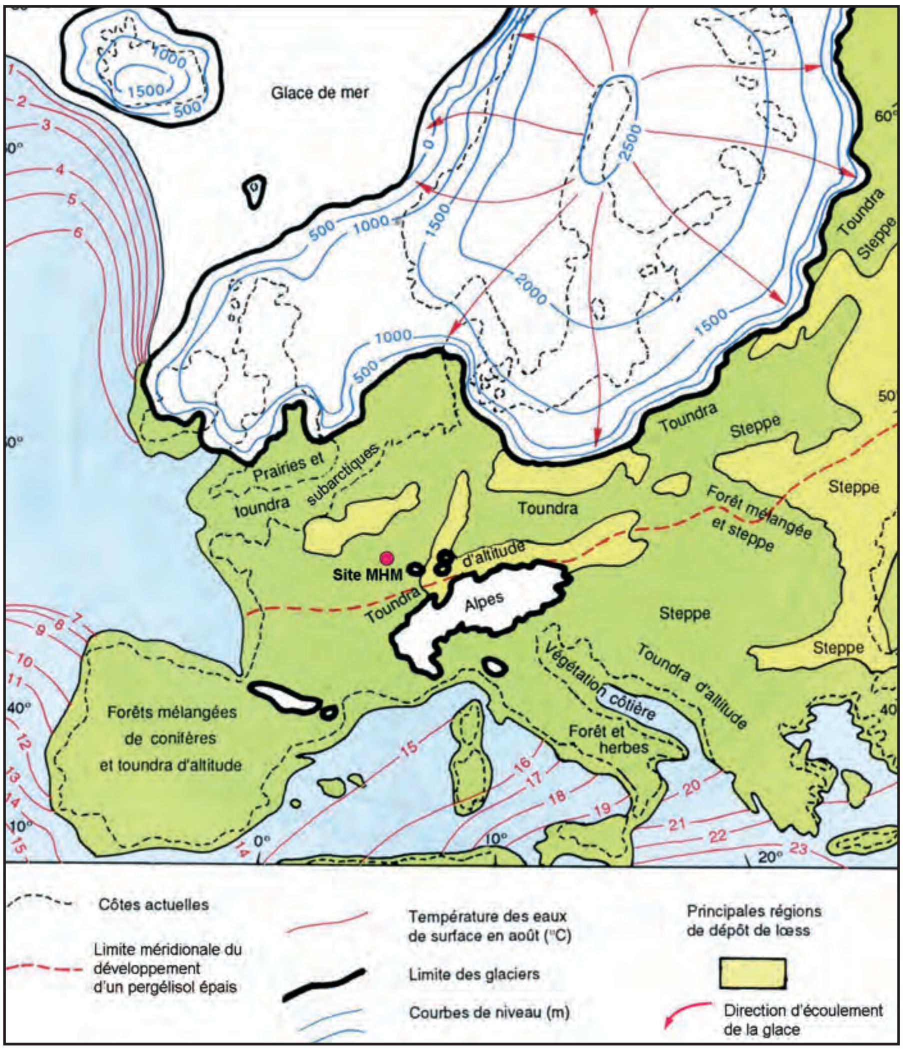
Finally, the hydraulic heads measured in the Oxfordian and Dogger formations are similar and, at the transposition zone scale, do not represent an effective driving force for water displacement in the Callovo-Oxfordian formation. Given the argillites low permeability, the vertical water flow velocity (appraised by the Darcian velocity) is in the order of a few centimetres per 100 000 years in the Callovo-Oxfordian formation.

3.3.2 Investigated outlets and a predictable evolution

The various boreholes drilled within the sector have improved the hydro-geological model, on the one hand by to the measurement of hydraulic heads in the Dogger and Oxfordian formations and, on the other hand, by the acquisition of porosity and permeability data for the carbonates within these two formations. The hydro-geological modelling which includes these acquired data and the overall geological representation of the sector provides the water flow configuration within the sector.

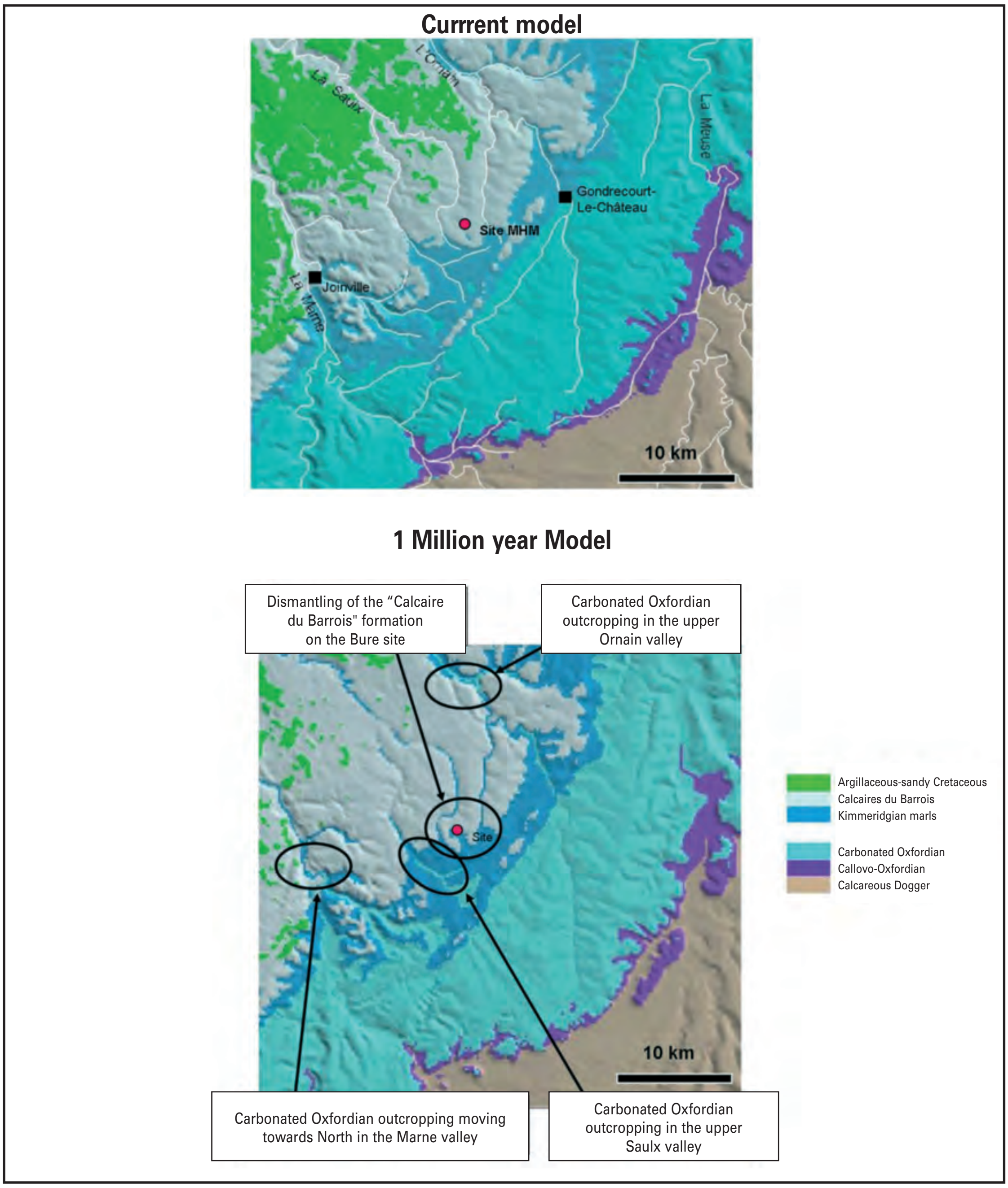
The flows in the Dogger and Oxfordian formations are generally horizontal and directed from source zones constituted by the plateaux areas to the south and east of the site, towards the centre of the Paris basin. However, at the site position, due to outcrops proximity, some of the flows in the Oxfordian formation head towards a local low point, in the course of the Marne river in the south west. As mentioned above, hydro-geological modelling indicates very long transfer times in the transposition zone. Beyond this zone and close to the Marne faults, the flow could be more rapid, linked to dissolution processes along the fractures in the Oxfordian formation (this situation has been observed in a borehole drilled in 2003) likely to increase the overall permeability of surrounding formations.

Modelling of climatic variations taking into consideration, in particular, the impact of human activity (within the context of global climate change), enable a reasonable and internationally agreed prediction (European BIOCLIM programme) of the major climatic changes and their consequences (variations in temperature and rainfall, changes in vegetation) over at least the next 200 000 years. These climatic changes, in particular the alternation of glacial and inter-glacial stages, constitute, with the slight uplift, the main erosion driving force. The surface and underground flows will also evolve in the very long term due to erosion.



Icecap and main environments extension during the last maximum glaciation (circa 18 000 years ago)

The study of the topographical model modification over the last two million years provides valley deepening ranges (approximately 15 m per hundred thousand years in the sector), and cuesta relief retreat and terrain ablation ranges on the plateaux surfaces (approximately 2 to 3 m per hundred thousand years in the sector) for the various glacial cycles, which can be extrapolated into the future. Erosion will gradually lead to the disappearance of the Barrois limestones, meaning the Kimmeridgian formation outcropping, or even the Oxfordian formation one, at the laboratory site



Sector morphology evolution from today until 1 M years

This possible evolution over the next million years has been modelled in 3-D and served as the basis for modelling foreseeable water flows over the next 500 000 and million years. Only flow directions in the Oxfordian formation show any notable change with the gradual disappearance of the flows towards the centre of the Paris basin, to the benefit of the Marne outlet in the south west of the sector (valley of the Saulx river) and the appearance of a new outlet in the valley of the Ornain river, ten kilometres or so to the north of the Meuse/Haute-Marne laboratory site.

RFS III.2.f. ***The geological barrier: technical criteria for site selection.***

"The site shall be selected so that the depth envisaged for the repository guarantees that the geological barrier confinement performance shall not be significantly affected by erosion phenomena (particularly after a glaciation), by the effects of an earthquake, or by the consequences of a common intrusion. It should be considered that the thickness of the superficial zone liable to be affected in this way is in the order of 150 to 200 metres."
These criteria concern both site stability and its hydrogeology.

- **Stability**

Site stability should be such that any changes to the initial conditions due to the geological phenomena that may occur (glaciation, earthquakes, neo-tectonic movements) remain acceptable with respect to repository safety.
In particular, for a period of at least 10 000 years, stability (which includes a limited and predictable evolution) must be demonstrated.
These phenomena must be assessed for each investigated site, both qualitatively and quantitatively, by reference to the present situation, to the recent past (historical) and, above all , to the more ancient one (Quaternary and, where necessary, end of the Tertiary period). This will enable an assessment of the parameters characterising them and their variations, and to examine their influence [...].

- **Hydrogeology**

Site hydrogeology should be characterised by a very low permeability of the host formation and a low hydraulic head gradient. A low regional hydraulic head gradient shall also preferable for the formations surrounding the host formation.
Hydro-geological measurements should be carried out over a much wider zone than the repository site in order to build flow models taking into consideration flows from the source zones to the outlets. These regional configurations should allow simulating the intensity and direction of groundwater circulations.
Account should be taken of discontinuities or heterogeneities whose nature and geometry may tend to significantly reduce the geological barrier efficiency. These objects should therefore be identified and characterised with the greatest care, in order to, where applicable, avoid them at the site.

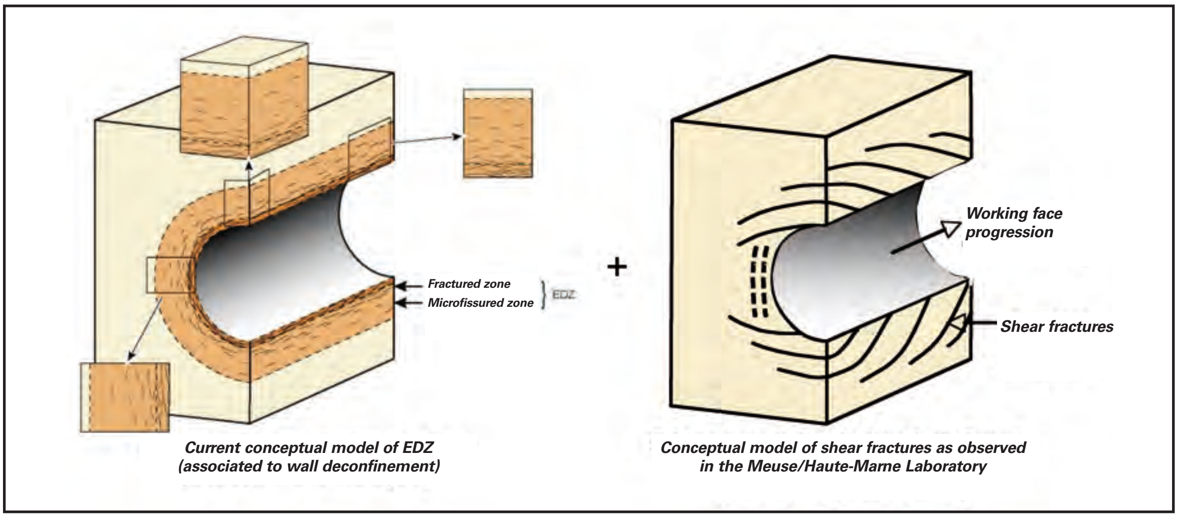
3.4 The impact of the construction and operation of a repository on the host formation

The construction and operation of a repository create stresses (thermal, mechanical, geo-chemical and hydraulic) in the host formation near-field. The research programme aims to provide the data required to assess the consequences of disturbances on the host formation and its confinement performance.

3.4.1 – Impact of the creation of the underground structures

3.4.1.1 Mechanical disturbance and damage to the zone around the structures (EDZ)

The excavation of underground structures disturbs the surrounding rock, creating a damaged zone (EDZ) likely to form a future preferential pathway for water. Micro-fissuring is observed depending on the rock strength and the structures depth. Fractures may as well form ahead of the excavation work face (zone submitted to shear stresses) and in a ring at the structure wall (deconfinement-induced fracturing zone). These phenomena are observed around structures installed in similar formations. They have been studied in several countries for ten years by research teams working on argillite samples and in Mol and Mont Terri underground laboratories. They have also been subject to detailed investigation in the Meuse/Haute-Marne Laboratory in the drift at -445 m and the drifts at -490 m.



EDZ conceptual representation

During the tests carried out on the argillites, is observed from a particular load threshold (11-13 MPa in uniaxial compression) a firstly diffused micro-fissuring followed by an increasingly organised one as the load increases (described as mechanical damage). When the rupture point is reached (of fragile type when the mean stress is low), it leads to the creation of fractures.

Prior to the excavation of the Meuse/Haute Marne Laboratory drifts, 2D models concluded that a zone fractured by deconfinement could appear in the deepest zones of the argillite formation within the transposition zone (-630 m), where the strongest natural stresses occur. Its extent is governed by the structure orientation: less than 0.1 times the structure radius when structure orientation is parallel to the major principal geo-mechanical stress, less than 0.3 times the structure radius when parallel to the minor stress. Maximum permeability remains very low (estimated at 5.10^{-9} m/s). At a shallower depth (around 500 m such as directly below the Underground Laboratory), there may be no fractured zone if the structure orientation is parallel to the major stress or less than 0.1 times the structure radius when orientation is parallel to the minor stress.

A microfissured zone develops beyond the fractured zone according to these models. It may extend several metres for structures with a diameter of tens of metres (0.5-0.7 times the radius for orientation parallel to the major stress depending on the depth) but very low permeability prevails (estimated at 5.10^{-11} m/s) because of the limited connectivity of the microfissure network.

EDZ around the structures

Excavating structures may lead to the creation of a damaged zone (EDZ) that may take several forms at the excavation wall. Thus the same distinctions are made as in the Mont Terri underground laboratory (see figure hereafter):

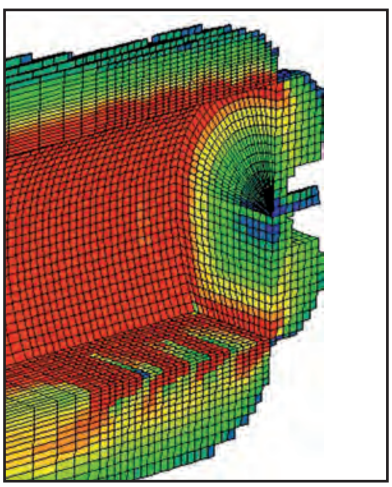
- *a deconfinement-induced fractured zone* in the immediate vicinity of the structure. It is produced if the rupture threshold, that is the maximum mechanical strength of the rock, is exceeded; it is characterised by the appearance of more or less connected fractures parallel to the drift axis and that may increase rock permeability;

- *a microfissured zone*. It forms when the fissuring threshold is exceeded, either immediately at the structure wall (if the fractured zone has not yet developed), or behind the fractured zone. It results from mechanical unloading caused by excavation of the structures: the induced deformations take the form of diffuse, poorly connected micro-fissuring. This low connectivity limits the increase in permeability.

It can also be produced by the side effects of the excavation work progress. In that case, shear fractures oblique to the drift axis may appear ahead of the excavation work face. As they are intercepted by the drift as excavating work is progressing, only the ends remain at the wall, forming a network in "chevrons" (see figure above), which is similar in extent to the microfissured zone. Beyond the microfissured zone there is a zone said to be mechanically "influenced" where may occur limited modifications of the stress and deformations field, with no impact on the properties of the rock (particularly its permeability).

At level -490 m (the level with the highest clay content), the observations and measurements made during experimental drift excavations have been compared with the modelling results, taking in account the difference in the drift shape (horseshoe section) and disturbances due to the use of a hydraulic rock breaker.

- shear fractures are observed ahead of the excavation work face and extend to a maximum 2.5 m away from the wall. The formation of these fractures is accurately reproduced by 3D digital simulations of drift excavation work, making allowance for the excavation work face and its progress. Once beyond 0.2-0.5 times the drift radius, the permeability to water of these shear fractures is less than 10^{-12} m/s. It is 10^{-8} to 10^{-11} m/s close to the wall.
- in the deconfinement-induced fractured zone, the permeability values measured are less than 10^{-8} m/s, some of them approaching 10^{-10} m/s. These measurements are in line with the estimated permeability value for fractured argillites (5.10^{-9} m/s). The maximum extent of the fractured zone around the laboratory drifts when related to radius, is about 0.2 times their radius, that is the same magnitude as given by the 2D simulations (0.1 radius);
- beyond the fractured zone, the permeability to water measurements give values of less than 10^{-12} m/s, namely less than those attributed to microfissured argillites. Therefore they indicate limited or nil micro-fissuring, and very low permeability of any intercepted shear fractures. This is consistent with the fact that the high mechanical stresses applied to the shear fractures limit significantly the increase in permeability.



3D modelling of shear fractures at drift wall

Mark of shear fractures

These observations on EDZ permeability are consistent with those made on argillite samples and in the Mont Terri laboratory. Additionally the latter suggest that EDZ permeability tends to diminish during geomechanical evolution through creep and argillite swelling that gradually close the fractures. Thus in the very long term, EDZ properties tend to match those of undisturbed argillite because the fractures close up through the effect of the stresses returning to equilibrium.

The conditions of shear fractures occurrence and their geometry seem to be governed by the excavation conditions (rate and regularity of excavation work and of ground support emplacement at the wall, ground support at the excavation work face). The layout of the first experimental drifts at level -490 m has also revealed mechanical interactions between structures in relation to their spacing.

To be on the safe side, Andra has designed a system (hydraulic cut-off through a groove backfilled with swelling clay), to intercept the fractured formation ring at the seal level and to limit flow along drifts. This system is the subject of the "KEY" experiment previously mentioned.

In the more carbonated upper levels of the Callovo-Oxfordian (stronger and a little shallower than the mean level of the formation with the highest clay content), the observations and measurements made in the Underground Research Laboratory shafts and in the drift at -445 m show that no fractures are created. The thickness of the microfissured zone is around 0.1-0.2 times the structure radius. These characteristics are favourable because repository shafts would be sealed at this very level.

3.4.1.2 Desaturation

The operation of a possible repository will require drift ventilation: the relative humidity and temperature of this constant airflow being different from those in the medium, pore water in the Callovo-Oxfordian argillites will be drawn towards the external wall of the drifts and evaporate on contact with it, air gradually replacing water in the argillite adjacent to the structures (desaturation). Observations in old structures, for example in the Tournemire tunnel built a century ago, show, however, that this phenomenon of desaturation of argillites is a slow one.

Tests on samples provided an estimation of the desaturation velocity and its consequences on the mechanical behaviour of the Callovo-Oxfordian argillites. In particular, they indicate that:

- desaturation rigidifies the argillite, which boosts its mechanical strength. The increase in uniaxial compression strength linked to low relative humidity is about 0.45 MPa per degree of humidity. However, if there is significant desaturation, it may also lead to diffuse micro-fissuring. This heals with resaturation;
- the extent of the desaturated zone around the structures does not exceed the extent of the damaged zone and mainly affects the fractured zone because of its higher permeability than the microfissured or sound argillites one (note that desaturation could locally penetrate the shear fractures, but this penetration would be limited as these fractures permeability is very low). The extent of the desaturation stabilises fairly rapidly and only develops negligibly after a decade or so.

In-situ measurements in the underground laboratory should confirm these data ("the Interdisciplinary Observatory on the EDZ") in order to establish the long-term desaturation velocity of the argillite and observe its effects on the mechanical behaviour at different relative humidity levels.

3.4.1.3 Oxidation-reduction reactions

The penetration of air introduces oxygen into the argillite to a depth which corresponds at its most to the extension of the desaturated zone. The argillite contains minerals, such as pyrites, and organic matter which react with the oxygen (oxidation-reduction reactions) and consume it. The ratio between the volume of oxygen entering the argillites and the consumed one is such that oxygen is neutralised. The chemical characteristics of the argillites are not modified and the effects and extension of this chemical disturbance are very limited.

3.4.2 Impact of exogenic materials (cement, concretes, metal etc.)

3.4.2.1 Cementing materials (concretes and mortars)

They are liable to be widely used in a repository, particularly for lining underground structures. In contact with the natural medium fluids, they deteriorate very slowly (over several tens of thousands of years) and release elements such as silicon and, above all, calcium (the "alkaline plume") which can modify the confinement properties of the geological medium and swelling clay based structures through mineralogical changes.

The European Ecoclay project (17 bodies from 8 European countries) studied the phenomena and consequences associated with the propagation of this alkaline plume in the clay structures (cell plug, seals) and in the Meuse/Haute-Marne site argillite. It concluded that *there is a small extension of the alkaline disturbance in the geological medium and limited effects on the transfer properties of the argillites (diffusion velocity and permeability) and on the swelling capacity of the engineered barrier clay*. The limitation of the effects of the alkaline plume is due to the clay strong "buffer power". This disturbance can be further reduced by using so-called "low pH" cement. The digital simulation of the alkaline plume in a repository situation using models established during this work results in a limited disturbance which never exceeds the extension of the microfissured zone and does not induce any changes in the hydraulic properties.

The results of the experiments in the Meuse/Haute-Marne laboratory will substantiate the models produced in "surface" laboratory. Samples of cement-based materials are emplaced in the Callovo-Oxfordian argillites and experiments carried out to validate the reaction processes.

3.4.2.2 Metallic materials

The corrosion processes of metallic materials in a repository situation, widely expected to occur in the underground installations (disposal cell ground support, over-pack, etc.), have given rise to numerous studies, particularly into archaeological analogues. *They have thus determined the corrosion inception threshold and its rate in a deep clay-based medium. They have shown that, in the absence of oxygen, which will be the case in the repository post-closure phase, metallic materials corrode, producing minerals which stabilise their deterioration.*

The corrosion of metallic materials releases iron ions which can react with the clay-based minerals and change their composition. Experiments aimed at characterising this alteration have shown that the mineralogical transformations are limited in intensity and in their extent; they remain in the order of a few centimetres.

The corrosion of metallic materials also leads to the production of hydrogen in gaseous form, which interaction with the argillites must be taken into consideration. As indicated above, an experiment (carried out in borehole EST363) enabled to measure the gas inlet pressure in damaged zones (2 to 3 MPa) and in sound argillites (4 to 5 MPa), that is the gas pressure necessary to overcome the capillary phenomenon confining the water in the rock porosity. Experiments on samples have also provided biphasic flow parameters (water and gas).

3.4.3 Thermal impact of waste packages

Certain waste packages contain elements that release their energy in the form of heat: it is therefore important to study any thermal impact on the host formation.

Experiments conducted on samples have shown that the mineralogical transformations of the Callovo-Oxfordian argillites resulting from such a thermal phase are negligible as long as the temperatures reached are not too high and the thermal phase is not too long. In particular, they showed that applying a temperature of 70° C for a period of 10 000 years did not cause any major disturbance. Thus, the dimensioning criteria could be deduced: namely a temperature of below 100°C over several centuries and a return to a temperature of under 70°C before 1 000 years.

The influence of temperature on the hydro-mechanical behaviour of argillites was also studied in laboratory by varying the temperatures and the level of saturation of the samples. *Up to around 70°C, there is practically no visible effect* on the mechanical parameters (elasticity, plasticity threshold, creep velocity); beyond that, the most noticeable effect is an increase in the creep velocity.

4. Transposition of the laboratory results to a larger scale

The impact assessment of the construction and operation of a repository on the host formation, particularly of the disturbances that the various stresses (thermal, mechanical, geo-chemical, hydraulic and hydric) might induce, was conducted mainly on the Underground Laboratory site by means of experiments and sampling.

The many detailed data obtained on the Meuse/Haute-Marne Laboratory site (particularly boreholes and 3D seismic campaign on a 4 km2 area) and the geological knowledge of the sector under study enable an initial assessment of the ability of the Callovo-Oxfordian layer and its geological environment to eventually host a radioactive waste repository.

With this aim in mind, a transposition approach was developed, aiming at defining a geographical domain that can be considered as being geologically equivalent to the Underground Laboratory site, both from the viewpoint of the formation confinement properties and of the disturbance characteristics that a repository would generate.

4.1 Basic principles of the transposition approach

In order to define the transposition approach, the various characteristics of the Callovo-Oxfordian layer that contribute to its confinement capability, are taken into account. They must be considered at the whole layer scale, including its geometry (thickness) and the factors that might adversely affect its homogeneity (sedimentary gaps, transmissive faults).

At this scale, the geometric factors that would be liable to modify its behaviour with respect to an eventual repository must be taken into account as it is the case with depth, which influences the mechanical behaviour.

The confinement capabilities must also be studied at the level of the detailed configuration of the layer components that govern transport and retention properties.

At overall formation level, it is first and foremost the layer homogeneity, both in terms of the vertical distribution of the levels and their lateral continuity, which must be examined. Faults are liable to interrupt the continuity of the sedimentary layers or modify their "large scale" properties, essentially permeability. The transposition zone extension must therefore exclude the identified faults. Must also be taken into consideration: abrupt thickness variations, since potentially associated with faults, and absence of significant correlation between identified levels, since it may correspond to major sedimentation gaps.

The thickness of the layer in the transposition zone must also be greater than or equal to that observed on the Laboratory site (the greater the thickness, the better the confinement capability) and its depth must not exceed a limit beyond which the geo-mechanical strength criteria could not be met.

At the level of the minerals and their layout in the rock, the confinement properties of the Callovo-Oxfordian argillites are the result, as for any other material:

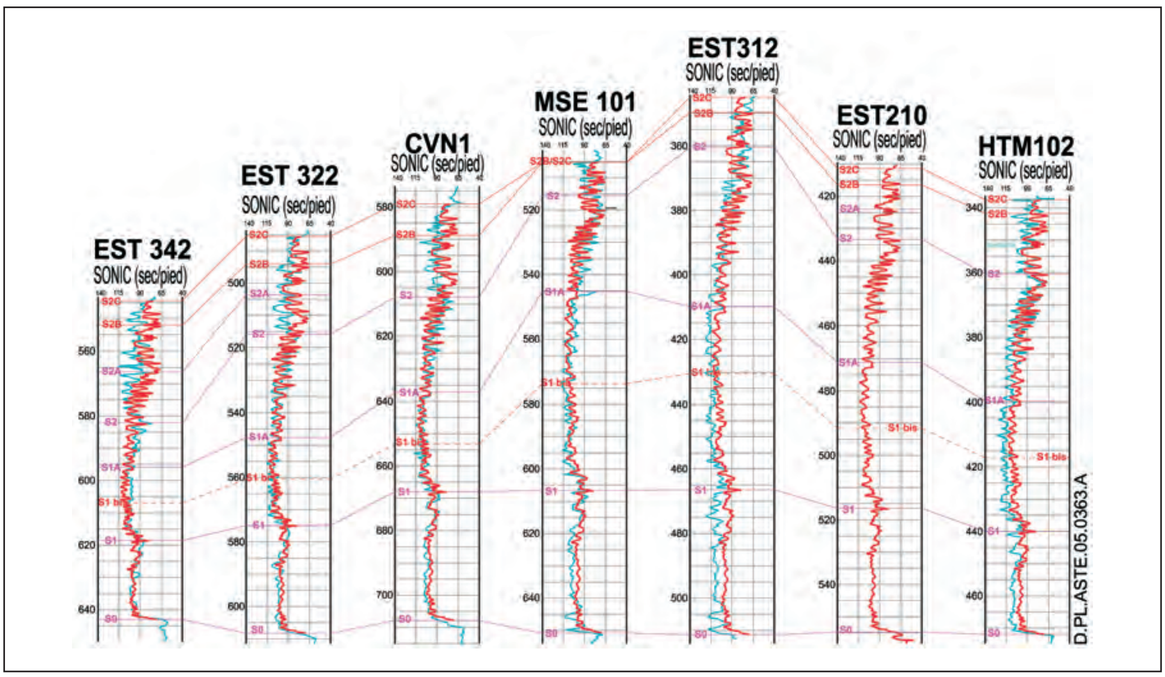
- firstly of the intrinsic properties of the various constituents and, thus, of their relative proportions and distribution within the rock (for example the thermal conductivity of the argillite depends on the proportion of the quartz and calcite grains, which are good heat conductors, but also on the way in which they were deposited during the formation of the rock and, thus, on their layout within the rock),

- secondly, of the rock pore geometry, which impacts on the possibility of water circulation or migration of chemical elements in solution in the water. This geometry is due to the layout of the minerals which constitute the rock at sedimentation time and to the diagenetic processes occurring during their later geological history, particularly clogging phenomena. Therefore must be investigated what, in terms of deposition and diagenesis conditions, might vary the spatial geometry of the rock pores (distribution of minerals, deposition configuration, change in clogging nature or intensity, etc.).

Defining a geographical area which is geologically equivalent to the Underground Laboratory site therefore boils down to understanding the environmental conditions that have governed the nature of the minerals that *constitute the Callovo-Oxfordian formation, their layout and the geometry of the porosity at all scales. The 2D seismic profiles and oil and gas exploration drilling campaign, to the boreholes drilled between 1994 and 1996, to the 2003 drilling campaign (FSP) and surface mapping operations, provided a detailed exploration around the underground laboratory of a geographical zone covering approximately 700 km2. The geological studies carried out since 1994 thus allowed to determine the zones in which these conditions can lead to situations noticeably different from those in the Meuse/Haute-Marne underground laboratory.*

4.2 Current transposition possibilities

Geological surveys have established detailed mapping of faults. Apart from the major tectonic structures (Marne faults, Gondrecourt graben,...) bordering the investigated zone, no major vertical displacement fault has been found in the Callovo-Oxfordian formation, nor in the overlying Oxfordian horizons, nor in the upper part of the underlying Dogger in the northern half of the investigated zone (700 km2). The transposition zone thus excludes the areas around the major known accidental features to the east and west of the sector.



Comparison in between EST 210 logs (drilled on the URL site) and other ones recorded in the sector, showing good correlation of various Callovo-Oxfordian sequences. (Sonic travel time in micro-second/foot).

As far as the thickness of the formation is concerned, accurate mapping of the Callovo-Oxfordian formation clearly defines the upper and lower limits, which are easy to identify from the seismic data. The various boreholes have confirmed this mapping:

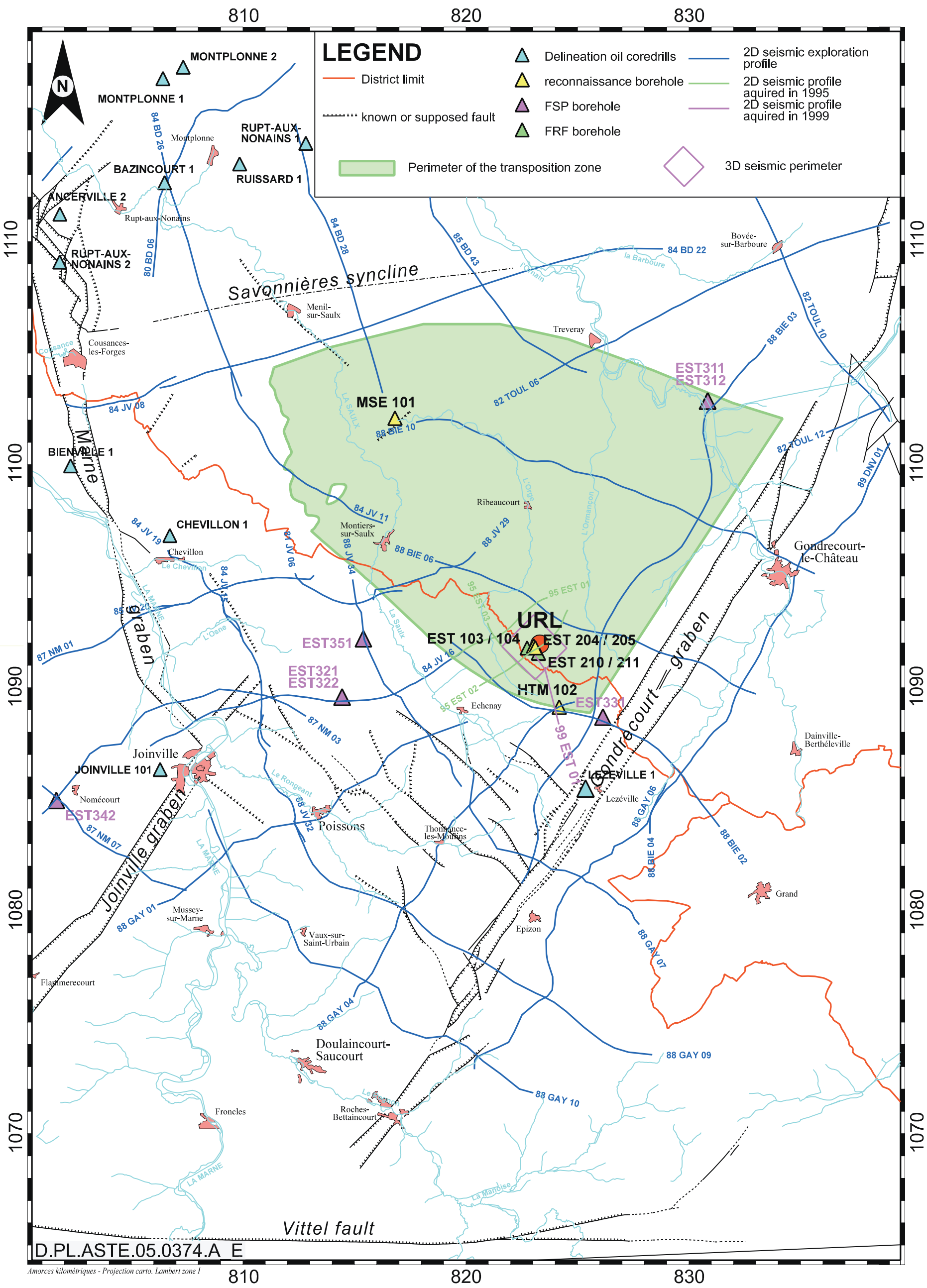
- starting from the underground laboratory site, the thickness of the Callovo-Oxfordian formation increases as one moves towards the northeast of the sector studied, due to the argillite deposition conditions, therefore enhancing the confinement capability,
- the median depth of the formation (490 m in the Underground Laboratory) reduces slightly in a small area to the east and south of the Laboratory (the mechanical disturbances should be there lower) and increases in the remainder of the geographical zone investigated, but with no change of mechanical disturbance type, as long as the depth remains less than 630 m, value that has been adopted as being the one that guarantees a mechanical behaviour similar to the underground laboratory site one (this depth is reached in the northwest corner of the sector, roughly bordered to the south by the Val d'Osne and to the east by the Saulx river valley).

As far as the mineralogy is concerned, and consistently with the Underground Laboratory boreholes, the logs recorded in the boreholes located in the investigated zone, have identified the same three sedimentation sequences in the formation, which confirms that the Underground Laboratory is representative of a large geographical zone. They also show that the various levels of the Callovo-Oxfordian formation are correlated over large distances (several tens of kilometres) and that their layout is not disturbed by facies variations or sedimentation gaps liable to modify their hydraulic properties.

The deposition and diagenesis conditions having been relatively uniform, the arrangement of the minerals varies little, which means a relatively constant porosity geometry (and, thus, constant permeability and diffusion velocity) over the major part of the sector studied.

In summary, all the results of these studies combine to delineate a geographical area, geologically equivalent to the Underground Laboratory site, of approximately 200 km² to the north and west of the Underground Laboratory.

Localisation of the transposition zone (Meuse/Haute-Marne site) with position of the various Andra boreholes



Dossier 2005 Argile

The repository and its installations

4

The repository and its installations

1. The design approach

The studies conducted by ANDRA aimed at designing a safe repository and assessing the feasibility of operating it in the Callovo-Oxfordian argillites of the Meuse/Haute-Marne site, with a reversibility rationale.

In order to assess the concrete solutions taking in account the waste characteristics and the geological formation studied, ANDRA adopted technical design options and studied them from the point of view of their engineering, their behaviour over the various timescales and their safety. The results of the studies, supplemented by industrial experience feedback from similar installations, enable to check the possibility of designing, building and operating a safe, reversible disposal facility.

• From preliminary concepts to concrete solutions

The preliminary design of a repository installation consists of:

- *defining an overall repository architecture* and its lay-out within the geological medium whose confinement qualities must be preserved,
- *selecting the design options*: i.e. identifying the components of the repository and their roles, and the operating principles,
- *defining the technical specifications* for dimensioning and the components (materials, drawings),
- *defining the processes involved in manufacturing or building and operating these components*,
- *integrating these processes into an industrial organisation* for building, operating and, eventually, closing the repository.

The research carried out is aimed at proposing simple, robust, non-optimised options, designed to assess the feasibility of a repository. The selected architectures only represent one possible solution among others, liable to change.

• Until 2001, ANDRA studied various architectures, so-called "preliminary concepts": exploring a fairly vast range of options for dealing with the various technical issues and solutions, associated with their feasibility, safety and reversibility. Several types of disposal structures geometry, materials, operating procedures and handling options were studied.

• In 2002, based on the lessons learned from these studies, ANDRA adopted a limited number of concepts which formed the basis of the studies carried out until 2005 and allowed a more in-depth analysis to be conducted of the disposal facility design, its safety and its reversibility. These concepts aim to identify concrete, justified solutions, in order to have a design available for each type of waste package so that the feasibility of their disposal in the Callovo-Oxfordian argillite of the Meuse/Haute-Marne site can be assessed.

The repository is designed around a modular, flexible architecture consisting of basic bricks, or repository modules, able to receive groups of packages with similar characteristics. The choices made in 2002 concern the design options of these modules, more particularly:

- the design of the disposal packages: the primary packages, delivered by the producers, may be supplemented by additional devices (over-packs) to form disposal packages. Their dimensions and materials have been studied in association with possible manufacturing technologies, their performance and handling procedures,
- *the underground cavities or "disposal cells"* in which the waste packages are emplaced: geometry and dimension, possible construction procedures, package emplacement principles and disposal cell closing principles, if the choice is made after a period of observation.

Flexible architectures

The repository architectures have been studied in order to take in account various categories of packages (type B and C waste and, if necessary, spent fuel). The solutions proposed are flexible enough to be able to tolerate changes to the inventory and waste package management procedures. In particular, each family of packages can be accommodated, irrespective of the fact that other families may or may not be present in the repository. This search for flexibility leads to contemplating a distribution of package categories (B, C, spent fuel) into separate zones and a gradual construction of the repository installations in modular form (modularity).

- **Options demonstrating technically feasibility, but not engraving forever repository architecture and design.**

Engineering studies have led to design the various components, then to check their industrial feasibility (construction, operation, operational safety etc.). The main points of the design have been studied based as far as possible on existing industrial experience feedback in the nuclear, mining and civil engineering fields. The options proposed, which are described hereafter, do not freeze the repository architecture. At this stage, they represent a technical vision of what a repository installation may look like, but which is likely to evolve; indeed major work remains to be performed concerning the project industrial development, in order to carry out more detailed engineering studies into such a repository.

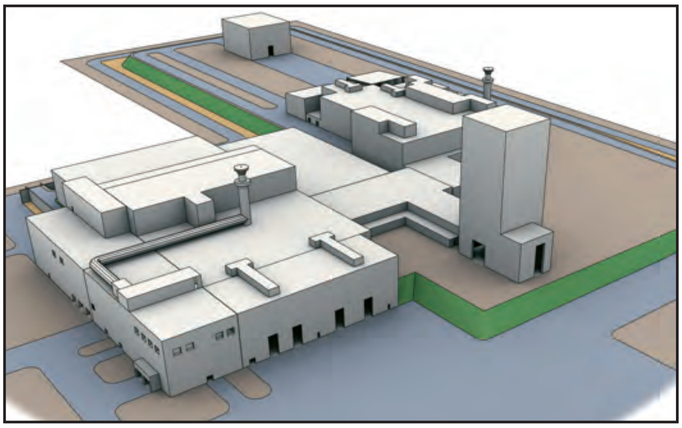
Estimated cost of a repository

Repository cost assessments have been carried out in line with design studies. At the feasibility study phase, such assessments are, of course, subject to uncertainties, as some identified risks can increase costs and design optimisation can lead to savings.
The assessments conducted by Andra are based on the expertise of major engineering firms and companies in the nuclear, building and mining sectors, industrial operating feedback from the only geological waste repository currently in service (the Waste Isolation Pilot Plant (WIPP) located at a depth of 600 m in New Mexico, USA) and current tax and insurance practices.
The repository cost given (approx. €15 billion) corresponds to scenario with all spent fuel (UOX and MOX) reprocessed. This scenario does not claim to freeze any industrial strategy for managing the cycle back-end. The cost of the repository could therefore change according to the hypotheses adopted in a future strategy.
The cost of the repository depends on three key items:
- investment costs (37%), which cover the construction of surface installations, construction and closure of underground installations, and over-packing for transforming primary packages into disposal packages.
- operating costs (40%), which include labour costs, equipment maintenance and replacement (renewal), and energy and consumables for a century-long operating period.
- miscellaneous costs (23%), which mainly cover taxes, insurance and design costs.

2. Overall installation configuration

A repository installation would include surface installations, structures connecting the surface to the underground structures and the underground structures themselves. These various installations allow the repository to be built gradually, waste packages to be received at the surface, their transfer and emplacement underground, their observation and monitoring and the closure of the various structures when so decided within the context of a reversible management of the disposal process.

2.1 General description of surface installations



Surface installations (project)

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Surface installations include the buildings for receiving the primary packages, the workshops for preparing the disposal packages, and buffer storage areas for regulating the throughputs of the industrial processes. The spoil from the excavation of the underground installations is stored on a spoil dump; it will be used later as back-fill material.

2.2 General description of the structures connecting the surface to the underground installations

In order to connect the surface to the underground installations, the design studies have led to propose *four shafts, each one with a specific function*: a waste package transfer shaft, a personnel transfer shaft, a service shaft (spoil and large equipment) and a ventilation shaft for renewing the air. These conventional diameters (6 to 12 m) shafts are fitted with current devices that have proved reliable in the mining industry. In line with the dead-end architecture concept, they are grouped together within a single zone and located upstream hydraulically of the repository zones. Seals are built in the shafts, when closure is decided, to prevent water circulation.

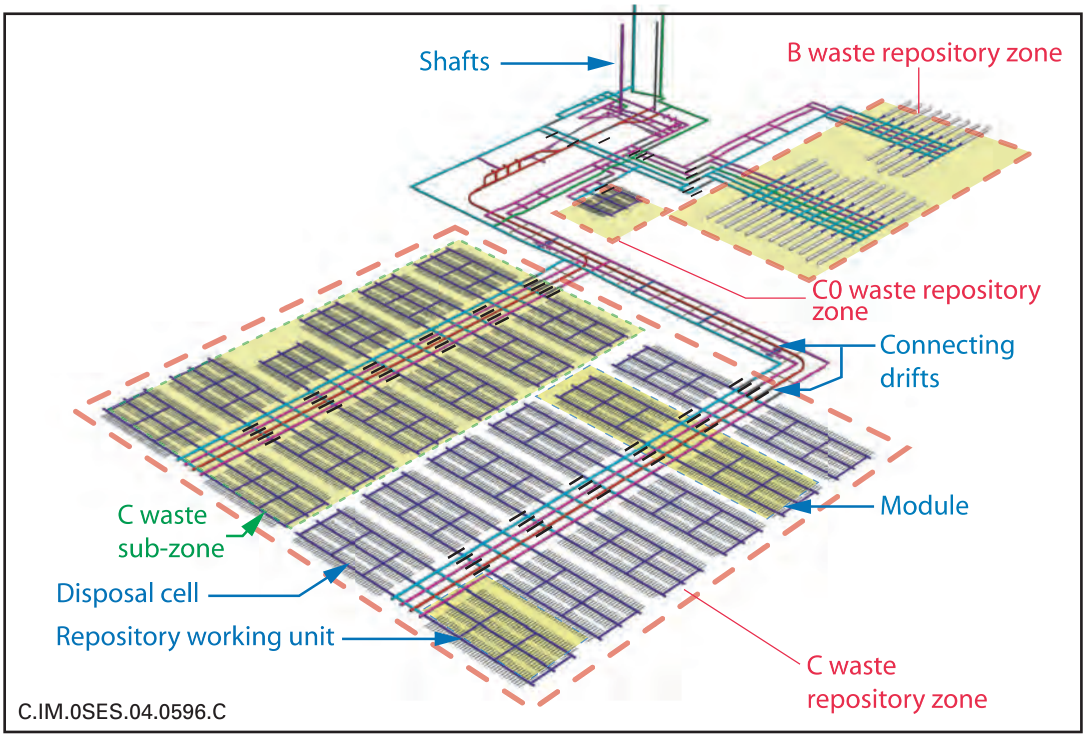
At this stage, the option of a ramp (helical inclined drift used in mines for underground access) has not been selected, but means an interesting variant in terms of flexibility.

2.3 General description of the underground installations

2.3.1 General organisation

• **The architecture** proposed for the underground installations is horizontal with little vertical extension. In order to maximise the thickness of the argillites located above and below the repository, the structures are placed in the middle of the formation on a single level.

• **The repository zones** are separated from each other according to waste type and the repository is divided into sub-assemblies: the various categories of package (B, C and, where applicable, spent fuel CU) are emplaced in separate zones, subdivided into modules and disposal cells which receive the packages. In zone B, a module corresponds to a single disposal cell; in zones C (and CU), it groups together from one to several hundred cells. The modules are constructed and filled progressively to meet the disposal requirements. Several modules may be under construction or operation simultaneously within the same zone.



General lay-out of the repository

Each sub-assembly is built according to a dead-end architecture and can be isolated from the other ones by seals. These arrangements limit interactions between repository zones and strengthen the system robustness. This compartmentalisation also simplifies the understanding and modelling of the behaviour of the repository. Finally, the modular architecture contributes to achieve the objective of repository management and development flexibility, providing the possibility to act while constructing the repository and allowing for possible design evolution.

• **Specialised access drifts** connect shafts to repository zones. They are used to transfer packages, materials for construction, sealing and back-filling and to ventilate. This contributes to the sound management of the coexistence of construction activities (disposal cell excavation), nuclear operations (package emplacement) and ventilation.

• **Disposal cells, drifts and shafts** are fitted, when it is decided to close them, with seals consisting of slightly permeable swelling clay plugs which prevent water from circulating inside the repository. Handling drifts, access drifts and shafts are then back-filled in order to achieve the entire repository mechanically stability.

Search for compactness of underground installations

The search for compactness is motivated by:

- a reduction of the excavated volume, limiting the operational cost and the volume of the spoil to be stored on surface,
- the optimum use of the underground footprint in the Callovo-Oxfordian formation,
- a simplification of the drift network, making operation easier.

2.3.2 B waste repository zone

The modularity of this zone means the separation of the different types of package and therefore provides an easy understanding of the overall system, particularly by considering independently waste packages with and without organic matter. The footprint will be in the order of one hundred hectares.
Type B cells are sub-horizontal tunnels, with a maximum length and diameter of 250 m and 12 m respectively, in which packages are stacked on several levels. A concrete lining provides the structure mechanical stability. Adopted for its durability, facilitating reversibility, concrete also means a chemical protection function for the packages and thus contributes to the retention of radionuclides.
When disposal cell closure is decided, the very limited clearances between the package and the disposal cell walls are not filled, in order to facilitate the closure operations and, if decided at a later date, possible package retrievability; the cell access drift head is sealed by a swelling clay plug. In the long term, each type B waste cell constitutes a compartment isolated from the others.

Type B waste disposal packages

Type B waste covers a wide range of primary packages with different packaging, geometries and radiological and chemical contents. In order to simplify the repository operation, primary packages are emplaced in parallelepiped concrete containers. The disposal package thus constituted can consist of 1 to 4 primary packages. Its weight can vary from 6 to 25 tonnes approximately and its dimensions between 1.20 m and 3 m.

2.3.3 C waste repository zone

The C waste package repository zone can also be separated into sub-zones: one for the disposal of old C waste (C0 waste) which would concerns 200 disposal cells, and two others for the disposal of type C waste currently produced or yet to be produced, each containing 6 modules of 400 cells, or a total of 4 800 cells. This zone footprint of approximately 500 hectares in the case of scenario S1a with re-processing of all the UOX and MOX spent fuels and package emplacement in the repository after 60 years of cooling for the concepts studied, is largely determined by thermal considerations, in particular, the duration of pre-disposal storage of primary packages; this footprint could thus be reduced by almost half, would the pre-disposal storage period be doubled.

C waste cells are dead-end horizontal tunnels, 0.7 m in diameter and 40 m long. They have a metal sleeve as ground support which enables packages to be emplaced in and, if necessary, retrieved out. They contain a single row of 6 to 20 disposal packages, depending on their thermal output. Packages with a moderate thermal output are lined up without spacer; otherwise, they are separated by spacing buffers (dummy package without waste, but providing a spacing in between packages to decrease heat output).

When it is decided to close the cell, it is sealed by a swelling clay plug.

Disposal packages for vitrified C waste

In order to prevent water from entering waste during the thermal phase, each primary package is placed in a watertight over-pack made of non-alloyed steel, which thickness (55 mm) is very cautiously dimensioned in order to withstand corrosion. Its lifetime is estimated at several thousand years. The standard disposal package weighs from 1.7 to 2 tonnes, is 1.60 to 1.25 m long and 0.6 to 0.65 m in diameter.

The disposal of spent fuel

The disposal of spent fuel (CU) was studied in case they are not re-processed.
Spent fuel from EDF reactors could be emplaced in a cylindrical steel envelope containing 1 or 4 assemblies depending on the fuel type. The thickness of this envelope (110 mm) provides water-tightness over at least 10 000 years. The design of the package prevents any criticality risk over the different timescales. The 4-assembly package weighs 43 tonnes, is 1.25 m in diameter and 5 m long; single-assembly package weighs 8 to 10 tonnes, is 0.6 m in diameter and 4.5 m long.
The design of CU disposal cells should be in principle similar to that of type C cells, also dependent on thermal dimensioning. They are dead-end horizontal tunnels (40 m long) containing a single row of packages spaced by buffers. However, unlike type C cells, a swelling clay engineered barrier is placed between the package and the geological formation. This barrier is fitted with an internal sleeve for inserting and, if necessary, retrieving the packages.

3. B waste packages and cells

3.1 The requirements

B waste primary packages represent over 80 % in number (approximately 200 000 primary packages) and more than 90 % in volume (approximately 80 000 m3 of primary packages) of HLLL waste.

They vary greatly in:

- their dimensions (diameter from 0.4 to 1.5 m, height from 0.7 to 1.7 m, weight from 0.3 to 7 tonnes), - their lifting and handling systems which are specific to each original installation (more than a dozen),
- the materials of their containers (carbon steel, stainless steel, concrete, fibrous concrete, reinforced concrete),
- their radiological contents: type B waste packages generally have a radiation level requiring personnel radiological protection.

Thus, the solutions studied for the design of disposal packages and cells aim to suit the operational management requirements whilst also meeting the long-term safety objectives.

3.1.1 Grouping primary packages in standard containers

B waste primary package handling requires a multiplicity of operational processes which is opposite to the search for a simple solution. It is therefore proposed to group the primary packages in standard disposal containers. This solution provides a reduction of the throughput handled and a standardisation of the operating equipment and underground structures; it therefore contributes to the simplicity and robustness of the reversible disposal operation.

3.1.2 Aiming at repository compactness

The volume represented by B waste packages requires compact solutions which limit the excavated rock volume and remain compatible with the control of rock damage (and of the temperature for some sligthly exothermic packages).

This objective for repository compactness leads to the absence of radiological protection into the containers: increasing the container size would limit the number of disposal packages per cell and would require more cells to be built.

3.1.3 Providing safety during the operational phase

In addition to the resources implemented to ensure operational safety in the repository, the disposal cells and waste packages must be designed and managed so as to:

• *protect personnel from package radiation and radioactive dissemination risk*. Due to the absence of a radiological protection function integrated into the disposal packages, their emplacement and, if necessary, retrieval and as well monitoring and maintenance operations, must therefore be remote-controlled. The disposal cell must be designed to meet and facilitate this requirement;

• *control gas (particularly hydrogen) liable to be produced by certain primary packages*. Certain primary packages produce hydrogen by radiolysis of materials (organic matter, embedding materials such as bitumen etc.). The excessive accumulation of hydrogen in the disposal container entails a risk of packages rupture. It must therefore be designed to allow the hydrogen to escape. Furthermore, particular attention is paid to controlling the risks associated with the presence of hydrogen in the air in disposal cells and drifts. Specific prevention, detection and protection measures are envisaged;

• *provide mechanical stability of the structures during their operation*. Although stiff, the Callovo-Oxfordian argillites are insufficiently strong mechanically for the excavations at a depth of 500 m to be self-supporting. By lining the structures, we can manage this risk during the operational phase and beyond, for ease of reversibility.

3.1.4 Providing long-term safety after repository closure

In order to fulfil the long term safety functions, disposal cell design and construction procedures aim at:

• *limiting the mechanical (microfissures and even fractures) and chemical disturbances induced by the repository in argillites in order to preserve the medium favourable properties*. The excavation procedure, the geometry and orientation of the disposal cells have been designed to limit mechanical disturbances due to excavation. The long-term control of these disturbances, after the rupture of the cell lining (after approximately a thousand years), is ensured by limiting the void space rate inside the cell (in and between the disposal packages) so that their eventual resorption does not create excessive distortion.
Andra has also assessed and checked the limited nature of chemical disturbances on the retention properties of argillites under the design and operating conditions envisaged,

• *controlling water circulation around and inside the modules and cells*. Controlling water circulation in disposal cells means slowing down the alteration kinetics of the waste packages; it requires that the radioactive nuclides migrate essentially through the geological barrier, in order to benefit from the favourable retention properties of the Callovo-Oxfordian argillites. For this purpose, disposal cell design must prevent water advection inside the cell. *Therefore, hydraulic insulation through a low permeability seal is provided in between the disposal cell and the connecting drifts;*

• *protecting waste, limiting radionuclide dissolution, protecting packages from physico-chemical attack in order to contribute to the radionuclide retention.*
The container and disposal cell can limit the release of radioactive nuclides contained in the waste, by controlling the possibility of chemical damage to the waste (for example corrosion) and to their embedding matrix (for example bitumen), and radionuclide solubility. The material adopted for the container and cell enable physico-chemical conditions to be imposed in the cell, particularly an alkaline pH of between 7 and 12.5, that favour the immobilisation of certain radionuclides.

3.1.5 Ensuring reversibility and fitting packages with the necessary robustness for retrievability

Disposal reversibility entails the following objectives:

- *the ability to retrieve disposal packages* using the resources used to place them in position,
- *disposal package durability*: Andra has decided to use a concrete formulation that favours the absence of chemical reactions liable to generate early damage,
- *structure durability* as from their design, to preserve a structure geometry with only slight distortion for as long as possible, in particular by *maintaining the operational clearances for retrieving* the packages using resources similar to those used to emplace them. The materials and preliminary dimensioning proposed by Andra for concrete structures in cells and access drifts meet this requirement,
- *modularity* consistent with progressive repository operation.

3.2 The B waste disposal container

The design of the disposal container, particularly its geometry, is linked to the disposal cell one, with the aim of achieving *repository compactness and simplicity of the operating processes.*

3.2.1 Description of the container

The concept proposed is a pre-fabricated and stackable container made of reinforced concrete with a slight fibre content, which contains from 1 to 4 primary packages and, at maximum 3 m wide - 3 m high, weighing less than 30 tonnes. The performance levels of its material and its mechanical design *provide durability over the century timescale required for reversibility.* The containers are dimensioned so that they can be stacked (up to 4 levels) and have sufficient mechanical strength to limit the consequences of a fall for the primary packages that they contain.

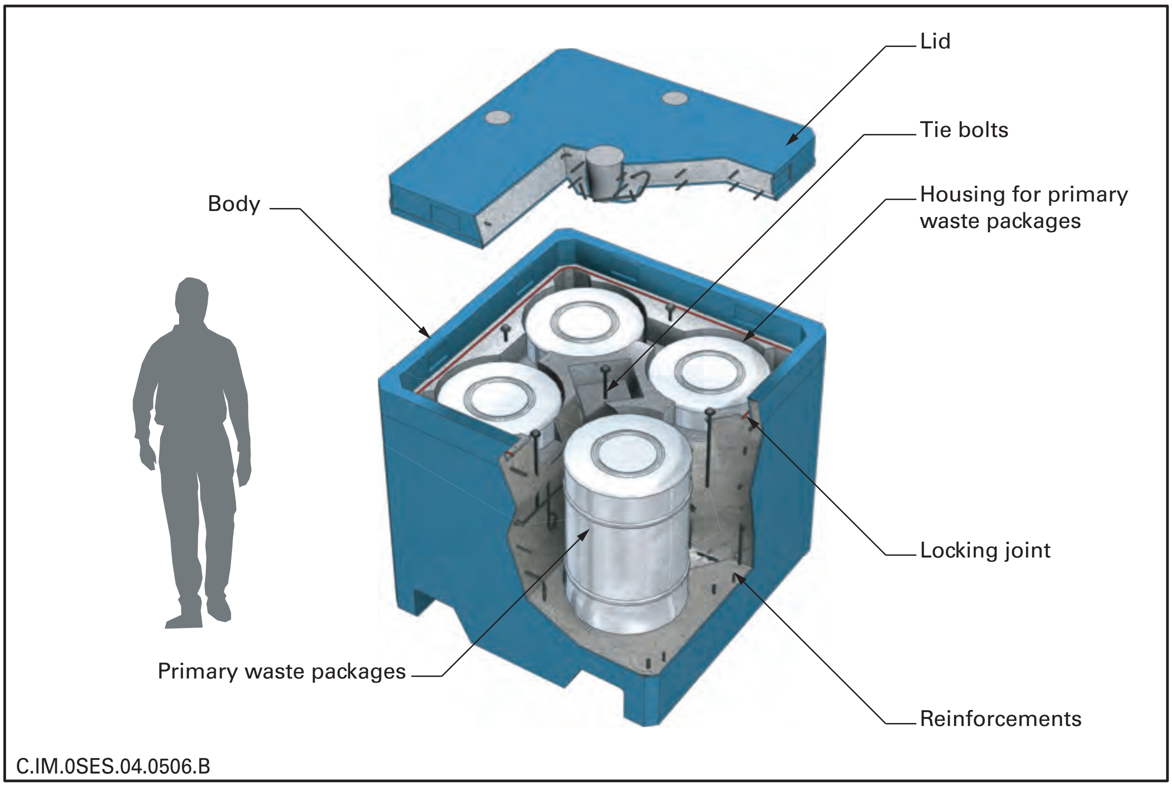
• **Its parallelepiped geometry** is the most suited to the cell dimensions and cavity, limits the void spaces to those required for package emplacement: *it thus optimises the compactness of the repository.* It also offers the ability to leave the residual spaces between the packages when closing the cell, which makes it easier to retrieve them in the context of reversibility.

• **The container** *is designed to evacuate the hydrogen* produced by certain primary packages.

• *Thanks to its intrinsic characteristics,* ***the concrete*** *provides the required durability over several centuries and creates a favourable physico-chemical environment* (for example, alkaline pH conditions limiting the corrosion of metallic components) which contributes to limiting the release of radionuclides into the geological medium. The search for mechanical strength (both compression and bending/tensile strength) and the ability to withstand dropping have led to the selection of high performance concrete (BHP 75 MPa). The fibres and reinforcements are made from stainless steel to provide corrosion resistance; they provide tensile/bending strength (around 5 MPa) and reduce the risks of microfissuration.

The type B waste container consists of two pre-fabricated parts.

- *The casing* integrates housings, adjusted to the size of the primary packages in order to limit the volume of the internal void space to the clearance required for inserting the primary packages. At the top there is an additional space, which leaves room for the handling claws. The container wall is 110 mm thick.
- *The lid* is a plate emplaced on the inside of the external side-walls and rests on the centre of the container. It is 150 mm thick. The container is closed by a cementitious material (locking joint) which provides cohesion between the lid and the container. In order to avoid the risk of tearing out in the event of the container falling, the lid is also secured to the casing by 5 threaded stainless steel tie bolts.



Standard disposal container (B2 reference package)

Dimensioning the container in case it falls in the cell

The container mechanical integrity in the event of a fall (height of 6 m) in the disposal cell is not a container dimensioning criterion: the aim is to check that the primary package remains intact and continues to confine the radioactive materials. During various stages of the transfer process, the disposal containers are lifted to a maximum height of 6 metres, for emplacement in the cell. The container drop modelling from such a height demonstrates that the disposal package withstands well and that the primary packages remain mechanically intact. These results have been validated by a number of full-scale drop tests.

3.2.2 Manufacturing the container

The container manufacturing principle consists of maximising the number of stages implemented in a non-radioactive environment in order to optimise costs and be able to carry out exhaustive manufacturing quality control. The casings and lids can thus be pre-fabricated in a factory, outside the nuclear context, using a moulding technique. The other operations would be carried out in shielded cells in the surface repository installations: loading the primary packages into the container, closing the disposal package (by locking concrete joint or cementitious material) and inspection of the package prior to transfer to the disposal cell.
The full scale demonstrators produced in 2004 showed the technical feasibility of the options proposed, and the good control of the processes used to produce items meeting the quality requirements (particularly the absence of fissuration). A test program in 2005 has confirmed the performance levels of the closure process and container behaviour when dropped.

Compatibility with the long-term pre-disposal storage options

The container design studies were conducted in liaison with the CEA in order to ensure that the studied objects are identical for both long-term storage and geological disposal. The concept proposed thus meets the requirements of long-term storage and those of geological disposal:

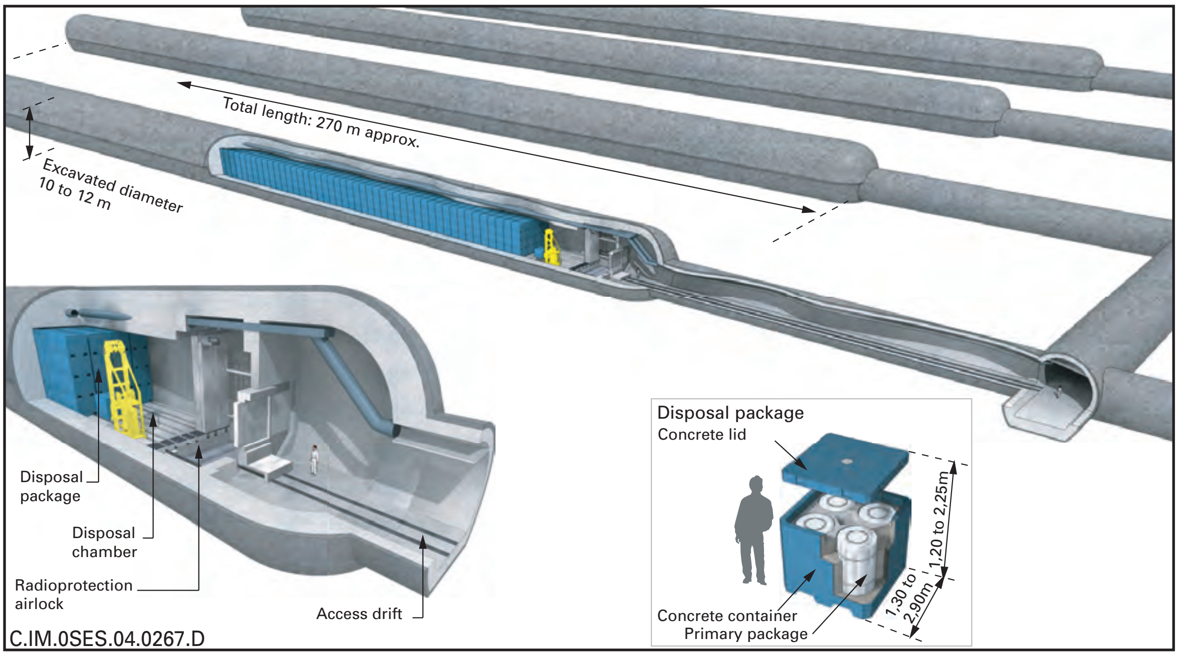
- *durability of the container over a several century period,*
- *ability to retrieve the primary packages* after a phase of long term storage,
- *diffusion, in the storage situation of the hydrogen* given off by the primary packages through the container lid, in order to give priority to the protection of the primary packages (de-saturated conditions provided by storage ventilation). In the repository situation, vents can be made at the top of the body so that the hydrogen migrates in the ventilated areas of the cell.
- *identical handling* facilities for both storage and disposal.

B waste disposal package demonstrator

3.3 The disposal cell

3.3.1 Description of the disposal cell

The disposal cell proposed by ANDRA is a dead-end horizontal tunnel with a useable length of 250 m and an excavated diameter of 12 m. Given that the highest terrain pressure (major principal geo-mechanical stress) is horizontal, the cell is aligned parallel to this stress in order to minimise damage to the rock during excavation. The nearly circular or horseshoe shape of the excavation adapts well to the various package dimensions and minimises excavation and concrete volume. Cell lining dimensioning is intended to guarantee the structure mechanical stability over a period of several centuries.



B waste disposal cell while in operation

The disposal cell for type B waste consists of:

- *a disposal chamber, the body*, irradiating, not accessible to personnel, rectangular in shape and 4 to 7 m wide depending on the packages size. The packages are positioned inside it on 3 or 4 levels and in 2 to 4 columns across the cell. For handling and ventilation, limited clearances (10 to 15 cm) are left between the top of the packages and the cell roof, as well as in between the package columns and between the packages and the cell walls;
- *a disposal cell head* (approximately 13 m long) fitted with an dual-gate airlock, to provide personnel radiological protection. The disposal package transfer cask is docked with the outer door of the airlock in which there is a remote-controlled lifting trolley which retrieves the package from the cask and conveys it into the disposal chamber.

The cell access drift is designed to receive a seal - consisting of a very low permeability (less than 10^{-11} m/s) swelling clay core and of concrete abutments - which closes the cell when it is decided. In order to improve sealing effectiveness, the drift useable diameter is reduced to 5 or 6 m, depending on the packages, and its ground support is designed so as to limit any mechanical disturbances.

The dimensioning and mechanical stability of B waste cells

The cell stability and the limitation of the ground mechanical disturbance are provided by various components that are effective over different timescales: the ground support providing safety of the cell at construction, the lining which provides the structure stability over a period of at least a century. This lining consists of a concrete ring and a filling, and forms a rectangular disposal chamber adjusted to the geometry of the stacked packages.

- **The ground support**, positioned gradually as the cell is excavated, consists of a mesh, short bolts and a 25 cm thick shotcrete layer.
- **The cell lining ring** only works under compression and does not have to be reinforced, which improves its durability. It consists of a 70 cm thick layer (at the level of the arch roof) of high performance concrete(BHP 60 MPa).
- **The filling concrete** which reduces the residual void spaces to less than 5% between packages whilst maintaining a functional clearance (ten centimetres or so) between the packages for a period of at least a century, for repository reversibility purposes.

Otherwise, the disposal cell stability has been checked with respect to earthquakes and this aspect is not dimensioning.

Limited chemical disturbances

• Materials

If the concrete (pH of around 12) contributes to the creation of a favourable physico-chemical environment for the long-term protection of disposal packages and metallic components in primary packages, it does, however, induce concrete/argillite interaction phenomena liable to degrade the latter retention properties. The extension of the chemical disturbances has been assessed as being limited to a few tens of centimetres. The introduction of large quantities of concrete therefore has no impact on the overall properties of the argillites located above and below the repository (thickness greater than 50 m)

• Ventilation

The flow of dry air in the cells induces a de-saturation of the lining concrete and of the rock of the cell walls, and encourages oxidation of the materials and argillites close to the lining wall. Studies show that this oxidation remains limited to a very small thickness of wall rock (around ten centimetres) and has no effect on the retention properties of the sound rock.

The addition of oxygen can also cause oxidation of metallic components present in the cell: this is however very limited due to the relatively dry state of the air.

Most B waste packages give of small quantities of hydrogen and traces of gaseous radionuclides. *Cell ventilation aims at reducing hydrogen accumulation* and limiting equipment and materials contamination by gaseous radioactive nuclides. *During operation and until closure, all B waste cells are permanently ventilated. The hydrogen release rates* are so low that stopping the ventilation for several weeks can be considered without risk.

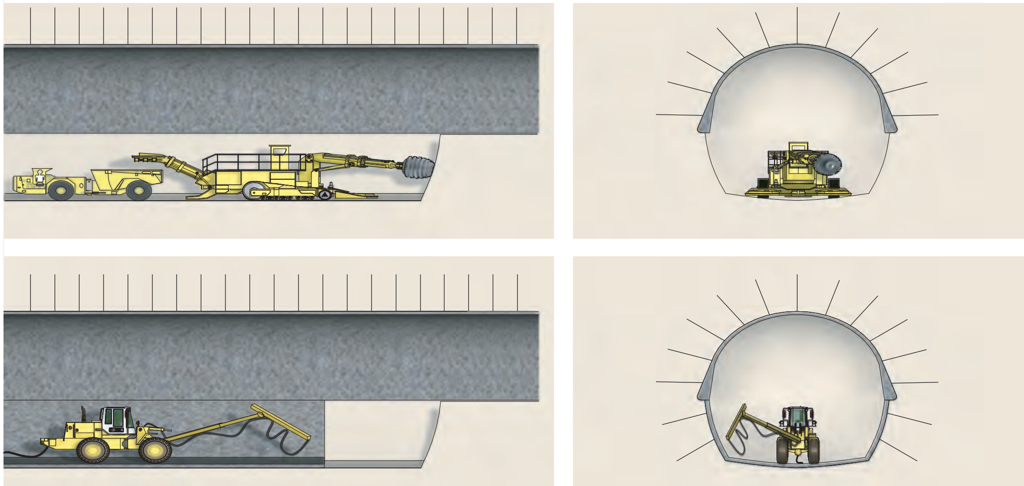
3.3.2 The construction of B waste cells

The construction procedure envisaged would be broken down into three successive phases.

• *Excavation of the cell body and entrance drift*, which can be carried out by a high-power road header. This method of excavation disturbs the rock very little and appears well suited to the characteristics of the argillites and the geometry of the cell. The cell section can be excavated in two passes: first the upper part, then the lower one; excavating the smaller diameter entrance drift would need a single pass.

• *The immediate fitting of the ground support which provides "on site" safety*. For the cell body, the support type studied is short bolting (bolts sealed using cement slurry) accompanied by shotcreting a reinforcing metallic mesh. Support by metallic arches, although possible, was not adopted at this stage as it introduces a larger quantity of steel.

• *Fitting of the lining which provides the structure stability over a period of several centuries*. For the cell body, the lining is concrete, poured *in situ*. The use of pre-cast concrete voussoirs has been rejected as they could lead to a large quantity of steel (reinforcements) and would be difficult to put in position with two excavation passes. The lining and filling concrete could, *in fine*, be poured using hinged metal shutters.



Excavating and lining a B waste disposal cell

Abroad

The concepts studied in other countries for disposing of type B waste or alike in sedimentary rocks are fairly similar. The primary packages are grouped into disposal packages, usually parallelepiped, and the cells are fairly large excavations (up to 10 or 15 m) depending on the mechanical behaviour of the host rock. The NAGRA concept is the most similar to Andra's one, due to the similarity of the host rock geotechnical characteristics. *The most noticeable difference between these foreign concepts and Andra's one lies in the decision to fill the void spaces between packages* within the cell (except for the WIPP concept, but the salt-bearing rock has different behavioural properties making it possible to fill these spaces in the medium term). In the case of the Andra concept, keeping these void spaces, while minimised at most by design, was adopted in order to ease the reversibility operation.

In Switzerland (NAGRA), the feasibility of an underground repository is studied in an argillite with similar mineralogical and mechanical properties to the Callovo-Ofordian one. The disposal packages are stacked on 2 or 3 levels in 9 m high, 7 m wide tunnels. Once the packages are emplaced, the residual void spaces are filled using a cement mortar. The cell is closed by a concrete plug and a clay seal is fitted at the entrance to the type B waste zone.

In Japan (JNC), the concept chosen for a generic sedimentary site is a circular tunnel with a useable diameter of 10 m with a 60 cm thick concrete lining (meaning an excavated section of 11.2 m). The primary packages are grouped together in disposal packages. For the more irradiating waste, an engineered barrier (1.2 m thick) made up of bentonite (swelling clay) and sand is placed between the packages and the lining. For waste with a low radioactivity level, there is no engineered barrier. The void spaces remaining in the cell are filled using a mortar or cement type material.

In Belgium (Ondraf), the concept (currently being revised) consists of stacking waste packages in drifts of 3 to 6m in diameter then filling the void spaces in between the waste drums, with concrete or a similar material. This concept is adapted, in particular, to the properties of the Boom host rock, more clayey and much more plastic than the Meuse/Haute-Marne argillites.

In the USA (US DOE), the Waste Isolation Pilot Plant (WIPP), operational repository installation dedicated to the transuranic military waste disposal, is constructed at a depth of 650 m in a salt-bearing formation. The type CH waste packages (Contact Handled or packages with a low level of radioactivity) are stacked in rectangular chambers (4 to 5 m high, 10 to 15 m wide). The void spaces are not filled.

In Germany (DBE), studies are underway in order to design a radioactive waste repository without heat release, in a marno-calcaire layer on the site of the former Konrad iron ore mine (Lower Saxony). The primary packages are grouped together in cylindrical or parallelepiped disposal packages, then stacked on 3 levels by a lifting trolley in existing chambers (widened and/or lengthened if necessary) or in new 7 m wide 6 m high chambers. They can be up to 1000 m long. After filling 50 m of cell, a concrete wall is erected to isolate this section, the void spaces in which are filled by a cement-based material.

Functions and principal components of B waste cells

Functions	Period	Concrete lining	Disposal cell Section	Seal in the access drift	Cell entrance dual-gate airlock
Transferring packages to their repository location	Operation		X		
Mechanically supporting the structures	Operation and observation	X	x		
Protecting personnel against radiation	Operation and observation				X
Enabling disposal packages retrieval	Operation and observation	X	X		
Preventing water circulation	Post-closure			X	
Limiting radioactive nuclides release and immobilizing them in the repository	Post-closure	X		x	
Delaying and reducing radioactive nuclides migration	Post-closure			x	
Limiting mechanical deformations in the Callovo-Oxfordian argillites	Post-closure	x	X		
Sub-dividing the repository[8]	Post-closure			X	

Légend : **X** essential component in performing a function
x contribution of a component to a function

3.3.3 Emplacement of B waste disposal packages in cell

The proposed design results in a four-stage process for emplacing the disposal package in its cell, which could be carried out semi-automatically under the control of an operator.

• *Docking the cask at the airlock and extracting the package*: after its transport in the drifts, the protective cask is docked at cell head level, thus providing radiological protection to the personnel present in the drift. After opening the airlock outer gate, the handling trolley moves forward to retrieve the package from the cask. Once the package has been retrieved, the airlock gates are closed and the empty cask can move away.

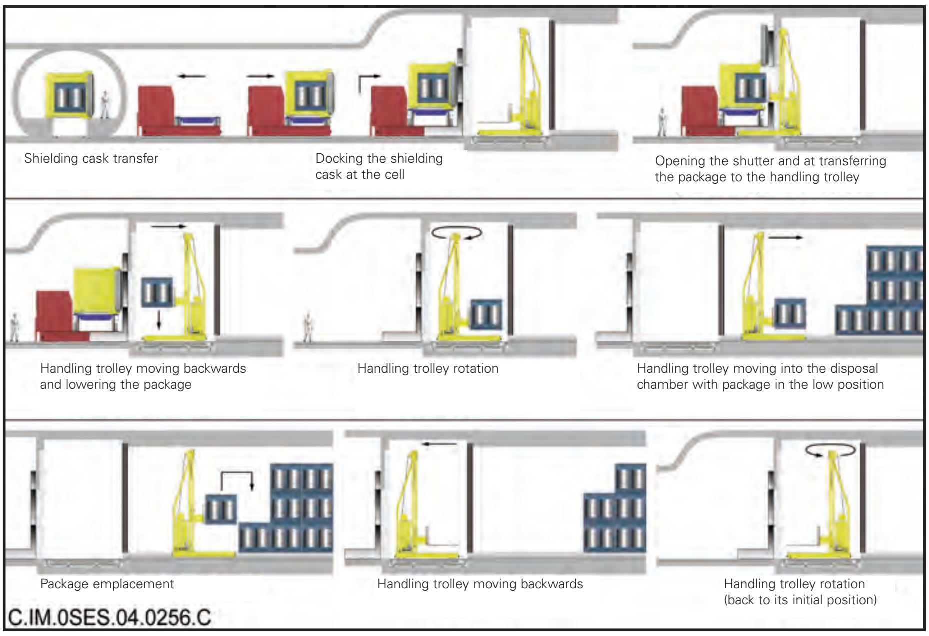
• *Rotation and orientation of the handling trolley*: the mobile platform in the airlock rotates the handling trolley loaded with the package through 180°, then shifts it laterally in order to place it in the axis of the required disposal row.

• *Transfer and placement of packages*: the inner gates of the airlock are opened to allow the handling trolley to pass through into the disposal chamber. The package is transported in the lower position to avoid any risk of fall and stabilise the trolley. Once in front of the packages already emplaced, the trolley stops, lifts the package to the height of its emplacement level and emplaces it.

[8] *Compartmentalising the repository is not stricto sensu a safety function, but an arrangement adopted with regards to safety functions.*

• *Return of handling trolley*: the trolley repositions itself using reverse gear in the airlock, awaiting a new cycle. The inner gates of the airlock are closed.

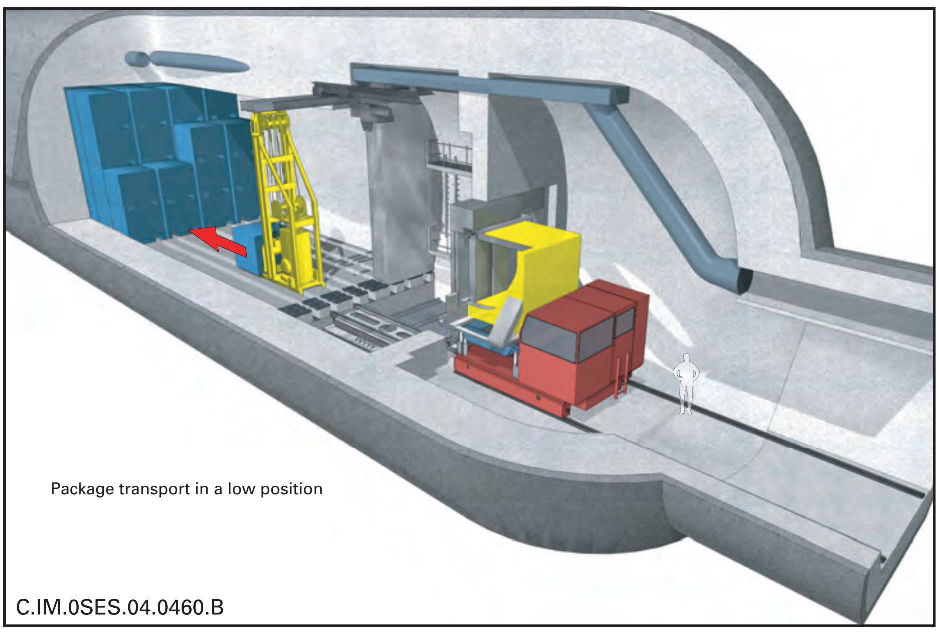
Packages retrieval would be performed the same way by simply reversing the process.



Synopsis of B waste emplacement in a cell

Handling: an electric lifting trolley

Handling heavy packages (6 to 25 t) stacked at several heights and emplaced in a 250 m long cell requires a remote-controlled mobile machine capable of moving the load lengthwise, sideways, up and down and rotating through 180° to pass from the position "opposite the cask" to the position "opposite the disposal cell". Its reduced profile (4 m) limits the volume of the cell head not used for disposal and facilitates movements when retrieving the package from the cask and emplacing it in the cell.



Emplacing B waste pachages in a disposal cell

4. C waste packages and cells

After having studied the options between disposal of either C waste primary packages or after over-packing, as for type B waste, ANDRA preferred the second option, but for different reasons.

The design of the cells and general architecture of the C waste repository zones aim to meet the various long-term operational and safety requirements. In particular, the management of the heat released by the waste and the long-term safety requirements (protecting packages in order to restrict the release of radioactive nuclides, repository compartmentalisation and disposal reversibility) appear to be the dimensioning factors.

4.1 The requirements

4.1.1 Preventing water reaching the glass during the thermal phase

The high level of β-γ activity of vitrified C waste results in a considerable amount of heat being released, which decrease over time according to the isotope decay. The exothermicity of C waste induces a temperature increase in the repository, which is liable to:

- *increase the glass alterability* (glass in which the radioactive nuclides are trapped) whose constituents, particularly silica, gradually dissolve in contact with water or whose chemical form changes to form a gel on the surface of the glass, which leads to a release of radionuclides,
- *modify the behaviour of the radionuclides* which would be released into the water after glass alteration by water. A temperature in excess of 50°C increases the uncertainties concerning the behaviour of the radionuclides in solution and accelerates diffusion velocity of chemical species.

Consequently, Andra decided to prevent water reaching the glass for a period of several thousand years, by adding a container to the C waste primary package in order to:

- avoid the risk of piercing the primary stainless steel container by corrosion through water contact, which could occur after several decades, and a dissemination of radioactive nuclides which would make package retrievability operations trickier (reversible management),
- prevent early alteration of the glass, accelerated by the temperature, which would be accompanied by radionuclides release (safety).

The container tightness duration is longer than the thermal phase of C waste, i.e. the period following waste emplacement in the repository, during which glass core temperature is in excess of 50°C.

Duration of thermal phase: different parameters

For a given type of package, the duration of the thermal phase depends on 3 parameters.

- Waste age when emplaced in the repository: the thermal power of the C waste primary packages depends on the nature of the package and decreases over time with radioactive decay.
- The maximum selected temperature inside the repository: *Andra adopted a maximum temperature of 100°C in the disposal package and 90°C in contact with the rock*. Meeting this criterion determines disposal cell design (number of packages per cell, distance between adjacent cells etc.).
- *The modular architecture of the repository zone*: disposal cells are organised into sub-assemblies (repository compartmentalisation and progressive construction). In order to determine temperature evolution within a cell beyond 300 years, it is necessary to add distant cells heat flows to the local effects. In fact, the heat released by a package diffuses gradually.

The thermal phase duration assessment is based on simulations at the scale of each cell, then at the level of several adjacent cells and finally at the level of the entire repository zone (cf chapter 6).

4.1.2 Managing heat release

In the repository, the temperature increase due to heat released from the waste (which reduces over time according to the radioactive period of the radionuclides) can generate complex coupled processes at temperatures over 100°C in the rock. It can also cause irreversible mineralogical transformations in the Callovo-Oxfordian argillite if excessively high temperatures are reached over too long a period. Therefore the thermal power received by the argillite must remain limited so as not to cause any mineralogical transformation. The studies into the behaviour of argillites have demonstrated that a temperature of 70°C over 10 000 years causes few or no irreversible transformations.

In order to remain in an operational range in which phenomena are known and, thus, reduce any damage to the argillite, the objective is to *restrict argillite temperature to these values*. Basically, it means that the thermal dimensioning of the cells and the architecture of the C waste repository zone aim to restrict the temperature to 90°C at the interface "disposal cell – argillite" and to ensure that the temperature will be below 70°C, in the geological medium on the cell boundary, before a thousand years, which provides a safety margin with respect to thermal effects.

4.1.3 Providing long-term post-closure safety

In order to fulfil the long-term safety functions, the cell design and construction procedures aim at:

• *protecting the disposal packages*. A primary objective is to maintain a physico-chemical environment that favours the over-pack durability objective and, thus, to prevent corrosion. In order to reduce the period during which corrosion rate is the highest (aqueous corrosion under oxidising conditions), air (and thus oxygen) must be prevented from re-entering the cell from the ventilated access drift. Once the over-pack is damaged and water is in contact with the glass, the cell must also maintain conditions that favour a slow glass dissolution rate and a slow release of radionuclides by the glass. Another objective is thus to restrict the renewal of the water in contact with the glass after the cell has been closed. Also, once waste package envelope is damaged, water flowing out of the cell (means of transport of the radionuclides released by the packages) must also be restricted. In the long- term, after re-saturation, this restriction relies on the low permeability of argillites and on the cell seal water-tightness;

• *limiting mechanical distortion in the medium* by reducing the residual void spaces in the cells and in the disposal package to prevent, in the long run, their resorption due to the alteration of materials causing distortions that damage the argillites;

• *controlling physico-chemical disturbances*: the disposal container is designed to prevent water arriving in contact with the primary package and avoid a premature alteration of the glass during the thermal phase. It is also essential to ensure that the container materials do not cause excessive disturbances on the glass and its environment in the longer term, particularly the water pH, which is expected to be kept between 7 and 9 due to the sensitivity of glass dissolution to this parameter.

Three corrosion phases

The cell evolution has three corrosion phases:

- *dry oxidising conditions* (confined air) causing hardly any corrosion;
- *then aqueous corrosion under oxidising conditions* which means a steel corrosion rate (concentrated at the cell head) of several tens of microns per year. This phase is very limited in duration;
- *finally corrosion under anoxic and reducing conditions* during which the steel corrosion rate is reduced to a few microns (or even less than a micron) per year.

4.1.4 Ensuring reversibility and allowing package retrievability

The objective is to retain the ability, for at least a century, to retrieve the packages, to intervene in the operation and closure of the repository or to modify its design.

The ability to withdraw packages essentially requires the disposal packages and structure geometry to be "maintained in condition". The mechanical and geometrical durability of the components surrounding the packages (disposal cell sleeve) must be maintained to take account of corrosion and the increased pressure exerted by the argillite. This involves:

- *limiting corrosion, by reducing the duration of the aqueous corrosion period under oxidising conditions* in which the corrosion rate is high,
- *maintaining a functional clearance around the disposal packages inside the cell*, dimensioned at best in order to prevent damaging the argillite in the long-term through resorption of void spaces.

In addition, *the architecture modularity* provides flexibility in repository management.

4.2 The C waste disposal container

4.2.1 Description of the container

Andra opted for *an individual cylindrical non-alloyed steel container containing a single C waste primary package.*

• **An individual container** offers great flexibility in cell design (particularly their thermal dimensioning) and package management. It minimises the dimensions of the objects to be handled, which is possible due to primary packages standardisation.

• **Non-alloyed steel** (P235) presents two advantages that limit the risk of failure damaging the container tightness and durability, particularly along welds.

- *This type of material presents a robust behaviour and its corrosion processes are well understood*. As far as aqueous corrosion is concerned, experimental results and modelling indicate that generalised corrosion is the dominant mechanism in the medium and long-term and that its rate can be quantified based on experimentally validated models. Iron archaeological analogues over 2 000 years old support the assessment of the corrosion processes and provide a temporal reference with respect to the durability of steels over a significant timescale. In addition, as non-alloyed steels corrosion models are only very slightly sensitive to water chemistry, they require less precision concerning the chemical environmental conditions (in particular, they are compatible with uncertainties concerning the composition of the Callovo-Oxfordian interstitial water), and with respect to the composition of the metal and its structural and surface condition.

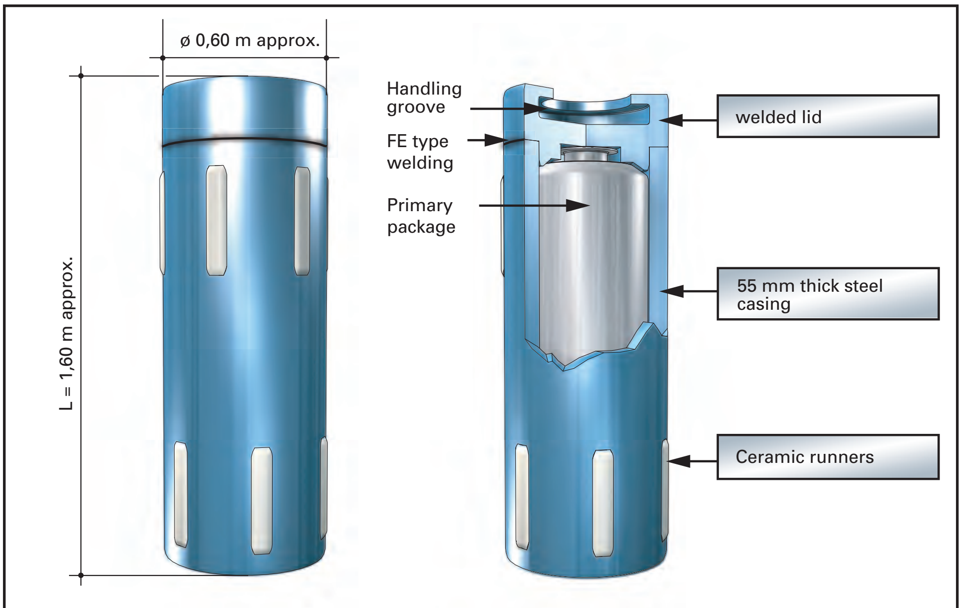
- Its use *(metallurgy, weldability, control) is based on industrially proven technologies*. Andra chose P235 non-alloyed steel because of its good welding properties and adequate mechanical characteristics with respect to the dimensioning of disposal packages.

The C waste container

The type C waste container has a P235 non-alloyed steel casing fitted with ceramic runners (pads) and a P235 non-alloyed steel lid (welded to the casing by electron beam) to meet tightness requirement.

- **The casing** consist of an envelope (55 mm thick) providing confinement over a period of 4 000 years based on conservative models, notably by assuming corrosion inception as of its emplacement in the repository, then corrosion in an oxidising medium for a decade or so. Its interior is designed to limit any void spaces and, on the outside, ceramic sliding runners allowing its handling in the disposal cell through a pushing technique. They prevent direct steel/steel friction between the package and the cell sleeve, which may damage the package during its transfer, facilitate sliding and thus limit the pushing forces.

- **The lid** is 55 mm thick. Its internal shape, adapted to the primary package profile, helps to limit the amount of void space. A groove machined into the outside enables its vertical and horizontal handling using a grapple; it is dimensioned to leave sufficient room for deploying the grapple fingers, even in the event of corrosion (for possible retrieval within the reversibility context).



C waste over-pack principle

Studies into other metallic materials

Andra has studied other metallic materials for the container: metals (copper, titanium) or chrome, nickel and manganese-based passivable alloys (property achieved through the formation at the metal surface of a fine corroded layer that protects then the metal), that present very low corrosion sensitivity and can be used in small thicknesses.
The studies into passivable alloys showed a greater sensitivity to the repository environment (highly oxidising conditions, temperature, presence of aggressive species such as chlorides etc.) and the possibility of corrosion by pitting. Furthermore, as with noble metals, they require innovative techniques in order to use them to form a watertight envelope. Andra did not select the solution of passivable metals, but is actively monitoring work carried out on these alloys.

Fall-resistance compatible with the adopted operating procedures

The calculations carried out to assess the package ability to withstand a fall are based on a fall height of 1.60 m corresponding approximately to the maximum height at which the packages are handled in the surface installations. The results of the calculation show that the impact area on the container is subjected to very localised plastic distortion (slight flattening) in the order of 20%. The remaining part of the container is not deformed. In conclusion, the dimensioning resulting from the corrosion resistance and mechanical strength requirement at a pressure of 12 MPa (corresponding approximately to the time taken by overburden formation to reach a state of mechanical equilibrium) gives the container sufficient strength to withstand a fall from a height compatible with the planned operations.

4.2.2 Manufacturing the C waste container

As for B waste packages, C waste packages can be manufactured in two phases. In the first phase, the container casing and lid are pre-fabricated. For the casing, it was preferred to obtain a casing body and bottom with a single piece using an industrially proven technique, boring and hot-drawing a solid steel block (cavity obtained by metal deformation). In the second phase, the disposal packages are made up in shielded cells in the repository surface installations: emplacing the vitrified waste primary package into the container, fitting the lid and welding it through electron beam technique, inspecting the weld before transfer to the disposal cells.

Electron beam welding (EBW) under vacuum

Andra studied several lid welding processes:

- welding with filler metal based, around several processes: Laser /YAG used for thin steel but still under development for welding large thicknesses of steel, TIG processes (Tungsten Inert Gas arc welding), MIG, MAG (Metal Inert/Active Gas welding) but welding times are not, however, suitable for thick pieces,
- welding without filler metal based around electron beam (EBW process) and friction processes. The latter, currently under development in Sweden by SKB for welding 50mm thick copper contains, is not directly transposable to thick steel welding.

At this stage, Andra has preferred the electron beam welding (EBW) under vacuum, which has the following advantages:

- process requires no filler metal (well-suited for use in a shielded cell),
- industrially-proven process on thick steels (up to 200 mm),
- small area thermally affected by welding,
- low risk of cold fissuration (welding under vacuum),
- process can be automated,
- welding carried out in a single pass (high welding speed) and high productivity (welding 5 to 10 times faster than the TIG and MIG processes).

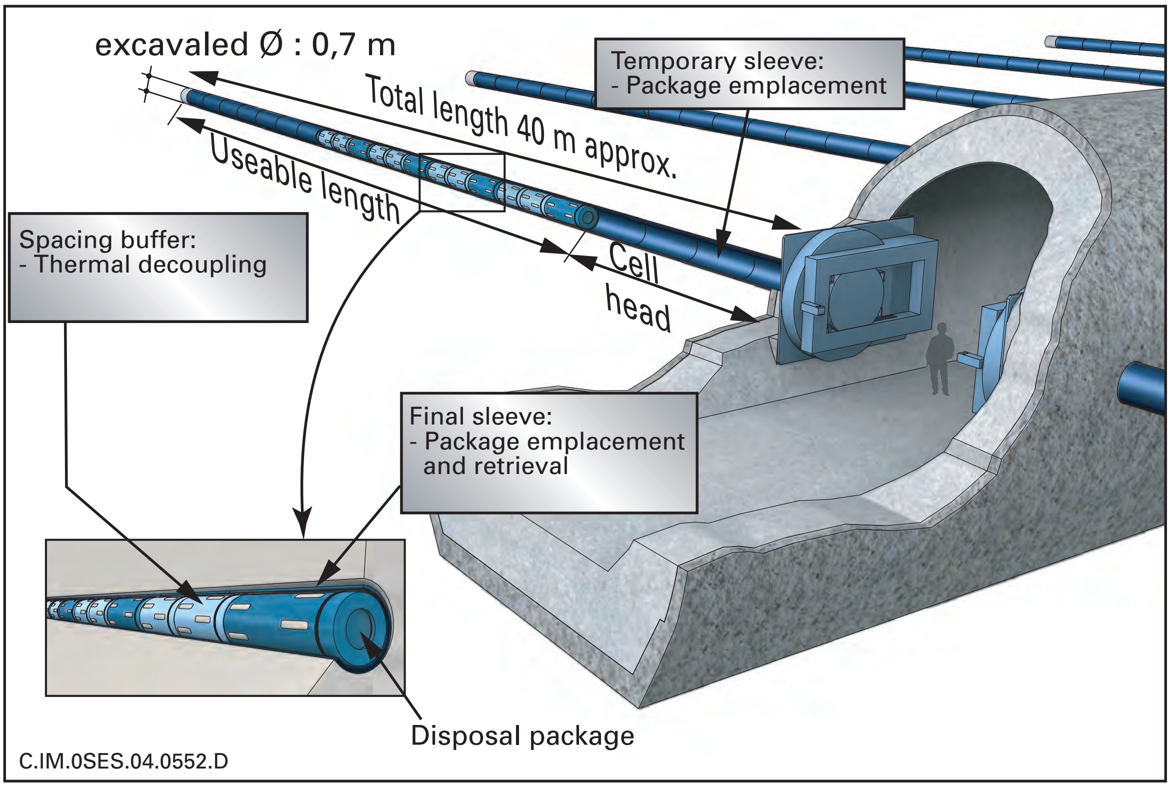
Given the similarity to the container planned for spent fuel, the electron beam welding technique and its associated inspection processes are currently being qualified in 2004-2005, as part of an ANDRA/EDF/CEA demonstration programme, through two full-scale spent fuel CU package disposal container demonstrators. Two tube sections are specifically manufactured to qualify these processes.

4.3 The C waste cell

4.3.1 Description

The C waste disposal cell proposed by Andra is a dead-end tunnel (700 mm in diameter, 40 m long) with a metallic sleeve. Its length has been limited to facilitate the demonstration of its technological feasibility (excavation, package emplacement). The disposal cell can contain 6 to 20 packages depending on their thermal output. The packages releasing most heat are separated by spacing buffers. The heat is evacuated by passive conduction in the geological formation: no ventilation is required. The disposal cell is served by an access drift.

To reduce the extension of the argillite zone liable to be fractured by construction work, the cells are laid out parallel to the major principal geo-mechanical stress. They are spaced so as to limit the temperature in the geological medium to under 90°C. They are laid out at right angles to the access drifts and grouped into modules. When closed, each module (approximately 400 cells per module) is separated from the others by seals.



C waste cell while in operating configuration

The type C waste disposal cell consists of a useable internal volume (or body) dedicated to package disposal and a cell head, which accommodates the cell closing seal.

• **The cell body** (30 m long) consists of a metal sleeve inside which the packages are emplaced. The sleeve allows to slide waste packages in and meets the reversibility requirement. Its thickness (25 mm) enables the internal functional clearances to be maintained, facilitates retrieval if necessary and gives the structure durability over a hundred-year timescale. In order to maintain a favourable chemical environment, it is made of carbon steel, of a similar grade to that of the disposal packages thus avoiding galvanic corrosion phenomena.

Inside the metal sleeve, the highly exothermic packages are separated by spacing buffers, which limit the temperature. These buffers provide a thermal decoupling of the waste packages in between themselves and therefore a heat flow reduction which dissipates by conduction in the rock. They contribute to reduce the number of cells required.

• **The cell head** (8 m long) is fitted, during the operational phase, with a temporary sleeve for package emplacement. While in operation, it is closed by a very thick steel door, the shuttering device, to which the disposal package transport cask docks, and which provides radiological protection to personnel present in the cell access drift. The package is retrieved from the cask and emplaced in the cell by means of a pushing robot integrated into the shielding cask. After filling the cell and whilst waiting for it to be closed, the shutter can be removed in order to be re-used on other cells; a protective cap is then fitted in order to reduce air exchange with the access drift, and thus the corrosion rate (limiting the duration of the oxidising aqueous corrosion phase).

When it is decided to close the cell, the *cell head sleeve section can be retrieved and the cell head can be sealed*. This seal consists of three components: a steel radiological protection plug, a very low permeability (less than 10^{-11} m/s) swelling clay plug, a concrete abutment plug.

A geotechnical dimensioning leading to a very small damaged zone

Geotechnical calculations indicate that for a 500 meter deep cell oriented parallel to the major principal geo-mechanical stress:

- *no fractured zone forms through the rock deconfinement phenomenon,*
- *the micro-fissured zone, generated at construction, does not extend beyond 0.5 times the cell radius*, i.e. approximately 20 cm .

A C waste cell fitted with its permanent plug (seal) thus constitutes a closed hydraulic and chemical system.

Cell thermal dimensioning

The heat produced by the disposal packages is evacuated purely by passive conduction into the geological formation (no ventilation). In order for the temperature not to exceed its upper limit (90°C in the rock), the geometrical parameters of modules are adjusted to the thermal power of the packages when they are emplaced in the repository, thermal power which decreases as the packages are ageing. This dimensioning also takes into consideration the requirement for compactness (minimising the total excavated volume). Thus, the distance between two adjacent cells (inter-axial distance) varies from 8.5 to 13.5 m and the number of packages per cell from 6 to 22.

Modules for disposal packages	C0 AVM	C0 R7/T7	C1	C2	C3	C4
Age (years): duration of initial package storage	20	20	60	60	70	70
Number of packages/30 m long cell	22	18	8	7	7	6
Inter-axial distance between cells (metres)	8,5	8,5	12	11	13,5	13
Pitch between packages (metres)	0	0	2,4	3,1	3,1	4,0

A metallic sleeve with sufficient steel thickness

Maintaining the structural integrity of the cell and entrance drift, and the functional clearances over several centuries with the context of possible package retrievability, requires a sufficiently thick cell sleeve and good performance of the drift concrete lining. The sleeve integrity can in fact be affected by:

- the argillite creep which will fill the annular void at the sleeve extrados and compress the latter,
- the expansion of the ground and of the steel (due to package temperature) which, during the first decades will create compressions. These compressions will reduce as the package radioactivity will decay,
- the sleeve corrosion with rate of around 1 to 2 mm/century in anoxic condition.

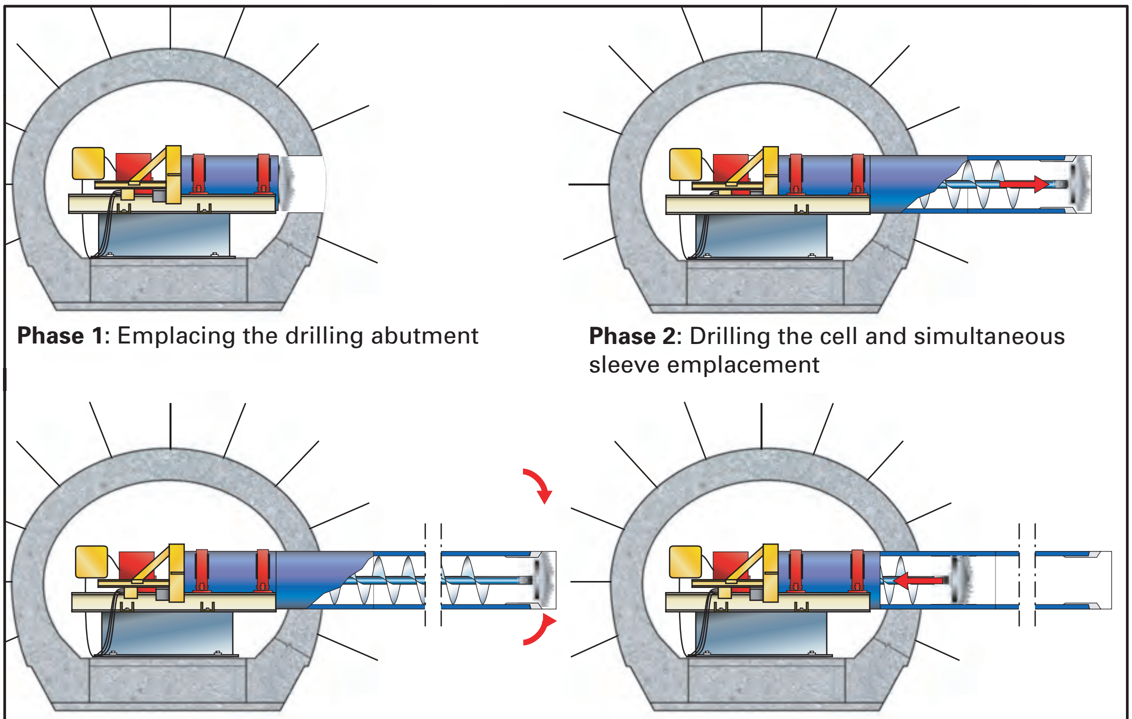
The sleeve thickness has been calculated cautiously at 25 mm for non-alloyed steel, allowing a corrosion safety margin of 5mm and a thickness of 20 mm in order to be able to withstand an isostatic pressure of 12 MPa.

4.3.2 Constructing the C waste cell

The preservation of the geological formation integrity in the ground close to the cell is the key criterion in selecting the construction procedure. To this end, the sleeve is fitted as early as possible during construction.

- **Excavation:** the horizontal boring technique can be used. The cell is bored out by a bit which cuts the rock at a diameter close to that of the sleeve external diameter and which is followed up as it advances by a tube which supports the rock.

- **Putting the permanent sleeve** in place, while excavating, limits the disturbances in the ground and prevents the risk of destabilising the walls. The sleeve sections, welded together, are pushed (they do not rotate while emplaced) by a tube pusher fitted to the boring machine. They can be assembled by automatic welding, a reliable and industrially-proven process (used in laying pipelines). The tube end is blanked off by welding on a metal plate using a robot.



Phase 1: Emplacing the drilling abutment

Phase 2: Drilling the cell and simultaneous sleeve emplacement

Phase 3: End of the drilling phase

Phase 4: Retractable drilling tool retrieval

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Drilling sequence of a C waste disposal cell

> ***Boring***
>
> The drilling bit is rotated by a motor which remains in the handling drift (on the boring machine); a drilling string transmits this rotation and the thrust to the bit. On the other hand, the rotary motor of the micro-tunnel boring machine, the alternative technique, penetrates the excavation and is located just behind the cutting wheel. The thrust on the tool is transmitted by a tube, generally left in place to serve as metallic lining.

A C waste cell variant with an engineered barrier

The reference solution selected for the disposal of C waste packages is said to be "without an engineered clay buffer barrier". This solution assumes a sleeve in direct contact with the ground. In fact, studies have shown:

- *the absence of the formation of a fractured zone* around the cell when 500 m deep,
- *the creation of a small microfissured zone*, whose permeability does not alter the diffusive transport conditions in the near-field around the cell,
- *a long-term evolution that re-closes the microfissuration* around the cell (creep phenomena on support and clogging).

The uncertainties concerning the geotechnical characteristics, the rheological models or the long-term evolution before placing in support, may lead to the appearance of a fractured zone in the argillite around the cell, which in any case would be limited to a very small thickness (a few cm).

To be on the safe side, Andra has studied a variant with an engineered clay-based buffer whose main function is to form a diffusive barrier, which would increase packages protection against aqueous alteration. In the reference solution, this function is performed by the argillite. The use of an engineered barrier would only be necessary if the hydraulic characteristics of the argillite in the near-field around the cell (damaged zone) were significantly damaged, which is not the case according to the current knowledge.

Abroad

The Belgian, Japanese and Swiss concepts for the disposal of vitrified waste in clay formations have some characteristics in common with Andra concept. *At first, the use of steel over-packing*. Almost all concepts entail *separating packages* from each other for thermal reasons. In order to minimise the space occupied, *horizontal disposal is preferred to vertical one*.
However, depending on the lifetime assigned to the over-pack and the corrosion types, steel thickness and type (carbon or stainless) vary; the compartmentalisation into dead-end sub-assemblies proposed by Andra is not always considered in foreign projects.

• **In Belgium (Ondraf)**, the concept described in the 2001 SAFIR 2 document in a clay-based medium (fairly soft clay, 200 m deep) involves the use of a stainless steel over-pack for primary packages. The disposal packages are inserted into a stainless steel sleeve, centred in a circular drift (2.4 m in diameter) and are surrounded by an 80 cm thick engineered barrier consisting of pre-fabricated swelling clay blocks (mixed with sand and graphite). A concrete lining (25 cm thick) provides ground supports. The package disposal drifts can be either dead-end ones or open ones; package emplacement entails a transfer over 200 m maximum within the stainless steel sleeve. Alternative concepts have been envisaged and are currently under study.

• **In Japan (JNC)**, the H12 report concept (1999) covers various geological contexts and envisages two main options: vertical pits (approximately 4 m high and 2.2 m in diameter) with a single package, horizontal disposal tunnels (2.2m in diameter excluding any lining) containing several packages separated by a few metres. The primary package is protected by a carbon steel over-pack. An engineered barrier (30 to 70 cm thick depending on the geology and the over-pack strength) made of pre-fabricated swelling clay blocks with 30 % sand is emplaced between the disposal packages and the ground.

• **In Switzerland (Nagra)**, the concept of a repository in a clay-based site (fairly stiff clay at a depth of 600 m) described in the Opalinus Clay Project, Technical report 02-05 (2002) proposes a very thick (25 cm) carbon steel over-pack, with a target lifetime of 10 000 years. Waste disposal package are emplaced in a lined drift on swelling clay cradles. The distance between adjacent packages is 3 m. The voids spaces in between and around packages are filled with pulverulent swelling clay which is slightly compacted *in situ*.

Functions and principal components of the C waste cell

Functions	Period	Metallic sleeve	Metal plug and shuttering device	Disposal cell plug	Spacing buffers
Transferring the packages to their repository location	Operation	X			
Mechanically supporting the structures	Operation & observation	X			
Protecting personnel against radiation	Operation & observation		X	x	
Disposal package retrieval	Operation & observation	X	x		
Preventing water circulation	Post-closure			x	
Limiting radionuclides release and immobilizing them in the repository	Post-closure	x		X	
Delaying and reducing radioactive nuclides migration	Post-closure			x	
Limiting mechanical deformations in the Callovo-Oxfordian argillites	Post-closure	x		x	x
Heat dissipation	Any	x			X
Sub-division of the repository[9]	Post-closure				

Légende : **X** essential component in fulfilling a function
x contribution of a component to a function

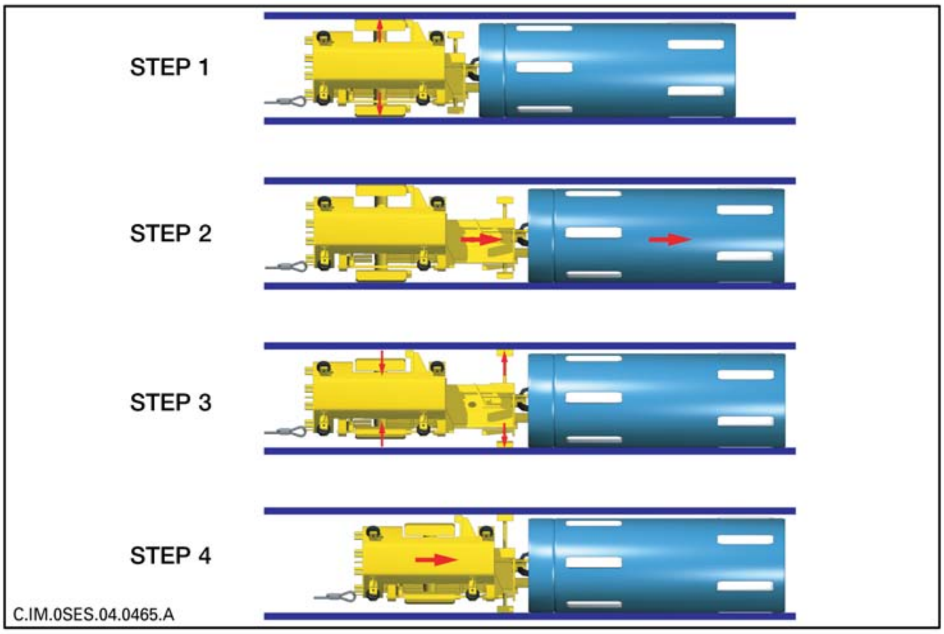
4.3.3 C waste disposal package emplacement in cells

The proposed design leads to the use of four steps for emplacing disposal package in a cell; these steps can be carried out semi-automatically under operator control.

- *Docking the cask at the level of the shutter* at the cell head. Mechanically coupled during the docking operations, the cask and shutter doors open simultaneously, thus ensuring radiological protection for the personnel present inside the drift.
- *Introduction of the mobile pushing robot and the package* into the cell sleeve.
- *Package emplacement* in the cell by pushing with the pushing robot.
- *Return of the robot into the cask, closing the cask and shutter doors.*

The process can be reversed in order to retrieve the emplaced disposal packages.

[9] *Compartmentalising the repository is not stricto sensu a safety function, but an arrangement adopted with regards to safety functions.*



Pushing robot operating principle

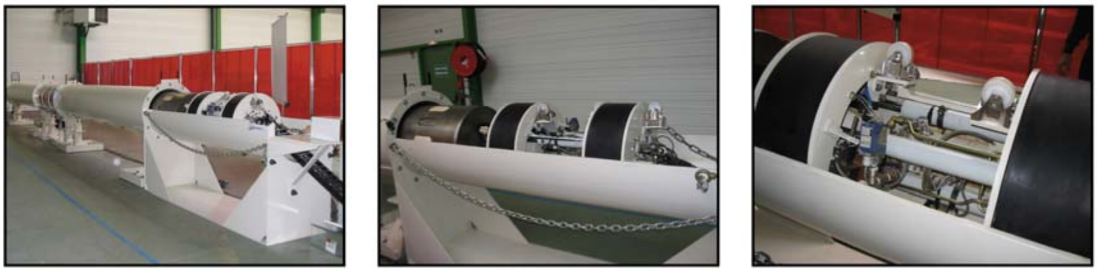
The mobile pushing robot

Emplacing the cylindrical packages (2 tonnes, diameter from 0.6 m to 0.65 m, length from 1.3 to 1.6 m) in a horizontal cell with a circular cross section requires the use of a remotely operated device which can be housed within the shielding cask and capable of transferring the package to its final position with the least possible package / cell functional clearance.

Andra has considered three solutions:

- *transfer of packages on air cushion,* which was the subject of a conclusive feasibility test in Sweden, but with a far greater diameter load (1.8 m) than that the C waste disposal package one,
- *transfer of packages by a self propelled carrier robot.* This would increase the size and weight of the protective cask and require more development,
- *transfer of packages by a self-propelled pushing robot* with step-by-step metric increment, solution adopted by Andra. This device is simple and robust, well adapted for C waste package weigh and minimises the clearance between the package and the cell sleeve. It is currently being tested in the framework of the European ESDRED project (European research project on disposal technologies coordinated by Andra in the framework of the European Union VIth Framework Program for Research and Development).

Completely hydraulic, in order to combine small size and high power, the pushing robot (1.3 m long, 0.55 m in diameter) is made up of a structure fitted with rollers and hydraulic pistons. While pushing the package into the cell with its longitudinal piston, the robot is immobilised and blocked against the cell sleeve by the extension of its lateral jacks. It is connected to the cask by hydraulic supply hoses and a return cable that allows the robot to be repositioned inside the cask after package emplacement. This robot has been subject to a full-scale test that has resulted in the technological validation of the "horizontal pushing" principle.



Essai à l'échelle 1 de poussage à l'horizontal par robot mobile d'un colis C dans son alvéole

5. Disposal of spent fuel (CU)

Direct disposal of spent fuels (CU) could be considered, if these were not reprocessed in the future. Andra has designed a container for direct disposal of spent fuels from EDF pressurised water reactors (UOX, URE enriched uranium, MOX fuels).

The design of the disposal cell reflects similar issues to that of the C waste cell: management of the dissipation of heat produced by spent fuel by respecting similar temperature criteria, creation of a favourable environment for the waste packages, allowing reversible management. However, some of the special characteristics of spent fuels, such as the more intense heat release lasting over a longer time period, have led to the proposal of different design features, particularly the insertion of a swelling clay engineered barrier between the waste disposal packages and the argillites.

5.1 The container for spent fuel assemblies

The UOX (uranium oxide) and MOX (mixed uranium and plutonium oxides) fuel assemblies from EDF reactors *have a high residual heat rating that decreases slowly*. In the same way as for the C waste, Andra has designed a container *aiming at preventing the arrival of water in contact with the fuel assemblies during the thermal phase and thus at contributing to limiting the effect of temperature on the radionuclide physico-chemistry in the geological environment. Andra has chosen to set the minimum duration for the water-tightness of the spent fuel container as 10 000 years.*

The proposed container is cylindrical and made of unalloyed steel (P235). It is made up of a body and a lid, welded together by electron-beam.

The quantity of assemblies per container is fixed at 4 UOX type (CU1) fuel assemblies in order to limit the thermal load of the waste disposal package and for handling purpose. For MOX (CU2) and some UOX fuels, due to their heat rating and the criticality risk, only one assembly is placed in each container.

As for the C waste containers, the steel thickness determines water-tightness duration. On the base of a pessimistic model for generalised corrosion, the container thickness has been designed to meet the requirement of maintaining confinement for at least 10 000 years (110 mm for the container with 4 assemblies, 120 mm for the container with one assembly).

Inside the "four- assembly" container, *a solid internal insert (made of cast iron) provides the spacing between the 4 fuel assemblies: this arrangement guarantees sub-criticality, improves the thermal transfer inside the package, ensures the mechanical strength of the package in order to withstand external pressure and limits the residual voids in the packages. In the single assembly container, the mechanical strength of the package is provided by the casing, which is designed to be thicker.*

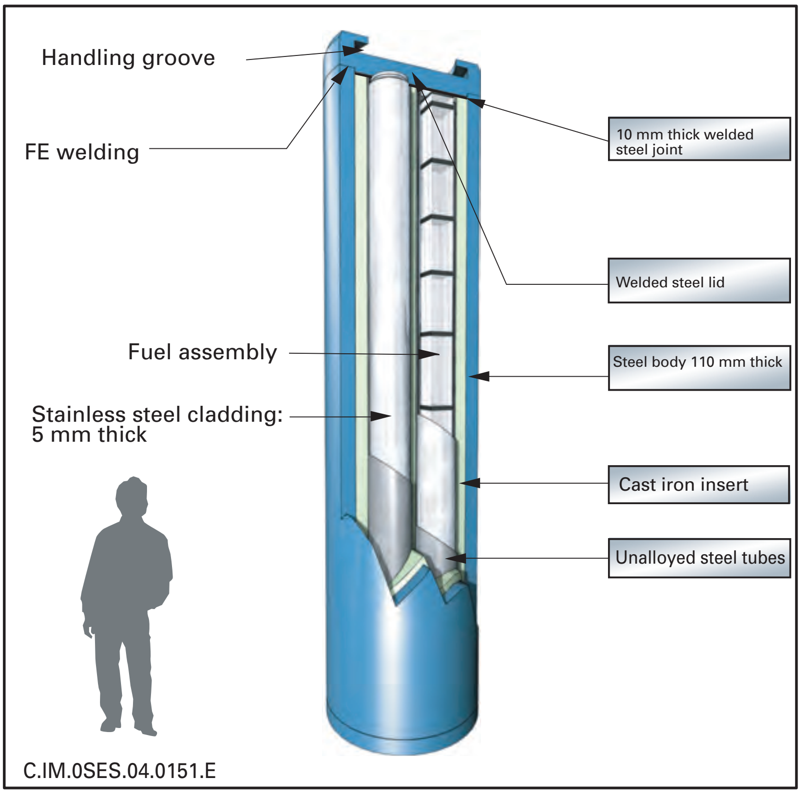
The four assembly package (UOX)

• **The body** is made up of a cylindrical ring (casing) made from P235 carbon steel (useful thickness 110 mm) and a welded-on base with the same useful thickness and of the same material.

• **A cast iron insert** (thickness 40 to 45 mm) with 4 compartments (for each of the UOX fuel assemblies) is moulded inside the body.

• **The lid** is made from P235 steel with a total thickness of 280 mm: 110 mm are provided for corrosion, the remainder is designed for mechanical strength, the weld root face, and the creation of a handling interface similar to that of the C waste package, but larger. This lid is electron-beam welded to the body in the same way as for the C waste package made of the same material.

The solution with 4 UOX fuel assemblies per container would allow to manage approximately 98 % of the quantitative inventory of UOX spent fuel considered by the research studies.



Large diameter "four- assembly" package for spent fuel (UOX or URE)

The criticality risk is controlled

The spent fuels contain a mass of residual fissile matter that requires the safety-criticality risk to be taken into account. When unloaded out of the reactor, a UOX fuel assembly contains 10 kg of residual fissile matter, of which 4 to 5 kg is Uranium^{235} and nearly 4 kg is Plutonium^{239}. A MOX fuel assembly contains 20 kg of residual fissile matter, of which 16 kg is Plutonium (12 kg of Plutonium^{239}).
Research results have lead to limit the fissile matter concentration, therefore the number of fuel assemblies, inside the disposal container. The waste disposal packages are designed so that each one provides sub-critical conditions.
The criticality risk assessment considered all phases of container life, particularly in the very long term, taking into account the evolution of the fissile matter masses, the geometry and materials used for packaging and the package environment. Research has demonstrated that the risk of criticality can be controlled.

Container demonstrators (with 4 assemblies) were manufactured in 2004-2005 in the framework of a tripartite Andra / CEA / EDF program: the container envelope (casing) was obtained by forging from a steel block, the cast iron insert was moulded directly inside the steel casing. The base and the lid were then added and welded by electron-beam.

Emplacement of large diameter spent fuel containers (with 4 assemblies) inside disposal cell can be performed using a specific air cushion device: the package is raised by air cushion units fixed to a cradle, which is then pushed by a self-propelled carriage. This principle has been successfully tested by SKB in Sweden and also as part of the European ESDRED project.

Emplacement of small diameter containers (with one assembly) can be done with the same procedure as that used for the C waste packages (similar diameter).

Compatibility with the industrial and long term storage options

To ensure the container compatibility with the current industrial storage and the long term one developed by CEA, and to offer the maximum possible management flexibility, fuel assemblies from EDF Pressurised Water Reactors (corresponding to spent fuel CU1 and CU2 packages) can be taken into account both in their "bare" or "pre-conditioned" versions in individual cylindrical cladding, as defined by CEA long term storage research study. Two alternative models of container are therefore proposed: one with square section compartments for bare assemblies, the other with cylindrical compartments for assemblies with cladding.

5.2 Cells designed to manage the heat release and contribute to long term safety functions

The control of release of radionuclides after deterioration of the container depends mainly on the existence of a diffusive barrier (homogenous materials, with low permeability, and with the lowest possible diffusion coefficients), which allows *the cell to function as an almost completely closed chemical system*. The low solubility of some of the components making up the assemblies and the local confinement of the dissolved species limit spent fuel alteration and immobilise at best the radionuclides inside the cell.

The argillites, through their very low permeability, impose a favourable environment for the package protection. However, in contrast to the reference solution proposed for C waste, Andra has adopted the insertion of a swelling clay engineered barrier between the rock and the package, due to the spent fuel characteristics (high quantities of actinides) that cause slower thermal decrease and the possibility of long term thermo-hydro-mechanical effects on the near field argillites.

The swelling clay engineered barrier

The lowest possible permeability and highest possible thermal conductivity: these are required properties of the clay engineered barrier.

Low permeability aims at creating a diffusive environment around the packages. Research studies have demonstrated that a permeability of approximately 10^{-13} m/s is achievable on a small scale, given that the target on the structure scale can be met by a permeability of 10^{-11} m/s.

Thermal conductivity dissipates the heat given off by the waste. Research studies have demonstrated that it is possible to obtain a conductivity exceeding 1.5 W/m/°C in the long term (saturated material) and exceeding 1.2 W/m/°C during the thermal peak (desaturated material).

The formulation of the material used for the engineered barrier (dry density) must allow sufficient swelling pressure to be developed (between 0.5 and 7 MPa) in order to absorb construction voids within the cell and ensure residual swelling pressure to maintain low long term permeability.

To obtain the required properties, the following characteristics are considered:

- *a mixture of swelling clay* (approximately 70%) and sand to improve the thermal conductivity (approximately 30%);
- *choice of "MX80"* or equivalent type clay (low permeability, even at low density);
- *dry density* approximately 1.6 for the clay and *saturation degree* of approximately 80% when emplaced.

The proposed disposal cell is a dead-end tunnel approximately 2.5 m (CU2 type package) or 3 m (CU1 type package) in diameter with a total length of 45 m, with a metallic ground support, inside which the swelling clay engineered barrier is emplaced. Inside the barrier, a metal sleeve accommodates the packages. As for the C waste cells, the heat produced by the packages is evacuated by passive conduction into the geological formation. The thermal dimensioning has defined the distances separating two adjacent cells, the number of waste disposal packages per cell, and the requirement to separate packages with spacing buffers.

The cells are grouped in modules dedicated for each type of spent fuel package (CU1 and CU2).

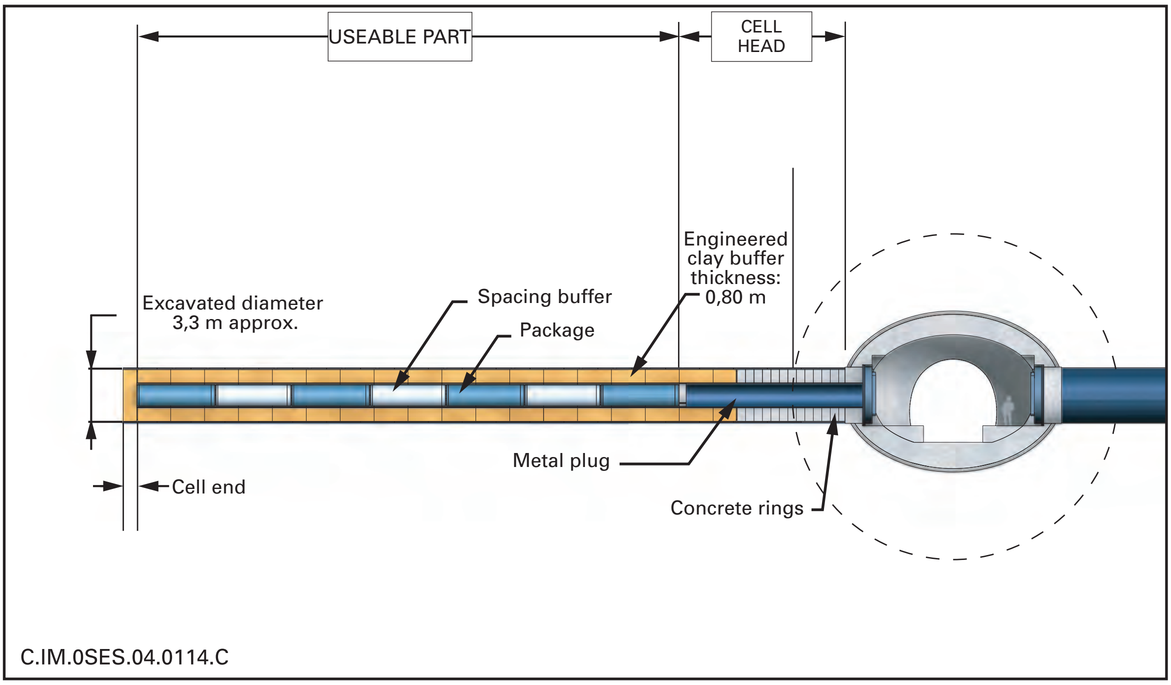
The cell includes two parts.

- **the useful part (body)**, approximately 35 m in length, is equipped (from the rock towards the interior) with:

- metallic ground support made up of steel casings approximately 25 to 30 mm thick that constitute the thrust tube during excavation, protect the personnel during construction and support the engineered barrier cylindrical segments[10],

- an engineered barrier 800 mm thick made from prefabricated rings of swelling clay and sand. Its main function is to constitute an exclusively diffusive environment that comes into play when the spent fuel container reaches the end of its lifetime,

- a metal sleeve to house from 3 to 4 packages (depending on their heat rating) separated by spacing buffers.



Longitudinal cross section of a CU cell

- **the cell head** (10m long) is made up of a temporary metallic lining to allow package emplacement. When closure is decided, this metallic lining is removed after setting up a biological protection metal plug, then a swelling clay core is inserted inside the engineered barrier rings and a concrete plug is poured to provide mechanical support.

The disposal cell can be excavated using a micro-tunnel boring machine.

[10] The ground support is slotted to enable engineered barrier resaturation.

Abroad

Spent fuel direct disposal is the option adopted in the United States of America, Sweden and Finland for management of the nuclear fuel cycle backend. Switzerland and Belgium have also carried out research into direct disposal as a possible option.

Andra concept, *like all the foreign projects in a saturated environment* (with the exception of the USA Yucca Mountain project) *relies on a swelling clay engineered barrier* either emplaced during cell construction (Belgian, Swedish and Finnish concepts), or once package has been emplaced in the repository (this avoids the use of a metal sleeve, but means concurrent combination, in the disposal cell, of civil engineering type operations and irradiating nuclear material handling operations.

• **the Swedish (SKB) and Finnish (POSIVA) concepts** are designed for granite sites. 4 to 12 assemblies are placed in a copper container (approximately 1 m in diameter and 50 mm thick) fitted with a cast iron insert. The cells are vertical boreholes 1.75m in diameter (KBS3-V), for housing one container only, surrounded and capped with swelling clay. SKB and POSIVA are also currently carrying out research into a horizontal alternative (KBS-3H) using a supercontainer (made from copper surrounded with a prefabricated swelling clay engineered barrier) emplaced inside disposal drifts several hundred metres in length. The main reason for this alternative was to reduce the total length of access drifts.

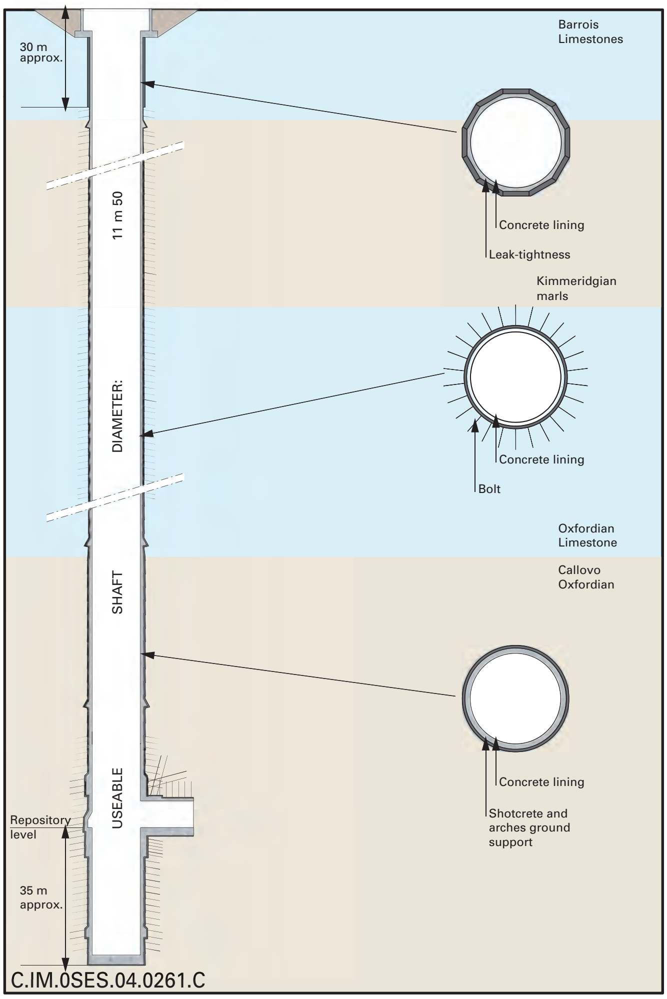
• **the American Yucca Mountain project (US/DOE)** is dedicated to civil and defence spent fuel. The geological formation is a volcanic tuff. The disposal cells are horizontal open-ended drifts (5.5 m in diameter, 970 m long), in which the packages are lined up, without an engineered barrier, but in a raised position under a titanium "umbrella shield" to protect them from local percolation (rainwater) and localised corrosion. Contrary to the other projects, the heat produced by the packages is evacuated by a ventilation system passing through all the disposal drifts.

• **the Belgian concept (Ondraf)** is described, in the 2001 SAFIR2 report, as an adaptation of the C waste concept. The waste disposal package is a stainless steel container 9.5 mm thick, housing only one assembly, in cladding, for criticality reasons. The cells are horizontal tunnels (2.7 m in diameter, 600 to 800 m long) with a concrete lining (25 cm thick) fitted with 4 longitudinal tubes separated by swelling clay. The packages are, depending on their heat rating, either lined up inside these tubes (MOX) or in groups of 4 in the section (UOX). The thermal dimensioning criteria are a temperature of less than 100°C at the container surface and a temperature increase in the overlying aquifer of less than 6°C.

• **In Switzerland (Nagra)**, a concept similar to the C waste one is considered. The spent fuel assemblies are placed, in groups of 4 or 9 (depending on whether they come from a PWR pressurised water reactor or a BWR boiling water reactor), in a steel container (approximately 1 m in diameter, 150 mm thick) designed for a lifetime from 1000 to 10 000 years. An alternative, with increased durability, would be a copper container with a steel or ceramic insert. The disposal cells (2.5 m in diameter, several hundred metres long) are horizontal and orientated in the direction of the major stress. They are not lined: there is just a bolted mesh ground support for safety. The cells are open-ended (accessible at both ends, therefore opposite to the dead-end concept). Disposal packages are emplaced on compacted swelling clay cradles. The annular space between the packages and the cell walls is backfilled, as soon as packages are emplaced, by projected bentonite in the form of compacted granules.

6. Shafts and access drifts

The shafts and drifts accessing to the disposal cells are used to transport the personnel, equipment and material required for the construction of the structures, *and to transfer the waste disposal packages* to the disposal cells. *They are also used for the networks* (water, power supply, communication, etc.) and *provide ventilation*, an essential component for controlling health and safety conditions.



Longitudinal cross section of the waste package transfer shaft

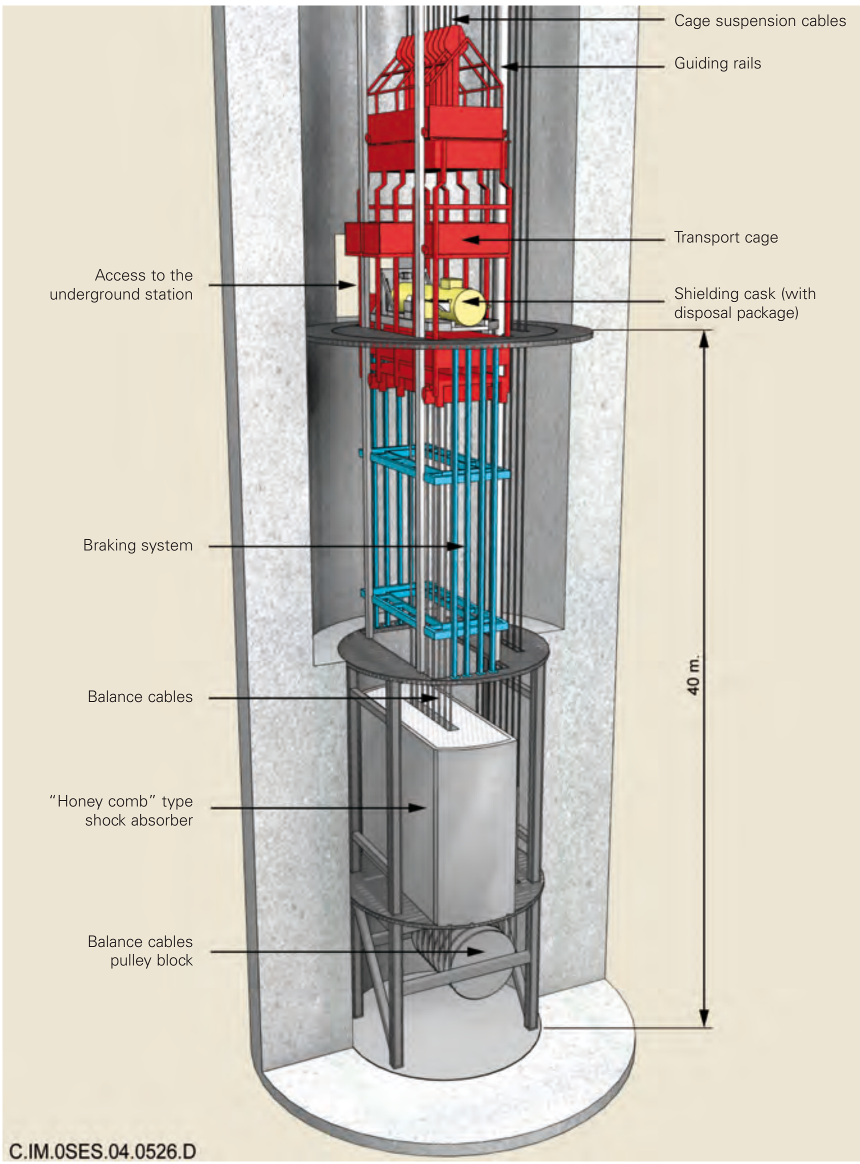
6.1 Shafts connecting the surface and underground structures

To reach the repository underground installations, two types of structure, generally used in the mining industry, can be considered: shafts, which are vertical structures equipped with machinery to lower and raise loads in cages suspended on cables, or ramps, which are inclined drifts (with a slope of less than 15 %) in which vehicles with pneumatic tyres are used. Note, however, that, in mining installations, ramps are usually associated with shafts.

The *solution proposed by Andra is an "all shaft" option* adopted for the sake of simplicity (only one type of structure) and for the greater possibilities of shafts to be adapted to large throughputs.

For safe management of the coexistence of the different types of activity, the *shafts are specialised by function*. They could be four in number.

- *One shaft* (useful diameter approximately 12 m) is *strictly reserved for waste package transfer*. This shaft is fitted with a cage, with an approximately 110 tonnes maximum working load, for lowering or raising packages and shielding casks. Other equipment, widely proven in the mining industry (friction pulley systems, fall arrester) is provided in order to make the system extremely reliable. Specific technical devices are, however, used in order to limit the consequences of any fall: a braking system and a fall shock-absorber, shaft fitted with airlock and independent ventilation system that can be coupled to a highly efficient filtering system.
- *Two shafts are used for the other transfers*: one (useful diameter approximately 11 m) for personnel; the other one called service shaft (useful diameter approximately 6 m), for materials and heavy equipment (broken rock and excavation muck, concrete, mining vehicles, etc.). These two shafts also provide air input.
- *One ventilation shaft* (useful diameter approximately 10 m) is dedicated to air exhaust: general air exhaust (during construction and operation), exhaust of air likely to be contaminated in the event of an incident (air from the package transfer shaft), smoke evacuation in the event of fire.



Lower part of the package transfer shaft with the shock absorber

The ramp as an alternative

Many mines are equipped with both shafts and ramps (inclined drifts with slopes of from 10 to 15 % in general), which use has become widespread following the introduction of diesel powered mining equipment and belt conveyors.

A *ramp* presents an interesting flexibility in terms of operation as it can be used without throughput interruption by very different vehicles. Throughputs are, however, more limited, and the risk of incidents is higher.

In the case of the feasibility study for the repository at the Meuse/Haute-Marne site, the good mechanical properties of the overlying formations and their low aquifer characteristic mean favourable conditions to build a ramp. The repository level is deep (500 m) for a ramp but not without precedent. The moderate level of some throughputs, notably concerning excavation muck of B and C0 waste zones, constitutes as well a favourable feature to consider the ramp option.

Apart from the exhaust air function, for which the ramp is useless, the comparison between the two types of access does not give very clear-cut results. Andra has studied 2 types of ramps:

- *a service ramp* (useful diameter 6 to 8 m) designed for easy truck traffic, could be considered as a replacement for the service shaft for the construction and operation of the B and C0 zones. This would be made up of 8 straight sections, each 340 m long with a 15% slope, connected by half circles with a 10 % slope and 30 m radius. A chimney would facilitate ventilation and smoke removal from the structure during construction and use. Bays would allow trucks to cross each other;
- *a ramp for lowering the packages* designed to limit the speed of impact in the event of loss of control of a vehicle transporting the packages. This helical drift (useful diameter 7 m, slope 10 %) would eliminate the risk of a long free fall. Each square shaped loop would be composed of straight sections (80 m long) and curved ones (10 m internal radius). At each curve, an emergency escape route would allow the truck to be stopped would a problem occur. A chimney would connect the loops together and provide a dedicated air circuit for the ramp, independent from the repository ventilation. The structure is equipped with a concrete roadway and with electrical power networks, etc. Electric trolleys similar to the vehicles used to transport the packages inside the repository and fitted with redundant braking systems would be used to convey down the packages and bring the casks back to the surface.

Other countries

For the WIPP (disposal facility for transuranic radioactive waste exploited in the United States of America) and for the Gorleben project (Germany), the "all shaft" option was adopted at depths of respectively 650 and 900 m, in sedimentary formations, with a salt host layer. Sweden and Finland are considering mixed solutions combining shafts and ramps, at a depth of 500 m in granite.

6.2 A drift network structured for underground transfers

The network of drifts and underground infrastructures is designed both for the management of co-activity, i.e. the coexistence, at the same time, of construction and operation activities, and to provide flexibility for the construction, operation and closure of the repository. It meets operational and nuclear safety requirements, particularly for the evacuation of personnel and quick access for rescue teams if necessary, as well as smoke evacuation in the event of fire, to limit at best the extent of the smoke filled zone.

Several measures are proposed.

• *the access drifts are sub-divided* into main drifts connecting the shaft to repository zones and secondary drifts connecting the repository zones to the main access drifts. They are grouped in bundles of parallel drifts. Drifts in the same bundle are connected by perpendicular drifts, the interconnecting drifts, to allow passage from one drift to another in the event of an accident (evacuation of personnel, passage of rescue vehicles).

• *the access drifts are specialised by function in order to* separate the transport of packages from other throughputs.

- *the drifts for the package transfer* are used for transporting packages and casks between the transfer shaft and the cell access drifts, and also provide fresh air input in full section inside operating repository modules.
- *the construction drifts* are equipped with roads adapted to pneumatic tyres trucks or with railway tracks. They are reserved for other transport (construction machinery traffic, personnel, material and equipment transports, extraction of broken rock, etc.). They also provide fresh air input in full section inside the working zones.
- *the ventilation drifts* serve for the exhaust air from excavation and operation working sites to the ventilation shaft. The exhaust air return can also be performed within dedicated ducts installed in the other drifts.

Drifts designed according to throughputs

At the current stage of the research studies, relatively small diameter drifts but in greater number are preferred (which implies provision of specific ventilation drifts) with respect to large diameter ones (which could accommodate ventilation or smoke removal ducts). The access drifts are designed for the specific throughputs (trucks, ventilation), with the aim of limiting drift diameters:

- *the size and number of trucks* for material, equipment and personnel: the minimum dimension that allows passage of a truck, the possible requirement to allow truck passing each other, possible presence of pedestrians;
- *the ventilation flow*, which implies minimum cross sections for air flow, depending on ventilation requirements. Fresh air is transported in full section by the package transfer and construction drifts; air exhaust is performed via ducts or specific ventilation drifts. Smoke removal is performed by means of special ducts. For health and safety reasons, air velocity is limited in the drifts where personnel circulate and work.

A change in repository construction and operation pace could change the rates of excavation work and package emplacement in the repository, and, as a result, the drift architecture and dimensioning. The infrastructures were designed using conventional hypotheses for construction and operation pace in order to assess feasibility. They can be adapted for a different pace, with a modification in infrastructure capacity.

7. The surface installations

The surface installations are used for the reception of the primary waste packages, transported inside shipping casks by road or rail convoys from their production or surface storage sites, then for preparing waste disposal packages for transfer into the underground installations. They also provide support for the construction and operation of the underground installations.

The surface installations can be divided into four main zones of activity:

- *a nuclear zone (approximately 25 ha)*, where the primary packages are received and temporarily stored, then prepared as waste disposal packages; these activities are similar to those in some industrial nuclear installations such as the COGEMA reprocessing plant at the Hague or the Dutch COVRA storage facility,
- *an industrial zone (approximately 35 ha)* regrouping technical workshops and warehouses with equipment required for underground work;
- *an administrative zone (approximately 20 ha)* regrouping the offices and other buildings, vehicle parks;
- *a broken rock dump* (approximately 120 ha for the S1a scenario) where the broken rock from excavation is stored; would spent fuels be disposed of in the repository, the broken rock dump would have a larger footprint, as excavation work would be greater. Some of this broken rock will be used for backfilling the underground installations.

Surface contamination controls

Controlling systematically the absence of surface contamination (smear test) will be performed at reception of each shipping cask, on each primary package once removed from the shipping cask, and on each waste disposal package before its emplacement in the transfer cask. In the event of measurement exceeding the regulatory threshold ($4 Bq/cm^2$ for beta and gamma emissions, $0.4 Bq/cm^2$ for alpha emissions), the primary packages could be temporarily stored before being shipped back to the producer.

Dossier 2005 Argile

Reversible operation of the repository

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Reversible operation of the repository

The reversibility of a repository operation can be defined in terms of its ability to be managed in a progressive and flexible manner in such a way as to leave *freedom of choice* to future generations. With this aim in mind, the disposal process can be broken down into *successive stages* which, from the construction of the first modules to the eventual closing of a repository module or zone, provide the possibility of a *stand-by or observation period before deciding* to move on to the next stage or to reverse the disposal process. Moving from one stage to the next is not a definitive choice - turning the page - but a reasoned choice, in full knowledge of scientific, technical, economic, social and environmental parameters, and the consequences of the passing onto the next stage.

Reversibility thus means the development of a flexible approach, with periods whose length can be adapted and which is best understood in terms of *levels*. In order to propose such an approach, Andra studies and research consisted of:
- analysing the main stages of the repository life and the associated time scales, in order to determine the key stages that need a human intervention,
- figuring out a staged management of the repository, with decision milestones. The passage from one stage to another should make the repository increasingly more passive, while gradually decreasing the level of reversibility and consequently the monitoring and maintenance requirements.

Andra has taken these objectives into account in the design options of the proposed repositories, notably by means of a modular architecture, a search for a simplification of the operations to be conducted underground, by the dimensions and the choice of durable materials. However, reversibility in no way represents a compromise as far as the safety objectives are concerned: the aim of reversibility does not include any technical measures that could significantly interfere with a safety function.
Reversibility is also made possible by knowing the evolution of the state of the engineered structures and the definition of means of actions, on a time scale of at least centuries: that has led to the study of operational systems for repository management, notably package retrievability and observation instrumentation which could be integrated within the structures.

Progressive, long term operations

The industrial commissioning of a repository starts with the arrival, on site, of the first packages and their emplacement in the repository inside the first structures constructed. Considering reasonable technical hypotheses for the packages reception rate, the operation of the repository could last from several decades to a century. Emplacing the waste packages in the repository progressively and over a rather long period offers flexibility for the management of the repository development and allows the feedback of lessons learnt. This allows a step-wise decision-making process and is favourable for reversibility.

1. The activities carried out in the repository installations

1.1 Description of the different activities

The activities carried out in the repository involve structures construction, nuclear operations and structures closure.

Because of the overall duration of these phases and the aim of proposing a flexible operating plan for the repository, these different activities can take place simultaneously. Fields such as maintenance, monitoring and observation for the purpose of the reversible management of the repository complement the main activities.

1.1.1 Progressive construction

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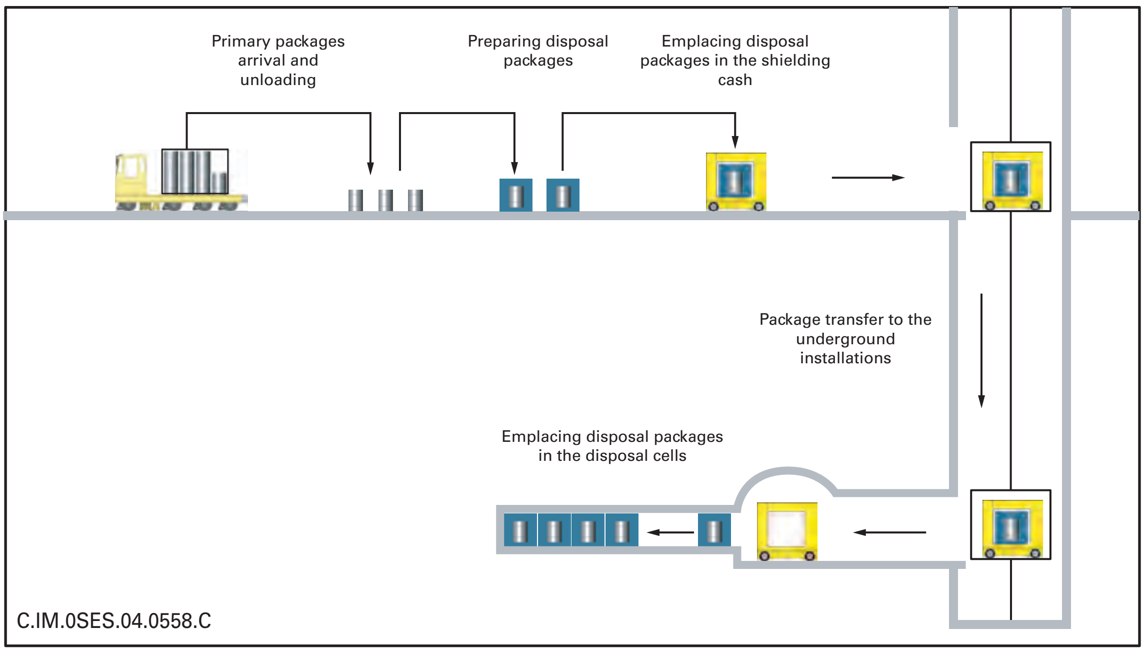
After an initial construction phase, i.e. *the construction of the structures and equipment necessary for the first waste package disposal* (surface installations, surface-underground connecting structures, first package disposal module and access drifts to this module), construction work can be organised in a flexible way: disposal cells, modules and drifts can be constructed and fitted out as required, i.e. at the desired operating rate.

1.1.2 Nuclear operations

They include nuclear operations in the surface installations (primary waste package reception and conditioning in waste disposal packages) and in the underground installations (transferring packages inside the underground installations, emplacing them inside the disposal cells and, if required, retrieving them).



Basic diagram of nuclear operation of the repository

Nuclear operation is characterised by similar constraints to those of current nuclear installations (specific radiological protection equipment, zoning according to the degree of risk of contamination and exposure, etc.). The primary waste packages delivered to the repository site are removed from their shipping casks and then placed in waste disposal package in the surface installations. Each waste disposal package is then transferred inside a cask, which provides radiological protection for the personnel from the time the package leaves the building until it reaches the underground installations via the waste package transfer shaft. Underground, the cask is docked with the cell entrance: by means of remote-controlled equipment, the disposal package is extracted from the cask and put in its final place in the cell.

1.1.3 Structure closure

Unlike a storage facility, a "reversible" disposal facility can be made passive, i.e. constituting a robust and safe system in the long term not requiring any human intervention after its closure.

Closure therefore consists of putting in place the various seals (swelling clay plug in the cells and drifts) and backfilling the drifts within the framework of a staged process complying with the reversibility requirement and of back-filling the drifts with argillite excavated from the geological formation.

1.1.4 Related activities: monitoring, observation, maintenance

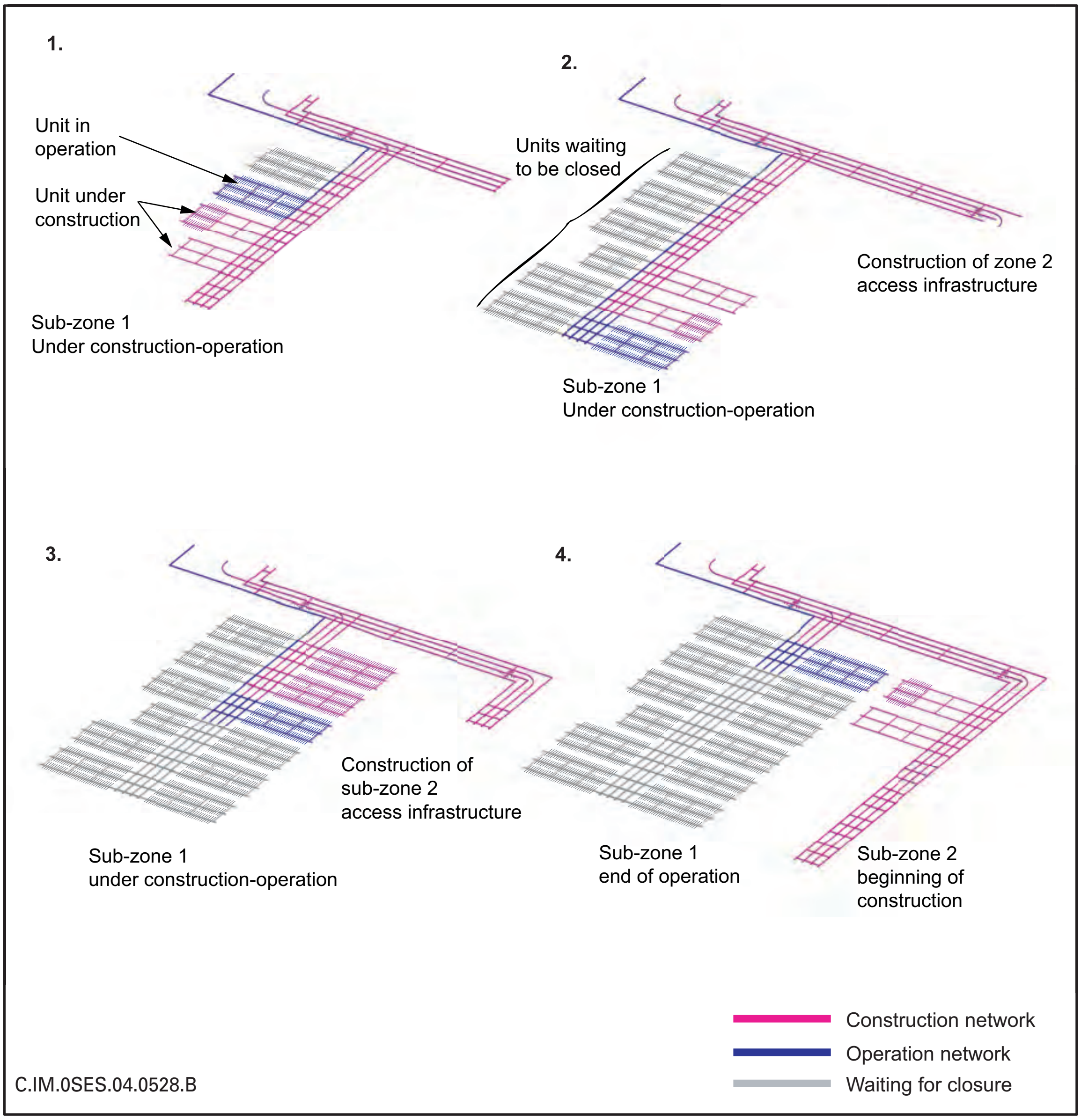
The aim of *monitoring* is to guarantee operational safety, in particular for the protection of personnel (working conditions) and the environment during operation. Beyond monitoring, the aim of observation is to record the repository behaviour, by learning about phenomena and following their evolution, to provide scientific and technical information on which to base the reversible management of the repository and help in decision-making. Monitoring and observation are closely linked and fulfil the same motivation: increasing confidence in the repository process and control.

The maintenance of the underground structures, together with monitoring and observation, helps to guarantee the preservation of the functions allocated to the structures throughout the repository operation, i.e. until the closure stages. This activity makes use of normal civil engineering methods, particularly for the access to underground structures. It has the purpose of ensuring correct and completely safe operation of the equipment used for package emplacement or their possible retrieval.

The management of co-activity in the underground installations

Management of the coexistence of nuclear and non nuclear activities (co-activity) and the design of the access drifts are based on two fundamental principles:

- The *separation of nuclear operation activities*, characterised by special risks and constraints (radioprotection, transport safety, etc.), from the activities of construction/closure, to avoid any operational interference. This separation principle means that the option of having two dedicated throughput circuits was chosen: one for nuclear operation activities, especially the transport of casks containing the packages, and which is organised around the waste transfer shaft and package transfer drifts (nuclear operation); the other for the activities of construction/closure and which is organised around the service shaft and work drifts.
- The *progressiveness of construction and operation*, which offers management flexibility (particularly the possibility of modifying the repository design or its management mode by taking operating feedback into account.



Construction and operation stages in a C waste repository zone

1.2 Operational safety

The industrial activities in the repository surface and underground installations means the application of operational safety measures very similar to the current ones in nuclear installations: physical protection measures, instructions, detection and alarm systems, intervention equipment, procedures and inspections, and also training and raising the awareness of personnel. These measures have the purpose of:

- preventing conventional risks (fire, handling and traffic accidents, falling blocks, electrical hazards…),
- confining the radioactive material, limiting the release of gaseous radionuclides and controlling contamination,
- protecting operators and the public from irradiation (protective shields, keeping operators away from sources of radiation…),
- preventing a criticality accident.

Andra has identified potentially dangerous situations, both during the construction and the operation of the repository and after the reversible closure of the installations. The probability of occurrence and the gravity of their consequences were then estimated in a qualitative way according to the previously defined preventive, protective and control measures. This risk analysis was conducted in relation with the design research studies for the repository.

A preliminary assessment was carried out about the effectiveness of the measures concerning the risks of radiological exposure and risks due to emissions of harmful gas from the package. Andra has also undertaken more detailed studies for some risks (for example, fire in the underground installations and the package fall in a shaft), considering their potential consequences and their impact in designing the installations.

1.2.1 Results of the dosimetric assessment for normal operations

For normal repository operations, the results of the dosimetric assessment demonstrate that, due to the measures taken in the proposed design for the installations and their operating mode, the *exposure doses received remain lower than the limits fixed by Andra (5 mSv/year for workers subjected to regular monitoring and 0.25 mSv for the public) and much lower than the current regulatory limits (20 mSv/year for workers, 1 mSv/year for the public).*

For workers, the highest doses, in a range of between 2 and 4mSv/year, would be associated with the reception operations for the primary packages, transfer and emplacement of the waste disposal packages in the cells and the installations monitoring and maintenance. The levels associated with other activities would not exceed 2mSv/year. These preliminary results do not take into account any future study for optimising radio-protection.

For the public at the site limits (500 m from the surface installations), external exposure is nil, due to the distance from these nuclear surface installations: only the impact of the radioactive gas released into the atmosphere has been estimated, using a conservative approach. The most pessimistic estimations result in a dose of 0.001 mSv/year, negligible compared to the regulatory limit (1mSv/year).

1.2.2. Results of the assessment of the risk due to the emission of non radioactive gas by the packages

Some B waste packages (B2 and B5.1) release non radioactive gas (hydrogen mainly and methane) which could cause an explosion if ignited while in high concentration in air. Two measures prevent this risk: *sufficient ventilation* in surface buildings and underground drifts to dilute these gases and, *for these categories of waste, the use of waste disposal packages fitted with porous lids or vents* to avoid the risk of hydrogen accumulation inside the packages and to evacuate the gas.

The assessment concluded that the planned ventilation rates were enough to control these risks correctly during the operation, even if the ventilation is temporarily stopped.

The cell post-closure phases do not entail any risk either. In the event of return into a sealed cell, ventilation would be re-established in order to evacuate the gas accumulated inside the cell.

Some B waste packages (B2 bituminised sludge packages) also release carbon monoxide (CO) and carbon dioxide (CO_2). Again, buildings and drifts ventilation is designed to ensure sufficient dilution of these gases, which are, moreover, only produced in very small quantities.

The thermal risk: a minor risk for the operating personnel

The heat released from the C waste and spent fuel disposal packages does not cause any thermal risk for the personnel during their storage and transfer in casks because the temperature rise on the cask external wall will be limited to 15°C maximum above ambient temperature. This is also a minor risk in the underground installations; the heat released from these packages inside the cells will be evacuated through the formation and by ventilation in the drifts.

1.2.3 Studies of the risks due to accidental situations (fire, falling package, cage falling in the shaft)

The risk analysis highlighted several risks that were the subject of particular studies due to their specificities (risks linked to the underground nuclear context) or their influence on the design of the repository and its equipment.

1.2.3.1 Study of the fire risk in the underground installations

Study of the fire risk in the underground installations

The case of fire breaking out inside the handling equipment, while transferring a waste disposal package between the surface and the disposal cell has been studied. This would not affect the integrity of the waste package being transported, which benefits from double protection: the transport cask, which, in addition to radiological protection, also serves as a thermal shield, and the waste disposal package itself. There is therefore no risk of radioactive dissemination in the event of fire.

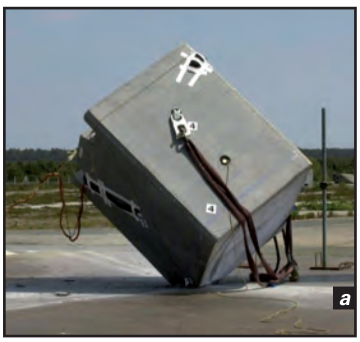
Andra has paid particular attention to the fire risk in the underground installations, to its prevention, detection and protective measures. Additional studies were developed in order to ensure that the solutions recommended for the design and operation of the installations would, if necessary, permit the evacuation of personnel in satisfactory conditions of safety.

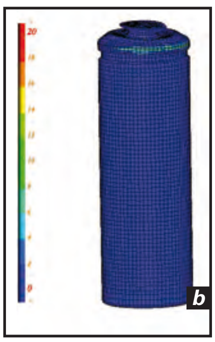
Simulations demonstrate that the repository design, with bundles of parallel drifts connected at regular intervals by interconnecting drifts, would allow personnel to move away from the fire, to rapidly reach a parallel drift supplied with fresh air (outside the smoke exhaust circuit) and return safely to the surface. In the special case of a fire breaking out during the construction phase within a dead-end drift, personnel unable to reach an interconnecting drift to escape could shelter inside a fire-resistant, smoke-proof mobile refuge fitted with the necessary utilities (water, compressed air…) while awaiting the rescue team.

1.2.3.2 Study of the consequences of a B waste package falling while it is being placed in a cell

The B waste packages are placed in a cell by a remotely controlled trolley (operator located outside the cell). Several measures can prevent a package falling while being emplaced in a cell: control of the cycle package emplacement in the repository, choice of a very stable lifting trolley, mechanical design of the waste disposal package... Andra has however assessed an accident scenario: a package emplaced inside the cell falls from the highest level of the package pile, i.e. from a maximum height of 4 to 6 m. This scenario encompasses all the handling operations inside the repository installations.

Simulations have demonstrated that the fall of the waste disposal package could cause mechanical deterioration (fissures) in the package, but that even in the most pessimistic hypothesis (waste disposal package falling on a corner), the primary package integrity and its confinement capacity were maintained. These results have been confirmed by full-scale drop tests carried out on B disposal package demonstrators. In a pessimistic dropping configuration (drop from a height of 6 m onto a corner of the lid), the damage caused to the primary packages was limited to minor deformation at the top of the packages without tearing or breaking their envelopes.





(a) Test of a B waste package drop

(b) Digital simulation of the a B waste package drop consequence on its primary package

(c) Drop test carried out with B waste package demonstrator confirming the digital simulation results (absence of damages to the primary packages apart from minor deformation)

1.2.3.3 Study of the cage falling in the shaft while loaded with a transfer cask

Experience acquired in underground mining and the recommended prevention measures (independent braking devices on the driving pulley, independent bundle of suspension cables, near bottom braking system, but also the operating, maintenance and inspection procedures) make the fall of the cage in the shaft during the transfer of packages very unlikely. Would such an event occur in spite of these preventive measures, the presence of a shock absorbing device at the bottom of the shaft would limit damage to the transport cask: simulations have proved that the cask would remain mechanically intact; the B waste package could be damaged, but primary packages would not be affected; the C waste disposal package (or spent fuel if this is the case) placed inside would withstand the shock without breaking. There would not, therefore, be any loss of confinement.

Studies have, however, considered both the "cask breaking" hypothesis and the "radionuclide release" one. Additional devices could then be implemented in order to isolate the shaft and to limit releases towards outside to a very low level.

The criticality risk from spent fuel assemblies following this type of fall has also been studied. Criticality does not appear possible, due to the measures proposed to limit damage to the disposal package.

1.3 A reversible operation

The reversibility approach proposed by Andra goes beyond just the technological possibility of retrieving packages and can be defined as the *possibility of progressively and flexibly managing the repository*. The purpose is to be able to integrate feedback and technical advances into repository management and, more generally, to leave future generations with a freedom of decision for the management of the radioactive waste.

1.3.1 A staged process

Andra has opted not to fix the duration of reversibility from the outset, but rather to consider levels of reversibility. The aim is to offer maximum flexibility for the management of each stage, with particular emphasis on the possibility of maintaining the current state before deciding to pass to the next stage or return to the preceding one.

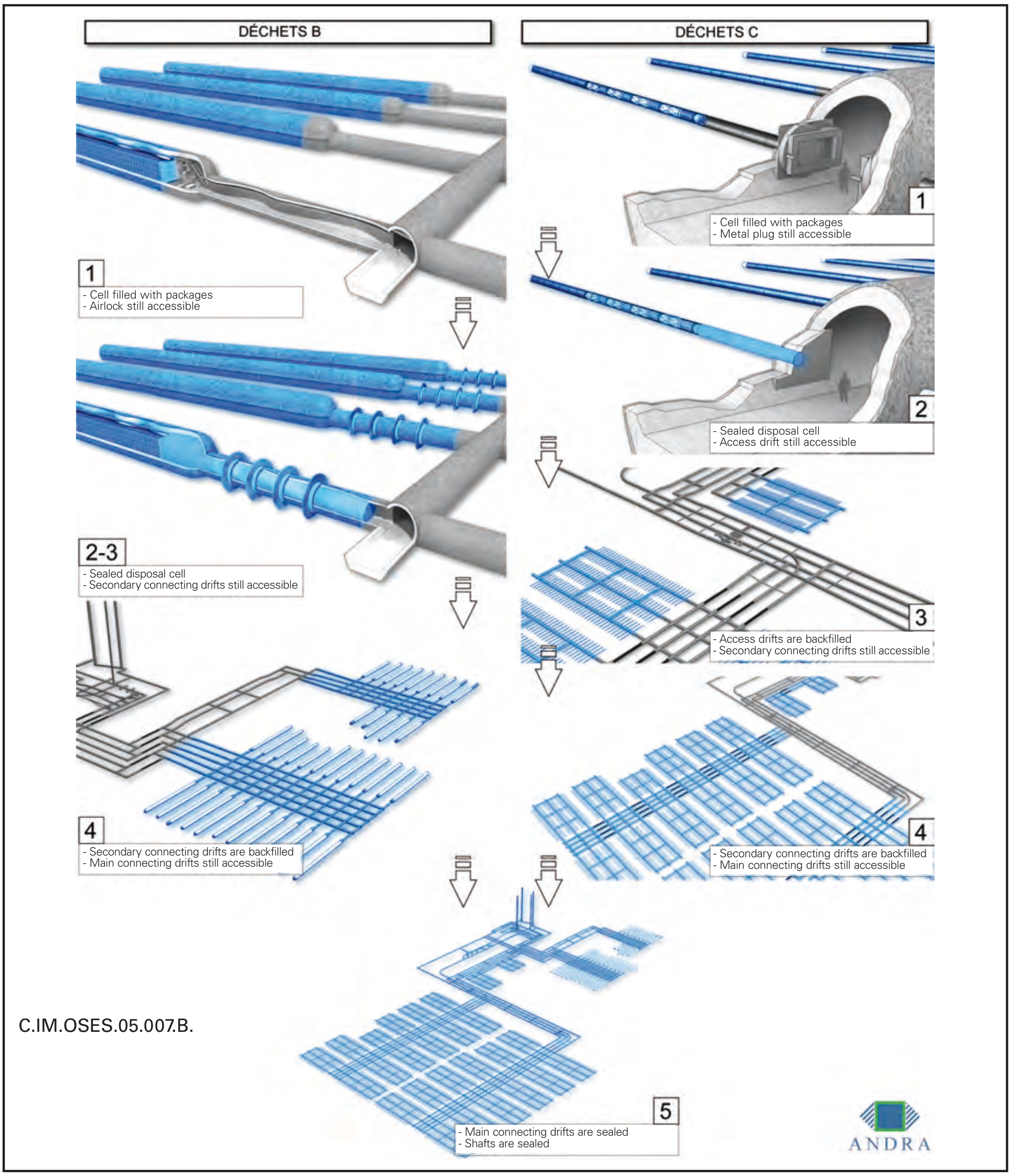
The repository management process is thus designed as a succession of stages to be passed through, without a preconceived duration. The passage from one stage to another is neither final nor laid down in a fixed operating plan. On the contrary, each stage is associated with choices: return to the preceding stage, maintaining the current state, passage toward less reversibility. The repository design (modular architecture, the aim of simplifying the operations carried out, the dimensioning and the choice of durable materials etc.) has the purpose of providing the greatest possible level of choice.

1.3.2 The key stages of the repository process

Several stages can be identified in the repository management process and its progressive closure, turning it into a passive and long-term safe installation.

- **"After emplacing the packages"**: the cells are filled with disposal packages but not sealed. Devices at the head of the cells protect the personnel present in the access drifts to the cells. The drifts are ventilated and all the underground infrastructures are accessible. *This phase is comparable to a storage configuration.*
- **"After sealing the cell"**: this stage starts after cell closure with a swelling clay plug. The cell access drifts are ventilated and the sealed cell heads are accessible.
- **"After closure of a module"**: this stage starts after sealing and back-filling of all the components in a module. For B module, which consists of a single cell, this stage cannot be distinguished from the preceding stage. But, for C waste (or spent fuel), module closure includes back-filling the access drifts within the module. The connecting drifts serving the module remain ventilated and accessible.
- **"After repository zone closure"**: this stage starts after backfilling and sealing of the connecting drifts within a repository zone. The main connecting drifts that allow access to the repository zone remain ventilated and accessible.

- **"Post-closure"**: this stage starts after sealing and backfilling the shafts and corresponds to the end of the repository management process. The repository is then in "post-closure" configuration. After closure, an observation period could be considered for the repository and its environment. *The installation is made completely passive; i.e. it provides protection for man and the environment without any human intervention.*



Possibles milestones in the progressive operation and closure of the repository

The whole process could take place over a period lasting from several decades to several hundred years if required. The progressiveness of closure gives the possibility of putting into place a staged decision-making process and keeps at all times the possibility of returning to the previous stage. *The progressive operating plan outlined above is by no means the only possible scheme; more stages or different durations could be considered. The modular design proposed for the repository and the flexibility offered for its operating mode allow the operating plan to be adapted by taking into account the knowledge of the repository's condition provided by observation.*

1.3.3 Possibilities for *in situ* observation as input for the reversible repository management

Repository management choices are based on an understanding of its evolution over several centuries: the integration of observation equipment has the purpose of contributing to the management of the reversible disposal process.

This consists of monitoring the evolution of the different structures and their environment, in order to ensure their durability and to detect any possible need for action (e.g. maintenance) to keep open the different management options: maintaining a structure in good condition for a certain period of time, passage to the next stage by sealing the structure, return to the preceding stage by re-establishing the access to this structure. It provides as well feedback for improving the repository design and management.

Observation also provides data for understanding the conditions for any retrieval of the disposal packages.

More generally, observation allows us to check that the operation conforms to the forecasts and to improve the repository behaviour models using the data acquired.

Observation and measurement devices (deformations, temperature, interstitial pressure, etc.) with their data transmission network are placed *in some B, C and CU instrumented observation cells, in the access structures (shafts or ramps) and drifts*, as soon as soon as built, to observe their evolution during operation, before and after their sealing. Other more numerous cells could also be fitted with lighter instrumentation devices, to confirm the behaviour observed in the instrumented observation cells and to transpose the results to the entire repository zone concerned.

The variables to be observed during the various stages of the repository process are those that allow us to monitor the evolution of the structures, to obtain regular assessments of their stability and to quantify the various phenomena by which a possible to return to an earlier stage is governed:

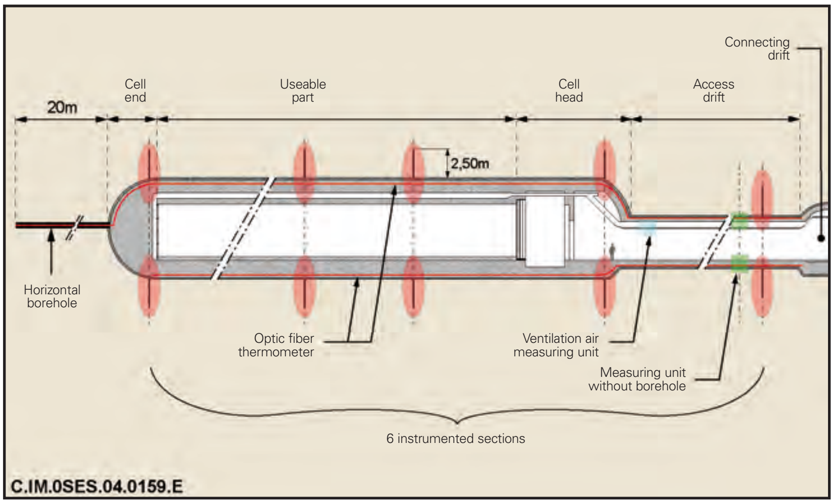
- *For B cells*, these are the stresses caused by the geological formation on the lining, the saturation level in the environment near the structure, the gas production by some waste, and the temperature for B cells with slightly exothermic waste.
- *For C waste* (or spent fuel) disposal cells, observation concerns the thermal field in and around the cell, the mechanical stresses caused by the geological formation on the metallic sleeve, the saturation level in the environment close to the cell and the composition of the atmosphere in the cell, which governs corrosion of the metal components.
- *For access structures* (shafts and drifts), observation has the purpose of monitoring the mechanical evolution of the linings and identifying any need for maintenance in order to extend their lifetime. It also allows monitoring the mechanical evolution of the rock in the near field behind the lining at the level of the future seals, particularly for the formation and evolution of any damaged zone.

Repository management also requires monitoring of parameters related to safety. This monitoring concerns nuclear and operational safety (absence of dangerous conditions or radiological contamination, mechanical stability of the structures) and long term safety issues (for example the temperature reached inside the cells or the slight influence of prolonged ventilation on the argillite). The monitoring or observation equipment must operate reliably over long periods of time, despite being inaccessible to the operators, often in aggressive environmental conditions (radiation and temperature).

Monitoring

Developed in association with the operational safety functions, the monitoring program aims at anticipating the development of risk situations and initiating interventions before these situations occur. Monitoring can signal the need for possible maintenance and keep at best flexibility of the repository process. It covers the maintenance of operating equipment in good condition (safety devices, ventilation system, networks…), the operations themselves (management of personnel and throughputs, radio-protection, fire…), the mechanical strength and the dimensional stability of the structures, the air quality (dust, toxic element…), working conditions (potentially explosive atmosphere, temperature…).
It also allows controlling long term safety criteria compliance (for example temperature limits and the void space rate inside the structures) and, during the operation-observation phase, to check that the evolution of the structures does not exceed, in an irreversible manner, the operating limits set for long term safety.

Another important requirement is discretion, i.e. equipment must not disturb the operating conditions, nor deteriorate the structures strength, nor interfere with the safety functions allocated to the structures or the favourable properties of the environment (for example the hydraulic performances of the seals and the Callovo-Oxfordian); finally, as far as possible, equipment should not interfere with the phenomena being observed.
The design of the monitoring equipment for the shafts, drifts and B cells benefits from the feedback acquired from road and rail tunnels and concrete structures such as dams and the containment walls of nuclear power plants; for C waste and spent fuel cells, feedback comes from pipelines, piping or foundation piles; for the rock, from data acquired in underground laboratories.
State of the art developed from feedback of many civil engineering structures monitoring suggests the following "good practices":
- equipment redundancy, using either different technologies or multiple examples of the same device, to check measurement consistency and limit loss of data in the event of device failure,
- choice of good quality equipment, relevant with the ranges to be measured and the required accuracy,
- well planned distribution of the monitoring equipment, notably through preliminary modelling,
- integration of the observation equipment right from the design phase.



B waste instrumented observation cell

Monitoring equipment suitable for the repository

Several measuring technologies are used in civil engineering structures: their reliability for an observation program is proven.

- **Deformations, mechanical displacements and strains:** vibrating cord extensometers (measurement of local deformation) and with long base for boreholes or backfill (deformation over greater distances), vertical pendulums (tri-axial monitoring of structure movements).
- **Evolution of the damaged zone (EDZ):** inductive multi-sensor extensometers in boreholes, interstitial pressure cells, acoustic recording by geophone or accelerometer.
- **Pressure of the interstitial water and flow rates:** vibrating cord interstitial pressure cells.

- **Relative humidity:** dew-point hygrometers.
- **Temperature:** vibrating cord sensors (local measurements), optical fibres (measurement over long profiles).
- **Concentration of toxic gas, corrosion, contamination:** hydrogen detector, visual inspection, sampling, ultrasonic measurements and indicators for corrosion, mass spectrometry for radioactive contamination.
- **Transmission and centralisation equipment:** electrical cables and, above all, optical fibre sensors and low frequency or very low frequency electromagnetic (wireless) transmission.

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2. Reversible closure of underground structures

2.1 Progressive closure

Sealing repository cells, then backfilling and sealing drifts and shafts: the repository can be closed in several stages in line with the approach put forward for reversible management.

Low permeability seals prevent water circulation in the repository and isolate it hydraulically from the overlying geological formations, in a passive, robust way, over the long term. Implemented in the cells, drifts and shafts, these seals complete the favourable characteristics of the site and the installation design arrangements. Limiting water flows helps to recreate a state close to the natural one in the argillite, at repository scale, and mitigate waste package deterioration, which would lead to radionuclides release by deteriorated packages and their migration via the drifts and shafts. By sub-dividing the repository, these multiple seals also increase the resistance of the confinement system with respect to altered situations. The filling material adopted for these seals is swelling clay, because of its low permeability, its ability to absorb deformation, and its compatibility with argillite.

Backfilling the drifts aims at limiting mechanical deformations in the geological medium, especially the extension of the damaged zone which the convergence of the excavations (when the lining no longer plays its part) could induce over the long term, in order to preserve the favourable confinement properties of the Callovo-Oxfordian argillite.

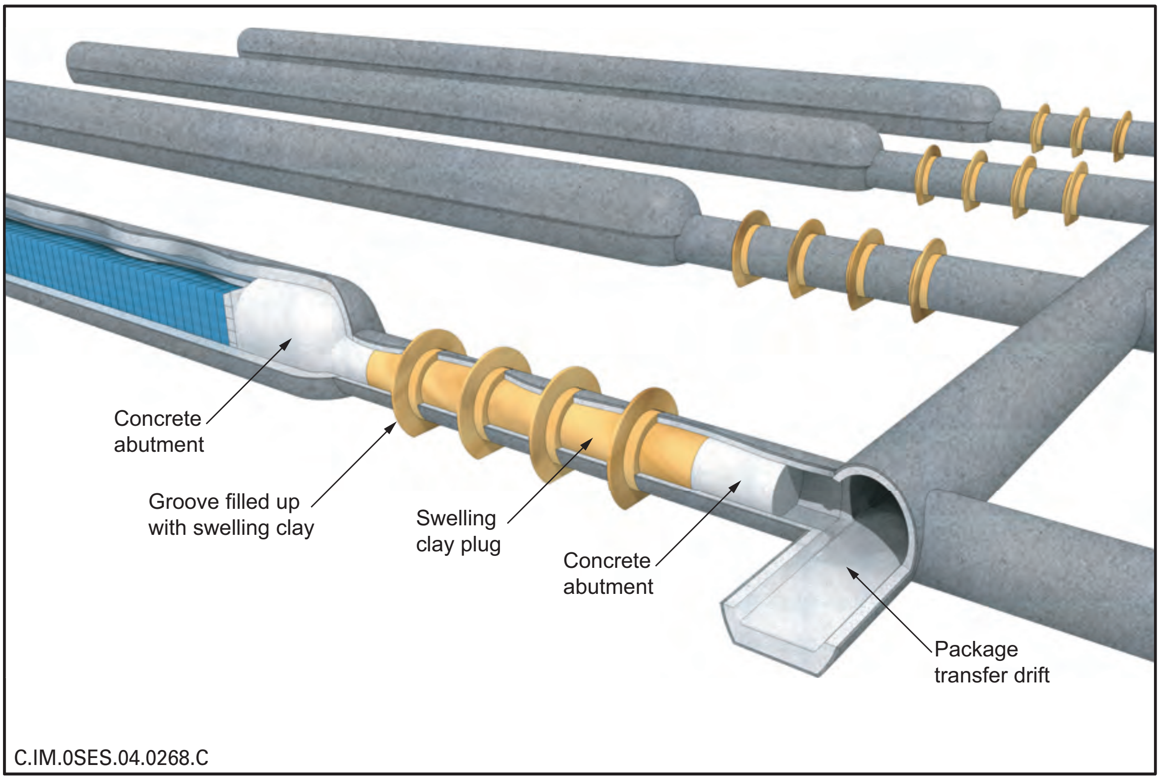
Andra has studied various sealing dispositions, giving priority to simple technical options and taking the phenomenological evolution of the structures over long periods into account for their design.

Emplacing bentonite blocks in the groove excavated with a trenching saw (KEY experiment) in the Meuse/Haute-Marne Laboratory

2.1.1 Disposal cell closure

2.1.1.1 Sealing B waste cell

The closing procedure for B waste cell involves the following phases:
- *installing a radiation shield*, made up of a twin row of concrete blocks, using the same handling equipment as for the packages,
- *dismantling the cell head installations*, together with those of the airlock and the entrance drift,
- *backfilling the cell head and construction of an upstream abutment* with concrete poured up to the access drift,
- *excavating grooves (30 cm in width and 1.5 to 3 m in depth)* in the cell access drift through the lining to cut-off the potentially fractured zone and reach the intact or micro-fissured argillite (anchor of the seal),
- *backfilling the grooves with swelling* clay to reduce the overall permeability of the seal,
- *emplacing a swelling clay seal core (about 35 m long)*,
- *construction of a downstream concrete support base (about 5 m in length)*, poured as a single block and anchored in the lining.



B waste disposal cell after sealing

Excavating grooves

The proposed technique to cut out grooves limits creation of newly damaged zone; the rock is cut away using a saw fitted with cutter picks (a tool similar to the "cutting machines" used in salt mines and in underground structures, for example to pre-split roofs). Then the groove is filled with swelling clay similar to the sealing core one.
The technological feasibility of creating a groove has been tested in the Mont Terri laboratory (EZ-A test) and in the Meuse/Haute-Marne laboratory (KEY experiment). The test was carried out to assess the feasibility of making this type of grooves and then emplacing a clay material (pre-compacted bentonite blocks), and to check the system performance in cutting off the fractured zone of the rock.

2.1.1.2 Sealing C waste cell (or spent fuel cell)

The closing procedure for package disposal cell C involves the following phases:

- *installing a metal plug for biological protection*, once the last package has been emplaced, using the same handling equipment as for disposal package emplacement in the cell,
- *dismantling of the temporary head sleeve* to ensure direct contact of the plug with the rock,
- *immediate emplacement* (or simultaneous one) *of a swelling clay plug (about 3 m in length)* to avoid leaving the rock without a mechanical support. The swelling clay is compacted in situ to provide adhesion in between plug and rock and avoid all risks of void spaces,
- *construction of a concrete plug (about 4 m in length)* for mechanical confinement of the swelling clay, by pouring or shotcreting.

Spent fuel cell closure would be carried out with the same principle as C waste cell one.

2.1.2 Drift closure

Closing access and connecting drifts involves:

- backfilling them to ensure long-term mechanical stability of the installation as a whole and limit deformations in the rock. In the light of the large volumes of backfill required, Andra has studied the possibility of using the argillite excavated as the base material for the backfill (crushed and prepared material after their storage in the broken rock dump),
- then sealing them using the same principles as those set out for sealing the B waste cells.

2.1.3 Shaft closure

When decided, the shafts connecting the underground installations to the surface are sealed. Sealing a shaft consists of the following chronological process:

- *filling the shaft base and the drifts linked to the shaft underground stations with concrete* to ensure mechanical stability of the installation as a whole,
- *emplacing a swelling clay seal* over a height of about 30 m to isolate the repository from the overlaying formations and the biosphere. The lining is dismantled in order to bring the swelling clay into direct contact with the argillite and enhance its adherence. Modelling has shown the feasibility of this operation without causing any further damage.
- *backfilling the shaft* with argillite excavated, up to the surface, with *a plug of swelling clay (about 10 to 15 m in thickness)* at each level where small aquifers are found (Oxfordian on the one hand, and Tithonian and Kimmeridgian on the other hand) to isolate these levels from the others.

2.2 Reversible repository management

The evolution of the structures is a determining factor for taking action concerning the disposal process. Phenomenological analysis shows that the structures will remain in good condition for a period of one or more centuries and that over that period of time, the conditions in the repository will remain close to those of a storage facility. Andra has integrated into the structural design the possibility of package retrieval, which could be decided on by future generations, to make it easier.

2.2.1 Behaviour of the structures and the ability to take action concerning the operating process

2.2.1.1 The B waste cells

Two phases have a significant impact on the behaviour of the B waste cell during repository operation.

• The "after package emplacement in disposal cell" phase
The cell is ventilated and accessible under the same conditions as during package emplacement; its head is fitted with the radiological airlock and the mechanical systems for putting the packages in place. Access drifts are ventilated, maintained and accessible. B waste cell is characterised by a geotechnical stability that keeps functional clearance.

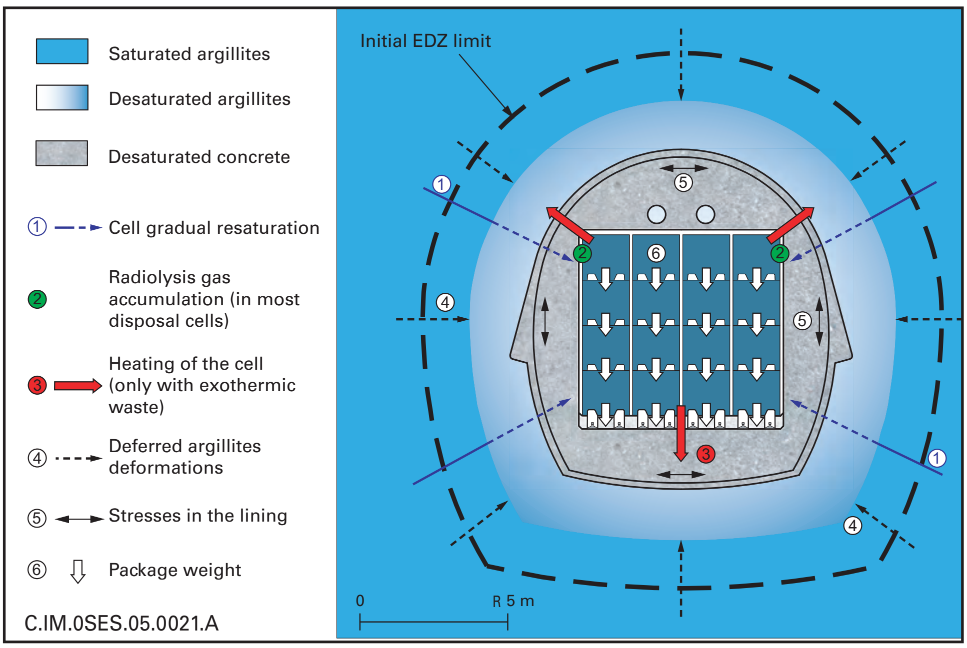
During that phase, the ventilation system removes radiolysis gas and heat which may be given off by certain packages, while the lining deformations are too minor to modify the geometry of the repository chamber.

The package retrieval period is thus limited by the lining service life. This service life is at least 200 to 300 years. During the operational phase, the observation systems would enable to reassess the forecast service life and to refine it at regular intervals. Would it be planned to extend this service life over longer periods of time, human intervention would be necessary, especially to retrieve packages and adapt the installations.

The disposal conditions are similar to those of a storage facility

• The "after sealing the cell" phase
Once the cell has been sealed, the level of accessibility of the packages is reduced and the loss of cell ventilation leads to modifications in the physical conditions inside it, especially by triggering its resaturation and the seal's one. However, this evolution takes place at a very slow rate due to the very low permeability of the argillites. The absence of water in the cell for at least several centuries strongly limits chemical deterioration of the lining, the disposal packages and the primary packages. The evolution of the cell results above all from the very slow, progressive increase in the thrust exerted by the Callovo-Oxfordian argillites on the lining during their resaturation. This thrust is weak enough for the lining and the filling concrete to remain intact during several centuries. The lining and the functional clearance between the packages and the walls are thus not deteriorated after cell closure.

In the same way, the slow evolution rate of the seal makes its dismantling easy in the event of a decision to reverse the process in order to retrieve the package or return to operating conditions similar to the storage ones.



Schematic representation of the main phenomena inside a B waste cell after closure

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The very slow evolution pace of the cell and the seal maintains the possibility of package retrieval without limitation over time, other than that already mentioned in the previous phase, i.e. the cell lining service life. Maintaining connecting drifts and shafts, together with their ventilation, ensures full accessibility to the cell access drift seals.

The subsequent "after closing a repository zone" and "post-closure" phases do not have any noteworthy impact on the evolution and management of B waste cells, other than their reduced level of accessibility.

2.2.1.2 C waste (and CU) disposal cells

Their evolution during the use of the repository is marked by three main phases.

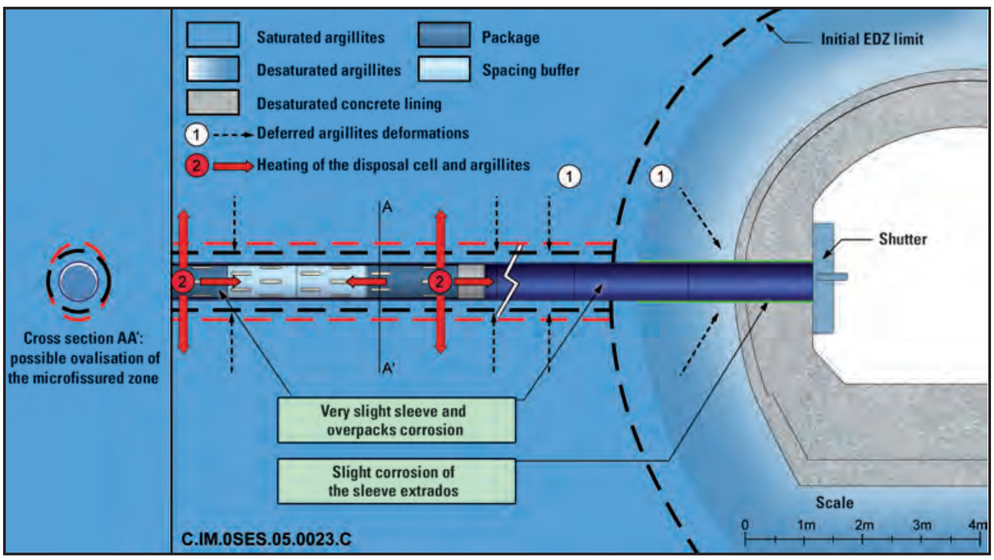
- **The "after package emplacement in the cell" phase**

Once filled with packages, the cell is fitted with a radiological shielding plug inserted in the sleeve. Its head, equipped with the mechanical system for emplacing packages, remains accessible under the same conditions as during the package emplacement phase. The access drifts are ventilated, maintained and accessible.

During this phase, and also during the subsequent ones, the disposal cell evolution is mainly linked to the heat given off by the waste, thus leading to a fairly fast rise in the temperature of the cell and the argillites; together with the access drift walls heating (60°C at most). In the drifts, the ventilation keeps the air at a temperature compatible with interventions by the personnel. Thanks to the clearance left in between the packages on the one hand, and between the packages and the lining on the other hand, the heat expansion phenomena do not create any thermomechanical constraints on the packages and the deformations are too small to block them.

The disposal cell physico-chemical environment and the sealing cap placed at the cell head to limit exchanges of air with the drift, lead to a very slow corrosion rate of the sleeve, thus ensuring its durability. Little or no water can come into contact with the packages, thus strongly limiting container corrosion. In practical terms, the possible package retrieval is hardly limited in time by the disposal cell evolution, which is very slow. With the proposed design, the sleeve remains in good condition for a period of several centuries (200 to 300 years, and probably much longer). In the same way as for the B cells, human intervention would be necessary, if it was planned to extend that period.

The functional clearance left in between the packages, and the sleeve and packages integrity facilitate possible package retrieval. Package management and especially their retrieval if necessary, is thus similar to storage conditions.



Schematic representation of main phenomena in a C waste cell after package emplacement

- **The "after sealing the cells" phase**

Once the cell has been closed, ventilation is maintained in the access drifts and the sealed cell heads are accessible under the same conditions as during the previous phase. It is technically possible to dismantle the seal and retrieve the packages.

The absence of noteworthy sleeve corrosion allows relatively easy package retrieval for a period of at least 200 to 300 years after emplacement, as in the previous phase. Observation of the thrust exerted by the ground on the sleeve and sleeve deformations in some instrumented observation cells will provide a means of reassessing the sleeve service life, independently of cell closure.

Keeping ventilation in operation in the access drifts has no significant impact on the evolution of the cell and their plug, nor on the sound (undisturbed) rock thickness with a view to long-term safety.

- **The "after closing a module" phase**

The closing procedure for a module is characterised by sealing and backfilling the access drifts to the cells. The ventilation system is maintained in the access drifts to the modules. The fact of closing the module drifts does not have any noteworthy impact on the cells; it is, above all, the backfilled drifts and the concrete abutment at the head of the cell that undergo very slow evolutions due to stopping the ventilation and emplacing backfill materials.

Drift resaturation is very slow, and lasts tens of thousands of years. The backfilled drifts lining which can no longer be maintained will also deteriorate very slowly, mainly due to anoxic corrosion of the reinforcing structures or arches by the small quantities of water seeping in from the rock. Over a time frame of a few decades or a century after backfilling, the drift backfill and lining evolution is very limited.

This phase is thus characterised more strongly by the reduced accessibility to the packages due to drift backfilling than by the phenomenological evolution of the module.

As for B waste cells, the subsequent "after closing the repository zone" and "post-closure" phases do not have any noteworthy impact on the evolution and management of C waste cells, other than their reduced level of accessibility.

2.2.1.3 The behaviour of the connecting structures during the "after closure of a repository zone" phase

- **The decision to close secondary connecting drifts (inside the repository zones)** constitutes a major phase, which makes access to the packages increasingly difficult, even though there are technical solutions for clearing out the drifts.

For the B repository zones, backfilling secondary connecting drifts only reduces their accessibility to a limited extent, as the volume to be excavated is relatively small (a few tens of thousand cubic metres).

On the other hand, for the C waste (or CU) repository zones, the accessibility of the packages is considerably reduced because the volumes that have to be excavated are significantly greater. The evolution of the backfilled drifts in these zones is very slow; the temperature tends to be homogenised in the rock and backfilled drifts, and there is only limited heating. Complete resaturation of the seals and backfills is slow (one thousand years for the seals, several thousand years for the backfills) and the longer the ventilation, the slower the resaturation. This slow resaturation limits chemical deterioration (due to corrosion or hydrolysis) of drift lining. *The absence of significant evolution in the structures after closure, for one or more centuries, facilitates a possible backward process to dismantle a seal or retrieve packages.*

- **The main connecting drifts** that are still accessible can be left as such for a period of several centuries or so, due to their lining design, the fact of keeping the ventilation system in service, and the possibility of maintenance if required. The fact of keeping the ventilation in service does not increase the extent of the microfissured rock zone that appears at rock wall at drift construction, nor that of the already desaturated argillites zone (level of saturation close to 90%) by several decades of ventilation.

- **The same is true for the shafts** whose stability is ensured by their design for a period of several centuries.

In the same way as for closure of the secondary connecting drifts, the closure of the main connecting drifts between the repository zones and the shafts can be carried out progressively. Furthermore, one of the shafts could be backfilled and sealed before closing all drifts to provide feedback on closing a shaft before the post-closure phase.

2.2.2 Modalities for package retrieval

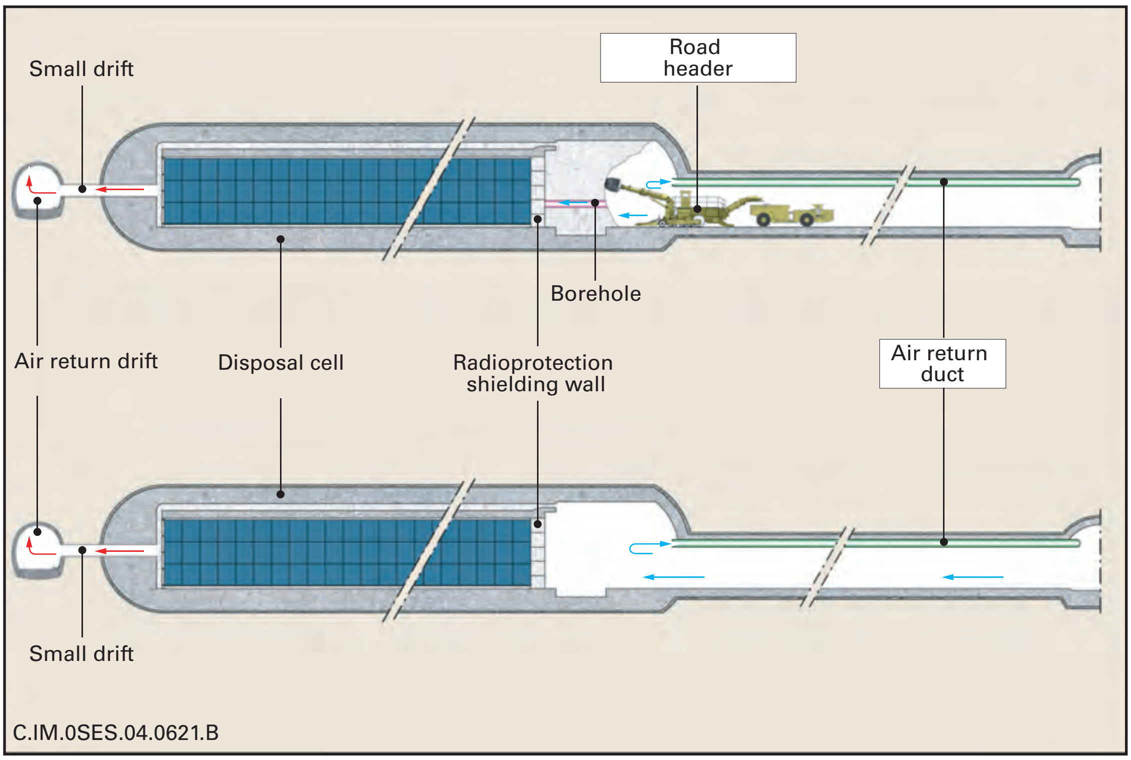
Retrieving disposal packages could be decided by future generations. To make retrieval easier, Andra has integrated this eventuality into the selected design of the installations. The retrieving equipment and procedures are similar to emplacing ones. Nonetheless, retrieval conditions vary depending on the disposal cell situation, whether sealed or not and whether access drifts and module drifts are accessible or not.

2.2.2.1 Retrieving B waste packages

In the design of the B packages and cells, there are two elements making easier package retrieval:
- *the package durability and robustness.* Concrete provide the packages with a mechanical durability of several centuries. The minimal recourse to metals and the use of stainless steel limit corrosion phenomena,
- *the stability of the cell lining and the long-term durability of functional clearances.* Lining design, the concrete making it up and the physico-chemical conditions of its environment ensure long service life and mechanical stability of the disposal cell for several centuries. Moreover, its shape minimises the residual clearances with the packages; this avoids clearance filling in between them, which would keep packages stuck to each other and to the structure.

The equipment and procedures for retrieving the packages are similar to those used for emplacing them but the preliminary preparation work differs depending on whether the cell has been sealed or not.

- *After package emplacement*, they can be retrieved at any time, as in a storage facility. Repair work is limited to equipment maintenance if retrieval is carried out a few years after package emplacement, or to replacement of equipment that has become obsolete, in the case of retrieval after several decades.
- *After cell closure* (sealed by a swelling clay plug confined mechanically by a concrete abutment), it is necessary to check the atmosphere in the cell beforehand by drilling a horizontal cased bore-hole from the drift through the entire length of the seal. It is then necessary to restore ventilation to evacuate the hydrogen and possible gaseous radionuclides given off by packages: several solutions can be envisaged, and especially drilling a specific air return drift to remove the air via the cell end.



Deconstruction process of the seal (B waste cell)

Clearing out the access drift to the cell and demolishing the seal can be performed using a mining boring machine, while radiological protection is being provided by the concrete biological protection wall closing off the cell. After that, it is possible to re-equip the cell head (installation of the shielded gates and the mobile floor in the airlock, etc.) using a procedure similar to the initial construction operations. The packages can then be retrieved.

2.2.2.2 Retrieving C waste (and CU) packages

In the design of the C (and CU) packages and cells, there are several elements that make easier package retrieval if this proves necessary or desirable:

- *the durability of the containers and their separation using ceramic elements (pads or runners)* that avoid steel to steel contact with the sleeve and prevent the stiking phenomena due to corrosion that can occur when two elements made of the same steel type are in direct contact. The repository packages thus remain free in the sleeve,

- *the integrity of the cell sleeve* designed to limit longitudinal and radial deformation over a period of several centuries and to keep the handling space between sleeve and package.

Here again, the package retrieving equipment and procedures are similar to those used for emplacement but the preliminary preparation work differs depending on whether the cell has been sealed or not.

• *After package emplacement,* a metal plug is inserted in the cell to provide radiological protection for the personnel present in the access drift and the cell head is fitted with a sealing cap that limits air renewal inside the cell. These systems can be opened at any time. After checking the situation at the cell head (making sure no gas is present that could hamper the retrieval operations and checking the condition of the temporary sleeve), the cell is re-equipped (especially by putting the shutter back in place) to enable docking the cask and the handling equipment. Packages can be retrieved using similar equipment (mobile robot and hoist) to emplacing one.

• *After the cell closure* (by a swelling clay plug confined mechanically by a concrete plug), it is necessary, after checking the atmosphere and making a visual inspection of the disposal cell, to remove the seal and install a ground support casing in the cell at the same time. These operations can be carried out by a horizontal boring machine. A temporary sleeve can then be installed and connected to the cell body sleeve. The cell head can then be re-equipped (putting the shutter back in place) for package retrieval using equipment similar to emplacing one: a protective cask fitted with fixed equipment (hoist) and a mobile robot.

• *After the module drifts closure,* connecting drifts seals can be demolished using the same procedure as for demolishing the B waste disposal cell seals. Backfill excavation is performed as well using traditional mining techniques. The condition of the drift lining must be inspected as clearing progresses and, if necessary, reinforced using bolts or arches as in current civil or mining engineering.

2.2.3 Levels of reversibility and the possibility of differentiated management

Technical analyses and studies enable various levels to be defined concerning reversibility, according to the stepwise proposal.

2.2.3.1 Overall flexibility of the disposal procedure

The modular design of the underground architecture enables progressive implementation of the disposal procedure, both for waste package emplacement in the cells and installation closure. The initial phase of package emplacement in disposal cell would thus only concern a fraction of the total waste inventory.

This gradual approach would also enable coexistence of cells, drifts or modules at various stages of reversibility. Thus the initial phase of the closing procedure would only concern closure of the cells in certain modules, with the other architectural components remaining accessible and maintained.

Such an approach enables various management scenarios and testing of various configurations for benchmarking, and refining the disposal process management while enhancing overall flexibility. It is hence possible to make the most of feedback from the initial phases of the process and therefore to modify the design of the repository structures and the means and procedures used for construction, operation and closure.

2.2.3.2 2 Possible access to the B waste modules and disposal cells

As long as the cells have not been sealed, B waste disposal is fully reversible. This entails continued ventilation in the access structures to the repository modules and inside the cells. An observation programme concerns some of the B waste disposal cells (instrumented observation cells).

The cell access structures must also be observed, monitored and maintained if necessary. The repository thus provides the same package management flexibility as a storage facility and creates relatively constant environmental conditions that are favourable for long package service life. *Packages can be retrieved by simply reversing the procedure used for their emplacement.*

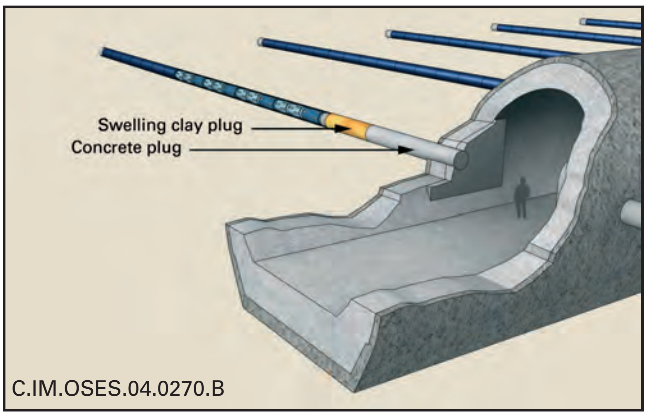
Cell sealing reduces the level of reversibility, since it reduces package accessibility. Package retrieval, if adopted, remains technically possible provided that the lining has remained intact, thanks to conservation of package integrity and functional clearances in the disposal cell. Nonetheless, it involves preparatory work: clearing out the seal, re-equipping the cell head (airlock) and restoring ventilation in the cell.

Apart from this reduction in package accessibility, repository management flexibility is not limited by closure of one or more cells: the possibilities of construction, operation (of other repository modules or zones) and waiting periods before backfilling connecting drifts remain unchanged.

2.2.3.3 Possible access to C waste (and CU) modules and disposal cells

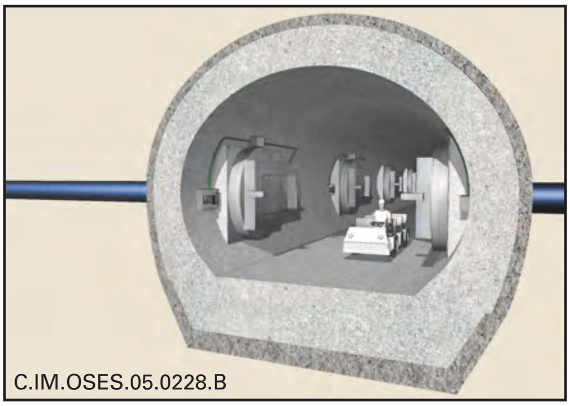
There is full reversibility for C waste (or CU), in the same way as for B waste, *provided that cells have not been sealed. It too involves continued ventilation in the access structures to repository modules.* As for B waste, an observation programme concerns some of the C waste disposal cells (instrumented observation cells).

Package management, and especially package retrievability, is equivalent to that of a storage facility, even though the conditions for evacuating heat (by conduction in the rock or in the swelling clay barrier) are different.



C waste cell after sealing

Sealing some or all of the cells in a module reduces the level of reversibility, especially due to the reduced accessibility to the packages. However, the amount of work required for removing the clay plug and its concrete abutment is moderate (a few cubic metres per cell). Package retrieval involves specific operations that have been studied and appear possible from a technical standpoint. Closing one or more cells does not affect flexibility in repository management.



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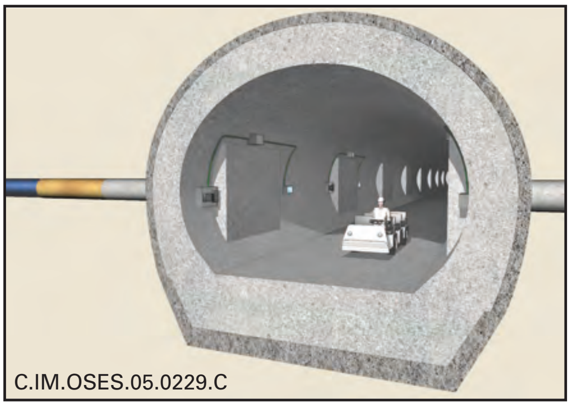
Accessibility to C waste cell head for package emplacement



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Accessibility to C waste cell head after sealing

Backfilling access drifts inside a repository module leads to a greater reduction in the reversibility level than the previous phase, because it reduces package accessibility to a more significant extent, even though it is technically possible to clear out considerable lengths of closed drifts. A greater amount of work is required to return to a previous phase.

2.2.3.4 Possible access to the main drifts and the shafts

In the following phases of progressive closure of the connecting drifts and the shafts, the reversibility level decreases solely due to the reduced accessibility to the packages: thus, to return to an earlier phase, the quantities of materials to be cleared out are equivalent to the quantities excavated to build the structures.

As long as the access structures (shafts and drifts) have not been backfilled, it is necessary to maintain them. Structures ventilation, for its part, can be continued in full or limited to certain zones. Access to a zone in which ventilation has been stopped would only be possible once restarted, and after a certain waiting period (ventilation turnaround time).

2.2.4 Minimum period of reversible management of the disposal process

Throughout the disposal process, the mechanical stability of the disposal cells conditions the possible package retrievability.

The design of B waste cell lining and C waste (or spent fuel) cell sleeve ensures their mechanical stability for 200 to 300 years without any particular maintenance, and almost fully independently of the closure phases carried out. Taking into account design margins, disposal cells should in fact be stable for even longer periods. Observing these structures would enable regular reassessment of their service life. To extend package retrievability beyond two to three centuries, specific work would be necessary (increasing maintenance, reinforcing structures, reconstructing, etc.), and it could involve temporary retrieval of emplaced packages. The work complexity increases as the various closure phases are carried out, since it involves re-opening of sections that have been sealed off, to access the disposal cells.

The period of stability of access structures lining (drifts and shafts), for its part, can be increased by maintenance work as long as these structures remain accessible. As in the disposal cell case, the period is at least several centuries. Here again, *in situ* measurements while these structure are open, and in some cases after closure, would enable to assess this period with greater accuracy.

We can consider that the ultimate phase in terms of reversible management will be marked by mechanical rupture of the disposal cell lining. Beyond that limit, indeed, retrieving packages blocked by the geological formation would involve simultaneous implementation of mining and nuclear operations. Although this would be technically possible (feedback from mining high grade uranium ore), their implementation means a low reversibility level.

A period of two to three centuries thus constitutes the minimum period during which the staged reversible management process could be implemented without involving operations on a major scale from a technical standpoint. In concrete terms, this means that whatever the level of closure reached in the repository, retrieving packages from a disposal cell is possible, once access to the cell has been restored, using handling equipment similar to waste package emplacing one. To further extend the period, it would subsequently be necessary, from a technical standpoint, to take specific steps.

5

Dossier 2005 Argile

The long-term behaviour and safety of the repository and its environment

6

The long-term behaviour and safety of the repository and its environment

One of the main purposes of the deep geological waste repository is to provide a facility that, eventually, will not require human intervention and will be able to evolve passively in complete safety. In order to do this, a knowledge corpus is required to describe the long term behaviour of the repository with a high degree of confidence and to provide a basis for the safety analysis.

During the repository operating phase, safety is based on a conventional operational approach similar to the one in other facilities of the same type. The main difficulty lies in the co-existence of mining and nuclear activities. Achieving a high degree of safety depends mainly on design provisions, the competence of and permanent monitoring by the repository management staff.

As regards reversibility, the repository observation period is similar, from the point of view of safety, to the operating phase: the same rules for personnel protection apply. The reversible management, in fact, involves the presence of personnel to control, monitor and maintain the facility. As well, time limits cannot be arbitrarily fixed for reversibility. Duration of one or more centuries does not seem to raise particular difficulties for the installations such as they are designed. Would is be necessary to extend this duration, the installations must gradually be adapted and the waste management strategy must be further examined.

This chapter presents a third phase of the repository lifetime: its long term post-closure behaviour and as well the safety approach and analyses aiming at ensuring that the repository would be able to evolve, after closure, without the need for human intervention, while meeting the objectives of protecting man and the environment. At this stage, the phenomenon of radioactive decay over time constitutes one of the most important components of the system.

The mode of analysis proposed, or safety approach, is based on several principles.

- *The safety analysis depends first and foremost on a thorough knowledge of phenomena liable to evolve in the repository and an understanding of the long term behaviour of the repository and its environment.* It involves scientific work, experiments results, models and their configuration in the form of a phenomenological analysis.
- *However, given the number and the duration of the occurring phenomena, the repository constitutes a fairly complex system.* The safety analysis is a tool which, on the basis of in-depth knowledge of the phenomena, determines priorities by highlighting key issues. The analysis draws on a rich and complex phenomenology, a cautious framework, which can be represented in the form of simplified models and digital simulations. Based on this schema, it tests the relevancy of the safety functions attributed to the various components and assesses the overall performance of the passive disposal system. It takes into account uncertainties regarding the repository evolution, the validity boundaries of the models and possible variations of the parameters. It deals with uncertainties as well as situations that deviate from the expected evolution in the form of incidents that are independent of the designer intention (for example, intrusion into the repository) or failure of certain components. It culminates in a body of calculations and analyses, the purpose of which is to assess the compliance of the calculated impact of the repository with radiological protection regulations. It produces safety indicators, that is to say, parameters used to assess repository safety in a quantified form. It sets forth the various safety margins of the disposal system.

Finally, it allows assessing the concept robustness of deep geological disposal.

1. The long term behaviour of the repository and its environment - main points

Understanding the phenomenological evolution of the repository and its geological and surface environment is closely linked with its design and constitutes one of the cornerstones of the safety analysis. *This understanding, in particular because of its systematic character, must allow for processes that condition or control radionuclides behaviour and migration. It is then possible to verify that the repository, as designed and its surrounding geological medium guarantee safety.*

The analysis applies to the construction and operating phase (one to several centuries) of the repository up to its closure as well as the post-closure period, which covers a time scale of a million years according to the waste radioactivity decay period.

The description of phenomenological evolution is based on current scientific and technological knowledge and takes into account all kinds of associated uncertainties. In this context, *the "normal" phenomenological evolution of the repository is the evolution considered the most likely* as regards scientific knowledge. *This evolution is the result of repository design provisions that take advantage of the favourable characteristics of the geological medium and contribute to limiting phenomena complexity and uncertainties regarding the phenomenological behaviour of the repository.*

Describing the phenomenological evolution of a set of engineered (packages, cells, modules, drifts, shafts, etc.) and natural components (geological host rock and surrounding formations) means an overall knowledge of all the processes governing the evolution of the repository and their coupling. The main phenomena affecting the repository must therefore be successively dealt with while focussing on their implications on other processes. For this reason, *the thermal, hydraulic, chemical and mechanical phenomena processes are dealt with before those associated with radionuclide release and transfer.*

- **Analysis of phenomenological evolution of repository situations**

In order to appraise the repository complexity, Andra has broken down its evolution into different situations: each of these situations corresponds to the phenomenological state of part of the repository or its environment at a given time in the repository lifetime and reflects the thermal, hydraulic, chemical and mechanical phenomena involved with their chronology and coupling. Together, these situations, known as phenomenological analysis of repository situations, or PARS, define the complete and continuous phenomenological evolution of the repository and its geological environment.
The PARS analysis provides:

- *results that can be used directly for design studies of the repository and its engineered structures,*
- *elements of analysis on the influence of the operation and reversibility duration with regard to the different phenomena. In particular, it has been demonstrated that the post-closure repository evolution scheme is not very sensitive to the hypotheses taken into account for the duration of operation, which could continue for several centuries as shown in Chapter 5,*
- *input data for modelling and digital simulation of the phenomena and their interaction, in view of safety analysis in particular.*

Two principles underlie the PARS: concern for completeness in order to meet the safety analysis requirements, concern for the traceability of the hypotheses and choices made during the research process in order to update the analysis as knowledge is acquired and the project develops.

Architecture that simplifies the understanding of the repository behaviour

The compartmentalisation (sub-division) of the structure architecture contributes to simplifying comprehension of the thermal and hydraulic processes related to the repository. Setting repository zones apart from each other by a distance of several hundred metres means almost independent thermal and hydraulic evolutions in these zones. Inside a repository zone, the distance in between modules and in between disposal cells allows thermal and hydraulic interactions. However, the structure of the medium and the design proposed considerably limit the extent of these. In these conditions, the analysis of the repository evolution can be approached almost independently to describe the B, C and CU repository zones. This very significantly simplifies the study of the consequences of this evolution on radionuclides release.

• Modelling the phenomena and their coupling, simulation

Besides identification work, modelling and simulation tools are required for each repository situation in order to assess and quantify, on a large scale and in the long term, evolution caused by identified phenomena. Tools have therefore been associated with each repository situation in order to *analyse and simulate the operation of the repository by extrapolation for periods of time that are beyond the field of experience*. This work is based on the identification and characterisation of the phenomena governing the repository evolution and the interaction between its components.

The modelling and simulation approach

The modelling approach is based on a detailed description first of the geometry and the characteristics of the repository components, the geological medium in particular, then of the different processes that could modify the initial state of the geological medium on a macroscopic scale (far field) and of the repository (near field).
The representation of the geological medium uses data obtained at the surface, from borehole and sampling, and directly from the underground laboratory or by geophysical seismic campaign. 3D modelling software developed for the oil industry such as GOCAD is used to integrate them. The physics and chemistry of the processes governing the repository evolution and its environment are described on the basis of the results of experiments and behavioural laws.
Various calculation codes are then selected on the basis of their relevancy to best take these phenomena into account and simulate them for the different scales in terms of space (different components of the repository and the geological medium) and time (different phases of the repository lifetime).

1.1 The thermal evolution of the repository and its environment

The emplacement of exothermal packages (C waste, CU and to a lesser extent some B waste) in the repository is accompanied by a gradual but transient increase in temperature in the repository and the Callovo-Oxfordian layer; it peaks up and then falls with the radioactive decay of the waste. The repository and geological medium then return to their initial natural temperature.

Although it is not, or only to a small degree, influenced by other hydraulic, chemical or mechanical processes that govern the repository evolution, the thermal load does affect these processes, notably both corrosion phenomena and release and transport of solutes.

Sub-dividing the repository considerably reduces thermal interaction in between the repository zones and inside these zones. As the amount of heat given off by the packages decreases with time, the thermal influence of the repository zones is negligible at a distance of 100 to 250 m vertically and horizontally speaking (median level of the Callovo-Oxfordian layer). *From the thermal point of view, the different repository zones, set 250 m apart, are therefore (very largely) independent from each other.*

The repository design limits the temperature to 90°C at most at all points in the rock. It also ensures the return to a temperature of below 70°C before one thousand years. A detailed analysis shows that, in the case of exothermal waste cells, the return to temperatures of approximately 40°C occurs after a few millennia (1,000 years in the case of C waste cells, 6,000 years in the case of CU), far earlier than water-tightness loss in the disposal packages and radionuclide release.

Finally, the increase in the temperatures in the Callovo-Oxfordian layer does not lead to any mineralogical modification of the argillites that could alter their confinement capacity.

1.1.1 A thermal phase of a thousand years duration giving rise to transient phenomena of an overall limited scale

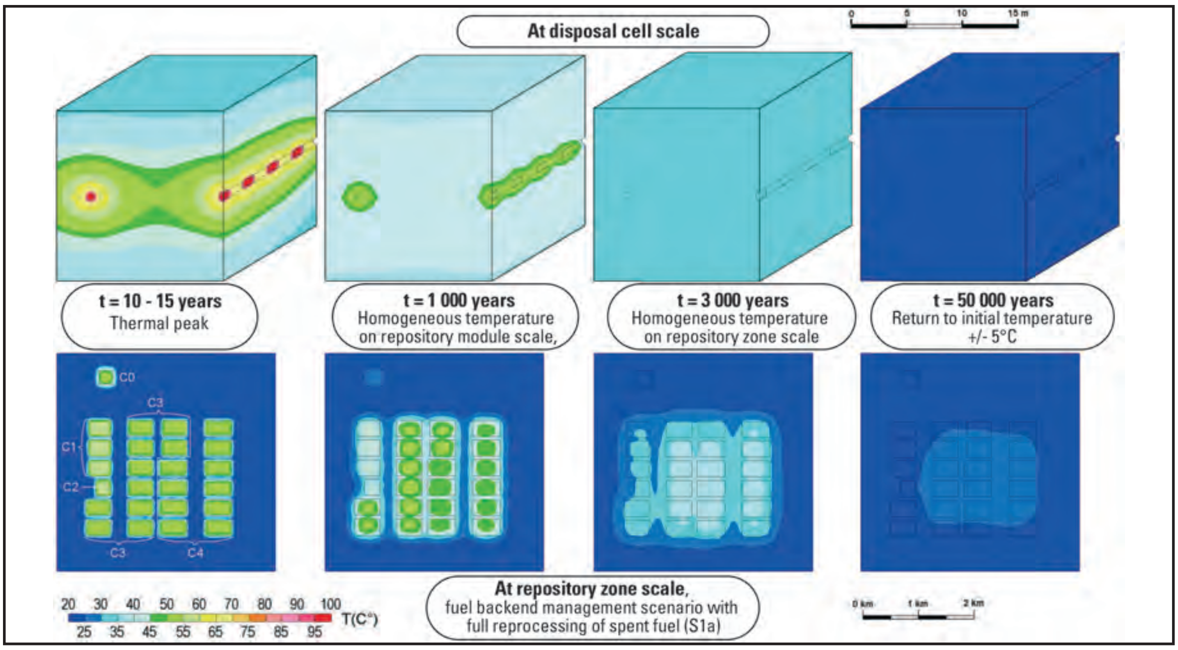
The thermal evolution of the repository is considered at different scales: disposal cells and the first metres into the Callovo-Oxfordian layer around them on the one hand, and more generally, on the scale of the geological formations (far-field).

In the disposal cells, maximum temperatures are reached within a few years in the case of the most exothermal B waste (70°C), after 10 to 20 years in the case of C waste and CU (90°C).

On the scale of the modules, temperatures become homogeneous with decay: in 500 years in the case of B waste repository modules (where they are at approximately 35°C in this time), in 1,000 years in the case of C waste modules (40 to 45°C) and in 3,000 years in CU modules (40 to 45°C).

On the scale of the repository zones, the homogenisation of the temperatures takes longer: 2,000 years in the case of B waste zones (25°C), 3,000 years in the case of C waste zones (30 to 35°C) and 10,000 years in the case of CU (30 to 35°C). These temperature levels then reduce and *the duration of most of the thermal load in the repository and Callovo-Oxfordian formation is limited to a few thousand years*. These periods of time are very short compared with those of the thermal processes driving natural evolution of sedimentary formations (which range from several million to tens of millions of years).

Temperature increases only give rise to moderate thermal gradients. The highest gradients (of the order of several tens of $°C.m^{-1}$) are reached in C waste and CU disposal cells during the first years after package emplacement but they drop rapidly as the temperatures in the repository zones become homogeneous. They are lower in the Callovo-Oxfordian layer (a few $°C.m^{-1}$) and limited to the immediate proximity of the cells (several decimetres to a few metres) over a period of approximately 100 years. As in the case of the repository, they drop rapidly as temperatures become homogeneous.



Temperature evolution in a C waste repository zone, cross section and horizontally

In the Callovo-Oxfordian surrounding formations, the maximum temperature increase is reached after 500 years and remains limited : to 20°C maximum at the boundaries of the Callovo-Oxfordian formation, to 5°C in the upper Oxfordian and less than 1°C in the case of the Kimmeridgian and Barrois formations.

Consequently, if, moreover, its limited duration is taken into account, the thermal load is not a determining parameter in the phenomenological evolution, at a macroscopic scale, of the Callovo-Oxfordian layer and the surrounding formations.

1.1.2 Limited and controlled consequences

Given the limited duration of the thermal processes and the maximum temperatures reached in the various zones of the repository, the argillite layers initial properties and the repository components characteristics are not, or only to a small extent, affected. In particular, the mineralogical transformations in the Callovo-Oxfordian formation are small.

The thermal load that affects the repository and the Callovo-Oxfordian layer does not cause any significant mechanical phenomena, in particular, mechanical damage at the scale of the formation. The temperature increase kinetics is slow (several decades) and the thermal load is homogeneous enough at the scale of the Callovo-Oxfordian formation. The field of thermo-mechanical stresses therefore does not cause damage (fracturing) to the layer at a macroscopic scale.

The limited duration of the thermal phase means that the phenomenological evolution of the repository and its geological environment takes place, for the most part, in natural temperature conditions. In particular, the leak-tightness duration of C waste and CU containers, which is linked to their corrosion resistance and mechanical strength (at least 4,000 years and 10,000 years, respectively), means that radionuclide release and then migration are not, or only to a small extent, affected by the thermal load as the cell temperature is lower than 40°C.

The temperature field and its evolution over time are, however, taken into account in the dissolution models of the containment matrices (glass for example) to determine the parameters governing the transport of radionuclides (solubility, distribution coefficient or partition coefficient between the solid and soluble fraction) in the repository and its immediate environment.

1.2 The hydraulic evolution of the repository and its environment

As major component of the phenomenological evolution, *the hydraulic evolution of the repository and its environment has a significant impact on the chemical and mechanical evolution and, therefore, on the degradation of waste packages and ultimately on the release of radionuclides by the packages. In addition to the chemical evolution, it determines the mobility of the radionuclides released and their transfer into the biosphere.* Therefore more particularly:

- *The initiation of the chemical processes* (degradation of the concrete, for example) requires the presence of water and their continuation over time and space depends significantly on the water flows and/or the quantities of solutes liable to be transported by these flows or displaced by diffusion in the water,
- *The mechanical behaviour* of the repository components and the Callovo-Oxfordian argillites also depends on the presence of water. This dependence can be direct, as in the case of the argillites (while excavating or operating in particular) and the cell plugs and seals whose plasticity and rupture behaviour depend on their saturation state. It can also be indirect, via chemical processes such as corrosion that modify the mechanical resistance of the steel components,
- *Radionuclides release* results above all from the chemical and mechanical degradation of the packages under the effect of water (corrosion of the metal containers, attack of the concrete containers, alteration of the glass matrix). After the radionuclides release, their transfer into the biosphere depends partly on the flow of water and the transport conditions of the solutes in the repository, then in the Callovo-Oxfordian layer and the surrounding formations.

Prior to the repository construction, the geological formations are at hydraulic equilibrium:

- *In the Callovo-Oxfordian layer*, very small water flows are organised vertically between the carbonated formations of the Dogger and the Oxfordian due to the hydraulic head gradient between the two formations.

Given the low permeability of the Callovo-Oxfordian formation ($5{\cdot}10^{-13}$ to $5{\cdot}10^{-14}$ m/s on average), these water flows are very low (a few hundredths of a millilitre per year and per m^2) as is their velocity (approximately a few centimetres per 100,000 years). In this context, the transport of solutes in the Callovo-Oxfordian layer takes place mostly by diffusion;

- *In the calcareous Oxfordian and the Dogger formations*, water flows are horizontal. Given the permeability of some levels of these formations (10^{-9} m/s to 10^{-8} m/s on average), solutes transport takes place there essentially by advection.

The repository disrupts this initial hydraulic state. The shafts drain the water from the upper formations during repository operation. The presence of the repository also brings about the desaturation of the argillites surrounding the ventilated underground engineered structures during the operation phase and after closure during the hydrogen production phase related to the repository metallic components corrosion (waste containers, cells components, etc.). *The hydraulic disturbance caused by the repository remains limited to the repository itself and the Callovo-Oxfordian formation on account of its low permeability. It disappears after approximately 100,000 years and a new state of hydraulic equilibrium is then established in the repository and the Callovo-Oxfordian layer.*

After several hundred thousand years, and up to a million years, the climatic cycle effects are liable to give rise to modifications in the morphology of the ground surface. During this period, the geodynamic evolutions and their impact on the surface are the main factors that influence the geological environment, in particular that of the overburden formations.

1.2.1 Local hydraulic disturbance in the overlying formations associated with repository operation (secular time scale)

Leak-tight throughout the Tithonian, the access shafts of the repository have no hydraulic impact on this formation. The water flows in the other surrounding formations, the Kimmeridgian marls and the calcareous Oxfordian formation, are so low that shaft sections intercepting them do not need to be leak-tight. The shaft presence causes a hydraulic head drawdown in these formations and possible desaturation: in Kimmeridgian marls, the hydraulic head drawdown is limited and the extent of the desaturated zone does not exceed a few decametres radially around the axis of the shafts; it is greater in the Oxfordian formation and the desaturated zone extends to several hundred metres.

After repository closure, shaft sealing in the Callovo-Oxfordian formation and the water flows in these formations allow a return to hydraulic equilibrium: in a few hundred years in the calcareous Oxfordian layers and several thousand years in the Kimmeridgian marls because of its lower permeability.

The hydraulic disturbance caused by the shafts on the overlying formations is therefore a local reversible phenomenon that will have disappeared before the arrival of radionuclides in the overlying formations (the latter is not liable to occur before several hundred thousand years).

1.2.2 Hydraulic disturbance due to the repository in the Callovo-Oxfordian formation

1.2.2.1 During the operating phase: desaturation of the Callovo-Oxfordian formation around ventilated engineered structures limits very significantly the chemical processes and argillite creep

The ventilation of the drifts, access shafts and B waste cells during operation leads to *the desaturation of the surrounding argillites* combined with the hydraulic head drawdown progressing gradually in the argillites. In the drifts and access shafts, desaturation affects the entire concrete infrastructure and the excavation damaged zone (EDZ) over a few years. It then propagates very slowly as far as the sound argillites over the one or more centuries of the duration of the operating period.

Desaturation progresses in a similar fashion around the B waste cells. Like the concrete components of the cells, the disposal packages are highly desaturated.

On the other hand, the absence of ventilation in C waste and CU cells, in addition to their plugging (leak-tightness lid during the operation phase) prevents desaturation of the surrounding argillites.

The operating period can be considered a "dry" period in the case of ventilated structures. Chemical processes are then (very) limited, especially the concrete chemical degradation of the infrastructure and of B waste disposal packages. From the mechanical point of view, the non-saturated state of all or part of the excavation damaged zone tends to delay or halt the argillites creep, thus limiting the mechanical loading of the repository ground support.

1.2.2.2 Post-closure: the transfer of corrosion hydrogen and the resaturation of the entire repository over several tens of thousands to a hundred thousand years

The resaturation of the engineered structures by argillites water begins once they are closed, as does that of any argillites which were eventually desaturated by ventilation during the operating phase. Given the low permeability of the argillites, it is a slow process. It is associated with the production of hydrogen from the corrosion of metal components (and to a lesser extent, the radiolysis of water or organic matter), which delays the return to complete saturation.

Given the very low corrosion rates (a few microns/year[11]), the main hydrogen production phase lasts for several thousand years (of the order of 5,000 years) in C waste and CU disposal cells and several hundred years (of the order of 500 years) in the case of B waste cells. On the basis of experimental work carried out on samples and in borehole, and aiming at evaluating the hydrogen transfer properties in argillites, modelling was carried out to appraise hydrogen behaviour.

Hydrogen dissolves until saturating the near-field water. The excess is then expressed in gaseous form and migrates by biphasic flow through the damaged zone up to the drifts and the sound argillites once the gas pressure has increased sufficiently to enable the gas to enter the rock. In the case of CU cells that contain a greater amount of steel, gas production is faster than its evacuation by biphasic flow; gas pressure in the disposal cell increases until reaching the pore-opening (or micro-fracturing) threshold of the argillites and swelling clay components (cell plugs or seals). Micro-fracturing allows the gas to flow out of the disposal cell and this does limit pressure increase. It has been observed on samples and through borehole testing that the microfissures close again once the gas has passed through without altering the hydraulic properties of the rock (the water permeability of the argillite remains unaltered).

[11] These rates are rather conservative with respect to the expected ones, which could in fact be of the order of a fraction of a micron per year. The quantity of hydrogen is therefore overestimated. With lower corrosion rates than those taken into account, gas pressures would be lower and the effects even more limited.

In all cases (B, C waste and CU cells), the gas pressure inside the cell remains lower than rock fracturing pressure (12 MPa): it is 7 MPa maximum in B waste cells, 6 to 7 MPa in C waste cells and 9 MPa in CU cells. As it is evacuated into the geological medium and repository drifts, the gas pressure in the cell decreases until it can no longer migrate biphasically and moreover via micro-fracturing; it therefore evacuates slowly by diffusion in dissolved form.

The transfer of hydrogen in the Callovo-Oxfordian formation does not bring about significant desaturation of the rock (argillites saturation is greater than 97% in the near field and 99% in the far field). During the hydrogen production phase, gas pressure in the cell leads to an increase in the interstitial water pressure in the near field which gives rise locally (a few metres around the cells) to hydraulic head gradients. These gradients disappear as the pressure drops and the gas is gradually evacuated. Their extent is limited and the very low permeability of the argillite means that the dominant transport of the solutes, however, remains diffusive on the scale of the Callovo-Oxfordian layer.

After several thousand years, the hydrogen flow gradually reduces and resaturation takes place slowly. Over a period of several tens of thousands of years, the repository is not totally resaturated and this contributes to significantly limit the chemical degradation processes of the repository components (concrete, argillite) which require the presence of water. The gradual resaturation of the repository at macroscopic scale is completed from one to two hundred thousand years after closure.

1.2.2.3 After total resaturation of the repository: a new state of hydraulic equilibrium

After total resaturation of the repository, a hydraulic equilibrium is established in the repository and the surrounding Callovo-Oxfordian formation:

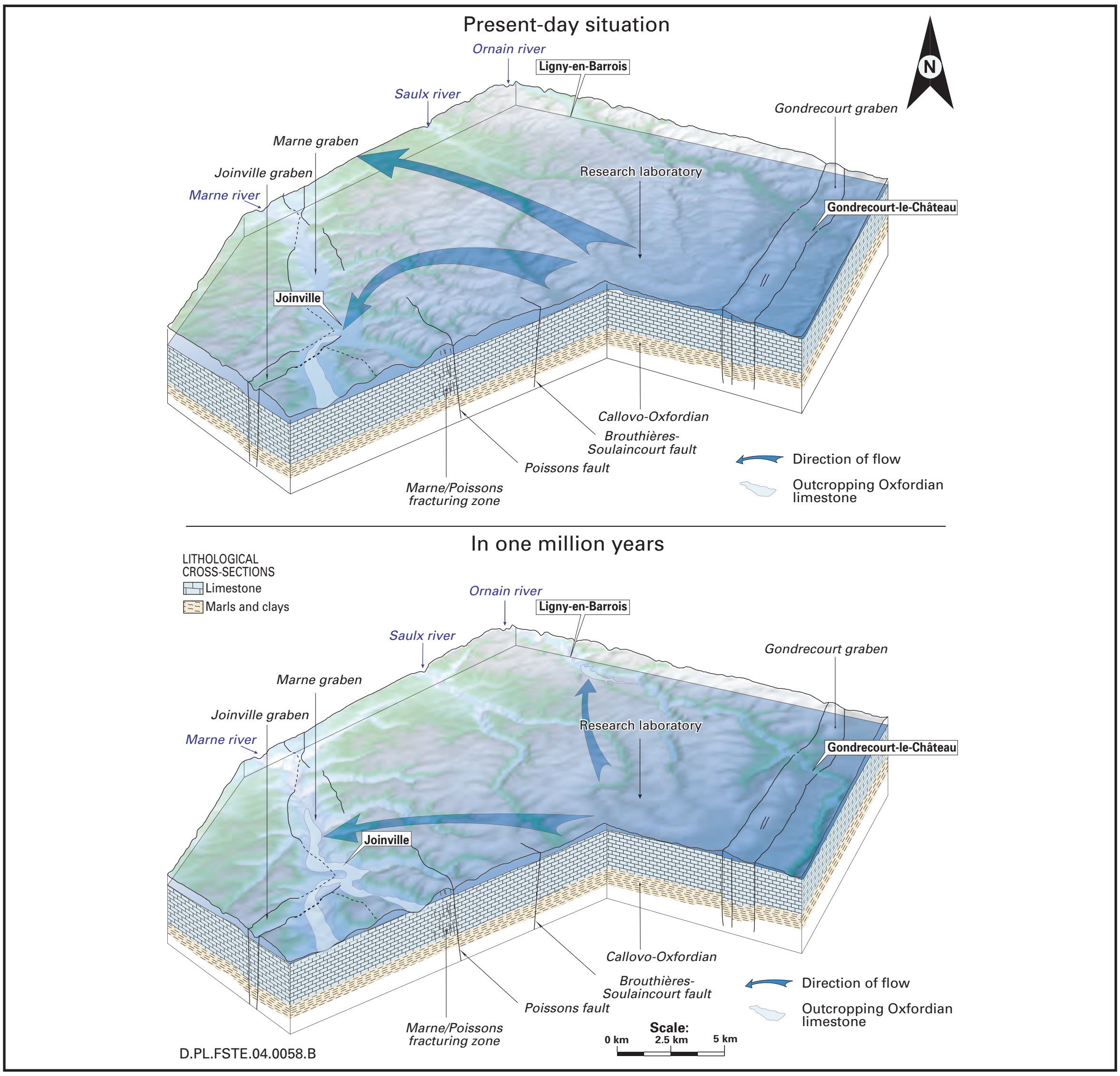
- laterally, beyond a few hundred metres from the repository, the Callovo-Oxfordian formation returns to its initial hydraulic state,
- vertically, the repository drains a small proportion of the flows through the Callovo-Oxfordian formation: a water flows appears along the repository engineered structures and the shafts (several tens to several hundreds of litres per year), far too little to transport solutes by advection. *Diffusion is the dominant mechanism of solutes transport (radionuclides in particular) and everything is similar as in the initial state prior to the repository construction.*

In this hydraulic context, the chemical and mechanical evolution of the repository and ,in fine, the release and transfer of the radionuclides in the Callovo-Oxfordian formation take place.

1.2.3 The evolution of flows and transport over a time scale of several hundred thousand years is related to geodynamic evolution

Geodynamic evolution means the gradual erosion of surface terrains due, in particular, to climate change: their hydraulic effects therefore affect the geological formations overlying the Callovo-Oxfordian formation, in particular the calcareous Oxfordian formation where flows are modified.

Studies on the future climatic changes in the northern hemisphere show *a succession of glacial cycles* every 100,000 years approximately over the next million years. Depending on whether or not the anthropic effect (impact of human activities) is taken into account, the next glacial maximum is expected to occur in between 100,000 years and 600,000 years. During the glacial maxima, glaciers are not expected to appear the latitudes of the site studied and permafrost does not reach the Callovo-Oxfordian formation.



Schematic representation of the evolution of water flows in the calcareous Oxfordian layer, at the current state and in a million years

Over the next million years, glacial cycles and ground uplift entail *an erosion* of several tens to some hundred metres depending on the topography. This will result, after 300,000 to 500,000 years, in valleys deepening down to the Oxfordian formation and a drop in the level of the plateaux. To the east and south of the sector, these topographical modifications push back the outcropping zones corresponding to the recharge areas of the formations to the west and north-west and decrease the hydraulic head in the surrounding formations, in particular the calcareous Oxfordian formation. *It is therefore only on a time scale of 300,000 to 500,000 years that the geodynamic evolution gradually modifies flow directions in the overlying formations* and, to a lesser extent, in the underlying Dogger formation. In the Oxfordian formation in particular, the direction of the initial north-west regional flow becomes attenuated and new local directions appear with new local outlets in the deepening valleys. However, *flow rates in the carbonated formations of the Dogger and of the Oxfordian remain similar to those observed currently in the transposition zone*.

Because of its depth, the Callovo-Oxfordian layer is not directly affected by erosion. Water flow remains similar to the current state (in the transposition zone, generally vertical ascending) but with a greater hydraulic head gradient (ranging between 0.1 and 0.4 m/m) *still without modifying the solutes transportation which remains mainly diffusive*.

1.3 The chemical evolution of the repository and its environment

The thermal and hydraulic evolution of the repository and its environment define the context of its chemical evolution:

- *associated with hydraulic and thermal evolution, the chemical evolution determines the mechanical behaviour of the repository components*. For instance, the chemical degradation of concrete by Callovo-Oxfordian water gradually alters the mechanical properties of the ground support of the repository structures,
- *radionuclides release by the waste packages is the result of* chemical processes, for example, the corrosion of metals that results in the gradual loss of leak-tightness of the C waste and CU packages, and the aqueous dissolution of the glass that gradually releases radionuclides,
- *after release, the radionuclides solubility, their mobility and their possible transfer into the Callovo-Oxfordian argillites depend on the surrounding chemical conditions.*

Chemical evolution

Chemical evolution arises from various imbalance kinds:

- *chemical imbalance* resulting from the contact occurring between interfacing materials (argillite from the Callovo-Oxfordian formation, metal from B and C waste and CU packages, concrete of the B waste packages and ground support, swelling clay of the seals and plugs, argillite of drift backfill, CU uranium-plutonium oxide matrices , bitumen, etc.), chemical compounds and different kinds of fluids,
- *thermal imbalance*: temperature is an important parameter of chemical reactions and its increase, due to exothermal waste packages, above all affects the repository and Callovo-Oxfordian formation,
- *hydraulic imbalance*: water is necessary for the development of chemical reactions which extent then depends, in many cases, on water flow and the exchange of solutes participating in these reactions.

Chemical processes are above all interface processes that involve the repository and the near-field Callovo-Oxfordian formation. The surrounding formations are far enough from the repository in order not to be significantly affected.

The hydraulic properties of the Callovo-Oxfordian argillites (very low permeability, low diffusivity) significantly limit water flow in and around the repository before and after the complete saturation of the repository. During the partial saturation phase (first tens of thousands of years of the repository evolution), the reduced availability of the water in contact with the repository components significantly limits their chemical degradation. After resaturation, the progression of the chemical reagents involved in the chemical disturbance is slow on account of their diffusive transport.

Chemical evolution is therefore dominated by very slow concrete degradation processes, corrosion of metal components and the alteration of waste that leads to the slow and gradual release of radionuclides.

1.3.1 Limited chemical disturbance mainly affects the repository and the near-field Callovo-Oxfordian formation

The hydraulic and chemical properties of the Callovo-Oxfordian formation and in particular its significant capacity to provide a "chemical buffer" limits disturbance caused by the repository and its immediate environment. The repository does not give rise to a chemical effect on the Callovo-Oxfordian formation beyond a few metres at most from the engineered structures; in particular, the chemistry of the interstitial water is not modified. Given both their distance and the capacity of the Callovo-Oxfordian formation to significantly limit the progress of these disturbances, the surrounding formations are not affected by the chemical evolution of the repository.

Therefore, the chemical disturbances develop at the interfaces between repository materials (used in cells, drifts, etc.) and the rock (or the swelling clay engineered barrier of CU cells).

The alkaline disturbance of the argillites when in contact with the concrete engineered structures (drifts and B waste cells in particular) is characterised by two mineralogical zones:

- the first one, remineralised by cement-based water, covers the fractured zone of the EDZ (with an metric extent at most). It means hydraulic properties close to the sound argillites ones, low permeability in particular,
- the other one, slightly disturbed, presents too similar hydraulic and mechanic properties to the sound argillites ones.

On the scale of the Callovo-Oxfordian layer, the consequences of alkaline disturbance are limited to a metric-extent zone corresponding to the fractured zone. The transformations of mineralogy and of the chemistry of the associated water do not tend to modify radionuclides migration process within the layer.

Swelling clay plug and seal performance: very limited chemical perturbations

Alkaline disturbance also affects swelling clay elements (cell plug, engineered barrier of the CU cells, drift seals). These interactions are, however, limited and do not alter the properties (low permeability, swelling and retention capacity) nor the components performance on a macroscopic scale.

• **in the case of C waste and CU cell**, alkaline disturbance develops in the plug made from swelling clay (bentonite) in contact with the support base concrete. Its extent after one million years is approximately 60 cm in the case of the remineralised zone and is less than 2 metres in the case of the slightly disturbed zone. Over more than 80% of its length, the cell plug is subject to no mineralogical disturbance liable to modify its hydraulic properties.

• **in the case of B waste cell and drift seals**, the ground support and lining concrete degrades very slowly, over several hundred thousand years, giving rise to limited alkaline disturbance in the core of the swelling clay and in the EDZ cut-off anchoring keys: the swelling properties and hydraulic role of the cut-off grooves are preserved over a time scale of a million years. Because the disturbed fraction of the swelling clay core is very low compared with its volume, it also preserves its mechanical and hydraulic properties.

The inflow of oxygen via air ventilation disrupts the chemical situation of the argillite in ventilated engineered structures and leads to mineralogical transformations caused by the oxidation of certain components of the rock (mainly pyrites and organic matter); this is *the oxidizing disturbance*. It affects the immediate vicinity of the fractures created by the excavation work: it only affects a limited extent of the shear fractures (about one metre) and their immediate surroundings (a few centimetres); it penetrates a few centimetres at the most into the deconfinement-induced fractured zone of the rock around the structures.

Therefore, the oxidizing disturbance only affects a small fraction of rock components.

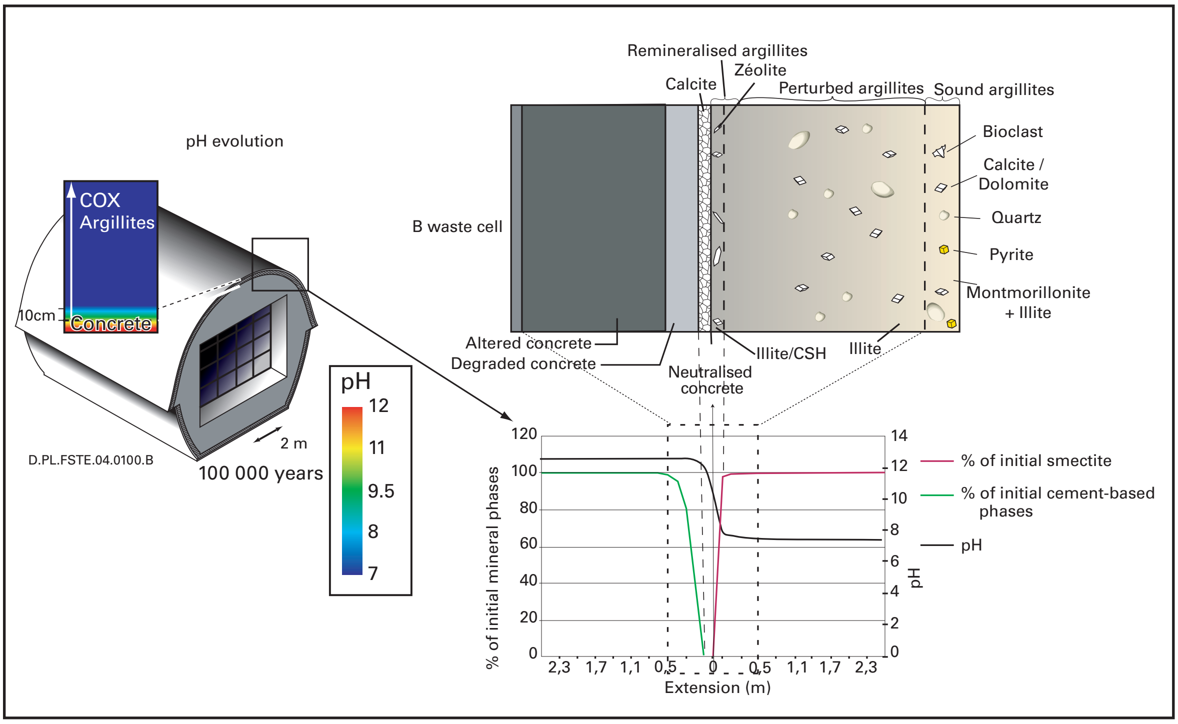
What is known as iron/clay disturbance develops at the interfaces between the metal components of the C waste (and CU) cells and the Callovo-Oxfordian argillites (or the swelling clay engineered barrier) due to the interaction between iron and clay minerals of the argillite (or bentonite engineered barrier). It has a very limited extent (a few centimetres).

In summary, the chemical disturbance caused by the repository in the Callovo-Oxfordian layer is essentially limited to a thickness of less than one metre to a few metres which is not very significant when compared with the minimum buffer zone thickness of 50 m of Callovo-Oxfordian between the repository and the surrounding carbonates.

1.3.2 Radionuclide releases following the slow package degradation takes place in a chemical environment that favours their immobilisation

• In B waste cells

Chemical degradation first affects ground support and lining concrete. Associated with small water flow and slow solute transfer in argillite, the "chemical buffer" capacity of concrete and the thickness of lining and ground support limit the advance of chemical degradation fronts towards the packages: the latter remain in a stable cement-based environment over several hundred thousand years. After several hundred thousand years, the chemical degradation of the cement-based materials by argillite water affects an area near the disposal cell walls and leads to a water chemistry that is different from that of sound concrete. However, the solubility and retention of most of the radionuclides are not significantly modified compared with those of sound concrete. Sound cement-based conditions are maintained at the core of the cell, notably in waste packages; the concrete envelope of the disposal package is chemically preserved over several hundred thousand years.



Scheme of alkaline perturbation in argillites around B waste cells and of lining concrete degradation at 100,000 years

The slow degradation of primary B waste packages therefore develops in a cement-based environment that is favourable for waste and perennial; its duration ranges between several tens of thousands of years in the case of bituminised waste and several tens of thousands of years to several hundreds of thousands of years in the case of technological waste and hulls and end caps packages. Radionuclides release occurs gradually in a chemical environment favourable to radionuclide immobilisation (solubility and retention).

• In C waste (and CU) cells

Metal component corrosion is very slow with rates of a few microns per year, or even less. *In this context, C waste package over-packs and CU containers should preserve their mechanical strength and their leak-tightness for durations that are considerably longer than the design planned duration (4,000 and 10,000 years respectively): of the order of 15,000 years in the case of C waste package over-pack and 30,000 years in the case of CU containers.*

With the loss of container tightness, radionuclides begin to be released by the waste packages. In the case of vitrified waste, it is assumed that dissolution in a clay medium continues for several thousand years *in the case of C0 glass and approximately several hundred thousand years in the case of C1, C2, C3 and C4 glass. Apart from the labile fraction (immediate availability) representing 10 to 35% of the radiological inventory, CU assembly oxide matrices dissolution lasts for several tens to hundreds of thousands of years if a radiolytic dissolution model is taken into account (dissolution is controlled by oxidizing species formed by water* *radiolysis). The latter, which was adopted, is more pessimistic than the conventional dissolution model (dissolution is controlled by uranium and plutonium solubility and transport in the disposal cell and argillites reducing conditions). The conventional model is currently used internationally used and leads to a duration for release of over a million years. Corrosion of stainless steel and zircaloy assembly claddings lasts over several tens to hundreds of thousands years.*

The chemical composition of the water that comes into contact with the waste (and fuel assemblies) is close to that of the argillites interstitial water (in particular it has a reducing character and neutral pH), which is favourable to the immobilisation of a significant fraction of the inventory.

1.4 The mechanical evolution of the repository and its environment

The thermal, hydraulic and chemical evolution define the context of the mechanical evolution which constitutes an important parameter for repository operation and observation both from the point of view of the underground engineered structures construction and the possible retrieval of packages in the framework of reversibility. After closure and in the long term, mechanical degradation of the waste packages participates in the radionuclides release, although the latter is mainly governed by chemical processes. The hydraulic properties of the seals, cell plugs and mechanically damaged argillites (EDZ) depend, in part, on the state of mechanical stresses in these engineered structures. The mechanical evolution therefore plays a role in *the establishment of the water flow in and around the repository and the transfer of radionuclides once released.*

Before repository construction, the Callovo-Oxfordian formation and the geological medium are at mechanical equilibrium and the state of the stresses has been stable for several million years. The repository causes locally an imbalance and a mechanical evolution related to structures excavation (which leads to a loss of confinement of the rock around these structures), then to the thermal, hydraulic and chemical processes involved in the repository and geological medium.

The transient period before the total resaturation of the repository contributes to limiting the structures chemical degradation and their mechanical properties modification. After returning to the saturated state, given the slow water flow rate and velocity (in and around the repository), the chemical degradation processes and, consequently, the modification of the mechanical properties of the repository components are slow and of limited extent.

The mechanical effects associated with the repository are restricted to the Callovo-Oxfordian formation in the immediate vicinity of the engineered structures. Indeed, the distances in between the cells, on one hand and in between the repository modules, on the other hand, limit or prevent mechanical interference between the engineered structures. The effects of excavation in the Callovo-Oxfordian formation around the engineered structures are limited to a maximum zone of a few metres (EDZ), as compared with the minimum "buffer zone" thickness of 50 metres of sound Callovo-Oxfordian formation between the repository and surrounding formations (carbonated Oxfordian, Dogger).

1.4.1 The creation, around the engineered structures, of an excavation damaged zone (EDZ) with a trend to heal with the long term deformations of the argillites

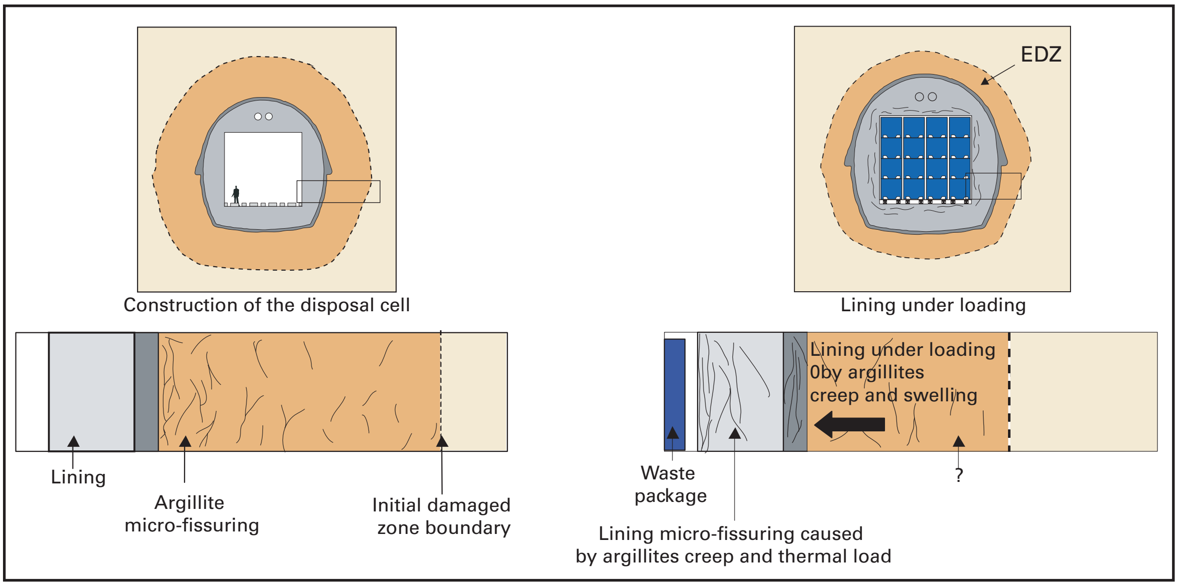
Excavating structures redistributes the stresses and deformations in the argillites, leading to the formation of a damaged zone (EDZ) in the rock in the immediate vicinity of the structures. This initial damaged zone is characterised by the appearance of more or less connected fissures, whose density decreases with distance from the wall. Two concentric zones are conventionally distinguished that relate to rock deconfinement by excavating: the first one in direct contact with the structures, corresponds to connected fracturing parallel to the axis of the structure (fractured zone) while the other one located at the first one periphery, corresponds to diffuse, hardly connected fissuring (microfissured zone).

Excavating can also create shear fractures ahead of the excavation work face that are oblique to the axis of the structure. Following excavation work, only shear fractures ends remain at the walls, thus forming a "chevron" network. The extent of these shear fractures is about the same as the microfissured zone one.

Rock deconfinement at the edge of the structures may lead to an increase in the argillites fractured zone permeability by a factor of about 10 000 compared to the sound argillites one (5.10^{-14} - 5.10^{-13} m/s). The argillites permeability in the microfissured zone is increased by a factor of about 100. The permeability of the sheared zones beyond the fractured zone approaches or is less than that the microfissured zone one.

In hydraulic terms, the initial damaged zone observed around the structures can thus be considered as two concentric zones:

- the permeability (5.10^{-9} m/s) of the first one (the fractured zone) is very much higher than that of the sound argillites. It extends to less than one metre (about 60 cm according to the models) for a B waste disposal cell and about a few centimetres (less than 5 cm according to the models) for a C waste disposal cell;
- the permeability (5.10^{-12} to 5.10^{-11} m/s) of the second one is less modified when compared to sound argillites. The extent of this zone is at the most equal to that of the microfissured zone, that is less than 6 m for a B waste cell and 20 cm for a C waste cell.



Schematic EDZ evolution around a B waste disposal cell, from operating phase until post-closure (first thousand years up to 10,000 years)

The selection of materials that are well integrated in the geological medium from the chemical point of view, their emplacement procedure and the limitation of void spaces in the engineered structures confer an overall mechanical stability on the latter and avoids the propagation or intensification of the initial damaged zone.

During the partial saturation phase of the repository, in particular *around B waste cells, drifts and shafts* where the argillites become desaturated, the chemical and mechanical processes such as concrete degradation and argillites creep are slowed down. Desaturation stiffens the argillites and can lead to hydric fissuration over a thickness limited to a few decimetres around the engineered structures. This does not increase the extent of the initial damaged zone. With resaturation, argillite swelling tends to heal this hydric fissuring. In the long term, the gradual nature of the mechanical load on the cells (argillite creep), the small rate of void spaces in these engineered structures and the slow chemical degradation of their components do not lead to sudden fracturing of the engineered structures: their mechanical evolution is gradual over a time scale of several thousand years and does not lead to the propagation or intensification of the damaged zone.

Around the C waste and CU cells, temperature increase in the argillites during the first decades after package emplacement in the repository gives rise to thermomechanical stresses. Around the periphery of the cells, these can result in a fractured zone with a maximum extent of some ten centimetres. In the cell plug, clearance minimisation and bentonite swelling (effective in a few years to several decades) as well as a more limited temperature (less than 70°C) do not lead to the development of a fractured zone. Beyond this thermal phase, the return to a natural stress field leads to the re-establishment of the initial damaged zone.

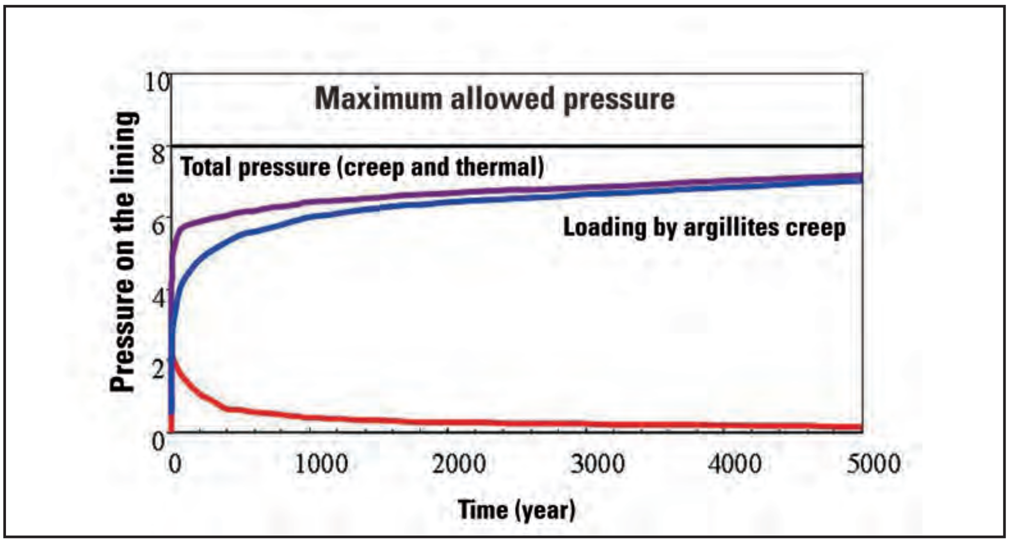
In the long term (over a time scale of several tens of thousands of years), the deferred deformation of the argillites results in a gradual loading of the underground engineered structures. The ground support of these engineered structures, then in the longer term the backfilling materials, take up the stresses. Creep, accompanied by the resaturation of the argillites, gives rise to the closure of any fracturing of the rock and compresses the micro-fracturing of the damaged zone. *This gradual healing of the rock tends to re-establish a degree of permeability close to the sound rock one*. As regards sealing of the B waste cells and drifts, the construction of anchors (cut-off grooves backfilled with swelling clay) provides interception of the whole fractured zone and thus re-establishment of the continuity of the medium.

1.4.2 The underground engineered structures are mechanically stable over a time scale of several centuries to several thousands of years

During the operation and reversibility period, the non-saturated state of the repository is accompanied by argillite creep slowing down, or eventually stopping, and the absence of chemical degradation (or very limited degradation) of the engineered structures components.

The mechanical evolution of the engineered structures is limited and their stability ensured.

- *The B waste cells and drifts* are only fully saturated several tens of thousands of years later. The absence of saturation limits the chemical degradation of the lining concrete by the argillite water and preserves the mechanical properties of the components (or slows down significantly their evolution). Similarly, the desaturation of the argillites around the engineered structures delays, and even blocks, argillite creep, thus limiting the loading of the linings which guarantees the mechanical stability of the engineered structures. *The resumption of argillite creep with the gradual resaturation of the argillites results in stress on the linings that do not reach their mechanical resistance threshold before a few hundred to a few thousand years which ensures the stability of the engineered structures over these periods of time*.
- *Around C waste and CU cells* which are not ventilated during operation, the argillites are saturated. The saturation of the CU cell engineered barriers is reached after a few hundred years. Argillite creep and engineered barrier clay swelling enable filling functional clearances around the cells during the course of this same period. Because of the slow progress of their corrosion rate, *the metal sleeves conserve their mechanical integrity for at least several hundred years which guarantees the stability of the engineered structures over these same periods of time.*



Plot showing mechanical loading of B waste cell lining by argillites creep

1.4.3 The slow mechanical evolution of the repository over several hundred thousand years

After the complete saturation of the repository, its mechanical evolution is governed by the slow chemical degradation processes of its components, argillite creep and the swelling properties of swelling clay.

At closure, the engineered structures (essentially the drifts) are backfilled to reduce at best the remaining void spaces. The materials used have swelling properties (seals) and sufficient stiffness (backfill) to withstand the stresses arising from the geological medium. The materials properties are not, or are only slightly, affected by the chemical processes which, conversely, sometimes improve the engineered structures backfill (for example, the expansion of corrosion products) or their stiffness (the chemical degradation of concrete which leads ultimately to its calcification). By limiting long term argillite creep, this backfill prevents deformation on a macroscopic scale, stops the argillite from fracturing and allows the return to a state of homogeneous mechanical stress.

Over a time scale of several hundred thousand years, the erosion associated with climate changes expected over the course of a million years and internal geodynamics (uplifts and earthquakes) are not liable to significantly modify the natural stress field on a macroscopic scale or cause deformations in the geological medium. In the zones subject to erosion, the gradual reduction of eroded terrain loading means locally a reduction in terms of vertical stress. This reduction has no effect on the mechanical behaviour of the geological formations, particularly the Callovo-Oxfordian formations and the repository.

1.5 Main points of the evolution of the repository as regards the radionuclides release and transfer

In the long term, waste package degradation leads to radionuclides release in the disposal cells; this occurs directly as water arrives or gradually as water alters the waste or its matrix, for example through the aqueous dissolution of the glass matrix.

The chemical environments encountered by the radionuclides determine their solubility and retention. A large proportion of the radionuclides are immobilised in the near field and do not migrate. The radionuclides that can migrate beyond the disposal cells do so very slowly by diffusion. A very small proportion of the radionuclides ultimately reach the surrounding formations after diffusion in the Callovo-Oxfordian argillites.

1.5.1 Slow and limited release of radionuclides beyond the repository

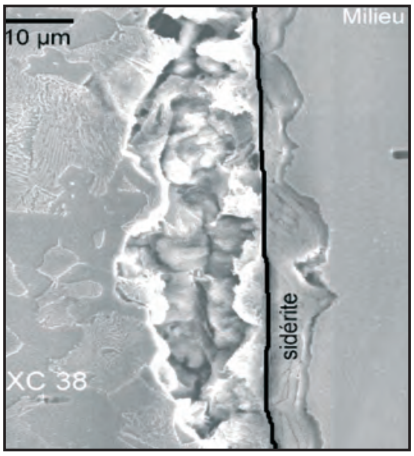
1.5.1.1 The non-saturated period of the repository

As long as the cells are not saturated, the waste is preserved from any water arrival. Non gaseous radionuclides remain confined in their matrices and in the elements which constitute the waste.

Some B packages, however, release traces of gaseous radionuclides that can migrate in the near-field in gaseous form in the non-saturated zone. Tritium, krypton^{85} and argon^{39}, which are very short-lived if compared to resaturation duration, disappear in approximately one thousand years, before the end of resaturation and do not migrate out of the repository. Carbon^{14} and chlorine^{36} are longer lived nuclides and dissolve in the near-field in the interstitial water with resaturation. They can then migrate in dissolved form. The proportion of carbon^{14} liable to migrate in gaseous form is very small (of the order of one m^3); it becomes dispersed in the geological medium, with no impact, as transfer times are much longer than its half-life (5,700 years).

1.5.1.2 The slow degradation of the disposal packages

The slow degradation of the disposal packages and the resulting release of radionuclides begin with the disposal cells resaturation.



Corrosion as seen with electronic beam microscope

• The slow chemical degradation of B waste packages in the cells

The degradation of B waste packages only begins significantly with the resaturation of the cells which occurs after several tens of thousands of years. According to today conservative models used, the majority of the waste present in B packages degrades gradually over periods of time ranging from several tens of thousands of years after water arrival in the case of metal waste (carbon steel, stainless steel, etc.) and bituminised sludge (B2), and several hundred thousands years in the case of other metal waste (zircaloy). Only the elements located on the surface of the B waste are liable to be released at water arrival.

• The low corrosion kinetics of the metal containers of the C and CU packages and the slow aqueous dissolution of glass (C) and oxide matrices (CU)

In the C waste and CU cells, the release of radionuclides begins after the loss of leak-tightness of the containers (cautiously estimated, on the basis of corrosion rates, at 4,000 years in the case of C overpack and 10,000 years in the case of the CU container). After the loss of leak-tightness of the containers, *water arrival inside the packages initiates the dissolution process of the oxide matrices and the glass, and radionuclide release*.

The C waste glass alteration models lead to dissolution over several hundred thousand years in the case of C1, C2, C3 and C4 glass. In the case of the former C0 glass, the model proposed at this stage results in dissolution over several thousand years. The CU oxide matrices dissolution takes place over a time scale of several tens of thousands of years to one hundred thousand years using a cautious approach with a radiolytic dissolution model, and over a million years with a conventional dissolution model. Furthermore, CU cladding and structural material corrode slowly over periods of time that depend on the geometry of the items.

1.5.1.3 Disposal cells: physical and chemical environments with slow evolution and contributing to the low mobility of the radionuclides

The physical and chemical environments of the (B, C and CU) cells encountered by the radionuclides when released result in the high retention and low solubility of most radionuclides. The latter are absorbed (trapped) or precipitate inside the cells. Combined with slow diffusive transport, *these phenomena give rise to long enough transfer times in order to allow the significant disappearance of the majority of the radionuclides by radioactive decay inside the cells*. Only a few long-lived mobile radionuclides, such as iodine^{129}, chlorine^{36}, caesium^{135}, carbon^{14}, calcium^{41}, selenium^{79} and toxics such as boron migrate significantly out from the cells.

Radionuclides: specific behaviours in terms of solubility and retention

The radionuclides can be classified in three broad groups in terms of solubility and retention in clay environments (Callovo-Oxfordian argillites, bentonite of engineered structures, argillite-based backfill) or in cementitious medium (B waste cells):

- *"mobile" elements* characterised by high solubility is high and low to nil retention, such as iodine or chlorine, for example.
- *"somewhat mobile" elements* characterised by high solubility and strong retention, e.g. caesium.
- *"barely mobile" elements* characterised by low solubility and strong retention such as actinides (e.g. uranium or plutonium) and lanthanides (e.g. samarium and europium).

The radiological inventory of the waste packages mainly consists of elements in the latter two categories.

1.5.2 The Callovo-Oxfordian formation: the limitation of the transfer of the most mobile radionuclides

Over a period of a million years, radionuclide transport in the Callovo-Oxfordian argillites is dominated by diffusion: transfers are slow and at least one hundred thousand years is required for mobile radionuclides to reach the limits of the Callovo-Oxfordian formation (at least 50 m on either side of a repository constructed in the median level of the formation). Half the radionuclides released migrate downwards (towards the Dogger), the other half migrate upwards (towards the Oxfordian formations).

Migration times must be compared with the radioactive decay periods of radionuclides liable to migrate (soluble, not or to a small extent delayed), in particular carbon^{14} (half-life of 5,730 years), selenium^{79} (half-life of 65,000 years) and chlorine^{36} (half-life of 300,000 years).

Therefore, only a very small proportion of the radionuclides inventory contained by the waste is liable to be found in the surrounding aquifers over the course of the next million years: iodine^{129}, chlorine^{36} and to a lesser extent selenium^{79}, calcium^{41}, stable boron.

The other radionuclides, not very soluble and highly retained by the argillites such as the actinides, remain confined inside the Callovo-Oxfordian formation: their very slow diffusive transfer combined with their radioactive decay means a migration over a few metres at most around the repository over a period of one million years.

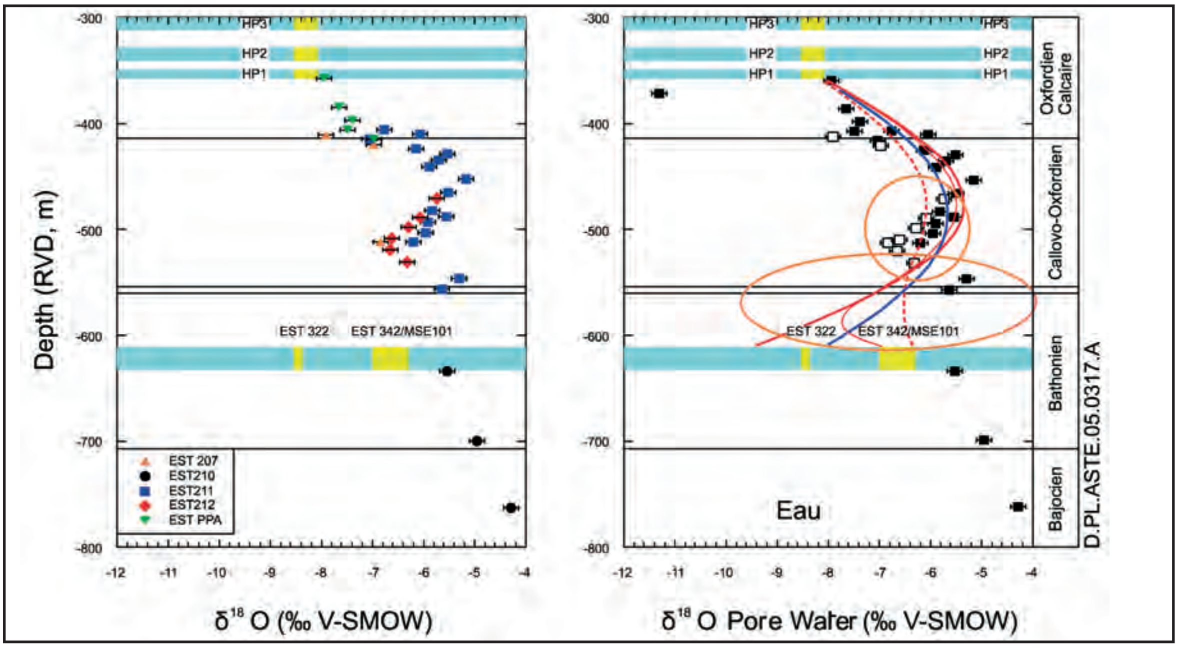


Illustration of diffusion phenomenon inside the Callovo-Oxfordian formation with natural tracers (profile of oxygen isotopic composition in pore water) – Right: diffusion modelling

1.5.3 Radionuclides transfer into the surrounding formations

Radionuclides reaching the Callovo-Oxfordian formation boundary migrate into the carbonated formations of the Dogger and Oxfordian both by advection and dispersion, and then move towards the natural outlets.

In the Dogger formation, the radionuclides migrate horizontally towards the west-south-west at a very slow velocity up to a few kilometres over a time scale of a million years.

In the overlying formations, transfer pathways evolve with the hydrogeological changes brought about by surface evolutions. Over the course of the first 100,000 years, flows are comparable to the current regime, defining a natural outlet in the Marne valley to the west of the laboratory site and regional pathways extended towards the north-west. They are gradually modified and after 500,000 years, surface erosion will have modified main flow directions. The outlet in the Marne valley remains but the regional pathways disappear while appears a second local outlet to the north of the site in the Ornain valley.

2. The long-term repository safety assessment

The safety approach is based first and foremost on the behaviour of the repository such as it can be described on the basis of the body of scientific knowledge acquired. It sets out to organise this knowledge in the form of a safety model that provides a simplified but cautious representation of the phenomena and their development over time. It also tests the validity boundaries of this representation by weighing up the consequences that the variation of certain data would have. It also goes on to deal with situations that are not included in the evolution as foreseen or envisaged by the repository designer.

Ultimately, this work culminates in quantitative evaluations of the overall performance in the form of indicators that characterise the possible impact of the repository on man and the environment in particular. It appraises the validity of the safety functions initially established for the repository and is a test of the whole system robustness. In this respect, the performance assessment constitutes an *a posteriori* validation of the design ensuring that the functions assigned to the different components of the repository by safety are effectively fulfilled. It also provides a simple representation of the repository and its evolution, which is an important prerequisite of confidence in the evaluation process.

Finally, a safety approach necessarily forms part of an iterative and progressive approach. By putting the various phenomena into perspective and assessing their quantitative significance, it contributes to evaluating their relative weight and the consequences of any remaining uncertainties. It also orientates subsequent research by highlighting fields where scientific advances could contribute most to safety.

2.1 From understanding phenomena to safety calculations

The studies and research activities conducted provide detailed knowledge of the properties and behaviour of the various repository components (waste packages, materials, geological medium), allowing a general overview of phenomena likely to occur (corrosion, mechanical evolution of engineered structures, saturation, chemical evolution, etc.).

The safety analysis approach must integrate these various factors to construct a simplified and consistent history of the repository evolution, adopting cautious hypotheses and rather conservative simplifications. This history constitutes a scenario that is not intended to represent reality in the future, but rather to encompass the full range of probable situations likely to occur, with the assurance of representing a conservative and even penalising view. This scenario constitutes the basis of a quantified assessment by means of safety calculations.

2.1.1 Purpose of the assessment

Based on the acquired understanding of phenomena and repository behaviour over time, the objective is to conduct a repository performance assessment, i.e. to analyse how the natural medium and engineered components ensure the long-term safety objectives. This essentially amounts to evaluating, *in fine*, the radiological impact associated with a dose exposed to the public.

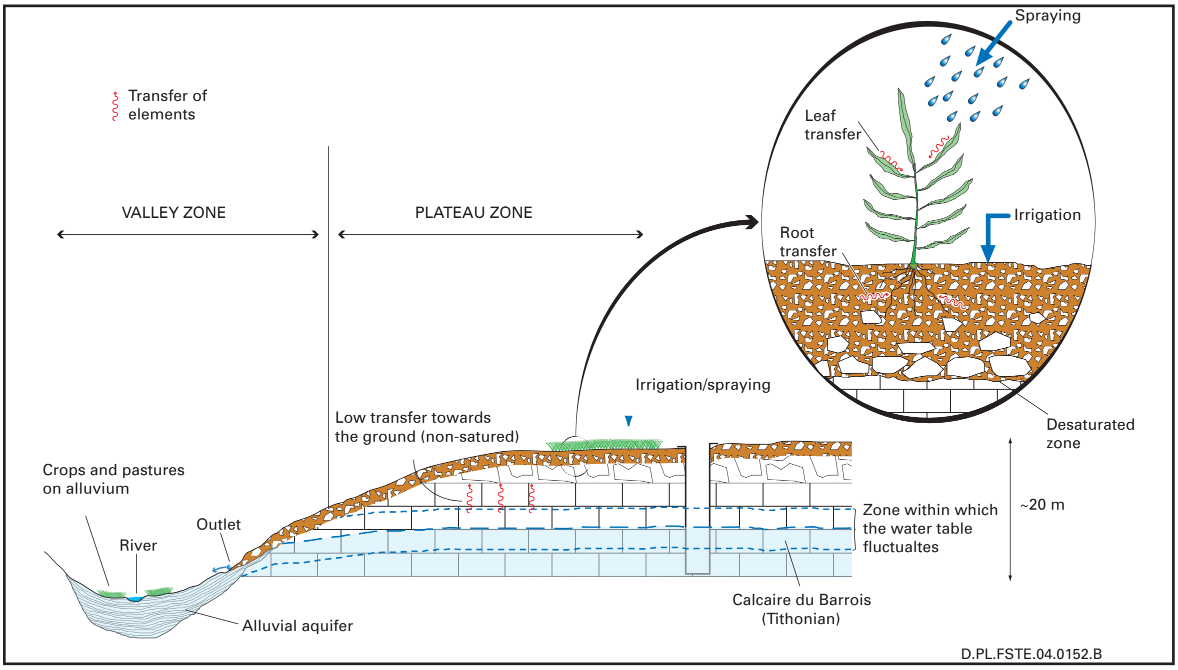
The repository impact on man and the environment must comply with strict radiological protection standards. The objectives to be adopted are indicated in the basic safety rule RFS III.2.f for a period of at least 10,000 years, with a value of 0.25 mSv per year, i.e., one quarter of the public exposure dose admissible for non-natural exposure and approximately one-tenth of the dose received per year due to natural radioactivity. Beyond 10,000 years, the issue is the duration for which the calculations should be conducted. In keeping with international practice, a period of one million years is adopted, which is a time constant representative of the radioactive decay and repository evolution processes. Maximum impact is reached before this duration, which is quite long but nevertheless compatible with available knowledge concerning the geological medium (which has shown its stability over much longer periods).

Toxic chemicals

The assessment is also intended to ensure the absence of impact due to the toxic chemicals present in the waste, by appraising their possible migration into the environment over one million years using methods similar to those used to determine radionuclide migration.

2.1.2 Impact assessment

According to the prescriptions of the International Commission on Radiological Protection (ICRP) and the recommendations of the basic safety rule RFS III.2.f, radiological impact is measured based on the individual committed dose calculation for the critical group, i.e., individuals susceptible of receiving the highest dose through exposure to radioactivity emitted by the facility considered.



Model of radionuclide transfers from the geosphere to the biosphere at the Meuse/Haute-Marne site

Critical group

It is defined based on a study of the living habits of populations around the site considered. This leads to the definition of one or more 'reference' groups. However, the mere knowledge of the quantity of radioactivity present in the environment does not immediately yield a dose value. It is necessary to formulate hypotheses regarding the manner in which the radionuclides present may reach humans, particularly through the food chain.
Such an assessment presents specific difficulties when conducted over a period of approximately one million years. At that time scale, we cannot reasonably expect to obtain an accurate assessment of living habits in the sector considered. The definition of the reference group, referred to as the 'critical group' in such a context, is therefore based on simple and very pessimistic hypotheses, assuming that small groups of humans live near the repository and derive most of their subsistence from local production (vegetables, domestic animals, water). The critical group is therefore conventional, but the practices attributed to it guarantee an extremely cautious measurement of the dose to which the population could be exposed.

Over the one million years period adopted for the safety assessment, the environmental conditions are subject to variations (particularly climate conditions). Current studies provide a forecast of their main characteristics, at least in the form of general hypotheses.

One last factor needs to be defined for the impact assessment: outlets, i.e., locations where radioactivity may reach the environment. Since the main radioactivity transport vector is water, these outlets may consist of rivers, aquifers or water wells. In order to identify these outlets, the evolution of the geological medium and the radioactivity transfer pathways from the repository must first be represented.

Dose impact calculations constitute the reference method privileged at the international level. Other indicators are also defined so as to complete our understanding of the safety level obtained by repository concepts. For example, the flow values evaluated at the interface of the Callovo-Oxfordian host formation are used to assess its confinement characteristics. Nevertheless, these indicators only express physical quantities of radioactivity and cannot be associated with regulatory or recommended threshold values.

Indicators in the safety analysis approach

The analysis of the results does not only consist of comparing the dose rate at the outlet with the regulatory value of 0.25 mSv per year. It also relies on various intermediate indicators that allow for the following:

- understanding the individual operation of each barrier with respect to transfers, and evaluating their performance in terms of assigned functions.
- eliminating certain uncertainties. For example, unlike the dose rate, the "radionuclide flux at the interface of the host formation" is independent of the uncertainties associated with surrounding formations.

The indicators used are in particular:

- distribution percentage of advective and diffusive flows in the repository and in the Callovo-Oxfordian formation. These indicators are used to evaluate the performance characteristics of the 'preventing water circulation' function, and also, indirectly, those of the 'limiting radionuclide release and immobilise them inside the repository' function.
- quantities of radioactivity emitted or released by the packages, engineered structures, host formation and at the outlets throughout the duration of the analysis, as compared to the initial quantity present in the packages. This indicator is also suitable to evaluate the 'limiting radionuclide release and immobilise them inside the repository' function and the 'delaying and mitigating radionuclide migration' function.
- activity flow-rates over time at the exit of each of the components represented (package, cell, seal, host formation, possible outlets), allowing for appraising the mitigation capacity of the various confinement barriers, particularly the geological barrier. This indicator is used to evaluate the performance of the "delaying and mitigating radionuclide migration" function.
- Solution concentration mapping in the host formation, surrounding formations (in particularly the aquifer horizons). This mapping is used to represent the pathways of radioactivity and toxic chemicals in surrounding formations at different dates.

Regarding maximum impact values, two types of situations can be distinguished:

- *normal evolution of the repository*, i.e., situation deemed most probable or reflecting a repository behaviour in accordance with that expected by its designers. In this case, in order to obtain a robust approach, it is recommended to compute the dose assessment under conditions guaranteeing its pessimistic character. The dose rate of 0.25 mSv per year is then adopted as a reference threshold value.
- *altered situations* corresponding to highly improbable situations. In this case, the calculated impact is not only considered as an absolute value, but also in terms of the situation likelihood and the chronic or punctual character of the exposures. In such situations, it is possible to encounter dose evaluations exceeding the threshold value of 0.25 mSv per year but deemed acceptable due to their low probability.

2.1.3 Scenario concept and modelling approach

Despite the knowledge acquired through research, we cannot expect to produce a detailed, step-by-step description of the repository evolution over one million years covering the full complexity of all the phenomena involved. Under such conditions, given the simulation tools currently available, the safety calculations used to determine impact cannot be conducted. In addition, uncertainties remain for certain parameters or models.

The approach adopted to assess the repository impact therefore consists of representing the repository evolution in a simplified manner, referred to as a scenario. This scenario is not meant to provide an exhaustive description of the repository evolution. On the contrary, it offers a more readily understandable view, with phenomena represented so as to yield high or conservative repository impact values. All the phenomena present during the repository evolution are not necessarily represented, but this does not mean that they are neglected or ignored in the safety analysis. The results of the preparatory studies prior to the safety calculations determine whether phenomena are represented in a simplified manner or not at all. The scenario thus defined is therefore not an accurate representation of the repository evolution or a prediction of what will happen. It is constructed so that the repository impact in a normal situation will be less than the evaluated one in the scenario. The so-called "safety margins" are neglected, i.e., data not fully determined but nevertheless favouring repository safety. This scenario is referred to as the normal evolution scenario.

The second step after scenario definition is to develop a model allowing for the calculation of the associated impact. Choices must be made in order to develop a robust model taking into account possible uncertainties as regards to phenomena representation or physical parameters values. This leads to the definition of a general model suitable for calculations and performance assessment and also ensuring consistency with the objectives of the safety assessment and of the normal evolution scenario definition. It is referred to as the 'safety calculation model' or 'safety model'. The choices made are recorded so as to be able to modify them whenever necessary.

Modelling approach

First of all, in order to understand the system, we use more or less complex scientific models that take into account each process within the repository and its environment.
In order to obtain a preliminary representation of the system and determine the preponderant parameters, the acquired knowledge is used to derive conceptual models constituting a simplified but robust approach that takes into account the main determining factors. These models are used in preparatory calculations to assess the impact of the various phenomena and make decisions regarding possible simplifications (for example, by neglecting one phenomenon in favour of another dominant one).
Finally, the system is completely represented within the scope of the safety model, which reflects the normal evolution scenario and constitutes a simplification with respect to the conceptual models. This simplification takes into account the results of the preparatory calculations.

The models and parameters that best reflect the physical reality as we understand it must be distinguished from those intended to provide a pessimistic representation (referred to as "conservative" or "penalising" depending on the degree of pessimism). The model selection strategy is based on the following selection principles:
- in case of low uncertainty, the most scientifically supported model ("phenomenological" model) is selected
- in case of high uncertainty, a 'conservative' or 'pessimistic' model or value is selected
- the most simple and robust models are privileged, as long as this choice does not lead to underestimating the impact

The notion of "low" or "high" uncertainty inevitably entails a degree of subjectivity, even though in certain cases it may involve statistical considerations (dispersion of experimental values, level of confidence, etc.).

The experts in charge of proposing the models and values discuss decisions regarding uncertainty on a case-by-case basis. In keeping with the recommendations of the international experts group that reviewed Andra activities in 2003, the approach adopted yields a description as accurate as possible of the choices made and their justifications, so as to make the relationship between the conceptual models and the safety calculation model as explicit as possible.

Different types of models and values

• **Phenomenological (or best estimate) model:** the model that, all other parameters being fixed, is deemed to yield results fitting at best those obtained by experiments and/or observations. This choice is theoretically made without reference to any impact. A phenomenological model or value must be based on a representative number of measurements and a physical argumentation demonstrating that it is the most representative according to reliable data.

• **Conservative model:** model used to obtain a calculated impact that falls within a range of high values (with all other parameters fixed elsewhere) In the simplest case, where the impact increases (or decreases) as the parameter value increases, a value is chosen from the upper (or lower) range of available values. If no measurement is available, the model uses internationally-available data, as long as these data are explicitly presented in the literature and can be transposed to the studied case.

• **Penalising model:** model not referring to phenomenological knowledge, chosen conventionally to lead with all certainty to an impact greater than the calculated one with possible values. For example, this may correspond to a physical limit.

In order to complete the development of the normal evolution scenario, other calculations are also performed; namely sensitivity analyses conducted on the safety model to test parameter sets or models different from those selected as most representative. The approach may consist of selecting extreme values for certain parameters, corresponding to highly penalising situations, or also more favourable values. In all cases the objective is to measure the impact of these variations and determine whether a more in-depth study is required, either to increase safety margins or further reduce certain uncertainties. This approach also allows assessing the respective importance of the various parameters.

2.1.4 Uncertainties management

The safety assessment and the fulfilment of the safety objectives cannot be split from identifying and processing uncertainties. As a general rule, uncertainty comes from the absence of specific data or knowledge regarding one of the components of the system analysed, or from the random character of certain phenomena. In the case of the deep geological disposal analysis, it may involve lack of knowledge in parameter values, partial understanding of certain coupled mechanisms, or the difficulty to predict the occurrence of certain events in the long term.

The following can be distinguished:

- *uncertainties regarding the intrinsic characteristics of a repository component*, possibly associated with inaccurate measuring techniques, the spatial variability of a component, or the model governing the definition of the value to be characterised.
- *uncertainties regarding the processes governing the repository evolution.* Once data concerning all system components has been acquired, the manner in which these various components interact and affect the system evolution still needs to be properly understood and represented. This representation is based on models; it involves various uncertainties as it proceeds by simplification (with respect to a more detailed representation of the phenomena) and requires extrapolations in time and space. This is particularly the case with coupled phenomena, generally more difficult to represent.
- *technological uncertainties.* At feasibility stage, the technical systems to be implemented have not yet been fixed and there are several possible options with varying consequences for the long-term safety of the repository. Moreover, within the scope of a stepwise repository management process, it is highly improbable that the repository will remain in operation according to its initial design throughout the expected duration.
- *Events susceptible of occurring in the repository environment.* We generally distinguish phenomena of natural

origin occurring on the surface (climatic, tectonic events, etc.), theoretically predictable but often involving large uncertainties, and events due to human activity (intrusion, anthropic effects), in most cases unpredictable beyond a reasonable time scale. Partially conventional approaches are typically adopted to limit the impact of such uncertainties. In accordance with basic safety rule RFS III.2.f, it is assumed that human behaviour in the future will be globally the same as today.

An uncertainty or risk is safety related if it can put at stake repository performance assessment. Risks and uncertainties are taken into account using different methods:

- the first method, to be privileged whenever possible, is to control uncertainties, i.e., taking them into account in the repository design itself by defining design measures that make the system robust with respect to the considered uncertainty,
- the second method is to integrate the risk or uncertainty in the repository performance assessment, i.e., taking the possibility into account by selecting a penalising choice either in the reference calculations, or in sensitivity ones.
- for uncertainties which could not be managed by the two methods described above, the sequence of events induced by the risk in question (thereby constituting an altered situation) must be identified and its consequences must be evaluated. It is therefore necessary to make sure that this situation likelihood is low. Since it is not possible to evaluate each conceivable altered situation individually, they are grouped into families of similar situations. Each family is associated with an altered evolution scenario that describes a configuration with similar effects than the situations represented, but with more serious consequences. The altered evolution scenario therefore represents an 'envelope' situation encompassing altered situations that are theoretically different but with similar effects.

2.1.5 Simulation and calculation tools

Once the global safety model (itself composed of various elementary models) has been defined, the last step is to implement this model by means of specific software and digital codes that effectively perform the calculations. Andra has used codes specifically dedicated to the various phenomena (transport, hydraulic, thermal, etc.) and integrated into a simulation platform called “ALLIANCES” and co-developed with the French Atomic Energy Commission (CEA).

ALLIANCES SIMULATION PLATFORM

The ALLIANCES platform is intended to provide researchers and engineers with a tool to perform safety assessments that takes into account the specificities of such work, i.e.:

- the requirement to manage very large amounts of data
- the need to execute complex calculation sequences involving different models
- a significantly large number of calculations (several thousands of simulations)
- a requirement to control data and results so as to produce specific analyses for each parameter

The other main objective of the ALLIANCES is to eliminate the numerical difficulties associated with code coupling. Indeed, code sequencing can generate digital artefacts if the overall consistency is not observed. One of the main assets of this platform is to provide a software framework in which consistency is checked.

Finally, the platform also enables benchmarking various softwares, thereby testing the consistency of the results obtained and constituting an additional guarantee of data reliability.

The modelling capacities of the ALLIANCES platform version are listed in the table below.

Models	Components	Examples of applications
Hydraulic - satured - unsatured - transient	Castem Porflow Trace	- flow in porous mediums - resaturtion of disposal cells
Transport - simple - extended	Castem Porflow Trace	- contaminant transport (toxic chemicals or radionuclides)
Chemistry - complexing - ion exchange	Chess PhreeqC	- leaching - alkaline disturbance - oxidising disturbance - ageing - release
Chemical transport	Castem MT3D Trace Chess PhreeqC	- leaching - alkaline disturbance - oxidising disturbance - ageing - release
Package - glass - bitumen	Prediver Colonbo	- package degradation - release
Sensitivity - sampling - analysis	LHS Kalif Pastis	Sensitivity to hydraulic and transport characteristics for safety assessments

In 2004 and 2005, the ALLIANCES platform has been used operationally by Andra and its partners to perform safety calculations and performance assessments. This work amounts to several thousand calculations and only a very small number of incidents have been encountered during its execution, thus demonstrating the good control of the digital aspect of the evaluations.

2.2 Normal evolution scenario and its associated safety model

2.2.1 General data

• Representation in space

The repository consists of several distinct zones corresponding to different types of waste. In the normal evolution scenario, the different zones are considered as superposed at the same location but analysed separately, so their effects cumulate. This eliminates the need for zone distribution hypotheses. At the current stage of research, in the absence of a specific location for the repository, the approach is cautious: it concentrates towards at a given outlet the fluxes which are higher than in reality.

However, in order to perform the calculation, a choice must be made regarding the repository location as it influences possible radioactivity transfer pathways in the formations surrounding the Callovo-Oxfordian host formation. The repository has been positioned in the same location as the underground laboratory in a purely conventional manner (although this location bears only a limited likelihood). As far as outlets are concerned, we have selected the most penalising ones with regard to the given repository location and among those resulting from the model describing water circulation at sector scale (hydrogeological model).

For the Callovo-Oxfordian formation, we have selected a minimum thickness (130 m) corresponding to the lowest value over the entire transposition zone, independently of the location adopted. We have also assumed that the repository is positioned in the deepest part of the zone, since such a position is penalising with regard to essential mechanical phenomena.

• Representation in time

Given the duration of the reversibility phase, the repository closure date is unknown by definition. This results in a partial indeterminacy as to the initial state of the repository at the start of the post-closure phase. The effect of the duration of the reversibility phase and of possible physical and chemical phenomena on the repository has been evaluated to ensure that the normal evolution scenario representation remains valid for the durations considered (one to several centuries). It appears that a plurisecular time period induces no significant variations.

The transient phases, during which the thermal, hydraulic and mechanical properties of the repository evolve significantly after closure and before returning to the natural equilibrium state, are taken into consideration.

Regarding heat, the thermal transient is explicitly represented based on calculations for the evolution of the temperature field within the repository. Thus, for the thermal phase associated with vitrified waste and spent fuel, the temperature dependency of the characteristics of the Callovo-Oxfordian argillite has been taken into account for the parameters most sensitive to the temperature field and for those most affecting transport under normal evolution conditions (i.e., diffusion and partition coefficients, when necessary). This is actually only useful in cases where radionuclides are susceptible of migrating during the thermal phase, which only corresponds to C waste and spent fuel container leak-tightness failure situations.

Regarding hydraulics, the desaturation and resaturation phenomena are too complex to be fully represented. Their respective weighs have therefore been determined through various preliminary calculations in order to obtain a simplified representation. The preparatory evaluations conducted for the hydraulic transient clearly indicate that the advective flow phenomena associated with the partial resaturation of the medium are not susceptible of creating really disturbing flows and are therefore negligible. In the same manner, the effect on transport of corrosion gas may be neglected; the latter creates hydraulic head gradients only in the near-field (a few meters around the disposal cell) and during limited time scales (a few thousand years); this does not modify radionuclides transport regime on the Collovo-Oxfordian scale. *Under these conditions, a completely resaturated medium as of the initial state is adopted for the scenario and the safety model.* This means that water is in contact with the waste as of the repository closure and although not very realistic, it provides for a simple approach to the situation. *It is also conservative, since neglecting the fact that water (the cause of chemical alterations and radionuclide release) reaches the waste much later.*

Regarding mechanics, repository-induced disturbances are taken into account through modification of rock properties in the damaged zone around the engineered structures. The damaged zone is represented in its state after excavation, neglecting long term closure and healing phenomena. Since thermomechanical phenomena (exothermic waste repository zones) and hydromechanical phenomena (desaturation, migration of corrosion gases) are not likely to significantly increase the initial damage, this is a pessimistic configuration.

In the long term, the surface environment will undergo modification. Therefore changes in terrain morphology will occur under the effect of climatic evolutions (glacial cycles, temperature increase, etc.). Given the depth of the Callovo-Oxfordian formation, the latter will not be affected by such phenomena. On the other hand, these transformations will modify flows in overlying formations. To analyse this point, two situations have been considered: a first model based on the current configuration of the geological medium, with corresponding flows in the various formations, and a second model based on the results of a prospective simulation after one million years. Calculations are conducted simultaneously using both models to obtain a representation encompassing all possible evolutions.

Evolution of the repository in the safety model

The repository evolution with time is as follows:

- as of the closure, it is assumed that an established hydraulic regime is achieved with a resaturated repository (water in contact with waste packages).
- the temperature of the waste is taken into account to determine the duration of the thermal phase (with a peak before 100 years for vitrified waste and 1000 years for spent fuel). The temperature dependency of the main sensitive parameters is taken into account during this phase.
- it is assumed that the initial damaged zone around the engineered structures does not heal.
- the modifications of the surface environment over time (under the effect of natural phenomena) are taken into account via two contrasted situations: the site current state and its prospective state after one million years.

• **Transport vectors**

Two vectors may favour the transport of the radionuclides or toxic chemicals contained in the waste: water and gas. The safety model only considers transport via water. Preliminary evaluations show that radioactive elements initially in gaseous state are not very susceptible of migrating (in gaseous state) and inducing an impact. First of all, they are short lived. Secondly they rapidly dissolve in water. At least, the quantity of others, such as carbon^{14} is too low to make an impact. The selected transport vector is therefore water, which, after contact with the waste, carries the radionuclides or toxic chemicals that can be present in soluble form.
The transport model represents the diffusion and advection in the geological medium. Preparatory calculations allow a simplification of the repository representation (access structures not constituting a specific transfer pathway are not represented).

Selection of radionuclides for safety calculations

A selection has been made among the radionuclides to be considered for the transport calculations. The objective is to obtain a representative base to assess the impacts and cover the main issues associated with the transfer of radionuclides towards man and the environment. For the normal evolution scenario, the following has been adopted:

- analysing actinide chains via a simplified preliminary calculation, so as to demonstrate that they do not need to be taken into account in the complete calculation. Given their high retention and precipitation in the geological medium, they do not contribute to impact at the scale of the safety assessment (million years).
- taking into consideration the fission and activation products that are *a priori* the most penalising ones over time.

The method defined consists of only selecting the radionuclides with a half-life of more than 1000 years and presenting, a priori, the most penalising behaviours. This approach has led to selecting 15 radionuclides: ^{129}I, ^{107}Pd, ^{135}Cs, ^{10}Be, ^{93}Zr (^{93}Nb), ^{36}Cl, ^{99}Tc, ^{41}Ca, ^{126}Sn, ^{59}Ni, ^{79}Se, ^{94}Nb, ^{14}C, ^{93}Mo, and ^{166}Ho.

Complementary analyses (transport calculations) have shown that radionuclides not selected do not effectively contribute to the impact.

For the toxic chemicals associated with the waste and with the repository components, a few chemical elements, seeming the most significant ones, were considered: boron, nickel, antimony and selenium.

2.2.2 Waste representation

• B waste packages

B waste is placed in concrete over-packs. These are assumed to be non-watertight but nevertheless they impose a homogeneous chemical environment (in equilibrium with that of the concrete cell) limiting radionuclide fluxes due to precipitation and sorption phenomena. This is a pessimistic representation, as it can be assumed that the concrete over-packs also ensure a water-tightness function, at least during the first phases.

Regarding the waste itself, the radioactivity release models and values adopted for the assessment depend on the waste type. In the absence of sufficient knowledge for B3 and B6 packages, we assume an immediate release as of the presence of water. For the other packages, time-based release models were adopted that take into account the corrosion of metallic elements constituting the waste (B1, B4 and B5 packages) or the alteration of the bitumen matrix (B2 packages).

B waste release models

Cemented or compacted miscellaneous technological waste (B3) and bulk technological waste (B6) radioactivity is assumed to be immediately available upon water arrival (they are termed as 'labile'). This choice necessarily leads to the selection of a penalising model.

For the other packages, release models and associated parameters are chosen among available models based on the following:

- their conformity with the experiments performed for validation purposes
- their validity in repository condition
- their ability to take into account the potentially disturbing phenomena that can be hazardous for waste containment

For activation product waste (B1), cemented structure waste (B4) and compacted waste (B5), it is assumed that the part of the inventory contained in the metallic elements is released during corrosion (after 100 000 years for B4/B5 zircalloy cladding, 200 000 years for B1 inconel components, approximately 15 000 years for B4/B5 inconel components, approximately 20 000 years for B1 stainless steel components, and 65 000 years for B4/B5 stainless steel components).

For bituminised sludge waste (B2), the release kinetics is represented by a model developed according to a phenomenology experimentally validated in the laboratory. It is based on water absorption by bitumen and on the behaviour of radionuclides assimilated with the soluble salts of the bitumen matrix. In this model, favourable phenomena, such as the insolubilisation of the radionuclides performed during initial waste treatment, are neglected. The release rate resulting from this model is inversely proportional to the square root of the time, leading to the release after 10 000 years of 90% of the initial mass contained in the bitumen packages.

Sensitivity studies have been conducted with penalising models that cover the uncertainties associated with the evolution of the packages:

- labile release for B1, B4 and B5 packages, to take into account the uncertainties associated with corrosion,
- for B2 waste, an alternative model assumes that the radionuclides are associated with the soluble salts (penalising hypotheses) and released as soon as the latter are in solution state, to take into account problems of creep, cracking, uncertainty in salt contents, etc. This model therefore depends on salts solubility and on the water flows through the cells. It leads to a progressive release over a period of 1000 years.

• Vitrified C waste packages

Vitrified waste is placed in a carbon steel over-pack. Given its design and based on preparatory calculations, a conservative lifetime of 4000 years is adopted for the over-pack, during which no release may occur.

The over-pack is characterised by a very robust design and will be subject to inspections for possible manufacturing defects. Nevertheless, we have cautiously included the possibility of such a defect in the calculation. At the current stage of the studies, its definition has an arbitrary character. The normal evolution scenario includes a number of container failures corresponding to approximately 1/10 000 of all containers, which is in agreement with experience feedback in this field (one C0 package, one C1 or C2 package and one C3 or C4 package). In the calculation, this failure is conventionally expressed approximately one century after the production of the primary package and leads to a penalising result (complete loss of leak-tightness).

Radionuclides release by the glass begins as soon as the over-pack loses its leak-tightness. The release models associated with glass dissolution and the corresponding parameters vary depending on the type of vitrified waste package:

- C0 glasses and glasses contained in a defective over-pack follow a model based on the initial dissolution rate of the glass and the exchange surface offered by it (V_0.S model).
- The other glasses (i.e., most of the inventory) follow a two-phase phenomenological model (V_0.SgVr model). This model is first based on the initial dissolution rate until silica saturation in the surrounding environment (similar to V_0.S model). Subsequently, in a second phase, the dissolution kinetics decreases to a residual rate (Vr). The transient between these two phases is not represented.

For C0 glasses, a sensitivity study has been conducted with conservative parameters for the V_0.S model. For C1 to C4 glasses, a sensitivity study has been conducted using the V_0.S release model.

• Spent fuel (CU) packages

Would spent fuel not be reprocessed, the assemblies are placed in a very thick carbon steel over-pack. Given its design and based on preparatory calculations, a cautious lifetime of 10 000 years is adopted for the over-pack, during which no release may occur.

According to a logic similar to that applied for vitrified waste (C waste), in the reference calculation it is assumed that a fraction amounting to approximately 1/10 000 of the containers is defective and loses its leak-tightness after 200 years (one CU1 container and one CU2 container).

Radionuclide release by the spent fuel assemblies begins once the container has lost its leak-tightness. The release model depends on the location of the radionuclides within the various physico-chemical subcomponents of the assemblies. The following can be distinguished:

- progressive release model for radionuclides contained in metallic components, where the release is assumed to be congruent with the corrosion rate of the components. This model leads to releases over periods ranging from approximately 500 years for radionuclides contained in structural inconel components to 20 000 years for radionuclides contained in the cladding.
- fuel matrix dissolution model under the effect of radiolysis (radiolytic model), leading to a progressive release of the radionuclides located in the matrix over approximately 50 000 years. This dissolution model, adopted in the reference calculation, is a conservative model more penalising than the model generally adopted at the international level.
- a fraction assumed as labile.

A sensitivity study has been conducted to test, on one hand, an even more penalising model in which the radiolytic dissolution rate is accelerated and, on the other hand, a model closer to those adopted at the international level in which dissolution takes place over several millions of years.

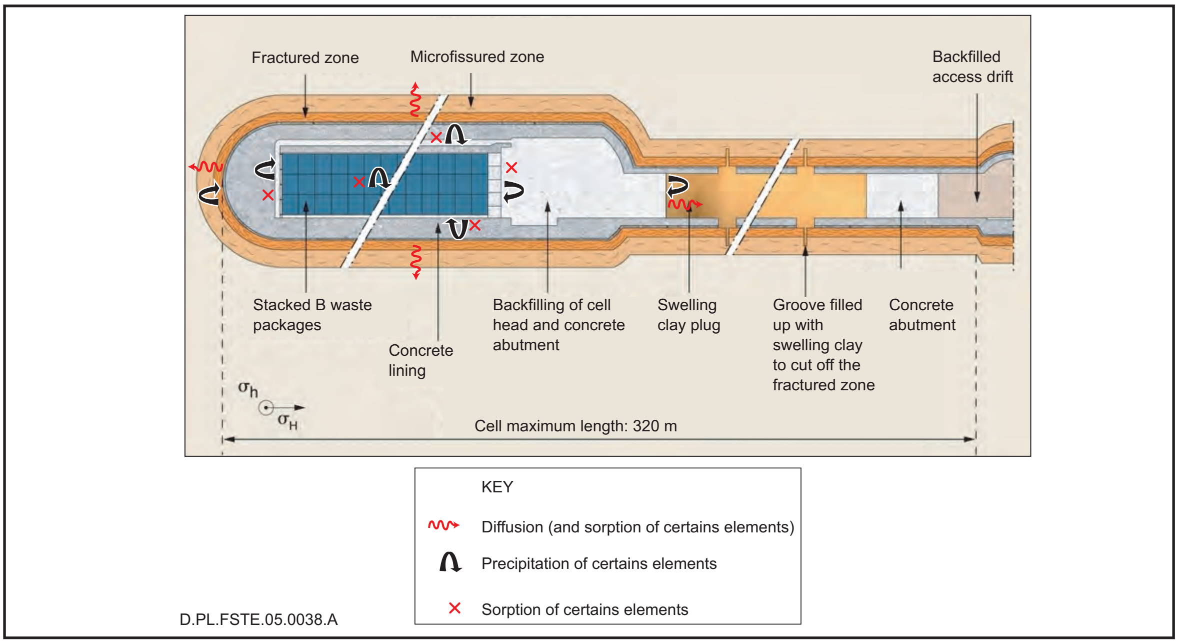
2.2.3 Representation of radionuclide migration in disposal cells

• B waste disposal cells

Once released by the waste packages, the radionuclides can migrate within the cell, subsequently reaching the Callovo-Oxfordian formation or the clay plug located at the head of the disposal drift.

Similarly to the disposal package concrete, the cell lining concrete is not assigned hydraulic or transport performances. It is represented as a homogeneous environment that ensures only chemical confinement by limiting toxic fluxes via precipitation and sorption phenomena.

The cell plug (and its anchoring in the rock) is intended to prevent or slow down the water flows possibly passing through it. It therefore has hydraulic properties. A value of 10^{-11} m/s is adopted for the swelling clay permeability, which leads to a lower performance than that observed within the scope of the TSX experiment conducted in an underground laboratory in Canada (full scale clay plug test). This is therefore a cautious choice as it reduces the expected performance. The nature of the clay plug (swelling clay) also leads to the attribution of chemical retention performance.



B waste disposal cell and radionuclide transfer phenomena modelling

• C waste disposal cells

Once released by the waste packages, the radionuclides can migrate directly towards the Callovo-Oxfordian formation, the clay plug or the repository drift contiguous to the cell plug.

The cell plugs are represented with properties identical to those of the B waste disposal cells (not including the anchoring, not available for C waste disposal cells due to their small diameter and the absence of a fractured zone directly at the plug level). Given their large number, it has been assumed that a fraction of 1/1000 of C waste disposal cell plugs is defective as of repository closure (due to the low hydraulic performance of the plug-rock interface). This choice does not affect transfers in the model considered.

• Spent fuel (CU) disposal cells

Once released by the waste packages, the radionuclides can migrate directly towards the Callovo-Oxfordian formation after migrating through the clay buffer engineered barrier, the clay plug or the repository drift contiguous to the cell plug.

Radionuclide transport in spent fuel disposal cells is represented similarly to transport in C waste disposal cells.

The specific characteristic is the presence of a swelling clay buffer engineered barrier around the cells. This engineered barrier is assigned hydraulic performance and retention properties similar to those of the plug. Given the continuity between the cell plug and the swelling clay engineered barrier, no cell plug defects are considered.

2.2.4 Migration in drifts or shafts

At the exit of the cells, a fraction of the elements released may reach the backfilled repository drifts, migrates through the latter and subsequently into the Callovo-Oxfordian argillite or towards the sealed shafts.

The drifts consist on one hand of the ground support and concrete slab (which remains in place) and, on the other hand, of the backfill. A cautious approach is adopted for the values of the hydraulic properties in the drifts, assuming a very high permeability for the ground supports (10^{-6} m/s). The permeability of the backfill (reworked excavated argillites) is assumed to be better (10^{-8} m/s), but this parameter has little influence due to the nearby presence of the ground support, with worse hydraulic properties.

The representation of the drift seals is similar to that of the B waste disposal cell plugs. The shafts are also equipped with seals, not anchored due to the absence of fractured zones in the Callovo-Oxfordian horizons where they are located. The performance characteristics of their swelling clay core are similar to those attributed to the drift seal cores.

2.2.5 Migration in Callovo-Oxfordian argillites

• In the damaged zone created during repository construction

The damaged zone located around the cells is represented with the maximum possible extent in the transposition zone (influence of depth). Moreover, it is recalled that the studies conducted have shown that the extent of the chemical disturbances induced by the presence of exogenous materials (alkaline disturbance, iron-clay interaction, etc.) is similar to the extent of the zone presenting mechanical fractures created while excavating structures and thus negligible compared to the extent of the micro-fissured zone. Furthermore, observations on argillite samples show a trend to self-healing, which would reduce ultimately the initial damaged zone. This type of behaviour, well observed *in situ* at Mont Terri, is not considered: the damaged zone is assumed as maintaining its initial characteristics over time. For repository structures oriented in the direction of the major principal stress (cells, drifts equipped with seals), the following is therefore assumed: 6

- *the fractured zone* has an extent equal to 0.1 times the radius of the engineered structure considered, mediocre hydraulic performance characteristics (5.10^{-9} m/s) and degraded diffusion properties. The solubility and sorption values of the various radionuclides correspond to the values adopted for sound argillites, as they result from the geochemical context imposed by the argillites.
- *the micro-fissured zone* may extend over up to 0.7 times the radius. It presents degraded permeability properties (5.10^{-11} m/s) and diffusion and chemical retention properties identical to the host rock ones.

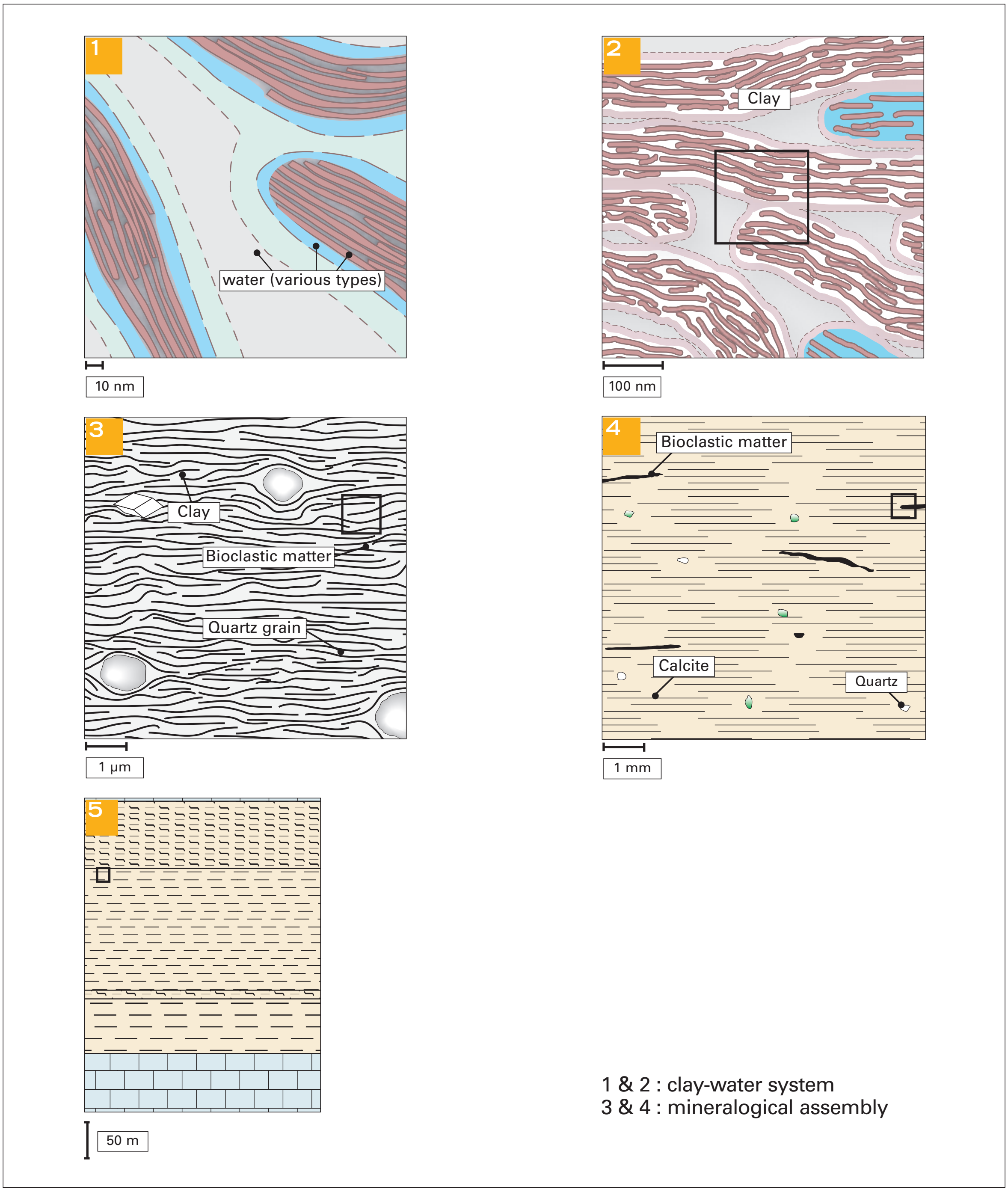
On one hand, in the case of the fractured zone, a sensitivity analysis is conducted to test a highly penalising scenario with a sand permeability value of 10^{-6} m/s,a complete absence of chemical retention capabilities and an infinite solubility of radionuclides.
On the other hand, for the microfissured zone, we have adopted a permeability value of 5.10^{-9} m/s and degraded diffusion and retention properties.

• In the sound argillites

Based on the various data acquired, the host formation is represented as a homogenous medium where radio-nuclides can migrate essentially via diffusion. Advection is taken into account but remains highly negligible.

The permeability values determined *in situ* or on undisturbed samples are between 10^{-14} and 10^{-13} m/s. The structure of the medium suggests permeability anisotropy and leads to cautiously adopting a value ten times higher for the horizontal permeability.

The reference calculation therefore takes into account a vertical permeability value of 5.10^{-14} m/s and a horizontal permeability value of 5.10^{-13} m/s. The influence of temperature on the permeability value is not included in calculations for the normal evolution scenario, but it is taken into account in the altered evolution scenarios because of its greater influence.



Schematization of the Callovo-Oxfordian argillite texture and porosity

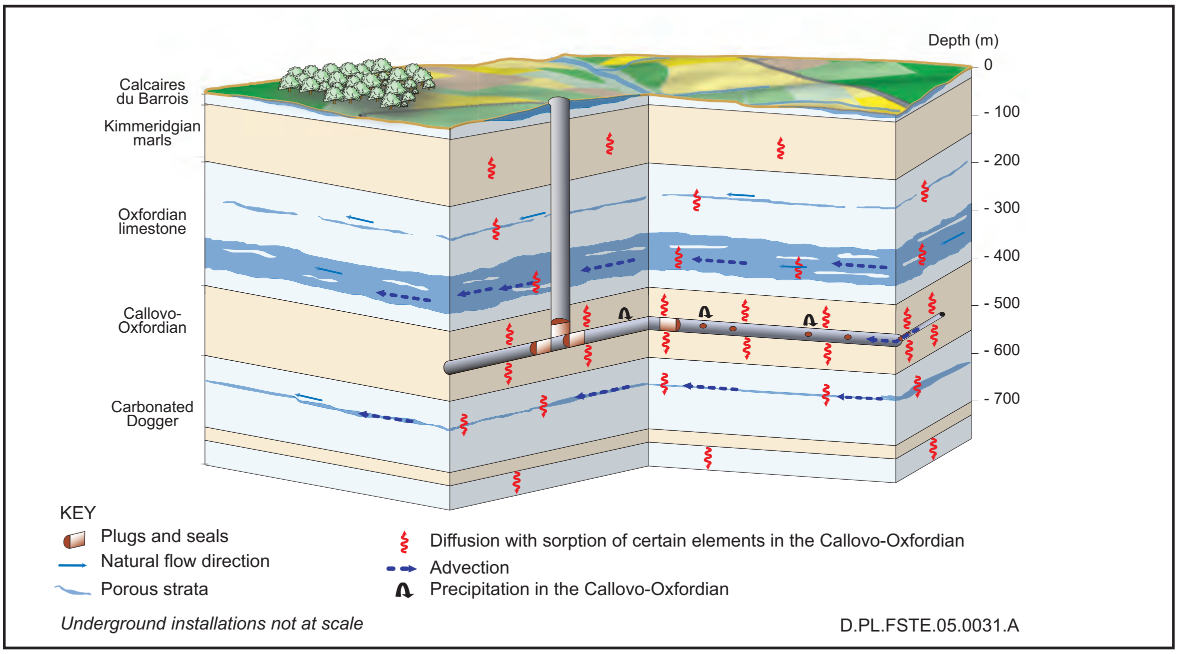
The argillites retention properties for the various elements included in the calculations correspond to the measured and determined values based on observations performed on samples. In order to cover the full range of uncertainties, conservative values have been adopted.

Sensitivity analyses have been conducted for the transport and geochemical parameters in the geological barrier, particularly for diffusion, porosity and delay coefficient values, and for the solubility limit values.

The pressure difference between the two formations surrounding the Callovo-Oxfordian argillites, means a hydraulic head gradient. In keeping with the hydrogeological models adopted, we have adopted the highest value observed over most of the transposition zone, i.e., 0.2 m/m for the current hydrogeological model and 0.4 m/m for the "one million years" model.

2.2.6 Migration in surrounding formations

Beyond the Callovo-Oxfordian formation, the elements transported penetrate the surrounding formations, where they can migrate via diffusion or advection/dispersion. The dominant transfer mode depends on the specific characteristics of each formation. The properties of these formations are represented in a conservative manner, assuming the continuity of the porous horizons where water may circulate.



Representation of surrounding formations and radionuclide transfer phenomena

The simplified representation of the surrounding formations consists of grouping together the layers with similar hydraulic and transport performance characteristics. They are modelled with constant thicknesses equal to those encountered right below the Meuse/Haute-Marne site. No geochemical performance possibly inducing a transport delay is assigned to them. No sedimentological evolution possibly leading to a reduction of the hydraulic properties of the aquifer horizons in the Oxfordian formation has been considered.

In the model representing the current situation, the following levels are distinguished from the Callovo-Oxfordian to the surface:

- *carbonated Oxfordian*, represented by distinguishing its various porous or non-porous horizons. From bottom up: a first series 60 metres thick with low permeability (10^{-11} m/s) corresponding to facies C3a-C3b, a porous horizon 50 metres thick with higher permeability (3.10^{-8} m/s), a series 150 metres thick representing the compact limestones of the inter-porous horizons (10-9 m/s), a second porous horizon 5 metres thick with high permeability (3.10^{-8} m/s), and a series 25 metres thick representing the compact limestones at the top of the Oxfordian (10^{-9} m/s).

- *Kimmeridgian*, represented by a single layer with low permeability (10-11 m/s) approximately 110 metres thick when overlaid by another formation (which is the case almost throughout the zone modelled).
- *les calcaires du Barrois* (limestone), represented as two layers, with a lower series where no karstic phenomena are observed and an upper series corresponding to the potentially karstic horizons of the formation. The Barrois limestone thickness in the zone modelled varies according to the surface topography.

In the "one million years" model, the above representation is modified to take into account surface erosion:

- *Kimmeridgian and the upper Oxfordian*: when outcropping, these formations have permeability values of 10^{-7} m/s. When they are overlaid, their hydraulic properties are similar to the current geological model.
- *Barrois limestone*: except for a few very limited locations, they have disappeared throughout the zone modelled.

Below the Callovo-Oxfordian, the Dogger is represented in both models (current and after one million years) as a layer with low permeability (10^{-10} m/s) and constant thickness (150 m). In this layer, a porous horizon with higher permeability (10^{-8} m/s) and low thickness (approximately 5 metres) is represented approximately 20 metres below the Callovo-Oxfordian to take into account the low water ingress observed in the Bathonian (apparently relatively localised water ingress).

2.2.7 Outlets selection

The development of water circulation models at sector scale allows for the identification of the various possible outlets, i.e., locations susceptible of producing water containing radionuclides released from the repository. The safety analysis must then select those that are the most penalising with regard to committed doses.

The selection of outlet locations within each hydrogeological model is based on the following principles:

- natural outlets are neglected. Despite being by far the most probable, they do not produce the highest doses (due to dilution).
- water wells are considered in the porous horizons of the surrounding formations, from which a critical group member collects the radionuclide-contaminated water for drinking purposes or agricultural use. Although less probable, these outlets are more penalising, since the contamination is less diluted. They are voluntarily located as close as possible to the conventional repository site in zones with low water flows, and in most cases at depths of approximately 50 to 100 metres. This pessimistic choice significantly increases the calculated impact.

This approach is more penalising than the recommendations of basic safety rule RFS III.2.f, which specifies that "*the outlets shall consist of rivers and shallow water wells*".

Among the outlets considered, the water well drilled in the Saulx valley appears to be the most penalising. It consists of pumping water at the first possible location in the immediate vicinity of the repository, selecting a zone with maximum radionuclide concentration levels. This outlet is therefore placed upstream of all the natural outlets possibly encountered by radionuclides during their migration through the surrounding formations. It is located near the site but outside the transposition zone, in a zone where the hydrogeological model provides for diffuse fracturing (today purely hypothetical) parallel to the Marne faults.

Diffuse fracturating zone

In the modelling, a diffuse fracturing zone in the Oxfordian (outside the transposition zone) has been considered on the basis of measurements performed in borehole EST321 (west of the Saulx), where a higher water ingress than in any other Oxfordian boreholes has been observed. This is a cautious hydrogeological modelling choice.

Outlets for the safety analysis

Based on the principles adopted for outlet definition, the hydrogeological model for the current situation shows several outlet zones.

In the overlying formations:

- a water well outlet located on the boundary of the diffuse fracturing zone, as close as possible to the repository (starting approximately at the Saulx valley), west of the Marne faults. This outlet captures the whole flow of radionuclides heading towards the Saulx river.
- another water well outlet, also located at the edge of the diffuse fracturing zone near the repository, that intercepts the radionuclides flowing towards the Marne.
- a water well outlet in the Barrois limestone or outcropping Kimmeridgian marls.

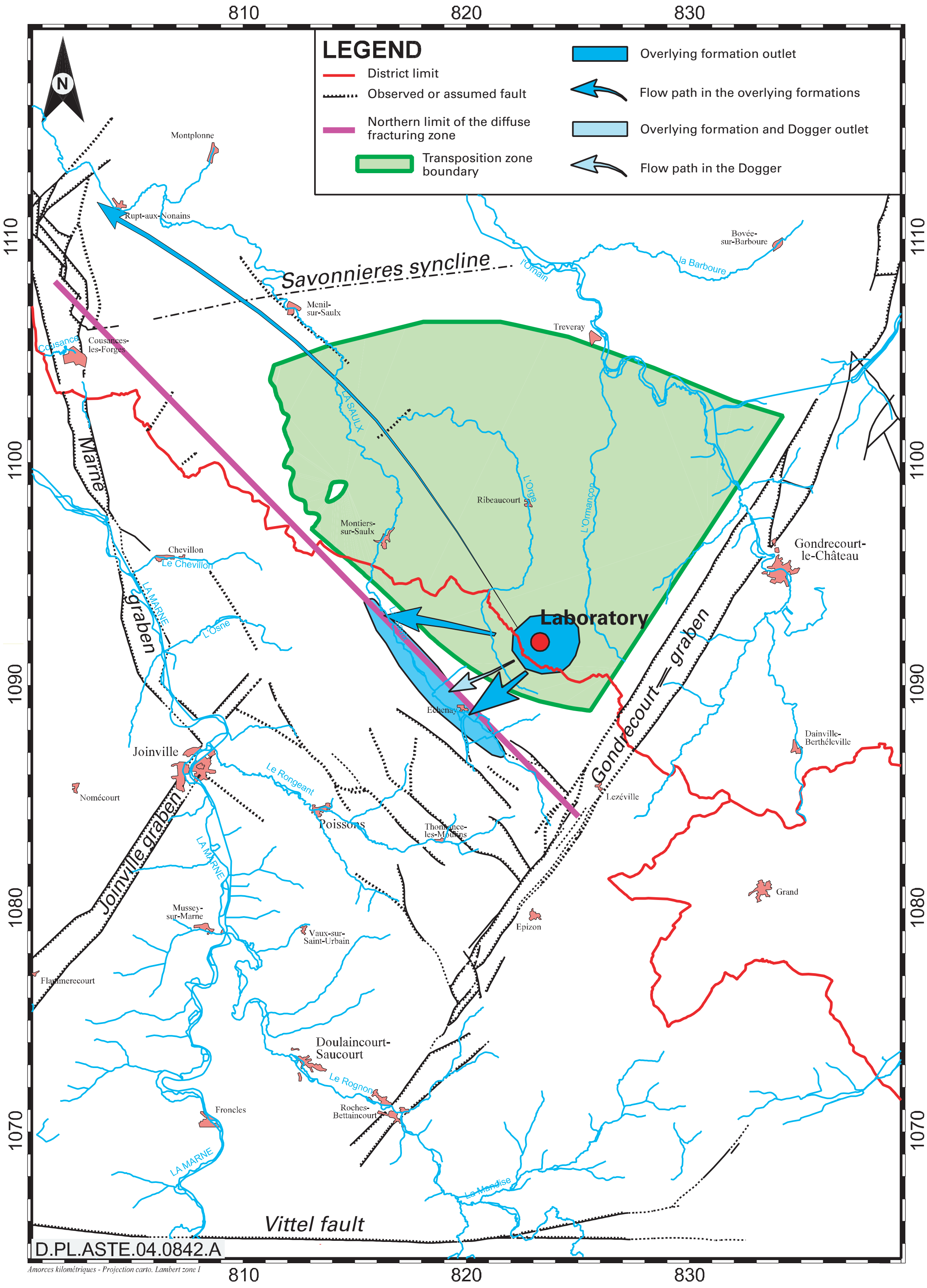
Dogger (underlying formation): no realistic outlets can be determined in the zone considered. We have nevertheless selected a conventional water well outlet near the Saulx valley.

In the hydrogeological model after one million years, surface erosion leads to evolutions of the outlet zones in the overlying formations:

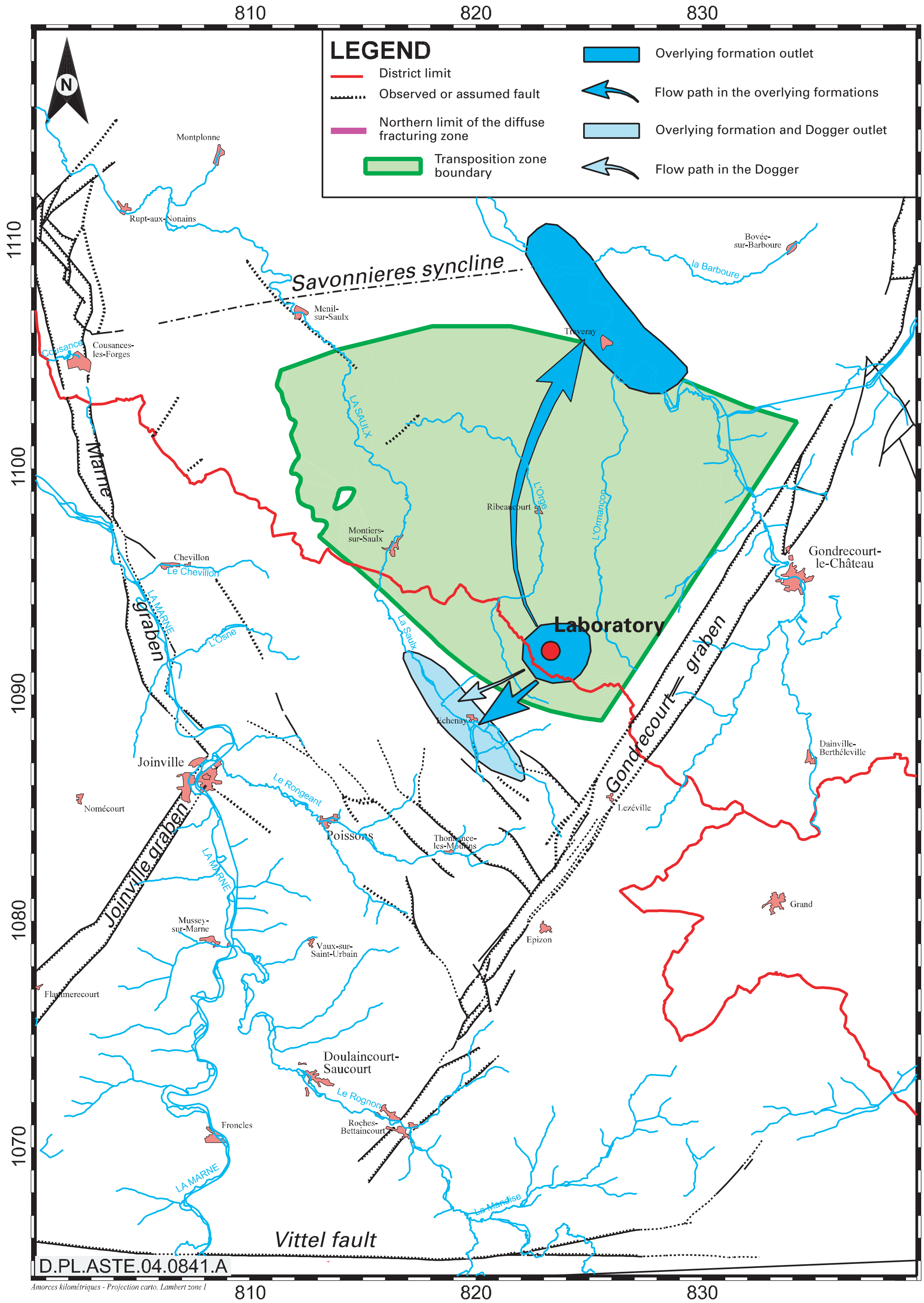
- an outlet appears in the Ornain valley. It is considered as a spring or a water well in the upper porous interval, showing properties that are slightly more favourable for such purposes (improvement of permeability associated with outcropping).
- the water well outlet located on the boundary of the diffuse fracturing zone as close as possible to the repository (starting approximately at the Saulx valley) is still relevant
- the water well outlet in the Barrois limestone or outcropping Kimmeridgian marls, is modified according to the topography evolution.

Dogger *(underlying surrounding formation)*: same conventional outlet.

Selecting outlets near the site significantly reduces the influence of the hydrogeological model on the impact assessment, therefore eliminating any influence by the Marne faults and the need for their detailed study. In any case, an outlet at this location will be less penalising due to dilution effects.



Flow pathways and outlets selected for the safety assessment (current hydrogeological model)

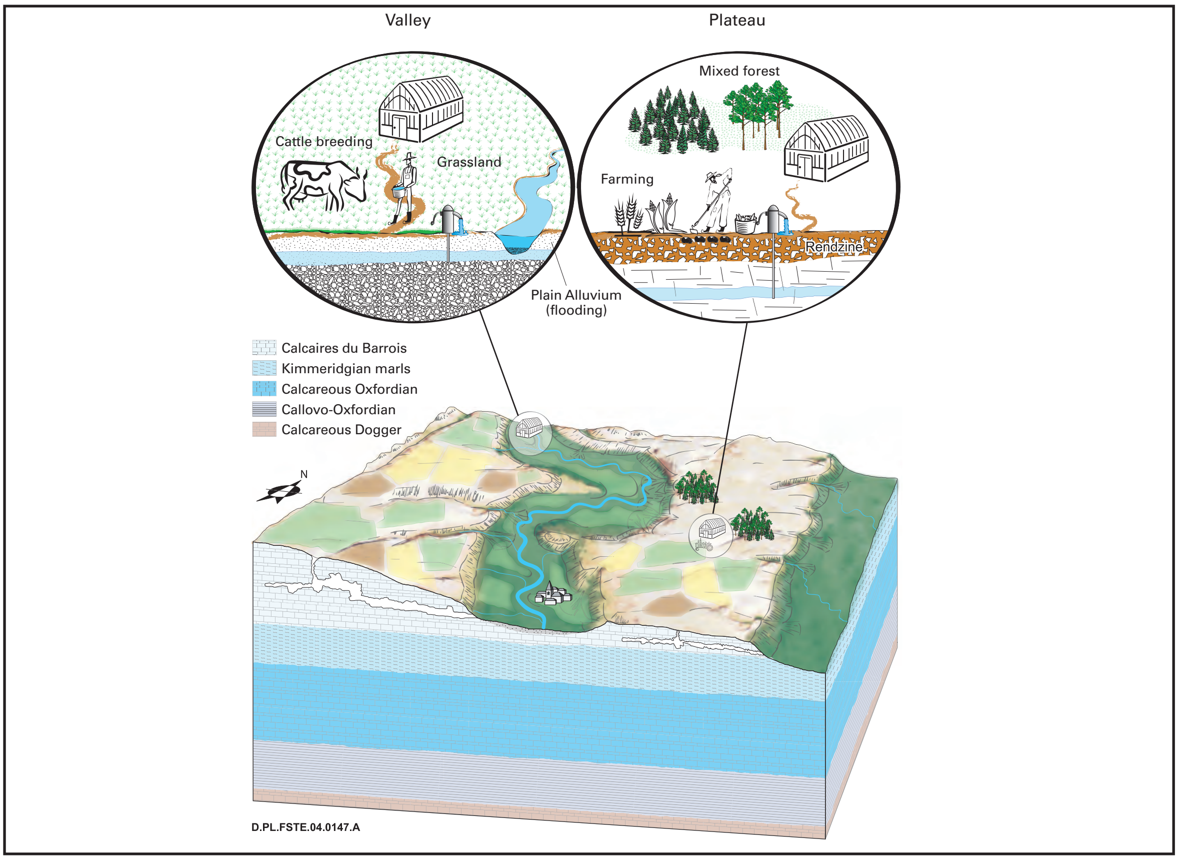


Flow pathways and outlets selected for the safety assessment ("one million years" model)

2.2.8 Biosphere

It is assumed that the water pumped from these outlets is used to water a vegetable garden or as drinking water. The model takes into account the transfer of radionuclides through the biosphere (via plants and animals) up to a member of a critical group, basically village-dwelling farmers obtaining most of their subsistence from their crops. A group living in complete autarky has also been considered.

The biosphere represents the last compartment of radionuclide transfer towards man and the environment. Within the scope of the IAEA BIOMASS international programme, three reference biospheres have been identified as possibly occurring in the Meuse/Haute-Marne region during the next million years: temperate biosphere (similar to the current one), boreal biosphere and tundra. Each of these biospheres is associated with agricultural practices adapted to climate conditions. For each of the climates considered, it is demonstrated that the 'village-dwelling farmers' group is associated with the largest number of transfer pathways and therefore constitutes the critical group. The temperate biosphere which allows to deal with the major number of impact pathways has been considered.



Schematic representation of the temperate biosphere

Biospheres

Three biospheres were defined within the scope of the BIOMASS programme:

- *temperate biosphere* currently prevailing in France, characterised by warm summers, cold winters and an average annual temperature between 8 and 10°C.
- *tundra*, corresponding to the habitat extending from the southern limit of the arctic icecaps to the northern limit of boreal forests. It concerns Northern America, Northern Europe and Siberia and is characterised by no trees and a very dry and cold climate (average annual temperature below zero).
- *boreal biosphere*, associated with a climate characterised by long, cold and dry winters (average annual temperature of a few degrees above zero). Boreal forests are present in regions capped with ice during previous glaciations. They constitute approximately 30% of the world forests, extending between 50°N and 60°N.

2.3 The results of normal evolution performance assessment

The normal evolution scenario and its associated safety model are the basic tools used for safety calculations. These form the basis of performance assessment, providing quantitative information on the repository behaviour relative to radionuclide release over different time scales. The selected presentation favours four angles of approach:

- assessment of the robustness of main safety functions of the repository;
- presentation of the most penalising doses according to different outlets and types of waste packages;
- feedback provided from sensitivity analyses, to appraise the weigh of certain variants on the results;
- a general assessment of the robustness of the repository concept.

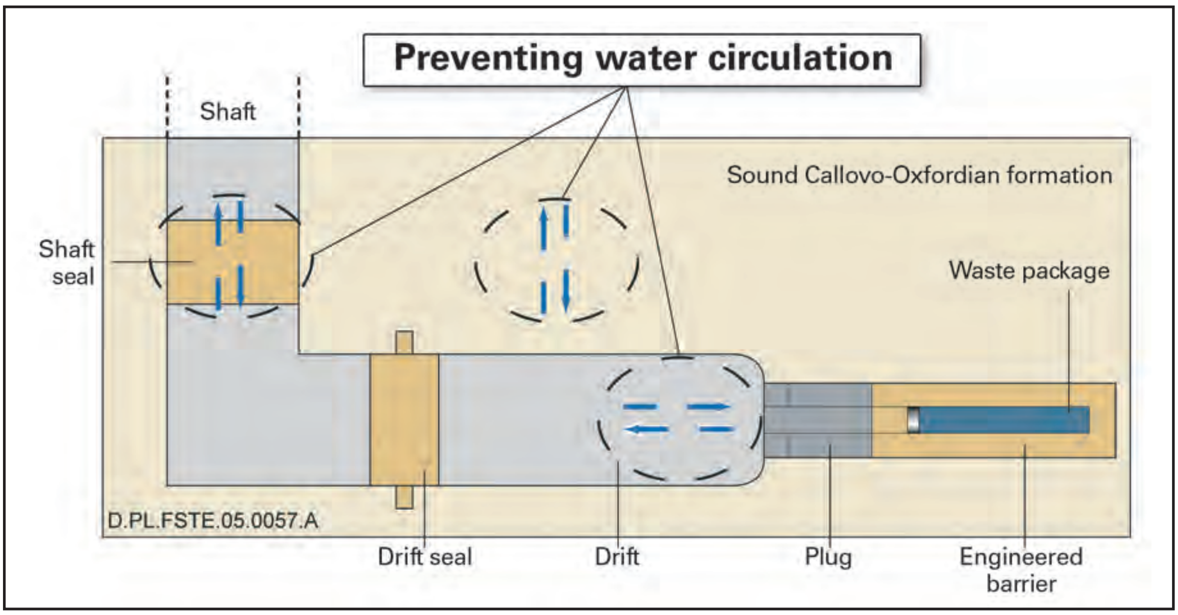
2.3.1 The main information obtained concerning safety functions

The conclusions of the analysis are presented for the repository three main safety functions as planned by the repository designer.

• Preventing water circulation

The repository architecture has been designed to prevent water movement (compartmentalisation, "dead-end" architecture, multiple seals) by making the most of the geological formation favourable properties (low permeability). The assessment must be used to appreciate whether or not transport in the repository is dominantly diffusive and whether or not advective circulation is minor. In particular, this entails checking whether radionuclides migrate towards the geological medium and do not follow the preferential transfer pathways along repository structure or drifts.

A simple indicator (Peclet number) is used to assess the respective importance of the two transport regimes. If Peclet number is less than 1, the dominant transport regime is diffusive. The calculations indicate a Peclet number in the Callovo-Oxfordian of about 0.13 for anions (negatively charged and more mobile species) and about 0.01 for cations (positively charged and more closely bound species). *Diffusive transport therefore predominates over the advective one: water circulation in the repository is very slight. This result is very robust in that sensitivity analyses using Callovo-Oxfordian performances degraded by a factor of ten with respect to permeability give similar results.*



Scheme illustrating the dead-end architecture and the multiples seals

6

A indicator for the "preventing water circulation" function: Peclet number

Peclet number is the ratio between the characteristic diffusive migration time and the advective transfer time. If diffusion predominates over advection, characteristic diffusive migration time is less than advective transfer time and Peclet number is less than 1. Advection predominates over diffusion when Peclet number is more than 2. For values between 1 and 2, diffusion and advection are co-dominant.

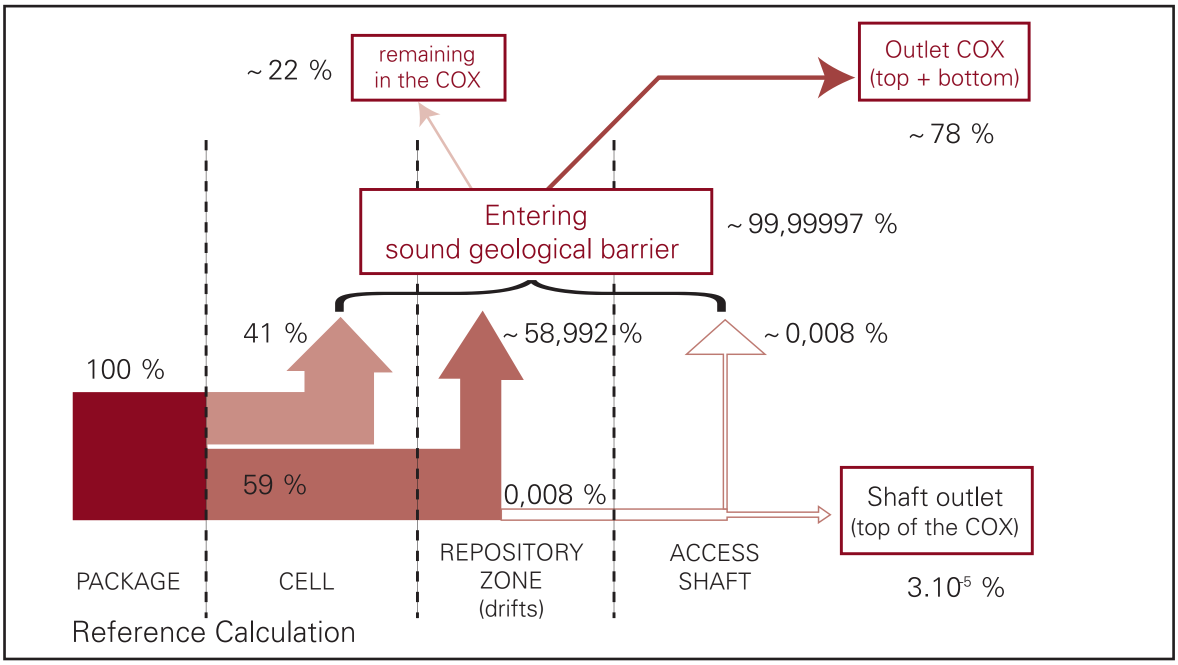
Another way of appraising the repository ability to slow down internal water flow, is to assess the preferred radionuclide transfer pathways. If the diffusive regime is dominant, sooner or later, mobile elements must migrate preferentially towards the geological medium and not through the drifts towards the shafts.

The indicator selected to assess the privileged migration medium is the respective mass distribution of elements either migrating via the structures from disposal cells to access shaft or finally migrating by diffusion into the Callovo-Oxfordian. The most significant quantitative assessment was performed for a long-lived radionuclide which is soluble and not retained by the medium - iodine 129. This has the advantage of being one of the most mobile elements as well as being the main contributor to the impact observed. Using it an indicator therefore provides a simple way of measuring repository design and geological medium performance.

Calculation reveals the following elements (on a scale of one million years and with respect to the initial inventory in the packages):

- as of release by the package in the disposal cell, more than 40% of the mass migrates towards the clay in diffusive mode;
- after migrating through the repository structures, more than 99.99% of the mass migrates into the sound geological medium;
- eventually, the drawdown that the shaft may induce, only carries a tiny quantity of iodine 129 which mainly migrates into the geological medium.

These results show that most of the mass is transferred into the Callovo-Oxfordian, which is therefore the privileged medium for transfer.



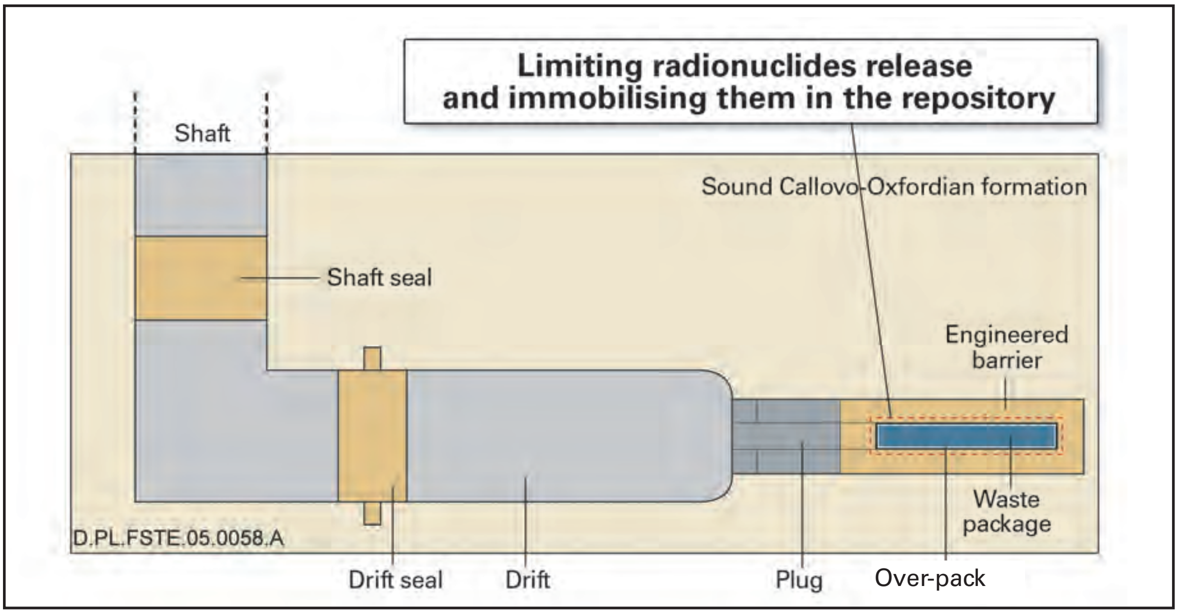
Distribution of the mass through the different calculation compartments (129I of CU1 packages

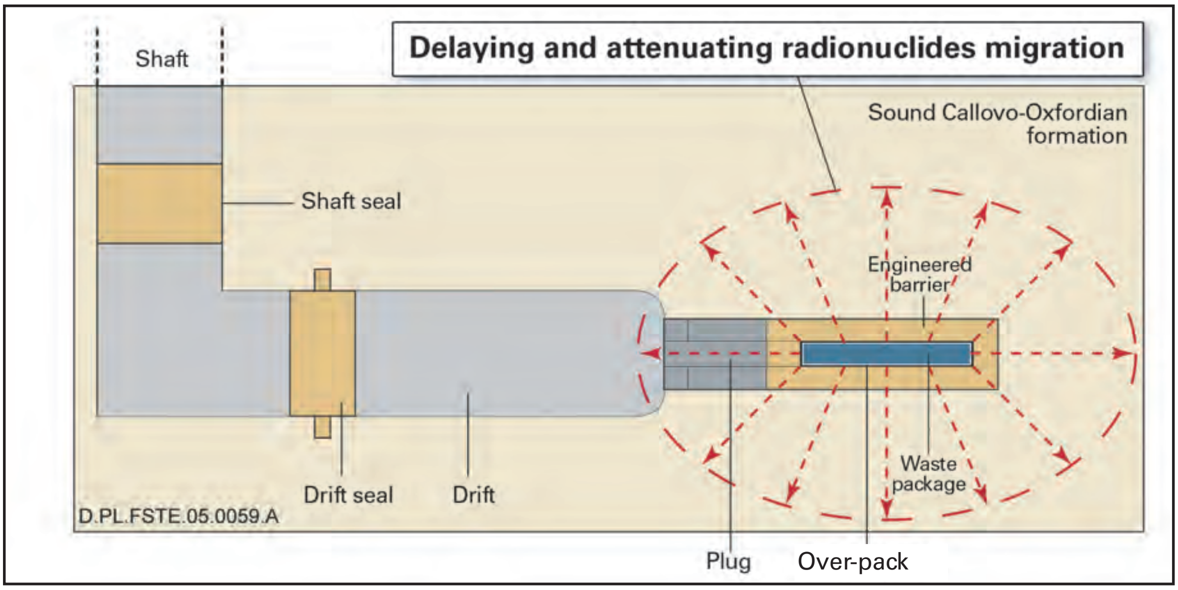
This guarantees that elements are transported by diffusion, consequently benefiting from the slow velocity and retention capacity associated to the argillite geochemistry. The risk of preferential transfer via the damaged zone, even with its pessimistic characteristics as described in the normal evolution scenario, is thus avoided. This supports the efficiency of the proposed design, which makes the most of the host formation favourable properties.

The "preventing water circulation" function is provided efficiently by the repository and constitutes an initial safety guarantee.

• Limiting radionuclides release, immobilising them in the repository, delaying and attenuating their migration

The second function consists of limiting radionuclides release and immobilising them in the repository. This function is performed by the waste package (containers and matrices) and geological formation (notably geochemical conditions leading to radionuclides precipitation). The repository third important function, mainly performed by the geological formation, consists of delaying elements transfer and attenuating their migration. This results from both geochemical properties which mean fixing certain elements and very slow diffusion velocity in the geological medium. The objective is to trap most of the radioactive inventory in the clay and delay the appearance of the residual part until a considerable amount of radioactive decay has taken place.





Schemes illustrating the functions "limiting radionuclide release" and "attenuating radionuclide migration"

One of the main indicators used to assess these functions is the attenuation coefficient provided by the geological medium, i.e. the inventory fraction of a given radionuclide which does not exceed a given distance.

Indicators for the functions "limiting the release and immobilising", "delaying and attenuating"

The performances linked to the functions: "immobilising radionuclides", "delaying and attenuating their migration" in the repository can be quantified using three major values linked to the molar flow rate of each radionuclide when migrating out of a repository element:

- maximum molar flow rate;
- the mass corresponding to the "molar flow rate" integration over the simulation period (1 million years);
- the time at which the maximum molar flow rate occurs.

At the end of the studied period of one million years, the main results are as follows:

- ten metres inside the Callovo-Oxfordian about half the radionuclides studied are fully attenuated (> 99%). They are therefore present in negligible quantity beyond this limit;
- at the top of the Callovo-Oxfordian, i.e. on leaving the host formation, the flow of most radionuclides is fully attenuated. The same applies to the bottom of the argillite layer;
- only four elements (iodine 129, chlorine 36, selenium 79 and calcium 41) still present a flow at the top of the Callovo-Oxfordian. However, calcium 41 and selenium 79 are already very strongly attenuated.
- among the four previous elements, only iodine and chlorine have smaller attenuation coefficients, 65 to 75% for chlorine and 20 to 50% for iodine.

Radionuclides	**Mass attenuation at the Callovo-Oxfordian boundaries (top and bottom)**	
	C waste / CU	**B waste**
^{108m}Ag, ^{93}Mo, ^{10}Be, ^{93m}Nb, ^{94}Nb, ^{99}Tc, ^{126}Sn, ^{166m}Ho	Total attenuation (100%)*	
^{14}C, ^{135}Cs, ^{107}Pd, ^{59}Ni, ^{93}Zr	Total attenuation (100%)**	
^{79}Se	> 99,95 %	
^{41}Ca	90 – 95 %	> 99 %
^{36}Cl	65 – 75 %	> 70 %
^{129}I	20 – 30 %	> 50 %

Attenuation in the Callovo-Oxfordian formation
* Total attenuation (100%) within about the first 10 metres of the Callovo-Oxfordian
**Very strong attenuation (over 90%) within about the first 10 metres of the Callovo-Oxfordian

Another indicator for the "delaying and attenuating radionuclide migration" function is the date of occurrence of radionuclide flow at a given point in the geological medium.

For the two previously-mentioned radionuclides, the diffusion properties in the Callovo-Oxfordian are such that they produce a very significant delay in the occurrence of the maximum radionuclide flow at the formation boundary, extending it to several hundred thousand years. Concerning chlorine 36, considering its period, radioactive decay starts to produce its effects before the appearance of significant flow at the clay formation boundary. The result is that iodine 129 is usually the element making the largest contribution to doses at the outlet. *The clay formation acts as a medium which delays the migration of mobile elements for a long time, up to several hundred thousand years*.

After leaving the clay formation, non-attenuated elements penetrate the surrounding formations (Oxfordian above, Dogger below). The hydrogeological model can then be used to assess the transfer time to the various outlets. These transfer times are short relative to those within the geological formation (about 50 000 years for the "one million years" model and 100 000 years for the current model, for the outlet closest to the Saulx river, which is the most penalising).

This means that, for the safety model representation, the surrounding formations play a very small, even negligible role. This is a logical observation in that:

- no retention property linked to geochemistry has been assigned to these formations, as a cautious approach, although it is probable that these formations or part of these have such properties;
- the selected outlets are located as closest to the repository and with deliberately penalising configurations.

These two elements emphasise that there are significant safety margins in this area, both by taking into account geochemical characteristics and actual outlets which will necessarily be less conventional and penalising than those selected.

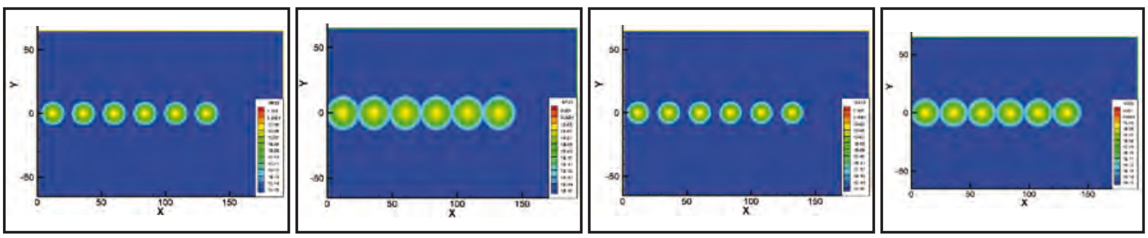
The functions "limiting radionuclides release and immobilising them" and "delaying and attenuating migration" are performed efficiently by the repository. Only a small quantity of radionuclides are likely to migrate out of the host formation and this will occur far away in time (100 000 years and beyond). These functions are mainly based on the argillaceous geological medium. As far as the "delaying and attenuating migration" function is concerned, surrounding formations have not been assigned any performance.

Examination of the main safety functions, independently of the dose assessments, leads to the conclusion that the repository will perform well, as expected by its design. This adds support to the choices made, both in repository architecture and in assessing the geological formation favourable nature.

Actinides in the normal evolution scenario

An additional specific analysis has been carried out concerning actinides (transport calculation) for the normal evolution scenario. It shows that they would remain totally confined in the Callovo-Oxfordian at the scale of the assessment (1 million years). Thus there is no need to build allowance for them into the full radiological impact calculation. This calculation takes up the main hypotheses of the full calculation.

The analysis reveals that chemical retention of the actinides is very high in the Callovo-Oxfordian. Actinide migration in the Callovo-Oxfordian over the next million years does not exceed about 10 metres as shown by the figures below (examples of neptunium and uranium). The characteristic diffusive migration times to the formation boundaries are at least of the order of 10^9 years. Accordingly the dose maxima would occur well after one million years and at very low levels.



at 200 000 years ***at 500 000 years***
237 Np isoconcentration plots
(Concentration in mol/m³; X and Y in metres)

at 200 000 years ***at 500 000 years***
233 Ur isoconcentration plots
(Concentration in mol/m³; X and Y in metres)

2.3.2 Dose assessments at the various outlets

The main indicator for assessing the repository impact is the dose at an outlet. This dose is assessed on the basis of the penalising selection of outlets as defined previously. The essential contributors to the dose are iodine 129, chlorine 36 and selenium 79.

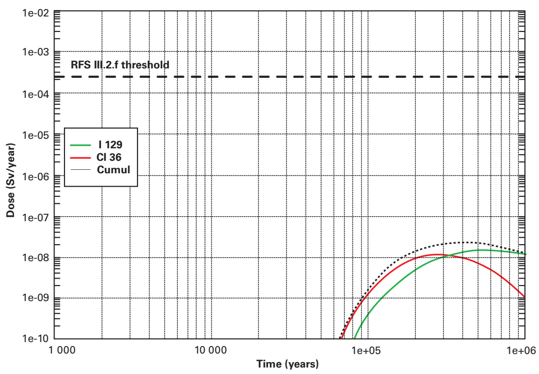
To provide clear and readable data, the results are presented for the outlet giving the highest doses, therefore the Saulx outlet for the Oxfordian. All the other outlets doses are lower than the Saulx one. This outlet corresponds to a conventional choice, not very realistic and very likely excessively penalising. In particular, the water well is located where radionuclide concentration is at its highest and where the available quantity of water is low, whereas there are greater water resources less than a kilometre further. The probability of this outlet to be actually implemented as water producer is therefore very slight.

The results are given for both hydraulic models (current and "one million years" models) and by presenting separately B waste, C waste and spent fuel.

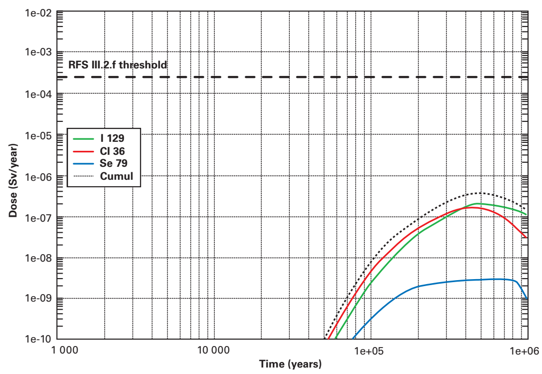
To obtain consistent and cautious estimates, the following conventions have been made for the waste inventory concerned. For B waste, a scenario with reprocessing was taken into account (table S1b). For glasses, we distinguished between the different categories of glasses, selecting the maximum quantity depending on the reprocessing scenarios (S1a for C3 and C4 glasses, S1b for C1 and C2 glasses, the quantity of C0 glasses being identical in all the scenarios). Finally, the doses associated with the EDF spent fuel (CU1 and CU2) were assessed using scenario S2 (reprocessing stopped) which gives the highest values. The results for CEA research and defence (CU3) spent fuel are also given. This method provides a separate vision of the impact of each type of waste. On the other hand, it must be emphasised that adding up the various impacts does not reflect a real situation because it comes down to more or less taking the same inventory into account twice (you cannot have C1/C2 and C3/C4 glasses in maximum quantities at the same time). Whatever happens, it is shown that, even with this bias, the global estimates remain much lower than the reference values.

Synthesis of maximum doses at the most penalising outlet (Saulx)

	Current hydrogeological model		Hydrogeological model at 1 Ma	
	maximum accumulated dose (mSv/ year)	Date of maximum dose (years)	maximum accumulated dose (mSv/ year)	Date of maximum dose (years)
All B waste scenario S1b	0,00047	370 000	0,00047	300 000
All C waste (C0, C1+C2 scenario S1b, C3+C4 scenario S1a)	0,0008	550 000	0,00083	490 000
Spent fuel CU1+CU2 scenario S2	0,022	410 000	0,020	330 000
Spent fuel CU3	0,000073	400 000	0,000067	330 000



Dose evolution at outlet (Saulx) versus time – B2 reference package (bituminised sludge) – hydrogeological model "one million years"



Dose evolution at outlet (Saulx) versus time – C1+C2 reference package - hydrogeological model "one million years"

Several conclusions can be drawn:

- in all cases, the dose is significantly below the reference value of 0.25 mSv per year (by least a factor of 10);
- the two hydrogeological models gives similar results in terms of dose levels. The 1 million year model gives maximum dose dates slightly earlier, but the differences are not very significant. This shows that the assessment is not very sensitive to the evolution of the hydrogeological model;
- the contribution of B waste appears slight in that it does not exceed 0.0005 mSv per year;
- the contribution of C waste is also several orders of magnitude below the selected reference limits (0.0008 mSv per year, taking into account the bias noted above);
- if disposal of EDF spent fuel (CU1 and CU2) is taken into consideration, the impact would be around 0.02 mSv per year. Would CEA fuel (CU3) be disposed of in the repository, the impact would be negligible (less than 0.00001 mS per year).

Some comments may clarify these results:

- the reference values are respected, by taking into account, per convention, the most pessimistic possible outlet;
- B and C waste generally contributes at a negligible level.
- if spent fuel geological disposal is planned, this would mean an acceptable impact (ten times less than the reference value), even by adopting a conservative release model when compared to international practice.

Impact of toxic chemicals

Impact calculations have also been performed for some representative toxic chemicals likely to be present in relatively large quantities in HL (high level) and ML-LL (medium level long lived) waste (boron, selenium, nickel, antimony):

- boron and selenium chemical impact has been assessed for packages of vitrified waste which contain the largest quantities.
- antimony is present in roughly similar quantities in vitrified waste, technological waste and spent fuel. The case of vitrified waste was covered.
- nickel is present in metallic waste, but above all in steel used in the repository (containers, sleeves, etc.). It is difficult, at this stage of the study, to define an inventory which is accurate enough with respect to quantities of nickel and to attribute release kinetics to each potential source. Therefore, to eliminate these uncertainties, Andra has taken a penalising approach, consisting of imposing a saturation concentration of nickel constantly all along the simulation (1 000 000 years) and throughout the whole repository.

The results of impact calculations are expressed both in terms of maximum concentration in the outlet (an amount which does not provide direct information on the health effect, but which is easier to understand) and in terms of excessive individual risk (EIR) for stochastic effects on health (carcinogenic effects) and hazard factors (HF) for risks with threshold effects (non-carcinogenic effects). A risk is generally considered to be acceptable with an EIR below 10-5 per year and an HF of less than 1. These indicators are assessed for the same critical group as for radionuclides.

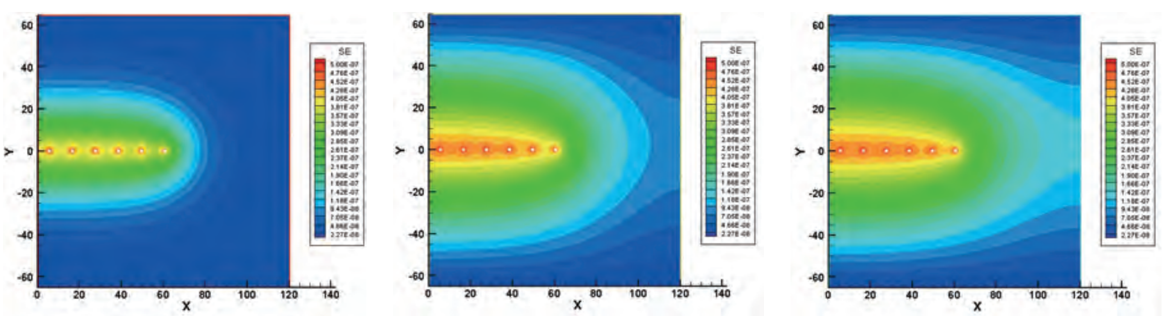
Of the four elements studied, none is identified as carcinogenic by ingestion and only nickel is accepted as carcinogenic by inhalation.

On the scale of one million years, the strong sorption of antimony in Callovo-Oxfordian argillites means that it is fully attenuated in the geological barrier. It therefore has no impact on the biosphere.

The results for the other toxic chemicals are given in the following table.

Chemical element (waste concerned)	Maximum concentration on the scale of one million years [µg/l]	Maximum HF – non-carcinogenic effects		Maximum EIR – carcinogenic effects	
		Ingestion	Inhalation	Ingestion	Inhalation
Boron (C1/C2)	0,05	3.10^{-6}	–	–	–
Nickel (C1/C2)	0,001	6.10^{-5}	5.10^{-4}	–	3.10^{-9}
Selenium (C1/C2)	0,00002	5.10^{-7}	–	–	–
Antimony (C1/C2)	0	0	0	–	–

These results show that the impact of toxic chemicals is negligible.



Isoconcentration plots showing selenium progression at 100 000 years, 500 000 years and one million years inside the Callovo-Oxfordian formation (from left to right) - Concentration in mol/m³, X and Y in metres

2.3.3 Sensitivity analyses results

The previous assessment is completed by sensitivity analyses to evaluate the robustness of the results, stating whether or not they are more or less sensitive to the evolution of certain parameters. These sensitivity analyses can also be used to determine which parameters have the most influence on the assessment. These analyses can be split into two main categories:

- the first one concerning waste package release models. In most cases, more penalising conditions are taken into account, with faster release. However, one exception concerns the spent fuel case, with a less penalising model based on classic dissolution, in accordance with international practice;

- the second one concerns the parameters characterising Callovo-Oxfordian argillites.

• Taking into account more conservative release models for waste packages would have only very limited impact , further safety margins still exist in the case of certain packages

Taking into account conservative models and parameters for package release has little effect. Faster package release does not change flow rate out of the formation nor their rhythm of appearance, considering the very long migration times in the geological medium. For example, considering 1000 years instead of 10 000 years for bituminized waste package lifetime has no effect on the calculated impact for this waste.

		Sum of spent fuel CU (CU1+CU2) scenario S2		Sum of C1 + C2 waste scenario S1b	
		Maximum accumulated dose (mSv/year)	Date of maximum dose (years)	Maximum accumulated dose (mSv/year)	Date of maximum dose (years)
1. COX parameters					
1.1.	***Conservative COX permeability*** (10 times the "phenomenological" value)	0,020(*) (ditto reference)	330 000 (ditto reference)	0,00047(*) (ditto reference)	490 000 (ditto reference)
1.2.	***Conservative transfer and retention parameters***	0,045	170 000	0,0037	200 000
1.3.	***Degraded EDZ*** Fractured zone: $K = 10^{-6}$ m/s, no geochemistry, water diffusion in water Micro-fissured zone: $K = 5.10^{-9}$ m/s, conservative diffusion and geochemistry	0,020(*) (ditto reference)	330 000 (ditto reference)	0,00047(*) (ditto reference)	490 000 (ditto reference)
2. Source term					
2.1.	***Conservative parameters of the radiolytic dissolution model for spent fuel*** (dissolution rate multiplied by 10 and conservative labile fraction)	0,020 (ditto reference)	330 000 (ditto reference)	Not applicable	Not applicable
2.2.	***Model for control by uranium solubility for spent fuel (CU)***	0,0024	310 000	Not applicable	Not applicable
2.3.	***V_0S model for C waste.***	Not applicable	Not applicable	0,00063	280.000
2.4.	***Labile release for B waste*** (B1, B4, B5)	Not applicable	Not applicable	Not applicable	Not applicable
2.5.	***Release rate of bitumen (B2)*** rate = 10^{-3} per year	Not applicable	Not applicable	Not applicable	Not applicable

*** : no specific dose assessments were performed and these studies were limited to intermediate indicators (radionuclide flow at Callovo-Oxfordian boundary). Since these indicator values are quite similar to the reference case ones, doses are not modified.**

Progress in research, a priori possible, would supplement greater safety margins by using more realistic modelling for some glasses and spent fuel

- for most C waste, the model used is the one which best reflects available knowledge of glasses, i.e. ($V_0.S \rightarrow V_R$) and is based on solid scientific knowledge. The consequences of a degraded model have been examined from a sensitivity point of view. This would lead to a significant increase in the contribution of chlorine 36 to the final dose, without putting at stake the dose limit (accumulated dose of 0.00063 mSv per year for C0+C1+C2 packages and 0.00049 mSv per year for C3+C4 packages). It would be interesting to have more information on the types of glasses for which the model $V_0.S \rightarrow V_R$ cannot be applied (C0 packages).
- considering a spent fuel release model based on classic uranium dissolution does affect results. Indeed, it entails much slower release kinetics via the oxide matrix (on a scale of several million years). Therefore, over one million years, most of the mass released by the packages corresponds to the labile activity fraction. The total impact of CU is reduced by a factor of ten (0.0024 mSv per year). This point is notable since the model tested for sensitivity is evaluated as more realistic in accordance with international practice than the one used by Andra in the reference calculation.

		Sum of spent fuel CU (CU1+CU2) scenario S2		Sum of C1 + C2 waste Scenario S1b	
1. COX parameters		**Maximum accumulated dose (mSv/year)**	**Date of maximum dose (years)**	**Maximum accumulated dose (mSv/year)**	**Date of maximum dose (years)**
1.1.	***Conservative COX permeability*** (10 times the "phenomenological" value)	0,00036(*) (ditto reference)	500 000 (ditto reference)	0,00047(*) (ditto reference)	310 000 (ditto reference)
1.2.	***Conservative transfer and retention parameters***	0,0028	210 000	0,00079(**)	220 000
1.3.	***Degraded EDZ*** Fractured zone: K = 10^{-6} m/s, no geochemistry, water diffusion in water Micro-fissured zone: K = 5.10^{-9} m/s, conservative diffusion and geochemistry	0,00036(*) (ditto reference)	500 000 (ditto reference)	0,00047(*) (ditto reference)	310 000 (ditto reference)
2. Source term					
2.1.	***Conservative parameters of the radiolytic dissolution model for spent fuel*** (dissolution rate multiplied by 10 and conservative labile fraction)	Not applicable	Not applicable	Not applicable	Not applicable
2.2.	***Model for control by uranium solubility for spent fuel (CU)***	Not applicable	Not applicable	Not applicable	Not applicable
2.3.	***V_0S model for C waste.***	0,00049	290 000	Not applicable	Not applicable
2.4.	***Labile release for B waste*** (B1, B4, B5)	Not applicable	Not applicable	0,00047 (ditto reference)	Not applicable
2.5.	***Release rate of bitumen (B2)*** rate = 10^{-3} per year	Not applicable	Not applicable	0,00047 (ditto reference)	310 000 (ditto reference)

**** : sensitivity studies were performed with CSD-C waste, which contribute the most to the dose impact.
As matter of fact, the reference case calculated dose is 0,00033mSv per year.**

• Callovo-Oxfordian permeability provides safety margins

The permeability values selected as a reference scenario for argillites appear to be robust based on experimental observations. The sensitivity analysis has, however, considered Callovo-Oxfordian permeability degraded by a factor of ten (horizontally and vertically). In this configuration, the transport mode is still diffusive without altering significantly flow at the host formation interface. We can therefore conclude that major safety margins are provided by the geological medium.

• Degradation of argillites retention properties partly modifies the list of radionuclides attenuated by the formation, but does not cause any major dose evolution at the outlet.

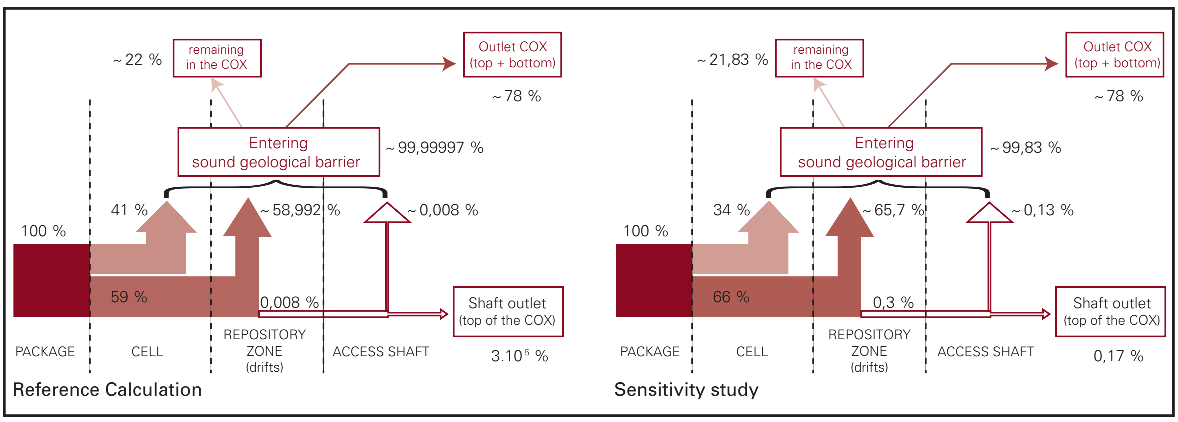
In this sensitivity analysis section, significantly degraded properties of argillites were considered for retention (increased solubility, reduced retention) and transport. Radionuclide transfer times and radionuclide flow maximum times are reduced (by a factor of 2.5 for soluble non-sorbed elements in the reference calculation, such as iodine 129 and chlorine 36). However, only the elements already mentioned which are not strongly retained in the geological medium (iodine 129, chlorine 36, and selenium 79) record significant flow while migrating out of the geological barrier. However, a minimal contribution by several elements such as beryllium 10 or carbon 14 is also noted. The lack of contribution by other elements emphasises the remarkable capacity of argillites to confine them.

In terms of dose assessment, the two situations can be compared for spent fuel (CU1 + CU2) which is the most penalising case. For the most penalising outlet (Saulx), the dose rises from 0.020 mSv per year to 0.045 mSv per year, still much lower than the regulatory references. However, a rather shorter time is noted for the dose peak occurrence (170 000 years instead of 330 000 years). Overall, this does not call into question the medium retention capacities and dose limit compliance.

• The damaged zone around the engineered structures plays only a modest part.

The sensitivity analysis considered a damaged zone, with permeability properties degraded by more than two orders of magnitude, with geochemical properties either non-existent or distinctly more pessimistic.

This configuration mainly affects the disposal function "preventing water circulation". Therefore, for the previously mentioned case of iodine, the fraction of iodine likely to be found in the shaft changes from 3.10^{-5}% to + 0.17 %. This is a clear relative increase but the absolute quantity remains negligible. Diffusion remains the dominant transfer regime. Indeed, the Callovo-Oxfordian low permeability strongly limits the water flow circulating in the structures. Under these conditions, even considering that the seals are not very effective, the water entering the repository is not enough to supply circulation via the damaged zone. No definite evolution of doses at the outlet is observed in this configuration when compared to the reference case. These results underline the overall robustness of the concept with respect to a damaged zone with degraded properties.



CU1 package ^{129}I – mass repartition in the various compartments

In conclusion, sensitivity analyses provide a reliability test of results acquired within the normal evolution scenario framework. In particular, they aimed to test the main parameters governing the repository safety functions. Three lessons can be learned from this:

- *maintaining a diffusive regime in the repository seems to be clear, even under considerably degraded conditions. In particular, a damaged zone with penalising properties would have little impact on the final assessment; the same applies to degradation of the sound rock permeability properties;*

- *a reduction in the rock geochemical properties would not be likely to call into question the main conclusions of the reference calculations;*
- *interesting progresses still exist with regards to certain waste package release models. They provide reserves for the safety analysis.*

Therefore, the main parameters governing performance, basically permeability and geochemical characteristics appear robust enough to maintain safety functions, even in considerably more pessimistic configuration than those expected.

2.4 Performance assessment in altered situation

2.4.1 Orientations for defining altered situations

The normal evolution scenario and its associated safety model provide a representation which includes the most likely evolutions of the repository. However, in order to take all uncertainties into account and explore unlikely situations, the safety approach also included the definition of different scenarios leading to an evolution which is different from the one described in the normal evolution scenario because of uncertainties or globally very unlikely risks.

This section of the safety approach is intended to explore the various possible dysfunctionnings which could occur in the repository system, in the form of so-called "altered" situations. In this way, it can be checked whether or not such situations consequences would remain acceptable. These situations are grouped into some scenarios termed as "altered evolution scenarios".

Determination of these altered evolution scenarios is based on a methodological exercise called qualitative safety analysis, which is intended to select the most relevant factors to take into consideration. For this, a review of phenomenological data describing repository evolution in time and space was performed in order to highlight the possible main uncertainties and to identify repository components failures. At the same time, an analysis was carried out on events likely to occur in the repository environment. These include external risk, of human or natural origin. To complete the work, this work was compared with the results of the ones conducted internationally (OECD/NEA).

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At the end of this examination, three altered evolution scenarios were selected: container failure, seal failure, drilling an intrusive borehole. These various possibilities were used for an in-depth examination of the robustness of repository functions:

- *For the function "preventing water circulation", the scenario with combined failures of seal anchorages (drifts and B waste disposal cell), and of C waste and CU cell plugs* appeared to be a pertinent test.
- *The function "limiting radionuclides release and immobilising them" is performed by various components depending on the period of time concerned:* containers initially (for vitrified waste and spent fuel), waste matrices, physicochemical forms of elements released, chemical and hydraulic conditions within the disposal cells (role of the geological formation). It is difficult to define a scenario covering the failure of all these components. Exothermal waste containers failure, leading to early release of radionuclides and diffusion in a thermal atmosphere, *a priori* accelerating diffusion outside the near field, is considered as a preferred case for scenario study.
- *The function "elaying and attenuating radionuclide migration" particularly involves the host formation*, even if seals and disposal cells are also involved. The scenario of an intrusive borehole, intercepting the geological formations and repository in various places, provides an assessment of the repository behaviour in this degraded situation, putting at stake the delay and attenuation function.

The three scenarios therefore illustrate the main cases of safety function failure. They do not describe all the possible combinations, but only those which appeared to have significant consequences. Finally, it appeared useful to add a fourth scenario to the previously defined altered evolution scenarios, to take into account a general degradation of safety functions. It is not based on lessons learnt feedback from the scenarios defined by Andra homologues, nor on the altered situations already identified. *It is a so-called "much degraded function", consisting of systematically reducing safety function performances by placing them completely outside the anticipated range with respect to normal or altered evolution scenarios.*

The results of safety calculations concerning altered situations must also be compared to thresholds. The main safety regulation does not provide any, as it appears difficult to define, generically, altered situations acceptability. Indeed, these situations "encompass" several altered evolutions, themselves resulting from various causes. Even if it is possible to assess the likelihood of every altered situation, it is more difficult to assess the likelihood of a scenario which may represent several situations, in stylised hypotheses. It can however be noted simply that:

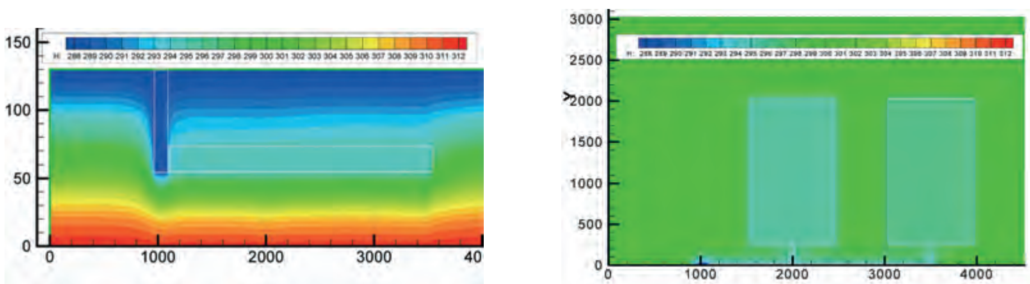
- the criterion of 0.25 mSv per year was retained as one reference among others, i.e. the results obtained by calculation will be compared with this value without requiring the calculated dose to necessarily respect this constraint;
- up to several mSv per year (maximum of 10), an altered evolution scenario can be considered acceptable on a case by case basis, if the probability of the situations described is sufficiently low. In any case, the intention is to reduce the impact of these altered situation by appropriate means;
- a calculated impact of more than 10 mSv must be trigger specifically studies. The possibly "over-encompassing" nature of the scenario must then be examined. In purely hypothetical situations, this type of impact is not necessarily unacceptable in itself, however.

2.4.2 The consequences of non-performing seals

The so-called "seal failure" scenario is intended to process different failure combinations of repository seals (shafts, drifts and module sub-divisions), then disposal cell plugs. This scenario includes any defect which could be linked to the development of a damaged zone around structures constituting a radionuclide transfer pathway. This scenario leads to:

- partially short-circuiting the geological barrier. The radionuclides could then preferentially migrate via the drifts and shafts, to the surface by advection;
- modifying hydric and chemical environmental conditions within the disposal cells, leading to failure of the package protection function.

Various combinations were envisaged: failure of all drift seals, failure of the shaft seal only and failure of all seals. A situation, in which the repository is abandoned leaving the shaft unsealed, is also considered.



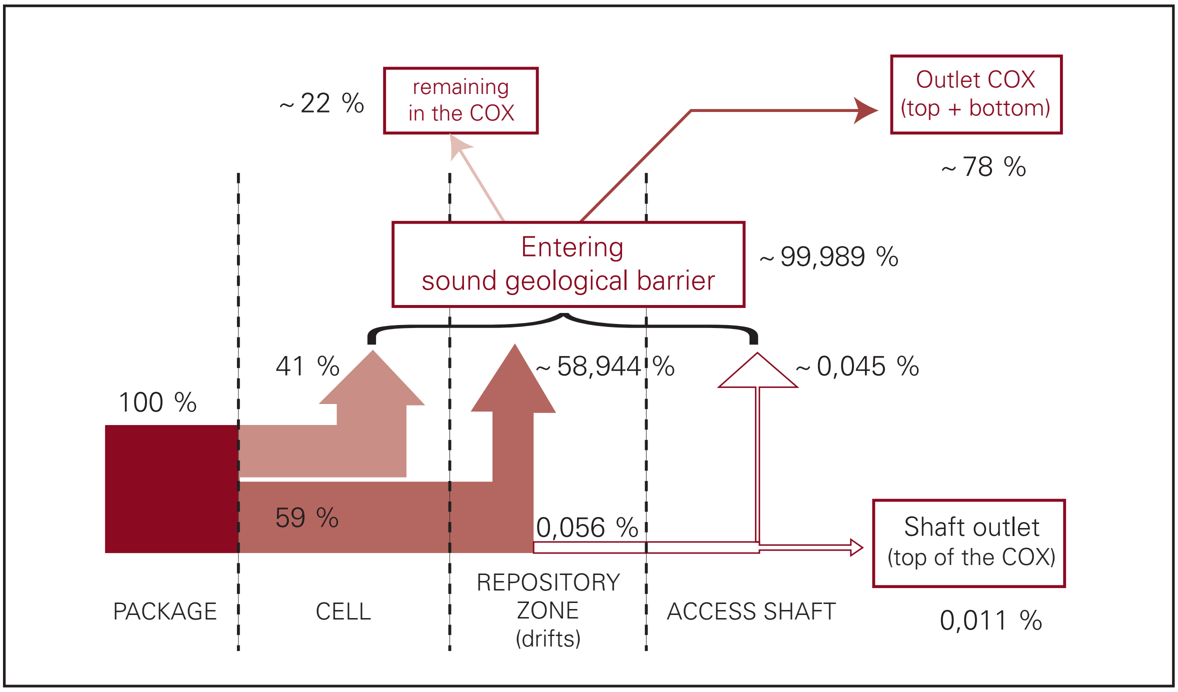
Vertical cross-section C1/C2 module ***Horizontal cross-section C1/C2 module***

Case "all seals failure" - representation of the impact on hydraulic head fields in the repository

Digital processing of these situations underlines the fact that impact remains very slight. In particular, several results were highlighted from a hydraulic viewpoint:

- in case of partial failure of the seals (shaft or drift seals), the hydraulic disturbance of the repository is limited because of the efficiency of the seal(s) which did not fail, acting in redundancy for the failed seals.
- in case of simultaneous failure of all shaft or drift seals, hydraulic disturbance is of course greater, but remains limited, notably because of the low permeability of the Callovo-Oxfordian and dead-end architecture.

In line with from what was observed in the sensitivity studies in damaged zones in the normal evolution scenario, water supply into the repository is not enough for circulation to take place in the access structures.



Altered evolution scenario"failure of all seals" – CU1 package ^{129}I – mass repartition in the various compartments

No matter what seal failure situations are studied, the impact associated with the fraction of activity migrating through the structures is negligible compared with the one diffusing through the geological medium. The dose at the outlet is therefore not modified.

Seals play an important part in "preventing water circulation" but the geological medium, through its "dead-end" architecture, provides redundancy by limiting water supply, evening the "all seals failing" case. The efficiency of repository safety functions is only partly based on seals. In particular, safety does not depend on a single component, which failure would be particularly prejudicial. This supports the overall approach by showing how the various disposal elements combine and "support" each other, when necessary, to guarantee the overall robustness of the system.

2.4.3 The consequences of early container failure

A *"package failure" scenario*, assumes that the containers are poorly manufactured during one month of mass production (leading to fifty C waste containers and thirty spent fuel containers being defective). The defective containers are no more considered leak-tight one century after primary package production.

The effect of this failure is minor, because the geological medium capacity to retain the radioelements, although initially reduced by the fact that the radionuclides diffuse in a hot environment, remains globally effective. The impacts occur earlier but are no different from those of the normal evolution scenario.

A case of *complete failure of all C waste and CU containers* was also analysed. This gave rise to a global assessment of the impact of premature container rupture. This situation is heavily penalising and purely conventional, in that no identified cause can lead to such early failure of the whole inventory.

- In this case, the radionuclides flow from the Callovo-Oxfordian is higher during the first 100 000 years. In spite of these differences, it was noted that the mass of iodine 129 released by the Callovo-Oxfordian over the whole period of analysis is only a few percent higher.

- For spent fuel however, this does not cause any significant difference because diffusion velocity remains very slow beyond the thermal period over a major thickness of Callovo-Oxfordian formation.
- For vitrified C waste, behaviour is different because release by defective packages is accelerated by thermal conditions. Contrary to the normal evolution situation, the release period becomes short compared to diffusive transfer times. Therefore, about 10% more iodine 129 is released by the Callovo-Oxfordian over one million years. However, this is still a small difference.

The dose at the outlet is not modified. On the other hand, the maximum dose occurs earlier.

Synthesis of maximum doses at the most penalising outlet (Saulx- "one million years" hydrogeological model)

	Altered evolution scenario "all packages defective"		**Normal evolution scenario (reminder)**	
	Maximum accumulated dose (mSv/year)	Date of dose peak (years)	Maximum accumulated dose (mSv/year)	Date of dose peak (years)
All C waste (C0, C1+C2 scenario S1b, C3+C4 scenario S1a)	0,0012	270 000	0,00083	490 000
Spent fuel CU1 + CU2 scenario S2	0,021	290 000	0,020	330 000

Processing the "package failure" scenario revealed that early failure of several containers or over-packs did not lead to any modification in the global impact of the repository. The effect of early release of radionuclides on the delay and attenuation function is slight, because the thermal transient period is short when compared to the global time required for transfer into the geological barrier.

In the penalising case of failure of all containers and over-packs, the effect of early release of radionuclides is clear at the Callovo-Oxfordian interface, with earlier dates of molar flow rate peaks. The geological barrier plays a major part because the dates on which peaks are registered, are still far (more than one hundred thousand years). Impact on dose levels is negligible.

2.4.4 Assessment of intrusion risks into the repository

A so-called "borehole" scenario assumes different situations where someone would drill one or more boreholes through the repository, then abandon them without plugging. Although, theoretically there is no exploitable resource on the Meuse/Haute-Marne site (oil, geothermal resources, etc.), this situation includes exploration by people who may be looking for resources. The situations considered result from abandoning one or more boreholes (dual-system boreholes or doublet). Depending on their location with respect to the engineered structures, this (or these) may partially or totally short-circuit the host formation.

This case considers the heavily penalising situation of a durable borehole (highly unlikely case but encompassing the possible impact of the successive drilling of several boreholes in nearby zones) intercepting a repository structure. For the sake of likelihood, it intercepts a repository structure which is large enough and close to the packages: a drift in the immediate proximity of a C waste or spent fuel disposal cell, and directly in a B waste disposal cell. In addition, it is considered that it is close to a drinking water well station (termed in French as AEP for "Alimentation en Eau Potable").

The calculations results show that such a borehole would have only a limited effect on the repository and its behaviour. From a hydraulic viewpoint, the efficiency of the various design systems, in particular seals and repository compartmentalisation, limits the borehole influence to the disposal cells close to the borehole. The borehole is not therefore in a situation where it could drain contaminated water from the host formation which, although water bearing, can, in any case, produce only very little. Even in the "dual boreholes" case, there is no likelihood of inducing circulation between the two boreholes leading to a significant increase in radionuclide transport.

The dose associated with drinking water from a borehole is not more than 0.012 mSv per year for a borehole intercepting a repository drift or disposal cell. Dose peaks nevertheless appear earlier, taking in account a deliberately early drilling date, in consistency with the RFS III.2.f recommendations.

In cautious approach, an even less probable and extremely penalising situation was considered, in which a borehole reaches a CU1 spent fuel cell (CU cell diameter being significantly smaller than B cell one). In this case, the dose due to the borehole was only 0.10 mSv per year.

The possible influence of a damaged zone with degraded permeability properties (which means poorly performing seals) was included in the sensitivity study. This extremely penalising case can be compared with a situation of double alteration. The calculation was performed for C2 waste. The dose due to the borehole is very small (0.00067 mSv per year against 0.00065 mSv per year in the reference calculation).

Dose synthesis

	Maximum accumulated (Barrois water well) (mSv/year)	Date of dose peak (years)
Bore-hole intercepting a repository drift		
C2	0,00065	25 000
C4	0,00053	23 000
CU1	0,0072	42 000
CU2	0,0012	43 000
Bore-hole intercepting a disposal cell		
B1, B5 non-organic	0,012	770
B2 (bituminised sludge)	0,00022	12 000

Studying the "borehole" scenario underlines the fact that the repository system is robust relative to this type of external event. All together, the low permeability of the geological barrier ,associated with its "dead-end" architecture, seal efficiency and extra confinement provided by the waste packages, contribute to limit the impact of any partial short-circuit of the geological barrier.

2.4.5 Hypothetical simultaneous degradation of repository functions

The last scenario examined is purely conventional: it consists of simultaneously selecting, arbitrarily, conservative or penalising values, for all the calculation parameters. This is equivalent to degrading all the repository components simultaneously, giving them only minimal performance (host rock with higher permeability, labile waste matrices for most B waste, bituminised and vitrified waste as well as spent fuel, as per the lower limit of performance predicted by the models, and seals bypassed by a strongly permeable excavation damaged zone).

This scenario is represented as follows:

- for the "preventing water circulation" function, a permeability of about 10^{-12} m/s was used, equivalent to the highest values observed in the clay. For the damaged zone, a penalising choice was made, with a permeability of de 10^{-6} m/s for the fractured zone and 5.10^{-9} m/s for the micro-fissured zone. No geochemical properties are considered for the fractured zone and only degraded properties for the microfissured zone. Therefore, the seals performed very poorly, as considered in the "seal failure" altered evolution scenario. In addition, degradation of backfill permeability was also included;
- for the "limiting radionuclides release and immobilising them in the repository" function, conservative release models were used for all the reference packages of the inventory model;
- for the "delaying and attenuating radionuclide migration" function, conservative values were used for transport and retention parameters in the clay.

The impact of this very altered, conventional situation is, nevertheless, still very close to the normal evolution scenario one. In the most penalising situation (Saulx outlet closest to the site), the calculated impact is less than 0.25 mSv per year.

Synthesis of maximum doses at the most penalising outlet (Saulx)

	"One million years" hydrogeological model	
	Maximum accumulated dose (mSv/year)	Date of maximum dose (years)
All B waste scenario S1b	0,0030	160 000
All C waste (C0, C1+C2 scenario S1b, C3+C4 scenario S1a)	0,0054	170 000
Spent fuel CU1 + CU2 scenario S2	0,12	150 000

This situation of simultaneous degradation of all repository functions is a conventional hypothesis which is not realistic. It can therefore be concluded that this situation provides a cautious approach of the most pessimistic evolution of the repository, but its occurrence probability is close to zero. Nevertheless, the dose calculated at the outlet appears low for such a configuration and much less than 0.25 mSv per year. *This emphasises the close complementarity between the various repository safety functions and the relevancy of this function-based approach. Indeed, although the three functions undergo degradation in their individual performance, the combination of all three still maintains repository safety.*

Actinides in altered evolution scenarios

Allowance has been made for actinides in the radiological impact calculations for the "seal failure", "bore-hole intrusion" and "much degraded operation" scenarios. They have not been retained in the "waste package failure" scenario; indeed although radionuclides diffuse in a hot environment initially, the thermal transient period is too short with regards to the actinide transfer time in the Callovo-Oxfordian to induce any other behaviour than that observed in the normal evolution scenario.

The radiological impact of the actinides at the outlets is nil in the "seal failure" and "much degraded operation" scenarios. The actinides remain confined in the repository near-field over the next million years in both these scenarios, because of their high retention and precipitation in the engineered components and the argillites.

In the "bore-hole intrusion" scenario, the actinides have negligible impact following drilling of a bore-hole near a C waste or spent fuel disposal cell. Even in the extremely penalising configuration of a bore-hole intrusion in a C waste or spent fuel cell, the actinide-related dose is only 0.03 mSv per year. The radiological impact of the actinides following bore-hole intrusion in a B waste cell is negligible as the latter are strongly retrained by the disposal package concrete.

3. Assessing the repository concept robustness

The research performed since the start of the Andra research programme has provided detailed information on each of the repository components. However, this knowledge of each basic component and its characteristic properties is just one stage. Indeed, the disposal system includes numerous components, all interacting with each other. The second part of the scientific work therefore consisted of determining, analysing and assessing the main phenomena within the repository, to measure their importance and provide a detailed representation of them. At the same time, the designer proposed repository architectures which are among the best able ones to make the most of geological medium.

The third stage consisted of processing the data to assess its robustness and see how the repository would meet safety requirements, in its current design and representation. This required a different type of work, consisting of:

- on one hand, using a simplified, but cautious, method of understanding repository function when setting up a safety model. This schematic representation was intended to emphasise the main phenomena and ensure that the hypotheses selected to represent the repository reflected, *a priori*, a compliant or pessimistic vision relative to the most probable reality;
- and on the other hand, taking into account the inevitable remaining uncertainties, by using more cautious, less realistic variants or altered scenarios reflecting major dysfunctions in the system.

All these elements were subjected to the safety analysis presented in this chapter. It provides a definition of a normal evolution scenario for the repository and its associated safety model. These are based on a simplified vision of the repository, adopting conservative or penalising values for areas of persistent uncertainties. They revealed the possibility of providing a cautious, but easily understandable representation of the repository.

One of the main objectives of this analysis was to examine the pertinence of the safety functions assigned to repository. Indeed, these functions reflect expectations relative to a disposal system, which themselves are the basis of this technical system assets.

Through various indicators, the analysis showed that the three main safety functions "preventing water circulation", "limiting radionuclides release and immobilising them in the repository" and "delaying and attenuating radionuclide migration" were effectively fulfilled by the proposed system. It emphasised that this was not only valid in a normal situation reflecting the most probable evolutions, but also in much more penalising situations. A significant degradation of the geological medium and components performance would not prevent the repository from fulfilling its functions. In particular, the transport regime in and around the repository remains diffusive, even under conditions which are extremely degraded when compared to all the current observations and measurements of the geological medium properties. Moreover, this conclusion is not challenged when altered scenarios are taken into account. At this stage, the repository appears to be robust in all the configurations envisaged with respect to its safety functions.

Otherwise, the analysis also showed that the repository would not depend excessively on any single component. They all make a significant, but not predominant, contribution to overall safety. For instance, seals play an important part, but are not likely to compromise, on their own, the overall repository safety. The same applies to C waste and CU containers, which prevent release under diffusive condition with thermal effect. This complementarity between the various elements appears to be an additional factor for robustness, because safety functions could be met in the great majority of configurations.

The host formation plays a major part, because it provides a significant contribution to controlling impact, not only in a normal situation but also in pessimistic conventional situations with various components failure or intrusion into the repository. This performance is modelled using cautious values to characterise its properties, which again, means that safety does not rely on a single element, and participates to the defence-in-depth concept which must lead to repository safety. The presence of several elements which can replace each other in the event of failure is therefore a strong added value of the current repository design.

At the end of the calculations performed within the context of the safety model under normal evolution, the repository performances meet, with wide margins, the dose objectives recommended by RFS III. 2.f. Generally speaking, incidental or altered scenarios lead to only a slight increase in the dose at the outlet. This proves that, even in highly unlikely situations, the repository constitutes an efficient concept.

More accurately, the impact caused by vitrified waste and packages with medium long life activity (B waste), is several orders of magnitude below the reference defined as a quarter of the dose acceptable for the public (0.25 mSv/year) and about one-tenth of the natural radioactivity to which the public is exposed. For spent fuel, which is not currently considered as waste and therefore only included for exploratory purposes, the dose is ten times lower than the reference.

The analysis also tested a configuration in which all repository functions were degraded, with containers no longer water-tight, low efficiency seals and a much degraded performance of the geological medium by adopting pessimistic values. This situation, which is extremely hypothetical in that it would require all the components to be defective, or have properties very much below those observed or modelled, still complies with the limits assigned in a normal situation.

Notwithstanding these positive results, the safety analysis also revealed some residual uncertainties and margins for potential progress which will provide useful orientations for future research developments. Indeed, the safety approach has deliberately given a penalising or conservative representation of some phenomena or components (release model of spent fuel, role of surrounding formations, damaged zone...). This representation means that only attested results are taken into account and will be refined through future experiments. *Therefore safety margins do exist. They are not characterised at this stage, but constitute reserves which can be used and provide added confidence in the disposal system pertinence and its ability to achieve effective protection for man and the environment against exposure to radioactive waste effects*.

In conclusion, the safety procedure supports the repository feasibility study. In the light of current knowledge and by applying cautious hypotheses, the consequences of the impact of a possible repository for man and the environment, appear to comply with current norms. It is important to note that this conclusion is obtained, while neglecting various safety margins and the feed-back which could be acquired during the repository operating and reversibility phase.

Conclusion

The 30 December 1991 Waste Act initiated a research process into different methods for managing high-level, long-lived waste. In this framework, Andra has conducted work to investigate the possibility of a deep geological waste repository, considering two rocks of differing nature, clay and granite. Some conclusions may be highlighted in the case of the clay medium studied at the Meuse/Haute-Marne site.

I. Fifteen years of considerable progress in research

Deep geological disposal has been investigated since the sixties in various western countries. *However, the period 1991-2005 in France was marked by acceleration in the progress of research. From this point of view, the 30 December 1991 Waste Act was a catalyst*. The schedule set by this Act led to bringing together skills and concentrating energy to produce a dossier in 2005 based on solid scientific and technical knowledge.

• A significant step forward in knowledge

Assessing the feasibility of a repository requires acquiring knowledge and investigating various fields: waste and material behaviour, history and properties of the geological medium, architectural design, understanding the phenomena occurring within a repository, modelling interactions, assessing safety. *An extremely rich harvest of results was reaped about all these topics. Fifteen years of research have laid down the foundations of a solid corpus of scientific and technical knowledge, providing an accurate view of the major issues and properties of all the repository components.*

Now, is available, for example, a historical view of the argillite layer studied at the Meuse/Haute-Marne site, from its deposition 155 million years ago. The Callovo-Oxfordian argillites have been surveyed extremely carefully, both though samples and *in situ*, providing an intimate knowledge of their properties. In this field, their mature degree reached by these investigations places them at the forefront of our knowledge of the geology of the Paris Basin.

• The advantage of the Meuse/Haute-Marne site where a wide range of measuring and investigative techniques have been used

In the case of the clay medium study, a decisive contribution of the period was the possibility of carrying out very thorough investigations on a specific site, the Meuse/Haute-Marne one. Andra has been exploring the site and its environment since 1994 and thus has acquired a thorough knowledge of the actual conditions of the geological medium.

With its two shafts and over 300 m of drifts, *the Meuse/Haute-Marne Underground Laboratory is currently a leading-edge scientific facility, comparable to similar international ones*. An important experimental programme is carried out and notably concerns: rock permeability with its chemical and diffusion properties, rock mechanical characteristics with its behaviour when excavated. It has produced very significant data, but also constitutes a valuable asset for future years. If so wished, it will be capable of supporting a study and detailed design approach through the production of measurement records over long periods, thus completing the results already acquired.

To investigate the Meuse/Haute-Marne site, Andra set out to gather together the widest possible range of measuring tools and survey technologies. Exploring the clay geological medium is a complex undertaking, requiring very specialized technologies, for example for measuring the permeability of a rather impervious medium or characterizing water that is present only in a very small quantity in the rock, which makes its extraction difficult.

From the start of the research programme, Andra built very strong ties with all its foreign counterparts so as to transpose, elaborate or validate the investigation technologies it needed. This preparatory work then enabled it to be immediately operational on the Meuse/Haute-Marne site.

The last fifteen years have therefore witnessed the development and improvement of a wide array of measuring and characterization technologies brought to their best level. For example, oil exploration technologies have been adapted and improved for meticulous geological exploration. All possible facets of investigatory means were used: surface observations (e.g. with the seismic survey), measurements on samples, testing and sampling in vertical or practically horizontal directional boreholes, characterizations in shafts and drifts. *The diversity of the experimental tools used provides complementarity and redundancy between measurements, which increases confidence in the results obtained*.

• Confirmation by foreign underground laboratories

In parallel with the programme carried out in France, foreign underground laboratories have played a very important part through their methodological and theoretical contribution, in particular those of Mol in Belgium and Mont Terri in Switzerland. The Mol laboratory has seen the development of measurement technologies for appraising all the phenomena present in clay. The Mont Terri laboratory has been used to prepare experiments conducted at Bure by offering the possibility of full-scale repetition. In addition, the similar nature of the two clays (Opalinus clay in Switzerland and Callovo-Oxfordian argillites) led to establishing an essential point: *at Mont Terri, it was shown that the results found on samples were also representative of large-scale tests*. This constitutes a weighty support for the work carried out at Bure. Furthermore, the models prepared based on the samples extracted at Bure were corroborated *in situ* at Mont Terri.

Foreign laboratories thus provided methodological and theoretical validation for the analytical approach conducted in France.

• Mobilization of a high-level scientific community and integration of research at the international level

Another basic asset of the research programme carried out since 1991 lies in the mobilization of the scientific community. At the launch of the process, the research remained relatively restricted to a circle of specialists or to a small number of bodies responsible for the work. Andra strived to involve the widest possible scientific community in its work. In other words, rather than keeping the investigations and research in-house or developing its own special skills, it always preferred to use the best laboratories in France or internationally for each topic. This meant a great deal of effort in arousing scientists' interest and familiarizing them with the problems involved.

In the end, this policy proved successful. It enabled nearly a hundred laboratories at the national and international level to be brought together around the theme of geological disposal. With their different perspectives these laboratories could pool their expertise, and develop cooperation and interdisciplinary outlooks. This is all the more important in that the originality of the research on disposal entails the need to muster together very varied scientific fields in order to achieve an overall understanding. At the same time, Andra instituted support for research training, in the form of thesis grants, which meant having active scientific resources readily available; about fifty or so young researchers over five years, were specifically dedicated to Andra research topics.

Mobilizing the scientific community ensured that the production of results was conducted and discussed according to the current standard of the academic world and within a framework of excellence.

The scientific initiative was not limited to mobilizing the French scientific community. *Andra has specifically extended its activity within an international framework*, by developing close partnerships with both its counterpart agencies in Europe and international research establishments. As an illustration, the Meuse/Haute-Marne underground laboratory has regularly hosted scientists from international organizations who have used their expertise in experimental work. The research has thus benefited from the best international skills.

Thus, after fifteen years, the French research programme is well-placed internationally and enjoys the recognition of its foreign counterparts.

• Regular external assessment

Finally, a programme of this scope would not be complete without assessments. *Andra regularly uses external experts and reviewers for comparing its study programmes, research and results with the best international practice*. An international review of its programmes was carried out in 2002 / 2003 and was very encouraging regarding the work conducted. In the spirit of progress driving the research, the recommendations of this review were integrated into the documents produced for 2005.

Andra strived to encourage the publication of its results in the best international scientific journals, at a rate of some forty articles a year over the last three years. Critical examination of the results obtained is mandatory for publication, which is also a guarantee of work quality.

The research programme therefore was provided with the tools needed for producing quality scientific data, within a framework characterized by stringency and concerned for scientific excellence.

2. The basic feasibility of geological disposal in a clay formation has now been established

Assessing the basic feasibility of geological disposal consists mainly in obtaining an overall perspective of the data collected on each research topic in order to build up an overview of the disposal system and assess whether it can protect man and the environment from the radioactive waste that would be emplaced there. All the elements gathered to date support its basic feasibility, for several reasons.

- **The Meuse/Haute-Marne site offers favourable geological conditions**

The Callovo-Oxfordian layer combines some very useful properties, matching those expected for the design of a repository in a clay medium.

Firstly, the layer is of considerable thickness (130 metres) and is broadly unaffected by faults. Its geological history is well-known. Since its deposition this history has been very quiet, which is a major argument for confirming its homogeneity and its extreme stability. It is almost not subject to earthquake and seismic phenomena.

The layer contains very little water, which movement is extremely slow, due to its very low permeability. Physical and chemical characterizations further show that it has a strong ability to retain and trap most of the chemical elements and radionuclides present in the waste.

It is suited to excavation by mining techniques and building structures within it only causes moderate disturbances, which are not in principle capable of creating preferential flow pathways.

There is a wide zone of more than 200 km^2 within which, *a priori*, these properties are met (the so-called transposition zone).

Finally, putting the collected data together has provided a model of the overall geology of the sector, including the formations above and below the Callovo-Oxfordian. *The geological medium therefore intrinsically offers favourable characteristics making it suitable for hosting a repository*.

- **Architectures have been designed to make the most of the favourable geological conditions**

It is not just a matter of having a geological medium with the right qualities; it is necessary to make the most of it appropriately. Engineering studies have defined simple and robust disposal concepts suited to the characteristics of the argillaceous layer, taking the utmost advantage of its qualities.

These concepts include cautious choices providing therefore design margins. The work has not been pursued up to the optimization stage, but has established that the proposed architectures were realistic, capable of being constructed and used to host the waste without any special difficulty. These architecture includes numerous features promoting overall safety, such as module separation, which compartmentalizes the repository zones, or its general lay-out, which limits the possibilities of water circulation. *In-depth design and engineering work thus supports the favourable natural properties of the medium and helps make the most effective use of them. In addition, studies relating to operational and nuclear safety, based on feedback from other mining or nuclear facilities, demonstrate the possibility of safe operation without any impact on the environment.*

- **Reversibility at the heart of the investigation approach and translated in concrete practical terms**

The architectures drawn up for the repository were selected according to their ability to allow for reversibility. The requirement of reversibility involves a cautious approach to waste management in an uncertain universe. It refers closely to the precaution principle. It also meets a legitimate requirement for modesty on the part of the scientist. When evolutions have to be forecast over very long periods and complex phenomena have to be managed, reversing the process must be possible.

Andra has developed a concrete approach to reversible disposal that is more than just the technological possibility of retrieving packages. It may be defined as a possibility for progressive, flexible, stepwise management of the repository. The objective is to allow future generations freedom of decision in waste management. Consequently, Andra has opted not to set a predetermined duration for reversibility. This involves offering as great a flexibility as possible in the management of each stage, allowing for the possibility of maintaining the status quo before deciding on the next stage or going backwards. The repository design (modular architecture, simplified operation, dimensioning and choice of durable materials, etc.) aims at allowing the widest possible choices.

Reversible disposal can thus serve two purposes. It can be managed as a storage facility with emplacement of waste and, if so desired, its retrieval by simple reversal of the disposal process. Obviously, maintaining this reversibility assumes human intervention, without, however, causing excessive workloads. But what basically distinguishes it from simple storage is that *it includes the possibility of being progressively closed, so as to be able to subsequently evolve safely and passively without human intervention*.

Investigations have shown *that a repository installation was reversible for a period of two to three centuries, with no intervention other than standard* maintenance and monitoring *operations*. Beyond this period, it would be necessary to carry out more extensive interventions, which remain technically possible.

The argillaceous geological medium and the concepts developed by Andra meet the reversibility requirement and make it a flexible tool in radioactive waste management. Reversibility also enables progressive confidence-building in the repository safety demonstration, while leaving always open the ultimate possibility of evolution independently of human intervention.

- **A safety overview that demonstrates the absence of significant environmental impact**

Would the choice be made to close the repository, a detailed assessment has been made of its behaviour over time and its possible impact on man and the environment.

Based on the scientific data obtained and the proposed repository architecture, an analysis has been made of the repository post-closure evolution.

This consisted in reviewing all the phenomena that will occur in it, examining their interactions, modelling the effects of possible disturbances so as to, *in fine*, predict waste behaviour and appraise the mechanisms capable of leading to a release of radioactivity. *A major achievement of the research is to have built up a history of the repository over the next few hundred thousand years which provides an understanding of the system evolution*, key parameters, risks and corresponding uncertainties.

Based on this very detailed view of the repository and its components, the safety studies aimed to give a simplified and cautious representation for assessing its performances.

The evolution of the repository under normal conditions has been represented and modelled using computational tools integrating recent advances in digital simulation (ALLIANCES platform). The objective was to examine the repository safety functions efficiency. These functions translate the expectations from a disposal facility, expectations which themselves justify the utility of this technical system. By means of various indicators, analysis has shown that the three safety functions ("preventing water circulation", "limiting radionuclides release and immobilizing them", "delaying and reducing radionuclide migration") were achieved by the proposed system. The cautious, or even pessimistic choices made provide significant safety margins. Thus, all the assessments display a high degree of robustness.

The analysis showed that these conclusions were not only fulfilled only under normal conditions, representative of the most probable evolutions, but also in altered configurations, clearly more penalising: a failure in repository components or an intrusion by drilling a borehole into the repository should not prevent the latter from fulfilling its functions, effectively protecting man and the environment from the disposed radioactive waste.

Overall, performance analysis shows that safety does not depend on a single element, but is based on defence-in-depth which involves multiple and redundant components. The presence of several elements that can take over from one another in case of failure thus constitutes a considerable added value of the current repository design and ensures the robustness of the disposal system.

Following the calculations performed within the framework of the safety model under normal evolution, the repository performances meet the dose compliance recommended by the basic safety rule RFS III.2.f, with significant margins. The impacts caused by vitrified high-level waste (C waste) and long-lived intermediate-level waste (B waste) are several orders of magnitude below the reference standard set at a quarter of the permissible dose for the public (i.e. 0.25 mSv per year).

The situation of great degradation of all the repository components, the geological medium included, was studied as well. It also led to an impact compatible with the references in terms of dose.

In conclusion, the safety approach underpins the repository feasibility study. In the light of current knowledge *and by adopting cautious hypotheses, the consequences for man and the environment that a possible repository could entail, appear to comply with the standards and recommendations in force. This conclusion has been reached with significant safety margins.*

3. Research that could be carried out with a view to site qualification and technological development

The research programme conducted over the past fifteen years included the necessary material to answer the basic feasibility issue. We may assume that this is confirmed with reasonable confidence. However, this is only basic feasibility (in its principle) and uncertainties do remain. There could be no question at this stage of an industrial approach or a complete performance and safety assessment, which would be essential for formally filing a licence application.

Without anticipating any decisions that the Parliament may consider appropriate, a few elements are necessary to clarify the current state of the investigations and identify the prospects that they may open up, where appropriate.

Four elements must be taken into account:

- although most of the parameters needed for assessing safety have been obtained in conjunction with the underground laboratory, experiments have only been carried out over short periods. Without calling into question the previous conclusions, a reasonable caution involves obtaining a series of data over longer periods, allowing experiments to carry on acquiring knowledge over subsequent years. This work, to be performed at the same time as other developments, will reinforce the overall approach;
- repository architecture has been assessed from on basic studies and feedback from other facilities. At this stage no full-scale technological testing of repository structures has been carried out. This would appear premature for establishing basic feasibility. In order to progress beyond this, it would be useful to construct demonstrators of disposal cells *in situ* and to actually test the possibilities of implementing the solutions investigated in an underground environment. Consolidating and optimizing the engineering would also be useful to reach industrial objectives, if required.
- research aimed at mainly characterizing the zone in the immediate vicinity of the underground laboratory. Studies at larger scale and with a wider mesh were conducted over a transposition zone of 200 km^2. However, the fine, detailed characterization of this zone has not been carried out. This means in particular that the issue of siting a possible repository within this zone cannot be achieved at present and calls for additional qualification work;
- finally, some elements of the repository system are currently represented using simplified and pessimistic models. This obviously adds safety margins, since effects favourable to repository safety are neglected. However, as part of a more exhaustive approach, it would be useful to quantify these margins and reduce the residual uncertainties at the same time. We should then be in a position to appraise, even more accurately, the level of confidence attributable to the safety assessments.

These various elements help clarify the main guidelines of the possible work programme beyond 2006, should the evaluators and reviewers confirm the relevance of Andra conclusions and should the Parliament decide to pursue work on deep geological disposal.

For the period beyond 2006, with all the reserves already made, Andra has tried to construct a development scheme aiming at producing a safety report with a dateline of a decade.

Initially, we should pass from the current phase of basic feasibility to a phase of development, optimization and detailed studies. This phase could extend over a period of approximately five years. It would first answer any possible questions raised by the evaluators in 2006 and focus increasingly on technological aspects and industrial implementation, while seeking to optimize the current proposed design. This would allow a progressive transition from a scientific to an industrial situation:

- firstly, the necessary information would have to be gathered for siting a possible repository installation. Accordingly, the transposition zone should be better defined based on additional information to that used to date, then a zone matching the footprint of a possible repository could be characterized in further detail in order to qualify it. This overall reconnaissance would especially include a large-scale seismic survey taking up the most of previous results on the analysis methods and their representativeness.

- from a scientific point of view, the research would basically relate to two major issues: changes of scale (to confirm the detailed validity of data obtained over limited intervals of time and space) and validating the understanding of phenomena and their couplings (full-scale and *in situ*) while accurately assessing safety margins. From a technological viewpoint, the issues to be tackled would relate to study the construction of repository infrastructures, together with handling or monitoring operations. As part of this, the Meuse/Haute-Marne laboratory is a tool for acquiring data and performing technological experiments directly within the concerned medium. These experiments would have two objectives: at first, full scale testing of the construction processes with their associated techniques and tools. Secondly, full scale validation (ie in a representative structure) of the scientific knowledge acquired from samples or at intermediate scale (for instance, experimental results obtained in drifts with regard to geomechanics). These tests would complete the progressive approach of scale change, in conjunction with design iterations.

This phase of development, optimization and detailed studies could be concluded with an overall technical assessment, an intermediate milestone before possible transition to a subsequent development phase.

Beyond this phase, assuming that the various scientific results and techniques are deemed favourable, it would be possible to pass on to an industrial development stage. In order to provide an order of magnitudes, such an approach might lead to an industrial installation by 2025.

Therefore, an analysis was conducted to specify the conceivable stages for pursuing research beyond 2006, if such were the conclusion of the Parliament. It offers an initial development scheme taking stock of the significant findings of the 1991-2005 period.

Glossary

Actinides: natural or artificial elements whose nucleus contains at least 89 protons. There are four natural actinides: actinium, thorium, protactinium, and uranium. The minor actinides (mainly americium, curium, and neptunium) are formed in a reactor by successive capture of fuel nuclei neutrons. Their radioactivity and their heat rating decay slowly. After the decay of the fission products with medium half-lives, the waste has a residual heat rating which results from the alpha activity of americium^{241}, which in turn gradually decays.

Natural and archaeological analogues: this expression is used to describe geological or manufactured objects that have undergone phenomena comparable to those that would be found in a repository and over similar periods. For example:

- Uranium deposits such as that in Oklo (Gabon) which has the particularity of having undergone nuclear reactions during its history (and hence contains numerous radionuclides in its waste) and for which radionuclide confinement and migration mechanisms have been studied;
- Bituminous marl formations that have produced natural cements through combustion, such as the formations in Jordan, in which alkaline disturbance mechanisms have been studied;
- Basalt glass (obsidian) produced by volcanic phenomena or man-made glass objects (especially stained-glass windows from the Middle Age) in which silica dissolution phenomena have been studied;
- Iron objects (weapons, shields, nails, etc.) dating from the beginnings of metalworking in Europe, between 500 and 300 B.C., found buried, and on which corrosion mechanisms have been studied.

Sensitivity analysis: the values used in safety calculations, which can be "phenomenological" (the values seen as being the most probable and representing acquired data in the best way,) or "penalising", are tested using sensitivity analyses. These are used to assess the variations in impact if we replace, for example, a best estimate value by a penalising one.

Anchoring or anchor key: excavating underground structures may induce in their surrounding, in the host formation, fractures. When closing B waste disposal cells or drifts with swelling clay plugs, the fracture zone is intercepted through an anchoring arrangement or hydraulic cut-off (groove filled with swelling clay briks).

Anisotropic: the state of stress is said to be anisotropic when the stresses are of different intensity, according to their directions

Argillite(s): type of clay-based rock indurated by compaction. It may contain other minerals than clay-based minerals (quartz and carbonates) and in high proportion (about 50%).

Bentonite or swelling clay: a material with very low levels of permeability that swells as it is hydrated.

Biosphere: all ecosystems, including all living organisms and the environment in which they live.

Temperature field: spatial distribution of temperatures.

Major principal geomechanical stress: maximum pressure exerted horizontally on ground and stemming from the direction of tectonic plates movement. Minor principal stress is the stress exerted in a direction perpendicular to the major principal geomechanical stress.

Natural stress: pressure exerted by formations on the rock

Advection/diffusion: The elements brought into the repository (elements making up the waste packages, building materials, etc.) can dissolve in water over time. They dissolve very slowly, at rates governed by chemical balances, and depending on the amounts of water percolating into the repository. Once an element has dissolved in water, it can move:

- by diffusion: under the effects of Brownian motion in matter, the dissolved element migrates from the zones in which it is present at the highest level of concentration in the water (close to the waste, for radionuclides) towards zones where its concentration level is lower; this phenomenon takes place very slowly,
- or by advection, i.e. carried along by the water if the latter is circulating.

Depending on water circulation velocity, advection movement can be either faster than the diffusion one, or slower, and hence negligible (we then say that diffusion is the predominant transport mode). It is the second situation which is expected in a repository; it can be achieved through the low levels of permeability found in

Callovo-Oxfordian argillites and the seals closing shafts and drifts.

Convection: this English term is used in case of movement only due by temperature gradients, while in French it may mean movement under any gradient

Hydraulic cut-off: see anchor key

Criticality: An accident due to criticality (triggering an uncontrolled fission chain reaction in fissile materials such as uranium^{235} or plutonium) can only occur in the presence of a sufficiently large quantity of fissile materials, greater than the "critical mass" (e.g. 60 kg of uranium enriched to 3.5% of uranium^{235}, or 510 g of plutonium), and a favourable environment, such as water. It leads to the emission of gamma and neutron radiation and to the release of radioactive fission gases (isotopes of iodine, krypton, neon, etc.). A sub-critical configuration consists of making sure that the geometry and the mass of fissile materials together with the kind of the environment in which the materials are located do not allow this type of phenomenon to be triggered.

Cuesta: The Parisian basin is made up of a series of clay and limestone strata that has slightly subsided at its centre. Subsequent erosion has revealed the harder limestone strata, which form an asymmetrical relief at its edges (with a gentle slop towards the centre of the basin and sharp slopes towards the exterior) known as a cuesta.

Drop in hydraulic head - drawdown: drop in water pressure.

Desaturation: reduction in the level of humidity in rock that can lead to fissuring of the rock walls.

Deconfinement: reduction of the mechanical stresses in the rock around an underground structure after its excavation.

Diagenesis: all the processes that have affected soft sediments as from the time of their deposit and have led to their transformation into rock. This began with expulsion of the water contained in the sediments, associated with minerals dissolution. It has led to recrystallisation and a reduction in their levels of porosity, together with modifications in the chemical composition of the minerals and the texture of the sediments. As a result of geological evolution, the gradual burial of the sediments led to an increase in pressure and temperature levels. Tectonic stresses and subsequent circulation of fluids led to other recrystallisations, which are very limited in Callovo-Oxfordian strata.

Logging: continuous measurement of a physical characteristic (electrical resistivity, sonic velocity, porosity, density, etc.) using a sensor run along a bore-hole.

Diffusion: see advection/diffusion

Dispersion: phenomenon resulting mainly from differences in migration velocities at a microscopic scale and tending to homogenise solute concentrations.

Dose: a dose (or equivalent dose) represents the quantity of energy received by the various organs et tissues when a person is exposed to ionising radiation weighted by a specific factor for each type of tissue or organ depending on its sensitivity to radiation. It is expressed in sievert. To give an example, the annual dose received by everyone due to natural radioactivity is about 2.5 milliSv per year.

Biphasic flow: simultaneous flow of a liquid phase and a gaseous phase.

Initial state or reference state: measurement of the initial parameters of a site which are likely to be modified during the work, so as to be able to monitor their evolution by making regular measurements.

Outlet: water transfer zone between the geological medium and the biosphere.

Exothermic: that gives off heat.

Directional (or deviated) bore-holes: bore-holes whose trajectory is not vertical, but is steered from the surface to reach geological objects that have already been located or follow a formation (the argillite stratum) in a horizontal plane.

Seismic geophysics: a process often used during geological prospecting to obtain an image of the ground and the strata making it up. An acoustic wave emitted by vibrator trucks on the surface travels at different velocities depending on the type of geological formation. The limit between two different types of rock constitutes a reflector that sends part of the acoustic signal back to the surface, to recording instruments ("geophones"). The time taken by the sound wave to travel from the transmitter to the reflector and back to the receiver is used to calculate the depth at which the reflector is located, and hence the depth of each stratum below the surface.

Hydraulic (head) gradient: difference in hydraulic level between two points as compared with the distance between them. It is expressed in metres per metre (m. m^{-1}).

Temperature gradient (or thermal gradient): difference in temperature between two points as compared with the distance between them. It is expressed in degrees per metre (°C. m^{-1}).

Buffers (or spacing buffers): inert dummy packages (they do not contain any waste) that are inserted between waste packages emplaced in a cell. They are used to space the latter out and ensure thermal isolation, thus improving heat dissipation into the rock.

Sound Callovo-Oxfordian buffer zone: the Callovo-Oxfordian thickness above and below the repository made up of undisturbed (or sound) Callovo-Oxfordian argillites

Conceptual models: these are used to represent the state of the geological environment or the behaviour of one or more components of the repository during their evolution. They describe thermal, hydraulic, mechanical and chemical processes for safety analyses and their associated digital simulations.

MPa: megaPascal. 1 MPa represents the pressure exerted by a weight of 10 kg on a surface area of 1 sq. cm.

Paleo-surface: former topographical surface at a given time in the geological history of a region. Traces of it can be found through the marks left by the exchanges phenomena between the ground and the atmosphere (hardened ground, concretions due to evaporation, etc.).

Permafrost: part of the ground that is permanently frozen.

Alkaline disturbance: all the transformations affecting solids and fluids, and caused by progression of alkaline water resulting from deterioration of the structural concrete.

Oxidising disturbance: all the transformations affecting solids and fluids, and caused by oxygen in the air supplied via the ventilation system.

Gas inlet pressure: pressure necessary to enable a gas to overcome the capillary forces exerted on water in small-diameter pores. The gas is able to move the water through the pores if its pressure is at least equal to the sum of the inlet pressure and the water pressure.

Activation products: these are formed by neutrons capture in nuclear fuel materials. Their radioactivity level is noticeably lower than the fission products and minor actinides one, but it has to be taken into account because some of the radionuclides concerned have long half-lives.

Fission products: they result directly from fission of uranium and plutonium atoms: caesium, strontium, iodine, technetium, etc., or from disintegration of fission fragments. Caesium^{137} (and its descendant le barium^{137}) and strontium^{90} (and its descendant yttrium^{90}) are the cause of most of the radiation and heat given off by HLLL waste, which remain at high levels for the first 300 years, taking into account their half-life of 30 years.

Seismic profile: 2D image built up from the measurements recorded by the geophones, showing the limits between the various rock strata (see seismic geophysics).

Radiolysis: transformation of organic matter or water due the effects of radiation.

Radionuclide (or radio-isotope or radioelement): radioactive substance. There are only a small number of naturally occurring radio-isotopes: some heavy elements (thorium, uranium, radium, etc.) and some light elements (carbon14, potassium40). The others, which are over 1,500, are created in the laboratory for medical applications or in nuclear reactors in the form of fission products or minor actinides.

Uplift: slow lifting of the Earth's crust.

Tracers: chemical elements or molecules that can be dissolved in water to follow the trajectory of underground flows, measure flow velocity and/or possible dispersion of elements in solution. Some are used in tracing experiments: these elements and molecules are then selected for their ease of detection, e.g. fluorescence (fluorescein), colour (rhodamine), electrical conductivity (salt), or radioactivity disappearing quickly (iodine^{134}). Certain radioactive elements are present naturally in the geological environment and we refer then to natural tracers; measuring their concentration in several points provide data about their arrival time and migration velocity on large time scale (a few thousands years to hundreds of thousands years).

Solute: element in solution in water, of natural origin or stemming from the repository (element resulting from deterioration of materials, traces of radionuclide, toxic chemicals, etc.).

Dump area: area where are stored materials stemmed from excavation (excavated waste or broken rock or muck).

Notes

Dossier 2005 Argile

Hilt to the reader

The *"Dossier 2005 Argile"* has been issued in a first edition in June 2005 and in a second one in December 2005. The second edition integrates in particular surveys and experimental results obtained in the Meuse/Haute-Marne Underground Research Laboratory after the first edition.

For this second edition, the following documents were updated:

- The synthesis report
- The volume "architecture and management of a geological repository"
- The volume "phenomenological evolution of a geological repository"
- The volume "safety evaluation of a geological repository"
- The reference document "Meuse/Haute-Marne site geology"
- The reference document "radionuclides and toxico-chemical elements behaviour"
- The volume n°4 (materials manufactured on the basis of excavated and reworked argillite) of the reference document "HLLL waste repository materials"

These updated documents are therefore dated December 2005.
The other documents remain unchanged and are still dated June 2005.

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