Report Series

Dossier 2005 Granite

SYNTHESIS

Assets of granite formations for deep geological disposal

June 2005

ANDRA

Agence nationale pour la gestion des déchets radioactifs

The present English version is a translation of the original "*Dossier 2005 Granite*" 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).

Contents

Introduction

I. Assessment of the feasibility of a geological high-level, long-lived waste (HLLL) 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 (HLLL), 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 partitionning and transmutation of the HLLL waste (1st 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 granite formation. Another report presents the detailed knowledge acquired in the field of clay 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 :

- act as *a global programme agency*, which orients the research and animates the scientific and technical community interacting in this field ;
- assess 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 (Aspö in Sweden, Grimsel in Switzerland) and is pursuing its work in order to assess French granite potentialities. 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 it 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 into a repository in a granite formation

II.1 A generic approach towards a geological study

Together with clay, granite is one of the geological formations studied by Andra in the context of the Law of 30 December 1991.

Since no site was available, studies on the granite medium were not meant to assess the feasibility of a repository designed to satisfy the specific aspects of a particular location. The objective of the research programme has been to assess the interest of the granite medium for a repository. Thus, Andra has identified and dealt with the major issues concerned by a repository in a granite medium, in order to check that granite medium is not ruled out by any of them and to examine possible technical options.

The approach has been to study generic architectural designs for a repository, based on the properties of the granite medium. The proposed options have formed the basis for analyses to understand the long-term of a repository and to assess its safety.

Granite studies: milestones since 1991

Within the framework of the 1991 Law, Andra carried out surveys between 1994 and 1996 with a view to site an underground laboratory in the south of the Vienne district. The granite massif chosen was granite overlaid by sedimentary formations, delimited from geophysical and geological data.

In 1997 the National Review Board (CNE) reported unfavourably on the Vienne site, particularly on the risks of fluids circulating between the granite and the aquifers exploited in the sedimentary overlying formations; it underlined the interest of "outcropping" granites that would have more favourable characteristics.

The Government decided officially not to retain the Vienne site on 9 December 1998 and planned for the research into other potential sites for a research laboratory in a granite medium. A consultation mission was organised in 1999 to present this project and assess public opinion on fifteen sites selected on the basis of geological criteria. These fifteen sites, submitted to a committee of national and international experts, were identified from previous selection approaches and advances in knowledge of the granite medium in France and abroad. The mission report in July 2000 highlighted the consultation process failure.

According to government expectations, Andra has designed in 2000 a research programme taking stock of current knowledge acquired in foreign underground research laboratories and in various geological environments.

The contextual differences for the studies between the clay and granite formations lead Andra to organise its research into two distinct projects: one to study a repository in a clay medium, based on the Meuse/Haute-Marne underground laboratory, and the second to study a repository in a granite medium.

Some studies were common to both projects, especially those involving waste packages and materials, but the results were applied specifically to each project.

In this context, the Dossier 2002 Granite put forward in 2002 a first assessment of the studies and research into a potential repository in a granite medium.

This report draws conclusions from numerous studies conducted since 1991. On this basis, it attempts to assess the interest of a granite medium for a high-level, long-lived waste repository.

This rationale forms the basis for the research programme focusing on four complementary areas for study:

- *Study of the granite medium*
A generic repository design depends on the properties of the granite. The research has included overall studies to understand and model the granite medium and an analysis of the variability in the characteristics of French granites, to adapt the design studies and carry out the safety assessments and analyses.

- *The generic design of a repository in a granite medium*
From design principles based on safety, the studies have proposed waste conditioning, generic repository architectures, operating methods and closure of the repository allowing for reversibility.

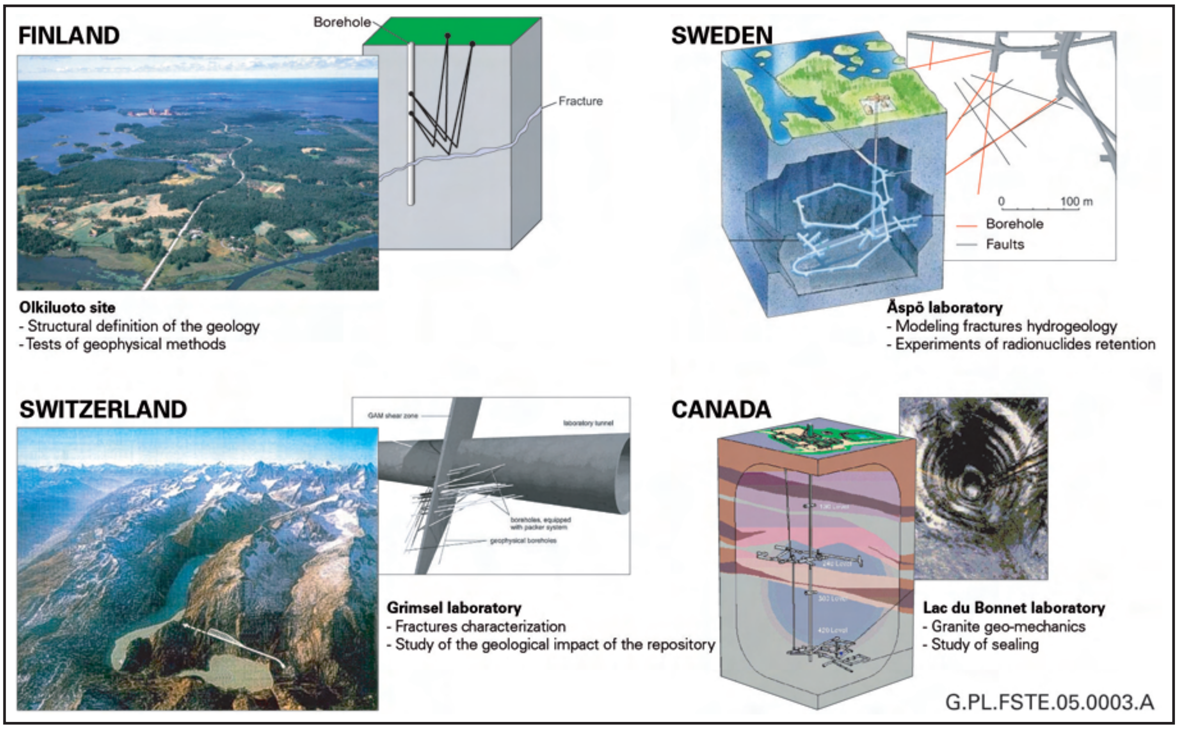
- *Repository behaviour and its long-term evolution*
Based on the proposed options, the studies have analyzed the long-term repository behaviour, to understand and model the thermal, mechanical, chemical and hydraulic phenomena involved in a repository in a granite medium.

- *Long-term safety analyses*
The safety analyses performed in the context of generic studies have not attempted to assess repository performance on one or several specific granite sites: they have identified the major parameters for the performance of a repository in a granite medium compared with the objectives of protecting man and his environment and appraised the robustness of the design options proposed.

II.2 Support from international cooperation and mobilisation of the national scientific community

Andra has relied extensively on foreign studies and has played an active part in experimental programmes in the Swedish, Swiss and Canadian underground laboratories.

The main cooperation themes have involved the study of the granite medium: structuring and fracturing of a granite massif, survey methods, underground water flows, retention capabilities of radionuclides in the rock and so on.



Examples of joint experimentation programmes with foreign partners

The repository design studies have also been based on demonstration elements acquired in underground laboratories and concerning the installation and behaviour of engineered repository components as seals, backfill, engineered barrier, etc.

Lastly, the study approach has benefited from feedback acquired abroad for the safety analysis of a repository in a granite medium, particularly in Sweden and Finland.

This approach has therefore made the most of the extensive knowledge acquired internationally on the studies into a repository in a granite medium.

Andra has also established national scientific partnerships (CEA "French Atomic Energy Commission", BRGM "National Geological Survey", the Forpro Research Group with the CNRS "French National Centre for Scientific Research" and the Ecole des Mines "School of Mines" in Paris). Apart from French research teams participating in foreign programmes, this has dealt with the issue of not transposing results obtained abroad to the French geological context without examining the scientific and technical relevance of such an approach.

II.2.1 The scope of the approach

Without any specific study site, the approach adopted, based especially on numerous data acquired internationally, has allowed Andra to ascertain the various aspects to be considered when designing and assessing a repository. It has led to proposals for "generic" repository designs, with the potential to ensure, in the French geological context, the suitability of a repository faced with long-term safety objectives.

This approach does not however claim to draw the same conclusions as an approach reinforced by surface surveys on a granite site followed by work in an underground laboratory. Only, such a complete programme could provide sufficient knowledge of the properties of a granite from which may be drawn a fair assessment of repository feasibility.

The specific characteristics of a site would require adjusting the design of the repository components to the properties of the granite studied, adapting its architecture to the massif structure, specifying how it is constructed and operated and assessing accurately the options retained with regards to long-term safety objectives.

II.2.2 Structure of the Dossier 2005

The Dossier 2005 includes firstly, the presentation, in the form of "reference documents", of the knowledge underlying the design of a repository and its analysis and, secondly, a three "volume" summary of the design options proposed and the related scientific and safety analyses.

• "Knowledge reference documents"
Andra has structured the acquisition of knowledge around reference documents. Three are shared with the "clay" dossier:

- repository materials reference document, grouping data relating to the behaviour of materials (steels, concretes, etc.) other than the rock formation hosting the repository.
- reference document on the behaviour of the high-level, long-lived waste packages, which summarizes the knowledge and models on waste behaviour in a repository environment,
- reference document concerning the waste inventory dimensioning model, which list all the high-level, long-lived waste produced and yet to be produced by existing nuclear facilities.

A fourth set of reference document specific to the granite medium assembles the data available on the French granites as a typological analysis.

• Three "volumes"
Three volumes summarize the knowledge acquired from the point of view of each of the areas in the study programme:

- *one volume on "Architecture and management of a geological repository"*
  Andra suggests generic options for repository architectures that are both feasible with respect to expectations, particularly safety and reversibility, and realistic from an industrial viewpoint. Based on available knowledge and technology, the technical options studied, chosen to be as simple and robust as possible, show that solutions do exist for a repository in a granite medium.

  The options have formed the basis for analyzing repository safety, particularly its behaviour and evolution over various timescales. This analysis is the subject of the two other volumes in the dossier.
- *one volume on "Phenomenological evolution of a geological repository"*
  The design and safety assessment of a repository is based on understanding its phenomenological evolution and that of its environment, to take account ultimately of the processes conditioning or controlling the behaviour and migration of radionuclides in the environment at the scale of a million years.

  This volume presents the body of knowledge acquired on the granite medium and on repository phenomenology.
- *one volume on "Safety analysis of a geological repository"*
  This volume describes the safety analysis approach to a repository in a granite medium in a generic study context.

Dossier 2005
Granite

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.

<table>
<tr><th>Period / Activity</th><th>Short-lived (SL)
< 30 years</th><th>Long-lived (LL)
> 30 years</th></tr>
<tr><td>Very low-level waste (VLLW)</td><td colspan="2">The Aube VLLW disposal facility
(excluding mining residues stored on site)</td></tr>
<tr><td>Low-level waste (LLW)</td><td rowspan="2">The Aube LILW disposal facility</td><td>Installation project for a radium/graphite disposal facility</td></tr>
<tr><td>Intermediate-level waste (ILW)</td><td rowspan="2">Research carried out under the Law of 30 December 1991</td></tr>
<tr><td>High-level waste (HLW)</td><td>Research carried out under the Law of 30 December 1991</td></tr>
</table>

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 containment 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 $1/2^n$ 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.
- *Bêta (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.

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.

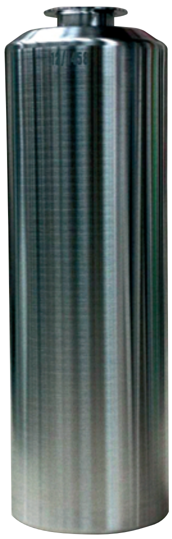
Spent fuel unloaded from the EDF reactors are reprocessed in Cogema plant at La Hague. The aim of reprocessing is to separate the uranium and plutonium, themselves not considered as waste, from the waste itself: fission products, activation products, minor actinides conditioned in La Hague plant [1]. 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 (mixed uranium - plutonium oxide) and URE (reprocessed uranium) fuels. After use in the reactors, they are stored temporarily while awaiting reprocessing according to EDF industrial strategy for managing the fuel cycle backend.

Nuclear reactor operations also generate intermediate-level waste: this involves devices 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 β-γ 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 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.

Its β-γ 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 containment, 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.

Standard container for compacted waste (CSD-C)

Concrete fiber-reinforced container (technological waste)

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 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

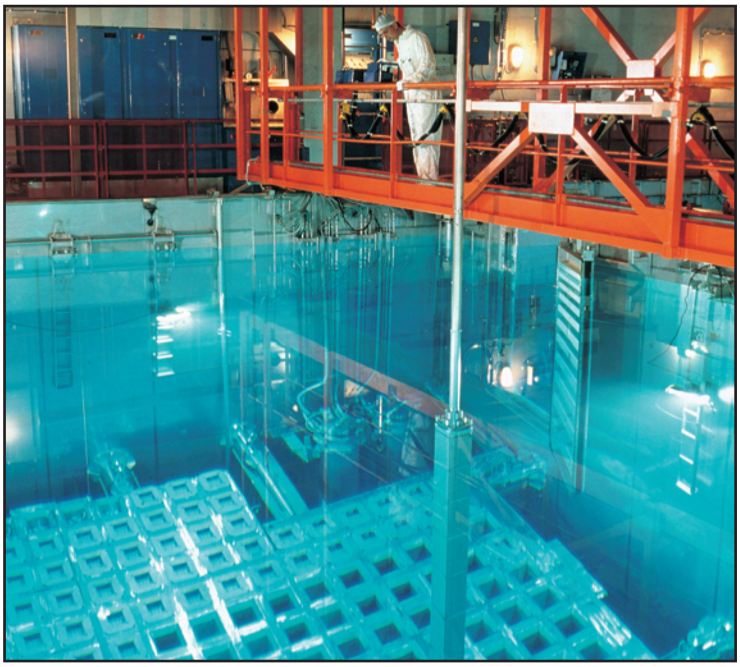
As input to the repository feasibility study, Andra, in close collaboration with the waste producers has drawn up an inventory model of HLLL waste. This inventory model allows for both *the waste already produced*, that is stored in conditioned and unconditioned form on the production sites and *the 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

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 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 rates are as follows: URE 45 GWj/MTHM, UOX1 33 GWj/MTHM, UOX2 45 GWj/MTHM, UOX3 55 GWj/MTHM, MOX 48 GWj/MTHM.

• **Scenario S1a** *assumes that all the SF 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 spent MOX 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 SF 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

• **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 and 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

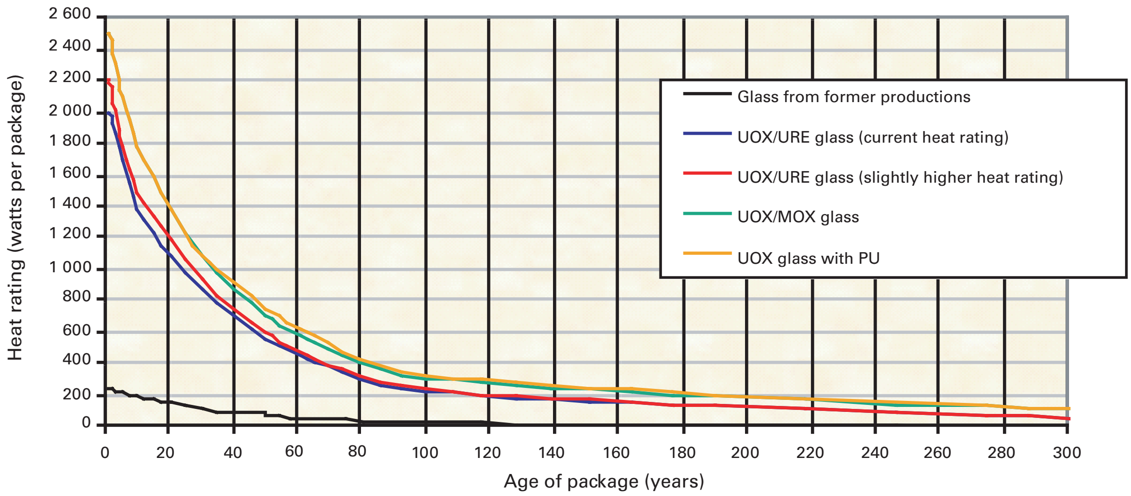
Various primary B waste packages, notably when embedded in bitumen or including organic matter (cellulose, PVC,…) produce gases such as hydrogen (1 to 10 litres per annum at atmospheric pressure per waste package) and also carbon dioxide gas and methane, resulting from the radiolysis of their constituents. 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 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 and 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

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.

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

Reference	**Scenario S1a**		**Scenario S1b**		**Scenario S1c**		**Scenario S2**	
package	Number	Volume (m³)	Number	Volume (m³)	Number	Volume (m³)	Number	Volume (m³)
B1	2 560	470	2 560	470	2 560	470	2 560	470
B2	104 990	36 060	104 990	36 060	104 990	36 060	104 990	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	1 350	775	1 350	775	1 350	775	1 350	775
Total	**199 815**	**81 105**	**197 115**	**80 615**	**197 115**	**80 615**	**168 265**	**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 (m³)	Number	Volume (m³)	Number	Volume (m³)	Number	Volume (m³)
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

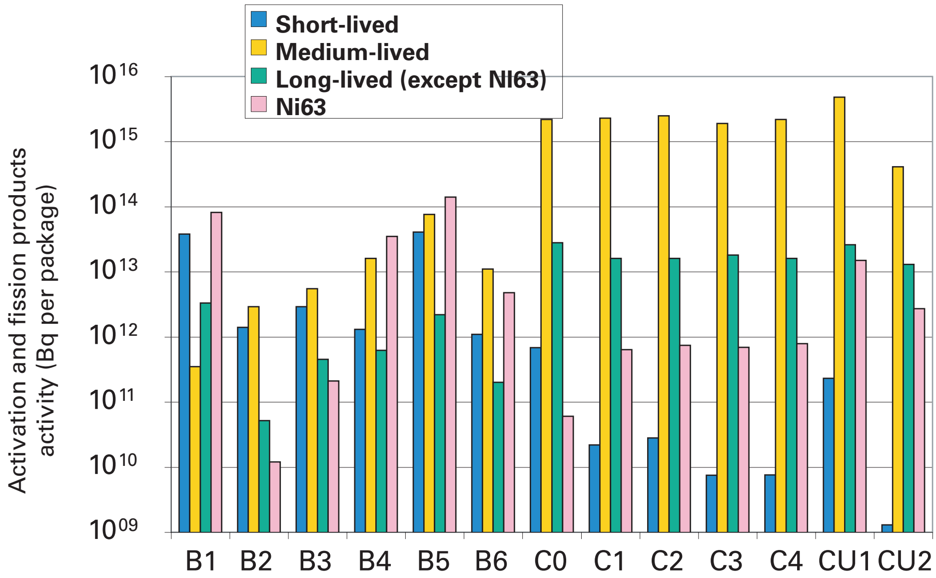
	Scenario S1a	**Scenario S1b**	**Scenario S1c**	**Scenario S2**
CU1 reference UOX assemblies	0	0	0	54 000
CU1 reference MOX assemblies	0	5 400	5 400	4 000

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).

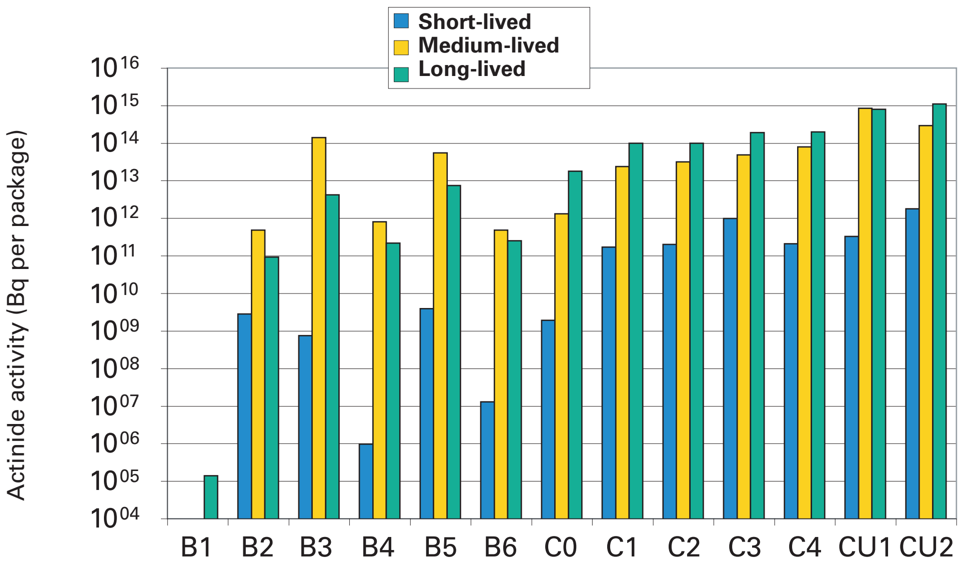
The long-lived fission and activation products (excluding nickel-63) present, on the other hand, much lower activity levels and are mainly concentrated in C waste packages. B waste packages contain these products too, but at activity levels that are two to three orders of magnitude lower. Nickel-63 is 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.

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 "$V_0 \rightarrow V_r$" 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.*

[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.

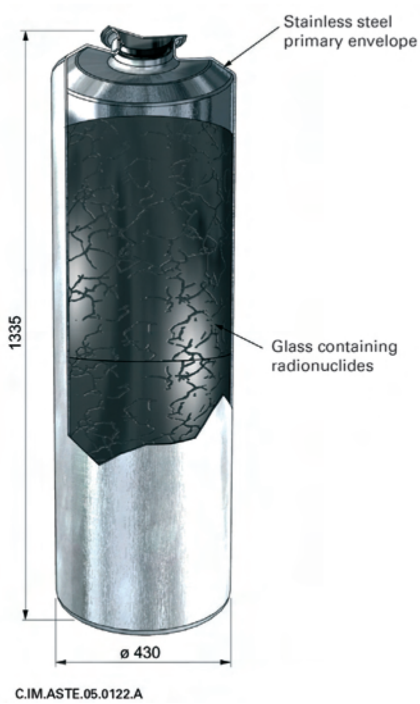


Diagram of an R7T7 vitrified C waste primary package

- 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 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, …).

1

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 (if 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 radionuclides in the other B waste packages 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)

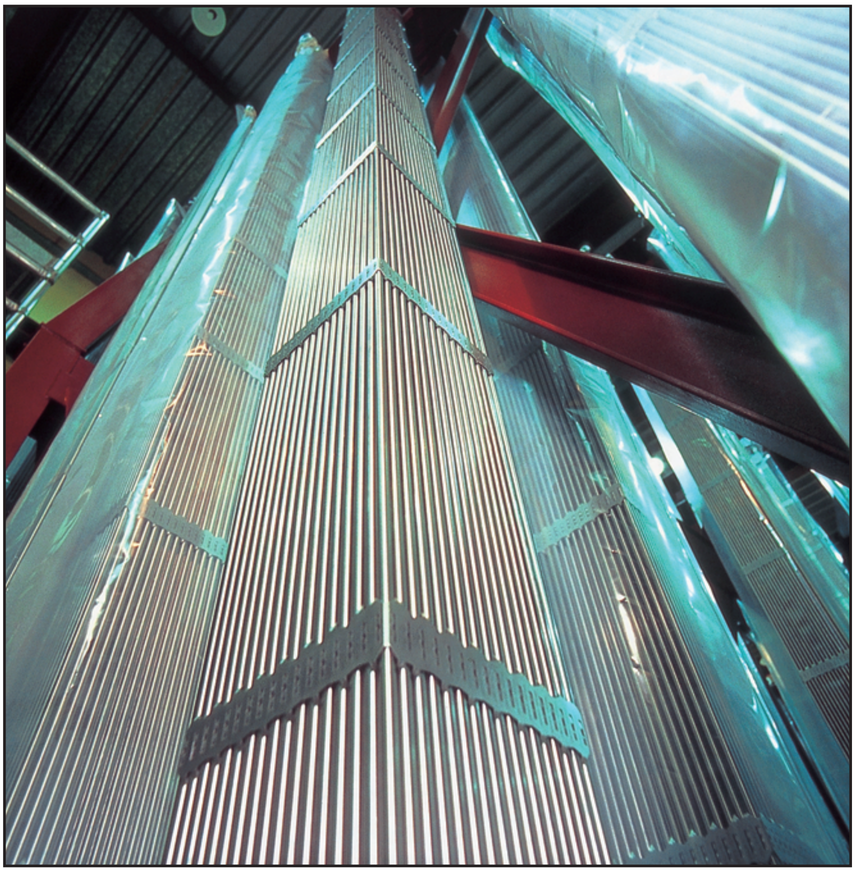
Research has concerned the behaviour of spent fuel once the waste packaging is no longer leak-tight. Spent fuel is made up of diverse materials and its physical and chemical state is heterogeneous when removed of from of the reactors. The location of the radionuclides also differs and schematically are 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 clearances 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 boundaries 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 boundaries 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 rate (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 Granite

2 Design study for a repository in granite medium

The concept of deep underground disposal is based on the idea that there are geological formations capable of confining, over very long periods, the radioactivity of waste packages to be disposed there. It is the geological medium (clay, granite, salt, etc) which must ensure very long term confinement of long-life radionuclides which might be released from waste packages. As such, it is the key element in the repository system.

Repository design in granite medium is thus based on the ability to *take advantage, over long periods, of the favourable properties of a geological formation, the granite.* The first stage of the repository design study consists of *identifying the safety functions associated with a repository* in order to meet the general objectives assigned to it: disposal of waste packages in the granite and long term isolation of the waste from man and the environment. This identification was carried out, based on a functional analysis within the framework of the safety approach.

Then, the granite medium properties on which the repository design is based, should be identified: general characteristics common to all granites and possible variations in properties between the various types of granite within the French geological environment.

The repository design study then leads to the *definition of technical systems* based on the granite medium properties and including engineered components to ensure waste isolation over long durations. The options proposed are adapted to each category of waste (B and C). Options for spent fuel (CU) disposal have also been studied. They fulfil the requirement of repository process *reversibility*. Described in chapter 4, they constitute the basis for safety analyses (presented in chapter 5) which draw up an appraisal of the performance and robustness of the proposed concepts.

1 Definition of repository safety functions

1.1 Functional analysis: safety-based design

The fundamental objective of long-term management of high level and long lived waste (HLLL) is to protect, over long periods, man and the environment from waste-related risks. *The response provided by a repository consists of confining this waste in a deep geological formation to prevent dissemination of the waste radionuclides. This confinement is passively ensured over large timeframes (up to several hundreds of thousands of years) without eventually requiring any maintenance and monitoring, as reminded by the Basic Safety Rule RFS III.2.f.*

General repository architecture

To sum up, a repository consists of a set of elementary cavities *(disposal cells)* excavated in a deep geological formation *(host formation)*. Waste packages are emplaced in these disposal cells, which themselves are grouped in large-scale sets *(modules)*. The latter are linked to each other by drifts, which are serviced by a network of access routes connected to the surface by access structures *(shafts and ramps)*. *Support installations* (reception of primary packages, conditioning, etc.) are located at *surface*.

Various repository phases

- **Preparatory phase for package reception:** construction of surface installations, connecting structures between the surface and underground repository installations and first repository modules.
- **Operation and observation phase:** the main function of the repository is to host packages in the geological formation. According to the reversibility rationale, operations proceed in stages, conserving at each stage freedom of choice for managing the waste and installations: reception and disposal of packages, construction of new modules, observation and monitoring of installations and their developments, gradual closure of underground structures (with backfills and seals), possibility of reversing the process. Although no duration has been set, *a priori*, for the reversibility phase, its timeframe is between one century and several centuries.
- **Post-closure phase:** the main repository function is to protect people and the biosphere from dissemination of radionuclides contained in the waste. This phase mainly consists of backfilling and sealing the underground installations and corresponds to the lowest level of reversibility. For duration of up to several hundreds of thousands of years, it is characterised by the total absence of human intervention (for example maintenance) in the underground installations.

The RFS (Basic Safety Rule) identifies confinement barriers: waste packages, engineered barriers (materials placed between the package and the rock) and the repository host formation which protects the waste from water circulation and intrusive human actions and limit and delay radionuclide transfer in the geological medium and biosphere.

In line with an iterative approach for design and safety, Andra has assigned safety functions to all repository components with a significant role (host repository formation, waste packages and engineered barriers). The characteristics of these components (for example type of materials and waste package thickness, cell dimensions, etc) have been determined for safety by incorporating the potential disturbance caused by the environment and uncertainties.

Design of a “multi-function” system thus completes the “multi-barrier system” concept. Certain components contribute to fulfilling the same function (complementarity) and to maintaining the function in the event of failure of one of them (redundancy). This safety function-based approach associated with checking of the level of performance of these functions is as well common to operational safety.

1.2 Long-term repository safety functions

Firstly, the underground repository shelters the waste from erosion phenomena and main human activities which after hundreds of thousands of years only affect a superficial ground thickness.

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

- preventing water circulation,

- limiting release of radionuclides and immobilising them within the repository,

- delaying and attenuating migration of radionuclides released by the waste.

Eventually, these three functions must be passively fulfilled (without human intervention). Some are only implemented at a late stage. For example, the repository’s 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 available but not yet operative.

1.2.1 Preventing water circulation within the repository

Confinement of radioactivity contained in the packages firstly consists of maintaining it immobilised there. The repository must therefore:

- *limit water renewal around the packages*, which is the main factor liable to alter package envelopes,
- *prevent advective transport of the radionuclides* in order, on the other hand, to restrict their possibility of migration through only diffusion, a very slow phenomenon, by limiting both the water flow reaching the repository and water circulation velocity between the disposal cells and the water conducting faults of the granite medium.

1.2.2 Limiting radionuclides release and immobilising them with in the repository

The arrival of water at the waste packages which constitute an initial radionuclide confinement barrier cannot be completely ruled out. Under these conditions, the role of the repository is to limit the release of radionuclides in the water and immobilise them in the waste or as near as possible.

By creating beneficial physico-chemical environmental conditions, repository installations can limit water alteration of the waste containers and, within these containers, of the matrices (glass, bitumen and cement) where the radionuclides are incorporated.

Once the water has started to alter the waste packages, the role of the repository is to limit the mobility of radionuclides likely to be dissolved in the water by creating reducing geochemical conditions (completed with pH control) in order to maintain and re-precipite these radionuclides in solid form (only some radionuclides, such as iodine 129 and chlorine 36, remain unaffected by these beneficial geochemical conditions).

1.2.3 Delaying and attenuating radionuclide migration

One of the repository functions is to delay and disperse, within the space and over time, the migration of radionuclides released by the waste in order to attenuate it:

- migration of radionuclides dissolved in the water is controlled by diffusion, dispersion and retention in the granite, the host formation of the repository,
- dissolving, in the water, of radionuclides likely to be released in gaseous form enables these elements to be controlled in a similar way,
- as a complement, the migration of radionuclides can be contained within certain repository components (engineered barriers and bentonite seal body, etc), and therefore delayed.

1.3 Safety approach during the construction-operation-closure phase

Occupational safety and protection of the public and the environment during repository operation phases are essential elements in installation design. This includes assessment of the main risks that notably workers face due to radioactive waste and underground working conditions.

Even if there is only one example of an operational geological repository of long-life radioactive waste throughout the world (WIPP's intermediate level long lived waste repository in the USA), there is a quantity of operating experience feedbacks on underground structures and handling of high level waste and spent fuel packages. The hazards are thus well identified and arrangements to prevent them and mitigate their gravity are routinely implemented.

At the generic stage of the Dossier 2005 Granite, operational safety studies were mainly based on those developed for the clay medium repository studies (Dossier 2005 Argile). They involved initial identification and ranking of hazards and a preliminary outline of associated management techniques.

Granite context specificities were also checked (for example, the more likely exposure to radon risks) as well as particularities of the concepts proposed for granite compared to those defined for clay to ensure that they did not cause any specific problem for the initial approach.

2 Granite medium

Repository design initially aims to take advantage of geological formation properties beneficial to underground disposal so that it fulfils the various safety *functions* assigned to it.

In the absence of a specific site, the repository design study cannot be based on the description of a specific granite massif. Therefore, design principles adopted by Andra are mainly based on properties common to all granites.

However, French granites have specific characteristics which the design studies must consider in order to propose relevant options. Andra has therefore drawn up a reference knowledge document on French granite details to identify the granite characteristics which could affect repository design.

2.1 Granite properties for radioactive waste disposal

For repository studies, the term *granite* means both the *rock* and the *geological formation*. The granite, geological formation, is usually organised in massifs [6]. Thus, the possibility of a repository in granite medium depends on rock properties and on the characteristics and geological context of the massif studied.

2.1.1 Granite rock: hard and resistant rock

The common perception of granite as a stone used for a long time as a lasting ornament, is that of a hard rock with very low porosity and very low permeability.

Rock mechanical resistance is naturally of interest for construction of underground structures. It enables the rock to be excavated without any significant ground support being required over volumes compatible with repository dimensions and depth. This mechanical resistance is attributable to the rock texture composed of quartz (crystallised silica) and feldspars (aluminium silicates).

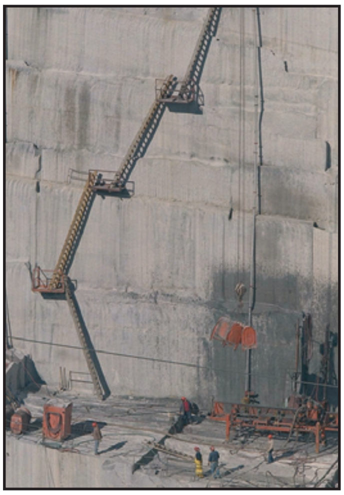
Quartz also contributes to the usually *high thermal conductivity* of the rock which makes it a formation likely to easily dissipate heat emitted by radioactive waste.

Granite rock contains very little water: its water porosity is usually less than 0.5%. Rock permeability is very low and can be on the limit of accessibility to *in situ* measurements.

These characteristics constitute interesting properties, *a priori*, for a radioactive waste repository.

[6] Unlike geological sedimentary formations which are usually arranged in superimposed layers (e.g.: the Callovo-Oxfordian clay formation of the Meuse/Haute-Marne site), magmatic formations, such as granites, often have bulkier geometries (three-dimensional) than planar. For granites, the term massif is generic and is applied to most of the arrangements likely to be encountered.

Unfinished obelisk in the Assouan granite quarry



"Rock of Ages" quarry (Vermont, USA)

2.1.2 A granite massif: a formation of vast dimensions and whose properties are explained by its geological history

A granite massif able to host a repository is a geological formation usually of vast dimensions which given rock resistance offers great flexibility for repository architectural design.

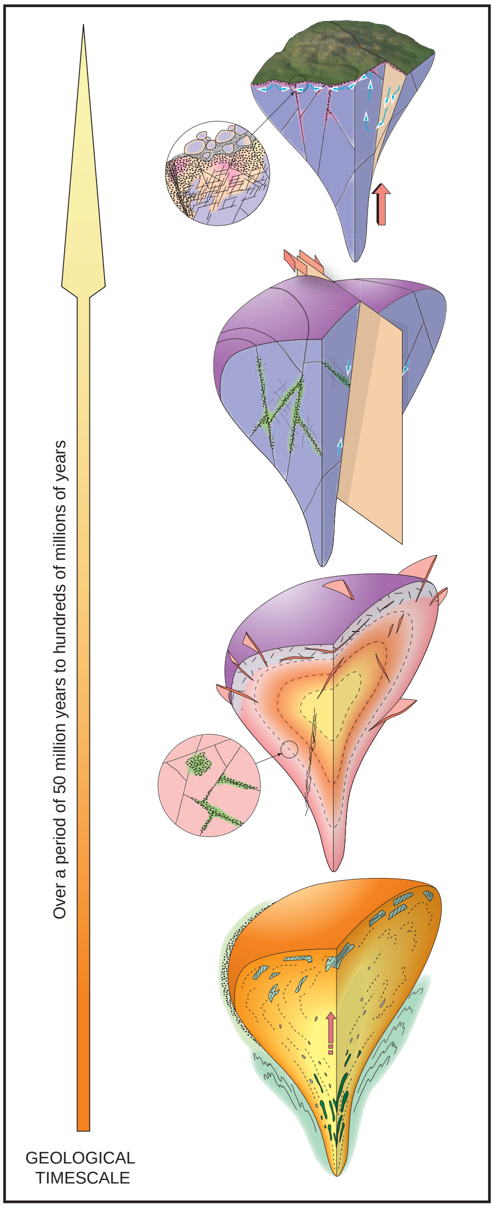
However, on the scale of a massif, granite is not a monolithic homogenous geological formation. It is essential to have a thorough understanding of it and model the structure with enough details to study how repository design could fit there.

This understanding is based on detailed characterisation of the massif studied thanks to methods applied during successive stages of site surveying. The complementarity of these methods enables a gradual surveying approach to be defined and adopted to the site studied (see chapter 3).

Interpretation of data collected is mainly based on reconstitution of the geological history of the granite massif. Compiling the geological history of a granite massif means understanding the phenomena which have produced and structured it over the course of time; it means as well integrating the various components of a massif according to a consistent and common rationale.

A granite massif: result of a deep-rooted geological history

A granite massif originates from the production of underground magma related to movements and collisions of plates which structure the earth's lithosphere. The original magma is formed and solidified at a depth of several kilometres. Conditions of this formation determine the granite structure and partly its fracturing.
The granite massif then becomes a constituent of the earth's crust and follows its evolution over the geological eras. It can thus be affected by further deformations and fracturing. It can be "altered" by circulation of hydrothermal fluids likely to modify rock composition and mineralise the fractures. Lastly, the earth's crust uplift and erosion phenomena can lead to outcropping granite massif at surface.
The massif keeps the traces of these different stages of its history: enclaves of surrounding formations crossed by the magma, local differentiations of rocks with different grain or mineralogy during crystallisation, alterations in the original mineralogy, types of minerals filling the faults and fissures caused during rock fracturing, etc. All these evidences enable the sometimes complex history of the granite massif studied to be reconstituted. This history determines the properties of the granite massif properties and as well of its environmental elements.



4. **Towards the surface**
- Upward movement of structure
- Outcropping
- Surface erosion and alteration

3. **At depths of a few kilometres**
- Brittle tectonic phases (major and minor fracturing)

2. **At depths of a few kilometres to several dozens of kilometres**
- Late magmatic phenomena
- Major fracturing at an early stage
- Slight fracturing
- Magma crystallisation

1. **At depths of a few kilometres to several dozens of kilometres**
- Activation
- Granite magma formations

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Stages in the geological history of a granite massif

Underground, the rock is “sound” (undisturbed) and variations in composition result from the original geological history of the granite. On the granite outcrops, between the surface and a hundred metres, the pattern of the rock fractures is emphasised by effects of alteration, decompression and then erosion of the rock.

The lithological type and mineralogical composition of the rock can also change from one point to another in the massif, depending on the mode of granite formation. As a general rule, these variations do not significantly modify rock mechanical properties and permeability.

More important is the *pattern of granite fracturing* resulting from its geological history. These fractures mean more or less marked discontinuity in rock properties which have to be taken into account for repository design.

Small-, medium- and large-sized fracturing

Fractures of different sizes run across granite massif. Their number depends on their size. Small-sized fractures (metric to decametric) are much more numerous than large-sized ones, of kilometric to pluri-kilometric extent. Medium-sized fracturing (decametric to hectometric) makes the transition.
Small-sized fractures can affect permeability of the rock where repository structures are to be constructed. Rock permeability depends on the properties of each of the small-sized fractures, their density and their extent. Small-sized fractures, which can be more or less connected, are usually very poorly water conducting. Granite permeability, apart from large and medium-sized fractures, is mainly low or very low and strictly limits water circulation.
Large-sized fractures, or faults, are the preferred pathways for water circulation in the granite which does not however mean that they contain large quantities of water. The largest faults, if not clogged with clay minerals, are the ones which store most of the granite water.

2.1.3 Slow underground hydrogeological flows

Water present in granite faults moves very slowly underground. Movement is driven by *hydraulic gradients* related to topography. Schematically, the more contrasting the topography, the bigger the gradients. However, the driving force which tends to move massif water is inhibited by high losses of hydraulic head in granite fractures. Irregularities in the detailed geometry of the fracture network prevent water movements.

2.1.4 Underground chemical environment beneficial to a repository

In underground granite, the chemical composition of water is usually balanced with the rock or fracture minerals containing it. The chemical environment is thus a reducing one. Water pH balanced with granite rock normally approaches neutrality or is slightly basic [7]. These conditions are beneficial both to durability of the materials which can be used in a repository and immobilisation of most of the radionuclides.

2.1.5 Granite faults and fractures: ability to delay radionuclides migration

If granite fractures potentially constitute places of water circulation, possible means of transfer of radionuclides released by the repository, they are also the seat of phenomena likely to immobilise and delay this migration. This major aspect is subject to important studies at international level.
In particular, experiments carried out *in situ*, notably in the underground laboratory in Äspö (Sweden) have especially identified the various phenomena involved in delaying radionuclides migration in fractures and have led to understand clearly their nature.
Determination of relations between these phenomena and geological and mineralogical characteristics make it possible to extrapolate experimental results for various types of granite depending on their own characteristics.

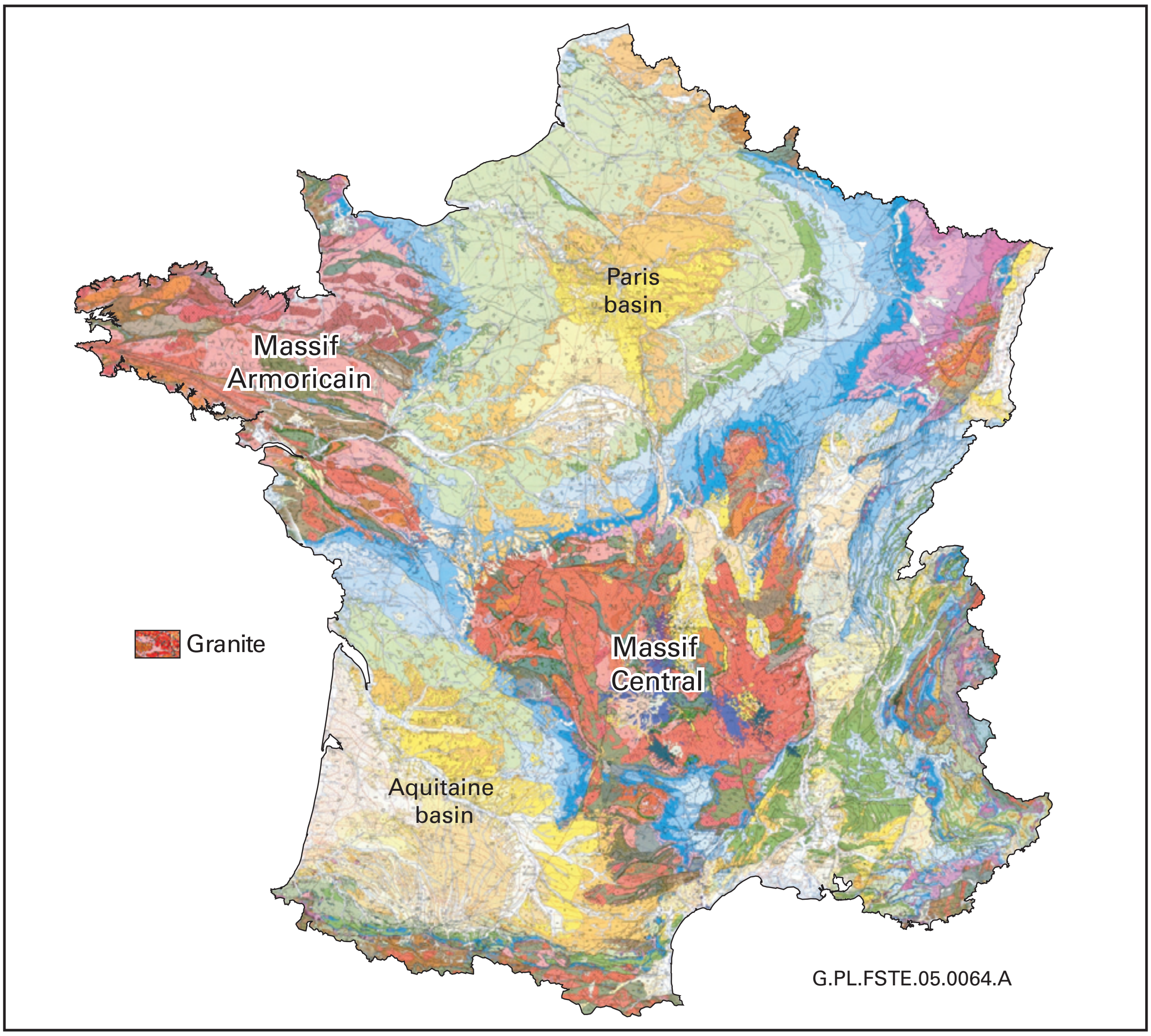
[7] On the other hand, in certain specific contexts, the pH can be slightly acidic.

2.2 Variability of granite within the French geological context

Although granite repository design is based on generic properties of the granite medium, it also incorporates specificities of the particular massif. *In the absence of a specific site, Andra has carried out a typological analysis* in order to collect data on the variability of French granites. Understanding the differences between granites is necessary to take into account these differences in the design and safety analysis in order to ensure that the selected design options meet the various safety functions.

2.2.1 An analysis method adapted to a siteless study context

Variability of French granite properties has thus been understood through *typological analysis* based on a large sample. The analysis focussed on the *Massif Central* and the *Massif Armoricain*, the two largest areas in the French territory of outcropping crystalline basement.



Granites in France

Granite areas which, obviously, could not meet the main criteria of the Basic Safety Rule, RFS III.2.f, were ruled out of this study. The areas to be considered have a surface above 20 km^2 and are located away from large faults [8]. An inventory of 78 granite areas was thus taken into account for the study.

The analysis *initially* consisted of describing granite characteristics by evaluating their variations, proven and potential, and the way in which they can affect repository design options. As granite massifs had seldom been surveyed *in situ* underground, excluding a few specific mining areas, their description was based on mapping of their outcropping surfaces. Extrapolation of geometric characteristics and fracturing to the underground granite was carried out on the basis of geological arguments.

Thermal and hydrogeological characteristics were defined from modelling and extrapolation. These were based on the borehole data available for aspects concerning hydrothermal "alterations" characterisation, thermal flux determination and transmissivity measurements. Sensitivity analyses corresponding to the level of uncertainty observed were also carried out based on modelling.

At a second stage, once the main characteristics of the inventory of granite massifs considered were sufficiently known, statistical analysis of their variability within the French geological context could be undertaken. This analysis leads to a granite classification, with respect to each property studied, and to the appraisal of the breakdown of variations in properties of French granites.

Moreover, a comparison of properties of the massifs studied and those of foreign granites provided validation of the use of the data collected in foreign underground laboratories.

2.2.2 Main analysis information: variability of French granite properties for repository design and safety analysis

• **Mechanical resistance** of granite rock differs according to the types of granite, mainly depending on their hydrothermal alteration. However, these variations are not normally likely to cause any significant differences in the granite response to excavation of structures. Differences for repository architectural design are thus minor and only affect detailed design of underground structures.

• **Thermal properties variability** of French granites is significant enough to be considered in the study of spent fuel disposal. The difference is significant with regards to Fenno-Scandinavian granites where the underground temperature is lower by around 10°C. For C waste, and *a fortiori* for B5 and B1 waste which is slightly exothermic, differences between granites do not lead to a significant modification of repository design (dimension).

Thermal properties and repository design basis

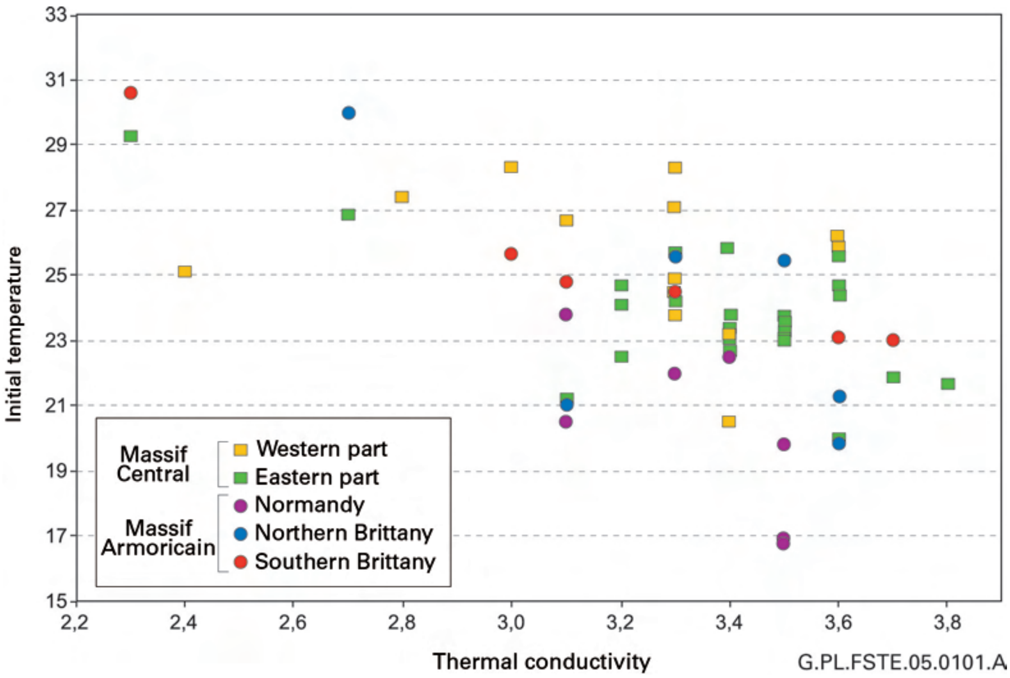
The temperature of underground granite and rock conductivity constitute significant parameters for repository architecture design basis. Repository design must take into account dissipation of heat released by C waste and, if the need arises, by spent fuel. In order to better distribute heat sources and control changes in repository temperature, the spacing of packages in the rock can be modified.
Initial temperature of underground granite cannot be directly measured without a borehole. Modelling was thus based on thermal flux mapping in France and thermal conductivity of rocks depending on their quartz content. Estimations made for a depth of 500 metres have led to uncertainties concerning initial temperatures of more or less 3°C/3.5°C depending on the massifs.

[8] A "buffer" distance of 1.5 or 3 km has been adopted depending on fault size.

…
The graph below illustrates the relatively contrasting situations between the different types of French granite. Initial temperatures at a depth of 500 metres vary between 17 and 30°C. Rock conductivity has a value of between 2.4 and 3.8 W/m/K.

The design of a spent fuel repository takes into account such differences: the MOX spent fuel footprint can thus be increased and decreased by 30%.

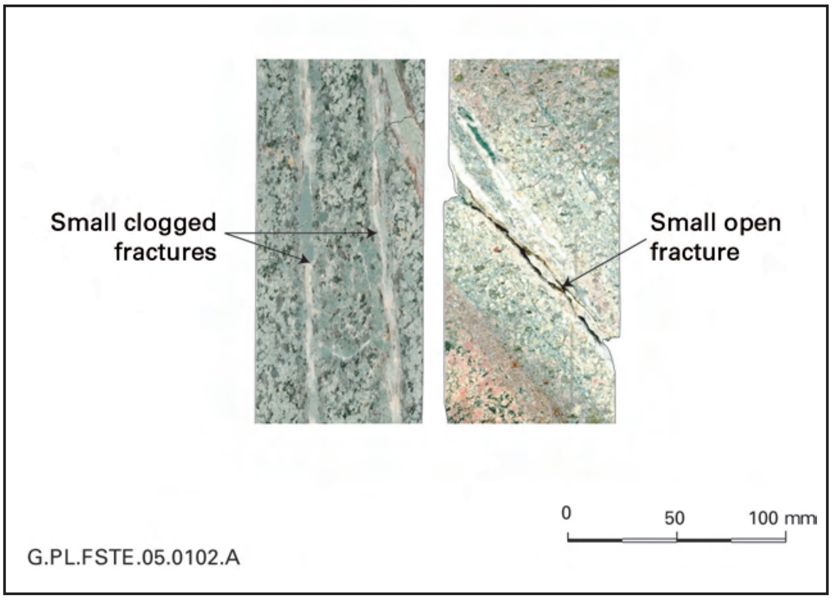
For C waste and according to the design options proposed, the differences have a far lesser effect on repository dimensioning. Mechanical resistance considerations limit thermal "gains" for the most favourable types of granite. Furthermore, installation of a clay engineered barrier of greater thickness between the packages and the rock for the concepts studied, buffers effects of differences in thermal conductivity between the granites.



Estimation of the temperature at a depth of 500 m for French granite massifs in different regions

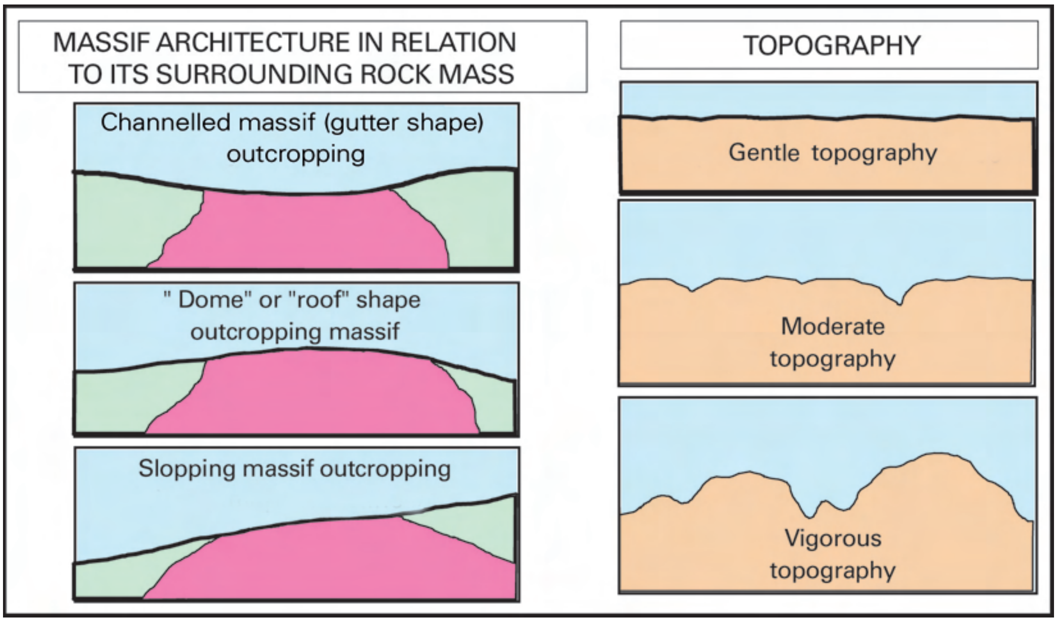
Geometry of large-sized fracturing in granite is a significant element for repository architectural design on a specific site. Depending on the tectonic history of the massif, the fracturing pattern is more or less regular and massif splitting is more or less pronounced. Analysis of a large number of French granites shows that even if the pattern of large-sized fracturing varies between massifs, the distribution of granite blocks where the repository could be constructed complies with rules relatively common to the French massifs studied.

Small-sized fracturing of granite also has a significant impact for repository design. Rock ability to delay and attenuate radionuclide migration will mainly depend on the characteristics of small-sized fractures.
Hydraulic conductivity of small-sized fractures is usually low or very low (less than 10^{-9}m/s). In the range of low permeability, the values can however vary mainly depending on the granites and types of fracture. They depend on their geometry, orientation and possible natural clogging with minerals and the same goes for radionuclide retention properties by fractures.



Clogged and open fractures as seen on granite core samples

The *morpho-structural* context of granite has also been analysed. Site topography and morphology determine hydraulic gradients, which are the driving force of underground flows. Differences between French massifs are significant. Typological analysis has identified three main morpho-structural granite arrangements, which are taken into account in safety analysis: granite massifs in topographical depression compared to the surrounding geological formations, domed massifs and sloping massifs. Each type can correspond to more or less accentuated topographies.



Morphologies of granite massifs and topography

From the hydrogeochemical viewpoint, the inventory and analysis of chemical composition of groundwater in French granites show that there is alkaline groundwater and carbo-gaseous one. Carbo-gaseous water is present in the Massif Central and can be linked to the geodynamic context and the more or less old volcanic activity. Alkaline water corresponds to composition close to equilibrium with the granite medium.

These differences in composition do not lead to modify design options principles. In the case of some granite massifs, they are taken into account by adjusting clay buffer engineered barrier formulations to the ground-water chemical composition.

Type of water		pH	Na	K	Ca	Mg	Li	SiO_2	Cl	SO_4	HCO_3
Alkaline	Site 1	8,80	4 400	142	128	1	78	1 790	227	1 010	1 800
	Site 2	8,86	5 430	116	850	3,3	55	850	4 200	1 350	2 750
Carbo-gaseous	Site 3	6,64	95 500	4 360	1 570	1 940	1 420	1 700	105 100	6 500	29 500
	Site 4	6,80	41 700	635	3 550	3 500	590	770	1 200	220	57 100
	Site 5	6,67	39 100	2 420	15 100	16 100	770	2 100	56 600	2 600	40 200

Examples of groundwater chemical composition in various French contexts (content in mg/l)

In terms of long-term geological evolution of a site, typological analysis of the granite massifs studied confirms that most of them are located away from active geodynamic areas, which means unlikely significant modifications in the long term to their geological arrangements, especially concerning underground fracturing. Climatic changes and erosion can also alter the hydrogeological and topographical context of a site in the long term. Variations exist between massifs mainly due to differences in morpho-structural context. The analysis has thus identified the main arrangements encountered within the French context and phenomena which could come into play within a timeframe of 10,000, 100,000 and 1,000,000 years. It should be pointed out that, on a scale of 100,000 years, the models do not show any significant differences in evolution between the massifs. Beyond 100,000 years, the situation of each massif is to be specifically taken into account for the study of a particular site.

3 General design options for a repository in granite medium

In order to fulfil *long-term safety functions*, the design proposed for a repository in granite medium consists of:

- using a variety of technical procedures to make the most of the beneficial properties of the granite medium, in particular its low permeability and mechanical resistance,
- designing engineered repository components (disposal packages, engineered barriers, backfills, and seals) so that they contribute to safety functions in terms of complementarity or redundancy with the granite medium.
- adopting design options which help limit repository disturbances of the granite medium.

In addition to the long-term and operational safety, design must meet *reversibility requirement*, closely linked to application of the principle of precaution provided for in the law of 30 December 1991. Beyond the possibility of removing emplaced packages (*retrievability*), reversibility is based on *cautious* management of a repository in successive stages, which, given the timeframes under consideration, leaves the options open for future generations.

These principles lead to adopting various technical measures for repository architecture and dimensioning, choice of materials for engineered components and disposal processes. Some measures, architectural in particular, are common to different categories of waste (B and C) and to spent fuel; others, as for instance design of engineered components, are specific to each waste category.

3.1 Making the most of favourable granite properties

The granite medium is characterised as a very low permeability rock, with high capacity for radionuclide retention and mechanically resistant. Since granite is intersected with fractures liable to conduct water, making the most of its favourable properties requires adaptation of repository architecture to this fracturing.

3.1.1 Architecture with compartmentalisation, adapted to granite fracturing

Repository architecture is organised into different zones by major categories of packages: B waste, C waste and spent fuel. These zones are sufficiently far apart to avoid interaction between different types of waste, particularly from a thermal or chemical viewpoint. Compartmentalisation of each repository zone also reduces quantities of waste and radionuclides which would be affected in cases of system failure or intrusion.

Apart from these design principles, repository architecture and compartmentalisation is imposed by granite fracturing.

• Construction away from faults

At repository scale, repository zones for the various categories of waste are constructed away from major faults of the granite massif.

Each repository zone is divided into *modules* grouping together a series of cavities (the disposal cells) for the same type of waste. Modules are located in granite blocks not intersected by large- or medium-sized faults, considered as since significantly water conductors. One of the basic principles of a repository in a granite medium is to *construct disposal cells in the very low permeability rock*. This does not mean that there can be no fracturing whatsoever in the rock but that small-sized fractures which may exist in disposal cell walls do not conduct water or in small quantities. Therefore water flow which might come into contact with packages is minimal.

Disposal cells are of a dead-end type (therefore with only one access to repository drifts), thus limiting possibilities of circulation of water coming from the drifts.

These principles regarding repository siting and architecture meet the requirements laid down in the Basic Safety Rule III.2.f, which states:

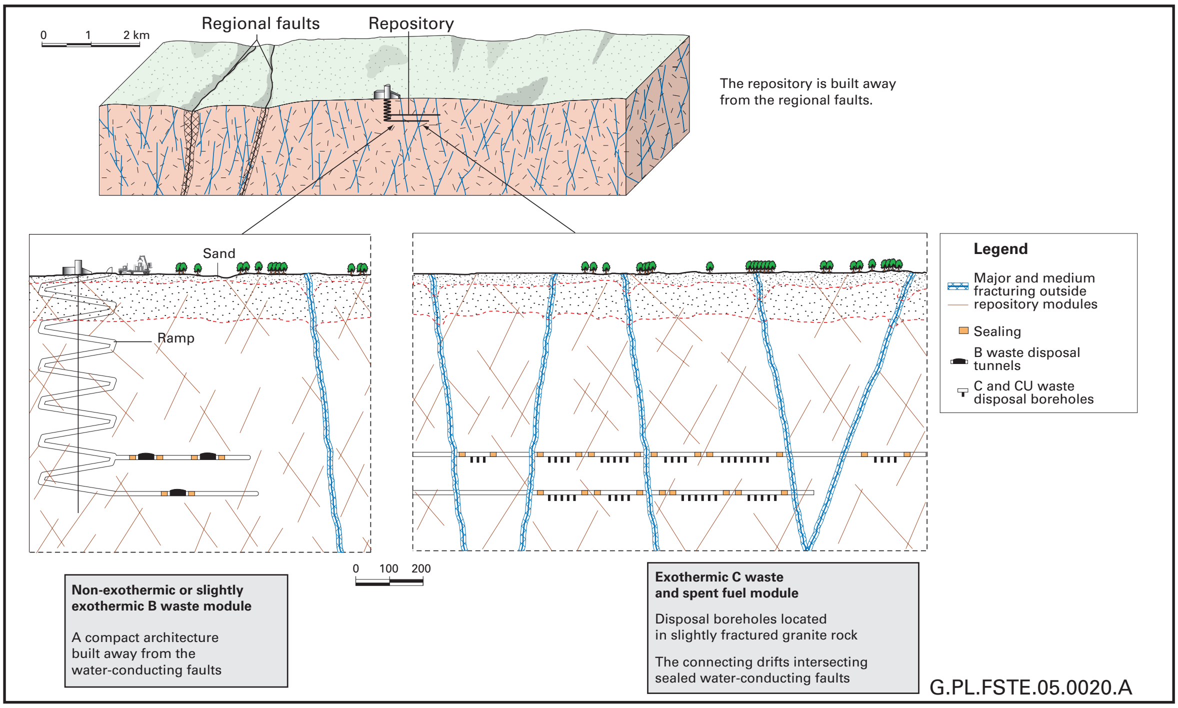
"Repository in geological formations must be located in the case of crystalline mediums, within a host-block exempt from major faults, as the latter are likely to be potential pathways of hydraulic movement. Disposal modules must be protected from medium-sized fracturing, although this may be crossed by access structures".

• Construction of modules with respect to waste heat transfer

At the module scale, the principle of adapting architecture to fracturing works differently for each type of waste. The footprint required for different types of packages may necessitate implementation of different options.

The inexistent (or low) heat transfer by B waste makes possible a design with compact disposal cells and therefore requiring only a low volume of granite. B waste disposal thus requires a little footprint and adjustment of architecture to granite fracturing is eased. Disposal modules are built so as to avoid fractures likely to cause advective water circulation.

C waste and spent fuel thermal characteristics define disposal modules dimensioning and lead to such large footprints that it is not possible to avoid the intersection of a module by a fracture, potentially water conducting [9]. Repository architecture must also be adapted to two levels of fracturing. Size of disposal cells allows them to be built in a very low permeability granite rock with minimal fracturing. Modules are installed in granite blocks, avoiding fractures which would let in too much water, the medium-sized fracturing as mentioned in RFS III.2.f.



Conceptual diagram for construction of repository structures in relation to fracturing

The large volume of granite rock available underground, for a repository between 300 and 1000 metres deep, allows for flexibility in adapting architecture to granite fracturing. General repository architecture can then be designed on one or more levels.

From a functional point of view, such architectural arrangements enable the repository to fulfil a primary objective of preventing advective water flow within the underground installations. As regards disposal cells, this helps to facilitate a diffusion transfer system. Water flow rates are limited in the module drifts. In addition, the repository is located away from regional faults, safe from major water circulations.

Such architectural arrangements also facilitate other repository functions, limiting release of radionuclides by disposal cells and their migration towards the environment.

3.1.2 A disposal process enabling “ongoing” surveying and characterisation of granite blocks where modules are constructed

Adapting repository architecture to fracturing means possessing detailed and accurate knowledge of the granite host rock characteristics. The surveying strategy may include several stages:

- surveying and characterisation operations from the surface, or from underground structures (geological medium qualification underground facility), in order to define the granite structure where the repository is to be built. An iterative approach between safety analysis and the various phases of granite site survey, on the surface and then underground, defines criteria for exclusion of faults (or fractures) which may or may not be intersected by repository connecting drifts and access drifts to modules and disposal cells,

[9] *Taking into account volumes and heat transfer, spent fuel disposal is more demanding in terms of footprint than C waste disposal.*

- on this basis, the process includes *in situ* characterisation of host-granite blocks for disposal modules before package emplacement. This stage of granite "ongoing" characterisation during the staged repository construction finalises module architecture and distribution of disposal cells in the granite according to fracturing.

Such a strategy aims at adapting repository architecture as best as possible to granite fracturing and to ensure that proposed design concepts fulfil their functions effectively as regards control of water circulation in the repository

3.2 Design of engineered components, complementary and redundant with the granite medium for long-term safety

At the scale of both the repository as a whole and the disposal cell, several arrangements are possible to ensure complementarity and redundancy between the granite medium and repository engineered components with respect to long-term safety. They particularly concern repository architecture and choice of materials for engineered components (disposal packages, engineered barriers, backfills and seals).

3.2.1 Multiple sealing of underground installations

Connecting drifts and access drifts to modules and disposal cells are likely to intersect water-conducting fractures. *In order to limit water circulation within the repository, seals are installed at various levels of the underground installations.*

In the case of disposal cells, water may come from drifts serving them. Drifts are likely to be crossed by a more water-conducting fracturing that the cell rock wall one. The 'dead-end' architecture of cells, their construction in granite rock of very low permeability, and low permeability 'plugs' at cell heads limit water circulation and aims at establishing a transfer system in the cells governed by diffusion phenomena.

At the repository module scale, water circulation is limited by:

- very low permeability seals installed in drifts to cut off modules from water coming from any possible intersecting faults,

- backfills of sufficiently low permeability in module drifts.

Disposal cell seals and plugs are made of swelling clay (bentonite), of very low permeability over long periods of time. Backfills may also incorporate clay materials to ensure sufficiently low permeability.

At the repository scale, connecting drifts between modules as well as structures between surface and underground are backfilled. Seals are installed in access structures where they intersect water-conducting faults.

3.2.2 A physico-chemical environment suitable for waste packages

Disposal cell design seeks to provide a suitable physico-chemical environment for waste and packages in order to control changes in state over time and limit release of radionuclides.

Such an environment is ensured by the materials used for waste over-packs, the choice of which depends on type, volume, radiological inventory and chemical nature of the waste, as well as by engineered barriers.

For B waste containing metal elements (B1, B3, B4 and B5 reference packages), the aim is to limit corrosion by providing a favourable chemical environment (reducing potential, pH 10 to 12.5), in particular by using concrete for waste over-packs. For bitumised B waste, the aim is to maintain, on the long term, bitumen confinement properties (B2 reference package) by controlling chemical conditions and temperature (between 20 and 30°C).

For C waste and spent fuel, emplacing clay buffers between packages and the granite rock attenuates chemical interaction between packages and granite groundwater.

3.2.3 Disposal packages which are leak-tight or of very low permeability over a sufficiently long period of time

In order to ensure complementarity with the geological barrier, primary packages are inserted in additional containers, to constitute disposal packages. A study has been carried out in order to ensure their leak-tightness or very low permeability over sufficiently long periods of time, which depends on types of waste and their radiological inventories.

2

A concrete disposal package has been chosen for B wastes. For some types (B1 and B5 packages, which have major radioactive content and do not release gas), disposal packages have long-term confinement properties (around ten thousand years). This performance is achieved by using a specially adapted concrete mix (with very low permeability and porosity) and a specific design (method of closing). This type of container limits water reaching primary packages as well as radionuclide release for this period of time.

For C waste packages, the aim is to prevent water from coming into contact with the glass for several thousand years. This period concerns the thermal phase (i.e. the period when the temperature at the heart of the glass is over 50°C) during which glass alteration phenomena by water are accelerated. *The proposed design is based on a very thick steel container.*

For spent fuel, a copper container is proposed, with long term leak-tightness property (up to several hundred thousand years). In contrast to C waste, radionuclides are not trapped in a confinement matrix (a fraction of the radionuclides is released upon contact with water, and the remainder is released gradually as the uranium oxide matrix dissolves). This option is based on the 'KBS-3' copper container, a concept adopted in Sweden (SKB) and Finland (Posiva). It was adopted by Andra at this generic design phase. Site data would justify revision of this option if adaptation of architecture to granite massif fracturing and engineered structures (backfills and seals) allow sufficiently long time transfer in the geological medium to ensure radioactive decay of radionuclides.

3.3 Limiting granite disturbance caused by the repository

While repository design aims to take into account the favourable properties of granite, it should be ensured that repository construction and its long-term evolution do not aversely affect the properties of the granite medium. The various arrangements studied involve structure dimensioning, choice of materials for engineered components and the disposal process.

3.3.1 Design limiting mechanical and thermal disturbance

Granite is a mechanically resistant rock. The structures (drifts and cells) are dimensioned to ensure mechanical stability in the long term.

Heat released by C waste and, if need arises also by spent fuel, means a temperature rise in the disposal cells and surrounding granite. In order to control the thermal phenomena induced, the aim is to keep the temperature in the cells lower than 100°C (and therefore in the rock). In practical terms, a maximum temperature of 90°C has been adopted for the hottest point in the swelling clay buffers for C waste cells and at the surface of spent fuel copper containers.

The essential parameters for repository architecture dimensioning in order to limit the temperature are on one hand, the number of disposal packages per cell and on the other hand, the spacing in between disposal cells. The C waste and spent fuel repository zones footprint is mainly subordinate to these thermal considerations and the thermal power released by the packages when emplaced in the repository.

3.3.2 Disposal process limiting hydrogeological and hydrogeochemical disturbance of the host granite massif for underground installations

Excavation of underground installations drains off granite groundwater and disturbs initial hydrogeology. As granite is only slightly permeable, this disturbance mainly affects the most water-conducting faults and fractures. In order to limit groundwater draining from the granite and by extension the quantities of pumped water while excavating the underground installations, it can be envisaged to resort to injection techniques for the most water-conducting faults and fractures intersected by the structures.

After a transient phase of disturbance related to underground installations excavation, equilibrium between water drainage and re-supply is established within the granite massif.

Appropriate management, depending on the granite hydrogeological context, of excavation of repository zones, their operation and then their closure constitutes then a means of limiting hydrogeological and hydrogeochemical disturbance of the granite.

3.4 Adaptation of design arrangements to long-term safety functions

The various options proposed contribute to one and /or the other of the major functions of a repository:

- *the function "preventing water circulation in the repository"* is mainly fulfilled by architectural and sealing arrangements. Repository architecture is adapted to granite fracturing,
- *the function "limiting the release of radionuclides and immobilising them within the repository"* is mainly fulfilled by systems implemented near the packages in order to permanently ensure favourable environmental conditions to the protection of waste and immobilisation of radionuclides released,
- *the function "delaying and reducing radionuclides migration"* makes the most of all technical measures adopted within the design options: structure design basis, choice of structure and package materials.

		Safety functions		
Design principles	**Technical measures**	**Preventing water circulation in the repository**	**Limiting release of radionuclides and immobilising them in the repository**	**Delaying and attenuating radionuclides migration**
Making the most of favourable properties of granite medium	**Architectural** Constructing cells in very low permeability granite rock	XXX	X	XX
	Constructing modules in the "blocks" apart from water conducting faults	XXX	X	XX
	Constructing the repository away from regional faults	XXX	X	XX
	Disposal process Ongoing characterisation of granite blocks	XXX	X	XX
Designing engineered components complementary to and redundant with granite medium	**Architectural** Multiple sealing of structures (cells, modules, drifts, surface-bottom connecting structures)	XXX	XX	XXX
	Materials A physico-chemical environment beneficial to packages and waste: engineered barriers and overpacks adapted to types of waste		XXX	X
	Disposal packages (containers, overpacks, etc) leak-tight or only slightly permeable for sufficiently long periods of time depending on types of waste		XXX	XX
Limiting granite disturbance induced by the repository	**Design basis** Structure dimensioning ensuring long-term mechanical stability	XXX		XXX
	Structure thermal dimensioning for control of phenomena caused by structure temperature rise		X	
	Materials Disposal packages and engineered barriers whose alteration does not significantly disturb granite retention properties			XXX
	Disposal process Disposal process managed so as to limit disturbance of granite hydrogeological and hydrogeochemical characteristics	XXX	XX	XXX

Technical measures and long-term safety functions for a repository in granite medium.
Contribution of technical measures to the function:
XXX: essential;
XX: significant;
X: secondary

3.5 Integrating reversibility

In addition to operational and long-term safety, *repository design must meet the reversibility requirement*. Reversibility is related to a cautious and staged management of a possible repository which, given the timeframes considered, leaves the options open for next generations.

Reversibility requirement involves, over the course of time, human presence, monitoring and maintenance activity which do not put at stake, whatsoever, long-term safety, the primary aim of the repository. But rather, based on a cautious and gradual management of the disposal process, reversibility can contribute to improving the confidence in long-term safety.

Reversibility requirement was at the heart of the analyses carried out for the study of a possible repository in granite medium. The design approach implemented by Andra aimed at proposing generic design options fulfilling the reversibility requirement.

Beyond the ability to retrieve disposed packages (retrievability), reversibility can be defined as the possibility of gradual and flexible management of the repository which leaves future generations with freedom to decide. With this aim in mind, the disposal process can be broken down into a succession of stages to be performed, which provides, from the construction of the initial modules up to closure of a module or of a repository zone, the possibility of waiting and observation time, before deciding to go on to the next stage or reverse the process. The completion of a stage is not a definitive decision, but a justified choice, based on thorough understanding of scientific, technical, economic, social and environmental parameters and the consequences caused by going from one stage to another.

In this perspective, repository design therefore considers the three aspects of reversibility:

- architectural arrangements beneficial to a gradual repository management,

- technical measures for going backward to the various disposal stages,

- means of observing repository status and its evolution at any time in the process.

3.5.1 Repository architectures incorporating and fostering reversibility

Simplicity and robustness of the concepts, durability of materials, modular design: repository architectures proposed by Andra incorporate reversibility requirements and facilitate its application.

• Simple and robust disposal concepts

Concepts proposed by Andra at this stage of the study are, by principle, simple and robust. Simplicity is based on the concern for technical feasibility and control of performance. Mechanical resistance of granite rock especially allows to limit support systems in structure design. Simplicity of options proposed by Andra facilitates the description of their evolution over time as well as their modelling. Robustness is based on resistance of the concepts in terms of safety and necessary scientific knowledge.

• Durable materials and systems to facilitate potential withdrawal of the packages

The aim of facilitating packages retrievability by future generations has led Andra to give priority to durable materials for packages and structures (concrete, steel, etc.), since their good preservation is the basic condition for reversibility. Their durability in a repository environment may be estimated at several centuries.

In addition, several systems combine to facilitate the reversible management of the repository and the possible retrievability of the packages: for example, regrouping the packages in standardised over-packs, identical handling systems for package emplacement and retrieval, incorporation of handling space in between the packages and/or between the packages and disposal cell walls.

• Modular design of underground installations for flexible management and changes in design

The architectures proposed are of modular design meaning that they enable the repository to be managed in a flexible way for example, construction and operation in stages thus facilitating incorporation of lessons learnt feedback.

Each package category (B, C and CU) is received in an assigned repository zone, constructed, operated and closed independently. Each repository zone is designed to be built and operated gradually as *successive cell sub-assemblies.* The closure is designed in the same way as for operation in a gradual manner organised into several stages: closing of cell sub-assemblies, which can be carried out at the same time as the creation of new sub-assemblies, closing of access to this sub-assembly, and then of the repository installations specific to this waste category and lastly of all installations.

As the repository is being developed in stages, new structures can be designed taking advantage of the lessons learnt and knowledge acquired during operation and observation of previous structures, as well as of technical progress carried out otherwise. It is as well possible to incorporate data from social, technical and scientific backgrounds.

3.5.2 Technical feasibility of reversing the process

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 cell (as in a storage facility). For later stages, Andra has incorporated arrangements for being able to gain access again to the installations which are closed and install the equipment required to retrieve the packages, would such a decision occur.

3.5.3 An observation programme supporting reversible repository management

Keeping options open during the repository process implies knowledge of its evolution and situation at all times, therefore requiring constant observation and implementation of the necessary measurement resources and systems. Andra has studied the possibilities of integrating measuring sensors in the structures without disturbing repository operation and safety.

In addition to the monitoring measures related to operational safety, the role of this observation programme is to check that repository evolution matches forecasts, to propose, if needed, actions to conserve the various management options and to compile lessons learnt in order to improve repository design and management. The data thus acquired will contribute to improve modelling and to increase the reliability of forecasts.

Abroad: consensus for a stepwise 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 making.
In 2002, the OECD Nuclear Energy Agency (NEA) also emphasised the fact that the reversibility approach in successive stages in line with a cautious and flexible process is considered "good practice". The NEA also insists on the need for making arrangements of an institutional, organisational, regulatory, political and financial nature as a complement to technical measures to implement repository retrievability and reversibility.
In the USA, the staged approach presented by the National Research Council (NRC) offers decision-makers an as large as possible range of options at each stage and is somehow similar to Andra's one. The NRC highlights the technical as well as the social, political and economic benefits of this approach compared to a "linear" approach.

Dossier 2005 Granite

Understanding and modelling granite

3

As a host geological formation for a repository, granite involves specific repository design constraints on account of its structure and properties. A site must therefore be surveyed and characterised with sufficient accuracy in order to adapt design arrangements to the structure and properties of the granite massif studied.

1 Surveying a granite site

The purpose of exploratory work on a granite massif is to collect site data and develop models with a view to design the architecture of a repository and demonstrate its suitability in terms of safety and reversibility objectives. The work is carried out over several stages through an iterative approach associated with design studies and safety analyses.

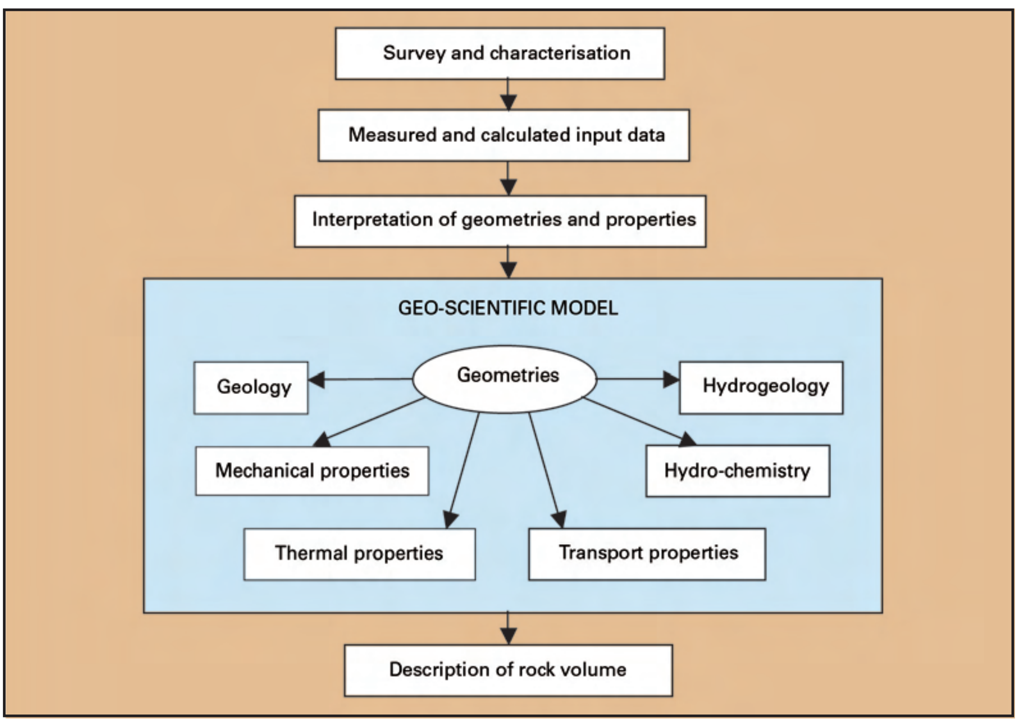
As a result, disposal concepts can be adjusted, at every stage, to the site and the uncertainties to be considered in the safety analyses can be reduced.

1.1 The aims of surveying a granite site

The geological description of a granite massif is based on the integration of data relating to the structure of the granite studied, especially fracturing, and the mineralogical and geochemical nature of the rocks forming the massif.

The hydrogeological and hydrogeochemical properties of the massif are also essential components in characterising a granite site. They concern the general hydrogeological context of the site, hydraulic parameters controlling water circulation in the fractures and hydrogeochemical factors governing radionuclide transfer and retention.

The geomechanical and thermal properties of granite also need to be considered on dimensioning the repository; they must therefore be characterised throughout the exploratory phases.



Understanding granite

Gathering site data constitutes the first step of a granite massif characterisation. Then, the second step, data integration, requires to analyse the consistency in between the various disciplines involved and to develop models representing the distribution of the granite's properties:

- *geological models* representing the structure of the granite massif studied and its fracturing in three dimensions,
- *hydrogeological and hydrogeochemical models* to simulate water circulation in the granite fractures and radionuclide transfer and retention,
- *geomechanical models* describing the geomechanical context of the site and the behaviour of the granite in response to disturbance, notably the thermal one, caused by a repository.

1.2 A staged approach

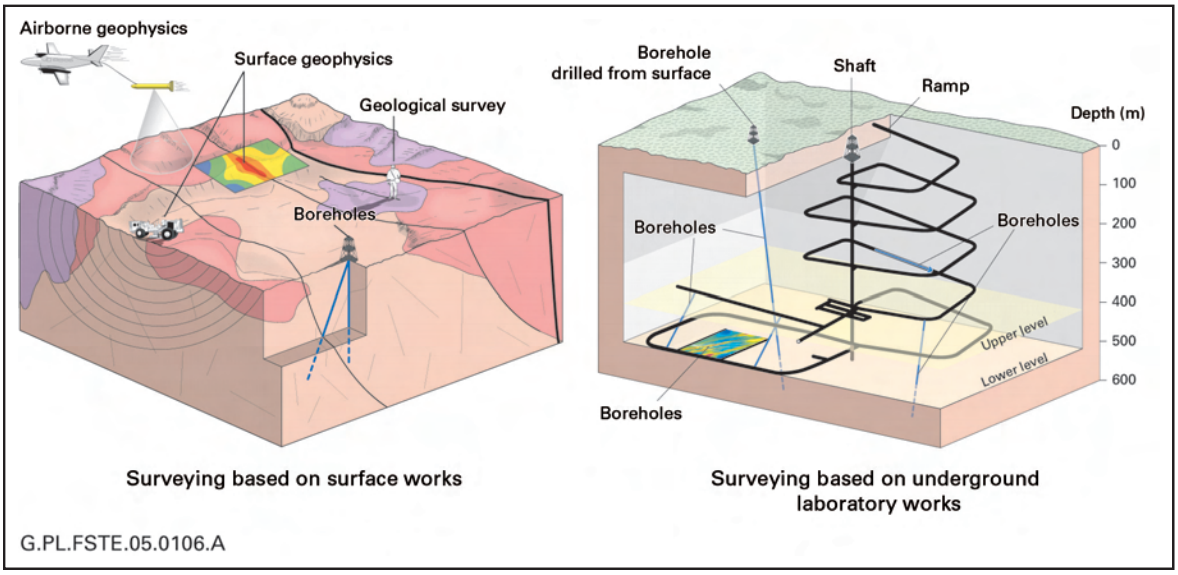
Characterising the properties of granite involves an approach and techniques which take account of the large volume of rock to be surveyed and the specific features of a fractured medium. This requires work on various scales, both on the surface and underground.

Some characteristics of granite cannot, with the techniques available, be characterised directly from the surface. For instance, the exact fracture distribution can only be determined *in situ* underground. Before underground surveys, the techniques adopted from the surface can be used to develop realistic fracture distribution models which will subsequently be improved *in situ*.

Before constructing a repository, the site surveying approach consists of gradually building up detailed knowledge of granite through two main stages:

- *surface exploration* to develop the models required for an initial assessment of the site's suitability for the installation of a repository. The absence of site characteristics ruling out repository feasibility is verified on the basis of design studies and safety analyses. A further aim of this stage is to specify the layout and research programme of an underground laboratory for *in situ* characterisation of the granite;
- *qualification through underground structures* to assess the suitability of the site for a repository. The work consists of specifying the geological, hydrogeological and geomechanical models of the granite site and models of radionuclide transfer and retention in the fractures. Site qualification is based on the design studies and safety analyses. This results in particular in the siting criteria for repository structures within the granite rock.

During construction of the repository, the precise adjustment of the repository architecture to the site's characteristics, especially the fracturing of the granite and the criteria defined during the previous stage, requires to carry out *"ongoing" surveying and characterisation work*.



Stages of surface exploration and underground laboratory qualification

2 Geological modelling

The geological modelling of a site aims at representing the structure of the studied granite in three dimensions (3D) and on various scales. Geological models act as a support for the hydrogeological, hydrogeochemical and geomechanical modelling of the site and the simulation of any radionuclide transfers in the granite which is the basis for the performance assessment of the repository.

2.1 What geological objects ?

A granite massif is a composite geological formation, which is the result of a multistage geological history:

- the genesis, emplacement and crystallisation of granite magma at variable depths according to the type of granite;
- one or more deformation and fracturing phases during and after granite emplacement;
- the rising of the geological basement and the erosion of overlying formations leading to outcropping granite.

Each phase in this geological history impacts on the composition and structure of a massif. The rock itself and its geochemical nature, mineralogy and homogeneity reveal the original history of the granite and the solidification phases.

Granite emplacement and the deformation phases are accompanied by hydrothermal fluid circulations characterised by mineralogical transformations of the granite mass or its fractures. The structure and fracturing of the granite provide indications about the various phases of tectonic deformation affecting a massif during and after granite emplacement and crystallisation.

Some rocks, originating more or less from the magma creating the granite, intersect the granite rock in the form of veins: fine-grain aplites, large-mineral pegmatites, basic dolerites, etc. These rocks also bear witness to the various phases in the history of the massif and often constitute guidelines to the modelling of the structure of the granite massif.

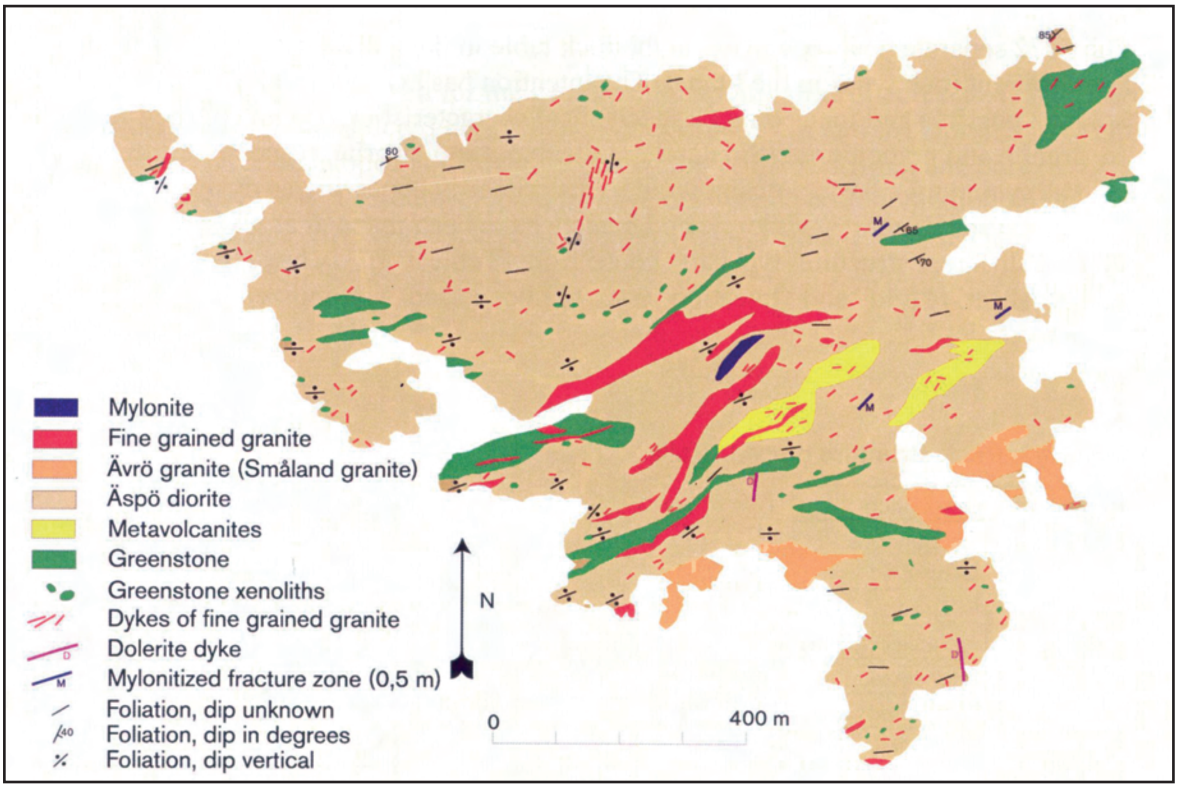
The surface parts of the granite are also an important element of the massif structure. Resulting from erosion phenomena leading to granite outcrops, they are altered and generally much more permeable than deep granite. They can form a reservoir of rainwater feeding the hydrogeological system of the deep granite (cf. 3.3).

Each one of these elements forms a component of the geological model to be produced and developed over the successive stages of surveying and characterising the granite.

2.1.1 Granite rock

A granite massif is, in the majority of cases, composite; in other words, the mineralogical nature of the constituent rock varies from one point of the granite to another. This is explained by the different primary origins of the magmas or by differentiation phenomena in the course of granite emplacement and solidification.

On a massif scale, modelling consists of defining the major composite granite structures of the massif. For example, the Charroux-Civray granite massif in the Vienne district, studied by Andra from 1994 to 1996, originates from various kinds of magma which were assembled as the massif was emplaced. Similarly, the Äspö laboratory in Sweden is located in a massif composed of two dominant types of granite: Ävrö granite and Äspö granodiorite.



Geological map of Äspö

At the repository scale, modelling consists of representing the relationships between the various components of the massif in three dimensions (3D). It aims to identify how the differences in nature between the various components of the granite can impact on the design of a repository and the safety analyses. For example, it involves ascertaining whether mineralogical differences significantly alter the thermal or hydraulic properties of the rock and assessing whether fracturing varies according to the nature of the various components. From this point of view, their contacts are important markers. These observations, in return, indicate the intensity of the deformations to which the rock is subjected.

The integration of data on the various scales contributes to the understanding of the geological history of the granite. Data consistency is an evidence of the soundness of the 3D geological models.

2.1.2 Fracturing of granite

As a result of its genesis and geological history, granite is a fractured medium. The fractures are the pathways where water flows through the granite. They are therefore potential vectors for the transfer of radionuclides from the repository to the environment. Their detection and 3D representation are an essential objective of geological modelling.

• Scales of fracturing

Fracturing of granite is observed on very different scales: from a crustal scale with the major faults structuring the subsoil basement, to micro-fractures on a mineral scale and observed under a microscope.

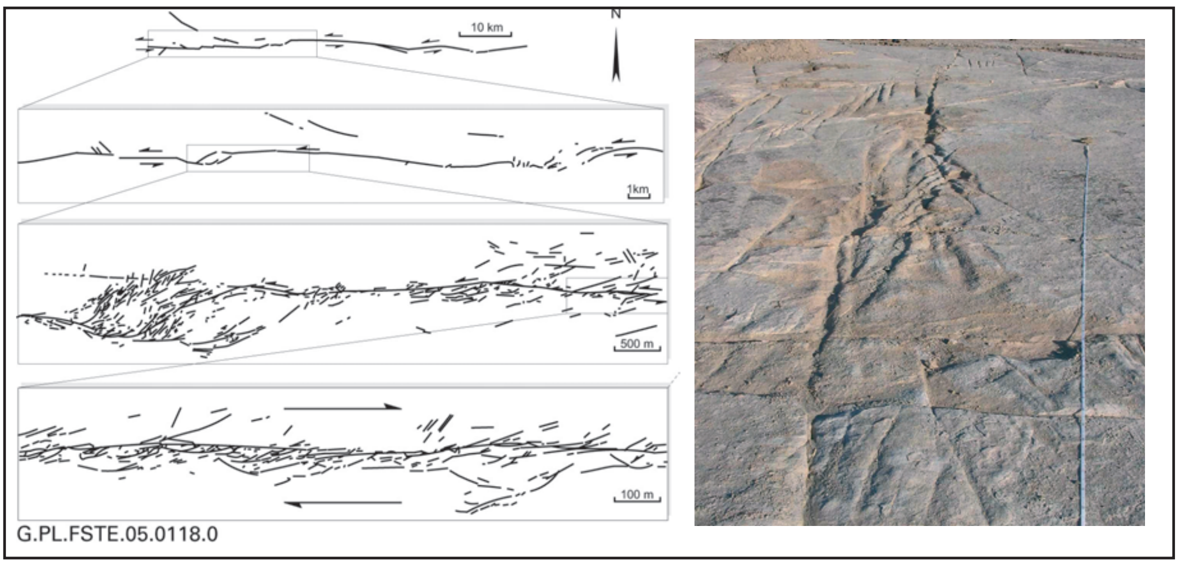
LENGTH	FRACTURING DOMAIN		ANALYSIS	TYPOLOGY
>100 km	MAJOR FRACTURING	REGIONAL FRACTURING	DETERMINISTIC	Crustal faults
10 km				Regional faults
1 km		LOCAL FRACTURING		Local faults
1 hm	MEDIUM FRACTURING	HECTOMETRIC FRACTURING	Limit depending on surveying progression	Hectometric faults
1 dam				
1 m	MINOR FRACTURING		STATISTICAL	Fissures Joints Small faults Gashes and fissures
1 dm				
1 cm	MICRO FRACTURING			Microfracturing Microfissuring
1 ìm				

Scales of granite fracturing

Major fracturing and minor fracturing are also differentiated by the way in which they are treated – deterministically or statistically:

- *small fractures* result from thermal "shrinkage" during magma solidification or subsequent deformation phases. Apart from zones of major granite deformation, they generally conduct very little water. The characterisation and modelling of minor fracturing are based on a statistical approach. Fracturing model input is the systematic geological survey which provides distribution laws of their main characteristics in the granite: size, orientation and dip;

- *large fractures, or faults*, always result from significant deformations in the granite massif during the tectonic phases. They are often a composite of several lower-order fractures. The mode and intensity of the fracture can vary from one point of a massif to another and from one massif to another, which leads to various fracture models dividing the granite massif up into "blocks" of different shapes. In order to detect and model them, large fractures and faults are based on a deterministic approach during the exploratory phases: they are generally large enough to be identified one by one and to form the structuring elements of granite modelling.



Details of the structure of a large fault on various scales

- *the treatment of "medium" fractures* forms the transition between these scales of fracturing. Its treatment will change as a granite site is surveyed. Treated statistically in the initial stages, it is based on a deterministic approach during phases detailing the structure of the granite on the scale of a repository module. This is particularly the case during the "ongoing" survey work while the repository structures are excavated.

• Mineralogy of faults and fractures

Faults are the result of shear breaking of the rock, causing slippage and partial crushing. Faults are therefore composed of elements of granite rock which are crushed ("brecciated") or even transformed into clay ("clay gouge") depending on the intensity of the deformation. Furthermore, the hydrothermal fluid circulations accompanying the fracturing phases in the granite mean the precipitation of specific minerals inside the faults. The mineralogical composition of the fracture-filling materials bears witness to various events at the origin of the granite and the physical and chemical conditions governing its structuring.
The modelling of fracturing therefore distinguishes between various families of fractures according to their geometry and the mineralogy of their filling materials.

View of a fracture plane

2.2 Methods

The surveying techniques of a granite site are adapted to the various stages of the approach and to the corresponding objectives. They combine:

- geological surveys through the direct observation of the granite either on outcrops at the surface, on core samples from boreholes, or on walls of underground structures;

- geophysical surveys providing images of the substratum on various scales.

2.2.1 Surface or underground geological surveys

Surface geological mapping is used to complete existing geological maps by outcrop surveys, the processing and interpretation of aerial photographs, satellite images and digital terrain models. It is an input for the production of 3D geological models from interpreted geological cross-sections.

Core samples taken from boreholes drilled from the surface or from underground drifts can be used to identify the various types of rock and their relationships, and to measure the density of fracturing and its characteristics (orientation, thickness, mineralogy, etc.). These measurements form the basis of the statistical analysis of minor fracturing.

In situ geological surveys of underground structures, drifts or shafts complement surface or borehole data with more details, particularly with regard to rock variability and the continuity of the fractures in 3D.

2.2.2 Geophysical methods

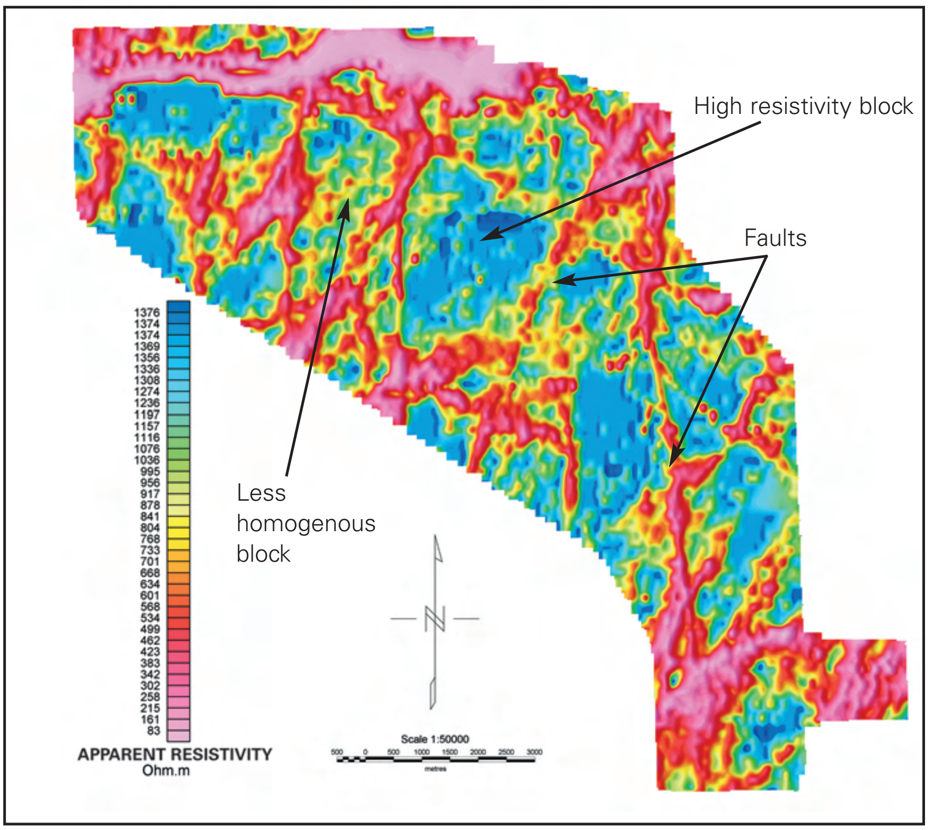
Together with surface mapping, *airborne geophysical methods* often form the first tools used in exploring a site. They are based on the measurement of various substratum properties: magnetic properties, electrical conductivity and radioactivity.

These methods, whose main ones combine aeromagnetism, electromagnetism and radiometry measurements in a single flight, can be used to cover large areas quickly and homogeneously, and are an input to the geological interpretations on regional and local scales.

Surface geophysical surveys are conducted less extensively to detect variations, on a local scale, in rock nature and medium heterogeneities: presence of homogeneous "blocks" of faults or fractures.

Underground geophysical methods, generally more complex to implement than on the surface, are effective when conducted in between drifts and/or boreholes. They include, for example, radar or seismic measurements.

The majority of the techniques used are largely tried and tested. They benefit from considerable feedback from mine prospecting. This is the case of airborne geophysical techniques which can be used to quickly differentiate between zones where physical properties, in connection with lithology and fracturing, remain homogenous or vary rapidly. The illustration below shows an example of apparent resistivity of a granite massif deduced from data acquired by aeromagnetism.



Airborne resistivity map showing the separation of a granite massif into "blocks" by faults (Cogema data)

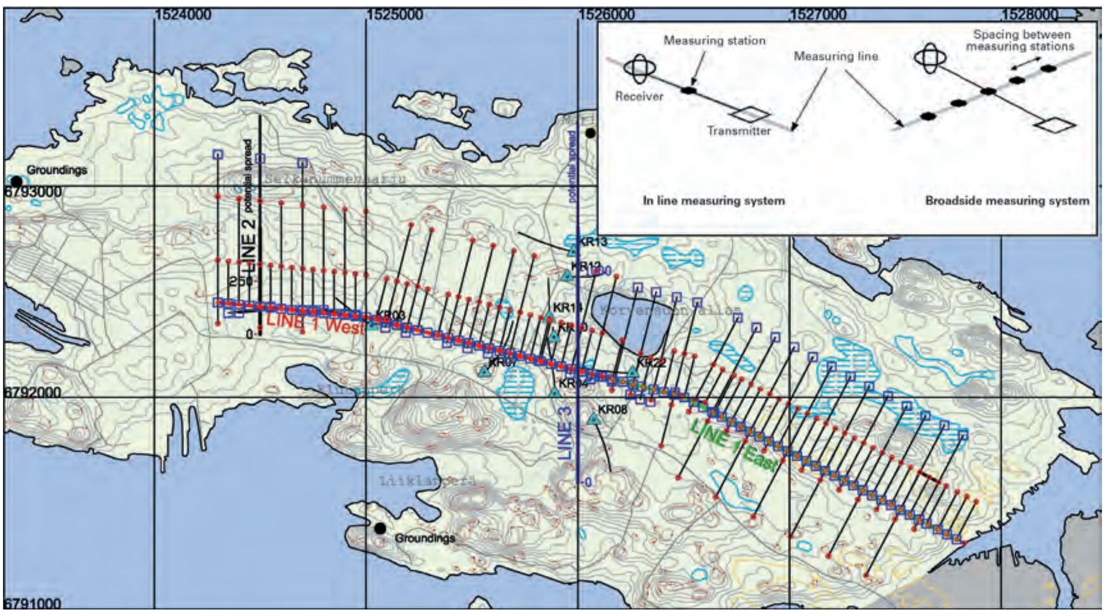
Other techniques have undergone more specific developments for repository studies, especially fracture exploration techniques, which provide sufficiently precise imaging of granite at various scales. In this respect, Andra has tested various electrical, electromagnetic and seismic methods with Posiva at the Olkiluoto site in Finland. Complementarity of these methods for the detection of faults or other geological objects, such as contact between rocks of different kinds, could be appraised through such tests. They have specified the field of application of methods to be implemented from the surface, boreholes or underground structures, at the various stages of exploration. The applicability of the methods tested in Finland to the French geological context has also been verified.

Testing geophysical methods with Posiva in Finland

In the framework of a cooperation agreement signed in 2002 to develop surface methods of characterising a crystalline site, Andra and Posiva tested two geophysical methods at the Olkiluoto site in 2002 and 2003: the first concerned electrical and electromagnetic methods carried out from the surface, the second, seismic methods using deep boreholes.

• Joint acquisition and interpretation of electrical and EM data

This work, combining conventional borehole electrical surveys with electromagnetic multifrequency measurements, was carried out to explore the 0-500 metre depth range.
The electromagnetic measurements were carried out over a 3400-metre long line across the Olkiluoto island using both in-line array and broadside array configurations for the transmitter-receiver stations (see illustration below). To best cover the 0-500 metre range, various transmitter-receiver spacings were adopted: 200, 500 and 800 metres.



Location of the electrical (LINE 1 West, LINE 1 East, LINE 2 and LINE 3) and electromagnetic measurement lines (in-line array: blue squares with 200 metres station spacing, broadside array: red with 200 metres and 500 metres spacing, light blue with 800 metres spacing) (kilometric grid). Inset, the measurement system.

The electrical and electromagnetic data underwent specific processing operations and were interpreted, first separately and then jointly. The final stage of interpretation integrated the borehole resistivity measurements and the comparison of the electrical and electromagnetic measurements with the results of earlier geological and geophysical surveys.

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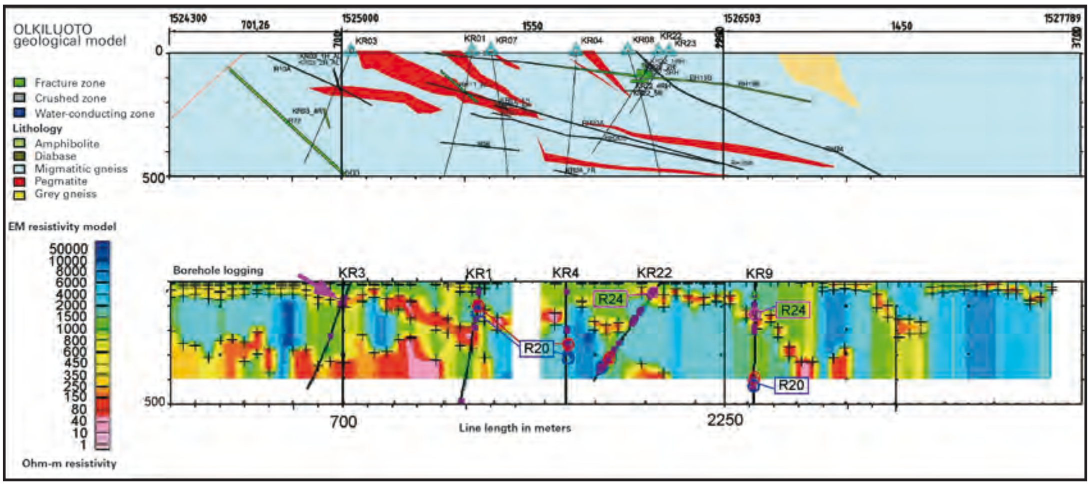

Geological cross-section and resistivity of the electromagnetic line (200 metres transmitter-receiver spacing, broadside array)

The combined use of these two techniques can be transposed to French granite massifs and provides good mapping of the 0-500 metre range volume of rock. Electromagnetic multifrequency survey locates horizontal or low-dip faults fairly accurately and assesses their continuity over a large depth range. Electrical measurements show good resolution up to 150-200 metre, and are notably applicable when characterising the altered surface zone of granites, generally encountered in the French case.

- **Acquisition and interpretation of seismic data from boreholes**

Two seismic techniques were implemented: WVSP and tomography.

- Walkaway Vertical Seismic Profile (WVSP) consists of using receivers lowered down in a borehole to record the seismic waves sent by a source displaced at a regular pace along a line at surface. The seismic source used was a modified, computer-controlled, hydraulic rock hammer mounted on a mechanical digger (photo below left). The receiver chain is equipped with geophones placed in eight three-component modules fitted with clamping arms (photo below right). The distance between the modules is five metres.

Seismic source (left) and set of eight geophones before they were lowered down a borehole (right)

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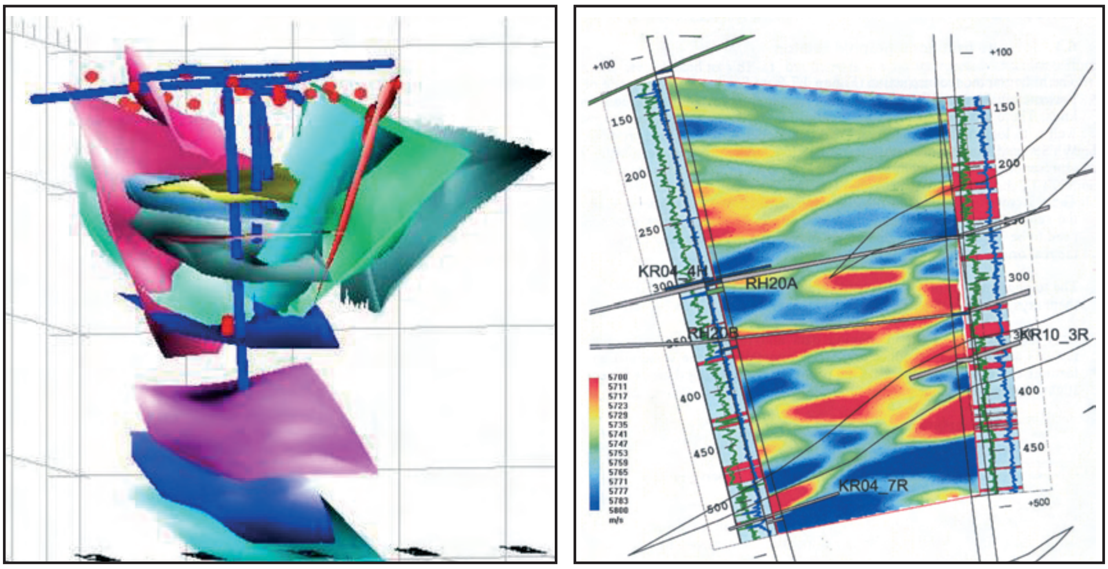
The number and position of the receivers were determined to identify faults or contacts between rocks of a different kind at various depths. They were chosen according to the orientation and dip of these geological objects off which the seismic waves are reflected. A total of four boreholes were used in this way and the sources were displaced along three lines.

Measurement processing and interpretation identified around twenty reflectors – mainly contacts between rocks of different kinds or fractures – which were then integrated into a consistent geological model (figure below). This technique, tested in Finland, is applicable to all granite environments.



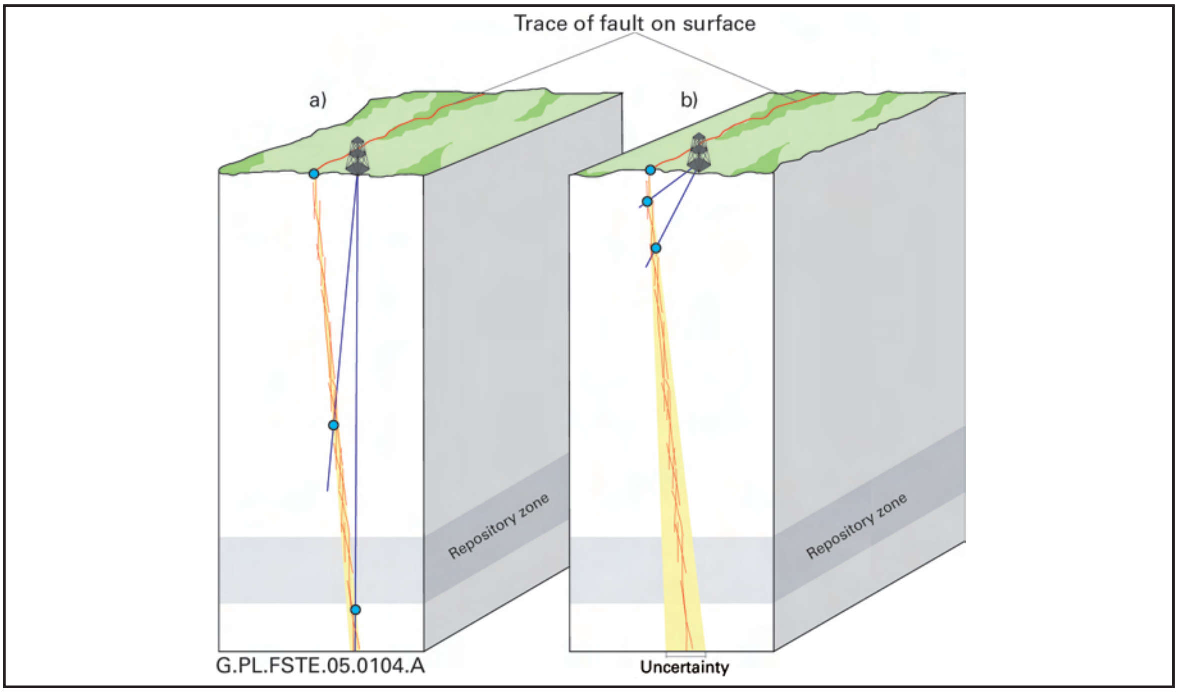
Left, interpretation of the WVSP reflectors. Right, tomogram of seismic velocities between boreholes KR04 and KR10

- *Seismic tomography* consists of recording, with receivers lowered into a borehole, the seismic waves sent by a source displaced at a regular pace in another nearby borehole. Measurements were taken between two deep boreholes at a distance ranging from approximately 250 metres near the surface to 150 metres underground.
- The piezoelectric seismic source produces high-frequency signals with significant penetration in the medium, from tens to hundreds of metres. It was displaced every two metres. The receivers consisted of a chain of 30 piezoelectric sensors two metres apart. After processing the data, the seismic wave velocity tomogram was compared with the borehole data to identify the continuity or discontinuity of the faults detected between boreholes (figure above).
- The tests showed that the technique can be used for borehole distances of up to some 250 metres, which would lead to optimise the number of boreholes to be drilled from underground structure.

2.3 Data integration and uncertainty processing

The main purpose of geological modelling is to produce 3D models of the granite structure, i.e. the distribution in the massif of the various geological objects composing either the rock itself or the fractures.

It also aims to identify and assess, throughout the exploratory stages, the uncertainties associated with the models produced in order to reduce them and, ultimately, identify those that cannot be reduced so that they can be taken into account in the safety analyses and repository design. For example, the complete, precise pattern of a fault is never totally accessible in 3D; therefore an input to repository design is the definition of the margins of confidence related to the modelling of such a structure (figure below).



Uncertainty regarding the fault line on the basis of borehole data:
a) from deep boreholes, b) from shallow boreholes

In this respect, consistency of the observations and the models produced on various scales is a key element in the interpretation of field data and its integration into a 3D model.

Ultimately, the understanding of the geological objects forming the model, i.e. the consistency of their integration into the geological history of the granite, is indicative of the robustness of the model. It is founded on both basic and specific studies often involving work beyond the perimeter of the concerned site.

2.3.1 The input of basic studies

Understanding the significance of the various rock units or fractures composing the geological model of a granite massif implies relocating them in the history of the granite from its genesis to the current period.

The questions most often examined concern the mineralogical and chemical composition of the rocks indicating the origin of the magmas. Interpretation requires age measurements or isotopic geochemical analyses, for example, to distinguish between magma families.

Analysis of the fractures and the various tectonic phases which gave rise to them is also an important area of study in understanding the history of the granite. By understanding how the fractures formed and to which episodes in the history of the granite the minerals forming them relate, one can carry out extrapolation, at the relevant scale, from field data collected in observation points or particular measurements: rock outcrops on the surface, boreholes and underground geological surveys.

Understanding the clogging of fractures by minerals resulting from the ancient circulation of hydrothermal fluids is therefore a point which is systematically studied while exploring granite massifs. Evaluating the effect of the extent and chronology of this type of phenomena is important in appraising granite rock permeability. Through the results of the work on the hercynian granites of France (particularly, the work carried out by the FORPRO research group at the CNRS), were specified in more details the following points: the chronology and extent of the hydrothermal circulation phenomena observed in both the west of the Massif Central and the Armorican Massif, thus leading to the establishment of a general framework of this type of study for a particular site.

2.3.2 3D modelling and visualisation tools

Progress in computing has considerably increased the possibility of modelling and visualising, in 3D, the structure of a geological formation, in particular granite and its major fracturing.

With the multiple angles of visualisation offered by computer tools, the consistency of geological and geophysical surveys carried out in a complementary manner and on various scales can be verified much more easily.

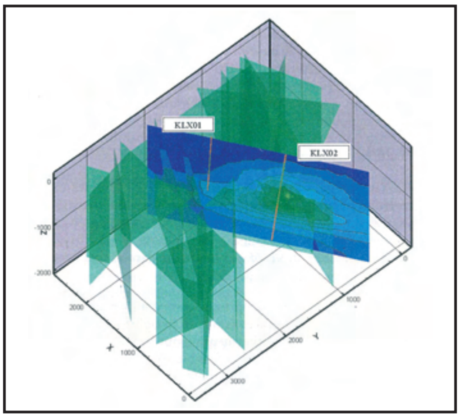
3D modelling and visualisation tools

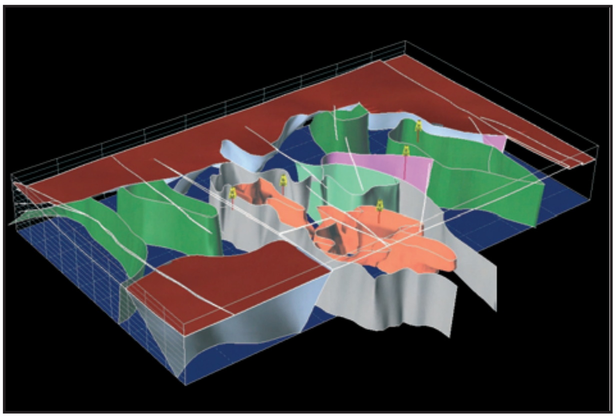
The data acquired over the course of the exploratory and characterisation stages is validated and integrated into a database. This includes direct measurements and calculated data. It is generally located in 3D such as, for example, a sample of rock or fluid in a borehole, or a physical or geophysical *in situ* measurement.

3D visualisation of the data is essential for the construction of geological models forming the backbone of the integrated models covering the various disciplines, first and foremost for the geometry of the structures. Visualisation tools must be able to represent the various elements of the geological model, i.e. lithology and fractures. They must additionally manage the location and results of samples, boreholes and geophysical measurements or interpretations. They must also integrate topography in the form of digital terrain models, images or satellite or aerial photographs. Such tools provide user-friendly access to the 3D models and enable them to be shared across various disciplines: geology, hydrogeology, geomechanics, geochemistry, etc.

Until quite recently, 3D visualisation was based on vertical cross-sections in two directions and plans at various depths. Today, computing provides interpolation and visualisation tools for the construction of true three-dimensional models. The main difficulty consisted in linking *database and 3D visualisation* for the various types of geological formation encountered, especially for the granite medium by taking account of fracturing on various scales.

SKB has developed a so-called RVS system *(Rock Visualisation System)* for the visualisation of particular faults and cross sections. Posiva has an equivalent system which has been supplemented by a mining visualisation tool for the structures observed in the Onkalo underground facility at Olkiluoto. In France, Andra has adopted visualisation tools from the oil industry for the representation of the Charroux-Civray granite massif (Vienne).





Left: visualisation of faults and cross sections with the RVS developed by SKB (Sweden).
Right: visualisation of the limits of the granites forming the Charroux-Civray massif (France).

3 Hydrogeological and hydrogeochemical modelling and transfer simulations

Hydrogeological models are the support for radionuclide transfer simulations for long-term safety assessments. They are used to evaluate the water flows liable to occur during repository excavation and operation.

Hydrogeochemical models complement the hydrogeological models for the understanding of current and past hydrogeological flows in the granite substratum. They therefore provide support to the radionuclide transfer simulations.

3.1 Issues relating to the modelling of a fractured medium

Hydrogeological and transfer models for granite are complex. This complexity stems from the representation of a fractured medium and the consideration of large scales of time and space in the studies of a repository. While low in term of rate and slow in term of kinetics, the water flows to be considered are essentially linked to fractures, whose distribution in the granite does not follow a single and simple law.

The methods used have undergone major developments in recent decades. The progress made in the oil industry has in particular been behind the methods and tools which could be adapted to the granite medium and the repository studies.

Around ten years ago, many radionuclide transfer simulations were performed on the basis of major simplifications of the fractured granite medium consisting of processing with the numerical codes of an equivalent porous medium. In this method of processing, the simulations take into account the largest faults and the role of the small-sized faults is processed by the allocation of hydraulic parameters weighted to the mass of granite.

With the progress achieved, fractures can be processed more explicitly in increasingly large volumes of rock and simplifications in the representation of the granite have been reduced. They are now regularly integrated into the models and simulations performed on an international level, with the general simulation approach relying on the complementarity of the two representations of granite: equivalent porous medium and medium explicitly represented with fracturing.

However, this does not clear up all the difficulties inherent in the models to be produced. The questions to be considered relate to the characterisation and the data to be gathered, and also to data processing and the problem of digital simulation. Ultimately, it is a matter of controlling the simplifications which must be introduced throughout the modelling process; in other words, understanding their full meaning, both in terms of the elementary phenomena considered and of their integration into the models and simulations.

Hydrogeological models in a continuous porous medium and in fracture networks

Hydrogeological modelling of a fractured granite massif comes up against two major requirements for modelling:

- firstly, it must take into consideration a complex network of fractures, down to the smallest fractures liable to be intercepted by a repository component, in order to appraise correctly the flows occurring there,
- and secondly, it is essential to extend modelling over sufficiently large volumes to ensure that all factors determining underground flows are taken into account: topography, hydrographic system often beyond the limits of the granite massif, hydraulic characteristics of the altered superficial parts of the granite massif, etc.

As it is not yet possible with current computing resources to use a fracture network model over the whole of the considerable volume that would need to be discretised on the small fracture scale, the solution involves the integration, on various scales, of "porous equivalent" models and models representing explicitly the fracture networks.

• "Equivalent porous medium" models

In a continuous porous medium model, flows are assumed to use the whole volume of rock available and comply macroscopically with Darcy's law. Water flows depend directly on the permeability of the medium. This model, valid for porous media, can be used for fractured rocks over a certain volume which depends on the geometric and hydraulic characteristics of the fracture networks in question.

For example, the generic exercises "Everest" and "SPA" to simulate radionuclide transfer in a granite medium were conducted, with the support of the European Union, on the basis of such assumptions.

On a regional scale, i.e. over areas exceeding a hundred square kilometres and terrain several kilometres thick (schematically 15kmx15kmx3000m), hydrogeological modelling is still based on such simplifications. Faults are taken into consideration in the model through the attribution of "equivalent" hydraulic properties to parts or the whole of the modelled volume.

• Models explicitly taking account of fractures

Several types of modelling can take a fracture network explicitly into account. *Discrete fracture network (DFN)* models, the most widely used, consider a medium in which, in steady state, only fractures play a part in the advective flow. The flow is thus restricted by the dimension of the fractures, especially thickness and width. The geometry of each fracture is defined, enabling the hydraulic connectivity of the network to be determined. Hydraulic transmissivity parameter is attributed to each fracture and then, hydraulic heads and flows can be calculated at any point of the network.

The field of application of DFN models is more specifically hydrogeological modelling and transfer simulations on the scale of a repository module (approximate volume: 500 m x 500 m x 300 m). With DFN modelling, all fractures extending up to approximately 5 m can be integrated.

• Integration of models of various scales and various types

Modelling scales must fit consistently with the various types of models. With today's computer tools, models performed at various scale can be integrated by successive iterations, and the consistency of parameters used on various scales can be achieved from the regional scale to the repository module and disposal cell scale.

In the absence of a specific study site, Andra's work consisted of dealing with each stage in the modelling process and checking that the methods, techniques and digital tools developed abroad would be applicable to the study of a site in French granite:

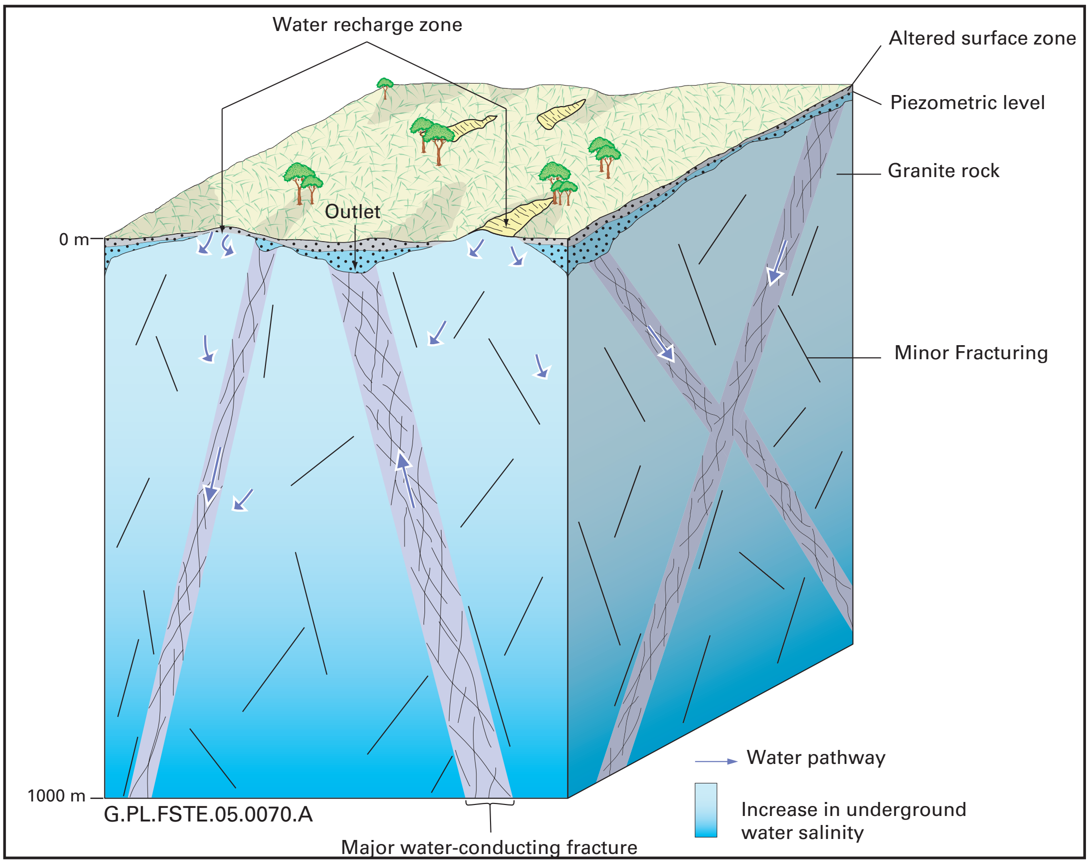
- an initial series of questions focused on the identification of phenomena and parameters affecting the hydrogeological, hydrogeochemical and transfer models in granite;
- it was then necessary to check that these parameters could be determined, for a given site, from field measurements or laboratory analyses;
- the final stages of modelling or digital simulation involved testing integration methods suitable for the considered scales of time and space and justifying the corresponding simplifications.

The results of these studies lead to the conclusion that application, on a French granite site, of each stage in the modelling process was confirmed through the feedback of previous lessons learnt. The realism of the models and simulations is sufficiently preserved by the simplifications cautiously introduced throughout the calculation process.

3.1.1 Hydrogeological models and parameters

In granite, fractures are the water flow pathways. The rock itself, a quite impervious and low porosity medium, practically makes no contribution to the water flow.

Major fracturing controls almost all water flows, which are generally low. Minor fracturing, when located in areas away from major fracturing, generally conducts little water.



Main elements of hydrogeology of a fractured granite massif

This conceptual model of hydrogeology in granite leads to base the architectural design of a repository on a repository modules layout positioned away from major fracturing. Therefore, in repository modules, the low water fluxes will depend on the hydraulic properties of the small fracturing in the granite walls.

Water flows in a repository depend on the orientation and value of hydraulic head gradient, driving force of underground flows. They depend, on the one hand, on the site topography and, on the other hand, on the properties of granite massif surface parts, which control rainwater infiltration. Generally, gradients get weaker deeper down which helps to limit water fluxes at repository level.

The hydrogeological modelling of a granite site is thus based on the fracture distribution, the hydraulic parameters of rock and fractures (fracture transmissivity and interconnectivity) and the values of the hydraulic gradients.

The groundwater chemical characteristics, especially salinity, can also affect hydrogeological and transport models. If the groundwater is very saline, its density may lead to a stratification of water versus depth. This may particularly concern coastal situations or ancient brine. Such situations are taken into account in the current site studies carried out in Sweden and Finland. This brings a feedback in this area.

3.1.2. Transfer and retention models in granite

Many radionuclides show little mobility in granite due to their low solubility under the chemical environment conditions prevalent underground: reducing medium, pH remaining close to neutral, etc. This is particularly the case with actinides. However, other more soluble radionuclides are mobile (iodine-129, chlorine-36 and caesium-135 for example). Therefore, both conceptual models showing the transport and retention of radionuclides in the granite rock and fractures, and parameter quantification elements to be introduced into the simulations, are needed. This important issue has formed the subject of a very active international cooperation, notably through experiments conducted at the Äspö laboratory in Sweden.

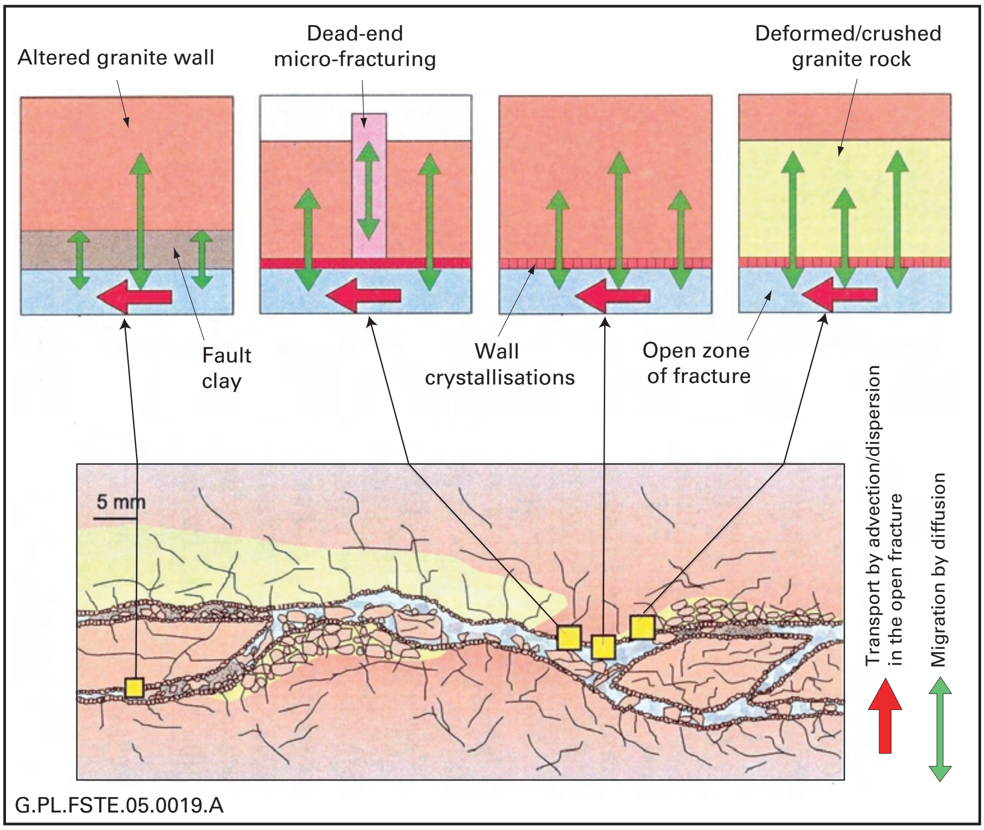
Various phenomena play a role in the transport and retention of radionuclides in a fractured granite environment, the main ones being advection, dispersion and diffusion.

When water circulates in the open parts of fractures, radionuclides in solution also move as they are carried by water. This is advective transport. The geometric complexity of the multiple pathways taken by the water flows leads to the dispersion of solutes in the course of transport.

However, the kinetics of water flow are slow. The diffusion phenomenon is therefore superimposed over transport by advection/dispersion. It concerns all moving elements, but also the numerous volumes still or moving very slowly, contained in the intimate structure of the fractures (small diverticula, rock wall altered to a greater or lesser extent, possible porous filling, etc.). Diffusion encourages the adsorption (trapping) of the radionuclides liable to fix themselves to the fracture walls or to "brecciated" rock minerals and elements filling the fractures and multiplying the accessible surfaces. By enabling certain radionuclides to leave the circulating water flow for some time, the diffusion and retention phenomena delay solute migration compared with advective transport.

This conceptual transport model (figure next page) has been enhanced through experiments carried out at the Äspö laboratory in Sweden. The experiments and associated modelling exercises confirmed the role of diffusion phenomena in the transfer of radionuclides in a fracture and identified the fracture components involved in transport, especially the role of stagnant zones where diffusion between fractures and the wall rock is high.

The transport parameters to be characterised are therefore essentially the coefficients of diffusion into the rock and the retention parameters of the rock and fracture minerals.



Conceptual model of fractures and transport phenomena

3.2 Data collection

Boreholes are the most commonly used means for underground hydrogeological or hydrogeochemical survey and characterisation work in a granite massif. At each stage in the exploratory process, from the surface or underground, the borehole techniques – coring or drilling – are adapted to the aims of hydrogeological or hydrogeochemical characterisation. There is a considerable amount of feedback in this area providing a very comprehensive range of tested techniques and tools suited to numerous contexts.

3.2.1 Hydrogeological data

The hydraulic conductivity of granite or, to be more precise, that of the fractures producing conductivity, is essentially determined by hydraulic tests in boreholes.

Various techniques are used depending on the extent of the hydraulic transmissivity of the fractures:

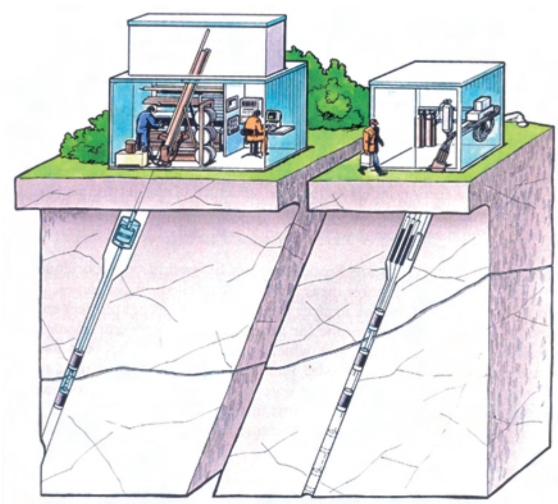
- for large fractures where transmissivity is significant, conventional hydrogeological techniques (pumping, current flow-meter logging, etc.) are adapted to determine the hydraulic characteristics of the granite;
- if transmissivity is lower, the “fluid logging” technique based on the detection of differences in electrical conductivity, and therefore salinity, is quite suited to locating low flow-rate fractures;
- if transmissivity is very low (as in the case of small fractures), the fluid logging technique is combined with differential flow logging in the borehole similar to the technique developed in Finland and used systematically in exploratory boreholes;
- finally, tests between fixed packers can be used for accurate characterisation of the granite rock, very low permeability rock by nature, and small fractures where transmissivity is very low.

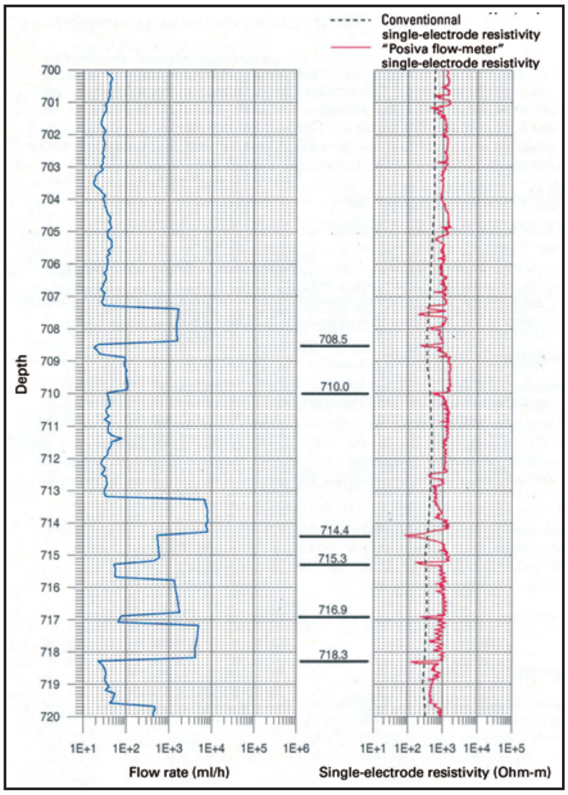
Fracture interconnectivity is another important parameter. It can be assessed by testing hydraulic interference between boreholes. This type of test particularly concerns large fractures (figure hereafter).

Other measurements can be carried out using equipment measuring the water pressure at several levels within the same borehole, through various measurement chambers positioned in between packers. With this technique, the water pressure of a specific fracture or fracture zone can be measured and the connectivity between fractures or groups of fractures can be evaluated.

The developments in these techniques, especially for oil exploration purposes, provide a complementary set of tools able to characterise the connectivity of a network of fractures on various scales: from tens to several hundred metres.

A third set of information concerns hydraulic head gradients, driving force of flows in a massif. The gradients are established on the basis of topographical data and piezometric measurements in boreholes.



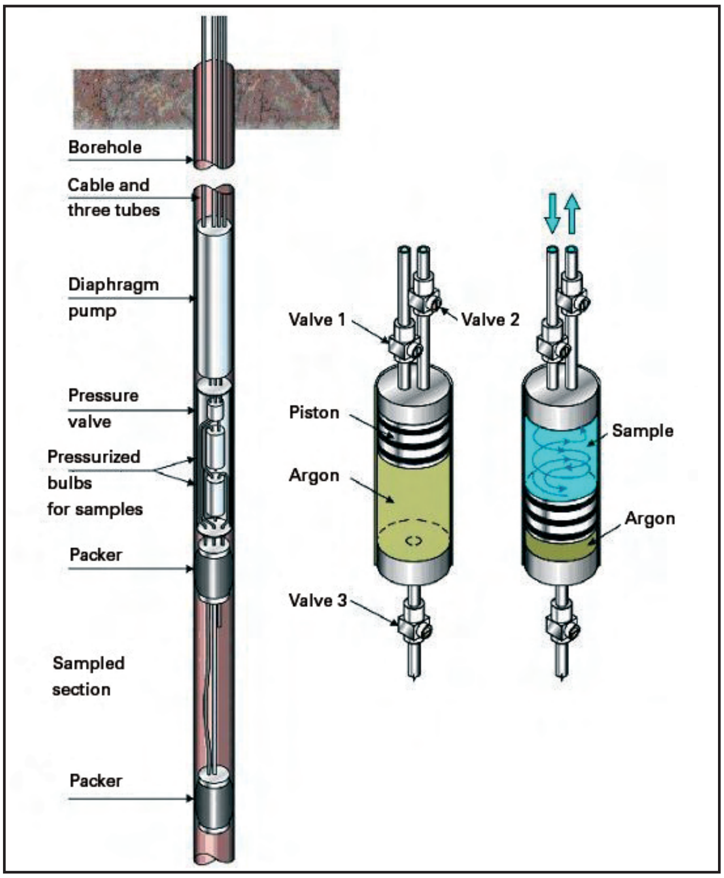


Left, schematic diagram of a hydraulic interference test designed to study fracture connectivity between two boreholes (SKB data).
Right, continuous measurements in boreholes showing the relationship between flow rate and electrical conductivity to determine the precise position of water conducting fractures (Posiva data).

3.2.2 Hydrochemical data

The composition of the water in a granite massif is determined from water samples taken from the boreholes.

Various techniques have gradually been developed to meet the requirements of the planned chemical or isotopic analyses. Depending on the water production detected by hydrogeological measurements, fluid samples can be taken directly from the water produced at the wellhead, or downhole using sealed bottles or continuous sampling techniques.



PAVE borehole fluid sampling system developed in Finland (Posiva data)

3.2.3 Transfer and retention parameters

The diffusion properties of the granite rock are established during exploratory work on a granite massif by samples taken from cored boreholes and underground drifts, as well as from surface outcrops if suitable with respect to alteration conditions.

Retention properties are linked to the mineralogical characterisation of the rock and fractures as well as to the intimate geometry of the voids and porous volumes. The values of the associated parameters are established from measurements on granite samples. Tracer tests between boreholes are conducted *in situ* to verify the consistency of measurements on the samples with extrapolated values, in relation with geological variability, on the scale of a large fracture.

• Analyses and measurements on granite samples

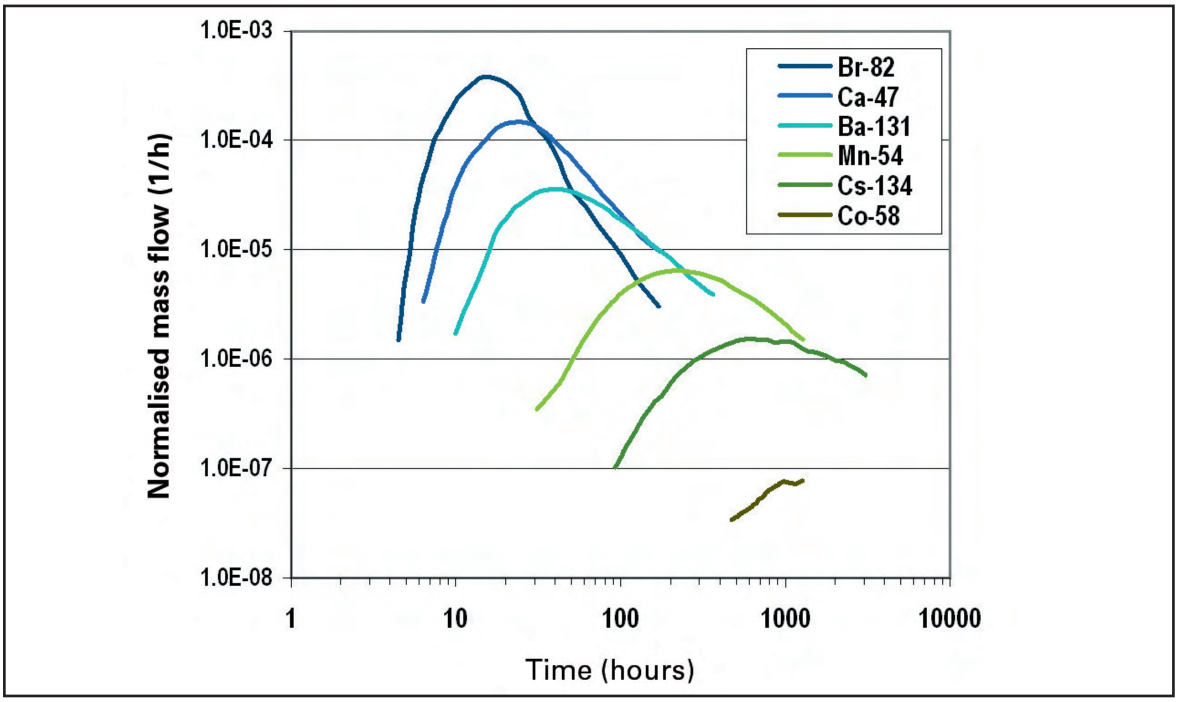
The diffusion coefficients of granite have been measured on several types of granite in France and abroad. They are generally performed by testing the diffusion kinetics of tritiated water through a few centimetre thick slice of granite. This method was used in the course of the works carried out by Andra from 1994 to 1996 on the Charroux-Civray granite massif.

As this massif is composed of several types of granite, extensive sampling of various types of rock was possible. The diffusion coefficients measured were generally very low with values most often below $10^{-13}m^2/s$. When the granite massif was subjected to major hydrothermal alterations during its geological history, the values could increase by a factor of 10 or 100.

• Tracer tests between boreholes

In granite, tracer tests consist of injecting a cocktail of tracers at a precise point of a fracture and observing its release, at a certain distance, in the same fracture or in another connected fracture. Providing that a sufficiently accurate geological and hydraulic characterisation of the fracture network has been completed beforehand, this type of test can be used to assess the delay on radionuclide transfer compared with water circulation.

A major experimental programme was conducted on such tracer techniques at the Äspö laboratory in Sweden ("TRUE" experiment). They led to the development of a conceptual transport model in a fractured medium and the quantification of differential delays between radionuclides. A delay factor of 250 was thereby detected on the same pathway in a single fracture for caesium compared with an undelayed element (bromine for example).



Comparative release curve of various tracers on a same pathway

3.3 Integration methods providing the link between site exploration and safety analyses

Methods are available today to integrate site exploration data into safety analyses and design studies. They are based on a complete modelling process from acquisition of geological data to simulation of radionuclide transfer, and on the full range of scientific knowledge contributing to an understanding of granite massif hydrogeology. Among these data, hydrogeochemistry forms a natural complement to hydrogeological models in understanding water flows in granite and its environment.

3.3.1 A modelling process which explicitly includes granite fracturing data

Questions relating to the integration of site data into safety assessments, through hydrogeological modelling and radionuclide transfer simulations, concern the following main aspects:

- integration of the various scales of space into the geological and hydrogeological models;

- inclusion of the variability in the fracture transport properties within a granite massif;

- inclusion of the various phenomena involved in radionuclide transfer and retention in a granite massif fracture network;

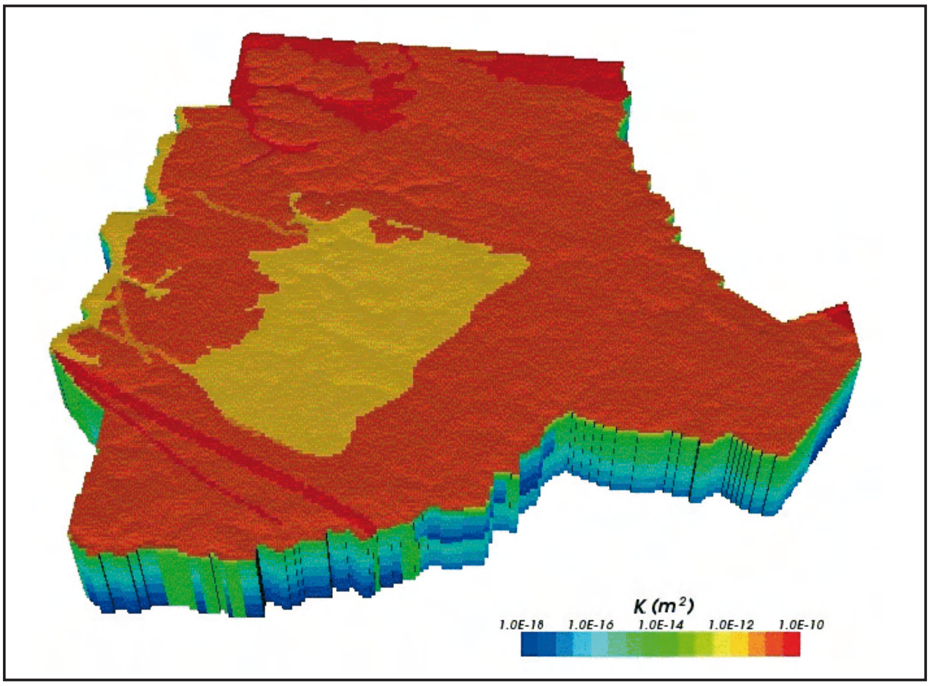
- integration of the various phenomena over large time scales.

These issues have been covered in numerous studies and applications, especially in the framework of the "Äspö Task Force" project, carried out in the context of an international cooperation agreement and based on the Swedish laboratory data. The various methods studied answer the questions raised and integrate site data into the various scales of time and space to be considered in the models. The methods are based on the explicit inclusion of granite fracturing data collected at a site. Due to the development of methods of modelling a granite medium as "fracture networks", site data can indeed be introduced into the modelling process without drastic simplification from the earliest stages of simulation. The simplifications form part of a gradual, iterative process designed to compare site data and modelling results throughout the stages of the site surveying.

Modelling process and site data

In a generic study context, Andra has carried out modelling exercises supported by knowledge acquired in the international framework and field data collected in France, especially at the Vienne site (1994-1996) studied by Andra or the Auriat site (Creuse) studied by the CEA (1980-1981). This has resulted in a typical outline of the modelling process to be adopted throughout the various exploratory stages of a site.

On both regional and massif scales, geological models represent the structure of a granite massif in its geological context. The models identify the various lithological units composing a granite massif and its surrounding formations. Major fracturing – regional or "local" faults – modelled by a deterministic approach, i.e. by establishing 3D geometry on the basis of geological surface mapping, geophysical surveys and boreholes drilled during exploratory work. Hydrogeological models in a "continuous porous medium" are established by integrating hydrogeological measurements from boreholes (pressure measurement, permeability, etc.).



Example of a 3D model showing the distribution of permeability and its evolution with depth

On the scale of the repository module, geological models include small fractures, characterised either from surface surveys or by underground structures. The geometry and distribution of these small fractures in a granite massif are processed in a probabilistic manner on the basis of site data. Processing groups the fractures into "families of fractures" with specific geological, hydrogeological and transport properties. Distribution laws, validated by inversion methods and by comparison with site data, deal with variability in the properties of fractures in granite on the scale of one or more repository modules in a probabilistic manner. …

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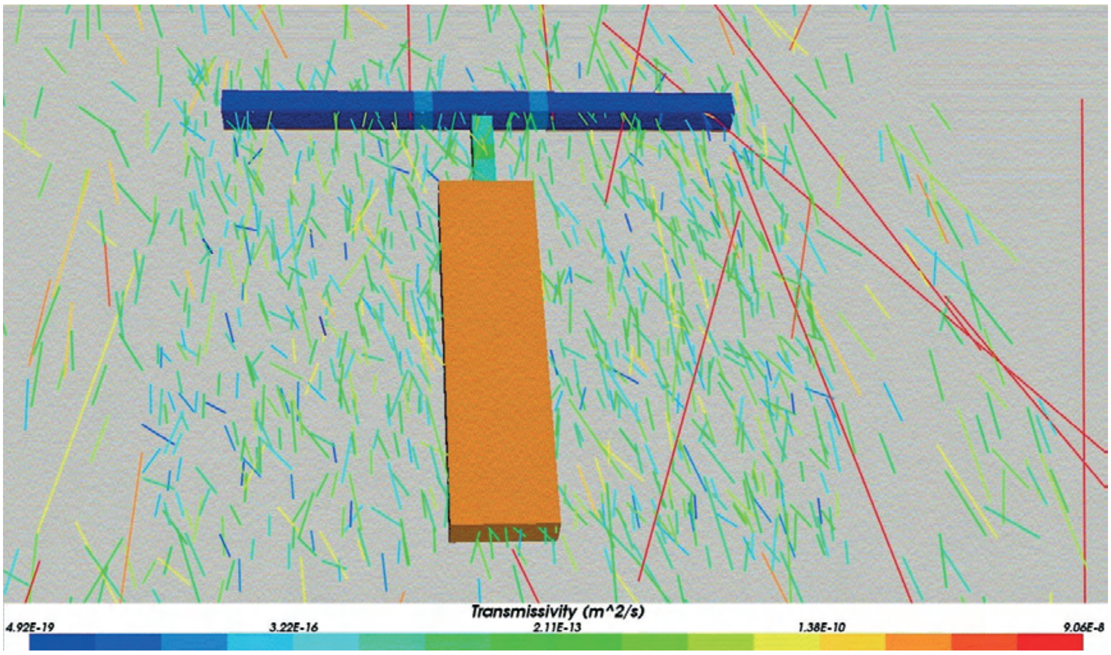


Fracture network on a module scale; intersections of fractures with a horizontal plane are classified by transmissivity

The various methods of integration guarantee continuity and provide a link for models on both regional and repository module scales. From a hydrogeological viewpoint, water flow balance and continuity in the distribution of hydraulic head gradients between the various modelling scales are the main elements ensuring that the various modelling scales are consistent with each other.

3.3.2 The input of hydrogeochemistry

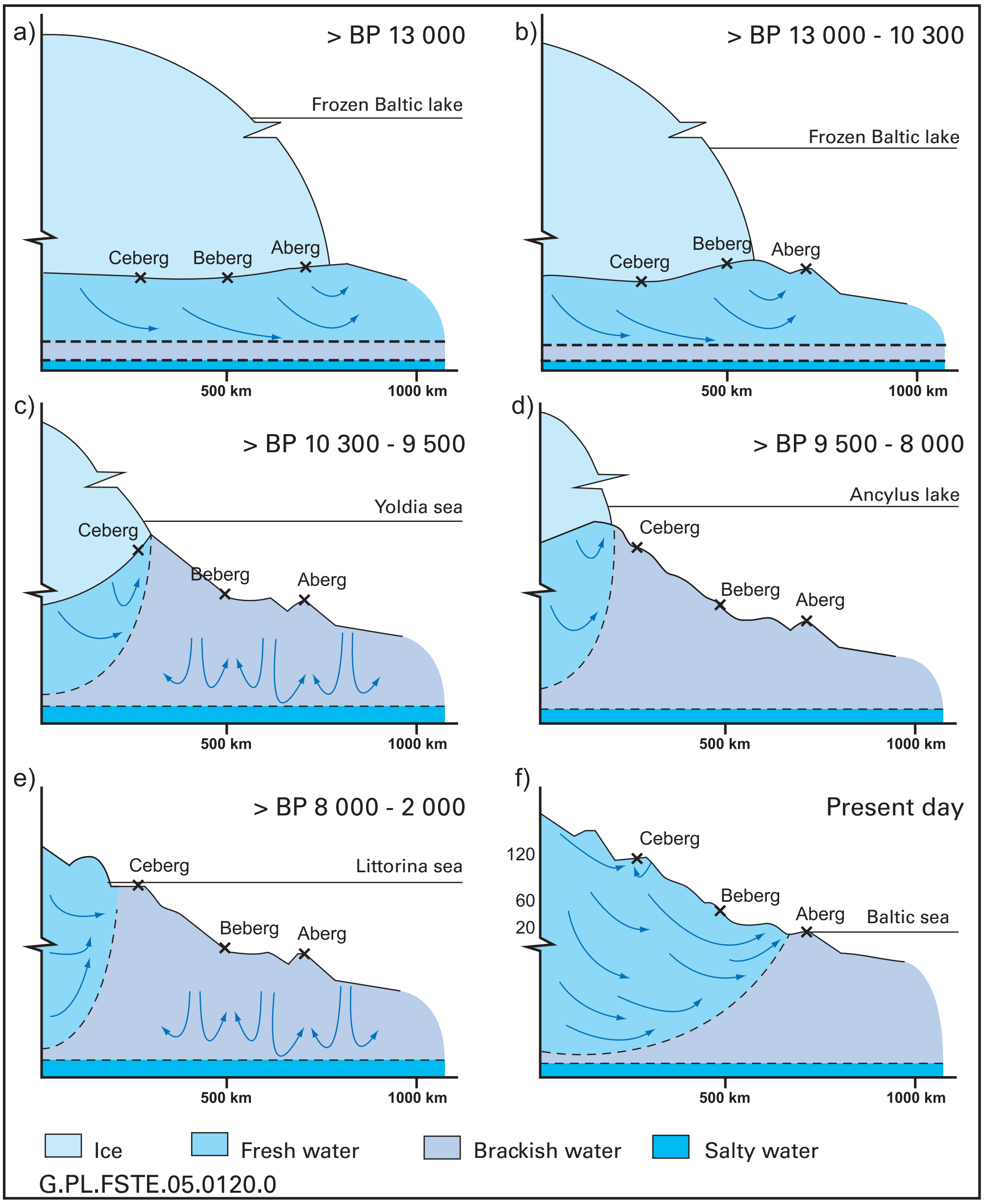
The composition of granite water reflects the chemical exchanges between the water, the granite rocks and fractures, and therefore the water circulations within the granite. Understanding and modelling these exchanges is a way of reconstructing their pathways.

The increase in water salinity with depth, often observed in granite environments, reflects the exchanges between deep, more ancient, water of a granite massif and the more recent shallower water. Isotopic evolutions in the composition of the water show the same tendency. This was observed at the Vienne site studied by Andra in France.

Successfully developed in Fenno-Scandinavia and Canada, methods of modelling exchanges between waters of different origins have made it possible to reconstruct the evolution in the chemical composition of granite water and its present distribution in a massif. Applicable in the French context, these methods provide elements required to validate hydrogeological and transport models to be produced on a site scale and over long periods.

Hydrogeochemical modelling of a granite site: the example of Äspö in Sweden

The geological and hydrogeological history of the Äspö region is dominated by quaternary glacial episodes which have controlled the paleogeography of the site with the presence, then the melting, of an icecap. There has been a succession of coastal sea and lake situations. The water circulating underground in the granite is therefore the result of a mixture of seawater, brackish water, water from melting ice and recent rainwater (figure below).



Postglaciation conceptual scenario of the evolution of the Äspö site (SKB data)

From the hydrogeochemical modelling methods developed from this paleogeographic outline, the evolution in the composition of waters of various origins and their current distribution in the granite massif was reconstructed. Model accuracy limited by the existence of a minimum proportion of 10% of a water of a given origin. The hydrogeochemical model therefore complements the hydrogeological models; it is notably used to validate the hydraulic properties of the granite on a site scale and hydrogeological models over large time scales

4 Geomechanical modelling

The considerable feedback relating to underground excavations in granite shows the feasibility of large and stable deep structures.

However, the construction of stable structures does not automatically mean the absence of any damage to the granite walls due to their excavation. Neither does it explain how would be the mechanical behaviour of the granite in the environment of a repository in response notably to thermal stress.

Understanding and modelling granite therefore also consists of providing an adequate description of the mechanical behaviour of the granite and its possible damage during the various phases of the disposal process. The consequences of this behaviour on the hydraulic properties of the massif and radionuclide transfer must also be assessed.

Therefore are needed:

- methods to characterise the granite massif studied from a mechanical point of view;
- digital simulation tools for the behaviour of the granite (fractured medium) in a repository.

4.1 Mechanical characteristics of the granite and data collection on site

The mechanical characterisation of a granite massif traditionally comprises two parts:

- characterisation of the mechanical properties of the rock, including the fracturing that may affect it;
- measurement of the natural mechanical constraints prevalent at depth.

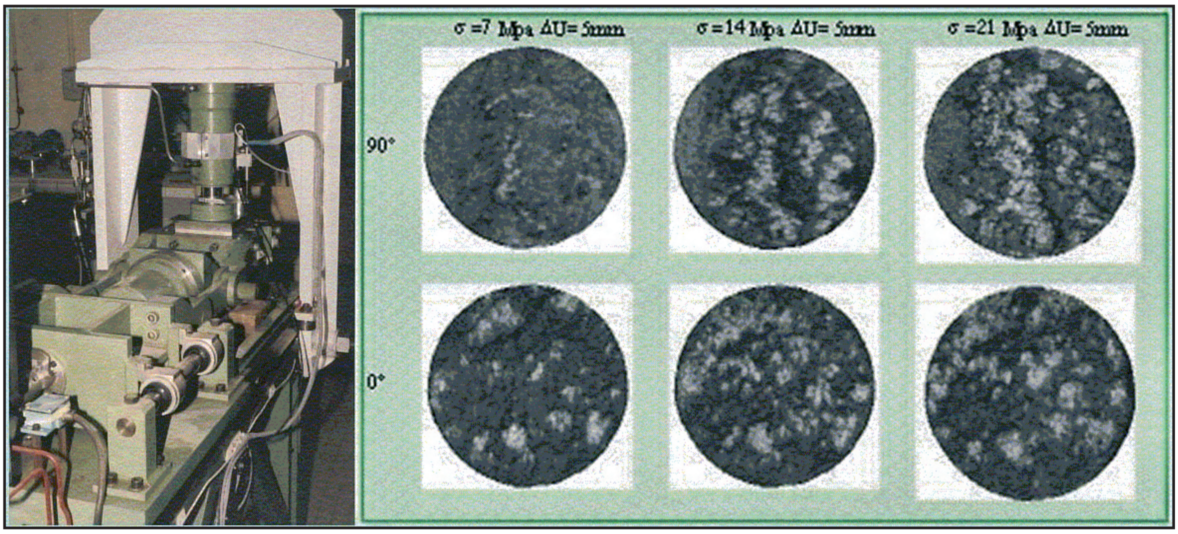
4.1.1 Mechanical characteristics of granite rock

Granite is a mechanically resistant rock[10], the mechanical behaviour of which essentially results from the massif fracturing.

Repository structures are to be located in rock with little fracturing; however, fracturing is characterised to ensure that it is not liable to weaken the rock around the structures. It depends on the “surface roughness” of the fracture and the nature of its minerals. Fracture strength is assessed by shear tests according to current experimental methods.

The numerous tests performed on samples on an international framework have provided a basis for the development of laws relating to the mechanical behaviour of the fractures according to their geometric and mineralogical characteristics. Full-scale *in situ* experiments are used to adjust the various coefficients used in the models on the scale of the studied structures. These were notably performed in the Swedish and Canadian underground laboratories.

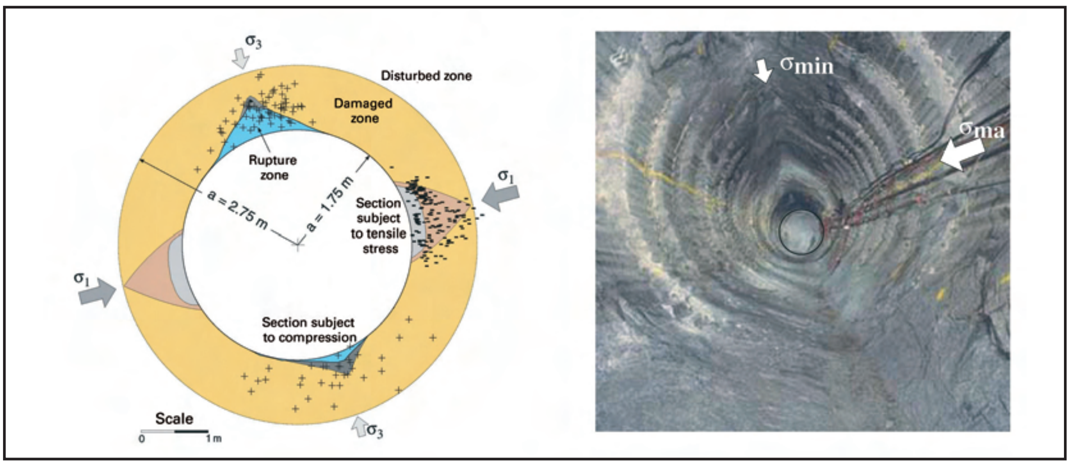
[10] Granite compressive strength is over 100 MPa; its tensile strength is over 6 Mpa.



Equipment used for shear tests on fracture samples in granite and photos of post-shear fractures surfaces (5 min) (Riss and al, 1997)

4.1.2 Natural underground stress in a granite massif

The mechanical stress state prevalent in an underground granite massif results from the weight of the overlying terrain and the geodynamic stress.
The sizing of a structure depends on the anisotropy of horizontal or vertical stresses underground. High stress anisotropy has, for example, been observed underground at the *Lac du Bonnet* laboratory in Canada. This corresponds to a quite specific situation: at this point, the granite massif below 300 m is not fractured and the tectonic stresses to which it has been subjected over its history could not have been released. The behaviour of drifts under such a configuration has been tested and their geometry adjusted. Mechanical models representing the behaviour of granite rupture under such conditions have been finalised.



Lac du Bonnet ***underground laboratory in Canada: damage to the granite wall of a circular drift subjected to a highly anisotropic stress configuration***

In the French tectonic context, the ratio between major horizontal stress and vertical stress is estimated at a value between 1 and 2. It shows a low anisotropy of underground stress and the construction of underground structures should be rather straightforward. This appraisal cannot be generalised, however, and must be validated by *in situ* stress measurements for each site.

Stress measurement techniques have progressed considerably in recent decades. These techniques include hydraulic fracturing tests performed in boreholes and adapted to granite which provide comparable values from one point to another of the massif. These tests consist of causing fractures to open in the rock through the injection of water under pressure. Open fractures are identified and characterised and, as a result, the orientation and value of the stresses are known. This type of test has been conducted in France and abroad; it enabled to develop measurement techniques and identify uncertainties linked to the inclusion of fractures initially existing in the rock in the processing and interpretation of the data.

4.2 Simulation of the mechanical behaviour of granite

Simulation of the mechanical behaviour of a fractured granite massif, under mechanical or thermal stress, calls on specific models focusing both on the behaviour of the rock matrix (continuous medium) and on the behaviour of the fractures as discrete elements. Development and validation work is still ongoing to determine effective solutions covering all aspects of behaviour of the rock massif.

The questions to be resolved stem firstly from the various scales and families of fracturing to be taken into consideration and, secondly, from the complex relationships between mechanical deformations of the fractures and changes to their hydraulic properties.

Thus, simulations are most often used to verify that the fields of deformation studied are of low amplitude, with no consequence at first sight on the mechanical, hydraulic and thermal properties of the massif.

For the design, dimensions are determined with safety margins and ensure that phenomena remain within the scope of the minor deformation field. The arrangements proposed for a repository in terms of the backfill, seal or swelling clay buffer are also means of limiting deformations in structures subjected to mechanical and thermal stress.

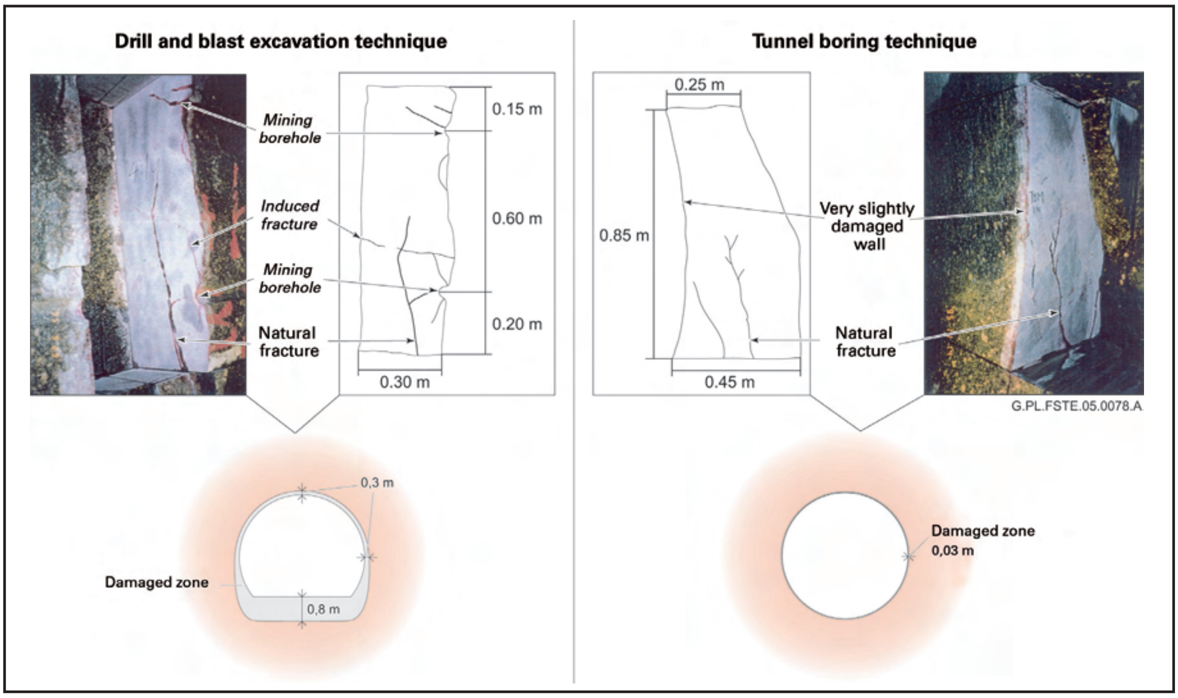
4.2.1 Modelling of mechanical damage to the granite walls of the structures

Stress concentrations may locally appear in the walls of the structures during excavation and cause damage to the rock and spontaneous flaking. Experiments conducted in underground laboratories have pinpointed the conditions under which such damage can occur, and tested the various digital models developed.

The models developed have provided the criteria with respect to occurrence of such phenomena; for example, relationships between the tangential stresses affecting the rock walls of the structures and the resistance of the rock measured by a uniaxial compression test. The various models, implemented on the basis a discrete fracture model or representing the granite in the form of grains ("particles"), are consistent and have led to the identification of uncertainties to be considered in structure design and safety analyse.

Experiments conducted at laboratories in Canada ("Room 209" and "Mine by experiment"), Sweden ("ZEDEX"), Finland ("Olkiluoto Research Tunnel") and Japan ("Kamaishi mine") have examined the creation of a damaged zone in the rock according to various methods of excavation (drill and blast, small diameter tunnel boring machine, etc.). They show that damage remains very limited (extending to less than one metre) in all cases and that it is possible to minimise it considerably by using boring methods (then a few centimetres extension).

Similarly, boring the granite for waste disposal vertical boreholes significantly reduces damage to the walls of the disposal structures. A highly detailed analysis of damage to the granite wall of drilled boreholes, carried out in the Olkiluoto research tunnel (Finland), has shown that damage is very minor and is reduced to destructuration of granite grains to a depth of one centimetre or less.



Damaged zone on the drift wall ("ZEDEX" experiment at the Äspö laboratory)

4.2.2 Coupled hydromechanical and thermo-hydromechanical models

The hydraulic properties of fractures, notably small fractures, depend on the stress state of the massif. The hydraulic transmissivity of the fractures is sensitive to normal stress exerted on the fracture planes. Local modification of the stress system applied here is therefore liable to change the hydraulic properties. This may be due to structure excavation or to the heating of the massif linked to the disposal of exothermic waste.

The simulation of the modifications to the hydraulic properties of a fracture network is complex both from a theoretical point of view and in terms of experimental validation. However, the various experiments conducted in France and abroad have identified the important parameters to be integrated into the simulations: geometry and mechanical properties of the fractures linked to the roughness of the fracture planes, the nature of the filling minerals at their hydraulic or mechanical openings, etc. Various behaviour laws have been proposed and digital models established.

International exercises carried out on this theme, such as the Decovalex or Benchpar projects which are notably based on the results of experiments in the Kamaishi mine in Japan, have concluded that mechanical models can provide the order of magnitude of the changes to the stress state and movements along the fractures of fractured granite. This defines the deformation system and field to be integrated into both the safety analyse and the design of repository architectures.

In particular, emplacing backfill and swelling clay buffers is an arrangement generally adopted for the disposal of spent fuel and exothermic C waste. Swelling clays contribute to the stability of the walls of the structures where heat-related stress impact is the largest.

5 Considering very long-term geodynamic evolution and climate change: geoprospective study

3

On the scale of several hundred thousand years, a granite massif and its environment are liable to undergo changes linked to internal (tectonic movements, earthquakes and volcanism) or external geodynamic phenomena (climate changes and surface erosion phenomena). The purpose of the studies is therefore to identify the phenomena that may be involved in the various timescales to be considered in the evolution of a repository.

Since there is no particular study site, this work had two objectives:

- to identify the factors of geodynamic evolution to be considered in site exploration in order to comply with the recommendations of RFS III.2.f. in terms of long-term stability;

- to assess the possible consequences of the evolution of a granite site on the environment of a repository, especially from a hydrogeological point of view.

The analysis was conducted generically on the scale of mainland France, with a focus on the granite regions of the Massif Central and the Armorican Massif. From a methodological point of view, the evolution of these regions over hundreds of thousand years in the future is assessed on the basis of the geological history of the last ten million years. This period includes the quaternary period (two million years) characterised by the installation of the current climate system.

5.1. Internal geodynamic phenomena

In terms of internal geodynamics and plate tectonics, the granite regions of the Massif Central and the Armorican Massif are situated away from active zones. They are therefore characterised by deformations of very low amplitude, even on the scale of several hundred thousand years. Vertical ground movements are very weak and seismic activity is minor.

Plate tectonics: France outside major deformation zones

The lithosphere, the solid, outer layer of the earth, is divided into a few vast domains ("plates"), the internal deformation of which can be considered negligible on this scale, separated by narrow zones where deformations are concentrated. These lithospheric plates move in relation to each other.

On this scale, France belongs to the Eurasian plate, bordered by the African plate to the south and the Atlantic opening to the west. On the scale of plate tectonics, deformations are concentrated in Alpine and Mediterranean zones bordering the African plate, as illustrated by the distribution of strong earthquakes recorded there. The granite areas of the Massif Central and the Armorican Massif are located away from these areas of major deformation and are therefore protected from significant tectonic movements on a scale of several hundred thousand years.

5.1.1. Seismicity

A geodynamic context showing very little activity does not equate with the total absence of any seismic manifestation, in other words earthquakes.

Numerous studies have been devoted to the assessment of the "seismic hazard" in France and have notably led to the seismotectonic zoning of the country. For disposal studies, the assessment of the seismic hazard pools together the data recorded regularly over decades ("instrumental seismicity"), the results of research over the historical periods ("historical seismicity") and the paleoseismic field studies aimed at detecting the trace of strong earthquakes from ancient times (thousands to hundreds of thousand years) in order to evaluate the intensity and possible recurrence. In this evaluation, the granite massifs of the Massif Central and the Armorican Massif are located in zones of low or moderate seismicity. In such a context, the seismic hazard is not a repository dimensioning factor. Indeed, it is often observed that earthquake impact is less pronounced underground than on the surface. The "free" surface of the earth is totally exposed to the effects of the seismic waves originating underground, whereas the length and frequency of the seismic waves are such that they cannot generally produce significant movements in the underground rock or structures.

The long-term evolution of seismicity is in relation with the kinetics of plate tectonics. With no foreseeable change on the scale of several hundred thousand years, no significant evolution in the seismicity level is to be considered for the future.

5.1.2. Volcanism

Volcanic formations exist in the central and eastern parts of the Massif Central. Geologically, volcanic activity reached a peak some 20 million years ago. Volcanism was still active locally in the quaternary period (2 million years).

If the actual cause of this volcanism is debated within the scientific community, it appears that the eruption points remain confined to precisely identified regions: the *Chaîne des Puys, Ardèche* volcanism for the geologically most recent events (less than 100000 years ago). Bearing in mind the very slow dynamics of these mechanisms, the creation of new volcanic regions on the scale of the next million years can be considered as quite inconceivable.

5.1.3. No notable evolution foreseeable on the scale of several hundred thousand years

All in all, the slow geodynamic evolution of the granite regions considered in the French geological context means that the consequences on a granite site are limited.

For all the granite massifs, no evolution is foreseeable on a ten thousand year-scale which meets the RFS III.2.f requirement which recommends that *"for a period which must be equal to at least 10000 years, the stability [of the site] (which includes a limited and foreseeable evolution) must be demonstrated".*

On the scale of a hundred or several hundred thousand years, the geodynamic context of the considered regions (Massif Central and Armorican Massif) indicates that a very slight evolution in a granite site is foreseeable for the majority of the granite massifs: indeed, underground stress changes are too slight to cause any changes to the hydraulic properties of the faults and fractures. In the case of a few granite massifs, particular situations linked to the proximity of major seismic faults (such as along the South Armorican shear zone) or volcanic activity (Massif Central), may require specific examinations.

Beyond the period of a few hundred thousand years, the consideration of the geodynamic evolution cannot simply be based on general factors. It must be specifically studied for each considered massif. However, a repository site located away from the major regional accidents or a few zones of potential volcanic activity (and thereby complying with the recommendations of RFS III.2.f), would most probably be subjected to slight local modifications on the timescales considered.

5.2 External geodynamic phenomena: erosion and climate change

Erosion is, in the long term, the main factor liable to alter the environmental conditions of a repository site. This erosion is primarily caused by the hydrographic network: rivers, streams, etc. It is the result of both ground movements and climate change.

Climate change

Climate change is a natural component of the earth's evolution. For almost 2 million years, glacial and interglacial periods have alternated at the latitudes of the French territory. The last glacial episode reached its peak 18000 years ago.
The astronomic climate theory links climate change to oscillations in the earth's movement around the sun. As a result, future climate change can be forecast with a return to new glacial cycles expected on a scale of around one hundred thousand years. It is also possible to appraise the possible consequences of human activity ("greenhouse effect") which would tend to delay this glacial recurrence.

Assessments made in various regions have led to generally similar estimates of the order of *5 to 20 metres maximum per 100000 years* for river valleys incision. Erosion rates on plateaux are much lower. These erosion phenomena, especially valley carving, are liable to change underground hydrogeological gradients and the pathways of the hydrogeological flows toward modified surface outlets. In connection with the recurrence of glacial climates, the formation of permafrost on the upper and surface layers of the granite massif can also temporarily modify water infiltrations and their migration within the massif.

Limited consequences for a deep geological repository

Generally, the changes foreseeable *on a scale of ten thousand years* are very slight for all granite massifs in France, with no significant impact for a deep geological repository.

On a scale of a hundred or several hundred thousand years, foreseeable climate change may, at certain sites, modify the water infiltration fluxes into the massif and the hydraulic gradients. This would notably be the case of coastal sites liable to be affected from a hydrogeological point of view by the retreat of the sea in glacial periods. It may also be the case of some Massif Central sites with rather deep permafrost (200 to 300 metres).

Beyond a period of a few hundred thousand years, the changes to be taken into consideration and their corresponding uncertainties may be greater, especially with regard to flow pathways between underground and surface. They concern particular situations such as that of the granite massifs of the Massif Central which drain towards the Mediterranean and which are liable to be affected, in the very long term, by more intense erosion phenomena than those draining toward the Atlantic side. Such situations should be examined on a specific basis to check whether foreseeable evolutions are likely to put at stake the environmental conditions favourable to a deep geological repository.

Dossier 2005
Granite

Description of repository design in a granite medium

4

The principles behind the design of a repository in a granite medium have been described in chapter 2: an architecture that takes advantage of the favourable properties of granite, engineered structures with complementary and redundant functions to those of the geological barrier, a dimensioning that limits the disturbance of the granite medium and that takes into account the variability of the characteristics of French granites.

This chapter presents a description of the repository concepts as proposed by Andra. Since this study was carried out in a generic framework, it cannot provide a precise description of the architectures that could be defined only for any given site. These selected concepts are possible solutions which feasibility is confirmed in technological terms. These reference concepts take also into account the phenomenological and safety analyses that have been conducted sufficiently systematically to ensure that all of the issues, relating to the design of a repository in a granite medium, have been examined.

The principles of the general architecture of a repository are described, particularly the arrangements that would allow it to be adapted to the geological configurations likely to be encountered in the French context.

The technical options adopted for the disposal of each of the categories of waste are then described, together with the components of the various repository zones used as a reference in the studies (package, cell and repository module).

In the last part, issues relating to the reversible operation of a repository in a granite medium are examined. As a preliminary approach and at this stage of the project, it was checked that the feasibility of the various planned operations complying with the reversibility rationale of the disposal management cannot be ruled out.

1 The general architecture of a repository

As a general rule, a repository includes surface installations, structures providing access from the surface to the various underground installations: connecting and reconnaissance drifts, shared infrastructures and repository modules.

1.1 Surface installations

The surface installations include the buildings for primary packages reception, the workshops for preparing the repository packages and the buffer storage facilities for controlling the throughput rates of industrial processes. The installations also include standard industrial equipment used for building and operating the repository's underground installations. In particular, the broken rock derived from excavating the underground installations is stored on a dump and will then be partly used as backfill material.

1.2 A general architecture for underground installations adapted to the granite structure

In terms of long-term safety, the architecture of the underground installations is mainly designed to take advantage of the *favourable properties of granite*, especially its mechanical strength and its low permeability in the "blocks" where it is not or only slightly fractured.

To ensure that these architectural arrangements are effective, even in case of partial failure, the structures are backfilled and sealed by devices that fulfil *complementary and redundant functions with those of granite*.

The proposed architectural arrangements also aim at reducing the disturbance to the properties of the granite medium, which could affect its confinement performance.

The structures connecting the surface to the underground installations (shafts or ramps) or between repository modules (connecting drifts) provides the transfer of the various material throughputs: those related to works (rock excavation and building materials), the ventilation air and the waste packages to be emplaced. The distribution and the number of connecting drifts are determined to ensure a fully safe co-activity of both construction works and (nuclear) operation in the repository. By principle, simultaneous construction and operation activities in the same drift are ruled out.

The proposed architectural arrangements ensure the reversibility of the repository's operation, i.e. the possibility of retrieving waste packages, acting on the repository management process and being able to change installation design.

1.2.1 The general architectural arrangements

In their principles, the architectural arrangements studied can be applied to all French granites. However, on a given site, it may be necessary to define architecture and dimensioning that take into account the specific characteristics of the considered granite formation.

4

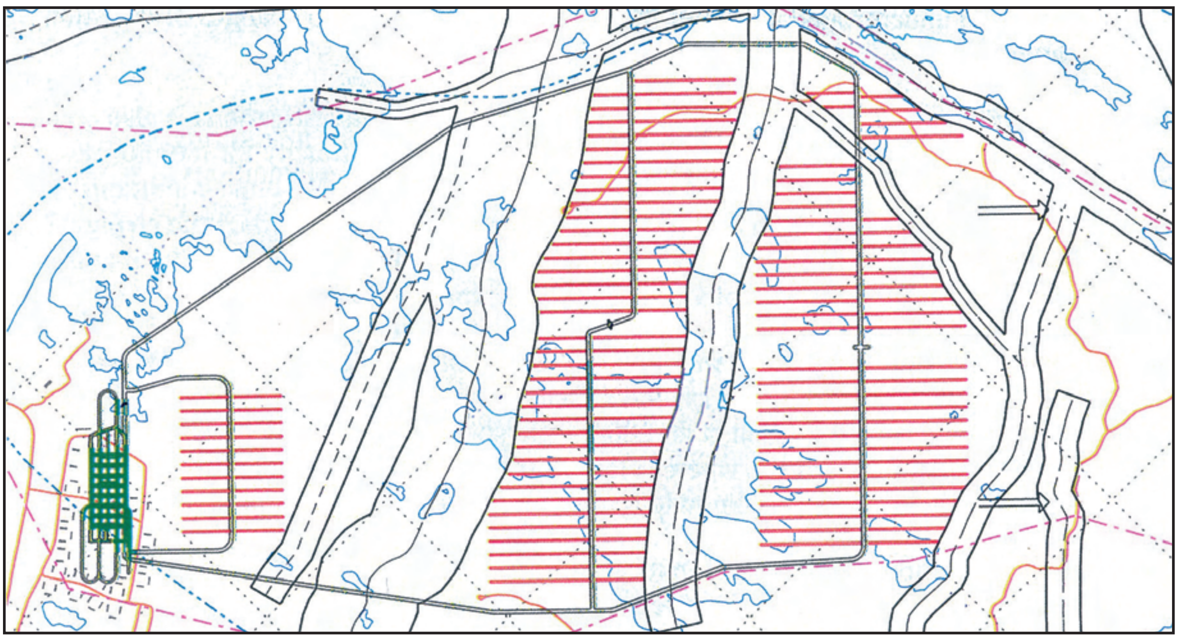
- **A modular architecture adapted to the fracturing of granite**

The general architecture of the underground installations is adapted to the structure of the surrounding granite. The repository modules are installed in "blocks" of granite located apart from water conducting fractures. A buffer zone of undisturbed rock of several tens of metres (depending on the local characteristics of the granite) is kept between modules and fractures. The distances between modules are generally of the order of hundred metres. The general architecture of a repository depends on the distribution of "blocks" in the granite massif hosting the repository.

The repository zones which include the repository modules for the same category of waste (B, C), or spent fuel if the need arises, are distinct.

To prevent interactions, especially chemical interactions, between waste packages of different types, each repository module will only include waste of the same type. For example, the B waste containing organic matter is disposed of in dedicated modules.

The modular principle of the repository architecture has been adopted in a similar way at international level by the various organisations conducting studies on the granite medium: Sweden (SKB), Finland (Posiva), Canada (AECL), Spain (Enresa), etc.



Modular architecture of the repository studied by SKB (Sweden)

Generally speaking, a modular architectural design of the repository, through its compartmentalisation, increases the safety by reducing the consequences of any possible failures at the module level. It is also an important factor for reversible management, because it provides the possibility of a phased approach for the geological survey, building and closure operations of the repository.

• The possibility of multi-level architecture

A granite formation generally provides a vast volume of rock with a depth of between 300 and 1000 metres, for a geological repository. This means flexibility to adapt the architecture to granite fracturing. Architectures on several levels are therefore possible, as studied in Sweden for the theoretical "Aberg" site, which was modelled on the basis of the Aspö underground laboratory data.

The analysis of the advantages and constraints of two-level architecture has underlined its interest: a distance of about 100 metres between each level would prevent thermal interactions between the C waste or spent fuel repository modules and would ensure the compliance with the maximum temperature criteria in the disposal cells.

• Structures connecting the surface and underground facilities (shafts or ramps) installed in relation to the local hydrogeological context

Shafts or ramps could be envisaged to connect the surface to the underground installations. They are generally designed as a complementary feature in the repository design. For example, in Finland, the "Onkalo" reconnaissance facility, which is likely to become an access to the waste repository, has a ramp as main connecting structure between surface and underground.

The number and the dimensioning of the shafts and ramps are adapted to their specific transfer functions and corresponding throughput rates: the evacuation of the excavated rock, transfer of materials, disposal packages, personnel and ventilation.

In terms of the long-term safety, these structures are installed in relation to the local hydro-geological context to prevent any drainage from the repository toward the surface. The access to the shafts and/or ramps can also be grouped together in the same zone to limit any hydraulic effects between structures and achieve greater control over the hydraulic regime in the repository.

• A systematic backfill of the structures and multiple seals

The connecting structures between surface and underground, and the repository drifts could intercept water conducting fractures. They are therefore backfilled to protect the repository modules from possible water circulation. Seals installed at key points in the drifts also prevent water arrival that could come from fractures intercepting drifts. The backfill and seals therefore have complementary and redundant functions in terms of long-term safety. Their detailed specifications depend on the characteristics of the granite site. In the context of such generic granite studies, both systems have been examined and adopted for all the repository zones.

Backfill is systematically proposed in the surface-underground connecting structures and in the repository drifts. In principle, the closer the drifts to the waste, the greater the requirement of the backfill hydraulic performance. In the repository modules, the drifts are backfilled with a low permeability material. Outside repository modules, the permeability of the backfill in the drifts and surface-underground connecting structures is specified in relation to the conductivity of the fractures likely to be intercepted and of the damage to the rock caused by excavation.

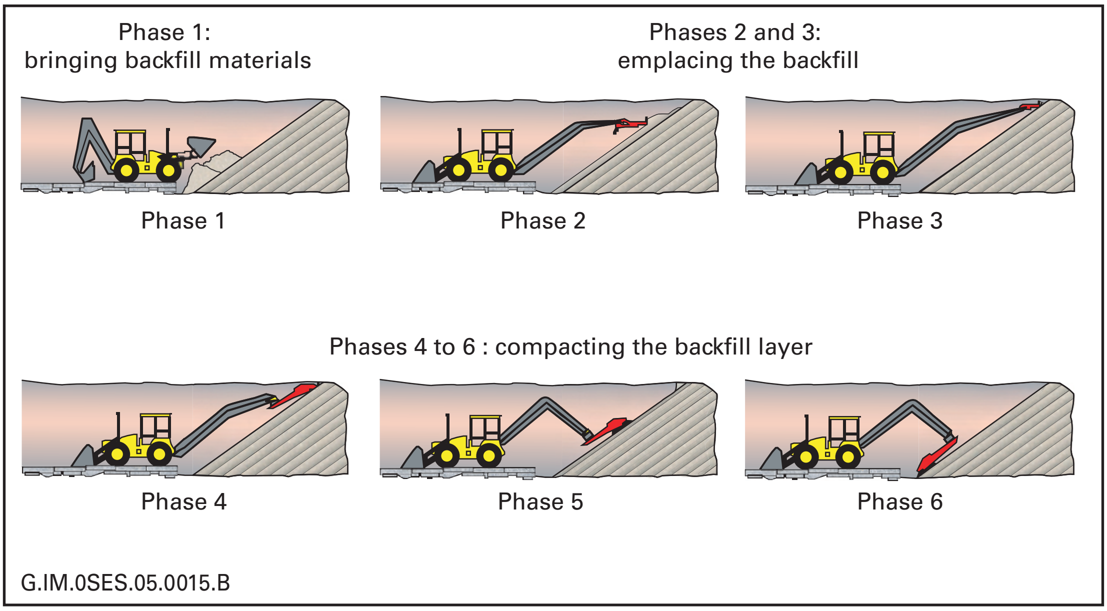
Very low permeability and long-lasting seals are systematically planned between the water-conducting fractures and the repository modules installed in relatively low permeability "blocks" of granite. Depending on the site configuration, seals could be planned in the surface-underground connecting structures or the repository connecting drifts to limit the direct water arrival coming from the superficial and more permeable part of the granite.

The design of the seals and backfill favours materials that reduce any disturbance to the properties of the fractures, most likely pathways for the transfer and retention of radionuclides in the granite. Notably, the concrete seal abutments could be made of low pH concrete to reduce the water alkalinity in the repository.

Backfill and seals are two complementary and redundant means for protecting the repository structures from advective water circulation. The techniques for closing the connecting structures were experimented in underground laboratories outside France, especially at Aspö (Sweden) and *Lac du Bonnet* (Canada). These experiments show the technological feasibility of such systems and specify their performance level.

Building a low permeability backfill

A backfill consisting solely of crushed granite cannot, even after compaction, be a sufficiently low permeability barrier to fulfil the required hydraulic function. Furthermore, a close contact must be ensured between the backfill and the rock, especially in drift ceilings, so as not to create an effective pathway along this interface.
To meet these requirements, the proposed technical option consists of a backfill partially made with swelling clay (bentonite). This proportion, from 10% to 30%, can be adapted to the site hydrogeology and adjusted in relation to the drift situation in the general architecture of the repository. The swelling clay contributes both to the low permeability of the backfill and, through its swelling, to the contact with the rock. The difficulty of backfilling a drift ceiling has been resolved by SKB that has developed a machine with a vibrating plate fixed to a mobile arm. Compaction results in backfill densities from 1.7 in the core to 1.5 at the outside, which are appropriate for obtaining low permeability (permeability of the order of 1.10^{-12}m/s for a density of 1.7; permeability of the order of 5.10^{-10}m/s for a density of 1.5).



Principle of installing a low permeability backfill

Installing very low permeability seals

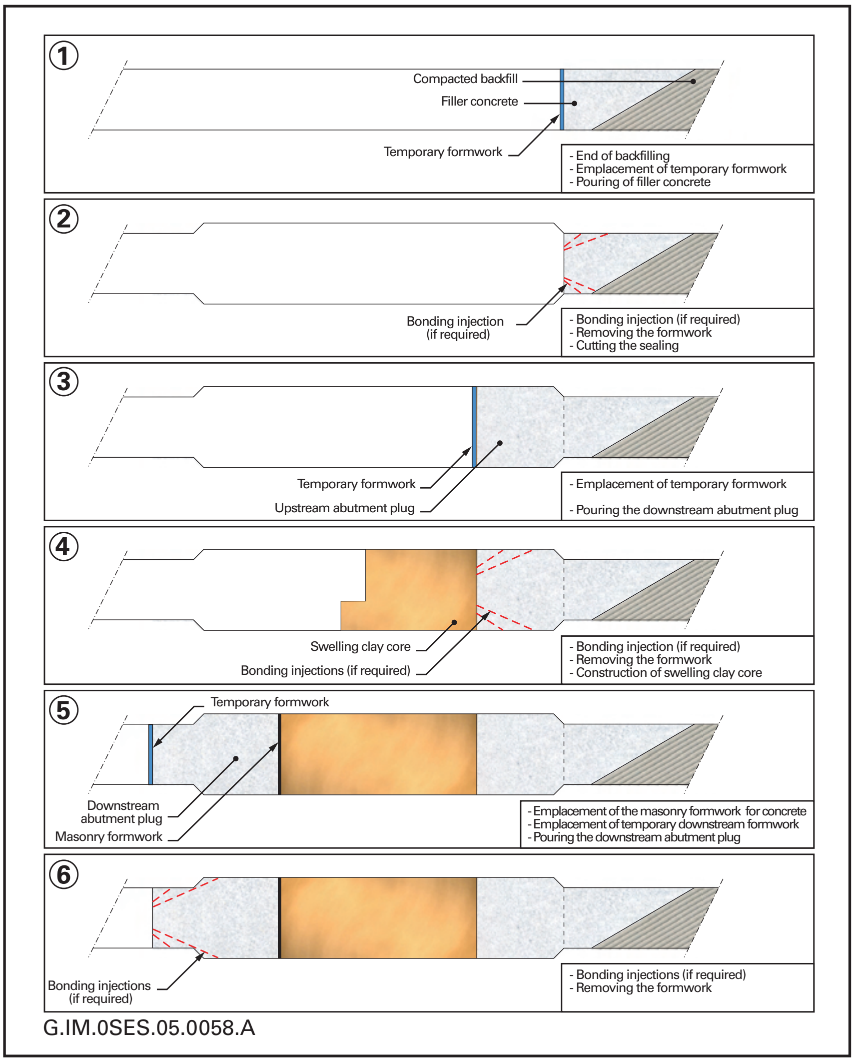
In addition to backfill that is systematically performed in the drifts, seals are installed at particular points in the repository, especially in between significant water-conducting fractures when intercepting drifts and repository structures.

The seals consist of a core of bentonite swelling clay 10 to 15 metres long. The clay core is supported by two concrete abutments that take up the forces caused by bentonite swelling and maintain the core under pressure.

The feasibility of constructing a clay core has been demonstrated by several experiments in underground laboratories outside France. It is done by stacking up interlocking clay "bricks". The full scale "Tunnel Sealing Experiment" (TSX) experiment, performed in the *Lac du Bonnet* laboratory (Canada), evaluated *in situ* the seal hydraulic performance: the overall measured permeability was very low, of the order of 10^{-11}m/s. The experiment also emphasized the importance of the quality of the contact with the rock.

To ensure a close contact between the sound rock and the clay core, it is planned to cut the seal zone into the rock wall beyond the area of damage caused when excavating the drift.

Building concrete abutments does not mean any particular problem. Preventing the possible degradation of the clay core performance, caused by concrete alkalinity, can be achieved by using low pH concretes, as it was tested *in situ* in the Canadian underground laboratory.



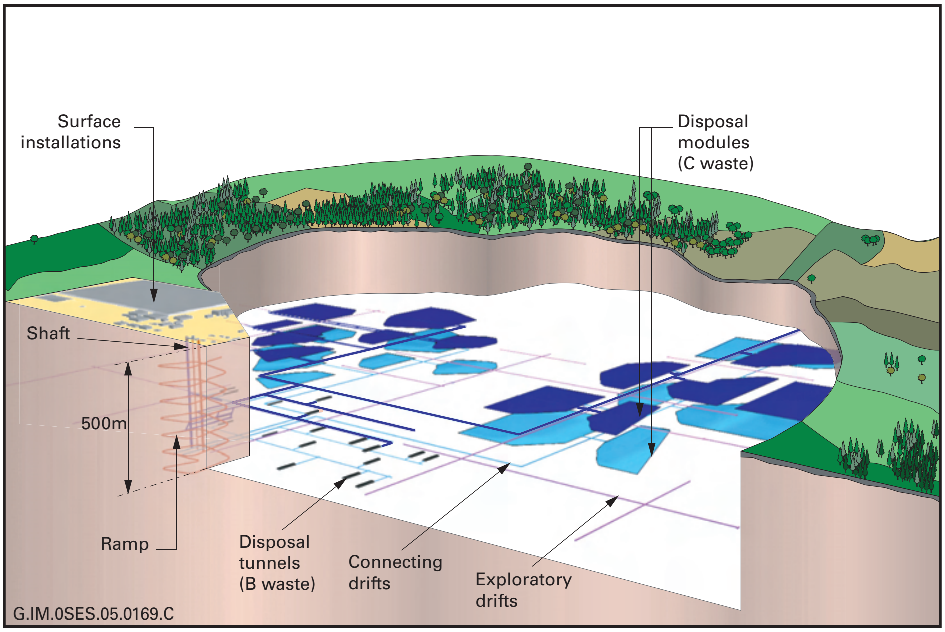
Principle of the seal construction

1.2.2 The reference architecture and ways of adapting to different geological site configurations

• **The reference architecture**

The repository architecture adopted as reference is an architecture on two levels that can be adapted to the largest number of configurations in the French geological context (figure below). The two levels are about 100 metres apart.

An arrangement on two levels reduces the repository footprint and makes easier the "ongoing" reconnaissance of the granite while excavating, in order to position the modules. This concerns not only the development of surveying instruments but also data interpretation and geological modelling of the granite. In most geological configurations of French granites, knowledge about one level is in fact transposable, at the scale of a hundred metres, to the neighbouring level.



View of the whole repository in a granite medium: surface installations and underground installations on two levels

The number of surface-underground connecting structures depends on the choice of the technical solution. An "all shafts" solution would reasonably require 4 shafts (about 10 metres in diameter). A solution with a ramp (6 to 8 m wide) for the construction operations would require 3 shafts.

The underground drift network includes a "bundle" of several parallel drifts (3 to 5 depending on the repository zones) to separate the throughputs associated with construction activities from those of nuclear operation activities throughout the disposal processes.

• **Adapting to different geological site configurations**

Several components can be adapted to the various configurations of French granite sites.

The repository zones for various waste categories can be distributed at different depths to suit the site thermal conditions. They can be more or less far apart from each other depending on the large-scale fracturing of the site.

The surface-underground connecting structures can be more or less grouped together depending on the distribution of the repository zones and the site hydrogeology. The choice between shafts and ramps for transferring materials and packages can also depend on the site conditions (topography, characteristics of the superficial parts of the granite, etc.).

Finally, the number and the distribution of connecting drifts depends on the installation of the various repository zones in the granite and the depth of the repository levels.

2 The B & C waste and spent fuel disposal concepts

For all the waste, the design of the repository modules is based on the principle of installing the cells in very impermeable granite rock, apart from water-conducting fractures.

However, the footprint to be considered in the repository general architecture depends on the various types of waste, in particular their volume and their thermal properties, and is more or less controlled by the distribution of water-conducting fractures in the granite. Because of heat production, spent fuel requires large footprints. This is also, to a lesser extent, true for most C waste. B waste, that are not or only slightly exothermic, are suitable for a more compact disposal, needing a smaller footprint.

Furthermore, the diversity of the physico-chemical nature of waste (bituminised sludge, glass, metallic waste, etc.) means a variable capacity to retain radionuclides. These differences lead to more or less severe requirements in terms of confinement performance and durability, for waste packaging and for disposal cell engineered barriers.

Thus, waste packages, engineered barriers, backfill and repository module drift seals are therefore designed in a specifically manner according to each type of waste. They depend on the module location and construction in the granite, and the physico-chemical nature of the waste.

2.1 The disposal of B waste

The volume of B waste, about 80 000 m^3, leads to adopt solutions which can ensure a rather compact disposal of packages in the cell. This limits the number of cells, the volume of rock to be excavated and the number of very low permeability granite blocks needed for installing the disposal drifts (tunnels).

Furthermore, the diversity of waste means that only those waste packages that are compatible with one another can be emplaced in the same cell. This compatibility concerns the chemical nature of the waste, their thermal release and possible gas production.

Several types of grouping are possible:

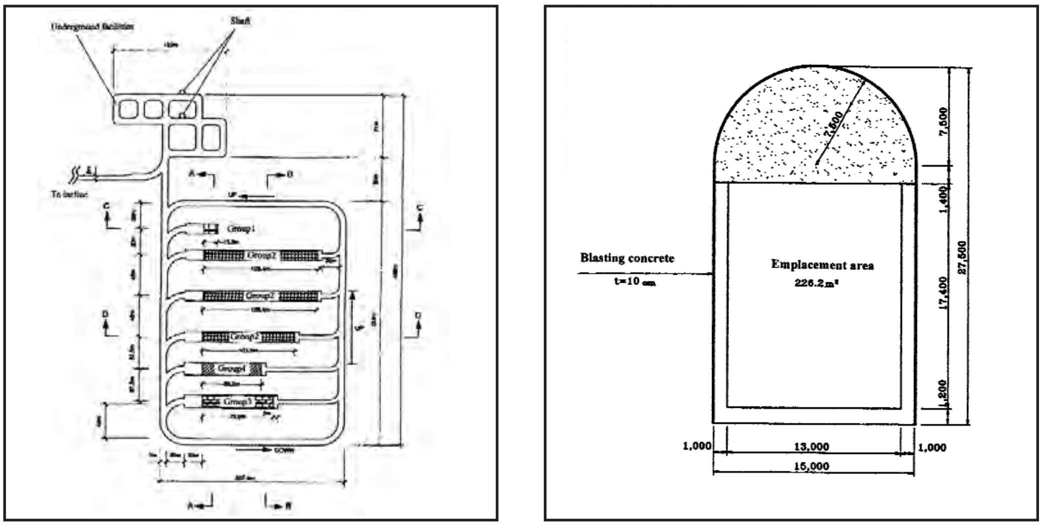
- Cells with waste containing organic compounds or organic matters which are likely to produce complexing species when altered by water.
- Bituminised waste (B2) cells.
- Cells with waste free from organic matter but producing hydrogen by radiolysis of the concrete in the cemented primary packages, or conditioned in a concrete shell (most B3 and B4 waste),
- Cells containing slightly exothermic waste (B1 and B5) free from organic matter and not giving off gas.

Therefore, starting from a standard design for the disposal cell, waste dimensioning and packaging are adapted to each of these cell configurations.

2.1.1 The reference B waste disposal cell: tunnel for stackable packages

Various architectures have been envisaged for B waste cells. The aim at compactness has led us to examine the possibility of cells in the form of very tall (about 30 metres) vertical, cylindrical "silos" like those chosen for the short-lived waste repositories in Finland (Olkiluoto and Loviisa) and Sweden (Försmark). This option has not been chosen at this stage, because of the difficulties relating to very tall stacks (stability, risk of packages falling when being emplaced, etc.).

Horizontal architectures with tunnel-shaped cells have been favoured. This option also studied by Japan and Sweden for their long-lived waste similar to B waste.



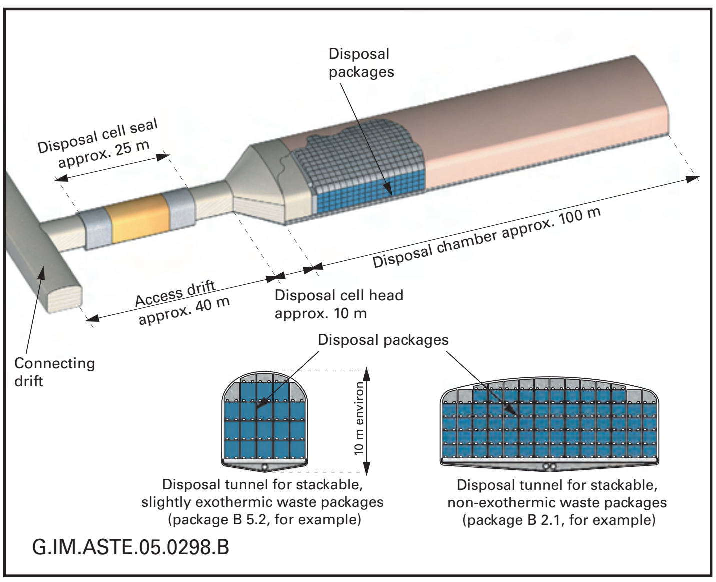
General architecture of a deep TRU waste repository in crystalline rocks and disposal tunnel for bitumised or low-level waste (Japan)

- **B waste disposal tunnels**

The solution proposed for the B waste cell is a horizontal tunnel in which are stacked several layers of disposal packages. The tunnels are dead-ended: their end, limited by the granite rock does not open onto a drift. This arrangement reduces water circulation in the disposal cells.
The tunnel lengths, varying from 70 to 200 metres, are adapted on one hand, to the characteristics and inventory of the various types of waste and, on the other hand, to granite fracturing.
Because of the mechanical properties of granite, the tunnels cross section can be quite wide (width of 10 to 20 metres) and this helps make the repository compact.
For the slightly exothermic waste (B1 and B5), design also takes into account temperature criteria relating to both the control of long-term behaviour of concrete packages and the behaviour of radionuclides in the cell. The maximum temperature adopted is 70°C (without taking into account heat evacuation through cell ventilating).

The tunnels are about ten metres high; about ten metres wide for slightly exothermic waste (B1, B5) and about twenty metres for non-exothermic waste (B2, B3).

The disposal tunnels are excavated with standard mining methods using explosives (drill & blast), the "soft blast" technique reducing damage to the rock walls. Tunnel height may require a “two-stage” excavation.



Disposal cell for stackable B waste packages

The disposal chamber is an irradiated volume in which the packages are handled by remotely-controlled equipment. The head of the cells is equipped with a radiological protection air-lock (dual-gate system) for handling operations.

If necessary, it is possible to place suitable concrete structures between the packages and the cell ceiling so as to fill the remaining spaces and protect the upper levels of the stacked packages from any dripping water.

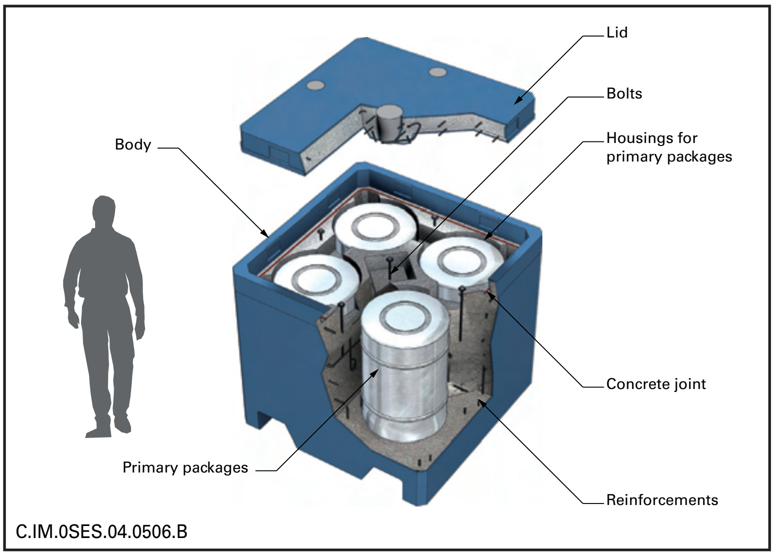
When the cell is closed, the volume occupied by the airlock (dual-gate system) is backfilled; the access drift is sealed by a very low permeability swelling clay plug.

• **The disposal packages**

The design of the disposal packages is identical to that proposed for the repository in a clay medium.

Operations simplification and package retrievability have led to the design of standardised parallelepiped-shaped concrete packages.

Depending on the initial packaging of the waste, the disposal packages contain 1 to 4 primary packages. They weigh between about 6 and 25 tonnes and their dimensions are between 1.20 and 3 metres. The disposal packages are handled by forklift truck type machine. Their design enables them to withstand dropping while being stacked in several levels in the disposal tunnels.



Standard disposal container

The body and lid are prefabricated (using a moulding technique) in reinforced or fibre concrete, whose formulation is chosen to give them a high performance and long durability.
For waste producing hydrogen, the concrete overpack is designed to evacuate the gas and prevent any excess gas pressure that could damage the packages.

For the more radioactive waste not giving off gas (B1 and B5 packages), a container, with a reinforced confinement capacity of at least tens of thousands of years, has been studied. This performance requires a very low permeability envelope, a very low diffusion coefficient at the scale of the packages and a long-term mechanical integrity.

Several solutions have been examined: they are based on the use of a single concrete formulation for all the components of the packages, reinforcement through fibres and without rods. Feasibility was achieved through the realisation of demonstrators of such container. The properties in terms of performance are still subject of a test and qualification programme in 2005. The Japanese agency RWMC has also studied a similar solution and has successfully produced a demonstrator.

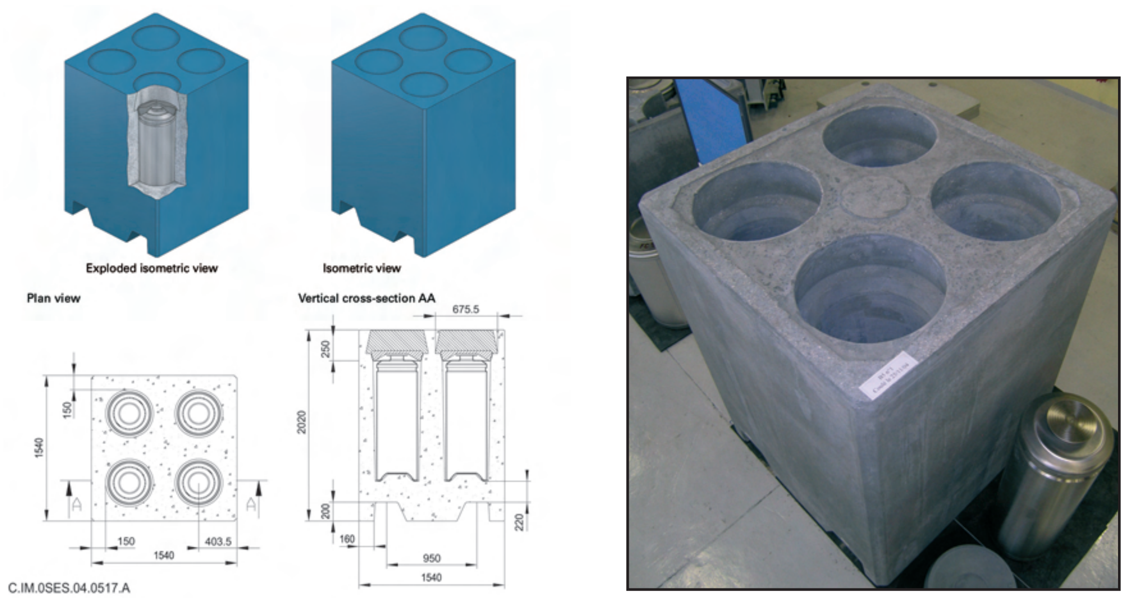
These results confirm the possible perspectives for the design of concrete B waste disposal packages having the required hydraulic and transport performances. They demonstrate the possibility of obtaining a long-lasting confinement of about ten thousand years. In a granite medium, this helps to meet the robustness requirements of the repository in terms of long-term safety, for a large number of site configurations in the French geological context.

The container with a reinforced confinement capacity

The analysis of the distribution of radiological activity between packages has demonstrated the interest of studying the feasibility of a disposal container with an additional confinement performance for certain packages (B1 and B5.2) which account for a large proportion of the radioactive inventory of B waste for certain radionuclides (niobium 94, zirconium 93, caesium 135, etc.). The container must last for a very long time (at least 10 000 years) and provide mechanical resistance over the same period.
The increased confinement performance uses the hydraulic and transport properties (diffusion, retention) of the concrete to limit and delay the migration of radionuclides released by the primary packages.
The container includes:

- a prefabricated body with 4 housings adapted to the size of the primary packages,
- 4 prefabricated individual plugs that close the housings once the primary packages have been inserted and provide the shuttering for pouring the individual lids,
- 4 concrete lids that are poured above the 4 housings.

The confinement performance is essentially determined by that of the body and by the quality of the binding between the poured lid and the prefabricated body (BHP "high performance" 90 MPa concrete with stainless steel fibres and no reinforcing rods).
A demonstrator of such a container has been produced jointly by Andra and the CEA.

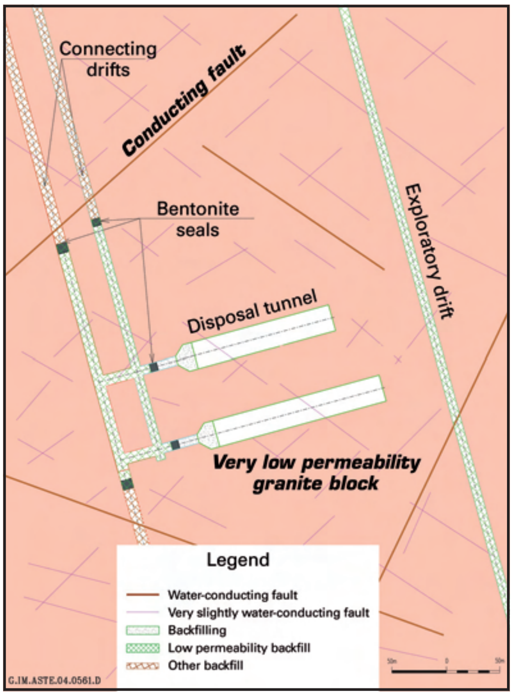


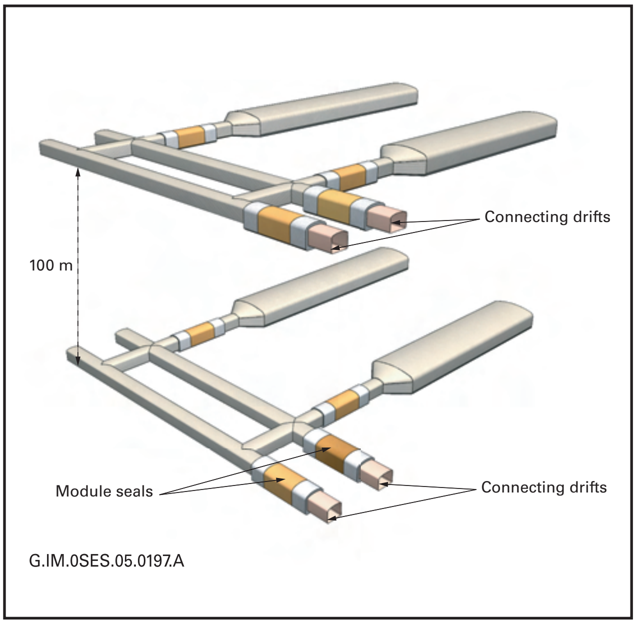
Disposal container with a reinforced retention capacity

2.1.2 The architecture of a B waste repository zone

The location of B waste disposal tunnels in the granite depends on the distribution of water-conducting fractures that must be avoided to protect the packages. The orientation, the extent and the connections between fractures depends on the site and varies from one geological configuration to another. The choice of tunnel concept allows to adapt the number, length and orientation of the tunnels according to the type of granite fracturing and to the underground natural stress configuration. A buffer zone (a few tens of metres) between the tunnels and the water-conducting fractures is determined in relation to hydraulic properties of the granite rock constituting the "block" where the disposal tunnels are to be located.

A "two-level" repository optimises use of the volume of low permeability rock available in between the water-conducting fractures.





Principle of locating B waste disposal cells

The number of tunnels necessary for accommodating the inventory of waste used as input for the study varies between 20 and 30 depending on the waste production scenarios (S1a scenario with full recycling or S2 scenario with recycling stopped) and the tunnel length (about 100 m). On the basis of a location of 2 to 4 tunnels per granite "block", the repository would require about a dozen blocks to be surveyed and characterised. Depending on the site, the distance in between the "blocks" could vary. The typological analysis of granite massifs has shown that, for most of the geological configurations studied, the "blocks" of granite rock with few fractures are grouped into "packets". This would enable us to design relatively compact architectures for the B waste repository zone.

2.2 The disposal of C waste

The design of the C waste repository is determined by their exothermal nature and the nature of their packaging (glass matrix).

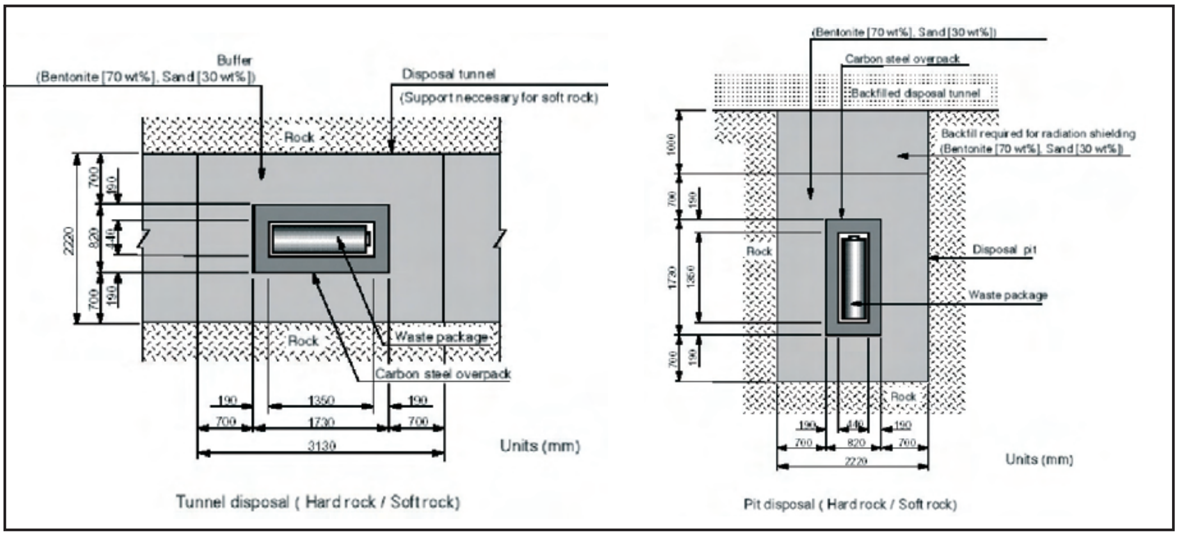
The management of the heat output of C waste is an important design factor for the repository. Controlling the repository behaviour involves taking into account the temperature criteria within the disposal cell (maximum 90°C) and leads to reducing the number of packages per cell and to planning a sufficient distance between cells.

The waste inventory used for the study led to a rather extensive repository footprint (a few km^2) mostly because of the constraints caused by faults and water-conducting fractures in the granite.

Adapting the repository module architecture to granite fracturing is achieved on one hand at the scale of the disposal cells that are located in a slightly fractured granite rock, and on the other hand at the scale of the module that is located apart from water-conducting fractures.

The repository design aims of taking advantage of the glass matrix of C waste to retain the radioactive elements. The aim is to protect the glass from both water and chemical interactions with other components of the repository. The design therefore includes a swelling clay buffer around the packages and an overpack that remains leak-proof as long as the temperature in the core of the glass remains above 50°C.

These design principles are similar with those studied for vitrified waste in other countries. In Japan, the H12 report of 1999 described a concept where the primary packages (CSD-V) are protected by a low-alloy steel overpack. The overpacks are emplaced in horizontal or vertical cells of about 2.20 m in diameter. An engineered barrier consisting of prefabricated swelling clay blocks (with 30% sand) is interposed between the disposal packages and the rock. The engineered barrier thickness varies from 30 to 70 cm, depending on the geology and the resistance considered for the overpack.



JNC (Japan) design for the C waste packages repository (from the H12 report)

4

2.2.1 The C waste disposal cell: small borehole (pit) with a steel overpack and clay buffer

The choice between horizontal or vertical cells in the granite depends on orientation and the distribution of small fractures that are liable to locally affect the very low permeability of the rock. In the French geological context, the analysis of small fracturing has shown that it is most frequently almost vertical. As a reference, it was therefore decided to study the vertical borehole design, which statistically limits the number of small fractures that could occur at disposal cell walls.

On a site where the distribution of the fracturing would be rather horizontal, a horizontal disposal concept could be adopted using the same design principles: a steel overpack and a swelling clay buffer.

- **The C waste disposal borehole**

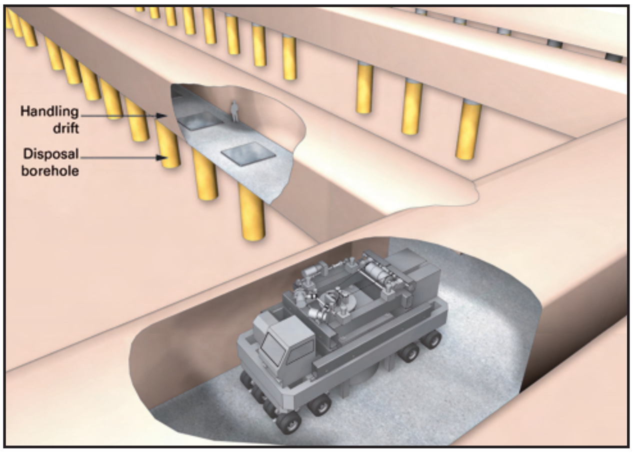
The solution proposed for the C waste cell is a borehole (circular pit), of a length limited to about 12 metres and a diameter of less than 2 metres, with a clay buffer interposed between the package and the rock. With such a borehole length, their location can be adapted to the small fracturing of the granite for all the possible configurations of the French granite context. These small diameter boreholes could be excavated by a boring machine.

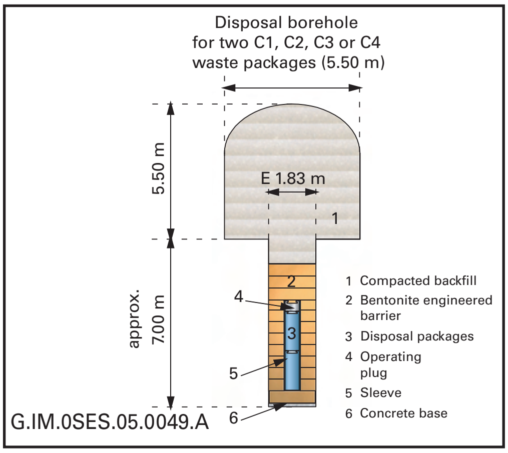
The number of packages per borehole depends on the heat output of the disposed waste. For moderately exothermic C0 waste, a disposal density of 5 packages per borehole would comply with the maximum envisaged length and with the criterion of a maximum temperature of 90°C at the hottest point of the engineered barrier. For the more exothermic C1 to C4 waste, a design with 2 packages per borehole would comply with this criterion for the large majority of French granites (after a 60 years cooling period of preliminary storage).

A steel sleeve is interposed between the engineered barrier and the packages to allow them to be emplaced in the boreholes. A gap left between packages and sleeve would make this emplacement operation and the possible retrieval of the packages easier.

The engineered barrier helps to ensure a migration mode for elements dissolved in water by diffusion, even if there are small fractures that slightly conduct water in the borehole walls. The characteristics of the engineered barrier (swelling pressure, density, hydraulic conductivity, thermal properties and plasticity) can be adjusted to the site conditions by means of suitable mineralogical compositions and manufacturing specifications. The swelling clays studied at international level, especially the "MX 80" swelling clay used as a reference in many studies, can be adapted to the configurations of the French context. Its thickness (60 cm) was determined to take into account possible long-term chemical interactions with the metallic sleeve and the steel overpacks.

The disposal boreholes are dead-ended: there is no access between their bottom and any repository module drift. This arrangement limits the possibilities of water circulating in the boreholes. At the top, they open onto a handling drift designed to ensure package emplacement in the disposal borehole.





C waste disposal cells (two packages per cell)

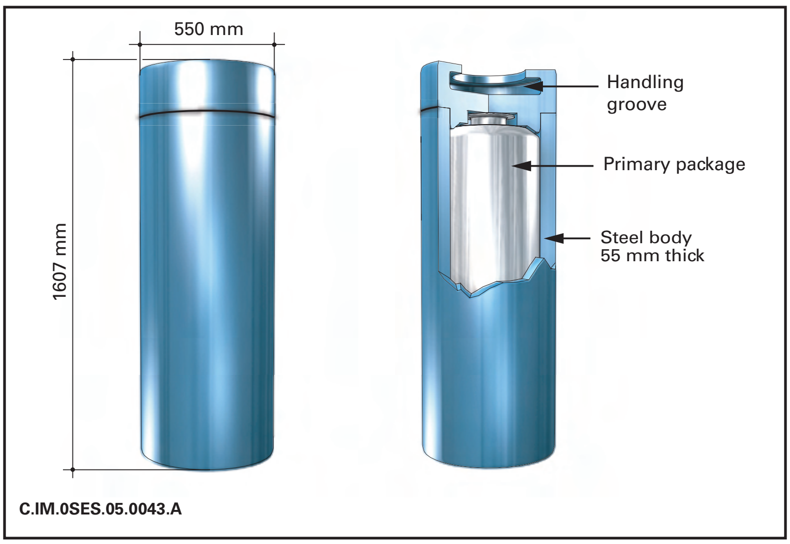
• The C waste disposal packages: a carbon steel overpack

The solution adopted at this stage, for its simplicity and robustness with respect to current knowledge and techniques, is identical to that proposed for the repository in a clay medium. It consists of an individual plain (unalloyed) steel overpack.

The overpack consists of a body and a lid made of the same material. The handling system is integrated inside the lid so as reduce the residuals gaps outside the packages.

The container thickness (55 mm) is determined to withstand any corrosion that is likely to occur after package emplacement. It provides sealing and mechanical resistance that lasts for several thousand years (by taking into account a force of about 10 MPa resulting from the water pressure and the swelling of the clay buffer engineered barrier).

The 1.6 metre long overpack has a diameter of about 55 centimetres.



Disposal packages for C waste (type R7/T7)

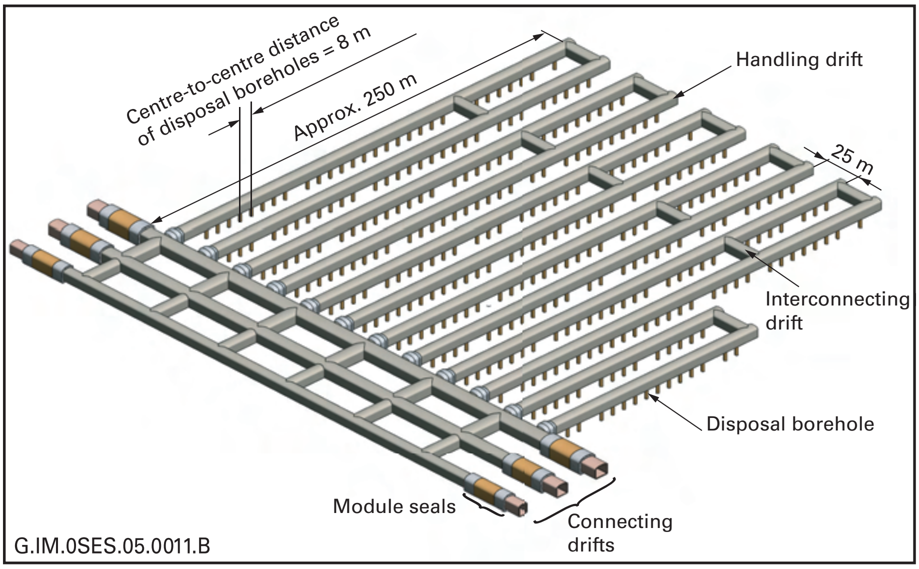
Several techniques could be envisaged to manufacture the steel body of the overpack. All have been tested industrially, in terms of dimension and steel thickness similar to the overpack ones. Once the primary package has been inserted in the overpack body, the lid is welded onto the body through the current electron beam method that achieves a full thickness welding and has little effect on the material's properties in terms of corrosion.

2.2.2 The architecture of the C waste repository zone

In the proposed architecture, the C waste repository zone is divided into several modules composed of handling drifts parallel to which are distributed the disposal boreholes.

In each module, the space between the handling drifts is 25 metres to prevent any mechanical interactions. The distance in between the disposal boreholes is determined according to thermal criteria, especially a maximum temperature of 90°C at the hottest point in the engineered barriers. For granite with average thermal properties in the French context, the spacing in between disposal boreholes would be about 8 metres. This configuration would lead, after about twenty years of disposal, to a maximum temperature of about 55°C in the rock wall of the boreholes for a natural rock temperature at 25°C.

The handling drifts are wide and high enough (5 to 6 meters) to allow the transfer, the emplacement and the possible retrieval of the packages in the disposal boreholes. Interconnecting drifts join each pair of handling drifts to meet the requirements of operational safety. They open onto a bundle of three drifts for the various throughputs between the modules and the access structures (shafts and/or ramp).



Typical architecture of a C waste repository module

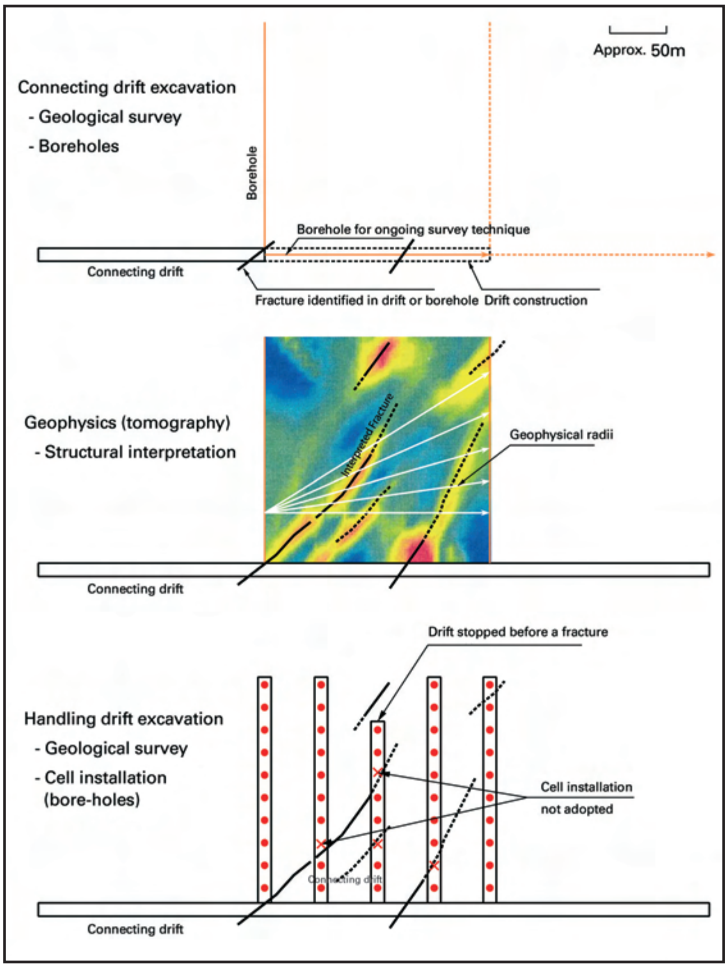
The repository modules are installed in the granite away from any faults (in general pluri-hectometric or longer faults) which would conduct large quantities of water and therefore must not be intercepted by connecting drifts. The geometry of this fracturing means that the handling drifts would be about 200 to 250 metres long.

With the waste inventory input considered for the study according to the production scenarios (S1a scenario with full recycling or S2 scenario with recycling stopped), 15 to 40 modules are needed, each module containing between 450 and 600 disposal cells. As for B waste, a "two level" architecture reduces the repository footprint and makes the granite survey and characterisation easier.

The installation of modules in blocks of granite away from any water-conducting faults does not exclude the presence of small rock fractures within the module. However, these must have a sufficiently low hydraulic conductivity so as not to adversely affect the confinement functions of the various repository components. Granite surveying and reconnaissance, prior to package disposal, aim to check that cell locations are suitable with the fracturing. As a result, it may be decided not to locate a certain number of disposal boreholes where the presence of small fractures would present an arrangement and a hydraulic conductivity that could put at stake the required robustness for long-term safety

Ongoing survey of granite for locating disposal boreholes of a C waste or spent fuel module

During the repository construction stage, the aim of the geological reconnaissance is to specify the disposal borehole location and to check that this location is suitable with the granite fracturing.
Firstly, exploration boreholes are drilled from the repository connecting drift in the axis of a few of the future handling drifts (for example one out of five or ten) along which the disposal boreholes will be distributed. Between these exploration boreholes, geophysical surveys (e.g. seismic tomography) identify the paths of any fractures in the granite rock. A diagram of the fracturing network is then produced using the geophysical data, geological surveys and hydrogeological measurement performed in these exploration boreholes. From this diagram, new exploration boreholes are then drilled in the axis of each of the future handling drifts. Their survey includes measurements aiming at testing the hydraulic conductivity of possible fractures. On these bases, it is decided whether or not to excavate the handling drifts.
Secondly, in the handling drifts, a geological survey is performed along the walls to confirm the correctness of the fracturing diagram. The planned locations for the disposal boreholes are then tested by vertical exploration of a length equivalent to that proposed for the disposal boreholes. Tests of water flow and geological survey of the small fracturing are then conducted to ensure the correct location of the disposal boreholes, i.e. their compliance with criteria established throughout the study stages prior to the repository construction. If compliance is not confirmed with sufficient confidence, the location will be ruled out. A 10% exclusion rate was considered to be likely in the SKB studies for the design of the KBS-3 spent fuel repository (Sweden).
After drilling the disposal boreholes, a final check is made on the basis of geological surveys and measurements of possible water flow rates in the disposal boreholes to guarantee their location suitability.



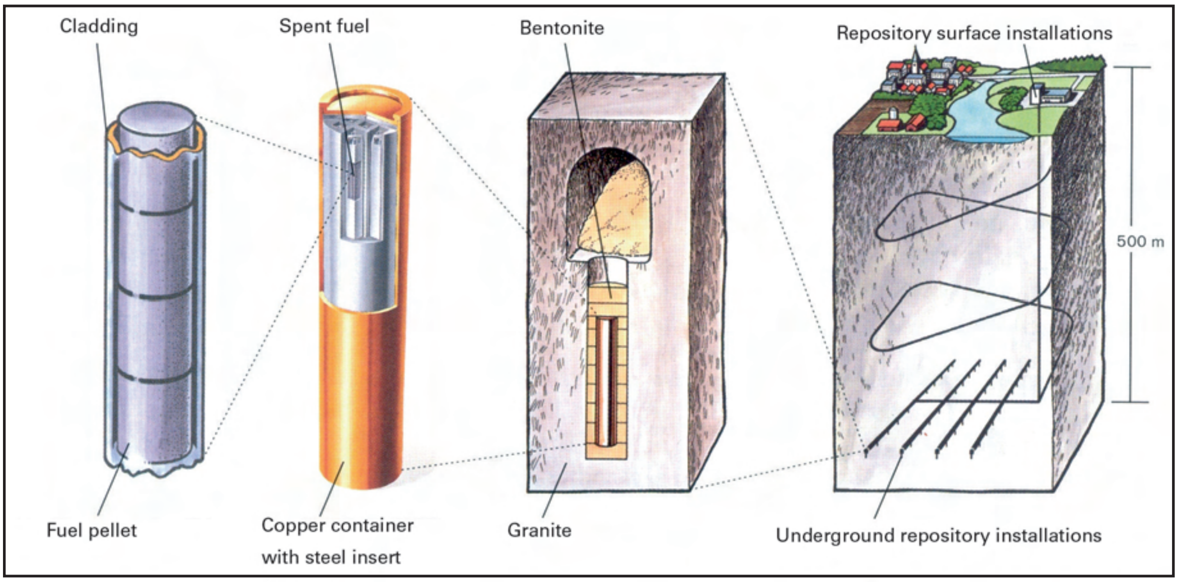
Principle for determining the degree of fracturing through the ongoing method (as excavation works progress)

2.3 The disposal of spent fuel

The architecture proposed for the spent fuel disposal is based on the same principles as that of the C waste disposal. The exothermal nature of the packages in practice leads to the management of the repository footprint using the same plan with modules installed away from water-conducting faults. The disposal boreholes are distributed along parallel handling drifts about 25 metres apart. The distance between disposal boreholes would be 10 to 15 m.

However, unlike C waste, spent fuel is not confined in a glass matrix: the spent fuel assemblies are therefore likely to release radioelements more quickly in case of water ingress from possible nearby faults. In fact, because of the footprint needed for spent fuel disposal (several km^2), the presence, near the disposal cells, of fractures conducting small quantities of water cannot be ruled out, even though the process of cells location avoids them as for the C waste case. The disposal packages must therefore be designed so that spent fuel assemblies are protected from water arrival for a sufficiently long time to withstand a possible failure of the drift sealing arrangements.

In the context of a study without any specific site, Andra has relied on the experience acquired with the "KBS-3" concept with a long-lasting leak-proof copper container. This concept was adopted in the 1980s by Sweden and became then the common reference for both SKB (Sweden) and Posiva (Finland) for their studies of a repository in a granite medium. Copper is a thermodynamically stable metal in environmental chemical conditions similar to those occurring underground in a granite massif. The repository is designed so that these conditions are maintained for the time scale considered by the safety analyses, i.e. several hundred thousand years. 4



The Swedish KBS-3 concept for spent fuel (SKB data)

Full-scale experiments of the main components of this concept are carried out in the Aspö laboratory.

The container durability requirements could be lower in the case of certain granite sites because of their geological nature. The Spanish organisation Enresa is currently studying the possibility of a spent fuel disposal concept with a durable steel container that would last for a few thousand years.

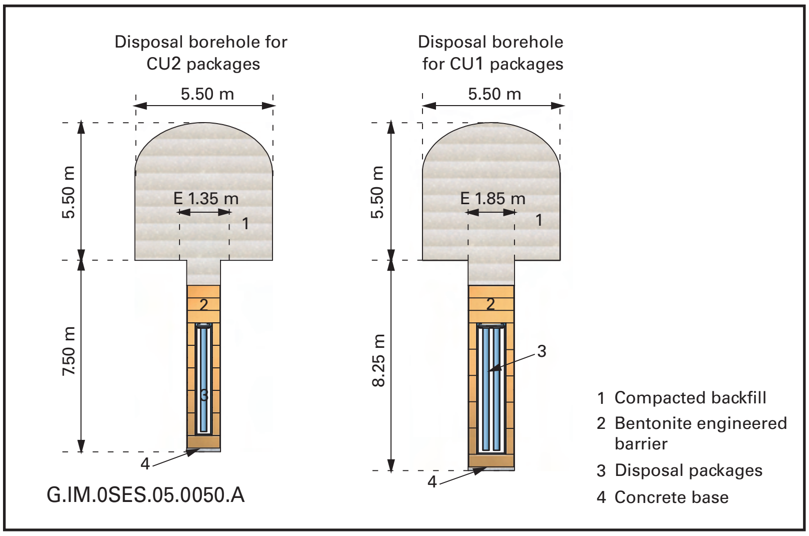
2.3.1 The spent fuel disposal cell: small boreholes with a copper container and a clay buffer (the "KBS-3" concept)

In the Swedish KBS-3 concept, the disposal cell is a small vertical pit (disposal borehole) containing a copper spent fuel container.

For several years, SKB and Posiva are also studying the possibility of disposal in horizontal tunnels, which reduce the volume of rock to be excavated. Andra monitors these studies; however, the many results already obtained on the “KBS-3” vertical concept have led us, at this stage, to propose vertical disposal boreholes as the reference option. Furthermore, as for C waste, the adaptation of the location of a vertical cell to the small fracturing of the granite is simpler in the case of a rather vertical fracturing configuration, which is generally the case in the French geological context.

• The disposal boreholes

The design of the disposal boreholes avoids components, especially metallic ones, that are likely to chemically interact with the copper container and to adversely affect its long term leak-tightness function. As for C waste, the swelling clay buffer ensures a hydraulic transfer regime by diffusion in the disposal boreholes even if there are small fractures in their walls. It helps to maintain chemical environmental condition compatible with the copper of the container while providing a chemical buffer to any water coming from the granite and the handling drifts. The bentonite rings around the containers have a thickness of about 35 centimetres.
The reduced dimensions of the disposal boreholes (about 8 m long and less than 2 m in diameter) mean that they can be excavated with a boring machine, as for C waste, thus greatly limiting the damage to the rock wall. The disposal boreholes are dead-ended, opening at their top onto a handling drift allowing the transfer and emplacement of the spent fuel containers.



Spent fuels disposal cells

• The spent fuel container: SKB studies and transposition to French spent fuel

The spent fuel container designed by SKB comprises a cylindrical copper shell (envelope) and an internal mechanically resistant cast iron structure (called the "insert").

View of the copper envelope and insert for BWR assemblies (source SKB)

The copper envelope consists of a cylindrical body onto which are welded a bottom and a lid. Its thickness (50 mm) allows the container to withstand a hydrostatic pressure of more than 5 MPa and a swelling pressure of the clay buffer engineered barrier of about 7 MPa. The mechanical strength of the package is ensured by the deformation of the envelope, which is then pressed against an internal rigid insert but without degradation of the envelope integrity performance. The feasibility of manufacturing tubes 50 mm thick has been demonstrated by SKB for various metallurgical manufacturing processes: manufacturing by extrusion, by drilling and drawing or by forging.

The cast iron insert is dimensioned to achieve, on one hand the container mechanical resistance and also on the other hand, the system non-criticality. It is designed in Sweden to house 12 type BWR spent fuel assemblies or 4 type PWR spent fuel assemblies (analogous to French REP spent fuel). This number is compatible with the maximum temperature criterion of 90°C at the surface of packages in the disposal boreholes after their emplacement.

The transposition to French spent fuel leads to an insert design with housing for 4 UOX (CU1) assemblies or a single MOX (CU2) assembly. The thickness of the cast iron in between the housings is designed to prevent any risk of criticality.

The container diameter is 1.15 m for CU1 and 0.65 m for CU2. Its length also depends on the fuel type: 4.50 m or 5.25 m.

Welding on of the lid, after spent fuel assemblies emplacement, has been largely studied by SKB. Various techniques have been tested: electron beam and friction. The tests showed that they are compatible with an industrial manufacturing process in a nuclear context.

3 The 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, 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 operations over a long period

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.

3.1 The activities carried out in the repository installations

3.1.1 The 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.

• Progressive construction

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. *"Ongoing" survey* of granite is carried out during the construction phase.

• Nuclear operation

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).

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.

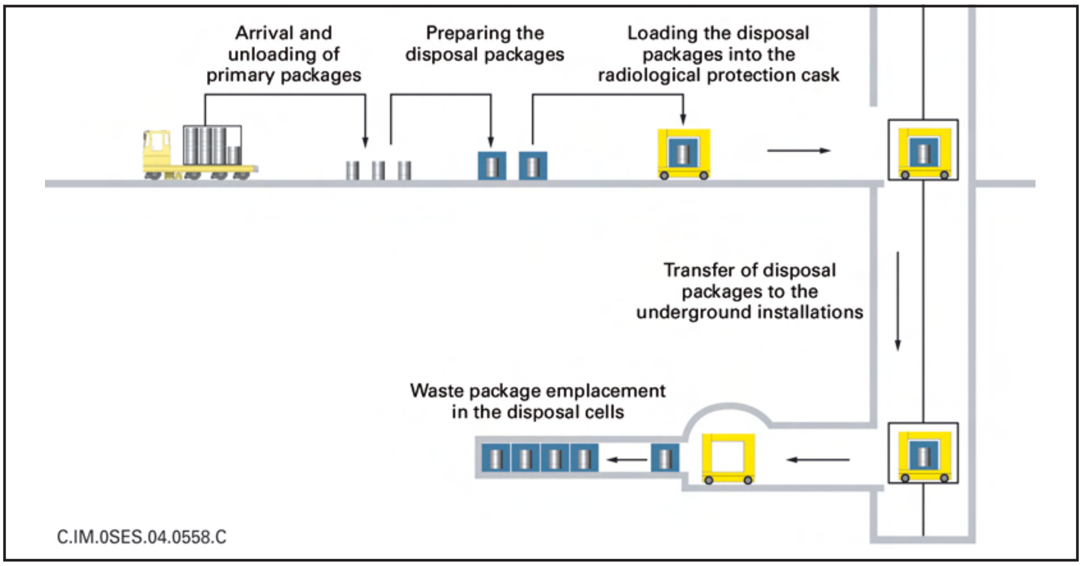


Diagram of the principle of nuclear operation of the repository

• Structure closure

Unlike a storage facility, a reversible repository 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.*

• Related activities: monitoring, maintenance and observation

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, it 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, which is organised around the waste transfer shaft and package transfer drifts (nuclear operation); the other for the activities of construction/closure, which is organised around the service shaft and works 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).

3.1.2 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.

- **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.

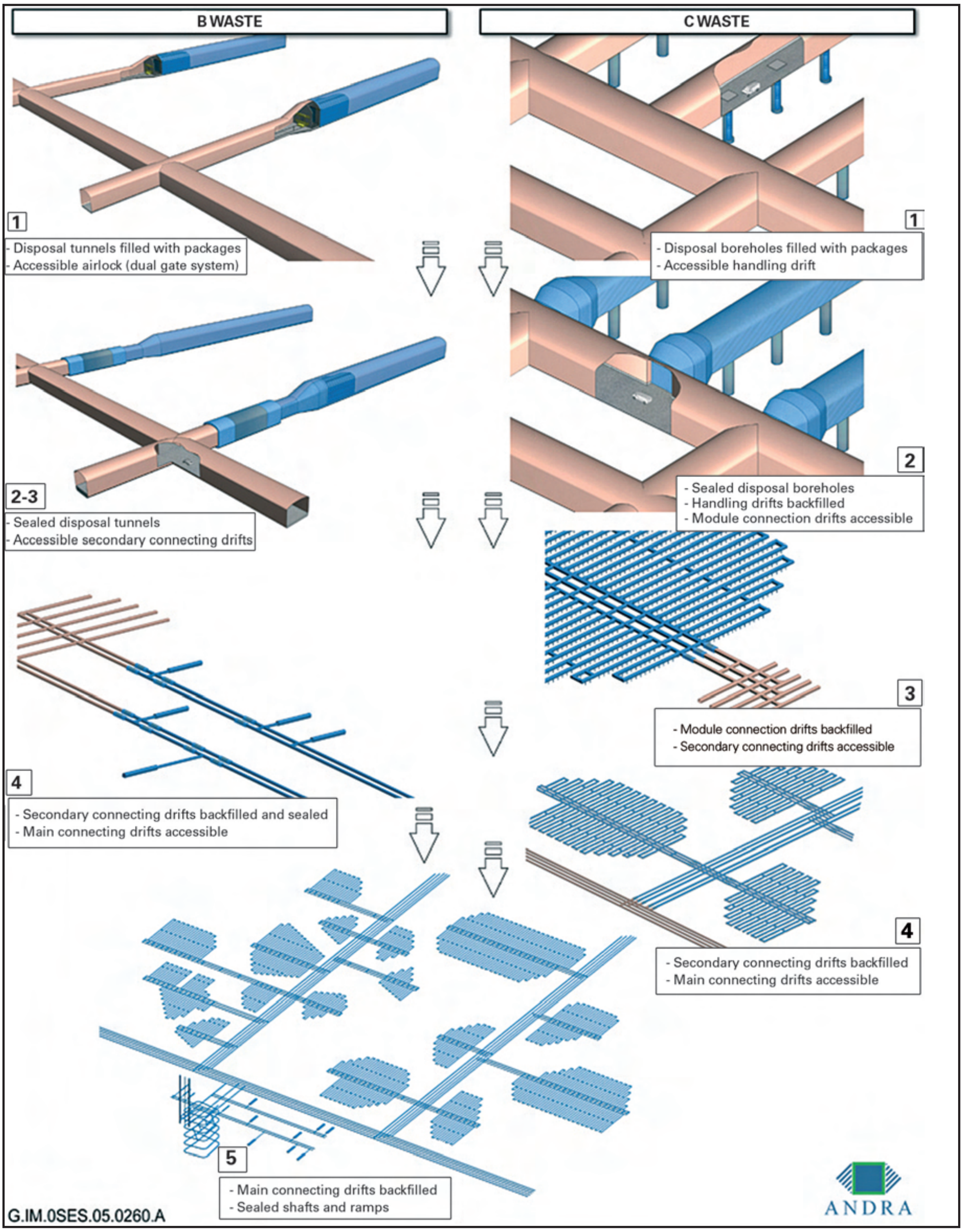
The repository management process is thus designed as a succession of stages to be passed through, without a preconceived duration. The passage from one stage to another is neither final nor laid down in a fixed operating plan. On the contrary, each stage is associated with choices: return to the preceding 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.

- **The stages in the repository management 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 module closure":* this stage starts after sealing and backfilling of all the components in a module. Module closure includes backfilling the internal access drifts connected to it. The connecting drifts that lead to 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.*

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 preceding 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.*



Stages in the operation and closure of a repository

• A programme of *in situ* observations to contribute to the repository reversible management

The choices of repository management 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 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 return to an earlier stage is governed:

- *For the B waste cells,* these are the kinetics of water arrival, the production of gas by certain waste and the temperature for the B cells containing slightly exothermic waste.
- *For the C waste (or spent fuel) disposal cells*, observations involve the thermal load in and around the cells, the mechanical behaviour of the swelling clay buffer and the rise in hydraulic head in the surrounding granite.
- *In the case of the access structures (shafts and drifts),* observations aim at monitoring the saturation of the backfill and seals and the increase in hydraulic head in the surrounding granite.

The "state of art" developed using the experience gained by monitoring many civil engineering structures and longer-term experiments in underground laboratories outside France suggest a series of good practices:

- The redundancy of structures, by using various technologies or duplicating instruments, to check the consistency of measurements and limit information loss in the event of a defective instrument.
- The choice of high quality and relevant tools in terms of the amplitude to be measured and the expected precision.
- An appropriate distribution of the observation equipment, particularly by using preliminary modelling.
- Integration of observation equipment as from the design stage.

Monitoring equipment suitable for the repository

Several measurement technologies are used in civil engineering structures and underground laboratories:

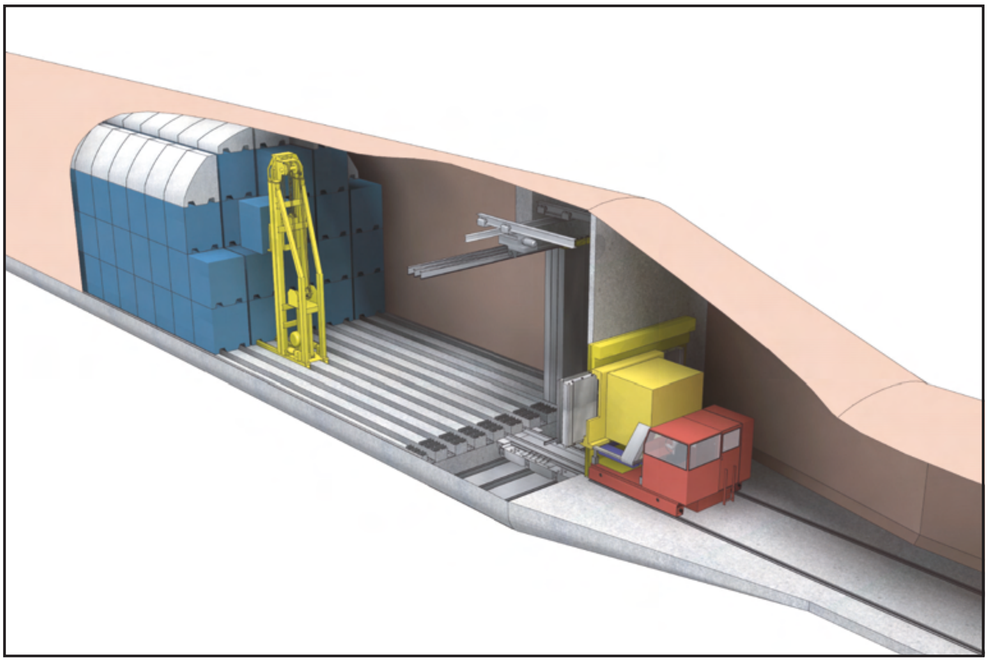
- *Temperature:* vibrating wire sensors (localized measurement), optical fibres (measurement on long profiles),
- *Deformations, mechanical displacements and strains:* vibrating wire extensometers (measurement of local deformations) and long-base ones for bore-holes or backfill (deformations over larger distances), vertical pendulums (monitoring displacements in three dimensions),
- *Water pressure and flow rate:* interstitial pressure vibrating wire pressure cells,
- *Relative humidity of engineered barriers, backfill and seals:* condensation dew-point hygrometers.
- *Concentrations of toxic gases, corrosion, contamination:* hydrogen detector, visual inspection, sampling, ultra-sonic measurements and reference samples 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

3.2 The reversible closure of the underground structures: the degree of reversibility

The staged closure of the underground structures leads to the passage to a lesser degree of reversibility. The stages in the process are similar for all packages but there can however be differences. These are caused both by the architectures of the various repository zones and by properties of their engineered components: seals, backfill, engineered barriers, disposal packages, etc.

3.2.1 The B waste disposal structures

As long as the tunnels remain unsealed, the reversibility of B waste disposal is total. The packages can be retrieved using the same method as those to emplace them, i.e. a remote-controlled fork-lift truck. The maintenance and monitoring relating to operation can be continued for as long as one wishes to keep the tunnels open.



The B waste repository: emplacement and possible retrieval of package

After closure of the tunnels (disposal cells), the installations at the tunnel head are dismantled, a seal is installed in the access drift and the ventilation is stopped. The evacuation of any water coming from small fractures in the granite of the tunnel walls is stopped. The stoppage of the ventilation can lead to an accumulation of gas produced by the packages. Water can also accumulate on the tunnel floor.

In these conditions, package retrieval would require prior operations, and notably:

- drilling boreholes through the seal to evacuate the gas that has accumulated in the tunnels, or water on the cell floor,

- re-establishment of the ventilation,

- dismantling the seal,

- re-equipping the tunnel head.

After reconstruction of the airlock and reinstallation of the ventilation in the disposal chamber, the packages could be removed using the same equipment as that used to install them, as the durability of the concrete of the packages ensures their integrity for several centuries.

Furthermore, the tunnel seal does not affect the possibility of operating in other tunnels, which ensures that the repository can be managed in a flexible way.

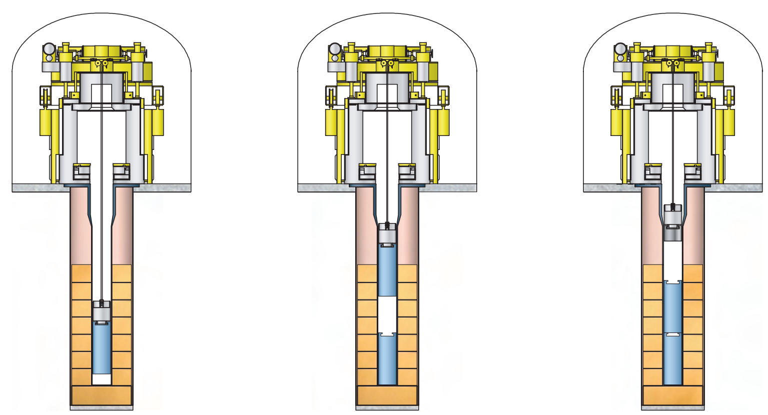
In the next stages, the progressive closure of the disposal tunnels access drifts, their backfilling and sealing reduce the accessibility to the packages. The dismantling of the seals and the backfill would require reinstalling the ventilation and water evacuation systems, which would involve standard and proven mining technology in a granite medium.

3.2.2 The C waste disposal structures

As for B waste, the reversibility of C waste disposal is total as long as the disposal boreholes are not sealed and the handling drifts are not backfilled. It would require maintaining the ventilation and drainage in the handling drifts.

The possible retrieval of packages would be performed using the same equipment as that used for their emplacement, i.e. a remote-controlled vertical handling system similar to that used for many years on the Cogema facility at La Hague.

The steel sleeve would allow the emplacement or possible retrieval of waste packages through one or more stages depending on the number of packages per borehole. The operating plug ensures a radiological protection function. The swelling clay buffer and the sleeve protect the packages from any water that could come from small fractures in the granite wall of the disposal borehole. So long as corrosion has not weakened the sleeve mechanical strength (a period of several centuries), the disposal packages remain free within the sleeve.



C waste repository: emplacement and possible retrieval of packages in disposal borehole

The sealing of the disposal boreholes by a bentonite plug plus the backfilling and closure of the handling drifts would reduce the accessibility to the packages and the degree of reversibility. Package retrieval would require access to the disposal boreholes and therefore removal of the backfill. Then the bentonite plug and the operating plug would have to be removed.

Repository module closure is also accompanied by backfilling of handling and connecting drifts, and the installation of seals at key points in the connecting drifts. The ventilation and the pumping of any water likely to come from small fractures in the drift walls are stopped. Accessing again to the handling drifts would require, as for B waste, reinstalling the ventilation systems, dismantling the seals and removing the backfill.

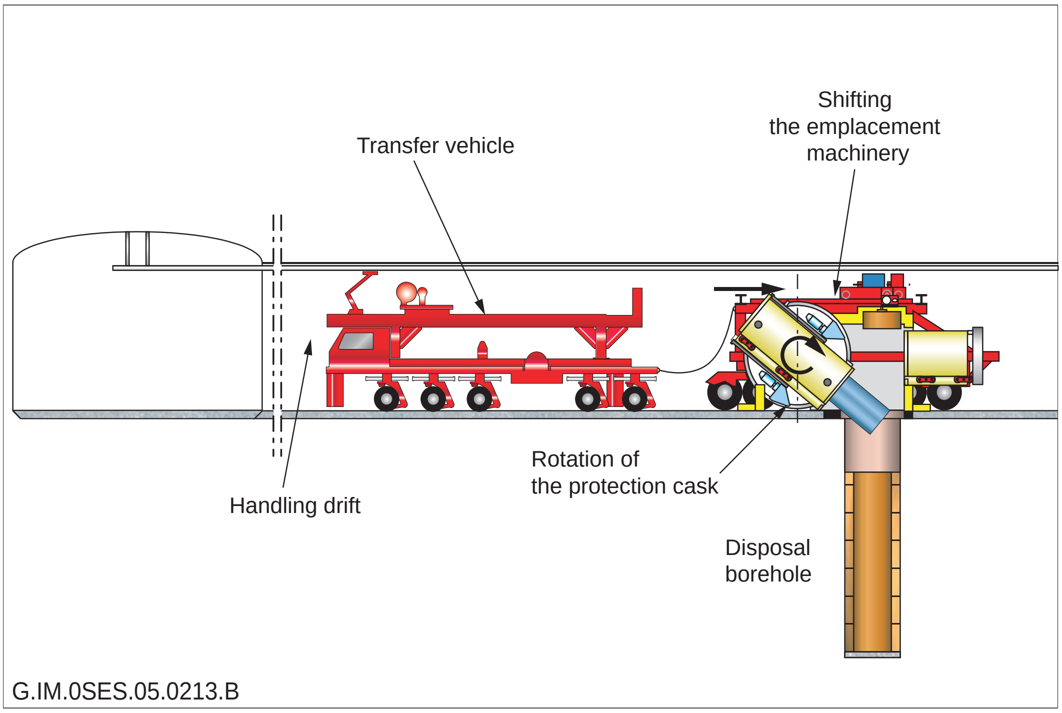
3.2.3 The spent fuel disposal structures

The stages in the process of a possible spent fuel repository are similar to those of a C waste repository. However, the proposed option of a copper container for the spent fuel repository (KBS-3 concept) leads to specific arrangements in terms of reversibility. The use of copper means that steel components cannot be used in the disposal boreholes to prevent any chemical interaction that would be likely to adversely affect the container. The sleeve that makes package retrieval easier cannot therefore be used. Similarly, to prevent any copper oxidation that could be related to handling drifts continuous ventilation, it may be necessary to close the disposal boreholes shortly after container emplacement.

In these conditions, the proposed option is to only emplace a single package per disposal borehole to ensure flexible management of the repository process and the organisation of possible package retrieval.

Package handling techniques have been the subject of an *in situ* demonstration in the Aspö laboratory in Sweden. SKB is also testing in the Aspö laboratory the removal of a disposal borehole plug through bentonite destructuration using a saline solution.

The progressive closure of the spent fuel repository modules uses the same arrangements as those proposed for C waste.



The KBS-3 concept (Sweden): principle of emplacing spent fuel containers in the disposal borehole (pit)

3.2.4 The main drifts and the surface-underground connecting structures

After repository modules closure, their access is possible through the maintenance of ventilation and water pumping. This stage can last as long as these technical systems and structure monitoring are still operational.

The following stages consist of closing the repository zones that contain the modules of the same category of waste then, the connecting structures between the surface and the repository zones (shafts, ramps, connecting drifts, etc.). As in the previous stages, the drifts are backfilled and sealed at specific points, particularly in relation to the possible interception of water-conducting faults by the drifts. This is accompanied by the stoppage of the ventilation and water pumping.

These stages include the sealing of the exploration boreholes drilled during the granite reconnaissance stage using swelling clay materials (bentonite) in order to prevent the possible consequences, in terms of long-term safety, of an uncontrolled hydraulic connection in between structures.

3.2.5 Conclusion on the reversible management of the repository

Generally speaking, the great mechanical stability of excavations in a granite medium favours the ability to retrieve packages and the flexibility of the disposal process management over very long time periods. The same is true for the durable disposal containers (several centuries at least for B waste and several thousands of years for C waste, and even longer for spent fuel).

However, structures evolution can eventually influence the adaptability of packages and installations management. This point mainly concerns the swelling, with water arrival, of the engineered barrier clay in spent fuel and C waste disposal cells, and for the latter, the slow corrosion of the disposal cell metallic sleeves.

Furthermore, the continuous operation for long periods in underground drifts, in particular the disturbances caused by ventilation and water pumping (B waste cells, access drifts to cells, connecting drifts), can have a hydrogeological and hydrogeochemical impact on the granite; these disturbances depend on the site context and, in any case, would appear to be reversible.

In the first stage of the disposal process, the packages can be managed as in a storage facility. They can be retrieved using the same methods as used for their emplacement, in a way that is as flexible as in a storage facility. Then, as the structures are closed, the degree of reversibility gradually decreases.

For C waste, the design of the disposal cell metallic sleeve involves a durability of at least 200 to 300 years without any particular maintenance, almost independently of whether closure stages have been reached or not. To extend this period, it would be necessary, from a technical viewpoint, to adopt enhanced maintenance of the disposal cells. Beyond the sleeve lifetime, package retrieval would require the simultaneous use of more complex processes.

Before spent fuel package retrieval, it would involve additional techniques when engineered barrier clay has become hydrated and swollen.

Generally speaking, repository observation would provide a regular re-assessment of the evolution and durability of the components (swelling of the swelling clay, lifetime of the disposal cell metallic sleeve) and the impact of the operation on the granite.

A duration of two to three centuries constitutes an envisaged period for managing the disposal process in a reversible manner without requiring technically heavy operations.

Dossier 2005 Granite

Long-term and safety

5

One of the main purposes of deep geological disposal is to build a facility which, ultimately, would not need human intervention and evolve passively.
This chapter describes the post-closure long-term behaviour of a repository, together with the safety approach and analyses intended to ensure that the repository will be able to evolve, without human intervention, once closed, while meeting its objectives in terms of protecting man and the environment.

The proposed analytical method - or safety approach - is based on a number of principles that are common to both clay and granite deep geological disposal studies.

• The safety analysis is based first and foremost on identifying and understanding the phenomena liable to occur in a repository in a granite medium, and on a long-term understanding of the repository and its environment. It draws on scientific research, the results of experiments and simulations, placed in perspective in the form of a phenomenological analysis.

• However, the number and duration of the phenomena occurring in a repository make it a relatively complex system. The safety analysis is a tool that, based on a thorough understanding of the phenomena involved, classifies them hierarchically, by highlighting the crucial points and representing the repository history in a simplified but robust and realistic way. From the repository rich and complex phenomenology, the analysis derives a conservative representation, known as the normal evolution scenario, which can be represented in the form of robust, simplified models with numerical simulations. The analysis then uses this representation as a basis for testing the suitability of the safety functions assigned to the various components and assesses the repository system's overall performance. It takes into consideration the uncertainties relating to the repository evolution, modelling validity limits and the possible parameter variations. This approach not only ranks the most significant uncertainties but also uses an altered evolution scenario, to cover situations outside the expected evolution, either incidents occurring independently of the designer's intentions (e.g. intrusion into the repository), or premature failures of certain components. The analysis yields a set of calculations and assessments intended to ensure that the repository complies with the objectives in terms of protecting man and the environment.

Unless a specific site is considered, the long-term safety analysis of a repository in a granite medium cannot claim to be thorough enough to reach conclusions regarding a facility robustness or the suitability of a particular site. With respect to impact assessment, quantified radioprotection objectives would be premature, in view of the lack of site-specific data. Therefore, the analysis can only be considered as preliminary.
In this context, the safety analysis was performed on the basis of generic repository architectures that allow for variability in the properties of the granites in French geological formations. The phenomenological analysis is based on the existing corpus of knowledge about granite media and the behaviour of engineered repository components, and in particular on information derived from experiments conducted in underground laboratories abroad.
Structured accordingly, the analysis made possible to identify and address the various issues relating to the safety of a repository in a granite medium, verify that none of the issues raised would rule out feasibility and highlight the key points in terms of both repository design and necessary site-specific work

Safety approach references

As the safety approach in *"Dossier 2005 Granite"* was not performed in the context of a site selection process or of the assessment of a particular site, it cannot refer to all aspects of Basic Safety Rule RFS III.2.f. issued by the Nuclear Safety Authority in 1991 and relating to such approaches. However, RFS III.2.f. describes a number of methodological principles and design options, that are appropriate even at an earlier stage. For example, the general objective of making all necessary provisions, to limit the repository impact and to consider its impact in both "normal" and "incident" situations, remains a relevant consideration at the study stage.
In general, RFS III.2.f. recommendations have been taken into consideration in the studies, while appropriately adapting their interpretation to the nature of the dossier.
In addition to the Basic Safety Rule, the internationally-developed principles (e.g. the AIEA draft safety requirement and the OECD/NEA definition of the "safety case") were also embodied when developing the safety approach for *"Dossier 2005 Granite".* Although the safety approach does not constitute a "safety case" in the NEA sense, the main aspects covered by these documents (the importance of the arguments clarity and transparency, the need to record and trace data sources, the emphasis on uncertainty management, etc.) were implemented when producing this dossier.

1 Evolution of a repository in a granite medium

Understanding the phenomenological evolution of the repository and its geological and surface environment is closely linked for the design process, and is one of the key aspects of the repository safety assessment. Understanding this evolution, notably exhaustively, makes possible to describe the processes that influence radionuclide behaviour and migration, and therefore to ensure that the repository, as per its proposed design, and the geological medium meet the long-term safety requirements.

A repository is a complex system involving multiple components (packages, engineered barriers and the geological medium) and which is subject to a range of often coupled thermal, hydraulic, chemical and mechanical phenomena. The repository components evolve over time as a result of these phenomena (which present different kinetics).

In order to ascertain this complexity, Andra has broken down the repository evolution into a series of situations, each corresponding to the phenomenological state of a part of the repository or its environment at a particular point in the repository life; these situations reflect the thermal, hydraulic, mechanical, chemical and radiological phenomena at work, and account for the sequencing and coupling of said phenomena. The analysis concerns not only the repository construction and operating phases of one or more centuries, but also the post-closure phase, therefore dealing with a timescale of one million years.

The set formed by these situations, known as the Phenomenological Analysis of Repository Situations (PARS) defines the complete, continuous phenomenological evolution of the repository and its geological environment. The PARS provides the framework for analysing the radionuclide release and transfer phenomena that must be taken into account in the long-term safety assessments.

1.1 Repository evolution – Overview

Within all the proposed arrangements of the repository design, compartmentalisation of the underground disposal installations into distinct zones and modules means a phenomenological evolution that is largely specific to each individual part of the repository. The influence of the various thermal, mechanical and chemical phenomena at work is largely limited to the perimeters of the various repository modules.

From a hydraulic perspective, excavating the surface-underground connecting structures, as well as the drifts and underground structures, drains water throughout the repository operational phase. This drainage must be considered on the scale of the repository as a whole. At post-closure, separating repository structures by seals and backfill allows each module to evolve independently.

The compartmentalisation of the proposed architectural structures helps to simplify the analysis. Such an analysis can be carried out to describe separately the evolution of the repository general infrastructure (shafts, ramps, connecting drifts, etc.) and the evolution of each zone (B, C and spent fuel). Other provisions also help to simplify the phenomena to be analysed:

- *the small number of engineered components* in the disposal cells limits the interfaces between different materials and their possible coupling,
- *the size of the structures* ensures that they remain mechanically stable over the long term, thanks to the great mechanical strength of granite. The "mechanical" component does not, therefore, govern the evolution of a repository in a granite medium.
- *the thermal dimensioning* and technical provisions restrict the temperature to domains in which phenomena description and modelling are well known. Thus, respecting a maximum temperature of 90°C at all points in the rock was adopted as a dimensioning criterion for the disposal zones containing exothermic packages.

1.1.1 General repository infrastructure (shafts, ramp and connecting drifts) - A short hydraulic transient and very slow long-term chemical evolution

During repository construction and operation, the infrastructure components (shafts, ramp and inter-module connecting drifts) drain granite groundwater via the intercepted water-conducting fractures. This drainage continues until the repository is closed. Excavation works lead to a rapid decrease of the hydraulic head in the main intercepted faults, since these faults drain most of the granite groundwater. The hydraulic head in the smaller fractures then also gradually decreases, after a delay that depends on the fractures interconnection.

Once the structures are closed, the hydraulic head increases in the opposite manner to that described above. After a few months, the hydraulic head in the larger faults reaches a level comparable to the pre-excavation situation. The hydraulic head in the lower hydraulic transmissivity and smaller fractures, is also gradually restored, after a period that depends on the granite fracturing configuration. The underground structures gradually fill up with water. The very low permeability seals dividing up the infrastructure make the resaturation processes for the different areas of the repository mutually independent. Accordingly, structures become saturated after a period determined by the density and hydraulic properties of the intercepted fractures and by the permeability of the backfill put in place. Generally speaking, these periods are of the order of ten years to a few decades. Such periods are short in relation to the timescales of several hundred thousands of years that are considered in the analysis. The disturbance to the hydraulic state of the granite massif caused by at first the hydraulic head loss and then the restoration process is a very short-lived transient. At the scale of the granite massif, the hydraulic situation returns to a state similar to the situation prevailing prior to construction of the repository.

The water drainage caused by the repository can lead to transient disturbances in the distribution of the chemical compositions of the granite groundwater. In particular, the original water stratification (the deeper, the more saline the granite groundwater) may be modified during the repository operating phase. The return to the initial conditions occurs over a longer period (measured in millennia) than the hydraulic head restoration. In the French geological context, any such disturbances would scarcely affect the chemical composition of the water in the repository. Any such modifications would not necessitate special design provisions, notably with regard to the formulation of containers and engineered barriers.

Once the structures are saturated, water movements in the connecting drifts are essentially dependent on the low permeability of the backfill and the intercepted fractures. Indeed, the damaged granite zone around structure walls created during excavation work has little influence on water flows in the drifts. Tests conducted at the Lac du Bonnet laboratory in Canada have proved the low hydraulic continuity of the damaged zone around drifts excavated using conventional “drill and blast” (with explosives) techniques. The "ZEDEX" experiment at Äspö laboratory in Sweden also proved the very limited extent of rock damage and low hydraulic transmissivity near structure walls when boring techniques (e.g. microtunneling machines) are used. The damaged zone therefore has only a very limited role in the drainage phenomenon. Furthermore, the feasibility of using very low-permeability seals anchored in the sound rock was demonstrated at the Lac du Bonnet laboratory ("Tunnel Sealing Experiment"). Such seals restrict water flows between drift sections with a diffusive or combined diffusive/advective hydraulic regime, corresponding to very slow movements.

Once the drifts have been closed and have resaturated, chemical exchanges take place between granite groundwater and the backfill. The slightly oxidizing environment (due to ventilation air and the possible arrival of water from shallower granite) becomes first anoxic, then reducing. Experiments in underground laboratories and on granite samples (notably the "REX" experiment at the Äspö laboratory) have demonstrated the natural ability of the minerals in the granite to fix the oxygen of the water. Over the long term, given that the backfill contains more than 70% of ground granite rock, the water tends to reach a state of equilibrium with the rock, and the chemical exchanges are limited.

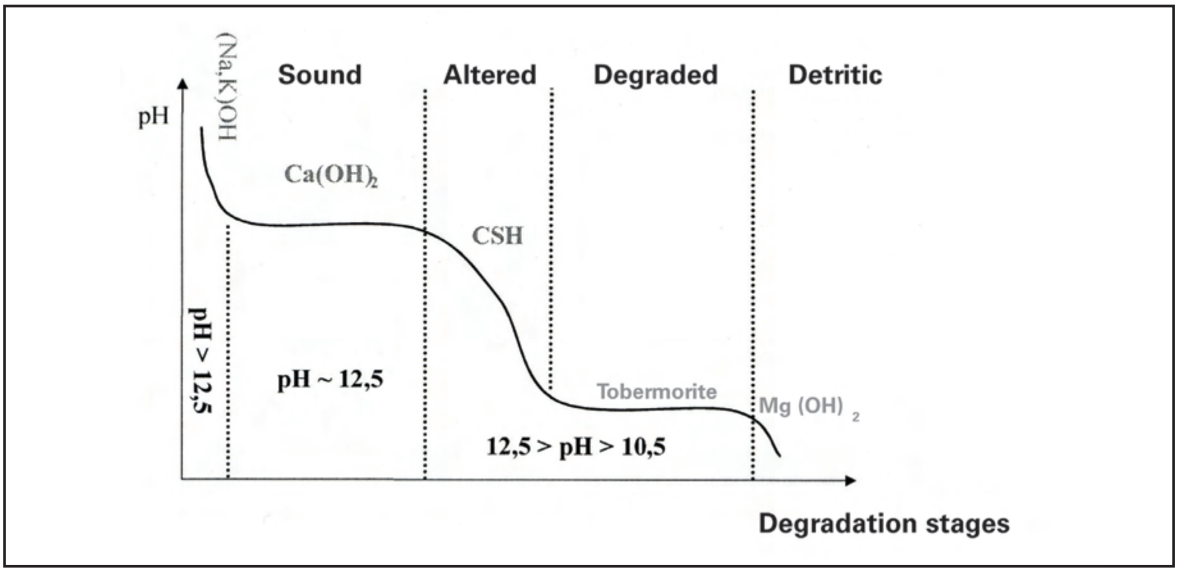
Put briefly, infrastructure facilities (shafts, ramp and connecting drifts) evolve very little over the long term: this is due both to the mechanical stability of the granite rock and the correlated absence of metal ground supports, the very similar composition of backfill and granite, and the very slow kinetic of water movements underground.

1.1.2 B waste disposal modules - Very slow chemical evolution dominated by the cementitious environment of the waste packages

By design, the tunnels and drifts in a B waste disposal module are located in very low permeability and very slightly fractured granite blocks. Accordingly, during the module construction and operation, the phenomenological evolution of the disposal tunnels consists only in a very slight drainage of water from the granite via the small fractures in the tunnel walls. Water is removed through the ventilation flow or a dedicated pumping system (dewatering system). Any alteration to the concrete disposal containers is restricted to the superficial, negligible effects of ventilation. Any radiolysis gases (e.g. hydrogen) released by certain packages (e.g. B2 bituminised waste) are removed by the ventilation flow and therefore do not affect the evolution of the packages themselves. Stacking slightly exothermic B1 or B5 waste increases the temperature, but the disposal tunnels are dimensioned to not exceed 70°C even when their ventilation system stops operating after packages emplacement. Peak temperatures are reached within a few years. With the other types of B waste, which are non-exothermic, there is no significant temperature increase.

Once the disposal tunnels are closed, resaturation begins when the ventilation and dewatering systems are shut down. The resaturation kinetic depends on the density of the small fractures in the tunnel walls. The process may vary from a decade to a few centuries, or even a thousand years with certain fracturing configurations. Water gradually fills the tunnels from the bottom upwards. After resaturation, there is no more hydraulic head gradient between the disposal tunnels and the surrounding granite. Consequently, any water movements are very limited, resulting in a primarily diffusive transfer regime.

In this context, a disposal tunnel evolution is essentially linked to the slow chemical processes in the stacked concrete disposal packages. From a mechanical perspective, over the very long term (between tens and hundreds of thousands of years), the degradation of the disposal packages can lead to a loss of cohesion of the stacks, causing a readjustment of their position in the disposal tunnels. However, any alteration of the disposal packages has little impact on the nature of the chemical environment in the disposal cells, which is essentially characterised by a reducing, strongly alkaline atmosphere (with the pH decreasing from 12.5 to 10 over the aforementioned timescales), which would tend to immobilise most of the radionuclides in the tunnels.



Stages in the concrete degradation process

The alkaline water resulting from the chemical exchanges between the granite groundwater and the disposal packages concrete can alter the properties of the granite at the repository walls. The small fractures at the tunnel walls are clogged by carbonate precipitation, thereby reducing the transfer potential. This point was demonstrated by the Hyperalkaline Plume in Fractured Rock (HPF) experiment carried out in the Grimsel laboratory, Switzerland. However, owing to its mineralogical composition, the granite rock is only superficially affected by the alkaline water.

Disposal tunnel sealing may also be affected by water alkalinity, which is liable to alter the properties (very low permeability, swelling and retention capacity) and performance of the approximately 10 m long swelling clay core that forms the functional part of the seal. However, the aforementioned disturbance, according to current estimations, extends for less than 2 metres after a million years. Consequently, most of the seal remains effective over the long term, helping to maintain a predominantly diffusive transfer regime in the tunnels.

Gas production by packages may also disturb the phenomenological evolution in the disposal tunnels over the long term. Radiolysis of some waste types (notably bituminised sludge) and moreover corrosion of the engineered components steel (primary waste containers) generate hydrogen. Preliminary assessments suggest that the gas pressure could in certain circumstances exceed the natural hydraulic pressure, i.e. 4 - 5 MPa. In this case, gaseous hydrogen could be transferred to the small fractures in the granite and through the seal toward the drifts. At this stage, no comprehensive quantitative modelling has been performed; it should nevertheless be noted that the repository and its drift network offer a significant expansion volume for gas dispersion. Furthermore, the consequences of the existence of a gaseous phase on radionuclide transport were studied in the "GAM" experiment at the Grimsel laboratory, Switzerland. This experiment proved that radionuclide transfer and retention in fractures were largely undisturbed.

In a nutshell, a disposal tunnel evolution is essentially determined by the continuous cementitious environment of the disposal packages throughout the repository life cycle, which in turn maintains the necessary conditions for immobilising radionuclides over very long periods.

1.1.3 Vitrified C waste and spent fuel disposal modules - A thermal phase and a very slow chemical evolution buffered by swelling clay engineered barriers

Once closed, the disposal modules gradually resaturate. Water from the granite fractures gradually saturates the handling drifts backfill and the plugs and swelling clay buffers in the disposal boreholes along the handling drifts. Disposal borehole resaturation may take anything from a decade to a few centuries or longer, depending on the hydraulic properties of the granite fractures. By design, the disposal boreholes are located in unfractured or only slightly-fractured granite rock.

• Disposal boreholes and engineered buffers

The transient phenomenon wherein the bentonite rings around the steel overpacks swell is also affected by the heat emitted by C waste packages. Numerous studies and experimental programs in underground laboratories have focused on the coupling between thermal phenomena and buffer resaturation. Examples include the "FEBEX" experiments in Grimsel, Switzerland, and the "Prototype Repository" in Äspö, Sweden, which involves *in situ* tests of spent fuel disposal concepts, the "TBT" experiment testing the behaviour of bentonite buffers at temperatures approaching or even exceeding 100°C. This research has yielded a thorough understanding of the phenomena at work and made it possible to satisfactorily model the swelling, pressurisation and behaviour of swelling clay structures when subjected to thermal load. In this respect, thermally dimensioning structures such that the temperature in disposal boreholes is limited to 90°C simplifies the simulations and makes them more robust. The swelling pressure of the plug and engineered barriers peaks at approximately 5 to 7 MPa.

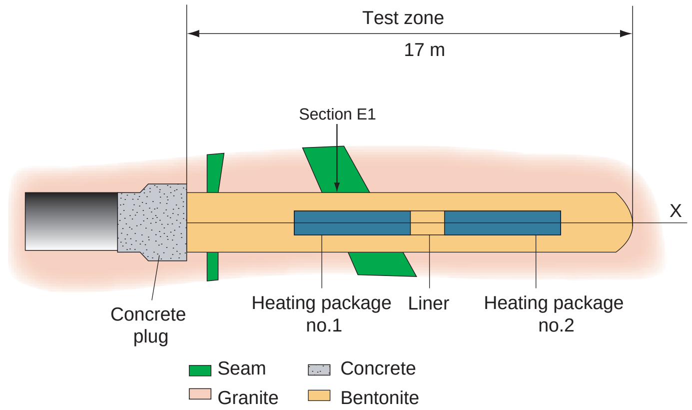
Experiment on swelling clay buffers

As for bentonite, the swelling mechanism for clay has been understood and successfully harnessed for decades. With regard to the repository studies, controlling the swelling in swelling clay buffers entails understanding the mechanism on the scale of the structures, i.e. demonstrating that:

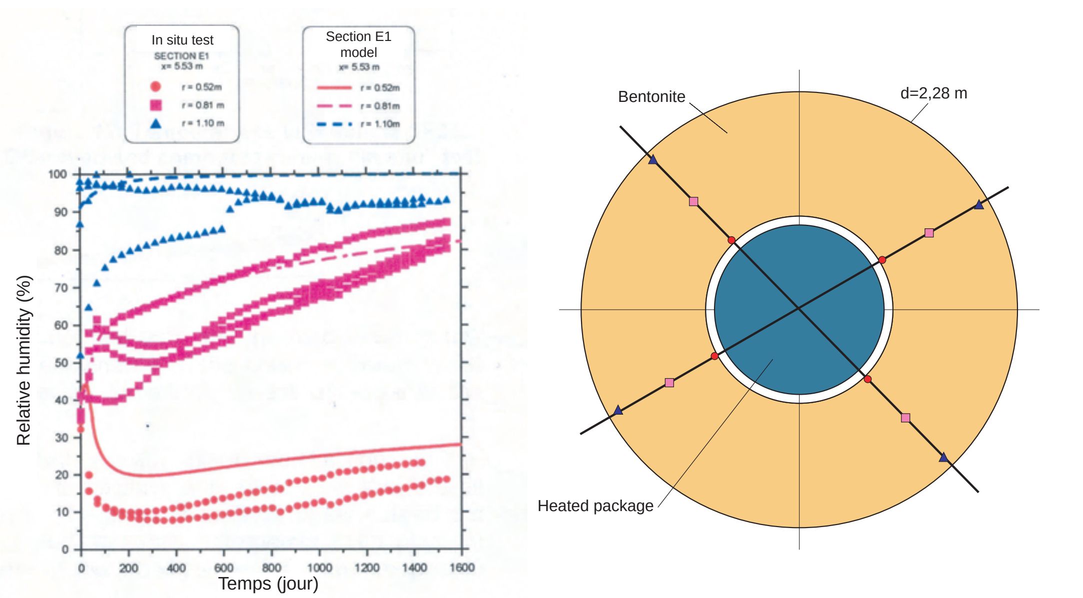
- the "joints" between the structures elements (i.e. bricks or rings) do not prevent homogeneous swelling,
- the heat released by the packages does not induce phenomena that irreversibly disturb the buffer swelling.

Experiments conducted in underground laboratories since the 1980's have explored these two aspects, initially on a small scale, but subsequently at full scale in conditions equivalent to those prevailing in repository situations.

The FEBEX experiment at the Grimsel laboratory has been testing the behaviour of a bentonite buffer in a large horizontal structure since 1997. Two heat sources simulate the presence of spent fuel packages. The water in the largely unfractured granite resaturates the bentonite, which swells progressively from the outer part toward the inner part near the package. This swelling has been monitored by instruments throughout the experiment, which began in 1997. In 2002, the part of the structure representing the heating package nearest the entrance to the structure (heating package no. 1) was dismantled (see figure below).



Scheme of the Febex experiment at the Grimsel laboratory in Switzerland



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Evolution of bentonite resaturation in the buffer

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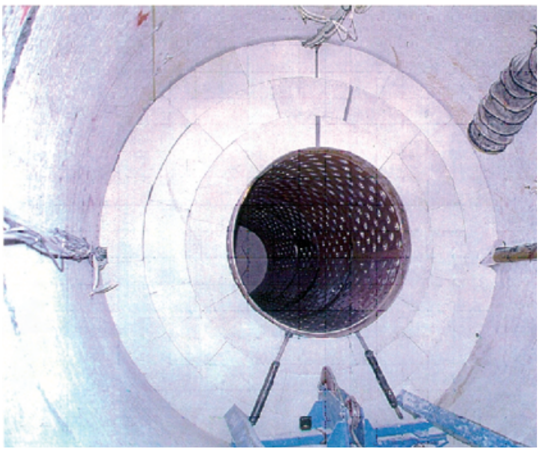
Instrument-based monitoring of the buffer showed that the swelling is consistent with the predictive models taking in account heating by the packages. The experiment confirmed, *in situ*, previous results obtained with samples and on small-scale mock-up tested in laboratory conditions.

Dismantling part of the experimental apparatus also showed that the joints between the bentonite bricks dating from when the buffer was built were no longer noticeable following the swelling process. These joints ceased to be preferential pathways for water in the structure. Swelling was complete throughout the structure.



a/ Prior to swelling, the swelling clay bricks present gaps at their joints

b/ When the structure has resaturated, the joints between bricks are no longer visible, as a result of the swelling within the buffer

After disposal boreholes resaturation and cell plug and bentonite buffer swelling, water flows through the disposal boreholes are very limited. Consequently, only very slow diffusive transfers can occur. In the disposal boreholes, the temperature reaches its peak (limited to 90°C by design) a few decades after closure, and then gradually decreases to a level similar to the natural geothermal temperatures, after a few thousand years (C waste case) or around ten thousand years (spent fuel case).

In this configuration, the evolution of the disposal boreholes is limited to the very slow chemical exchanges between the water, the disposal packages and the bentonite buffer.

• Overpack and steel sleeve in C waste disposal boreholes

With C waste, the disposal package is a 55 mm thick steel overpack. A 25 mm thick steel sleeve is placed between the package and the clay buffer for package emplacement and if necessary for easy retrieval. The steel overpack and sleeve may be altered, first by the partially oxidizing medium present during disposal borehole resaturation, then by the reducing medium generated by granite groundwater. Oxidizing alteration is minimised by the cell plug and the bentonite buffer. Over the long term, steel corrosion in reducing medium with the concomitant production of hydrogen is the main factor in overpack and sleeve alteration. The quantity of hydrogen gradually increases at higher pressures. As with B waste, the gas pressure could in certain circumstances exceed the hydrostatic pressure in the disposal boreholes (4 - 5 MPa) and cause gas to be transferred via the clay buffer toward the small fractures or overlying handling drifts.

Any reaction between alteration products (iron oxides) and the clay buffer bentonite can alter the buffer swelling properties. However, the swelling properties of the whole clay buffer will not be significantly affected as this alteration phenomenon is limited in terms of penetration and therefore rather superficial when compared to the buffer thickness (60 cm).

Steel overpacks corrode in a reducing medium at a very slow rate, approximately one micron per year, which means a leak-tightness for several thousand years at the proposed dimensions. Consequently, by the time water comes into contact with the waste glass matrix, the temperature at the centre of the package will be below 50°C, reducing the glass leaching rate and therefore the rate of radionuclide release.

From a mechanical point of view, the long-term degradation of the overpack causes a gradual readjustment of the swelling buffer and the internal layout of the disposal boreholes. This does not affect the chemical environment of the vitrified waste packages. Any radionuclide release occurs in a reducing medium, with a diffusive transfer regime controlled by the clay buffers, which contributes to the radionuclides immobilisation in the disposal boreholes.

• The copper container of the spent fuel disposal concept

The disposal concept adopted for spent fuel centres on the leak-tightness of a copper container with a service life longer than several hundred thousand years. This leak-tightness is dependent on maintaining a physicochemical environment in the disposal boreholes that preserves the thermodynamic stability of the copper. Accordingly, the design rules out the presence of steel components in the disposal boreholes in order to prevent any interaction between different metals. Furthermore, the buffers and disposal borehole plugs in contact with the containers following resaturation provide a reducing chemical environment that helps to preserve the stability of the copper. The engineered barrier bentonite (35 cm thick) of the disposal borehole acts as a filter against any elements liable to modify the container environment. The absence of any significant alteration of the copper container over the long term prevents the formation of corrosion products liable to affect the swelling performance of part of the clay buffers. Overall, in the long term, the disposal boreholes only evolve in terms of the response by the clay buffers to changes external to the repository, relating to the local geodynamic evolution. In the French geodynamic context, the foreseeable changes within a horizon of several hundred thousand years remain small, and not liable to significantly modify the physicochemical environment of the copper containers.

In summary, the evolution of C waste and spent fuel disposal boreholes is characterised by a gradual swelling of the plugs and clay buffers around the disposal packages during the thermal phase, which leads to a slow diffusive transfer regime. Once swollen, the swelling clay buffers provide a long-term physicochemical environment that helps to preserve the leak-tightness of the disposal packages and immobilise any released radionuclides.

1.2 Key aspects of the evolution of a repository with respect to radionuclide release and transfer

The phenomenological evolution of a repository in a granite medium determines the framework for the release of radionuclides from waste packages, and any subsequent migration from the repository to the biosphere.

The main vector by which radionuclides are released and transferred is water. Siting the disposal cells in granite rock of very low permeability and installing backfill and seals of low or very low permeability greatly restricts water movements inside the repository, which in turn helps to limit radionuclide release and transfer inside the structures.

Radionuclides: specific behaviour according to solubility and retention

Radionuclides can be classified in three broad groups according to their solubility and retention with regard to the granite medium (rock and fractures), the bentonitic clay medium of the engineered components (i.e. swelling clay-based backfill, cell plugs and buffers) or the cementitious medium (B waste cells):

- *"mobile":* characterised by high solubility and low to nil retention, e.g. iodine and chlorine,
- *"somewhat mobile" elements:* characterised by high solubility and high retention, e.g. caesium,
- *"very low mobility" elements:* characterised by low solubility and high retention, such as actinides (e.g. uranium and plutonium) and lanthanides (e.g. samarium and europium). The radiological inventory of the waste packages mainly consists of elements in the latter two categories.

1.2.1 Slow, limited release outside the repository

Apart from spent fuel disposal, for which the proposed design options involve designing a durable leak-tight copper container, radionuclides release by waste packages occurs as a result of degradation of the disposal packages by the water introduced as the cells (B waste disposal tunnels and vitrified C waste disposal boreholes) resaturate.

The length of time before water reaches the waste depends on the disposal cell resaturation kinetic, which varies from around ten to a few hundred years, or a thousand years in certain fracturing configurations.

• Slow chemical alteration of the B waste packages in the disposal tunnels

When water comes into contact with waste, only the radioactive elements at the surface of the waste are released. The other radionuclides are released as the waste is gradually altered; this process lasts from a few thousand years with certain metallic waste products (carbon steel, stainless steel, etc.) and bituminised sludge (B2) to a few hundred thousand years with other metallic waste products (zirconium alloy). The radionuclide release rate depends on the properties of the disposal packages concrete. With standard containers (e.g. for B2 waste), the released rate of radionuclides by the disposal package is essentially restricted by the alkaline properties of the concrete interstitial water. With containers featuring additional confinement capabilities (B1, B5.2 waste), the concrete hydraulic properties (low permeability and low diffusion coefficient) very significantly reduce the rate of radionuclides released, for as long as the aforementioned properties are maintained (i.e. between a few thousand and around ten thousand years).

• C waste: slow steel overpack corrosion kinetic and slow aqueous dissolution of the glass content

In the C waste disposal boreholes, radionuclide release begins after several thousand years, when overpacks are not anymore leak-tight. As water enters the packages it triggers the glass dissolution process and radionuclide release. The glass surrounding the C waste continues to dissolve over a period of between a few thousand years in the case of C0 glass, and a few hundred thousand years in the case of C1, C2, C3 and C4 glass.

• Disposal cells: largely stable physicochemical environments contributing to a low mobility of radionuclides

The physicochemical environments in the disposal cells (for B and C waste) help to ensure high retention and low solubility for most of the released radionuclides: the majority is adsorbed (trapped) or precipitates inside the disposal cells. Overall, the concentration of radionuclides in the disposal cell water is low. Combined with an essentially diffusive transfer regime, these phenomena means long enough transfer times between the packages and the disposal cell rock walls to allow many radionuclides to disappear by radioactive decay.

1.2.2 The role of granite in limiting the transfer of the most mobile radionuclides toward the environment

The most mobile and long-lived radionuclides are liable to migrate, within the disposal cell, from the disposal packages up to the rock wall. Granite rock constitutes an effective barrier to radionuclide transfer, on account of its very low permeability, low porosity and correlated diffusion-inhibiting properties: the diffusion transfer kinetics are of the order of one millimetre per thousand or several thousand years. The few small, slightly water-conducting fractures at the rock wall represent the only punctual pathways for radionuclides migration outside the cells. Due to the geometric, mineralogical and hydraulic properties of these small fractures, and the small hydraulic gradients, the flow-rate of radionuclides liable to be transferred outside the cells is small.

Radionuclides can migrate as well outside the disposal cells by diffusion toward the repository drifts, through the seals and backfill.

In the access drifts, radionuclides can migrate toward the granite via the small or medium-sized fractures intercepted by the drifts. The low permeability and retention properties of the backfill and seals are additional factors that delay the transfer of radionuclides in the repository.

Thus, the radionuclides liable to migrate beyond the repository are the most mobile and long-lived elements. Such elements include iodine 129, chlorine 36, caesium 135, carbon 14 and technetium 99 in the case of B waste, and iodine 129, caesium 135, carbon 14 and selenium 79 with C waste.

1.2.3 Radionuclide transfer in the granite massif and the repository environment

After transfer into the small fractures in the granite, radionuclides migrate towards other generally larger and more hydraulically transmissive fractures (faults). The pathway configuration depends on the fractures network arrangement and, in particular, the hydraulic interconnections. On the scale of a repository module, especially with larger ones (C waste case), there tend to be multiple pathways, which separate the radionuclide flows, allowing them to disperse towards the environment and the various natural surface outlets. This phenomenon mainly concerns the most mobile and long-lived radionuclides, such as iodine 129 and chlorine 36. The other radionuclides liable to be sorbed or precipitated in fractures (i.e. caesium 135, technetium 99, selenium 79 and carbon 14) are greatly retarded along their pathways.

2 Long-term safety analysis

In principle, the safety approach is based primarily on the repository behaviour, as predicted on the basis of the available scientific knowledge. The approach aims to formalise this knowledge within the framework of a safety model offering a simplified yet cautious representation of the various phenomena and their progression over time. It also tests the limits of validity of this representation by evaluating the hypothetical effects on overall performance, of varying certain parameters. Then, it also examines situations not included in the evolution model predicted or envisaged by the repository designer. Such events are also included in a representation, and their importance in terms of their probability of occurrence with their consequences must be assessed. In so doing, the approach examines any residual uncertainties and shows how they are accounted for.

The outcome of this work provides ultimately a series of quantitative evaluations, in particular in the form of indicators reflecting the any impact that the repository may have on man and the environment, or on safety function performance. It evaluates the validity of the safety functions and constitutes a test of the robustness of the overall system.

Adapting the approach for the generic context of studies of the granite medium

Unless a specific site is studied, the long-term safety assessment of a repository in a granite medium cannot claim to reach conclusions about a specific granite site, regarding the performance of the studied system.

However, based on the proposed generic repository architectures, the analysis examined all issues relating to waste disposal in a granite medium. In this context of generic studies, the approach also incorporated experience feedback from assessments performed abroad, in particular through comparison with the analyses using international "FEP's" databases.

Three geological site models were developed, to allow for possible variability in the properties of French granites. These models, based on an analysis of the properties of French granites, are representative of France's geological context. Without claiming to exhaustively cover all possible configurations, they make possible to examine how the main features of a granite massif are involved in evaluating a repository long-term safety.
The safety analysis in the *Dossier 2005 Granite* is methodological in nature; accordingly, Andra extended the range of methods already used, developed certain methods and strove to master the tools available internationally with the purpose of evaluating safety in a fractured medium.

Comparison with international "FEP's" databases

International FEP's databases contain a list of site characteristics and repository engineered components ("Features"), together with the events ("Events") and phenomena ("Processes") liable to influence the repository evolution. They form a reference base of the elements to be considered in safety analyses.
Drawing on the international FEP's databases, dealing with various types of host formation, a FEP's database relevant to the generic context of granite was produced. This FEP database was intended to be as exhaustive as possible and consistent with the databases of Andra foreign counterparts. To this end, a systematic comparison with the international databases managed by OECD/NEA was performed.
The second step was to compare it with the various components of the proposed generic repository architectures and the phenomena taken into consideration in the repository "normal" phenomenological evolution. Analysing the FEP's made possible to distinguish those expected to occur ("normal evolution FEP's") from those that would only occur as the result of a malfunction ("altered evolution FEP's").

2.1 From understanding phenomena to performing safety calculations

The phenomenological evolution of a repository in a granite medium is based on existing knowledge of the medium, and reflects the evolution expected by the designer through the design provisions adopted in order to limit the complexity of the phenomena and uncertainties relating to phenomenological behaviour. In this respect it represents the repository evolutions considered to be the most probable. Such evolutions are described as "normal" evolutions. Accordingly, its description, via the phenomenological analysis of repository situations (PARS), is an important part of the safety analysis.

Evaluating a repository performance by means of calculations that incorporate the phenomena involved in its evolution entails integrating them into a simplified and consistent historical representation. This history uses cautious assumptions and simplification must be performed in a conservative framework. The history forms a scenario that, while not claiming to represent the future reality, aims to encompass the full range of probable situations, in a penalizing approach. This scenario forms the basis for a numerical evaluation carried out with different models. Repository performance indicators can then be computed on the basis of these safety calculations.

2.1.1 Uncertainty management and the various scenarios considered in the framework of the generic studies into granite

It is not possible to conduct a meaningful safety analysis and achieve the safety objectives without identifying and dealing with uncertainties. In the context of generic studies of the granite medium, the objective was i) to identify the main types of uncertainties that must be treated when designing a repository in a granite medium, ii) and then by analysing them and performing related calculations, to assess the decisive parameters for repository safety and the associated risks.

The various studied scenarios have showed the role of the main repository components (i.e. the packages, plug, seals and geological medium) with respect to the repository safety functions: "preventing water circulation in the repository", "limiting radionuclides release and immobilising them in the repository", and "delaying and reducing radionuclide migration". Without claiming to be exhaustive, the scenarios were chosen after comparing the granite FEP's base with relevant international FEP's bases in order to identify groups of "normal evolution FEP's" and "altered evolution FEP's" that could be used via encompassing (envelope) scenarios to manage the main uncertainties.

Uncertainty classification

A distinction is drawn between uncertainties relating to the repository characteristics (Features), to events external to the repository (Events) and to the repository phenomenological evolution (Processes).

• Uncertainties relating to the repository characteristics ("Features")

- *about the repository project input data,* i.e. the inventory and package properties, independently of their behaviour in the repository,
- *concerning the intrinsic characteristics of the geological medium or a repository component.* They may relate to a lack of precision of measuring techniques, or to certain parameters that cannot be measured directly, which are therefore estimated on the basis of data available in the bibliography. They may also be due to spatial variability of the component, with respect to sampling that is necessarily limited. This applies when characterising rock with samples.
- r*elating to technologies.* The technological provisions to be implemented cannot be finalised at the generic approach stage. It is therefore important to make allowance for uncertainties due to variability of the repository possible operating conditions, and to limited knowledge about the conditions in which a particular technology can be used in an underground context.

• External events ("Events")

They are a particular form of uncertainty regarding repository evolution. A general distinction is made between natural phenomena occurring at the surface (e.g. climatic or tectonic events, etc.), which are theoretically predictable although often subject to considerable uncertainties, on one hand, and events attributable to the actions of man (e.g. intrusion and anthropic effects), which in most cases cannot be predicted beyond a reasonable horizon, on the other. Such events are treated as uncertainties on account of the disturbances they entail. Partially conventional approaches are traditionally used to limit the extent of the uncertainties to be taken into account. In accordance with RFS III.2.f., future human behaviour is assumed to be largely the same as the current one. On the other hand, it is possible to use a predictive approach, based on past evolutions, for most natural phenomena. Even in this case, uncertainties regarding the distant future should be taken into account.

• Uncertainties relating to phenomena governing the repository evolution ("Processes")

After obtaining data for all components of the disposal system, it is necessary to understand, and represent how they interact and influence the system evolution. Due to the complexity of the involved phenomena, a detailed understanding of each interaction may not be obtained and therefore an overall representation must be adopted in order to describe at best the functioning of the system. Representing phenomena through modelling is affected by uncertainties to the extent that it proceeds by simplification when compared to a more detailed representation of phenomena. It is particularly the case for coupled phenomena, generally more difficult to represent. This category includes uncertainties resulting from the need to predict the system behaviour over extended periods, from the limits of validity of modelling or from the existence of more than one model representing the same set of empirical observations.

Developing a normal evolution scenario for a repository in granite entails analysing the planned functioning of the repository. Various sensitivity calculations can be performed in order to also appraise the uncertainties relating to the characterisation of, on one hand, the granite hydraulic and transport properties and, on the other hand, the properties of the engineered components. The normal evolution scenario addresses the principal uncertainties involved in the repository design process; these uncertainties would then be managed along the site reconnaissance process.
A series of altered evolution scenarios covered cases involving the failure of the repository's main engineered components (packages, plugs and seals) as well as a failure in the reconnaissance process of the granite site. To a large extent, these scenarios cover most of the failures and uncertainties relating to the repository process.

2.1.2 The modelling approach

• Choice of indicators

Without any specific site, it would be meaningless to evaluate repository safety on the basis of a dose impact, since the calculations must take the site's environmental conditions into consideration. In a context of generic studies of the granite medium, a series of intermediate indicators were chosen instead, with the aim of understanding the individual functioning of the main repository components:

- indicators relating to the quantities of water transferred in the various parts of the repository assess the repository performance with respect to the "preventing water circulation" safety function,
- the quantity of radionuclides present at certain key points of the repository at different stages of its evolution assess the confinement performance of the various components, and facilitate the task of identifying overall robustness factors. This indicator relates more specifically to the "limiting the release of radionuclides and immobilising them in the repository", and "delaying and reducing radionuclide migration" functions.

• Choice of models and parameters values

As the research is being conducted for generic sites, it is important to specify the conditions in which the granite massifs were simulated in the calculations.
Relatively few massifs in France have been surveyed from a geological and hydrogeological perspective with a sufficient level of characterisation in order to enable a modelling approach taking the properties of a particular site into account. Furthermore, performing the calculation for a specific site would not be consistent with the objectives of the dossier, which is specifically intended to be generic in nature.

In order to allow for variability in the properties of French granite massifs, three geological site models ("M1", "M2" and "M3") were produced, based on a synthesis of available knowledge of French granites in the form of a typological classification. This typological analysis allows identifying and ranking the granite characteristics for which variability is most likely to influence a repository design.
The geological site models were developed before the hydrogeological models and radionuclide transfer simulations. They were described precisely enough to ensure their own geologically consistency and to faithfully reflect configurations representative of the French geological context. In particular, they are inspired by configurations found in the Massif Central and Armorican Massif. The models were not built with a view to comparing sites, and they do not claim to exhaustively represent all configurations liable to be encountered. Rather, they provide a realistic basis on which to appraise the role of the various characteristics with respect to hydrogeology and radionuclide transfer in safety analyses.

Accordingly, each model covers:

- different morphostructural configurations, i.e. the relationships between the granite massif, the surface topography and the other formations surrounding the granite massifs,
- different fracturing organisations, both for the small fracturing that must be considered on the scale of the repository structures and for the large one treated on the scale of the massif as a whole,
- granites of different lithological and mineralogical types.

Most of the calculations were performed using the M1 and M2 site models.

Main geological characteristics of the three site models

• The "M1" site model

- Large (several thousand km^2) hercynian granite massif, having a relatively contrasted topography and a "dome" morphostructural configuration favourable to long repository-to-surface hydraulic transfer times,
- Fracturing organisation characteristic of a tectonic affected by the Alpine orogeny,
- Granite of a type having an "average" mineralogy that is not particularly favourable to fracture clogging by hydrothermal minerals.

• The "M2" site model

- Small (approximately 100 km^2) hercynian granite massif, having a relatively uniform topography and a "depression" type morphostructural configuration, not so favourable for long repository-to-surface hydraulic transfer times,
- Fracturing organisation characteristic of hercynian granite fracturing, moderately affected by the Pyrenean and Alpine tectonics,
- Granite of a type whose mineralogy is favourable to fracture clogging by hydrothermal minerals.

• The "M3" site model

- Medium-sized (a few hundred km^2) cadomian granite massif, having a relatively uniform topography and an "inclined plane" type morphostructural configuration moderately favourable to long repository-to-surface hydraulic transfer times,
- Fracturing organisation typical of a cadomian granite affected by the hercynian tectonic and moderately affected by the Pyrenean and Alpine tectonics,
- Granite of a type having an "average" mineralogy that is not particularly favourable to fracture clogging by hydrothermal minerals.

The hydraulic and transport parameters relating to fracturing are established, on the one hand, on the basis of data already obtained in France, notably at the Vienne site (1994-1996), which was studied by Andra, and at the site in Auriat (Creuse département), which was studied by CEA (1980-1981), and, on the other hand, by comparing the geological characteristics of fracturing in the various site models. A large corpus of international available data (Sweden, Finland, Switzerland and Canada) was also a contribution in order to confirm the appropriateness of the parameter values selected for the simulations.

The sensitivity of the hydrogeological models and radionuclide transfer simulations to the fractures hydraulic and transport parameters was tested for each of the geological site models.

5

• "Test values" of the granite medium parameters

Certain simplifications were introduced into the geological models during the successive hydrogeological modelling stages, which were conducted on various scales (i.e. region, massif, repository and disposal module). It was also necessary to choose which hydraulic and transport parameters to include. Value ranges were considered both for the variability of the aforementioned parameters for each geological site model and for the uncertainties relating in particular to the techniques used to survey and characterise the fractured medium.

In the context of generic studies of the granite medium, it is not possible, however, to define the degree of conservatism of the "test values" adopted for the parameters. Such a definition would only become meaningful if undertaken in conjunction with the survey and characterisation of a specific site. However, a pair of values for the main hydraulic and transport parameters of the granite and fractures was tested in the normal evolution scenario. The resulting calculations allow appraising the sensitivity of repository performance to the various studied parameters, and to establish orders of magnitude for repository performance for the various design options and geological site models under consideration.

• Architecture modelling

The various components in the generic repository architectures adopted as reference for the safety assessments are represented by their main radionuclide transport characteristics. These characteristics notably include the hydraulic and transport properties of the disposal packages, plugs and buffers in the disposal cells, and the backfill and seals in the drifts and access structures. For each of these components, the existing knowledge of the materials and experience feedback from foreign safety analyses were used to test at least two models or parameters that enable to characterise the possible variability. The parameters and models are qualified (as "phenomenological", "conservative" or "penalising") according to the degree of conservatism with which they cover the uncertainties.

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.

• Modelling radionuclide transfers in granite - in "fracture networks" and in the "equivalent porous medium"

Modelling the transfer of radionuclides in the fractures in a granite massif requires certain simplifications, which can be achieved in two ways:

- *"fracture network" models* consider explicitly the fractures. In this case, the simplification involves grouping fractures together into families. Statistical laws are used to distribute their geological, hydraulic and transport properties across the granite massif,
- *"equivalent porous medium" models* take the simplification process further. The fractures are not explicitly modelled; instead, "equivalent" hydraulic parameters are assigned to the granite massif, or to certain parts of the massif, in order to implicitly take the fractures into consideration.

At the scale of the repository structures and immediate environment, the granite is represented using "fracture network" models. These fracture network models required the application of statistical distribution laws to assign the geological and hydogeological fracture properties in each of the studied site models.

At the scale of a site and the granite massif hosting a repository, the geological medium is represented using "equivalent porous medium" models. For each of the studied geological site models, the modelling process includes techniques for maintaining continuity between the different modelling scales of the granite and its fracturing

2.1.3 Simulation and calculation tools

Two types of simulation tools were used for the calculations. The tools used for "fracture network" simulations are those used internationally for studies of geological disposal. International cooperation initiatives, as notably the "Connectflow" project, address the development of nested "fracture network" and "equivalent porousmedium" models as a means of maintaining continuity between the various modelling scales involved in transfer simulations. The tools used for "equivalent porous medium" simulations are the same as used for the clay medium, for example (see table below).

Models	Codes
Hydrogeology and particle tracking in an equivalent porous medium.	- Connectflow (NAMMU component, 3D modelling, finite elements). - Geoan (3D modelling, finite differences). - Porflow (3D modelling, finite differences).
Hydrogeology and particle tracking in fracture networks.	- Connectflow (NAPSAC components, 3D modelling, finite elements). - FracMan (fracture network generation) and MAFIC (hydraulic resolution of networks, 3D, finite elements).
Transport in an equivalent porous medium.	- PROPER (COMP-23 component, modelling in compartments of engineered barriers, finite differences). - Goldsim (volume modelling of engineered barrier). - Porflow
Transport in fracture networks.	- PROPER (FARF-31 component, 1D modelling, stream tube concept). - Path Pipe (Pipe network for transport) and Goldsim (1D pipe network modelling)

Phenomena modelling and digital codes

5

2.2 The associated safety models

2.2.1 The safety model basic data

The most representative waste package types of each of the package categories (B waste, C waste and spent fuel) were retained as reference for the impact calculations:

- B waste of the B2 type (bituminised sludge) and the B5.2 type (compacted hulls and end-caps), representative of both the largest volume of B wastes, two types of wastes with sufficiently distinct characteristics (thermicity, radioactivity, chemical composition) and two packaging modes,
- C waste of the C2 type, representative in the radiological inventory of the largest part of the C waste,
- spent fuel of the CU2 type (MOX), for which the labile activity released at the arrival of water is, in case of a failure of the copper container, the highest among the various spent fuel types.

Similarly, calculations were carried out on the most representative radionuclides of a repository performance with respect to long-term safety. These radionuclides are long lived radionuclides and the most mobile:

- B2 type package: iodine-129, chlorine-36, caesium-135, technetium-99 and selenium-79,
- B5.2 type package: iodine-129, chlorine-36, caesium-135, technetium-99 and molybdenum-93,
- C2 type package: iodine-129, caesium-135, carbon-14, tin-126 and selenium-79,
- CU2 type package: iodine-12, caesium-135, carbon-14, tin-126 and selenium-79.

In addition, an actinides chain (thorium-229, uranium-233, neptunium-237, americium-241, plutonium-241, curium-245) was treated for methodological reasons for a part of the waste packages, namely, the B5.2 type packages and the C2 type packages.

2.2.2 Representation of the repository in time and space

By design, the repository consists of several separate zones corresponding to the various waste types. The assessment of the impact of a repository would, therefore, imply for a particular study site defining the general architecture of the repository specifically for the geological configuration of the investigated site. In the generic context of the Dossier 2005 Granite, this is not possible. The objective is more generally to identify by means of calculations and sensitivity analyses the main factors affecting a repository performances. To do this, the scenario treats separately the case of the various types of waste selected: B2 and B5.2 waste, C2 waste and CU2 spent fuel (MOX). The calculations are based on the representation of a repository tunnel of B waste (B2 and B5.2 wastes) or a module of C2 waste or spent fuel CU2 (MOX).

For this purpose, it was decided to keep in each of the considered geological site models the same emplacements for the tunnels (B waste) or repository modules (C waste and spent fuel) considered. This contributes to discriminating more simply in the analysis of the repository performance in granite the factors related to the package types from those related to the geological medium characteristics.

The choice of the emplacements was not aimed at subordinating the repository layout to the characteristics of the granite massifs of the three geological models. This would have been illusory considering the generic character of the data used. The emplacements were decided on based on the regional geological and hydrogeological models created for each site model, excluding the proximity of major fault zones and implantations clearly nonconforming from the hydrogeological viewpoint to the recommendations of the Basic Safety Rule RFS III.2.f. (steep hydraulic gradients, hydraulic unload zones right above the repository, etc.). Two theoretical emplacements were retained for each site model, which allows analysing how siting affects the long-term safety of the repository.

From a temporal viewpoint, the assessments are made for a repository after closure, at the scale of a hundred or so years after the start of its construction. This does not presuppose the duration of a reversibiity phase which is unknown by definition (century or multi-century). This assumption arbitrarily sets a common reference for all the calculations. Considering the minor resaturation transient durations mentioned above, the repository is assumed to be resaturated as of this date.

With respect to the geodynamic evolutions of a site over the very long term, the calculations do not take into account possible changes in the context of the granite massif which would be derived from them (for example, hydrogeology). Besides the fact that they would be insignificant in the French geological context in the scale of tens to hundreds of thousands of years, such changes would only be justified for a specific site, which is beyond the generic framework of the studies.

2.2.3 Representation of the waste and radionuclides release

• B waste packages

The representation of the packages is different for the two waste types (B2 and B5.2) retained for the calculations.

For the B2 waste (bituminised sludge), the disposal package is assumed as not being water-tight as soon as the repository is closed, which is a cautious assumption. The concrete container which is not impervious imposes, however, a chemical environment with a high pH (between 10 and 12.5), limiting the flux of some radionuclides thanks to precipitation and sorption phenomena. The release kinematics is represented by a model developed around a phenomenology experimentally validated in the laboratory. It is based on water take-up by the 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 during initial waste treatment are neglected. The proposed release rate leads, at 10,000 years, to a release of 90% of the initial mass contained in the bitumen.

For the B5.2 waste, the calculations make reference to the case of a container to which complementary confinement properties are assigned, that is, a container with hydraulic properties which limit the release of radionuclides for 10 000 years. The radioactive inventory contained in the zircaloy claddings and the structure waste causes in contact with water a release which is directly related to the corrosion rate and leads to a complete release in 100 000 years.

• C waste (vitrified) packages

The vitrified waste is placed in a 55 mm thick carbon steel overpack. This thickness ensures, considering the variations in the configuration of granite sites in France (particularly with respect to the chemical composition of the water), leak-tightness of several thousand years during which no release can take place. On an exploratory basis, the calculations were made with the same cautious assumption of a release starting after 1 000 years for the various site models.

The overpack design presents a high robustness with respect to possible manufacture defects. Nevertheless, we have cautiously included the possibility of such a defect in the calculation. At the current stage of the studies, its definition is arbitrary. A fraction of defective packages amounting to approximately 1/10 000 of the total number of containers is thus taken as an assumption, that is, one package for the C2 waste inventory, on which the calculations are based. The defect is conventionally expressed to take place approximately one century after the repository closure. It is evidenced in the calculations by a total loss of leak-tightness, which is penalising.

With respect to the glass itself, the release of radionuclides initiates as soon as the overpack loses its leak-tightness. For the C2 waste taken as reference in the calculations, the release rate complies with a so-called "$V_0S \rightarrow Vr$" phenomenological model consisting of two phases. In the first phase, the model is based on the initial dissolving rate of glass up to saturation of the surrounding medium in silica. Subsequently, in a second phase, the dissolution kinetics decreases to a residual rate (Vr). For C2 waste, the glass will dissolve over duration of approximately 300 000 years.

• Spent fuel packages

The proposed repository concept considers in its provisions the choice of a copper container of the KBS-3 concept developed by SKB in Sweden. The copper container is designed to be tight for long periods. Without a major external change to the geodynamic context, which is a hardly conceivable hypothesis in the French geological environment, leak-tightness is ensured for the period concerned by the calculations, that is, several hundreds of thousands of years.

As a precaution, the case of an initial defect of the container is treated in the normal evolution scenario according to a proportion of packages which is arbitrary at this stage in the studies and set in a similar fashion as in the analyses carried out in Sweden to one overpack for the CU2 retained inventory, which is the basis of the calculations. The defect is a hole of 5 mm2 at the container lid weld. The water which penetrates into the container causes the corrosion of the cast steel insert of the container and then its rupture after 20 000 years, which is the time determined from specific modellings conducted by SKB in Sweden. These 2 stages concerning the loss of the copper container leak-tightness form two successive phases of the model. 5

The release model depends on the location of the radionuclides in the assemblies. The following can be distinguished:

- *a progressive release model of the radionuclides* contained in the metallic components. The release is assumed congruent, that is, directly related to the corrosion rate of the components. This leads to release rates varying from 5×10^{-5}/year for the radionuclides contained in the claddings (the radionuclides contained in the zirconia at the surface of the claddings is considered labile) to 2×10^{-3}/year for the radionuclides contained in the inconel structure elements ;
- *a dissolution model of the fuel matrix* under the effect of radiolysis (so-called radiolytic model). This dissolution model adopted in the reference calculation is a conservative model more penalising than that the one generally adopted internationally;
- a fraction assumed labile.

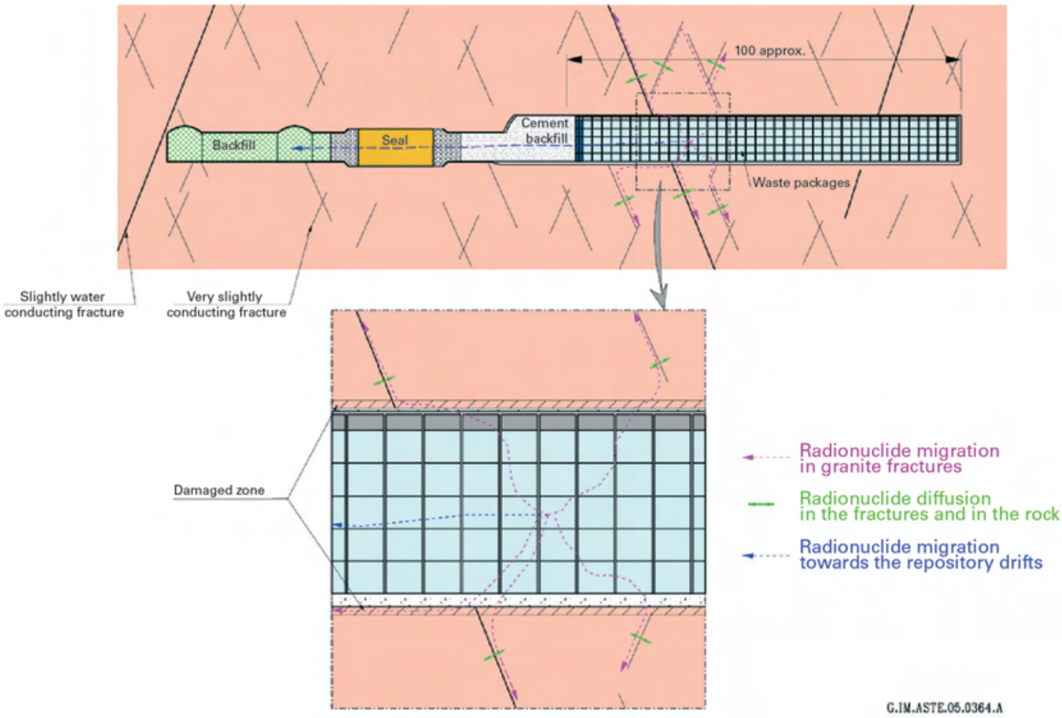
2.2.4 Representation of the migration of the radionuclides in the disposal cells

For B waste, the radionuclides migrate through the concrete of the packages to the granite in the wall of the disposal tunnels. The transfer system is a mixed diffusion/advection system. The concrete limits the flows of some radionuclides by precipitation and sorption phenomena, which are taken into account in the calculations.

The granite zone damaged by the excavation of the wall disposal tunnels is explicitly taken into account in the calculations with a thickness of 50 cm. It is interrupted by the seal at the tunnel entrance.

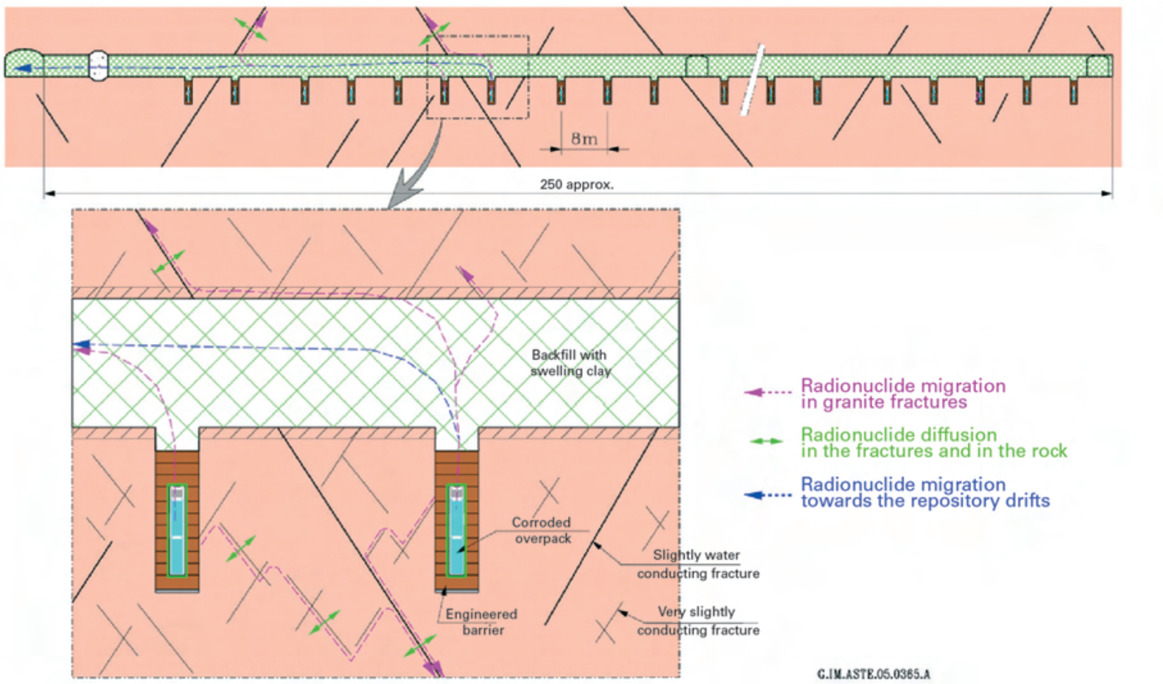
The purpose of the seal is to slow down the water flows which may pass through it. Therefore, it has properties which also limit radionuclides transfer. The values retained for the hydraulic parameters are based on the equivalent permeability obtained during the full-scale test of a clay-based seal during the "TSX" test conducted in the underground laboratory in Canada, that is, 10^{-11} m/s. This choice represents a cautious option in that it underestimates the conceivable performances subsequent to the test. The radionuclides migrate in the seal predominately by diffusion.

The kind of clay used for sealing leads as well to allocate performances of chemical retention of the elements.



Scheme of the migration of radionuclides in the B waste disposal tunnels

For C waste, and once the steel overpack lost leak-tightness, the radionuclides migrate through the clay buffer engineered barrier (60 cm thick) to the granite in the wall of the disposal boreholes. Transfer takes place by diffusion due to the very low permeability of the swelling clay buffer. The radionuclides also migrate partially according to the same diffusion system to the overlying handling drifts through the disposal cell plug made up of the same swelling clay (and 1.50 m thick).



Scheme of the migration of radionuclides in the C waste disposal boreholes and the handling drifts

For spent fuel, the figure of the migration of radionuclides is the same as for C waste. It only concerns, for spent fuel, the case of a defective container taken into account in the safety calculations.

2.2.5 Representation of the migration of radionuclides in the drifts and the access structures (shaft, ramp)

Leaving the disposal cells, a fraction of the released elements reach the backfilled drifts of the repository and transit through these drifts before migrating to the fractures in the granite at the wall of the drifts. The backfills made up of crushed granite and bentonite composites have a low permeability (10^{-10} m/s). The nature of the backfills is such they are also attributed retention properties. The values of the retention parameters are determined according to a proportion of 15% swelling clay.

The representation of the drifts seals is similar to that of the plugs of the B waste disposal tunnels. The hydraulic and transport phenomena taken into account in the calculations are of the same kind as the phenomena involved in the seals of the disposal tunnels.

For a repository in the granite medium, the quantity of radionuclides reaching the surface-bottom access structures (shaft and ramp) via the other drifts of the repository is negligible. In fact, the conducting faults intercepted by the drifts connecting the repository modules and the access structures form hydraulic barriers to the migration of the radionuclides. Also, the calculations assume that all the radionuclides released by the disposal cells of a module migrate to the granite within the granite block where the module is installed.

2.2.6 Representation of the migration of radionuclides in the granite

The representation of the migration of the radionuclides in the granite is based on the determination of hydraulic pathways in the network of the fractures of the massif, the repository host formation. These pathways are established from hydrogeological models at various scales: at the regional scale, that is, for a dimension of several hundred km^2 ; at the repository scale and its surrounding (also denoted the "far field"), that is, for a dimension of ten km^2 to several tens of km^2 ; at the repository module scale (also denoted the "near field"), that is, for a dimension on the order of a km^2 or a fraction of a km^2.

- **At the scale of the repository module**

At the repository module scale, the hydraulic pathways are determined from "fracture network" models, where the fractures of various dimensions are explicitly represented based on a stochastic processing of the geological and hydrogeological data. The calculations of the migration of radionuclides along these pathways involve:

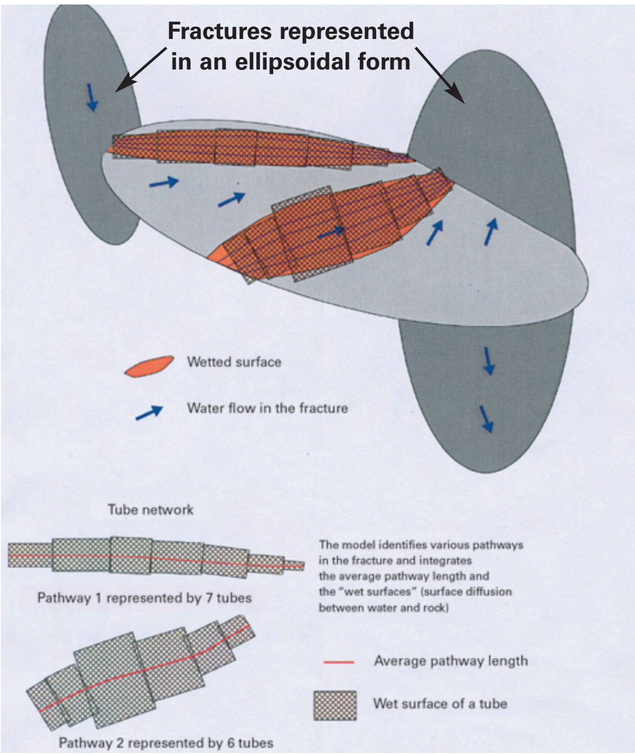
- advection phenomena (and associated dispersion phenomena), the main driving forces behind water movements;
- radionuclide diffusion phenomena in the rock on the fracture planes;
- radionuclide retention phenomena by sorption on the minerals of the fractures and the granite rock itself.

The representation of these phenomena in the complexity of a fracture network entails simplifications in the geometry of the pathways and the exchange surfaces between the water and the fracture planes. The adopted simplification modes are based on the results obtained from many experiments conducted in foreign underground laboratories, particularly within the "TRUE" programme and the modelling exercises of the "Aspö Task Force" conducted in international cooperation for fifteen years. The transport parameters for the calculations are determined from the results of these experiments taking into account, through the various in situ geological models, the potential variability of the mineralogical characteristics of the fractures and the types of granite represented. The variability concerns, in particular, the nature and intensity of the "natural clogging" of the fractures by hydrothermal minerals, as well as the diffusion properties of the rock to the planes of the fractures.

The pathways of radionuclides in a fracture network: the "tube" model

The "tube" model generally adopted for radionuclide transfer simulations in a fracture network is based on the observation that the irregularities of the geometry of a fracture and the fracture/fracture connections lead to generally channelled flows of water in the fractures (figure below). Tubes form a simplified representation of channeling which respond to the digital requirements of the calculations.

The water flux from the fractures passes completely into the model's tubes. Considering the low kinetics of the water movements, the radionuclides migrate by diffusion into the rock altered at the fractures plane: the contact surface between the water and the granite ("wetted surface") is an interacting parameter in the diffusion extent. The granite diffusion coefficients are generally higher at the fractures plane than in the sound rock, which is an element favourable for the retention of radionuclides. The retention parameters selected for the calculations take also into account the mineralogy of the granite rock at the fractures plane.

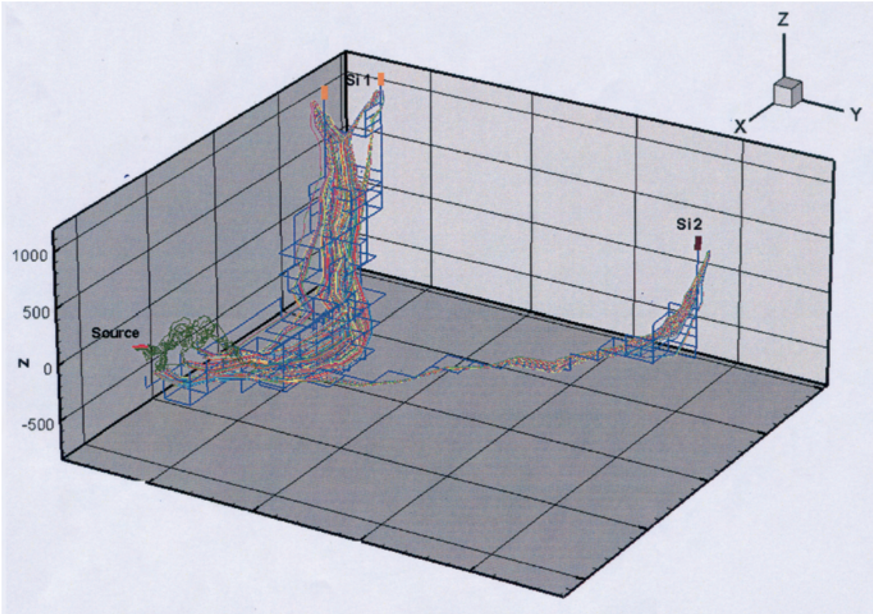


Tube model of water and radionuclides pathway in a fracture

• At the scale of the repository and the geological medium

At the scale of the repository and the geological medium, the hydraulic pathways are determined from models ensuring continuity between the representations in "fracture networks" and the representations in an "equivalent porous medium" on the regional scale. Along the hydraulic pathways, the representation of the migration of the radionuclides is similar to that made at the repository module scale.

The migration of radionuclides is represented up to the vicinity of the granite surface. The quantities of radionuclides are assessed when they enter the superficial part of the altered granite (that is, approximately a hundred - some metres under the surface). This choice allows, in generic assessments, getting around uncertainties related to the surface and site-specific environment.



Performance calculations of a repository in a granite medium: "tube" model of radionuclides pathways between the repository (source) and the outlets (Si1 and Si2)

2.3 Performance calculations: results and methodological lessons learnt

The performed calculations do not aim at assessing the impact of the repository on a particular site as the data required to perform this analysis are not available. The approach consisted of focussing on the indicators which translate the performances of the safety functions. These indicators cannot be compared directly to regulatory references, standards or recommendations of the Nuclear Safety Authority. Neither can they be used to compare the site models between them, which by the way is not the purpose of the calculation. In fact, if a site has less favourable characteristics with respect to a given safety function, it is not as such ruled out from the viewpoint of the repository overall safety, which combines the various functions within a system.

On the other hand, the following information can be obtained from the analysis of the calculations for each site configuration and more globally:

- the characteristics of the granite massifs which most influence the performance of the safety functions, either in the absolute (that is, on all the site models), or within a specific morpho-structural context (on a site model, in particular);
- the way in which the engineered components complete or provide a redundancy with respect to the performances of the host formation alone.

In addition, the use of several types of methods (calculations in an equivalent porous medium, calculations in fracture networks – designated hereafter under the term "DFN calculation") and different software provide useful instruction on the type of information which would be accessible according to the methods implemented, should an analysis is have to be conducted on a real site.

The calculations are presented according to three safety functions related to transfer by water:

- preventing water circulation in the repository;
- limiting the release of radionuclides and immobilising them in the repository;
- delaying and reducing radionuclides migration.

In addition to the normal evolution scenario (SEN) showing the performances of the safety functions in a context corresponding to the most likely phenomenology, so-called "altered evolution" scenarios (SEA) corresponding to accidental type situations were treated. Thus, cases of in-series failure of waste containers, seal failures, and bad survey of the granite fracturing were dealt with. The SEA provide additional information on the safety functions. They focus more completely than the SEN alone on the importance of each component by showing the effects of a loss of functionality of each on the others. They also allow making sure that the repository remains robust versus failures, even if unlikely.

Therefore, the results from the SEA are presented jointly with those from the SEN in order to complete information as the reading progresses.

2.3.1 Lessons learnt related to the function "preventing water circulation in the repository"

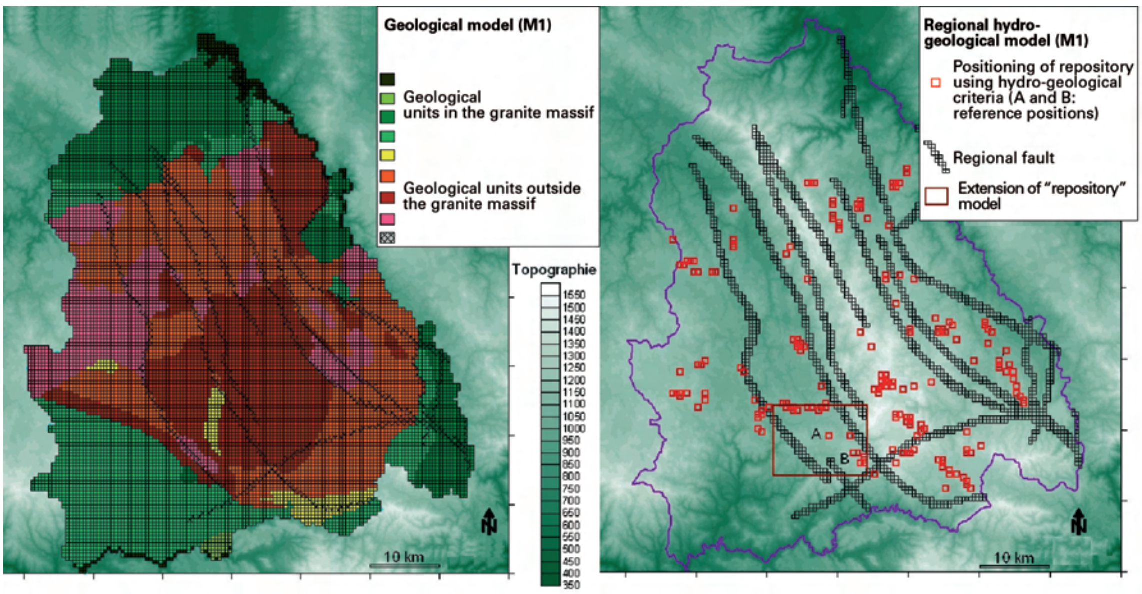
• Siting a repository at the "massif" scale

The purpose of the function is to limit the water flows into the disposal structures, which can both alter the repository materials and carry along the radionuclides toward the environment.

This objective may be met by adapting the repository to the various fracturing scales. In order to estimate how a massif may accommodate a repository, a first stage would be to determine adequate emplacements from the viewpoint of hydrogeology. On the various site models covered by the calculation, possible emplacements were thus determined based on the hydrogeological models built at the regional scale.

The representation of the mass is supported by modelling, which includes the geological data, the large regional faults, the topography (hydraulic recharge zones, hydraulic low points) and the large-scale permeability of the granite. This permeability is assessed by software by generating fractures on a random basis, while forcing the fractures to comply with the characteristics imposed by geology. The fractures transmissivity evolves with depth according to the laws derived from observations on French and foreign massifs.

This model serves as a support for the calculation of the hydraulic pathways between the repository and the potential natural outlets according to the various possible locations. Thus, sites can be proposed for a repository according to the criteria defined by the designer: for example, it is convenient to favour positions leading to long hydraulic pathways, or to slow transfer times, or to low water flow-rates. Final choices take also into account the criteria of the Basic Safety Rule RFS III.2.f, such as keeping a minimum distance with respect to large faults.



M1 site model: geological and hydrogeological context
Possible sites of a repository at the "massif" scale

In the example of the M1 site model, the calculations performed show that the hydraulic pathways can have distances significantly different from one position to another, or according to the pathways choices (from 500 metres for the shortest one to more than 10 km for the longest one). The "repository siting" within the massif allows favouring long hydraulic pathways and low flow rates. On account of this, two sites were adopted for the calculations.

These techniques could be implemented to identify a zone of interest for a repository within a massif.

- **Siting the repository modules**

During the construction of a repository in a granite massif, the reconnaissance approach consists of determining the positioning of the repository modules. With this approach, the positioning of the repository modules and the disposal cells is set during the repository construction work based on a precise characterisation of the locations. In the generic calculations performed, the positioning of the repository modules cannot be optimised as it would be within a complete reconnaissance approach of a site. A statistical adjustment was made based on the extension of the fractures using the fractures network model (DFN): for the B waste, the maximum dimension for a fracture intercepted by the disposal tunnels is by convention 80 m, and for the C waste, the maximum dimension is 300 m. This approach is indeed a penalising one close to a characterisation defect situation for some calculations (particularly for C waste) because, in a real situation, the repository would be progressively adapted so as to get the best out of the available sound granite blocks. The results shown below are, therefore, to be weighted due to the fact that repository module locations randomly distributed are not affected by such an optimisation. The analysis is, nonetheless, a good indicator of the issues which would underlie the characterisation and reconnaissance work of a site before and during disposal.

- **Transport regime within the repository structures**

An indicator which gives a good idea of the hydraulic system within the repository's structures is the dimensionless Péclet number, which is the ratio between the diffusion and convection times. For small values (and, in particular, less than 1), the hydraulic regime is dominated by diffusion. This indicator gives the ratio between advection and diffusion, but does not allow appraising absolutely the velocity at which each transport type takes place. To do this, the Darcy velocities (allowing to appraise the flow-rate at which the water transfers take place) can give an idea on the water flow-rates.

Definition of the Péclet number

$Pe = (T_d/T_c)$
where:
$Td = L^2\omega/De$
$Tc = L\omega/(K.gradH)$.
and:
Td, the characteristic migration time by diffusion [year],
Tc, the characteristic migration time by advection [year],
L, the migration distance [m],
ω, the total porosity in the drift backfill [-],
De, the effective diffusion coefficient in the backfill [m^2/year],
K, the backfill permeability [m/year],
GradH, the hydraulic head gradient [m/m] in the drift, derived from simulations in homogeneous medium.

In the drifts, the transfer system is essentially determined by the permeability of the backfills, the transmissivity of the fractures in the granite at the wall and the gradient. It seems possible to obtain a diffusion system in the repository drifts (table below), but this depends on the backfill permeability. An incorrect backfill emplacement degrading the backfill permeability by an order of magnitude (10^{-9} m/s instead of 10^{-10} m/s) over a drift section hardly affects the transfer regime. However, should the backfill permeability be more heavily degraded (around 10^{-8} m/s), the hydraulic regime within the repository may be affected. *The emplacement of such a backfill constitutes, therefore, a useful design arrangement, but whose performances would have to be defined according to the hydraulic regime on a given site.*

	Near-field granite		Backfilled drift		
	Hydraulic conductivity (m/s)	Hydraulic head gradient (m/m)	Hydraulic conductivity (m/s)	Péclet number ($Pe=T_d/T_c$)	Drift transfer regime
B2 waste (calculation made in 54 m of connecting drift between two seals)	10^{-11}	10^{-3}	10^{-10} 10^{-9} 10^{-8}	0,039 0,16 0,39	diffusive diffusive diffusive
	10^{-11}	10^{-2}	10^{-10} 10^{-9} 10^{-8}	0,39 1,6 3,9	diffusive mixed diff/adv advective
	10^{-10}	10^{-2}	10^{-10} 10^{-9} 10^{-8}	0,49 3,8 14	diffusive advective advective
C2 waste (calculation made in 15 m of handling drift between the edge disposal cell and the seal)	10^{-11}	10^{-3}	10^{-10} 10^{-9} 10^{-8}	0,012 0,099 1,1	diffusive diffusive mixed diff/adv
	10^{-11}	10^{-2}	10^{-10} 10^{-9} 10^{-8}	0,11 1,1 12	diffusive mixed diff/adv advective
	10^{-10}	10^{-2}	10^{-10} 10^{-9} 10^{-8}	0,13 1,1 10	diffusive mixed diff/adv advective

Estimation of the Péclet number in the backfilled drifts ("equivalent porous medium" approach)

• Robustness of the function "preventing water circulation"

It is important to check whether the performances of the function "preventing water circulation" are robust against a failure, regardless of its nature.

The altered scenario "defective sealing and plugs of disposal cells" envisions a situation consisting of not interrupting over approximately a thickness of 5 centimetres the continuity of the damaged zone of the granite in the wall of the horizontal structures. It focuses on the role of the backfills which have an effectiveness such that the sealing defect does not significantly alter the hydraulic transfer regime in the drifts. In a generic context, it is hard to distinguish the role of the seals from that of the backfills. It should be noted that for positioning a repository in a given massif the sound blocks would be first reserved for siting the disposal cells; on the other hand, the connecting drifts may intercept water conducting zones at the edge of these blocks. *In such a configuration, sealing the drift on either side of the intercepted fracture could mean a more effective arrangement than backfill alone.* In any case, within the framework of a real site configuration, it would be possible to favour either the seals or the backfill according to the objective sought, and to distinguish the role of each more clearly than in the generic configuration.

2.3.2 Lessons learnt related to the function "limiting the release of radionuclides and immobilising them in the repository"

This function covers all the physico-chemical phenomena which tend to prevent the dissolving of the radionuclides. It involves:

- the flow conditions in the disposal cells, which favour waste durability;

- the leak-tightness of the metallic containers, which isolate the radionuclides from the water;

- and the chemical conditions, which favour the insolubility of the chemical elements.

• Transport in the disposal cells

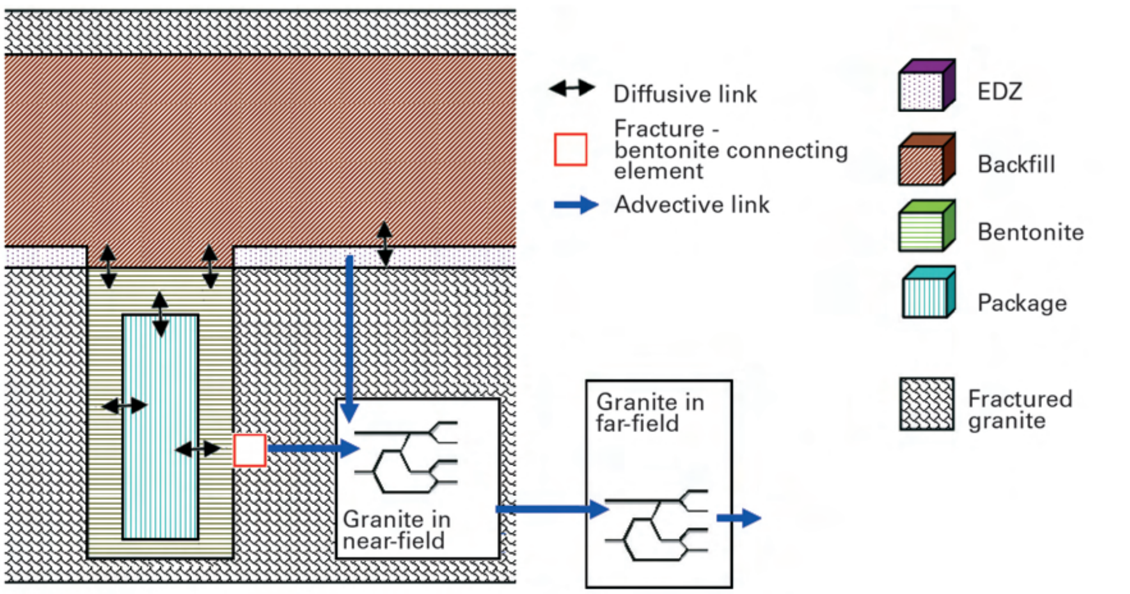
The function "limiting the release of radionuclides and immobilising them in the repository" depends on the setup of a diffusive system within the disposal cells, particularly for vitrified waste, which is the most sensitive waste in terms of the transport conditions in its neighbourhood. From this viewpoint, the indicators such as the Péclet number in the disposal cell are not directly performance indicators of the function, but allow determining whether this function can act under favourable conditions. The diffusive conditions within the disposal cells and low renewal rate of water allow to use, with greater confidence, release models leading to slow flow-rates.

In the disposal cells containing C waste and spent fuel, the Péclet number shows that the system is diffusive in all the cases (table below). The most influential parameters which contribute to maintaining this regime are, on the one hand, the presence of the buffer engineered barrier, and, on the other hand, the transmissivity of small fractures on the periphery of the disposal cell. The "dead end" architecture of the disposal tunnels also helps limiting quantities of water ingress.

Estimation of the Péclet number in the bentonite EB (C2 waste)	Near-field granite		Bentonite engineered barrier (bentonite EB)		
	Hydraulic conductivity (m/s)	Hydraulic head gradient imposed (m/m)	Hydraulic head gradient induced (m/m)	Péclet number (anion) ($Pe=T_d/T_c$)	Transfer regime in the bentonite EB
Horizontal gradient (calculation made with 0,60 m of bentonite in the radial direction)	10^{-11}	10^{-3}	$1,1 \times 10^{-3}$	~0,0004	diffusive
	10^{-10}	10^{-2}	$2,2 \times 10^{-2}$	~0,008	diffusive
Vertical gradient (calculation made with 5,30 m of bentonite in the vertical direction)	10^{-11}	10^{-3}	$1,1 \times 10^{-3}$	~0,003	diffusive
	10^{-10}	10^{-2}	$1,1 \times 10^{-2}$	~0,033	diffusive

Estimation of the Péclet number in the bentonite of the C2 waste disposal cells, ("equivalent porous medium" approach)

With respect to the calculations in the equivalent porous medium, which do not allow discriminating the disposal cells from one another, the calculations in the fractures network model (DFN) reveal that even if the regime remains diffusive inside the disposal cell for all possible cases, the situations can be locally contrasted according to the fractures intercepted by the disposal cells.



Modelling the transfers in a C waste disposal cell (DFN approach in granite)

Thus, exploiting the results obtained on the M1 site model (model for which the granite fractures have transmissivities in a range of values relatively rather high) shows that on ten sitings of C waste disposal boreholes statistically representative:

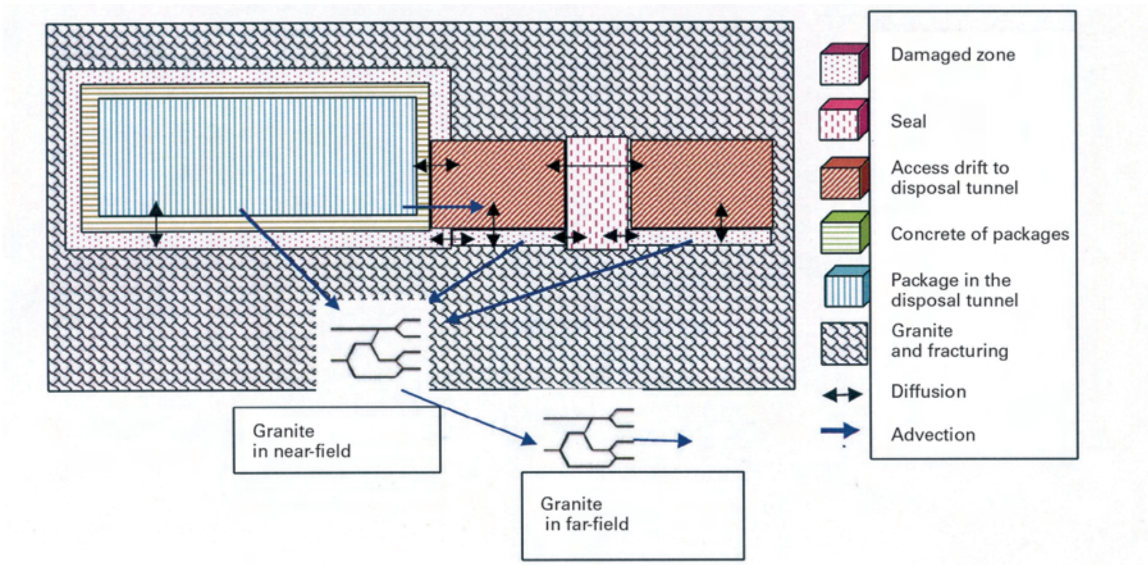
- three sitings of disposal cells are not crossed by water flows because they do not intercept any fracture;

- four sitings correspond to flow-rates lesser than one litre per year;

- three sitings correspond to flow-rates greater than one litre per year (ten some to several tens of litres per year).

It should be noted that these results do not take into account an optimised siting of the disposal cells such as it would be made by selecting granite blocks within which these disposal cells would be installed. Since fracturing is randomly generated in the model, this tends to amplify the role of the buffer engineered barrier. Within an approach for siting disposal tunnels in a real massif, the reconnaissance of small fractures and the selection of the most sound granite blocks would allow lessening the importance of the clay engineered barrier. In any case, the calculation conducted shows that the clay engineered barrier is an effective device, should the massif have a dense small fracturing or in case of a situation of a characterisation defect. In fact, the regime remains diffusive in all the tested configurations.

In the B waste disposal cells, the water flowing in the repository tunnels depends mainly on the transmissivity of the small fractures in the granite at the wall. The principle of siting the disposal tunnels in granite blocks which are very hardly fractured can lead to cases where the granite is practically impermeable: the transfer regime is diffusive between the disposal tunnels and the access drifts through the swelling clay seal. For slightly conductive fractures, small water quantities flow in the disposal tunnel between the fractures at the wall. The flows evaluated by the calculations in the fractures network model (DFN) are very small: tens to hundreds of litres per year for disposal tunnel volumes on the order of 10 000 or 20 000 m^3.



Model of the B waste disposal tunnel and transfer regimes (DFN approach in granite)

The calculations represent, in a simplified way, all the package stacks in the form of a homogeneous set at the scale of the repository tunnels. The concrete overpacking is continuous and in contact with the damaged zone of the granite at the wall. For concrete packages with a reinforced confinement capacity, the calculations take into account a degradation of the packages at 10 000 years represented by a loss of their initial hydraulic performances (low permeability – 1×10^{-13} m/s and low porosity – 10%). The results obtained from the calculations show that water flow-rates increase by a factor of 5 after a degradation of the packages, indicating the hydraulic slowdown role played by the packages in the disposal tunnels.

B5.2 waste disposal tunnels	Before 10 000 years	After 10 000 years
Water flow-rate in the tunnels	30 l/year	150 l/year

Comparison of water flow-rates in B5.2 waste disposal tunnels before and after 10 000 years (DFN calculations for the M1 site model – case of a granite characterised with small, slightly conducting fracturing)

• Role of the containers

Another aspect of the function "limiting the release of radionuclides and immobilising them in the repository" is the leak-tightness provided by the metallic containers. Initial analyses conducted on the performance calculations envision both high-performance containers and defective containers (a limited number in the normal evolution scenario, a greater series in the altered evolution scenario). The comparison of both situations provides a first appraisal of the interest of this device.

For spent fuel, the copper container has a sufficient durability over the safety demonstration period so that there is no release in the normal situation. In the package defect situation with the water arrival on the assemblies after approximately a century, the releases take place as the matrix dissolves. This dissolution extends over several thousands of years (approximately 5 000 years) if a conservative radiolytic dissolution model is used. With a "classical" dissolution model such as internationally adopted, releases take place over a period up to over a million years. However, in case of a CU container failure, the released radionuclides do not immediately migrate out from the disposal cell, because they are stopped or slowed down by the buffer engineered barrier.

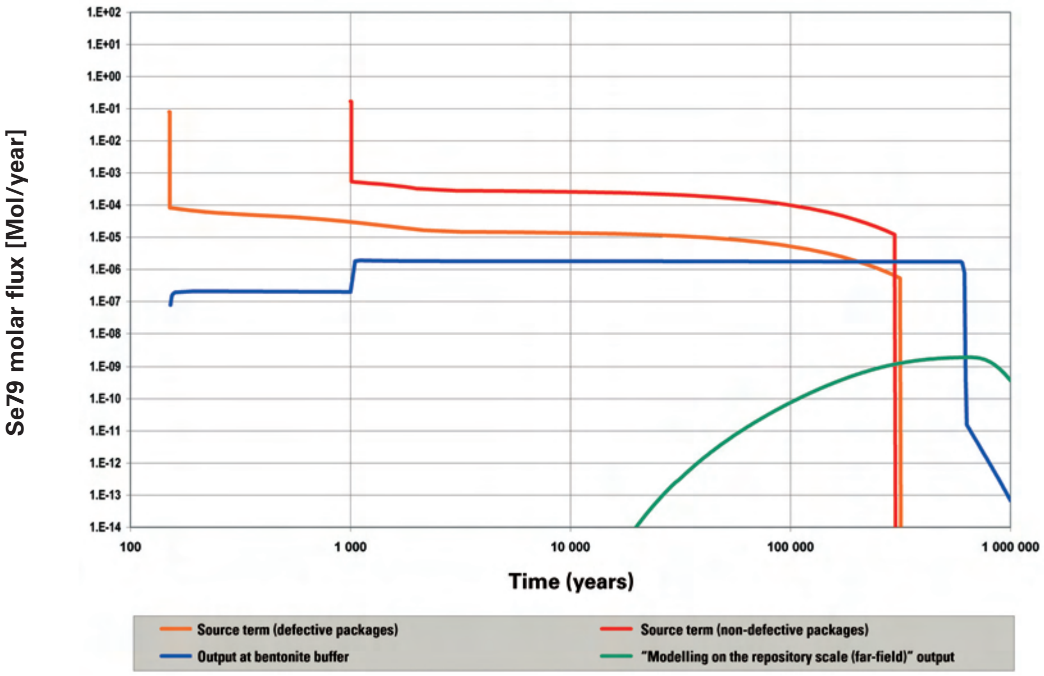
For C waste, the analysis compares two illustrative cases: the case of a repository module in which the overpacks "normally" lose their leak-tightness after 1 000 years and the case of a repository module in which a fraction of the overpacks (5%) are defective after approximately one century. The calculations show in the case of a fraction of defective packages a faster migration of radionuclides out of the granite near field for a period of a few thousand years. Beyond, the molar flux is similar in both treated cases.

It should also be noted that in a generic context and considering the data available it was not possible to explicitly represent the effect which temperatures significantly higher than natural temperatures (as temperatures which the radionuclides released by the defective containers could face) would have on the transport parameters. Such effects, when accounted for, could highlight better the role of the metallic overpacks for C waste.

To conclude, in the context of calculations carried out on generic models, where the distribution of the disposal boreholes is only partially adjusted to fracturing, the durable containers constitute a useful barrier to compensate for the geological medium. In particular, the durable copper container for spent fuel offers an appropriate option at this stage with respect to the adaptation to fracturing. Similarly, the overpack for C waste allows managing the uncertainties linked to the transport of radionuclides in a thermal environment. In a generic context, the containers constitute in any case a cautious design provision providing a complementarity with respect to the buffer engineered barriers and the geological medium.

• Precipitation in the disposal cells

The function "limiting the release of radionuclides and immobilising them in the repository" is also evidenced by a limited dissolving of the radionuclides. The calculations allow, indirectly, measuring the effects of this function by identifying the radionuclides whose migration is restricted by a solubility limit reached in the near field. Considering the concepts proposed by Andra, the sorption of the elements by the swelling clay (for the radionuclides coming from the C waste or spent fuel disposal cells) and in the concrete (for the B waste) is generally the factor limiting the migration of most of the radionuclides. For some radionuclides which are slightly sorbed, the solubility limit controls, however, the transfer. This is particularly true for selenium, whose flux is attenuated by several orders of magnitude when solubility is taken into account.



Limitation of molar flux by solubility – Example of selenium for a C2 waste module (M1 site model – DFN approach

2.3.3 Information related to the function "delaying and reducing radionuclides migration"

This function performances are shown by attenuation indicator (ratio between the mass of radionuclides exiting a compartment of the repository and the mass of radionuclides entering it; ratio between the maximum flux of radionuclides exiting a compartment and the maximum flux of radionuclides entering it) and the delay indicator (difference between the time of occurrence of the maximum flux out of a compartment and into a compartment). These indicators can be assessed at various locations:

- when exiting from the B waste disposal cells, they allow evaluating, by comparing them with the "release by waste" chronicle, the interest of attributing the hydraulic performances to the B waste packaging, particularly by comparing the case where these packages have hydraulic performances with the case where these packages have only chemical performances associated with a degraded concrete;
- when exiting from the clay buffer engineered barriers of the C waste and spent fuel disposal cells, they allow evaluating what these clay elements bring, particularly with respect to the contribution from the host formation;
- when exiting from the near field in the granite massif, they allow evaluating the performances of the small fracturing and the determining factors of these performances;
- when exiting the far field in the granite massif, they allow evaluating the global attenuation capacity of the massif and the transfer times within it, as well as the characteristics which most influence these performances.

• Delay and attenuation in the disposal cells

The function performances in the disposal cell are directly related to the model parameters: the sorption in concrete (for the B waste disposal tunnels) and in swelling clay (for the other disposal cells).

For B waste, a useful example of the role played by the concrete container, already seen above in the role it played in the protection of the waste against water flows, is to compare the releases in the near field between a non-degraded concrete container with hydraulic performances and a container having only chemical performances associated with a degraded concrete. The calculations carried out in an equivalent porous medium indicate that the container's role is more evident when the granite at the wall of the disposal cells is more fractured. In all cases (standard container or container with reinforced confinement), the calculations in the fractures network model (DFN) show that the B waste concrete overpacking has a straightforward effect on the retention of radionuclides very strongly sorbed in concrete (such as actinides) or more weakly sorbed like selenium 79.

For C waste and spent fuel disposal cells, the delay and attenuation performances of the disposal cells are less dependent on local fracturing due to the presence of the bentonite engineered barrier. The unsorbed radionuclides will diffuse through this barrier and migrate outside the disposal cell in a million years. The radionuclides sorbed by the bentonite such as actinides, tin-126 or to a lesser extent caesium-135 are significantly delayed in their migration. Thus, for caesium-135, the calculations related to the scenario of a defective spent fuel container show that the percentage of mass migrating outside the disposal cell through the clay engineered barrier is only approximately 8% after 100,000 years and 16% after one million years with respect to their initial mass (DFN calculations – M1 site model).

• Delay and attenuation in granite

Several parameters intervene to slow down the migration of radionuclides in the granite's fractures and attenuate the flux:

- the hydraulic properties of the fractures and their connectivity;

- the retention (sorption) properties of the fractures and the granite rock at the fractures plane;

- the topographical and morpho-structural arrangement of the granite masses for the far field.

As a result, the radionuclides are classified into two major categories:

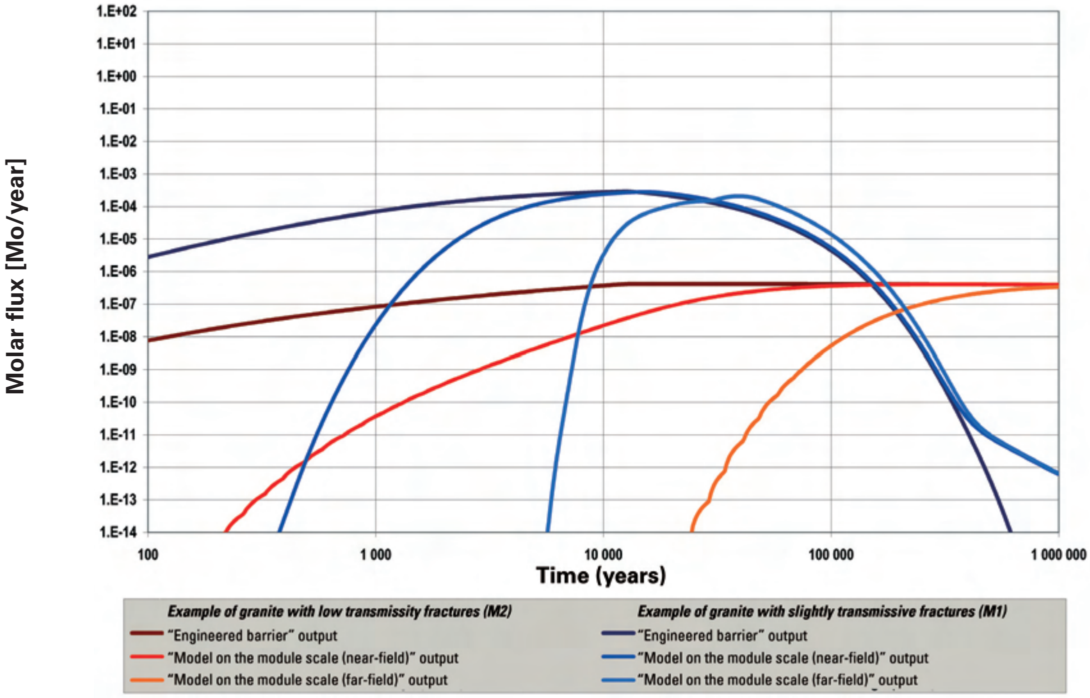
- *the unsorbed elements* (iodine 129, chlorine 36, etc.). Their transfer time through the fractures is the direct reflection of the length of the hydraulic pathway leading to the surface. For these radionuclides, the function "delaying and reducing the migration" is practically the same as the function "preventing water circulation". Their migration is essentially imposed by the topographical and morpho-structural arrangement of the massif – which controls the gradient and the length of the pathways – as well as the transmissivity and connectivity of the fractures;

- *the elements sensitive to sorption* at the fracture planes, which can be significantly delayed; sorption can then give them the time to significantly decay in the fractures planes, starting in the near field would the radioactive half-life be sufficiently short. It causes a spread of the signal emitted by the repository and, therefore, a reduction of the maximum mass flux between the entry in and exit from the massif.

1) Delay and attenuation in the near-field granite: influence of the hydraulic properties of fractures

The site models represent different fracturing configurations representative of geological configurations in the French context. The fractures transmissivity in the M2 site model is lower because they are clogged by hydrothermal minerals than the one in the M1 and M3 site models. For the generic studies, the intersections between the transmissive fractures are assumed to be systematically water conductive, which is penalising for many granite massif configurations. However, comparing the migration flux calculations of mobile radionuclides such as iodine 129 between the M1 and M2 site models shows the major influence of the hydraulic properties of the near-field fractures.

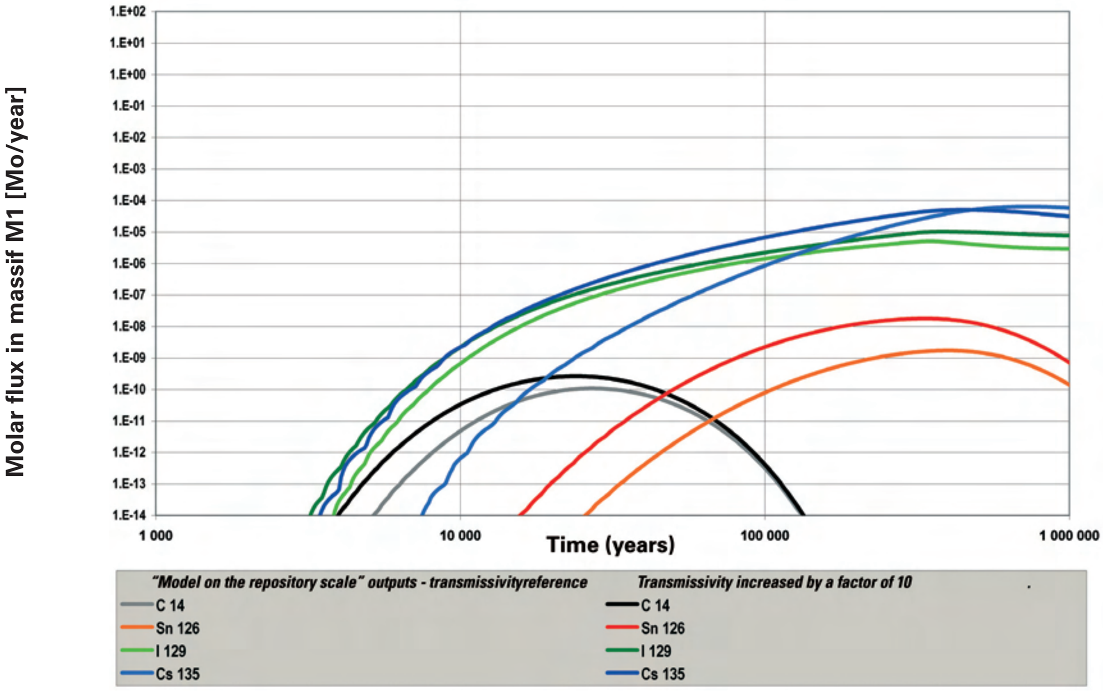
The case of B waste is easy to illustrate because there are few disposal tunnels and they are sited in almost unfractured granite blocks. Calculations are carried out for the most penalizing pathway of iodine 129 between the disposal tunnel and the model boundaries.



Migration of iodine 129 in the M1 and M2 site models – Molar flux for a B2 waste disposal cell (DFN approach)

For a granite in which the fractures have very low transmissivity in the near field (M2 site model), the maximum flux is reduced and iodine remains in the near-field granite over several hundreds of thousands of years. For granite in which the fractures are more transmissive (M1 site model), flux is higher and the total inventory of iodine 129 reaches the model boundaries after a hundred thousand years or so.

For C waste and spent fuel, a variation in the fractures transmissivity on repository performances, like for B waste, causes changes in the flux and migration times of the radionuclides. On account of the multiplicity of the radionuclide pathways corresponding to the various disposal cells in a module, the global situation is consequentially smoothed by the pathways variability. Thus, the influence of the fractures hydraulic parameters must also be examined with the other properties of the granite, particularly their geometric organisation, which determines the pathways. Sensitivity to the fractures transmissivity can be illustrated by the assessment of the model outgoing flux for the transmissivity values varying by one order of magnitude for all the fractures.

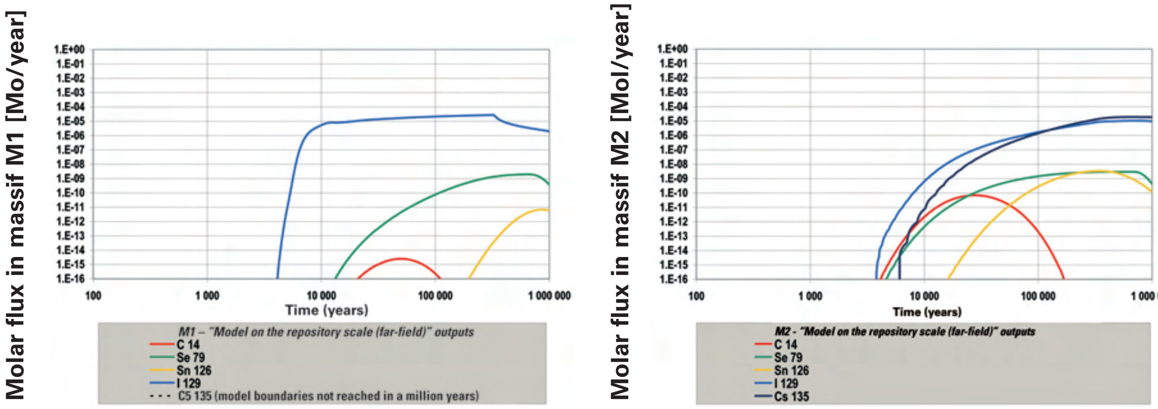


Sensitivity of performances vs. fractures transmissivity – Molar flux for a C2 waste module (M2 site model – DFN approach)

For unsorbed radionuclides such as iodine 129, the strongest transmissivities lead to a slight general increase in flux. For sorbed radionuclides, the increase in flow-rates associated with that of the transmissivities leads at the same time to a lower intensity in the diffusion and sorption phenomena in the fractures: for example, the molar flux of caesium is increased by several orders of magnitude at 10,000 years and 100,000 years; the maximum flux is not very different for a scale of several hundreds of thousands of years.

2) Delay and attenuation and delay in far-field granite: influence of topographical and morpho-structural configurations

Generally for all the granite massifs configurations examined, many radionuclides are sorbed during their migration in the near-field and far-field fractures. Thus, calculations show that the actinides do not reach the far-field model boundaries after a million years, regardless of the granite massif configuration studied.
The topographical and morpho-structural configurations of a granite massif determine the pathway lengths between a deep repository and the surface. Analysis of the hydraulic pathway lengths for the various geological site models considered confirms the differences between the configurations studied. The analysis was carried out on the two most contrasted cases studied, that is: the M1 site model, representative of a "dome" configuration, and the M2 site model, representative of a "depression" configuration. Thus, it shows that for the M1 site model the pathway lengths vary for the most part between 2500 and 6500 metres, while for the M2 site model the pathway lengths are on the average less than for the M1 site model and are between 1500 and 4000 metres. These differences tend to be smoothed at the level of the radionuclide transfers, because the granite characteristics at the repository modules level limit the migration of most of the radionuclides, particularly those less mobile. For the long-lived mobile radionuclides, particularly chlorine 36 and iodine 129, the hydraulic transfer times directly determine the migration times.
The graphs hereafter show, for C2 waste (vitrified), the radionuclides which reach the model boundaries in the case of the M1 site model. Only the radionuclides hardly sorbed are present (note that chlorine 36, relatively little present in the glasses, was not considered for the calculation). In particular, caesium-135 does not reach the model boundaries on the scale of 1 million years and remains in the massif. This is not the case for the M2 site model, a direct translation of shorter transfer times.



Attenuation of the radionuclide flux for M1 and M2 site models – Molar flux for a C2 waste module (DFN approach)

• Repository robustness to a possible characterisation error

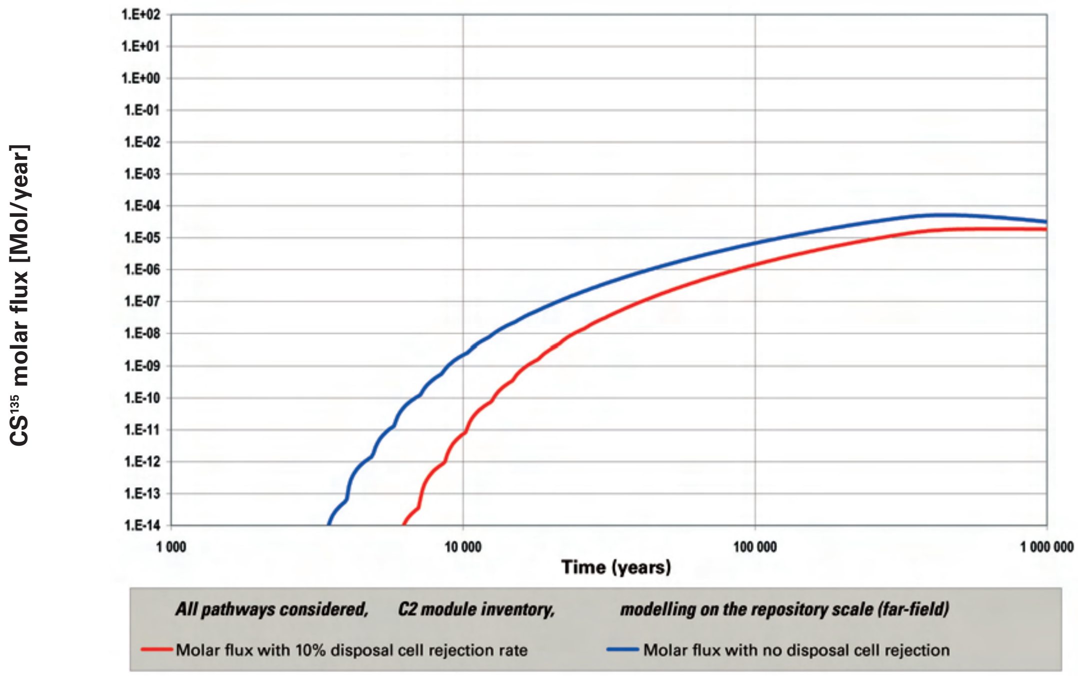
The altered "characterisation defect" scenario allows showing the importance of a more or less detailed fracturing characterisation. The adaptation of repository architecture to granite fracturing is subject to reconnaissance operations prior to the various site reconnaissance stages. A particularly important stage is the characterisation of the fracturing carried out, *in situ*, in the repository before excavating the disposal cells and emplacing the packages.

The consequences of a characterisation defect can be analysed by comparing a normal evolution scenario in which this characterisation is correctly carried out to a "characterisation defect" scenario which considers the non identification of fractures which should have been avoided.

For C waste, 10% of the possible positions of the disposal cells were excluded for the normal evolution scenario: these positions correspond to the most unfavourable near-field hydraulic conditions. On the other hand, for the characterisation defect scenario, all the possible positions for the disposal cells are considered.

The radionuclide transfers for the C2 module are calculated in both cases by distributing the corresponding inventory on the possible pathways coming from the disposal cells (10% of disposal cells positions rejected in the normal case and none rejected in the characterisation defect case). The comparison in terms of molar flux is given in the figure below.

For caesium-135, the 10% of disposal cell positions not rejected corresponding to the most penalising situations hydraulically lead to a maximum molar flux increased by a factor of 5 (after 400,000 years). The molar flux is increased by approximately two orders of magnitude at 10,000 years and by approximately one order of magnitude at 100,000 years. This underlines the importance of the characterisation and its influence on the system's overall performance. On a particular site, it would be advisable to specify earlier the effect of a sorting of positions of the disposal cells.



Comparison of molar flux with and without a 10% rejection rate of the disposal cells – Molar flux in caesium-135 of a C2 waste module in an M2 massif (DFN approach)

For B waste, and particularly B5.2 waste, the impact of a bad local characterisation would be relatively more sensitive in terms of quantities of radionuclides released than for C waste. This is due to the larger number of packages potentially concerned. A local characterisation defect of the small fracturing concerned by the installation of a disposal tunnel would not jeopardise the global performances of a B5.2 waste repository. In fact, the characterisation defect would only be considered sensitive in case of a large characterisation error, meaning that the disposal tunnels intercept a great extension (multi-hectometres) and significantly transmissive fracture, which is not realistic considering the proposed reconnaissance strategy and the small number of tunnels to be installed.
All in all, although the fracturing characterisation and the adaptation of the repository according to its hydraulic and transport characteristics appear important, the repository is, globally speaking, hardly sensitive to a local error. In fact, because of the fractioning (modules, disposal cells), a characterisation error would only affect a moderate part of the emplaced packages inventory.

2.4 Conclusion of the calculations

In a generic context, the calculations carried out cannot pretend to be conclusive either in the achievement of the safety objectives or in the performances of the safety functions of each component. Nonetheless, the calculations provide a wealth of important information from a methodological viewpoint as well as from the viewpoint of key determining factors, which condition the repository's safety.
From a methods viewpoint, the use of computational tools both "classical" (such as those carried out in a homogeneous medium) and more "specific for granite" (those carried out in a fractured medium) underline the complementarity of both approaches. The first kinds of tools ("classical" calculations) allow determining in a straightforward fashion the influence of the main macroscopic parameters: hydraulic gradient, large-scale permeability of the rock and the structures, Péclet number, etc. The second kinds of tools (calculations in the fractured medium) allow accessing more versatile information, connecting near-field performances to the structuring and distribution of small fracturing, or setting up a relationship between medium-scale fracturing and large-scale permeability. This information would have to be exploited under the assumption of a site reconnaissance in order to progressively determine from safety analyses the relevant criteria for the repository siting and architecture.
The reconnaissance of fracturing and the correct characterisation of its hydraulic properties prove to be important for controlling flows in and around the repository. At the repository modules scale, they lead to positions protected from moderate fracturing, where it is too water conductive. At the disposal cells scale, the

adaptation of the position of the disposal cells to small fracturing provides an additional opportunity to limit the flows and to favour long radionuclide pathways. Nonetheless, due to their large-scale fractioning, the repository modules of vitrified waste and spent fuel prove to be hardly sensitive to local characterisation defects. On the other hand, the B waste disposal tunnels because of their larger size may be more sensitive to the quality of the granite block in which they would be sited; a characterisation defect may affect the repository performance if a fracture of large extension and significant transmissivity is not detected. This case seems to be highly unlikely within the reconnaissance approach proposed for characterising a granite massif and considering the limited number of disposal tunnels.

From the viewpoint of results, the calculations carried out on a generic site show the good complementarity between the properties of the engineered structures and those of the geological medium. In the current state of knowledge, backfill performances prove to be significant for controlling flows within the repository, provided the site itself provides a controlled permeability and low gradients. The clay buffer engineered barriers ensure a diffusive system in the disposal cells and immobilise the hardly soluble radionuclides. The B waste concrete containers participate in both water flow limitation and radionuclides sorption. The C waste overpacks delay radionuclides release in the disposal cells. The spent fuel copper containers allow a durable confinement of the radioactivity and offer flexibility at this generic studies stage with respect to the repository siting and the fracturing. Retention in the granite fractures allows greatly limiting the flux of radionuclides subjected to sorption and, in favourable configurations, preventing their transfer to the model boundaries.

Although safety analyses - both qualitative analysis and calculations – are conducted on generic site models, with all the reservations attached to this type of exercise, they do not identify elements which would rule out the granite medium for a high level and long lived waste repository.

Conclusion

The Act of 30 December 1991 initiated a process of research into different methods for managing high-level, long-lived waste. In this context, Andra conducted work to study the possibility of a repository in a deep geological formation, examining two rocks of different nature: clay and granite. For granite medium, with no designated site, the purpose of the research programme was to assess the interest of the rock for a deep repository. With this aim, various issues concerning disposal in granite medium were addressed. Generic options for a repository were proposed in response to the applicable safety objectives

1. A generic study initiative on French granites backed up by studies and research on granite conducted abroad

To study the granite medium, Andra began by collecting the body of scientific knowledge available that could serve as a basis for the study of a geological repository. This concerned both granite mediums encountered in France, and also granite mediums studied by counterparts abroad (SKB in Sweden, Posiva in Finland, Nagra in Switzerland and AECL in Canada). This initiative resulted in a global view of the intrinsic properties of the rock and its potential for a repository.

Firstly Andra capitalised on all the knowledge acquired on French granite, especially through mining feedback or site work conducted during recent decades. The geological data available for roughly 78 granite areas larger than 20 km^2 spread across France (Massif Central, Armorican Massif) were collected and analysed. This provided an appraisal of the common characteristics and the properties variability of French granites.

In addition, Andra made the most of the French scientific community for major issues relating to the repository, especially for an understanding of the organisation of granite fracturing. This took the form of partnerships with research organisations and also a policy of training support for research, through thesis grants.

Foreign laboratories made a very important contribution, both for methodology and in providing scientific results. Andra made an important contribution to experiments in underground laboratories in Canada (Lac du Bonnet laboratory), Switzerland (Grimsel laboratory) and Sweden (Äspö laboratory). This enabled it to conduct experiments in partnership with its counterparts. It led to a comparison of studies and research, and also provided a thorough understanding of how some of the results obtained in these laboratories could be transposed into the context of French granite. In particular, surveying a granite block and modelling circulation in fractures in the Äspö laboratory backed up the understanding of the phenomena involved. The large majority of results obtained can be transposed to French granite massifs. Likewise, the sealing test conducted in the Lac du Bonnet laboratory demonstrated the possibility of effectively sealing a structure in granite to prevent water circulation. Finally, in a framework of partnership with Posiva, Andra participated in surface-based surveying at the Olkiluoto site, enabling it to test and control the various techniques.

The studies and research conducted by Andra are based on a large amount of work conducted abroad on disposal in a granite medium. In particular, repository design studies conducted by Andra are largely based on knowledge acquired abroad, especially in Sweden and Finland.

2. A repository in a granite formation is conceivable

Assessing the assets of granite for a disposal system means mainly the possibility of surveying and understanding the organisation of a granite massif, of studying how a repository could be built in this massif, and of appraising whether this repository could protect man and the environment against the radioactive waste emplaced therein. All these issues were addressed. The analysis stresses that, at this stage, there is no basic obstacle ruling out this possibility.

• Methods exist for surveying and characterising granite.

Work conducted in foreign laboratories or surface-based work at various sites led to successful testing of various granite characterisation and modelling methods which will be required to survey a site.

Methods exist for surveying a granite massif. Associated with modern modelling tools, these methods provide, a priori, an understanding of its organisation (arrangement of granite blocks, structuring of fractures, etc.) and its functioning in terms of underground water circulation.

• Generic architectures are proposed for a reversible disposal system in a granite medium.

Repository architecture must be adapted to the characteristics of the geological medium. Generally, sound granite is characterised by high mechanical strength and very low permeability. It is also a medium containing very little underground water. The proposed generic concepts harness these properties common to all granites and also take into account the specific features of granites in the French geological context.

However, fractures of the deep granite medium may allow slow circulation of water. The concepts proposed avoid this as far as possible by architectural adjustment to the various scales of fracturing: the disposal zones are located away from the main faults in the granite massif and the disposal cells are positioned in sound rock of very low permeability so that they only intercept fractures with little or no conductivity. In addition, the design allows for installation of low-permeability sealing and backfill which protect the disposal cells from the slow water movement that could occur.

Repository design also includes design of waste packages for each type of waste (B or C waste) or spent fuel. Overpacking options are proposed for B waste packages (concrete) or C waste packages (steel). These are similar to the ones designed for clay medium, with, however, the use of an enhanced confinement properties container for certain types of B waste. For spent fuel, if not reprocessed, the advantage of copper containers developed in Sweden and Finland and achieving very long duration confinement was examined.

Repository architectures proposed for granite are adapted to the fracturing of the medium and take advantage of the very low permeability and high strength of the sound rock. The rock properties are backed up by engineered structures ensuring confinement of radioactivity: overpacking primary waste packages in containers, sealing and backfilling the structures. In addition, many studies conducted for the clay medium case can be transposed when concerning operational and occupational safety, demonstrating the possibility of a safe operation without environmental impact, on the basis of feedback from other mining or nuclear facilities.

• Reversibility at the heart of the study approach and expressed in concrete practical terms

The generic architectures proposed for the repository were selected according to their ability to allow for reversibility under the best possible conditions. Andra has developed a concrete approach to reversible disposal that is more than just the technological possibility of withdrawing the packages. This approach, quite common to the clay medium study, may be defined as the possibility for a step-wise, progressive and flexible control of the disposal process. The objective is to allow future generations freedom of decision in waste management. In addition, Andra has decided not to set a predetermined duration for reversibility. This involves offering as great 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 backward. The repository design (modular architecture, simplified operation, dimensioning and choice of durable materials, etc.) aims at allowing the widest possible choices.

The reversible disposal system 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 essentially distinguishes it from a simple storage process is that it includes the possibility of being progressively closed, so as to be able to subsequently evolve safely and passively without human intervention.

The granite geological medium and the concepts developed by Andra allow to meet the reversibility requirement and to turn reversibility into a flexible tool in radioactive waste management. Reversibility also enables progressive confidence building in the demonstration of repository safety, always leaving open the eventual possibility of an evolution independent of human intervention.

- **Tested repository safety analysis methods.**

A reversible disposal system is designed to be closed if this option is taken. It is therefore important to examine the suitability of the proposed generic architecture for the long-term safety objectives, i.e. its ability to provide durable protection for man and the environment against the waste which would be emplaced in the repository. This examination was conducted using methods proven at international level, especially on the basis of i) a systematic analysis of the various characteristics of the repository and granite, ii) the processes governing its long-term evolution and iii) the possible events that could disturb it. This analysis is based on all the knowledge acquired in the field at international level, especially in foreign underground laboratories. In particular, this knowledge concerns interactions (thermal, hydraulic or chemical) between a repository and granite, as well as the important issue of radionuclide retention by the fractures.

In addition to a qualitative assessment, simulations have been run to obtain quantitative assessment information. This requires calculation means dedicated to the fractured medium which have been extensively developed at international level.

In a context of generic studies, this cannot involve repository impact calculations indicating radioactivity doses to which man and the environment may be exposed. However, quantitative assessments provide an understanding of orders of magnitude in terms of the confinement performance of granite and the various repository components. They indicate that, while ruling out site configurations not manifestly meeting the Basic Safety Rule RFS III.2.f. criteria of the French Nuclear Safety Authority, the proposed technical solutions would make the most of the favourable properties of granite.

From the methodological point of view, these analyses allow all numeric tools specifically developed for the granite medium to be tested. The simulations confirm that, assuming a site survey is to be carried out, means for assessing repository safety in a granite medium would be available throughout the research process.

The safety analyses carried out on the proposed generic repository architectures underline the availability of methods for assessing the long-term safety of a repository in granite: description of repository evolution over time, understanding and modelling of the phenomena involved and computer tools. Apart from the methodological lessons learnt, safety analyses have underlined the suitability of the proposed options and the absence, at this stage, of any element ruling out feasibility with respect to the safety objectives.

3. Overall Summary

The studies conducted by Andra in the context of the Waste Act of 30 December 1991 have been summarised in a status concerning the assets of the granite medium for a reversible disposal system. The main questions linked to the specific features of the granite medium have been identified and treated without revealing any aspects ruling out feasibility. Possible options both for the design of a reversible disposal system and for the safety approach have been defined at a generic level for granite. The main uncertainty concerns the existence of sites without a too high fracture density, which would be too demanding on repository architecture.

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