Safety Guide concerning the disposal of radioactive waste in a deep geological formation

RECORD OF REVISIONS

Rev.	Date	Comments
0	12 February 2008	First issue

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1. PREAMBLE

The organisation responsible for studying the disposal of radioactive waste in deep geological formations shall report to ASN regarding the conditions of application of this rule.

2. SUBJECT OF THE RULE

The subject of this rule is – for the disposal of radioactive waste in a deep geological formation – the definition of the specific objectives, as of the site investigation and disposal facility design phases, in order to guarantee its safety once the disposal facility is closed.

It covers the following points:

- the objectives regarding the protection of the health of individuals and the environment,
- the safety principles and the safety-related bases underpinning the design of the disposal facility,
- the disposal facility safety case method.

It complies with the provisions of Article L542-1 to L542-14 of the Environment Code, Articles L1333-1 to L1333-20 of the Public Health Code and their implementing Decrees, Planning Act 2006-739 of 28 June 2006 concerning the sustainable management of radioactive materials and waste, as well as the Joint Convention on the Safety of Spent fuel Management and the Safety of Radioactive Waste Management.

It takes account of the results of the work done in accordance with Act 91-1381 of 30 December 1991 regarding research on the management of radioactive waste, as well as the recommendations made by the technically competent international organisations (International Atomic Energy Agency [IAEA], Nuclear Energy Agency [NEA] of the Organisation for Economic Cooperation and Development [OECD] and the International Commission on Radiological Protection [ICRP]).

3. SCOPE OF APPLICATION OF THE RULE AND DEFINITIONS

3.1. Definitions

In accordance with Article L542-1-1 of the Environment Code:

- "a radioactive substance is a substance containing natural or artificial radionuclides, the activity or concentration of which justifies radiation protection";
- "radioactive wastes are radioactive substances for which no subsequent use is planned or envisaged";
- "a nuclear fuel is regarded as a spent fuel when, after being irradiated in the core of a reactor, it is removed once and for all";
- "ultimate radioactive waste is radioactive waste which can no longer be reprocessed in current technical and economic conditions, in particular by extracting its reusable part or by reducing its polluting or hazardous nature";
- "the disposal of radioactive waste consists in placing these substances in a facility specially fitted out to conserve them, potentially definitively, in compliance with the principles stipulated in Article L. L542-1 of the Environment Code".

- "deep geological disposal of radioactive waste consists in emplacing these substances in an underground facility specially designed for this purpose, complying with the principle of reversibility".

The system of disposal in a deep geological formation comprises the waste packages, the disposal facility and the geological medium. The disposal facility comprises the waste package disposal structures and the access structures. In this rule, the facility is considered to be closed once the access routes from the surface have all been filled in. The geological medium consists of the site's geological formations and notably the host rock. It excludes the surface layers if they are potentially subject to significant disturbance. The host rock is the geological formation within which the storage structures containing the waste packages will be positioned.

The components of the disposal system which generally play a safety role after closure of the disposal facility fall into one of three classes:

- the waste packages into which the radioactive substances are incorporated. In the rest of the text, the term package corresponds to the disposal package as emplaced in the facility. This concerns waste as conditioned by the producers and which may have undergone additional conditioning (addition of an overpack) so that their properties are as required for the safety of the repository;

- the engineered components. These are the components which fill in the disposal cavities and boreholes, fill in and seal the drifts and the surface-underground connection works;

- the host rock.

3.2. Radioactive waste concerned

The deep geological formation radioactive waste disposal facility is designed to accept ultimate radioactive waste which, after storage, cannot be sent for surface or subsurface disposal for safety reasons. This can notably concern:

- intermediate specific activity waste containing long-lived radionuclides in quantities such as they cannot be disposed of either in a low or intermediate level short-lived waste surface repository, nor in a low level long-lived waste repository;

- high specific activity waste containing significant quantities of long-lived radionuclides. This waste comes primarily from the reprocessing of spent fuel and is characterised by the significant release of heat;

- spent fuels which have not undergone reprocessing.

3.3. Geological formations concerned

The rule does not in principle exclude any type of geological formation, provided that the formations considered meet the essential criteria presented in Chapter 4.

3.4. Situations studied

For the purposes of the safety analysis, the following situations will be studied (see Chapter 5 and Appendix 2) :

- a reference situation corresponding to the foreseeable evolution of the disposal facility and the geological medium under the effect of events that are certain or highly probable;
- situations referred to as altered, corresponding to the occurrence of uncertain but plausible events, which are either natural, or linked to human actions, which are superimposed on the

reference situation and can accelerate the migration of radioactive substances between the disposal structures and the biosphere.

3.5. Reversibility of the disposal facility

Article L542-1-1 of the Environment Code stipulates that the disposal of radioactive waste in a deep geological formation "complies with the principle of reversibility" and Article L542-10-1 stipulates that the reversibility conditions shall be set by law.

The reversibility of the disposal facility implies appropriate operating methods, and facility monitoring systems. The objectives of this monitoring are specified in section 4.6.

The steps taken to ensure the reversibility of the disposal facility shall not compromise the operational safety and the post-closure safety of the disposal facility.

3.6 Oversight of nuclear materials

The guarantees applicable to the oversight of nuclear materials, as defined by the Defence Code, shall be taken into consideration as of the disposal facility design phases. The steps taken to ensure this oversight shall not compromise the operational safety and the post-closure safety of the disposal facility.

4. FUNDAMENTAL OBJECTIVE

4.1. Objective

Protecting the health of individuals and the environment is the fundamental safety objective of the deep geological disposal of radioactive waste. This protection must be guaranteed in terms of the risks linked to the dissemination of radioactive and toxic chemical substances.

After closure of the repository, the protection of individual health and the environment must not depend on monitoring and surveillance and institutional controls which cannot be maintained with absolute certainty beyond a limited period of time.

The geological medium is therefore chosen and the disposal facility designed so that post-closure safety can be passive, in order to protect individuals and the environment from the radioactive substances and toxic chemical substances contained in the radioactive waste, with no need for any intervention.

In this respect, the concept chosen for the repository shall enable the radiological impact to be maintained at the lowest level reasonably achievable in the light of acquired scientific knowledge, the current techniques and economic and social factors.

The characteristics of the chosen site, the layout of the disposal facility, the design of the artificial components (packages, engineered components) and the quality of their construction constitute the foundations underpinning the safety of the disposal facility. Their compliance with the fundamental objective shall therefore be guaranteed. The radiological and chemical impact assessments shall be carried out to check that the objective is indeed met. With regard to the radiological impact, the radiation protection criteria are presented below. With regard to the toxic chemical substances, the acceptability of their potential impact shall be assessed according to the regulatory criteria or, failing which, any available recommendations.

4.2. Radiation protection criteria

For the operational phase, the radiation protection criteria are those applied to Basic Nuclear Installations and comply with the provisions of the Labour Code (Art. R231-75 inserted by Decree

2003-296 of 31 March 2003) and the Public Health Code (Art. R1333-8 amended by Decree 2006-676 of 8 June 2006) regarding the protection of workers and the general protection of persons respectively.

For the phase following closure of the facility, the safety analyses presented shall include a determination of individual exposures expressed as an effective dose. The characteristics of the human being (sensitivity to radiation, eating habits, living conditions, general current knowledge, in particular in the technical and medical fields), will be presumed to be constant.

4.2.1. Reference situation

For the reference situation following closure of the disposal facility, the calculated individual effective doses shall not exceed the value of 0.25 mSv/year for prolonged exposure related to events that are certain or highly probable.

The individual exposure evaluations shall be based on a model of the evolution of the disposal system, in particular of the packages and engineered components, as well as on a model of the circulation of underground waters and the migration of the dissolved and gaseous radioactive substances.

The events to be considered are:

- events linked to the presence of the disposal facility, to construction flaws and to all gradual deterioration processes affecting the packages and engineered components,
- a range of probable natural events (climatic cycles, subsidence, tectonic uplift, seismic motion).

As the stability (which includes limited and foreseeable evolution) of the geological medium must – according to the criteria of sub-chapter 4.3 – be demonstrated for a period of at least 10,000 years, it shall be possible for the value of the results of the forecasts covering this period to be confirmed objectively, notably on the basis of explicit uncertainty studies. The dose constraint of 0.25 mSv/year shall be adopted to verify that the design of the disposal facility meets the fundamental safety objective. If this value is exceeded, this should lead either to a reduction in the uncertainties through an appropriate research programme or to a revision of the design of the facility.

Beyond this period, the uncertainties surrounding the evolution of the disposal system's environment gradually increase. Worst-case quantified estimates of individual exposure shall nonetheless be produced, possibly supplemented by qualitative assessments of the results of these estimates taking account of geological environment evolution factors, so as to check that the release of radioactive substances does not lead to unacceptable doses. During this check, the previously mentioned value of 0.25 mSv/year shall be retained as the reference.

4.2.2. Situations referred to as altered

After closure of the disposal facility, a number of uncertain but plausible events, whether natural or related to human actions, can disturb the evolution of the disposal system and thus modify the migration of the radioactive substances. Some situations resulting from these events could potentially lead to higher individual exposure levels than those associated with the reference situation.

To maintain consistency between limiting individual exposure in the reference situation and the hadling of the potential individual exposure levels linked to altered situations, the notion of risk (product of the probability of the situation by the effect of the associated exposure) can be used to take account of the probability of each situation giving rise to exposure.

However, a criterion based on a limitation of individual risk cannot be defined without precautions, given that it would imply a debatable equivalence between reducing the probability and reducing the individual exposure levels.

Moreover, it would probably be difficult, even impossible, to estimate the probability of events that could lead to exposure.

In these conditions, the acceptability of the individual exposure levels associated with the occurrence of uncertain but plausible events, will be assessed taking account of the characteristics of the resulting situation, its probability when this can be determined, the level, duration, scope and nature of the transfer of radioactive substances into the biosphere, and the characteristics of the contamination routes for the exposed individuals and groups.

Were situations of the type considered to occur, the possibility of intervention in order to mitigate the consequences should obviously not be taken into consideration during the design phase when guaranteeing the safety of the disposal facility after closure.

This is why the individual exposure levels associated with altered situations which would appear to be necessary for inclusion in the design of the disposal facility must be kept low enough with respect to the levels liable to induce deterministic effects.

Apart from the comparison between the effective individual doses calculated and the indicated values, whether in the reference situation or in altered situations, the assessment of the acceptability of the radiological impact of the disposal facility is above all the result of the analysis of the efforts made by the disposal facility's designer to ensure that individual exposure levels are as low as reasonably achievable, in the light of economic and social factors.

5. SAFETY-RELATED DESIGN BASES

5.1. Safety principles and functions

In the broadest sense, the safety of the disposal facility is built around a set of components (see sub-chapters 4.2, 4.3 and 4.4) and provisions (see sub-chapter 4.5) preventing or mitigating the migration of the radioactive substances or toxic chemicals to the biosphere, so as to protect humans and the environment.

The safety principles define the fundamental guidelines to be followed when designing the disposal system. This shall be designed using an approach based on the principle of defence in depth, a principle adopted internationally for the design and operation of nuclear facilities. Its design shall more specifically allow easy demonstration of its correct operation after closure. For nuclear facilities, the principle of defence in depth leads to the deployment of successive lines of defence to prevent the appearance or, as necessary, to mitigate the consequences of technical, human or organisational failures liable to lead to accident situations which could affect the protection of humans or the environment.

Safety following closure of the geological disposal facility is an essential subject which shall guide the design of the disposal system. The fact that it is impossible to predict interventions this far into the future means that passive measures are required. For the post-closure safety of the geological disposal facility, the deployment of successive lines of defence in the design of the disposal system implies that various complementary safety functions be allocated to the various classes of components in the system (see sub-chapter 2.1). The effect of this principle is to make the safety of the disposal facility dependent on the complementarity and diversity of the classes of components and on a certain level of redundancy in the safety functions, so that plausible failures of components cannot on their own compromise the safety of the facility.

The safety functions of the disposal system aim to ensure compliance with the goal of protecting human health and the environment throughout all the phases in the lifetime of the disposal facility. They are performed by components of the disposal system.

The safety functions of the disposal system after closure of the facility are as follows:

- to prevent the circulation of water through the disposal facility,
- to contain the radioactivity,
- to isolate the waste from humans and the biosphere so that the safety of the disposal facility is not significantly affected by climatic erosion phenomena or by ordinary human activities.

The performance of the disposal system must be weighed against the harmfulness of the substances contained in the facility and how this harmfulness develops. The probability of partial or total loss of a function of a component shall be inversely proportional to the radiotoxic potential of the waste emplaced in the facility. Therefore, the functions shall be guaranteed for a sufficient duration, taking account of their respective roles in the overall safety of the repository and the decay of the radionuclides contained in the waste. The duration and quality of containment shall be defined according to the nature of the waste.

A component of the disposal system can take part in one or more safety functions for a specified period of time.

The safety functions of the host rock shall be preserved, despite the effects due to the geological events liable to occur, as long as the dissemination of the residual activity of the emplaced waste is liable to lead to unacceptable individual exposure levels in the case of such events.

The possible consideration of an additional long-term role by the formations surrounding the host rock could be envisaged when they have a natural capacity for diluting, delaying and dispersing radioactive substances. The design provisions shall then be such that they preserve this natural capacity for dilution and dispersion.

The ability of the various components of the disposal system to achieve the performance targets shall be balanced against the uncertainties concerning the evolution of the disposal system and its environment. The design and construction provisions, as well as the methods adopted, shall thus be able to demonstrate that the required performance of the components of the disposal system will be achieved, given the reasonably predictable disturbances to which the disposal system could be subjected. It shall therefore be possible to describe the evolution of the disposal system over a sufficiently long period of time. Particular attention shall be paid to the technical feasibility of the packages and engineered components, as well as to the inspection techniques and resources used to ensure the quality of their production and justify the degree of confidence acquired in the ability of these components to perform their functions.

Valid quantitative goals for the performance of the various components of the disposal system can only be set following an iterative process, incorporating the experience acquired during the repository's safety study. This is why a prudent approach is adopted, consisting in choosing or designing each of the components of the various classes as efficiently as is reasonably possible, taking account on the one hand of its role in the overall safety of the disposal system and, on the other, the available knowledge and techniques as well as economic factors.

5.2. Waste packages

The following provisions concern the disposal package, that is the first component of the disposal system in its final form, as emplaced in the disposal facility. The packages take part in the safety of the disposal facility during the operational phase, as well as whenever necessary for the safety of the repository after closure of the facility.

The package's ability to contain the harmful substances shall be appropriate to the nature of the waste it contains, taking account of the environment in which it is located. To meet this objective, it is recommended that the package:

- prevent the dissemination of activity to the other components of the disposal system for a given period following its emplacement in the facility.
  - For the high specific activity waste and spent fuels, this containment shall notably be guaranteed for a period after which the contact temperature of the packages shall be low enough for any releases to take place in known conditions.
  - For intermediate level waste packages, this containment concerns non-gaseous radioactive substances. It shall be guaranteed for at least the duration of the operational phases.
  - The packages of high specific activity waste and spent fuels shall be designed so that this containment capacity is maintained for a reasonably predictable range of variations in the disposal conditions and, at any rate, in the case of an uncertain but plausible event leading to the creation of a "short-circuit" in the geological medium, occurring before the activity of the short and intermediate lived radionuclides contained in the facility has decayed sufficiently for the dissemination of the activity not to lead to unacceptable individual exposure levels.
- limit releases of radioactive substances, after partial or total loss of tightness of the device installed to take part in the containment function.

The characteristics of the packages taking part in the safety of the repository after closure of the facility shall be compatible with those required for the safety of the facility in the operational phase. The required design characteristics of the packages are presented in Appendix 1.

It shall be ensured that the disturbances caused by the packages in the disposal system create no negative effects compromising the safety functions to which the engineered components and the host rock contribute.

Studies shall be carried out to allow an evaluation of the performance of the packages, provide the data needed for the safety case and estimate the influence of the packages on the performance of the other components of the disposal system.

In accordance with Article L542-1-2 of the Environment Code (*"After storage, ultimate radioactive waste which, for nuclear safety or radiation protection reasons, cannot be disposed of on the surface or at shallow depth, shall require deep geological disposal"*), the design of the disposal system shall focus on allowing the acceptance of waste already conditioned and described by the nuclear licensees in accordance with the provisions of Chapter 1 of Appendix 1 to this rule.

The characteristics of the waste packages produced, being produced or for which production is planned, shall be known so that their properties can be taken into account in the design of the disposal system.

5.3. The geological medium – technical siting choices

The geological medium isolates the waste from human activities and from surface geological disturbances. It prevents the circulation of water in contact with the engineered components and waste packages. The role of the geological medium, the host rock in particular, also consists in containing the released radioactive substances by ensuring very slow migration and favouring sorption phenomena in the ground through which they pass.

The investigations to be conducted on the site to characterise the properties of the geological medium shall be guided by rigorous protocols tailored to the needs of the quantitative models and the specific features of the geological medium, utilising the most appropriate methods and tools. In this respect, Appendix 1 gives guidelines for the investigations to be conducted on the site, from the surface and in the underground laboratory.

The investigations shall be conducted in a way that ensures that the observation scale is compatible with the scale of a disposal facility.

The essential criteria when selecting a site are the following:

- *Stability*

The stability of the geological medium shall be such that any changes in the initial conditions as a result of any natural phenomena occurring (glaciation, seismic activity, neotectonic movements) remain acceptable in terms of the safety of the repository. The choice of the site and the design of the disposal facility should be such that the evolution of the disposal system can be determined over a period of time allowing a substantial decay in the activity of the radionuclides present in the inventory of waste packages. More specifically, the stability of the geological medium (incorporating limited and foreseeable evolution) shall be demonstrated for a period of at least 10,000 years.

- *Hydrogeology*

The hydrogeology of the site shall be characterised by very low permeability of the host formation and a low hydraulic gradient. A low regional hydraulic gradient will also be sought for the formations surrounding the host rock.

Hydrogeological measurements shall be taken over an area far larger than that of the site, to be able to build flow models taking account of the flows from the inflow areas up to the outflows. These regional models shall be able to simulate the speed and direction of underground circulation.

Any water-conductive discontinuities or heterogeneities, the nature and geometry of which could locally lessen the host rock's ability to take part in the safety functions, should be identified, characterised and taken into account.

- *Minimum depth requirement*

The site shall be chosen so that the depth adopted for the waste disposal structures covered by this rule is able to guarantee that the safety of the repository will not be significantly affected by erosion phenomena (notably following glaciation), by the effects of an earthquake, or as a result of "ordinary" human intrusion.

The thickness of the surface area that could be disturbed in this way is in principle about 200 metres.

- *Absence of extractable underground resources*

The site shall be chosen so that it avoids areas which could be of exceptional value in terms of underground resources.

Other properties shall be examined. Therefore:

- the siting choice shall take account of the mechanical and thermal properties of the rock, which determine the feasibility of the repository, that is the possibility of building a disposal facility whose effects on the geological medium are compatible on the one hand with the safety objectives both during operations and following closure of the repository and, on the other, with the reversibility of disposal;

- a quantitative description of the geochemical properties of the system shall be produced for an analysis of the radionuclides migration conditions. The geochemical properties of the rock in fact play an important role in the safety of the repository after closure of the facility in that, on the one hand, they can have an effect on the alteration of the packages and engineered components and, on the other, they govern the migration phenomena concerning any radionuclides released.

The various safety assessments performed to back up a siting choice shall show that the properties of the site adopted enable the protection of people and the environment objective to be met.

5.4. The engineered components

Before its closure, any voids remaining in the disposal facility, notably in the drifts and in the vaults around the emplaced packages, shall be reduced to limit damage to the host rock and, to the extent possible, restore the containment capacity of the host rock after closure of the facility. The items deployed to achieve this objective are the engineered components.

The safety functions to which the engineered components contribute are, on the one hand, to prevent water circulating through the disposal facility, by ensuring that the structures do not constitute preferential drains and, on the other, to contribute to containing the activity in the disposal system by limiting and delaying the migration of the radionuclides. They also contribute to isolating the waste from circulating water, notably by preventing the ingress of water other than that contained in the porosity of the host rock.

The functions, performance and characteristics of the engineered components shall be defined and justified in relation to those of the packages and the host rock, because their role supplements these two components in order to mitigate any weaknesses.

It shall be necessary to ensure that none of the materials making up the engineered component creates negative effects compromising the safety functions in which the host rock and the waste packages participate.

With regard to the design of the engineered components, the corresponding requirements shall be taken into account:

- removal of the heat and gases given off by the waste packages,
- reduction of the intensity of the mechanical stresses created,
- maintaining the physical-chemical conditions favourable to limiting the corrosion of the containers and the migration of the radionuclides.

The surface-bottom shafts and possibly certain drifts and certain structures of the disposal facility shall be sealed to ensure tightness of a specified quality. This concern shall be incorporated as of their design.

5.5. The disposal concept

The disposal facility shall be sited within a volume of host rock free of any large faults liable to create favourable routes for the circulation of water. The disposal modules shall be built at a distance from the surrounding aquifers and structures in which water could circulate, so as to ensure a sufficiently long radionuclides migration time between the disposal structures and the biosphere and ensure that this migration mainly takes place in a volume of rock that is disturbed very little by the presence of the disposal facility.

The design and location of the surface-bottom shafts shall limit the circulation of water, taking account of the need for effective sealing.

The presence of the waste packages, and of backfill materials, should not create effects prejudicial to the physical-chemical properties of the other components of the disposal system. In this respect, during the work to characterise the various components, particular attention shall be paid to determining the allowable temperature and deformation limit values.

The design of the disposal system shall take account of the evolution and the influence of the volumes of air present or of gas produced within the structures, notably the air contained in the backfill material and the gases (notably hydrogen) produced by corrosion, radiolysis and the effects of micro-organisms.

The disturbances resulting from the excavation of the disposal facility structures shall be as minimal as possible. More precisely, the disposal concept and the construction techniques shall be appropriate to the site and in particular minimise the scope and effects of the damage to the geological medium as a result of the excavation.

The following provisions would also appear to be favourable from the safety viewpoint, following closure of the facility:

- a positioning of the surface-bottom shafts appropriate to the geological and hydrogeological characteristics of the site, in order to help mitigate the migration of radionuclides;
- compartmentation of the disposal facility into modules that can be easily isolated one from the other in order to minimise the consequences of a hydraulic short-circuit in a part of the disposal system;
- the construction of disposal vaults using an architecture able to limit the speed of water circulation in the vicinity of the packages, independently of the role that the engineered components could play in mitigating this circulation;
- limiting the maximum temperature reached at the interface between the packages and the disposal structures to a value below 100°C;
- limiting the chemical disturbance of the disposal structures.

The suitability of adopting these provisions in the design of the disposal system shall nonetheless be confirmed on the basis of an analysis of their compatibility with safe operation of the facility and with compliance with the reversibility conditions.

5.6. The monitoring programme

A facility monitoring programme shall be implemented during the construction of the disposal structures and until closure of the facility. Certain monitoring provisions could also be maintained after closure of the facility. The need to implement this monitoring shall be taken into account as of the design of the disposal system.

Apart from its contribution to the safety of the facility during the operational phase, the purpose of the monitoring programme is to follow the evolution of certain parameters characterising the state of the components of the disposal facility and the geological medium, as well as the main phenomena responsible for this evolution. The monitoring programme based on constantly updated scientific knowledge, shall be able to demonstrate that the above-mentioned phenomena have indeed been anticipated and remain under control. It also provides the information needed for the management, operation and reversibility of the facility.

The means used for monitoring should not impair the repository's level of safety.

6. DEMONSTRATION OF SAFETY FOLLOWING CLOSURE OF THE DISPOSAL FACILITY

The safety approach is based on an iterative process to assess the safety of the repository after closure. This process is carried out periodically at the various phases of the development of a disposal facility, from design to closure. These assessments help either confirm or revise the provision set during the previous step, in order to demonstrate the safety of the repository.

At each step, the iterative approach shall concern the following three complementary aspects:

- the verification of the pro-safety performance of the disposal system components which are intended to participate in the safety functions, taken individually (waste packages, engineered components, host rock) and then as a whole;
- the assessment of the disturbances in the disposal system as a result of the interactions between its various components, and the estimation of the consequences of these disturbances on the safety functions, given the preventive and palliative provisions incorporated into the design of the system to minimise disturbances or their effects;
- the modelling of the future behaviour of the disposal system for a range of scenarios representative of the reference situation and altered situations, as well as an estimation of the radiological and chemical risks associated with each of these scenarios.

6.1 Verification of the acceptable performance of the components

The purpose of this verification is on the one hand to check the conformity of the various components with the objectives and criteria set out in Chapter 4 of this rule and, on the other hand and more generally, to check appropriate application of the defence in depth principle.

The complementary role of the various components of the disposal system shall be assessed by demonstrating that in the event of a malfunction by a plausible number of packages or a plausible number of engineered components of the facility, as well as in the event of alteration of the properties of the geological medium, activity releases remain limited.

This evaluation shall notably rely on a model of the disposal system which in particular makes it possible to assess the contribution of the various classes of disposal system components (see sub-chapter 2.1) and the geological medium to mitigating releases into the environment of the disposal facility, in the various situations that could be envisaged. Indicators other than dose may be used (estimated activity flux or concentration for various locations around the facility). Sensitivity analyses shall make it possible to more accurately identify the components and phenomena important for safety, in order to guide research and development and underpin the qualification activities for these components.

6.2. Evaluation of disturbances induced in the disposal system

This evaluation consists in studying and modelling the various phenomena and events that could lead to disturbance of the disposal system components taking part in the safety functions. The associated uncertainties shall be identified and taken into account in order to show that the components are correctly sized to ensure that the safety functions remain guaranteed with sufficient margins over an appropriate duration.

With regard to the geological medium, studies shall be carried out on the effects of the disturbances related to excavation of the disposal and access structures, as well as the combined effects of the thermal, mechanical, hydraulic and chemical disturbances that will affect it. Any disturbances of the geological medium induced by the presence of gas shall also be considered.

6.3. Evaluation of individual exposure

The approach adopted to verify compliance with the objectives defined in Chapter 3 consists in studying a limited number of situations representative of the various families of events, sequences, or combinations of events, for which the corresponding consequences are the highest from among the range of situations that could be envisaged. This approach is based on a selection of events considered to be reasonably conceivable and representative of the risks.

When studying the situations selected, the assessment of individual exposure levels consists in estimating on the one hand the future foreseeable behaviour of the disposal system starting from the initial state of the site as defined following the recognition programme, and on the other the effects on people that may result from its presence in the various situations specified in sub-chapter 5.4 and in Appendix 2.

The assessment of long-term individual exposure levels in particular requires that the following be available:

- all the data describing the disposal system (inventory of activity emplaced, characteristics of the various components, architecture of the disposal facility, etc.). These data shall either be pessimistic data tending to aggravate the estimation of the radiological impact, or average (or probable) data supplemented by ranges of uncertainty and estimations of possible variations over time;
- the basic data such as those needed to identify the species released (speciation) and evaluate their radiological effects on humans;
- the biosphere (see sub-chapter 5.6) ;
- the list and characteristics of the situations selected;
- the calculation models.

The presentation of the results shall make it possible to assess the radiological impact of the repository for the various situations studied and the corresponding uncertainties.

6.4. Situations considered

The selection of the situations studied comprises the following steps:

- identification of the events liable to occur,
- classification of the events according to their probability, their origin (the disposal facility, human activities, natural processes),
- the situations resulting from these events or a possible combination thereof,
- sorting of the situations into families,
- selection of the representative situations.

This selection differentiates between the reference situation representative of the probable events and the altered situations corresponding to the occurrence of uncertain but plausible events.

With regard to the positioning of these situations over time, the following periods will be referred to:

- an initial period characterised by significant decay of the activity of the short or intermediate lived radionuclides. The presumed conservation of the memory of the repository, for which provisions shall be made, will make any human intrusion during this period highly unlikely;

- an intermediate period, during which stability shall be demonstrated. This is characterised by the absence of major glaciation and the establishment of a reducing chemical environment in the vicinity of the disposal structures;

- the period subsequent to the previous period, for which the occurrence of major glaciation is considered.

6.4.1. Reference situation

The events to be considered are:

- the events linked to the presence of the disposal facility. Its impact will involve processes associated with the emission of heat, the emission of gas, mechanical, physical-chemical modifications, or the desaturation of the natural environment around the disposal structures. All the processes leading to the gradual deterioration of the packages and engineered components (corrosion of the containers and containment matrices, ageing of the engineered components, etc.) shall be considered;

- a range of highly probable natural events (climatic cycles, "greenhouse effect" linked to human activity, seismic activity, subsidence or tectonic uplift). Climatic cycles (external geodynamics) are accompanied by processes such as erosion/sedimentation cycles and modification of the surface hydrology and water circulation at depth.

6.4.2. Altered situations

The events studied in order to define these situations will be either events of the same type as those used to define the reference situation, but on an exceptional scale, or events for which the date of occurrence and how they develop are highly uncertain. These events will be divided into two categories, natural events and those linked to human activity.

The natural events to be considered include climate change of exceptional amplitude, exceptional seismic activity, exceptional subsidence or tectonic uplift, diapirism, magmatic activity, meteorite falls. Depending on the site chosen, some of these events may be ignored further to an appropriate analysis.

The events linked to human activity include direct or indirect human intrusion (boreholes, mines, cavities, surface or sub-surface constructions), package defects (unexpected degradation conditions, non-compliance with specifications, inappropriate specifications, manufacturing defects), defects in the engineered components (manufacturing or design flaws), undetected anomalies or faults in the geological medium.

As an example, the situations to be used for the analysis could be those given in Appendix 2.

6.5. Modelling of the evolution of the disposal system

The repository's safety analysis and the assessment of its impact on humans and the environment require modelling of the evolution of the components of the disposal system and the migration of the radioactive substances and the chemical substances released by the waste packages. This modelling shall be based on sufficient knowledge of the physical-chemical processes and the events which can affect the evolution of the disposal system and its environment and thus on an appropriate research programme and investigations.

The evolution of the disposal system is determined by the behaviour of the various subsystems of which it consists and which are inter-dependent. In this respect, a distinction is commonly made between the following two sub-systems, which are extremely different in terms of modelling:

- the near field, which comprises the packages, the engineered components and the part of the geological medium liable to undergo irreversible transformations as a result of the existence of the disposal facility;
- the far field, which is the part of the geological medium not directly affected by the presence of the disposal facility.

The models are simplified representations of real phenomena. It shall be shown on the one hand that these representations do not leave out important phenomena and, on the other, that the simplifications made lead to worst-case evaluations.

Given the importance of modelling, particular care shall be taken with respect to the quality of the data used (Chapter 6), and to the examination of the validity of the conceptual models and the calculation codes used. For this, it will in particular be necessary to take part in inter-comparison tests of models and compare them with experimentation results.

Given the iterative nature of the safety case, the level of modelling detail will also depend on the progress of the studies and the level of precision of the data collected during modelling.

6.6. Biosphere

The biosphere consists of the part of the environment easily accessible to human activities. It is liable to allow the transfer of the radionuclides from the disposal facility to humans, leading to internal exposure (inhalation, ingestion) or external exposure.

The transfer routes to and within the biosphere may include:

- the aquifers used by humans for water resources;
- the outlet area of groundwater liable to have passed through the disposal structures;
- the surface flow system for these waters;
- the ground liable to be irrigated or flooded by these waters;
- the plant or animal production liable to be used for human consumption and which could be contaminated;
- the atmosphere (transport and deposition of dust and gas).

It would appear to be impossible to predict the local evolution of the biosphere over very long time-frames. However, the foreseeable major regional climatic events could be taken into account by using the notion of standard biospheres, representative of the various potential states of the biosphere on a larger scale, in the light of these events.

Moreover, when calculating the radiological impact, hypothetical reference groups shall be used, representative of the individuals liable to be subjected to the highest exposure levels. These individuals shall be assumed to live off the land at least partially.

6.7 Consideration of uncertainties and sensitivity studies

Determining and taking account of uncertainties are essential aspects of the safety analysis.

The main sources of uncertainty are varied:

- uncertainties regarding parameter values,
- uncertainties associated with gaps in knowledge about certain phenomena,

- uncertainties surrounding whether or not the phenomena which could have an influence are considered exhaustively,
- uncertainties inherent in the conceptual models or the simplifications needed to produce models,
- uncertainties regarding future events or future human activities.

The safety case shall clearly identify the extent to which the on-site investigations, the results of the research programmes, the design provisions, the hypotheses used for the evaluation and the sensitivity studies have been able to assess and take account of the uncertainties. The residual uncertainties shall be assessed qualitatively or quantitatively, depending on their nature. Experts may be called on for their opinion and these opinions shall be remain traceable.

The evaluation of the performance of the components, of the overall behaviour of the disposal system and of the individual exposure levels shall be accompanied by relevant data intended to demonstrate the pessimistic nature of the results obtained, as well as the soundness of the design choices. Sensitivity studies shall also be carried out in order to highlight the most important parameters and justify the simplification hypotheses adopted.

The sensitivity analyses are able to identify the priority points requiring work regarding the definition (situations considered), the understanding and ranking of the processes involved (models) or characterisation (parameters) in order to enhance the credibility of the results of the evaluations.

6. QUALITY ASSURANCE

By implementing a monitored range of scheduled, systematic measures, ANDRA shall obtain appropriate quality based on written and archived procedures.

The areas concerned are as follows:

- the design, construction and operation of underground laboratories,
- the design of a disposal system and the qualification of its various components,
- monitoring of waste package production,
- acquisition of data on the sites and in the laboratory,
- the safety case and the corresponding modelling.

The operator monitors and oversees the actions of the contractors involved in these various fields.

APPENDIX 1

GUIDELINES CONCERNING THE WASTE PACKAGES AND THE INVESTIGATIONS TO BE CARRIED OUT ON THE SITE

A1 – 1 WASTE PACKAGES

A1- 1.1 Identification of waste packages

Without prejudice to any packaging supplements defined by ANDRA, the waste packages needed at the various stages of the facility design studies and the evaluation of repository safety shall be identified and updated by the nuclear licensees, in accordance with an identification requirement defined by ANDRA. This identification requirement shall be justified - according to the impact of the properties of the packages - in the repository's design and safety studies.

A data package collating all the characteristics of the packages liable to influence the safety of the repository shall be produced for each package family. These characteristics shall have been produced on the basis on the one hand of the characterisation tests and on the other on measurements or evaluations carried out on the packages produced. Depending on the case, the characterisation tests shall be performed on active or inactive packages or on samples representative of the industrial production process. The purpose of the tests, measurements and evaluation is to provide the information needed for the design and safety case. It is notably important:

- to determine the radioactive characteristics of the waste packages and their radionuclides inventory. In particular, a good estimation of the activity of the long-lived radionuclides and that of the volatile radionuclides must be obtained;
- to identify the chemical content of the waste packages, in particular the complexants or products liable to increase the solubility of the radionuclides or alter their ability to be retained by the other components of the disposal system;
- to identify the nature and quantities of the gases produced as a result of radiolysis, corrosion and alteration of the packages under irradiation or under the effect of micro-organisms;
- to evaluate the physical characteristics of the waste packages: density, homogeneity, filling ratio, percentage water incorporated, conductivity and thermal capacity, characteristic temperatures, mechanical characteristics, etc.; ;

- to determine the properties of the packages, notably those associated with their initial containment capacity and their evolution in conditions representative of the repository, that is, as applicable:
  - resistance to leaching,
  - outgassing rate,
  - mechanical strength,
  - chemical interactions (wastes/matrix, wastes or matrix/materials of engineered components, etc.),
  - thermal effects,
  - effects of alpha or beta-gamma irradiation,
  - effects of micro-organisms.

Studies of the long-term behaviour of the packages in the presence of various hazards liable to affect them (notably interactions with the materials of the engineered components and with the rock, effects of radiation or of micro-organisms) shall be carried out, more specifically to determine the degradation rates versus time, the nature of the degradation products and the interactions between the degradation products and the long-lived radionuclides contained in the packages (colloids, complexes, etc.).

Studies shall be carried out to determine the stable chemical forms of the radionuclides released by the packages in the disposal conditions.

A1-1.2 Acceptability of waste in the disposal facility

Article L. 542.12 of the Environment Code, amended by Act 2006-739 of 28 June 2006, states that Andra is tasked with producing the specifications for the disposal of radioactive waste and with giving the competent administrative authorities an opinion on the waste conditioning specifications, in compliance with the rules of nuclear safety.

In this respect, the properties of the packages shall be evaluated against the properties given in the following analysis chart:

- the materials making up the packages have no significant reactivity in the various environmental conditions encountered in the disposal facility during its operation and after its closure. The use of materials, the presence of which in the facility is liable to compromise the safety functions in which the packages and the other components of the disposal system participate, shall be avoided or limited. Any overpacks shall be made of materials resistant to corrosion in the variability conditions of the package's chemical environment, as expected during the target containment period. The other materials making up the package shall not compromise the maintained integrity of the overpack. The possibility of a chemical reaction between the waste and this overpack shall notably be limited, as should the possibility of a galvanic coupling between the various metal components of the package;

- the packages shall generate limited quantities of gas, compatible with maintaining their pro-safety properties, as well as those of the other components of the disposal system;

- the reactive or complexing substances present in the packages are in sufficiently small quantities for their release to create no solubilisation of the radionuclides or alteration of the ability of the radionuclides to be retained by the engineered components of the disposal facility and by the host rock in proportions that would compromise safety;

- the thermal characteristics of the packages are such that the effect of the heat released does not alter their containment properties and does not compromise the functions of the other components of the disposal system. The release of heat does not cause the appearance of phenomena that are too complex to understand and model in the repository safety case;
- the mechanical properties of the packages guarantee that no significant deterioration of their containment capacity takes place before closure of the facility, owing to the load from the envisaged stacking and, as applicable, after closure, for the period during which the dissemination of non-gaseous radioactive substances must be avoided. Furthermore, the voids which can be present in the packages do not compromise the safety of the repository;
- the characteristics of the packages are favourable to the prevention of criticality risks so that, whatever the initial geometry of the stack of packages and the conceivable stacking configurations as a result of degradation of the components of the disposal system after closure of the facility, the occurrence of a criticality accident remains improbable and the consequences related to the dissemination of activity during such an accident, if it were impossible to rule it out completely, would not be unacceptable.

The search for the properties presented above is comparable to a good practice to be implemented when industrial manufacture of the package is envisaged. However, it does not automatically imply the future acceptability of the packages which do not meet the required characteristics in full. Acceptance of the packages in the facility will be issued on a case by case basis, according to the safety analysis.

A1-2 INVESTIGATIONS TO BE CARRIED OUT ON A SITE

A1-2.1 Geological studies

A1-2.1.1 Long-term geological phenomena

These phenomena shall be evaluated qualitatively and quantitatively with reference to the current situation, the near past (historic) and the more distant past (Quaternary). This will make it possible to assess the values of the parameters, by characterising them along with their variations, and examining their influence. As a general rule, it will therefore be necessary to consider the site's regional geological environment.

A1-2.1.2 Hydrogeological measurements

Hydrogeological measurements shall be taken regionally, to be able to build flow models taking account of the flows from the inflow areas up to the outflows. These regional models shall be able to simulate the speed and direction of underground circulation.

A1-2.1.3 Thermal, hydraulic and mechanical modelling

Studies shall be performed, notably using coupled models of thermal and mechanical phenomena, to examine the influence of the packages emplacement processes and sequences on the mechanical behaviour of the disposal facility and in particular taking account of the prior cooling time and the density within the repository. These specific studies shall make it possible to determine the corresponding physical parameters and specify the influence of these phenomena. In this respect, during the work to characterise the various components of the disposal system, particular attention shall be paid to determining the allowable temperature and deformation values.

A1-2.1.4 Analysis of geochemical properties

A quantitative description of the geochemical properties of the system shall be produced for an analysis of the radionuclides migration conditions.

Mineralogical analyses of the materials of the host rock shall be performed and the possibility of geochemical evolution of these materials shall be examined, notably as a function of temperature and irradiation. The role of clayey minerals will in particular be studied.

A1-2.2 Investigations to be carried out on the surface

A1-2.2.1 Objectives

For each site, the objectives of the investigations shall be:

- firstly to determine its lithological, structural, petrographic, hydrogeological, thermomechanical, geochemical and tectonic characteristics, in order to make a particular assessment of its ability to meet the siting criteria (sub-chapter 4.3) ;
- to collate the data needed for modelling of the site for the purposes of the safety case.

These objectives could be supplemented by surface investigations, by recognition boreholes and by the study of materials extracted from these boreholes (water, gas and rock).

A1.2.2.2 Investigations from the surface

The investigations from the surface shall notably be used:

- to confirm the geometry of the geological formations of the site and its environment by means of structural studies and geophysical investigations;
- to identify any major faults in the medium by means of surface observations, tele-detection and geophysics;
- to refine the local neotectonic study;
- through a regional hydrogeological study, to determine the nature, position and characteristics of the possible outflows of waters coming from the disposal facility.

A1.2.2.3 Exploratory boreholes

The main purpose of the exploratory boreholes will be to determine:

- the permeability and porosity of the host rock and the surrounding formations; the exploration will cover the overall permeability of these formations, as well as the permeability differences liable to be caused by any sedimentary or structural discontinuities;
- the hydraulic role of any major faults;
- the hydraulic potential in the host rock and surrounding formations;
- the distribution of natural temperatures in the host rock.

In addition, as of the initial access to the host rock, it will be necessary to make a priority evaluation of its mechanical characteristics in-situ and its natural stress state, in order to have the data needed to predict its hydro-thermomechanical behaviour.

The possible presence of gases in the drilling fluids will be closely monitored, in order to obtain a first indication of the permeability of certain cracked media and to characterise any gaseous inclusions in the salt.

Finally, borehole logging will be required, in order:

- to verify the homogeneity or characterise the physical or lithological heterogeneities of the rock;
- by measuring various physical parameters, to make a detailed interpretation of the geophysical data acquired from the surface, between surface and boreholes, or between boreholes (density, propagation rates, etc.).

A1-2.2.4 Study of materials extracted from boreholes

The rocks of the geological environment will need to be characterised from the mineralogical, chemical, physical and mechanical viewpoints, on the basis of borehole core samples. Particular attention shall be paid to the mechanical parameters of the clay and the salt. As part of the exploration programme, the following shall be measured for all the media:

- the mechanical parameters (strength, deformability, viscosity);
- the thermal parameters (coefficients of conductivity and expansion, heat capacity);
- the porosity, permeability and thermo-poro-mechanical coupling coefficients. The anisotropy of these parameters shall be evaluated.

It will also be necessary to characterise the properties and the physical, chemical and isotopic composition of the interstitial waters sampled from the various permeable or relatively impermeable parts of the aquifers. The composition of these samples shall not undergo disturbances that are impossible to identify as a result of drilling work: resulting mixtures of naturally distinct waters, contamination by drilling fluids. The method of drilling and of taking fluid and solid samples shall be adapted such as to minimise any disturbance to them.

As of this stage, experiments carried out on samples shall also be able to reveal certain coupled effects (thermal, mechanical and hydraulic) and evaluate the exchange coefficients between the fluids and the mineral phases of the system.

Particular attention shall be paid to analysing physical and chemical heterogeneities in the medium at different scales, notably fracturing (density, orientation and filling of fractures) and variations in facies.

A1-2.3 Investigations to be carried out in an underground laboratory

A1-2.3.1 Objectives of the investigations

The objectives of the investigations in the underground laboratory shall notably be:

- to take measurements on the rocks in-situ or on the fluids that are as little disturbed as possible by the conditions of the experiment, in order to improve the understanding of the parameters already partially evaluated during the recognition programme carried out from the surface;
- to use more general experiments to determine the behaviour of the various rocks and fluids, taking account of the natural phenomena and the modifications caused by the construction of the future disposal facility;
- to qualify the methods to be used for the excavation, blocking and sealing of cavities and structures;

- to demonstrate the industrial feasibility of installing the engineered components by means of demonstrators;
- to contribute to demonstrating the feasibility of retrieving packages despite any corrosion of the containers and the thermo-hydro-mechanical effects.

A1-2.3.2 Measurements in-situ and on samples

Measurements shall be taken within the laboratory, to confirm or specify the values of the parameters and to assess their anisotropy, their spatial distribution, as well as scale effects.

The investigations to be carried out shall include:

- evaluating the overall water and gas permeability of the host rock;
- notably by means of measurements from the bottom, specifying the hydraulic role of any faults or fractures encountered;
- determining the geochemical properties of the waters and gases encountered during drilling of drifts and boreholes from the bottom, and monitoring them over a period of time, in order to specify the connections between the more or less permeable zones crossed;
- evaluating the initial stresses tensor;
- from the cavities excavated in the underground laboratory, assess the drillability of the rock and the behaviour of the walls (risk of flaking for hard rocks, convergence for plastic rocks);
- measuring deferred mechanical effects (relaxation, creep);
- specifying the geochemical properties that could influence the migration of radionuclides and notably determining the water-rock exchange coefficients measured on core samples,
- studying the properties of the geological medium affected by the excavation.

Any small fracturing shall be studied.

A1-2.4 Installation of measurement instrumentation to monitor the evolution of the site during the operational and reversibility phases of the disposal facility

In the light of the duration of the operational period and the disturbances created during this period, it would appear to be essential to make provision for appropriate instrumentation to monitor the evolution of the parameters concerning the site and the structures. This instrumentation shall be put into place as soon as possible, so as to ensure monitoring of the structures and the site, not only during, but also before the repository's operational period.

The following in particular should be monitored:

- the piezometry of the site,
- the movements and, more generally, the behaviour over time of the walls of the structures, which must remain open for a very long time (certain exploratory boreholes, access shafts, service drifts),
- the seismic motion,
- the thermal evolution of the host rock and its effects (stresses, displacements, fracturing, etc.)
- the hydraulic evolution of the host rock.

A1-3 PARTICULAR RECOMMENDATIONS REGARDING THE VARIOUS TYPES OF SITES

A1-3.1 Crystalline sites

In order to determine the major geodynamic characteristics of each massif, the following shall be studied:

- the post-Palaeozoic geological history of the massif,
- the recent geodynamic context (Pliocene and Quaternary),
- the current geodynamic context.

To evaluate the geodynamic context of each massif, the following shall be produced:

- a description and a localisation of the geological accidents liable to reoccur, that is as precise as possible,
- an estimation of the predominant geodynamic factors,
- an evaluation of the impact of expected movements on the hydrogeology and on the disposal facilities,
- a diagram of the geodynamic evolution of the massif, taking account of the predominant phenomena; this diagram shall notably allow a definition of the situations to be included in the individual exposure evaluations, in particular regarding the hydrogeological behaviour of the host rock.

A detailed interpretation of the results of the hydrological balance on the scale of each catchment basin shall be made in order to obtain an estimate of the infeed to the surface aquifer.

A1-3.1.1 Specific recommendations for granite sites

The following shall be defined as precisely as possible:

- the geological and structural context of the research area,
- the architecture of the granite massif (structural analysis, petrological analysis),
- the detailed map of the massif, in particular regarding surface formations and fracturing,
- the contacts between the host rock and adjacent formations,
- the tectonic context of the research area (kinematic analysis of the various types of discontinuities, microstructural analysis).

For the deep hydrogeology, data concerning fracturing at various scales (small fracturing, hectometric fracturing, major faults adjoining the host rock) and all the other information needed for modelling, shall be studied notably in order to evaluate the water transfer times and identify the outflows.

A1.3.1.2 Specific recommendations for shale sites

The following shall be defined as precisely as possible, at the local level:

- the lithostratigraphy of the shale formation,

- its cartography, in particular for any quartz sandstone levels,
- the detailed cartography of recent formations,
- characterisation of the cleavage: type, distribution, involvement of a single phase, modifications in the vicinity of faults,
- various scales of fracturing and its cartography.

These data shall be supplemented by an evaluation of the general geological framework.

For the deep hydrogeology, data concerning fracturing of the various types of discontinuities (fracturing at various scales, seams, quartz-sandstone levels, cleavage) and all the other information needed for modelling, shall be studied notably in order to evaluate the water transfer times and identify the outflows.

A1-3.2 Sites in saliferous formations

A summary of the most recent deep tectonic data available shall be produced. This summary shall on the one hand allow clarification of the geometry of the regional underlying formations (notably the rims and shelfs), examination of the presence of underlying evaporites and definition of the position and continuity of deep discontinuities and, on the other, allow evaluation of their influence on the stability of the site.

The following shall be defined as precisely as possible, at the local level:

- the main lithostratigraphic assemblies and sub-assemblies of the saliferous series (primary salt, secondary salt, brine pockets, carbonates, clays, sulphates, detrital materials) as well as the sedimentary discontinuities or types of dissolution breccia. Whenever possible, the deposition mechanisms, alterations and synsedimentary or diagenetic events that have occurred, along with their spatial distribution and chronostratigraphic reference levels shall be highlighted;
- the suprasaliferous formation (marly levels, sulphates, anhydrite, gypsum, dissolution breccia);
- the upper, lower and lateral limits of the saliferous assembly, in contact with its cap and its substratum (dissolution phenomena, alterations) ;
- the geometry of the base, that is the substratum of the saliferous series, in particular with regard to any discontinuities; the repercussions and expression of these underlying discontinuities in the evaporitic series shall be understood.

For the surface and lateral hydrogeology, a detailed interpretation of the results of the hydrological balance on the scale of each catchment basin shall be made in order to obtain an estimate of the infeed to the surface aquifers.

For all the aquifers, a regional hydrogeological survey indicating the infeed areas, any discontinuities, the outfeeds and the relations between the aquifers shall be performed, along with a hydrogeological balance.

A local hydrogeological survey shall be performed. It shall reveal on the one hand the geometrical characteristics of the aquifers (lithostratigraphic nature, morphology, continuity, etc.) and of the impermeable levels and, on the other, their hydrodynamic characteristics (permeability, transmissivity, porosity, etc.) notably taking account of the influence of fracturing of the ground and of all the other elements needed to quantify the flows (local pumping for example).

These hydrogeological surveys shall make it possible to assess the salt dissolution risks.

The following shall be studied:

- the various factors behind the current overall vertical movements and their combined effects,
- the consequences of the defined movements (possible modifications of the hydrography and hydrogeology) and their quantification (erosion, transport and sedimentation rates),
- the regional seismo-tectonic context.

The structural objects which had been active during the plioquaternary shall be defined as precisely as possible.

The previous studies shall be based on the sedimentological and paleogeographical history of the plioquaternary, supported by a detailed chronostratigraphic scale.

A1-3.3 Sites in clay formations

The nature and scale of the heterogeneities inside the host rock shall be determined locally (from the hydrogeological and geotechnical viewpoints).

The vertical (flexures and faults) and horizontal (sedimentary wedges, unconformities, facies changes) discontinuities which could notably play a possible role in the local hydrogeology shall be located and identified.

This work shall notably include an interpretation of the local geological data in terms of regional sedimentology (local paleogeographical reconstitution) in order to determine the driving forces (directions and nature) at work during sedimentation.

A description of the surface hydrogeology shall be made at the local scale in order to obtain an estimate of the infeed to the surface aquifers.

The following shall be determined for all the formations, as precisely as possible:

- a regional hydrogeological diagram showing the recharge and discharge zones and the relations between aquifers, as well as a preliminary hydrogeological balance,
- a local hydrogeological diagram showing:
  - the geometrical characteristics of the aquifers (lithostratigraphic nature, morphology, continuity, etc.) and the semi-permeable and permeable levels,
  - their hydrodynamic characteristics (porosity, permeability, transmissivity, etc.) both vertical and horizontal, notably taking account of fracturing of the land and all the other elements needed to quantify the flows,
  - their geochemical characteristics, their salinity in particular,
  - the hydrodynamic characteristics and the geometry of any vertical discontinuities which could lead to the interconnection between different stratigraphic levels.

With regard to regional and local scale geodynamics, the following shall be performed:

- a summary of the seismotectonic data on the regional scale,
- the recognition of the structural objects which could have played a role in recent local deformations.

APPENDIX 2

SELECTION OF THE SITUATION TO BE STUDIED FOR THE SAFETY ANALYSIS

A2-1. REFERENCE SITUATION

A2-1.1. Evolution of the system owing to the presence of the disposal facility

The effects of the work to excavate the disposal cavities on the hydraulic properties of the rock and the influence of the transient physical-chemical conditions around the structures on the hydraulic behaviour of the system shall be assessed.

With regard to the release of heat from exothermic waste, the following shall be evaluated:

- the stresses and strains induced by the thermomechanical effects on the host rock;
- their consequences on the flows and the migration of radionuclides, taking account of the particularities of the media (fracturing of granite, sedimentary heterogeneities in clay);
- the effects of any thermoconvection;
- the consequences of all the above effects on the underlying formations;
- the importance of the dehydration of clay minerals versus the temperature and the distance from the disposal structures.

A2-1.2. Evolution of the system as a result of natural events

The chosen evolution for the reference situation corresponds to that resulting from probable natural events.

A2-1.2.1. Climatic cycles

The succession of climatic cycles as set out in the Milankovitch theory shall be envisaged as the entire site is within a periglacial context. The influence of the presence of permafrost or a drop in sea levels (by about 100m) on erosion and its possible consequences on water flow at depth shall be evaluated. The effects of "greenhouse" type climate change linked to human activity, with the notable consequence being a rise in sea levels, shall be taken into consideration (interglacial period).

A2-1.2.2. Vertical movements

The amplitude of vertical movements (subsidence, tectonic uplift) and the associated mechanisms shall be evaluated on the basis of the observations taken on the site. The conceivable unfavourable effects on underground flows shall be assessed.

A2-1.2.3. Seismic activity

With regard to seismic activity, a level of seismic activity liable to be encountered during the various periods studied shall be adopted. There are uncertainties surrounding the possible seismic levels over periods appreciably longer than the historical period. To take account of this, several possibly cross-referenced approaches could be chosen in relation to the seismotectonic context. The degree of disturbance generated on the hydrogeological system by seismic activity shall be evaluated for relevant time and space scales.

A2-2. SITUATIONS REFERRED TO AS ALTERED

The events to be considered shall be divided into two categories, natural events and those linked to human activity.

A2-2.1. Altered situations linked to natural events

A2-2.1.1. Climatic cycles of exceptional amplitude

Exceptional amplitudes shall be taken into consideration for the climatic cycles liable to occur until such time as the activity contained in the disposal system has significantly decayed.

A2-2.1.2. Exceptional vertical movements

The values of these movements shall be evaluated from the data corresponding to periods of paroxysmal activity observed during the plioquaternary.

A2-2.1.3. Exceptional seismic activity

The characteristics of the maximum physically possible earthquake shall be identified on the basis of the tectonic context of the site.

A2-2.2. Altered situations linked to human activity

A2-2.2.1. Human intrusion

For this type of situation, it is necessary to set a date before which no inadvertent human intrusion can occur owing to the memory of the existence of the repository being maintained. This memory depends on the durability of the measures taken at archival of the institutional documents resulting from the regulations. In these conditions, the loss of the memory of the existence of the repository can reasonably be situated beyond 500 years. This value of 500 years will be used as the minimum date of occurrence of a human intrusion.

The definition of the characteristics of the human intrusion situations chosen is based on the following worst-case hypotheses:

- the existence of the repository and its location are forgotten,
- the level of technology is the same as today.

Exploratory borehole passing through a disposal structure

A situation involving a borehole passing through the repository with extraction of core samples shall be adopted. The examination of the core samples consisting of high-level waste gives rise to external exposure which shall be evaluated according to the type of examination carried out on these core samples. **Mine working**

- For crystalline sites, the situation is ruled out owing to the lack of any value in mining the sites studied.
- For clay sites, the working of a mine is not to be considered owing to the lack of any particular mining value for the existing formations at the depths envisaged for the disposal structures.
- For the saliferous sites, worker exposure during working of a mine reaching the repository will be evaluated.

Abandoned and poorly sealed exploratory borehole passing through a disposal structure

- For crystalline sites, the consequences resulting from modifications to the radionuclide flows and migration times will need to be studied.
- For sedimentary sites, the consequences of the interconnection between aquifers or between an aquifer and the disposal structures will need to be studied.

Exploratory borehole in a deep aquifer for water for consumption or agricultural use

The plausibility of pumping of water for consumption or agricultural uses from a deep aquifer shall be specified according to the water resources. The influence of pumping on the flows shall be assessed with a view to the evaluation of individual exposure levels.

Geothermal energy and heat storage

This situation does not need to be studied because the sites selected will not have any particular value from this point of view.

Other intrusion situations that could be envisaged for the saliferous sites

<u>Creation by dissolution of a cavity bisecting the repository</u>

The brine extracted from the cavity shall be assumed to be intended to provide salt for human consumption. The individual exposure levels resulting from ingestion shall be evaluated.

For this evaluation, the salt mining method, the geometry of the cavity, the architecture of the repository, the characteristics of the waste, the condition of the packages at the moment of the intrusion, the level and nature of insolubles contained in the saliferous formation shall notably be taken into consideration.

The following variants shall also be examined:

- the creation of a cavity by dissolution and use of the salt for purposes other than human consumption,
- double-well mining of the salt for human consumption purposes.

<u>Leached cavity which bisected the repository and was abandoned</u>

The brine pocket resulting from leaching of a cavity and remaining following mine working may communicate with the upper aquifer owing to incorrect sealing of the mine working well. After pumping, the water from this aquifer can be used for human consumption or for agricultural purposes. The individual exposure levels shall be evaluated taking account of the transfer routes by ingestion of drinking water and the consumption of agricultural produce from crops irrigated using this water.

The following variants shall be examined:

- interconnection of upper aquifers with the repository after a double-well salt mine has been abandoned,
- Interconnection with the upper aquifers of a mine close to the repository through the mine-working wells which were poorly sealed following the end of operations.

<u>A2-2.2.2. Component defect</u>

A component defect is taken to mean its failure to perform the function(s) assigned to it in the reference situation.

Geological medium

The presence of a fault is a hazard linked to incomplete knowledge of the site, as a result of the investigative means used:

- *crystalline sites:* a conductive fracture zone shall be envisaged in an area close to the disposal facility not detected owing to the means used;
- *clay sites:* when the sedimentation conditions allow the formation of sand lenses, the presence of undetected lenses of this type shall be envisaged, which can significantly increase the permeability.

Engineered components

The failure of an engineered component may be caused by a design defect in the seal of an access shaft or drift, or failure to comply with the specifications regarding the materials or their utilisation.

The consequences of these failures shall be studied.

For sedimentary sites, account shall be taken of the processes used to restore the medium to its original condition.

Waste packages

The existence of package conditioning faults could be considered in order to take account of the various uncertainties regarding the quality and ageing of the packages.