ANDRA's Strategy and Approach for Post-Closure Safety of Geological Disposal - 15128

L. GRIFFAULT* and S. VOINIS*
* ANDRA, French National Radioactive Waste Management Agency, Parc de la Croix Blanche, 92298 Châtenay-Malabry, France.

ABSTRACT

The French National Radioactive Waste Management Agency, or ANDRA, has, among its roles in management of radioactive waste, to ensure the protection of man and the environment from all radioactive waste generated in France. In order to verify compliance to the safety objectives, radiological and chemical impact evaluations are to be assessed. The objective of the paper is to present the overall approach for assessing the post-closure safety of French nuclear waste disposals in particular on the Geological Disposal.

INTRODUCTION

The December 30, 1991 French Waste Act [1] entrusted Andra, the French national agency for radioactive waste management, with the task of assessing the feasibility of deep geological disposal. This Act initiated a research programme to define methods for the long-term management of intermediate-level-long-lived and high-level (IL-LL/HL) radioactive waste with the objective to produce a report after 15 years of investigations, including a feasibility-assessment report on clay formations namely the "Dossier 2005 Argile" based notably on the work conducted on the site of the Meuse/Haute-Marne Underground Laboratory and in foreign laboratories.

The law of 1991, and the Fondamental Safety Rules of 1991 (RFS.III.2.f [2]) stated 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 generation*".

Several main iteration loops have been identified since 1991, each corresponding to a major milestone of the program: License application for construction and operation of the underground research laboratory (in 1996), submission of the Dossier 2001, submission of the Dossier 2005 [3], the feasibility assessment report, and the submission of the Dossier 2009 [4].

The feasibility "Dossier 2005 Argile" [3], presents the studies carried out for the deep disposal project in a geological formation and proposes a repository design in the Callovo-Oxfordian clay host rock, a 150 m thick clay layer at an approximate mean depth of 500 m, located in the Meuse/Haute-Marne area, East of France. In this dossier, an area of 250 km² (transposition zone (ZT)) was defined. Following, the "Dossier 2009" [4], comprises among others a safety option report and a site selection document which has proposed a 30 km² area (ZIRA) within the transposition zone for detailed geological investigations in view of the underground implementation of the disposal.

Since 2011, the project has entered an industrial design development phase and has become the Centre industriel de stockage en milieu géologique (Cigéo) (Industrial Center for Geological Disposal). In that framework a Dossier studying concept designs has been transmitted to the Nuclear Safety Authority in 2012.

Following the publishing of the Dossier 2005 Argile, the 28th June 2006 Act entitled "*Programme National de Gestion des Matières et Déchets Radioactifs*" (National program for radioactive waste and nuclear material management) [5] has set the deep geological repository in clay host rock as the selected solution for IL-LL and HL radioactive waste disposal in France. According to this 2006 Act, reversible waste disposal in a deep geological formation and corresponding studies and investigations shall be conducted with a view to selecting a suitable site and to designing a repository.

The Act stipulates that a national plan of management of the materials and the radioactive waste ("PNGMDR") makes an assessment of existing modes of management of the materials and radioactive waste. It is transmitted to the parliament and updated every three years.

On the basis of the conclusions of those studies, a Dossier of Safety Options will be submitted in 2015, to be reviewed before the application for the authorization of such a repository due in 2017, and subject to that authorization, the repository will be commissioned in 2025.

During the examination of the authorization of creation, the safety of Cigéo is estimated with regard to the various stages of its management, including its permanent closure. Only a law can authorize this one. The authorization fixes the minimal duration during which, as precaution, the reversibility of the repository must be insured. This duration cannot be lower than 100 years [5].

NATIONAL SAFETY REFERENCE TEXTS

For the Dossier 2005, the Basic Safety Rule of 1991 [2] provided a framework for long term safety expectations with respect to disposal design principles, favourable geological media choice criteria and study modalities. It presented the basic objectives which must serve as guidelines for the work on a geological disposal:

- "*The protection of people and the environment in the short and long term is the basic objective assigned to a waste repository in a deep geological formation*".
- The long term safety of the repository must not "*depend on an institutional control on which we cannot absolutely rely beyond a limited period*".

Furthermore, studies should show the ability to limit potential consequences to a level as low as reasonably possible (ALARA). The concept should include a multiple barrier system (namely the packages containing the waste, the engineered barrier, the geological medium itself), and rely on passive repository evolution without institutional control beyond a given timeframe.

The revised version of the Basic Safety Rule in 2008 (French Nuclear Safety Authority guide of 2008 [6]) keeps the same objectives of protection of people and the environment but indicates the major expectations with respect to a potential site, sets the safety principles and the design bases of the repository bound to the safety, and sets the method for the demonstration of the repository safety. It also indicates that both Radiological and Chemical impacts are to be evaluated.

It accounts for dispositions from the Environmental Code, from the Public Health Code and from the June 28th French Act [5]. It also account for international recommendations (AIEA, NEA, and ICRP).

The guide of 2008 also sets the main safety functions, declined from the first function of protection of people and environment:

- Resisting water circulation.
- Confine radioactivity.
- Isolate waste from surface phenomena and human activity.

Preservation of the favourable characteristic of the host formation is also recommended.

The guide also gives expectations in terms of demonstration of safety. It must rely upon:

- Verification of the performance of the components.
- Evaluation of disturbances induced by the repository.
- Evaluation of individual effective dose.
- Situations taken into account.

The guide requires safety to be quantitatively evaluated by the means of “situations” that encompass different possible evolutions of the repository that can be reasonably foreseen. The safety guide stipulates that two kinds of situations have to be addressed in the safety demonstration, “a reference situation” and “altered situations”:

- The “reference situation” refers to knowledge of the phenomena governing the evolution of the waste repository including the underground water circulation modelling with radionuclides transfers. Events to consider are:
  - ✓ Events due to the presence of the repository, and to the overall degradation processes of waste packages and engineered components (thermal, gas, mechanical effects, transient processes such as desaturation…).
  - ✓ A set of most probable natural events (climate change, seismic activity, subsidence or uplift, sedimentation and erosion cycles).

  For this situation, the calculated individual effective Dose shall not exceed the value of the 0.25mSv/year.

- “Altered situations” refer to events with low probability, yet plausible, occurring in case of natural events (high seismic activity, unusual glaciation...), or human actions likely to alter the expected behaviour. They concern Major climatic changes (including changes due to human activity, greenhouse effect), Exceptional vertical movements or earthquakes, Various possible forms of human intrusion, Waste package defects, and Engineered barrier defects (seal defects for example). As regards Human intrusion, Andra should define the scenarios regardless of the probability of the event, after memory of the existence of the disposal is considered lost (estimated at 500 years after closure in [2]).

The guide also recommends accounting for climatic events in the definition of biosphere leading to the description of biospheres typical of the different climatic states that can be foreseen in the future [7].

POST CLOSURE SAFETY APPROACH

The post-closure safety approach includes both quantification of the overall level of performance of the disposal system, and a systematic analysis of the associated uncertainties.

Figure 1 shows that, when assessing the safety of a waste disposal facility, development of scenarios constitutes the fundamental basis for the quantitative assessment as well as the choice of data and models to assess the scenarios. In accordance with the regulatory requirements, the system representation for the safety model thus developed is based on a reference scenario, the “Normal Evolution Scenario” (NES), “Altered Evolution Scenarios”, and “What-if” scenarios.

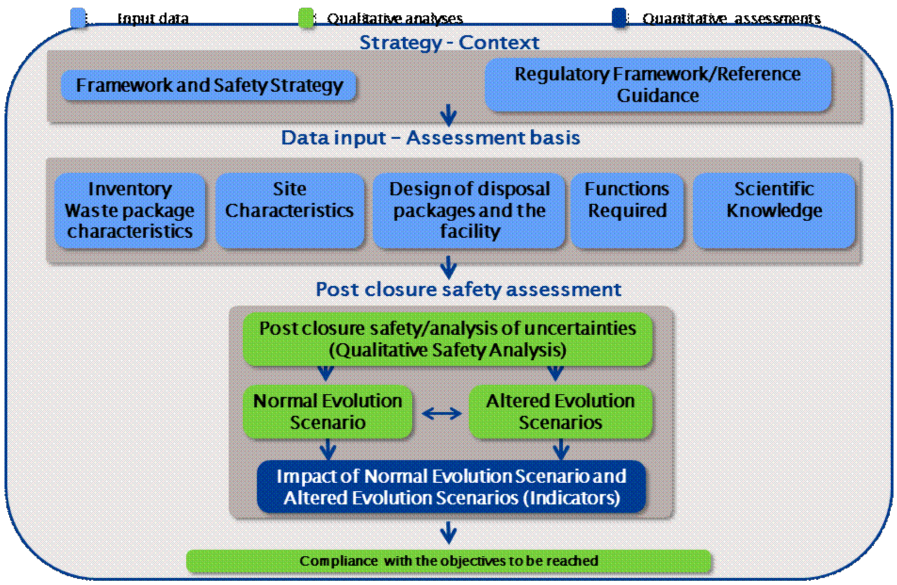

Fig. 1. Schematic Illustration of Andra's Post Closure Safety Approach

The NES answers several distinct objectives. Its main one is to verify that the repository, as designed and to the extent that its evolution over time is understood by contemporary science, fulfils the safety objectives assigned to it.

This general objective can be broken down into several inter-related goals:

- To confirm that the performance achieved, as indicated by the chosen indicators, is consistent with the predefined threshold values. This safety objective implies the need to present a vision that exaggerates the repository's potential impact.
- To verify the performances of the three main safety functions using appropriate indicators.
- To provide an overall simulation of the repository's expected evolution, in order to assess the expected behaviour in global terms, in the form of a necessarily simplified and partially conventional representation that nevertheless aims to be as representative as possible. The aim is to assess the relative importance of the main phenomena and the performance of the safety functions. This objective precludes the use of overly simplistic representations, which would make the models less representative.
- To provide a basis on which to judge the sensitivity of the level of safety to changes in the environment and the behaviour of repository components, and to use the sensitivity analyses as a tool for quantifying the repository's robustness.

Calculation results based on the AES scenarios make it possible to evaluate overall repository robustness.

The post-closure safety therefore requires calling on many disciplines (mining and nuclear engineering, earth sciences, material sciences, safety analysis) and implementing specific methods at the interface between those disciplines. According to the objectives fixed by the regulatory guidance (cf. [6]), the assessment therefore relies upon a series of key elements such as:

- Safety reference texts and guidances that are dedicated to waste disposals and particularly to the post-closure safety. As mentioned previously in the document, the 2008 guide from the Nuclear

Safety Authority (NSA) [6] sets for example the objectives of radioprotection, fixes the bases for design in respect with safety principles such as defence in depth, multi-functions principles, etc.).

- National and International practices.
- Basic data inputs such as the inventory and characteristics of the waste, the characteristics of the geological site, as well as their evolution with time and their potential interactions.
- The post-closure safety functions (isolation, limitation of release…).
- The architecture design and technical solutions.
- The scientific understanding concerning the long term evolution of the engineered components and the host formation, their potential internal interactions (thermal, mechanical, hydraulic, chemical, radiological, bacteriological, gas processes and their coupling), or external interactions (seismic, geodynamic evolution, climatic evolution). Andra's methodology used to describe the evolution of the disposal system is the "Phenomenological Analysis of the Repository System". Such an approach relies upon systematic spatial and temporal discretization of the main disposal system components base on their detailed description, by identifying their major characteristics and processes and the associated uncertainties [8].
- The handling of uncertainties and the development of scenarios. Andra has implemented a specific qualitative safety analysis methodology in the framework of the Dossier 2005 [3] namely called "QSA" that aims at each stage of the project development to link technology characteristics, functions and state of knowledge. This method, detailed in the next section, aims at exploring possible dysfunctions of the repository components (waste package defects, seal failures for instance), proposes design measures to reduce their occurrence, and identify scenarios to be assessed (Normal Evolution Scenario and Altered Evolution Scenarios). The QSA studies each uncertainty that may either (i) affect a component ability to perform a safety function, (ii) or have an influence on another component's ability to perform a safety function (Figure 2). A set of AES scenarios is then developed to provide a description of the calculation cases to be quantified in relation to the uncertainty(ies) or event(s) (internal or external) which affect the safety functions. The "QSA" offers an integrated and structured vision of all uncertainties, their impact on post-closure safety functions and how those uncertainties are managed. Details are presented in the following section of the document.
- Simulation and quantitative assessments. The repository's various components and its environment are then represented by safety models which are combined or concatenated to assess the safety of the entire disposal system. All indicators (dose but also transfer pathways, radionuclides flows through components…) are evaluated for compliance with safety objectives. Both reference and sensitivity cases within the NES and AES are conducted to evaluate the overall repository performance and robustness, as well as the individual contribution of each component to the safety functions to be fulfilled by the disposal system.

One key element to establishing scenarios is the handling of uncertainties. Andra's approach can be qualified as a "top-down" approach for the definition of the scenarios, as the function analysis is an input data to decline scenarios. In the normal evolution scenario, the components fulfil the expected functions considering their evolution with time and probable events occurring.

The repository does not undergo a unique evolution because uncertainties remain, therefore a qualitative safety analysis (QSA) is conducted, in which there is a systematic analysis of uncertainties on FEPs (Features Events and Processes) and their effects on safety functions.

This approach answers the 2008 NSA guide, which sets among the objectives of the post closure safety analysis, the identification and classification of uncertainties according to their consequences in the functioning of the repository, making sure that none is omitted.

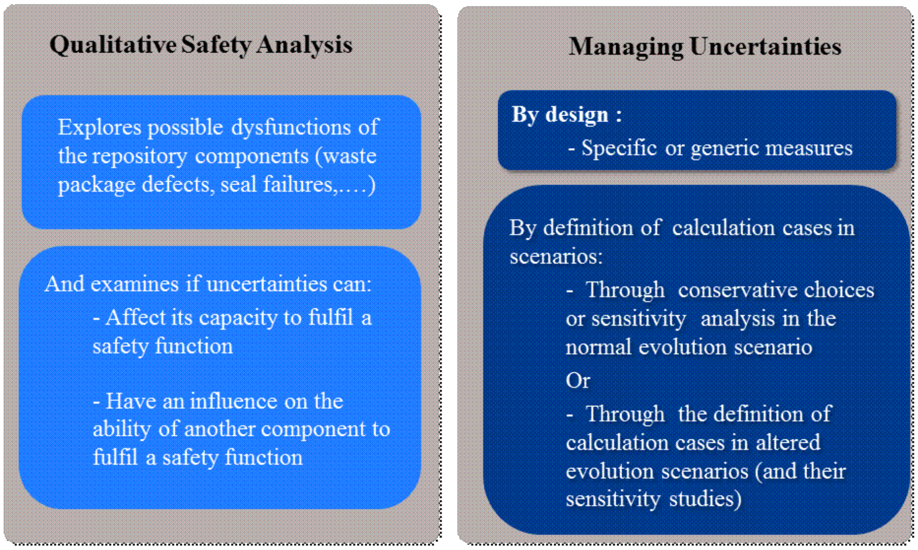

Fig. 2. Schematic Illustration of the Approach for Handling Uncertainties: the Qualitative Safety Analysis

HANDLING UNCERTAINTIES – THE QSA METHODOLOGY

The QSA contributes to the evaluation of the robustness of the repository by exploring possible dysfunctions of the disposal system (degradation of performances, waste packages defects, crosscut of the Callovo-Oxfordien…).

In the QSA method, uncertainty is the subject of a systematic study that identifies:

- Which component is concerned by this uncertainty, with, if relevant, the effects caused by one component on another by means of a perturbation?
- Which performance aspects of which safety function can become altered? A qualitative, but argued assessment, including the use of special calculations if relevant, is conducted on the risk of a significant reduction in the expected performances.
- If applicable, and if such information is useful, the time period involved.

Thus, the methodology determines and assesses, component by component and with respect to the safety functions assigned to each, if the uncertainty (of any type) can affect the ability of a component to realize its functions (Figure 3).

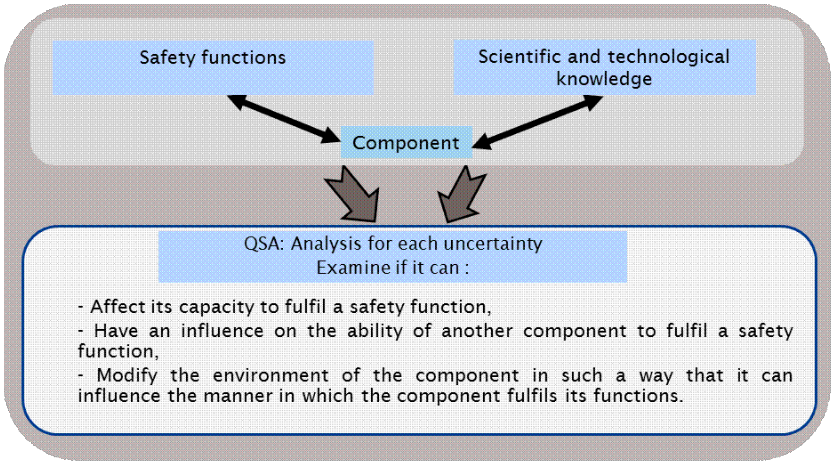

Fig. 3. Schematic Illustration of QSA Analysis for Each Uncertainty

QSA then proposes management of uncertainties (cf. Figure 2):

- By design measures which reduce their effect.
- By the definition of calculation cases in scenarios:
  - ✓ Within the "normal evolution scenario" and its sensitivity analysis (by adjusting the level of conservatism for the parameters for example).
  - ✓ Within the altered evolution scenarios and their sensitivity analysis.

As a first stage, the objective is to identify whether the uncertainties can be managed by design measures (see for example figure 4) or can correctly be covered by a calculation case in the NES, either in reference, or by a sensitivity studies. It must be confirmed that they would have little impact on the performance of the functions.

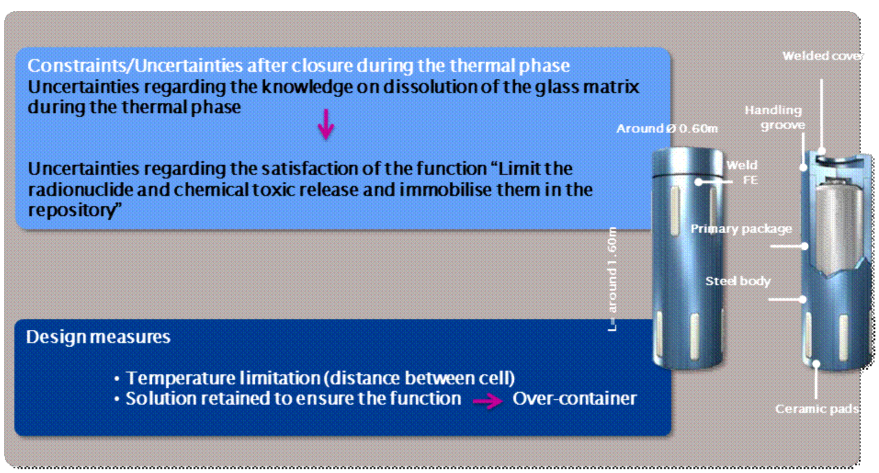

Fig. 4. Schematic Illustration of Uncertainties Managed by Design Measures

As a second stage, if the analysis reveals that the occurrence of residual uncertainties is very unlikely and the effect likely to degrade the performance of a safety function, then the analysis may lead to the definition of altered evolution scenarios corresponding to highly unlikely events and to dysfunction of safety functions (see Figure 5). For example, if a safety function can be affected and the evolution of the repository could start to diverge from normal, with a possible impact on other components, this effect is then specifically identified. Other uncertainties can have a direct influence on the confidence that can be given to a safety function. A set of four "Altered evolution scenarios" (AES) were developed in 2005 [3]:

- The "Seal failure" scenario.
- The "Waste package defects" scenario.
- The "Borehole" scenario.
- The "Severely degraded evolution" scenario.

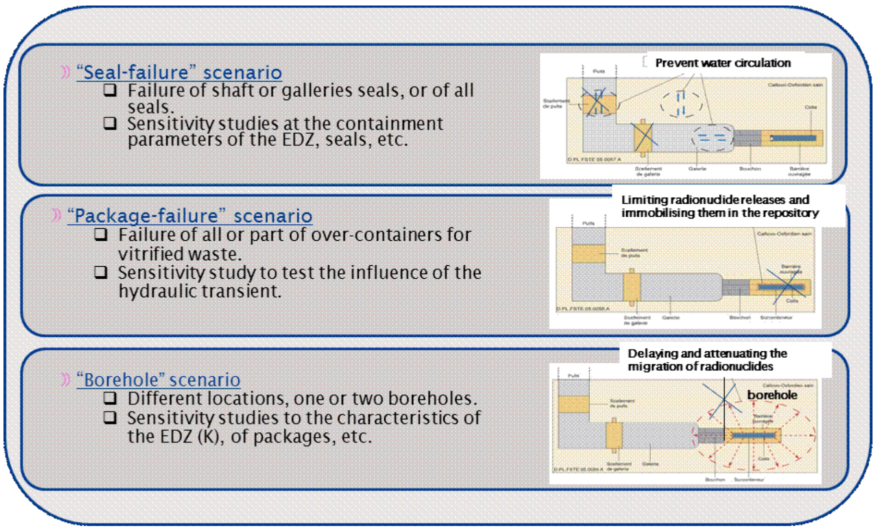

Fig. 5. Schematic Illustration of Three Scenarios Affecting the Safety Functions

A systematic component-by-component analysis is used in particular to identify the shared causes of the loss of several functions: for example, an incorrect assessment of the long-term behaviour of a material can affect all the components that contain it, even though these could have different functions.

The qualitative safety analysis provides an assessment of the degree of independence of safety functions, by identifying the possible uncertainties affecting several functions. The analysis includes a crossed-checked analysis of the uncertainties to list the possible common causes of degradation of the performances or identify effects of uncertainty accumulation. The appreciation is qualitative without becoming attached to the probability of a cause. Common causes may lead to grouping situations, when incompatible situations may lead to distinct calculation cases within scenarios.

A summary table is associated to the QSA methodology which allows a view on the type of uncertainty, the component(s) involved, the affected safety functions, a brief summary on management of uncertainties.

The qualitative safety analysis is a method for verifying that all uncertainties in particular in FEPs and design options have been appropriately handled. It leads to the identification of a series of calculation cases and as a result, the derivation of scenarios. It also has the potential to inform design decisions.

As regards the 2005 Dossier safety demonstration [3], NEA's FEPs database has not been used as an entry point, but as a comparison with the QSA to consolidate a comprehensive qualitative safety analysis, the Agency relied on the « features, events and processes » databases available internationally. The comparison between the FEPs databases and Andra's own analyses was an important exercise for the qualitative safety analysis, and provided supplementary information on several aspects, to finally end with consistency between the approaches. It proved to be very useful to safety engineers in ensuring that no fundamental characteristic of the components and no phenomenological process likely to have an influence on the repository had been forgotten.

DEFINITION AND DESCRIPTION OF SCENARIOS

”Scenarios” are simplified descriptions of the repository initial state and its evolution, based on the phenomenological analysis of the repository evolution:

- a “Normal evolution scenario” (NES), which purpose is to provide a bounding value for all likely or probable future evolutions. Events to take into account are those induced by the disposal system (including the progressive degradation of engineered components), and by probable natural events (such as for example the climatic cycles). However, the NES does not aim to provide the best possible description, and according to ICRP recommendations [9], it is not presented as a prediction of long term repository impact. Rather, its purpose is to provide a bounding value for all likely or probable future evolutions. Calculation results based on the NES are at the core of the performance assessment of the repository.
- “Altered evolution scenarios” (AES). They define “altered situations” that encompass unlikely events (those events as recommended by the 2008 NSA guide) and are based on a breakdown of a safety function (as regards to results from QSA). The AES represents these different situations in a “bounding” way, i.e. it provides a description that generally overestimates the different possible effects. In the example given from 2005 dossier, the AES would describe the loss of the function of the waste container by the total “disappearance” of the container after 200 years, i.e. earlier than the period for which it is dimensioned. As such, the AES allow better understanding of the role of the different components of the concept. For instance, seals limit the hydraulic influence of boreholes and can contribute in limiting the propagation of radionuclides in the underground structures in case of waste packages defects (control of the hydraulic transitory).
- “Conventional” or “what if” scenarios. While one could assess the plausibility of each AES, it is a more delicate matter to assess the plausibility of a scenario that may represent several situations in the form of stylised hypotheses. In that case, the what-if scenario may not represent any physically possible situation. As an example, a situation such as a whole series of defective containers resulting from a quality control error however used as the “what-if” basis for the “package failure” altered scenario evolution, which considers very early loss of the functionalities of the metal containers on a series of containers and for the entire inventory. This extreme “what-if” scenario finally covered all forms of uncertainty concerning the corrosion conditions.

  In 2005, various possible forms of human intrusion after closure of the repository were covered by the “borehole” altered evolution scenario [3]. For this type of situation, Andra follows the 2008 NSA guide. It indicates that it is necessary, in a cautious approach, to suppose that memory of the existence of the repository can be lost beyond a time period of 500 years and that the level of technology is the same as today.

Scenarios are inextricably linked with a safety calculation model that is used to evaluate the quantified impact. Once the scenario is described, the models and parameters are set.

Models may depend on parameters fitting and adjustments. Such adjustments are based on available experimental data; in numerical terms, this data may not be sufficiently representative to allow a mean and standard deviation to be calculated, which leaves a degree of freedom in the choice of the model's parameters. In some cases, chaining the selected models together to form the overall calculation model can result in an exaggeratedly complex representation of the repository that causes prejudice to the good understanding of the fundamental mechanisms.

Certain choices must be made in order to position the “safety model”, which forms the basis of the scenario assessment, in relation to the available conceptual models. They must be made in such a way that they do not result in the repository's impact being underestimated. For those reasons, standard terminologies for qualifying the models and parameters proposed by scientists have been defined to ensure that the « safety » choices are made on a standardised basis.

QUANTIFICATION

The ASN guide indicates that the individual effective dose is to be calculated. It also requires the verification of the performance of safety functions. For these reasons other indicators than dose can be proposed which show more clearly the repository’s intrinsic performances without requiring any assumptions on the surface environment and the biosphere. In particular, radionuclide concentration flows assessed at relevant emplacements with respect to the safety analysis of the repository (typically at the host formation outlet) allow refining the judgment on safety and overcoming some of the uncertainties. They allow comparing different situations or different design provisions in order to see which one is the most favourable with respect to the limitation of the radionuclide transfers, but they cannot be compared to thresholds.

Some indicators allow assessing the performance of individual component with respect to their safety functions (for example, molar fluxes of radionuclides reaching the roof of the Callovo-Oxfordian formation). They enable us to characterize the role of the components using a series of complementary indicators. Among the analyzed indicators are:

- The overall activity leaving the waste packages, the underground structures and the host rock, as compared to the initial quantity contained in the waste packages.
- The activity flux at each of these components.
- The concentration distributions of dissolved materials in the host rock and in surrounding formations.

Such indicators have been used in the safety analysis carried out in the Dossier 2005 Argile [3], 2009 [4] and 2012. For instance, results indicated:

- For the “resisting water circulation” function, the diffusive transport regime dominates in all configurations within the Callovo-Oxfordian host rock, and in most of the structures. It should be noted that this is not solely due to the efficiency of the seals: even when this is degraded in the sensitivity study, the flows remain limited overall, since the water from the Callovo-Oxfordian is insufficient to supply them.
- For the function of “limiting the release of radionuclides and immobilizing them in the repository”: The low solubility of many radionuclides in the cells means that their impact is heavily restricted; this is especially the case of Se-79. The containers and over-packs contribute to confinement, helping to delay the occurrence of dose maxima, but without strong influence on their magnitude. The properties of the Callovo-Oxfordian attenuate the flows even in the case of transfer in a thermal environment (see figure 6).
- For the function of “delaying and reducing the migration of radionuclides”, the diffusion times are slow in the Callovo-Oxfordian and enable a decay of all the radionuclides that could contribute to the impact, except for I-129, Cl-36 and Se-79. The last two are, however,

significantly reduced. The transport parameters prove sensitive in terms of the impact of these three radionuclides.

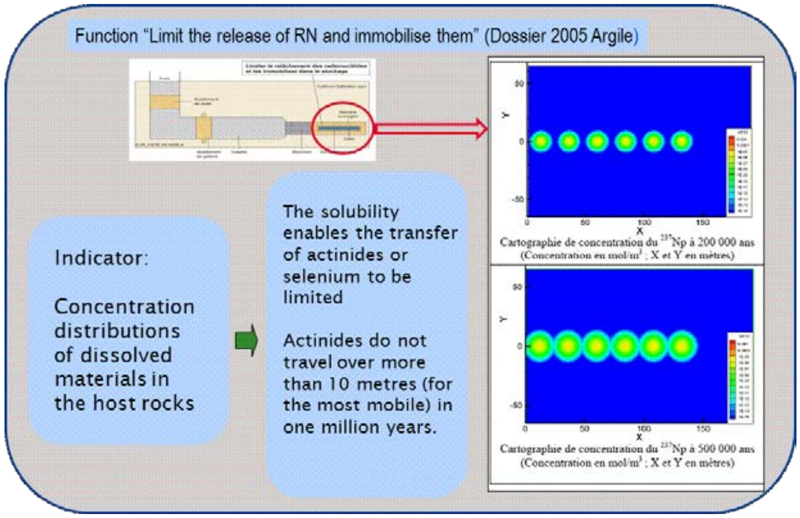

Fig. 6. Illustration of Dossier 2005 Results for the Indicator "Concentration Distributions of Dissolved Materials in the Host Rocks".

Such an analysis of indicators showed that the Callovo-Oxfordian is a particularly important component, whose characteristics ensure a good level of safety function performances, even in the event of other components failure (defective containers, inefficient seals) or even of degraded properties of the geological medium itself.

CONCLUSIONS

The post-closure safety assessment of a disposal requires accounting for some peculiarities:

- The necessity of approaching in a coordinated way the different life phases of the repository.
- The taking into account of timescales which extend beyond human experience.
- The strong relationship between technical design, scientific knowledge acquisition and safety assessments.
- The key importance given to the uncertainties management.

The post-closure safety therefore requires calling on many disciplines (mining and nuclear engineering, earth sciences, material sciences, safety analysis) and implementing specific methods at the interface between those disciplines.

When assessing the safety of a waste disposal facility, development of scenarios constitutes the fundamental basis for the quantitative assessment as well as the choice of data and models to assess the scenarios. Different types of scenarios are to be considered, including a base case scenario (Normal Evolution Scenario) and alternate evolution scenarios (Altered Evolution Scenarios).

One key element to establishing scenarios is the handling of uncertainties. Andra has implemented a specific qualitative safety analysis methodology in the framework of the Dossier 2005 [3] namely called "QSA" that aims at each stage of the project development to link technology characteristics, functions and state of knowledge. The "QSA" aims at exploring possible dysfunctions of the repository components (waste package, seal), proposes design measures to reduce their occurrence, and identifies scenarios to be assessed: Normal Evolution Scenario and Altered Evolution Scenarios. The analysis studies each uncertainty that may either (i) affect a component ability to perform a safety function, (ii) or have an influence on another component's ability to perform a safety function. The "QSA" offers an integrated and structured vision of all uncertainties, their impact on post-closure safety functions and how those uncertainties are managed.

A set of scenarios is then developed to provide a description of the calculation cases to be quantified in relation to the uncertainty(ies) or event(s) (internal or external) which affect the safety functions.

A set of indicators (dose but also transfer pathways, radionuclides flows through components…) are evaluated for compliance with safety objectives. Both reference and sensitivity cases within the NES and AES are conducted to evaluate the overall repository performance and robustness, as well as the individual contribution of each component to the safety functions to be fulfilled by the disposal system.

These results may influence the requirements and/or the specification of one or a set of repository's components or/and to launch complementary investigations or characterization of its environment.

REFERENCES

1. Loi n°91-1381 du 30 décembre 1991relative aux recherches sur la gestion des déchets radioactifs, Journal Officiel du 1er janvier 1992
2. Règle fondamentale de sûreté RFS.III.2.f (Basic Safety Rules). Nuclear Safety Authority 1991.
3. Andra. "Safety Evaluation of a Geological Repository – Dossier Argile 2005". Report Available in English on Andra's site www.andra.fr
4. Andra. Options de sûreté du stockage en formation géologique profonde. Etape 2009.
5. Loi n°2006-739 du 28 juin, 2006 de programme relative à la gestion durable des matières et déchets radioactifs.
6. Guide de sûreté relatif au stockage définitif des déchets radioactifs en formation géologique profonde, Autorité de sûreté nucléaire, 2008.
7. L. GRIFFAULT, J. BRULHET, Y. THIRY, S. VOINIS and E. LECLERC. Andra's Strategy and Approach Applied in Defining and Describing Biosphere(s) for Safety Assessment. IHLRWM Conference April 10 - 14, 2011 Albuquerque, New Mexico, USA.
8. Andra. "Phenomenological Evolution of a Geological Repository – Dossier Argile 2005". Report Available in English on Andra's site www.andra.fr
9. ICRP Publication 122. Radiological Protection in Geological Disposal of Long-Lived Solid Radioactive Waste