INSTITUTE FOR ENERGY AND ENVIRONMENTAL RESEARCH

6935 Laurel Avenue, Suite 201
Takoma Park, MD 20912

Phone: (301) 270-5500
FAX: (301) 270-3029
e-mail: ieer@ieer.org
http://www.ieer.org

Critical Review of Andra's Program of Research Conducted in the Underground Laboratory at Bure and in the Transposition Zone to Define the ZIRA

FINAL REPORT

prepared by

Institute for Research on Energy and Environmental Research (IEER)

for

The Local Committee for Information and Monitoring of the Bure Laboratory (CLIS)

Project Director
Arjun Makhijani, Ph.D.

Project Coordinator
Annie Makhijani

March 9, 2011

The authors of the report (in alphabetical order)

Prof. Jaak Daemen, Ph.D.
Prof. George Danko, Ph.D.
Prof. Gerhard Jentzsch, Ph.D.
Elena Kalinina, Ph.D.
Arjun Makhijani, Ph.D.
Krishan Wahi, Ph.D.

IEER Team

The various team members were responsible for the following scientific disciplines and wrote the corresponding chapters:

Chapter 1: Scope of work, conclusions and recommendations - Arjun Makhijani

Chapter 2: Seismic and seismological characterization of the transposition zone - Gerhard Jentzsch

Chapter 3: Characteristics and properties of the host and surrounding formations in the Transposition Zone affecting the contaminant transport in geologic media and long-term repository performance - Elena Kalinina

Chapter 4: Rock mechanics - Jaak Daemen with the participation of Krishan Wahi

Chapter 5: Thermal considerations - George Danko

Chapter 6: Comparison with other programs that have used underground research to select a ZIRA - Arjun Makhijani and Krishan Wahi

Translation and proofreading Translation: Annie Makhijani

Translation and proofreading Translation: Jean-Luc Thierry

Scientific Support: Annie Makhijani

Librarian: Lois Chalmers

This review is a translation of the official report: *Examen Critique du Programme de l'Andra sur les Recherches Effectuées dans le Laboratoire Souterrain de Bure et sur la Zone de Transposition Pour Définir une ZIRA: Rapport Final* (9 mars 2011 avec corrections 20 avril 2011). The April 20th corrections were minor and did not affect the text of this English translation (March 9, 2011).

Table of Contents

Acknowledgements

IEER's team is sensitive to the confidence that the CLIS has shown for a second time. We wish to thank the President of the CLIS, Mr. Canova, for the hospitality extended to us during our visit in August. We also thank the staff of the CLIS for its hospitality and cooperation, including Mr. Benoît Jaquet who facilitated the visit of the underground laboratory of the team August 18, 2010, and its support throughout the course of the project. We thank Andra for providing us with additional documentation we needed for our evaluation and for their hospitality during our visit to the underground laboratory on August 18, 2010. We also greatly benefited from the critical comments of the CLIS, its President, Mr. Canova, its Vice-President, Mr. Fernbach, Mr. Jean-Marc Fleury, a member of the CLIS and its Secretary General, Mr. Jaquet during their November 2010 visit to the USA to attend the IEER team meeting to discuss the preliminary report.

Arjun Makhijani
Annie Makhijani
February 11, 2011

Post script

IEER presented this report to the CLIS on 14 February 2011 at St. Dizier. On 16 February 2011, three members of the IEER team (Elena Kalinina, Annie Makhijani, and I) met with Andra at the Bure site. Benoit Jaquet, the CLIS general secretary was also present. At Andra's request, IEER had sent questions to Andra on 15 February relating to some of the principal concerns and recommendations in our report.

We had a very productive interchange, followed by lunch. Before we left, Andra also provided us with some documents we requested. We were very hospitably received and we wish to thank Andra for the informative scientific interchange, for the documents, and for the delicious lunch.

Andra provided written answers to our questions on 28 February As a result of some of the clarifications provided on matters of fact and further research by IEER, we have modified the report presented to the CLIS to a modest extent in the following ways:

1. Contrary to IEER's impression, Andra had used borehole data, and not surface seismic investigations to conclude that microfissures were plugged. IEER agrees with this approach for determining whether microfissures are plugged. Hence this finding has been changed (Chapter 1, Chapter 2 and a modification has been made in the texts of Chapter 2 and 3 to indicate this fact).
2. Andra stated that it uses standard earthquake catalogs in its analysis of earthquake magnitudes and intensities to be used for analyzing seismological issues at the Bure site. We have modified the text and finding to reflect this fact.
3. We further reviewed Andra's research on bentonite thermal conductivity, having found more detailed results in Andra's literature. We have changed the text to reflect our

current understanding of Andra's use of a higher conductivity value for bentonite than used in our calculations.

4. Andra provided IEER with a report that has data that show that a fault partly under the ZIRA (Figure 3-1 in the IEER report) does not run through the Callovo-Oxfordian formation but rather much below it, in the Dogger. We have added some text indicating that the IEER concern relating to this fault has been addressed.
5. Andra stated that it has an analytical process for determining whether, when, and how data from other sites is transferred for use in understanding and analyzing the Bure site and provided IEER with a paper published in a scientific journal discussing this topic. IEER has added some text in Chapters 4 and 6 to indicate that Andra has a procedure for addressing the transferability issue.

Except for the findings relating to items 1 and 2 above and minor changes relating to bentonite conductivity (item 3 above), all other findings and recommendations are essentially unchanged from the report presented on 14 February 2011.

We have requested the CLIS to post Andra's response to IEER's questions (the response also contains the questions themselves) along with the IEER report on the CLIS website. IEER believes that the IEER findings and Andra response relate the nature of the work remaining to be done and the interpretation of the data that have been collected already. That could provide the basis for a future fruitful interchange, should that be desired.

Finally, the whole IEER team, and especially the coordinator of this project, Annie Makhijani, and myself would like to thank the CLIS, including President Canova and Secretary General Jaquet for the warm welcome we received.

Arjun Makhijani
9 March 2011

Chapter 1: Scope of work, findings, and recommendations

1.1 Introduction

The work in France on the development of a deep geologic repository for high-level and medium-activity long-lived waste (abbreviated as HA-MAVL) is focused on a site near Bure, in the Meuse/Haute-Marne region. Andra has done several years of work in an underground laboratory at the site. It has also studied a 250 square-kilometer area[1] that is known as the transposition zone, which includes the underground laboratory. Andra is prohibited by law from locating the repository at the same location as the underground laboratory. Therefore, the study of the transposition zone is necessary for the selection of the location that is to be characterized for potential use as the repository.

In 2009, Andra selected a zone, called "*zone d'intérêt pour la reconnaissance approfondie,*" or ZIRA for short, for repository characterization. The goal of this review of Andra's work at the Bure site is to investigate whether the research that has been done in the underground laboratory and in the transposition zone was advanced enough and conclusive enough to determine and define a suitable ZIRA. A part of the review is to give an opinion regarding favorable as well as unfavorable elements revealed by the research so far. Based on this, the review also draws conclusions regarding the sufficiency of the work, regarding the important data that have been collected, and whether there are critical or important gaps in the data at this time that indicate further work is needed before reaching certain conclusions.

In sum, this report is about the selection of the ZIRA within the transposition zone which was earlier selected. We should also say what this report is not. It is not about the selection of the Bure site or the definition of the transposition zone. That had already occurred many years ago. Besides periodic reviews by the Commission Nationale d'Evaluation (CNE), Andra's work at the site, including the underground laboratory has been the subject of many reviews, including one done by the Institute for Energy and Environmental Research for the Comité Locale d'information et de suivi (CLIS).[2] We will refer to our earlier review and findings in this report as appropriate.

In the course of this review, the entire IEER technical team visited the Bure underground laboratory and the CLIS library and offices on August 18-19, 2010. We want to thank our hosts, Andra and the CLIS, for the informative visit that we had and for the warm reception we received.

1.2 Criteria for the ZIRA

Andra had already specified some criteria when it selected the transposition zone. The criteria for the ZIRA selection should be seen in this context. According to the Institut de radioprotection et de sûreté nucléaire (IRSN), Andra's criteria for the transposition zone were:[3]

---

[1] IRSN 2009 p. 1

[2] IEER 2005

[3] IRSN 2009 pp. 1-2. The bullet points are paraphrased and summarized from this IRSN document and are not an exact quote.

- An argillite formation in the host rock (Callovo-Oxfordian, or C-O) more than 130 meters thick.
- Structural properties similar to those in the underground laboratory, notably characterized by the absence of tectonic structures and distance from the major Gondrecourt fault of one kilometer and of the southwestern Marne fault of one-and-a-half kilometers.
- Sufficient mineralogical homogeneity within the transposition zone to ensure the necessary transport and retention properties.
- A depth of the host rock that would not exceed 630 meters to limit geomechanical disturbances due to drilling and excavation.

The selection of the ZIRA had the following five specific criteria:

- A thickness of the host formation of more than 140 meters.
- A hydraulic gradient less than 0.2 m/m.
- The maximum depth of the host rock less than 600 meters.
- The potential to construct the infrastructure perpendicular the incline of the host rock.
- A reduced thickness of the karstic layers (Barrois) to pass through to connect the surface to the underground (shaft or ramp).[4]

Andra has selected a 30 square-kilometer ZIRA in the southeast of the transposition zone. According to the IRSN, this is twice the area estimated to be required for waste emplacement.[5]

This report examines the state of the data, Andra's analysis of it (to the extent it is available to us), and Andra's conclusions about it to evaluate the extent to which the knowledge gained in the underground laboratory and the research in the transposition zone allows a confirmation that the selection of the ZIRA meets these criteria. As noted, we also recommend additional research in areas where it appears necessary or desirable to ensure that these criteria are met. As regards the criteria themselves, we would agree that they are sound.

Additional ZIRA criteria relate to surface features, such as list, such as surface water, location of surface installations near villages, etc. This report does not consider these criteria because its scope is limited to geologic considerations relating to the selection of the ZIRA.

1.3 Topics covered in the report

This report has five chapters following this introduction (whose author is Arjun Makhijani). The author (or authors) of each chapter is indicated, though it should be noted that this was a collaborative effort with input and suggestions for each chapter, including this introduction, being provided by the whole team.

Before listing the chapters and their contents, it should be noted that this review was done in a very brief period relative to the volume of documentation to be examined. The brevity was necessitated by the exigencies in which the CLIS found itself. Moreover, we found that Andra often states conclusions without providing references to the underlying data or analytical

---

[4] IRSN 2009 pp. 3-4

[5] IRSN 2009 p. 4

materials making it very difficult to trace the basis for Andra's conclusions. In this circumstance, we cannot be certain that the gaps we have found are actual gaps in all cases or whether there is a cache of data in a publication somewhere, such as a doctoral dissertation that contains the requisite information that we identified as a gap. Of course, we have tried to be as careful as possible in identifying gaps and making our recommendations, but this caveat should be kept in mind. We would advise that should Andra claim to have data or analysis to fill gaps identified or should it already have completed research recommended, it should provide the CLIS and its reviewers with the specific information that would allow a verification of the statements. It was partly because we could not always trace how Andra arrived at its conclusions that we conducted our own verification of Andra's statements in two chapters (3 and 5). This helped the IEER team to assess some of Andra's conclusions regarding the suitability of the ZIRA selection in relation to the specified criteria.

The remaining chapters are as follows:

> **Chapter 2: Seismic data and seismic characterization (Author: Gerhard Jentzsch)**. Some of the most important criteria for the transposition zone and hence also for the ZIRA relate to its homogeneity. The absence of microfissures, the extent of the Gondrecourt and Marne faults, and the evaluation of the 2D and 3D research done so far are considered in this chapter. In addition, the seismologic characterization of the site and its environs is considered. The characterization of the earthquake hazard in the region, the ability to estimate maximum expected intensity so as to design underground and above ground structures are also addressed in this chapter.
>
> **Chapter 3: Hydrogeological parameters (Author: Elena Kalinina)**. The chapter evaluates the state of Andra's research regarding the characteristics and properties of the host rock and surrounding formations in the transposition zone. This is to determine how these properties may affect contaminant transport in the geologic media and whether the various factors affecting that transport and long-term repository performance have been adequately taken into account. The chapter examines horizontal and vertical homogeneity (or lack thereof), the variations and uncertainties in hydraulic conductivity, and other hydrogeological matters of importance. The objective is not to assess the performance of the repository. That must await a characterization of the ZIRA. The objectives are to (i) determine whether these uncertainties can or should have been narrowed through further work in the transposition zone, and (ii) point to research areas and methods of analysis that can give a more accurate picture of the uncertainties at this stage prior to ZIRA characterization.
>
> **Chapter 4**: **Rock mechanics (Author: Jaak Daemen, in collaboration with Krishan Wahi)**. This chapter examines Andra's research on the mechanical response of the proposed repository system and argillite properties. The implications of inhomogeneities for the stability of emplacement holes or of construction infrastructure are examined. For instance, the evidence of the shear displacement along some fractures and the potential issues they may pose for satisfactory sealing of emplacement holes are discussed. The extent of Andra's research and the evidence presented on various related topics is examined.
>
> **Chapter 5: Thermal aspects (Author: George Danko)**. This chapter examines various thermal goals that need to be achieved for a repository in the transposition zone. It examines the thermal characteristics of the transposition zone and the repository layout to meet the

temperature criteria set by Andra. While recognizing that unreprocessed spent fuel is not currently required to be part of the design criteria, the chapter examines issues that may arise in case of the contingency that such disposal may be required in the future.

Chapter 6: Comparison with other programs (**Authors: Krishan Wahi and Arjun Makhijani**). There are a number of deep geologic repository programs around the world, with the most advanced ones in terms of investigations and schedules currently being in Europe. Several of these have underground research laboratories associated with them. This chapter briefly reviews some of the work done at repository and research locations in other countries for its relevance to the Bure project. It summarizes some of Andra's extensive collaborations with other programs, including Mont Terri in Switzerland and Mol in Belgium. It also briefly reviews the Engineering Studies and Demonstration of Repository Designs program (ESDRED, for short). Andra was the coordinator of the ESRED program.

Each chapter lists its own findings and recommendations. Some of the major ones are summarized here for convenience.

1.4 Findings and Recommendations

1.4.1 Strengths

1. **Andra and repository research**: Andra is a leader in underground laboratory research in a number of areas and has done excellent work that has advanced the state of the art and repository science and engineering through its own work and through its international collaborations. It has accomplished a remarkable and impressive research effort in support of its Bure repository program. The broad range and in depth efforts are absolutely outstanding. The IEER team was very impressed with the work being done in the underground laboratory, which we visited on August 18, 2010. Yet we have reservations as described below.
2. **ZIRA selection**: Andra appropriately used geologic criteria to narrow the zone in which to locate the ZIRA from the 250 km^2 Transposition Zone to 100 km^2. The underlying considerations were primarily sedimentological; the thickness and depth criteria were met. The 30 km^2 ZIRA was selected from this area using surface-related socio-economic criteria in consultation with the communities in the area. We have not examined socio-economic considerations relating to the selection of the ZIRA because they are outside the scope of this review. However, we note that since socio-economic considerations were used to narrow down the 100 km^2 to 30 km^2, the issue of whether the ZIRA is the best one within the 100 km^2 from a geologic point of view did not arise in our review.
3. **Major faults and seismic data**: The major faults, the Gondrecourt and the Marne, are outside the ZIRA and would provide favorable hydrogeological features in the directions where they are located. However, there are no comparable hydrogeological features in some directions. The 2D (2007-2008) seismic campaign on the transposition zone and the 3D (1999-2000) seismic campaigns centered on the underground laboratory at the site are convincing.
4. **Modular design**: The conceptual modular design approach for the repository lay-out is a sound one. Separating emplacement locations for various waste types by significant distances greatly enhances the credibility of the arguments in support of containment and

isolation performance and of implementing reversibility, even though it might incur a considerable additional cost.

5. **Thermal properties:** The measurement methods used by Andra are credible and believed to be capable of evaluating thermal properties correctly, even in anisotropic rock. The anisotropy in the thermal conductivity of argillite is an important detail when performing predictive thermal calculations. Our analyses confirm that an "equivalent" isotropic value (e.g., geometric mean of the component values in different directions) may be used to produce an adequately equivalent thermal response.

1.4.2 Findings

1. **Optimistic performance view**: Probably the most serious concern, overall, is a pervasive optimism in the interpretation of complex phenomena with regard to repository performance. One striking example of this, repeated in multiple reports, is the postulate that the repository will behave essentially as an ideal fluid over a million-year period: all voids will be closed and sealed, including void space in primary waste packages, disposal cells, disturbed rock (fractured and microfissures), and seals. All deviatoric stresses will vanish. In effect, Andra assumes that the repository generally will return to a pre-construction state or something close to it with regard to waste isolation characteristics and behavior. Andra's performance assumptions often seem very optimistic.
2. **Timetable**: The official timetable for the repository project is far too rushed, given the amount of research and characterization that remains. It will take more than a few years of additional work; however, since so much work still remains to be done, we cannot give a more precise estimate of the amount of additional time that will be needed. In any event, we believe that it will involve a significant extension of the present schedule.[6]
3. **Source term**: The source term has not yet been clearly defined. The design of the repository, performance assessments, the nature of the boreholes to be drilled all depend on the specification of the amounts and the kinds of wastes that will be disposed of. Andra has been allowed to proceed on the assumption that all wastes will be reprocessed. At the same time it has been suggested (but not mandated) that disposal of unreprocessed spent fuel should be considered. There is no specified quantitative limit to each type of waste and to the total source term. This is a critical gap that leaves in doubt a host of other questions, such as (i) the performance results, (ii) the size of the repository and (iii) whether the rock type and repository design can suitably accommodate the amounts and types wastes that may be disposed of, including spent fuel.
4. **Homogeneity and isotropy or lack thereof**: Andra relies on the homogeneity and isotropy of the Callovo-Oxfordian formation in its evaluation of the long-term repository performance. However, Andra's approach does not adequately represent the range of possibilities. Moreover, in some cases, the experimental data were excluded in a way that biased mean values and resulted in underestimating the actual observed range in the parameter values. This inadequate consideration of the variability in the properties of the

---

[6] The present schedule is: public debate in 2013; license granted in 2015, retrievability conditions decided in 2016, and waste emplacement to begin in 2025. See http://www.jaif.or.jp/ja/wnu_si_intro/document/2009/andra-geological_disposal-general.pdf (Andra [undated]).

host rock in the transposition zone is a major concern. Moreover, the ZIRA itself is inhomogeneous -- that is, the properties of the host rock change within the ZIRA. Specifically, the properties are different in the southwest or south of the ZIRA from those to the north or northeast of the ZIRA. This conclusion about heterogeneity is based on many lines of evidence, including those cited by Andra itself (as discussed in Chapter 3). However, Andra has largely ignored this heterogeneity except in a sensitivity analysis that IEER considers inadequate. While the impact of the inhomogeneities on the transport and retention properties may turn out to be small, Andra has not established the nature of the inhomogeneity within the ZIRA. Andra's assumption that inhomogeneities are not significant for performance is premature. .

5. **Diffusive and advective flow**: Andra believes that diffusive flow will dominate in the Callovo-Oxfordian formation. However, a probabilistic analysis of Peclet numbers as well as tracer data indicate that there is a significant potential for mixed diffusive and advective flow.

6. **Performance results**: Andra's performance analysis uses only a limited sensitivity analysis to explore the effect of the range in parameter values on performance. Moreover, Andra has not done a full probabilistic analysis using the appropriate ranges of parameters. As noted, Andra also optimistically assumes that only diffusive flow will occur. A simplified probabilistic safety analysis we performed with the parameter ranges consistent with the ones defined by Andra indicates that these uncertainties in the input parameters result in the uncertainty in the total maximum dose of five orders of magnitude. In contrast, the potential range in the total maximum dose defined by Andra as one order of magnitude (or two times when the proposed repository is located at the URL site) might be underestimated. Proceeding to a ZIRA selection without such a probabilistic analysis of performance using available data was methodologically inadvisable. Proceeding further without a full probabilistic analysis and an independent review of the parameters used in that analysis is also inadvisable.

7. **Earthquake potential**: The earthquake potential of the site appears to be low. We understand that Andra uses the standard archives of earthquakes. Similarly, Andra indicates at one point that a probabilistic analysis has been done for various return periods. Andra has evaluated ranges for the return periods for some specific locations. But we could not find a comparative analysis of how the ground shaking was maximized, given the catalogs of earthquakes used by Andra both for the operational period and the post-closure period. An easily accessible probabilistic analysis of acceleration and load is important for a review of the basis of design of surface facilities and especially waste handling facilities.

8. **Plugged microfissures?**: The microfissures found by Andra in the underground laboratory were plugged. Whether this will continue to be the case in the ZIRA remains to be determined, since underground characterization is needed to arrive at such a conclusion. Extension of the conclusion about plugging of microfissures to the ZIRA would be premature.

9. **Permeability change in EDZ**: We have a number of concerns regarding various aspects of the mechanical performance of the repository during the open period as well as after closure claimed by Andra. Specifically, host rock permeability may be increased by 3 to 5 orders of magnitude in the emplacement horizon, as indicated by some measurements, rather than being restored to within an order of magnitude as assumed by Andra.

10. **Slot Cutting**: The process of placing swelling clay seals includes cutting slots into the formation at selected intervals with the purpose of interrupting fluid flow along the liner/argillite interface. Portions of the concrete liner are removed to enable slot cutting at these intervals. However, the method of removing sections of the concrete liner is not mentioned. We are concerned that mechanical damage to the remainder of the liner is unavoidable under the proposed scheme. One option is to incorporate the slots (and the associated seals) at the same time the liner is installed to avoid removing sections of the liner.
11. **Measurement of thermal properties:** In spite of a very comprehensive summary of the thermal properties measurements, the choice of flash method will keep the questions open for the validity of the conductivity results in non-isotropic media such as the Callovo-Oxfordian argillite. Inconsistent heat conductivity values in subsequent Andra documents are a cause for some concern and need a traceability (quality assurance) check, even if the discrepancies are small and are thought to be insignificant.
12. **In situ thermal and disposal research**: Andra has not yet done sufficient work in the underground laboratory to ensure that the mechanical, thermal, and other criteria for disposal will be met. Specifically, Andra has not emplaced one or more full-size canisters with simulated waste, sealed the emplacement holes, and tested various procedures, assumptions and conclusions. As noted, Andra had done and continues to do excellent collaborative work with other programs. However, while collaborative work with others can provide and has provided critical experience and information in proceeding with the investigations at Bure, it is not a substitute for critical in-situ research in its own underground laboratory. Site-specific issues, such as damage during drilling of trial emplacement holes, provide a strong indication that further work is needed.
13. **Spent fuel disposal**: We recognize that Andra is not mandated to take into account disposal of unreprocessed spent fuel (either uranium or MOX) at the present time and that the design is proceeding on the basis of disposal of vitrified high-level waste and long-lived medium level waste. However, it is suggested that Andra also investigate updated waste disposal scenarios involving spent fuel. The borehole requirements for spent fuel disposal are drastically different and more difficult than for disposal of vitrified high-level waste. Specifically, drilling a 3.3 meter borehole for spent fuel disposal would present severe challenges, in view of the difficulties already encountered in a 0.7 m borehole (see Chapter IV).

1.4.3 Recommendations

1. **External review**: Andra has done a lot of good and in many cases excellent scientific work. However, its performance assessments tend systematically to the optimistic side and do not fully reflect the details of the data. In the course of this review, we could not determine some essential details of the scientific work that Andra has done but it appears that some data get omitted or downplayed in performance assessments. To avoid such optimistic assessments, a significant level of continuing independent external review, considerably beyond present external reviews, is needed. This review should be concurrent with the research, and continue through all phases, including after the start of

repository operation, if it is licensed. The review could be done by the IRSN; however it would need to be adequately staffed, with personnel from various relevant specializations, and sufficiently funded. It is necessary to independently review and thoroughly evaluate all aspects of Andra's voluminous scientific work and how it is incorporated into its performance and safety assessments.

2. **Redundancy:** Andra's performance assessments assume that the geologic medium will by itself be sufficient to meet the long-term radiological performance criteria. However, as noted, Andra's assessments are optimistic; a probabilistic assessment using the full range of parameters shows a much wider range of results than Andra's limited sensitivity analysis. Moreover, much research remains to be done. Further, the source term is not yet precisely defined. The combination of these factors results in large uncertainties in the performance assessment and indicates the need for Andra to consider alternative conceptual models, including waste containers that are much more durable that would be designed to play a role in limiting the source term beyond the engineered barriers. Currently, Andra assumes that the geologic features of the host rock alone will be sufficient to provide satisfactory performance over very long periods of time. An approach in which the engineered barriers provide a redundant isolation capacity for performance would also reduce the uncertainties in whether the performance goals can be met and is therefore desirable from that point of view as well. IEER had also recommended an approach to design that included such redundancy in its 2005 report.[7]
3. **Source Term:** The amounts and types of waste that will be disposed of at the repository should be definitively specified as soon as possible. Uncertainty about whether spent fuel will be disposed of and about the total amounts of fission products and actinides, including transuranic radionuclides, could lead to serious technical problems down the line. For instance, Andra is not now actively preparing for spent fuel disposal even though the requirements for such disposal are much more complex and severe from mining and stability considerations.
4. **Performance assessment**: Andra should carry out a probabilistic performance assessment using the full ranges of parameter values. Andra needs to take better account of heterogeneity, the potential for both advective and diffusive transport, in the vertical pathways. The circumstances that create the potential that the dose criteria might not be met should be identified and taken into account in design measures, such as reducing the source term in the far field. Such measures should be evaluated for their adequacy in addressing the problem, should it arise.
5. **EDZ evolution**: A reasonably conservative assumption, which we endorse, would be to assume that the EDZ does not fully repair itself to create in situ permeability and /or state of stress. In fact, it may be best to assume that the EDZ retains the worst state of estimated damage throughout the repository life.
6. **Factors in creep behavior**: The creep behavior of argillite is a complex function of at least three parameters that all vary, in space and time, in a repository environment. Specifically, tests show that deviatoric stress, saturation, and temperature all affect significantly the rate of creep. The interrelationship of these environmental factors and their effect on repository performance appears to have been treated rather qualitatively. A better integration of the combined influence of these factors is warranted.

---

[7] IEER 2005 p. 24

7. **Prototype repository:** Andra should consider building an experimental area in the underground laboratory similar to the Prototype Repository that has been built in Sweden in the Underground Laboratory. It should be designed to show, so far as is possible in an experiment lasting a few years, how the actual repository might work in practice, and to determine with greater realism some of the performance parameters that are specific to Bure, including the in-situ performance of HLW canisters under thermal stress.
8. **Horizontal versus vertical emplacement**: We recognize that there are important advantages to horizontal emplacement design including minimizing the vertical extent of the waste packages. However, given the difficulties of making large boreholes in this type of sedimentary rock, as evidenced by fractures and deformations in several boreholes drilled in the underground laboratory, the possibility for waste emplacement in vertical boreholes should be revisited, especially for spent fuel disposal. The holes for spent fuel canisters required will be very large – 3.3 meters in diameter and ensuring their stability using horizontal placement will present formidable challenges in the Bure argillite, should spent fuel disposal be needed.

1.5 References

Andra [undated]	Marielle Girard. *The Meuse/Haute Marne Centre: Underground Research Laboratory Technological Exhibition Facility*. [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, [undated]. On the Web at http://www.jaif.or.jp/ja/wnu_si_intro/document/2009/andra-geological_disposal-general.pdf. Possibly presented at the World Nuclear University Summer Institute in 2009.
IEER 2005	Institute for Energy and Environmental Research. *Examen critique du programme de recherche de l'ANDRA pour déterminer l'aptitude du site de Bure au confinement géologique des déchets à haute activité et à vie longue: Rapport final,* Préparé pour le Comité Local d'Information et de Suivi; Directeur du projet: Arjun Makhijani; Coordinatrice du projet: Annie Makhijani; Auteurs du rapport (par ordre alphabetique): Detlef Appel, Jaak Daemen, George Danko,Yuri Dublyansky, Rod Ewing, Gerhard Jentzsch, Horst Letz, Arjun Makhijani. Takoma Park, Maryland, IEER, 27 décembre 2004, avec corrections 11 janvier 2005. Links on the Web at http://www.ieer.org/reports/bure/1204index.html.
IRSN 2009	*Institut de Radioprotection et de Sûreté Nucléaire. Avis de l'IRSN sur les critères retenus par l'Andra pour le choix d'une « zone d'intérêt pour la reconnaissance approfondie (ZIRA) » en vue du projet HA-MAVL - Site de Meuse/Haute-Marne*. (Lettre IRSN/2009-166) Fontenay-aux-Roses: IRSN, 22 décembre 2009. On the Web at http://www.irsn.fr/FR/expertise/avis/Documents/Avis_IRSN_ZIRA_22122009.pdf.

Chapter 2: Seismic data and seismological characterization of the transposition zone

Strengths

1. In our view, the investigations at Bure are quite convincing. For instance the seismic investigations cover the whole area and they also cross the faults of the boundaries. Thus, these limits are completely characterized. This is clear from the various figures we have reproduced above from
2. Andra's documents. Andra's overall work is of good quality, but there are some gaps in the analysis.
3. Andra's 2D and 3D work is scientifically sound.

Findings

1. The microfissures found by Andra in the underground laboratory were plugged. Whether this will continue to be the case in the ZIRA remains to be determined, since underground characterization is needed to arrive at such a conclusion. Extension of the conclusion about plugging of microfissures to the ZIRA must be validated with data obtained specifically in the ZIRA.
2. Although the presence of vertical faults with a throw greater than a few meters is ruled out, it is clear that vertical water pathways exist, which can even be observed in local quarries. The calcites to be found close to the surface provide evidence of this.
3. The earthquake potential of the site appears to be low. We understand that Andra uses the standard archives of earthquakes. Similarly, Andra indicates at one point that a probabilistic analysis has been done for various return periods. Andra has evaluated ranges for the return periods for some specific locations. But we could not find a comparative analysis of how the ground shaking was maximized, given the catalogs of earthquakes used by Andra both for the operational period and the post-closure period. An easily accessible probabilistic analysis of acceleration and load is important for a review of the basis of design of surface facilities and especially waste handling facilities.
4. Errors related to units should be corrected in some of the reports. In a few instances, velocity units are shown instead of displacements, frequency in confused with period, etc.

Recommendations
1. Andra should provide an easily accessible probabilistic analysis of acceleration and load used that it plans use in the design of surface facilities, especially waste handling facilities, in the same place as the catalog of earthquakes used to derive them for ease of review.
2. In general, Andra should provide documentation of its results that is more accessible and easier to review.

2.1 Seismic data collection, investigations, research and analysis for the selection of the ZIRA

The main faults are seismically well investigated and documented.[8] 3D seismic results are described in two volumes (already from the year 2001); in addition new experiments were envisaged.[9]

The transposition zone was defined; a principal justification is that its characteristics are similar to those of the underground laboratory. According to Dossier Argile 2005:

> Finally, the **transposition zone** is defined as the surface area upon which the Callovo-Oxfordian properties and the geology of the surrounding formations are similar to those determined at the Meuse/Haute-Marne underground Laboratory site…. It represents an extension of the order of 200 square kilometres.[10]

This is complemented by statements of homogeneity in the ZIRA (Zone d'Intérêt pour la reconaissance approfondie - zone of interest for detailed research, which is the zone to be characterized for a possible repository). However, as we will see in the next chapter neither the transposition zone nor the ZIRA is homogeneous. The transposition zone is part of the host rock and, thus, the geological barrier. It should cover the volume of rock in which the radionuclides are trapped for the defined isolation period.

In an Andra report there is a short characterization of the transposition zone as being capable and stable to allow the building of the underground installations:

> It can support boring of underground tunnels and construction of underground facilities that would induce only moderate damage that would, a priori, not be susceptible to the creation of preferential flow pathways. There is an area of 250 km^2 that appears to have these properties. This is so-called transposition zone.[11]

It appears that the seismic investigations cover the whole area and they also cross the faults of the boundaries. Thus, these limits are completely characterized. According to Dossier Argile 2005:

> ***The Andra research area is bounded by:***
> - in the south east, the Gondrecourt-le-Château graben with a north east/south west direction,
> - in the south west, the Marne graben oriented north/north west. It extends south along the Poisson fault which is parallel to this graben
> - to the north, the Aulnois-Saint-Amand structure which presents slightly dipping layers.
> The Callovo-Oxfordian formation is composed of clay formations, argillites, which thickness varies from 130 to 160 metres in the study area. All the layers making up the Callovo-Oxfordian and the surrounding formations *are practically horizontal, with a slight dip from 1° to 1.5° towards the west and the centre of the Parisian basin.*[12]

---

[8] Andra Cartographie 2001 Figure 39ff.

[9] Andra Sismique 2001

[10] Dossier Argile 2005 Synthesis p. 65

[11] Andra Sûreté 2010 p.17

[12] Dossier 2005 Argile, Synthesis p. 65. Emphasis in the original.

In Figure 2-1 a geological block diagram of the Meuse / Haute-Marne sector is given.

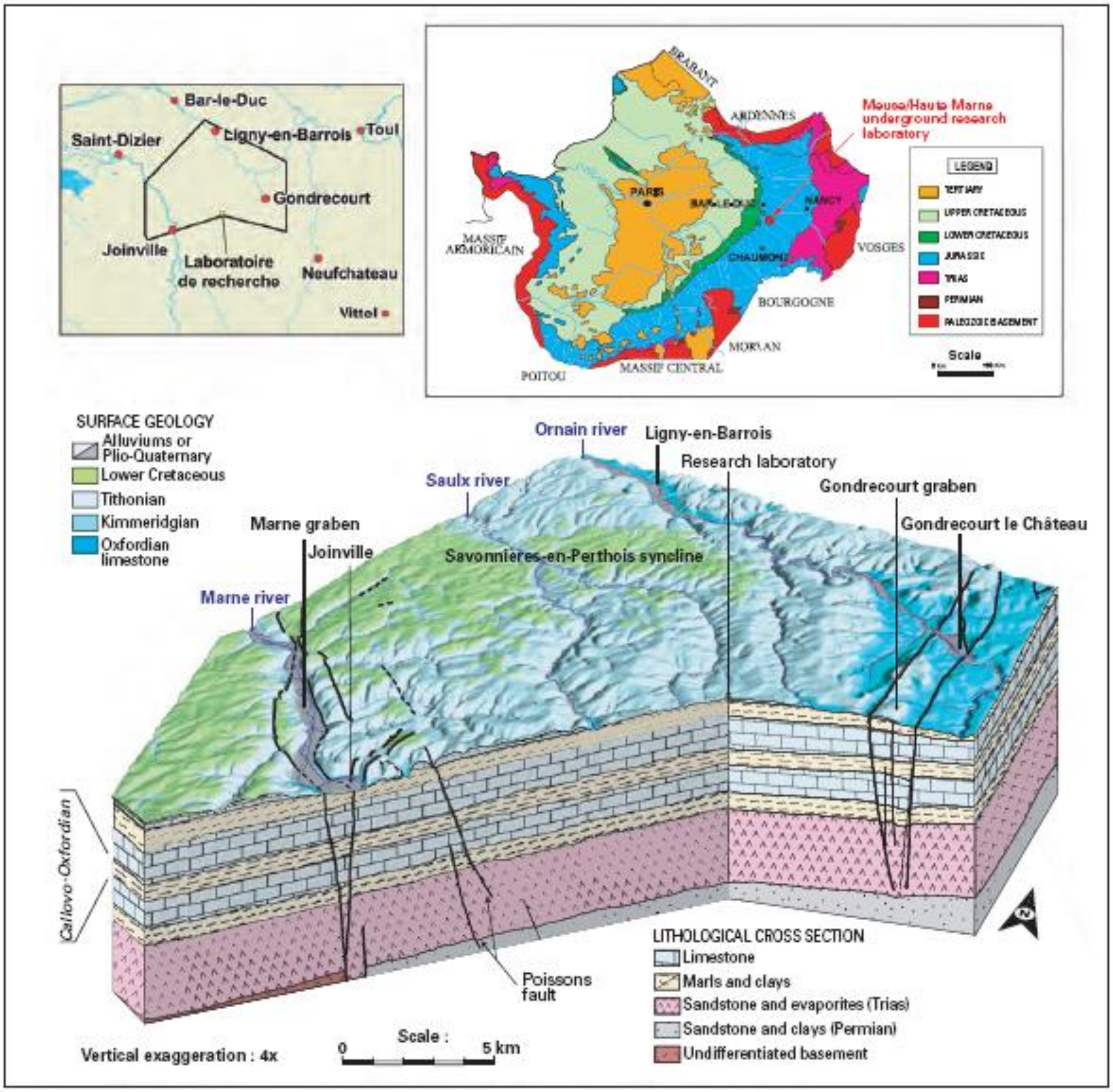


Figure 2-1. 3D geological block diagram of the Meuse/Haute-Marne sector (Source: Dossier 2005 Argile, Synthesis p.66).

2.1.1 Review of the research on the homogeneity of the transposition zone or lack thereof

In *Synthèse du programme de reconnaissance de la zone de transposition*,[13] the results of borehole investigations revealed microfractures (as described in Section 3.2.1.1 of this report). Although the presence of vertical faults with a throw greater than 10 meters is ruled out,[14] there is not enough data at present to rule out secondary faults with a throw of between five and 10

---

[13] Andra ZT 2009 Section 4.2.1.3 Les microstructures (p. 70)

[14] Dossier 2005 Argile, Synthesis p. 88

meters.[15] We note that there is evidence of vertical pathways; these can even be observed in local quarries. The calcites found close to the surface are evidence of that. At present we cannot say whether the vertical pathways are due to small faults or not.

Dossier 2005 Argile, Synthesis states:

> Due to the low permeabilities of the Oxfordian and Dogger formations, flow is very slow: hydro-geological modelling shows that, in the transposition zone, velocity is in the order of a kilometer per hundred thousand years in the Oxfordian, and even slower in the Dogger. These velocities are consistent with the results of analyses of chlorine-36 and carbon-14 isotopes. *The mean age of the water in the Oxfordian and Dogger formations is approximately 400 000 years and 1 million years respectively.*
>
> Finally, the hydraulic heads measured in the Oxfordian and Dogger formations are similar and, at the transposition zone scale, do not represent an effective driving force for water displacement in the Callovo-Oxfordian formation. Given the argillites low permeability, the vertical water flow velocity (appraised by the Darcian velocity) is in the order of a few centimetres per 100 000 years in the Callovo-Oxfordian formation.[16]

This last statement only holds true for rocks with a very low permeability without the presence of microfractures or for rocks in which essentially all microfractures are plugged. Evidence from the boreholes in the underground laboratory indicates that this is the case; the ZIRS remains to be investigated in this regard.

The reconstruction of the Oxfordian layer morphology derived from 3D seismic investigations shows that the rocks in this layer have permeabilities from 10^{-9} m/s to as high as 10^{-7} m/s. (See Chapter 3 for further discussion.) The length of the given section is about 3 km (Figure 2-2).

---

[15] Andra ZT 2009 p. 12

[16] Dossier 2005 Argile, Synthesis p. 95. Emphasis in the original.

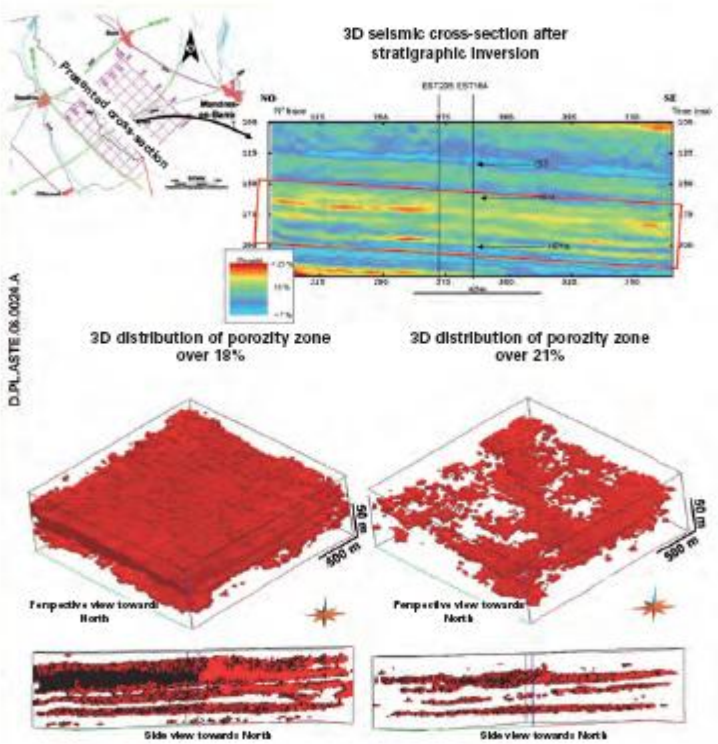


Figure 2-2. Reconstruction of the Oxfordian porous layer morphology on the basis of 3D seismic data (Source: Dossier 2005 Argile, Synthesis p. 95)

2.1.2 Seismic characterization

Andra has conducted a seismic characterization (more than 170 km of seismic lines and 2D and 3D seismic campaigns) as well as stress measurements. In addition to the already available seismic lines new lines were identified (Figure 2-3).

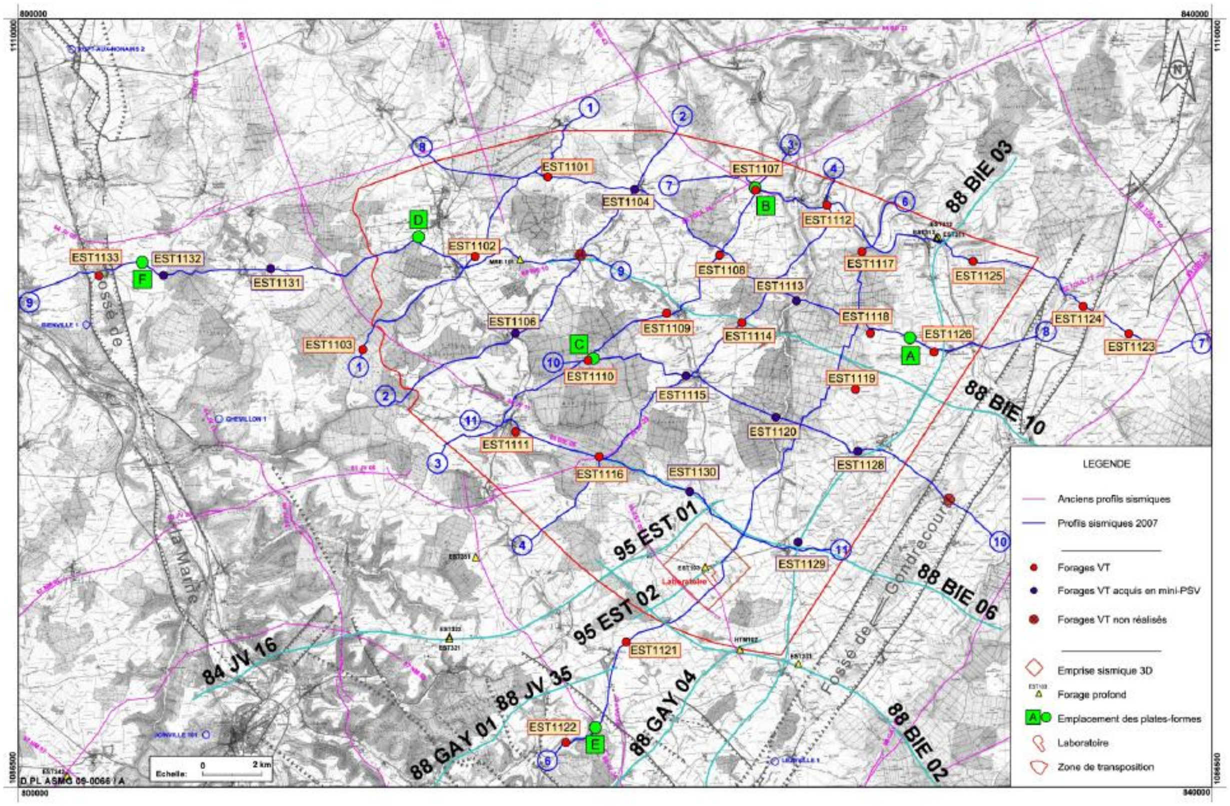


Figure 2-3. Localization of the 2D seismic work: New lines in deep blue and old lines in light blue; boreholes are also given (Source: Andra ZT 2009 Figure 2-3 (page 18))

Figure 2-3 should be compared to Figure 2-4 below, which provides seismic lines from Dossier 2005.

As we will see in Chapter 3, there are variations in porosity across the transposition zone. According to Dossier 2005 Argile, Synthesis:

> Certain levels of the carbonated Oxfordian have a higher porosity than the rest of the formation. Their organization appears directly linked to the initial sedimentation conditions. That explains their overall geometry organized according to their stratification as shown by the 3D seismic data recorded on site. Underground water circulation occurs mainly in these levels, also more permeable (up to 10^{-7} m/s).[17]

---

[17] Dossier 2005 Argile, Synthesis p. 94

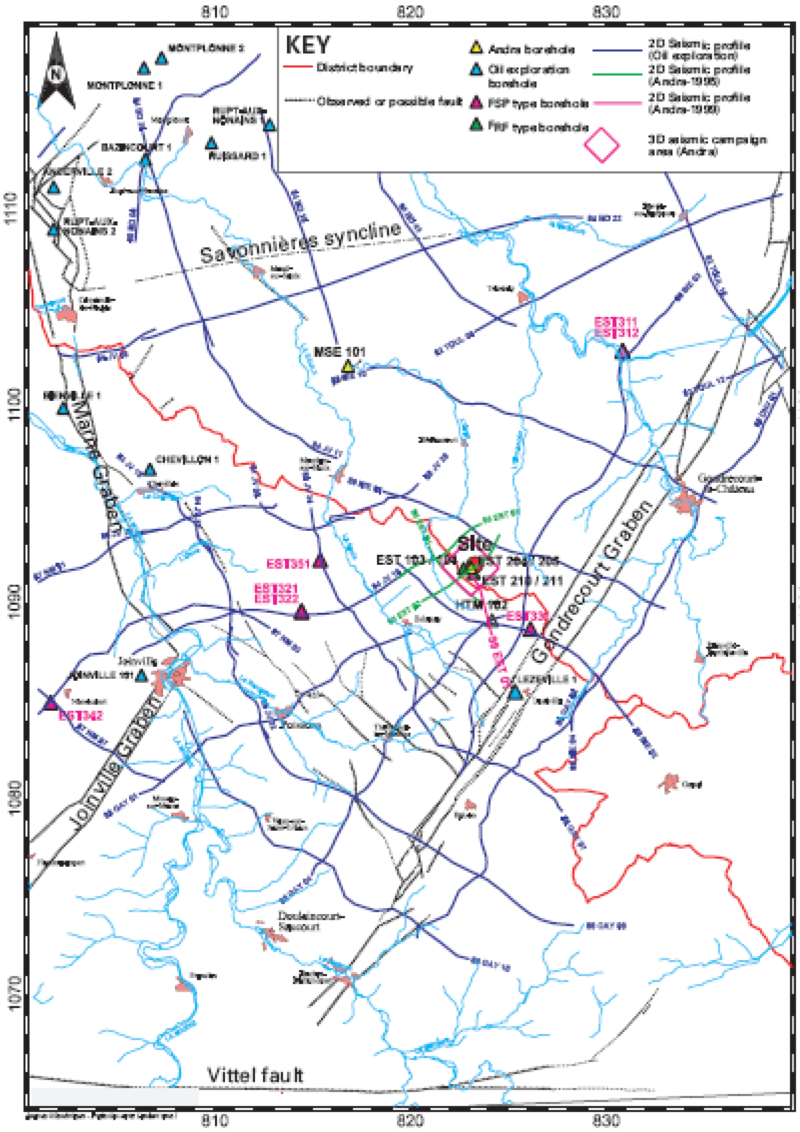


Figure 2-4. Location of the boreholes drilled by Andra and seismic profiles (Source: Dossier 2005 Argile, Synthesis p. 71)

2.1.3 Evaluation of the potential for research with a five-meter 2D resolution and 3D research.

One concern is resolution of seismic data. Specifically, the digitization rate of the old data (number of samples per second) might not be as high as new data. However, the digitization rate may not be the main issue. Rather, the problem could be the distances of the geophones and seismic lines, which define the resolution of the underground structures. According to Dossier 2005 Argile:

> The detailed examination of 350 km [Andra ZT 2009 gives only 174 km] of seismic profiles in the study sector *shows that the tectonic deformations that have affected the region in the last 150 million years are slight* and limited essentially

> to the Gondrecourt and Marne grabens, at the edges of the study sector. *Between these faults, the Callovo-Oxfordian layer is regular and practically flat, which facilitates the design of the repository architecture.*[18]

This statement is in principle correct.

Dossier 2005 Argile, Synthesis further states:

> **At the scale of the laboratory site,** *the 3D Seismic survey (1999-2000) covering 4 square kilometres and the cored bore-holes EST204 and 205 drilled along the two shafts axis provided greater precision of the geometry of the layers making up the underground part of the site.*
>
> The 3D seismic surveys provided an image of the volume of the laboratory site with a greater level of detail. It confirmed the fact that Callovo-Oxfordian argillaceous layer is regular with a thickness over 130m and a consistent geometry with the history of deposits which succeeded the Callovo-Oxfordian. There have been no disruptive phenomena in the laboratory zone since the formation of the Callovo-Oxfordian (great stability). [19]

This statement also seems to be correct. At least, the data provided does not show *disruptive phenomena*. However, could the lack of observation of disruptive phenomena be due to the insufficiently close spacing of the geophones and /or seismic lines?

Further according to Dossier 2005 Argile, Synthesis:

> These last three bore-holes surveyed the host formation along 1500m and allowed a comparison of the sedimentological and petrophysical characteristics at laboratory footprint scale with the data from the site 3D seismic survey. It showed that there were no fractures and *very few microfissures in the Callovo-Oxfordian on the laboratory site and that these microfissures were plugged. They are, moreover, located generally at the top and bottom of the layer. They are located one or several meters apart from each other with a metric extension.* In situ *measurements confirmed the very low permeability of the argillites.*[20]

Andra's conclusion based on borehole data that microfissures are plugged on the laboratory data is the right approach for determining the status of microfissures. Surface investigations do not have the necessary resolution to allow a determination whether small microfissures are plugged or not. Hence, the conclusion that microfissures are plugged cannot be extended to the ZIRA at present since underground characterization of the ZIRA has not yet been done. It would be premature for Andra to extend its conclusion about plugging of microfissures to the ZIRA and to the performance of the repository, especially as there are indications that the ZIRA is not homogenous as noted above and discussed in Chapter 3. In addition to the borehole data, it appears to us that the seismic work – the 2D and especially the 3D – is scientifically sound,

---

[18] Dossier 2005 Argile, Synthesis p. 84. Emphasis in the original.
[19] Dossier 2005 Argile, Synthesis p. 70. Emphasis in the original.
[20] Dossier 2005 Argile, Synthesis p. 73. Emphasis in the original.

although the results are hidden in different reports and the conclusions drawn are not always demonstrated by explicit reference to the data.

2.2 Earthquakes

2.2.1 Analyses of the earthquake hazard and catalogs of historical seismicity for the region

Dossier 2005 Argile provides the following conclusion about seismic activity:

> The tectonic activity in the region of the Meuse/Haute-Marne site is very low (low seismic activity, little crust displacement, perennial orientation of stresses) and the geological structure is stable, as evidenced by the absence of quaternary indices of tectonic activity on the faults surrounding the study area. In these conditions, the possible tectonic movements are limited to very low recurrence of pre-existing faults structuring the basement.[21]
>
> However, the risk of earthquakes near the site cannot be totally excluded on a scale of several hundred thousand years. To estimate the seismic risk over long periods of time, the faults near to the site are assumed as active and *maximum physically possible earthquakes (SMPP)* values are considered, despite the absence of seismicity and recent tectonic deformations. The very penalizing hypothesis, with a hypothetical earthquake of magnitude 6.1±0.4, is postulated as occurring 6 km from the site. *Then, to be on the safe side, we check that the repository structure can withstand such an earthquake.*[22]

The assessment of the seismic hazard for a specific site requires first the evaluation of the known seismicity and its distribution. Thus, it is necessary to collect all seismic events which occurred in that area and provide a table of all events as well as a map of the epicenters. The next step is to derive a seismo-tectonic model of the area under study. Usually, all seismic events within a radius of 200 km around the site are used. This leads to a deterministic approach.

Here it is most important to use a full catalogue that includes historic events.[23]

Accordingly, we read about the conversion of intensities and magnitudes:

> The magnitudes are derived from those of the SMHVs by increasing the intensity by 1 degree according to the equation ISMS = ISMHV + 1; this intensity increase of 1 degree corresponds to an increase in the magnitude of the reference earthquake conventionally set at 0.5. [24]

We are not clear on how Andra derived the increase in magnitude of 0.5 corresponding to an intensity increase of one. Applying the standard empirical formula for an earthquake at 10 km depth leads to a magnitude increase of 0.7.   While this seems to be a small correction, it should be noted that an increase of 0.2 degrees in magnitude corresponds to a doubling of the energy

---

[21] Dossier 2005 Argile, Synthesis p. 60

[22] Dossier 2005 Argile, Synthesis p. 85. Emphasis in the original.

[23] See, for example, Gutdeutsch, Kaiser, and Jentzsch 2002.

[24] Référentiel du Site 2010 Tome 3, p. 53. Translated from the French.

released.[25] While the intensity increase is larger for an SMS magnitude calculated in the way suggested by Andra, the reasoning behind it is not clear.

Different seismotectonic models were developed to test solutions and to solve the problem of choosing the design intensity for the site. Figure 2-5 below gives one model (MS1) for local sources.[26] In the legend of Figure 2-5 the values of the magnitudes are described as very high in comparison to the recent seismo-tectonic context in this part of Eastern France, which belongs to a tectonically stable region with a very low seismicity (which could be even characterized as aseismic).

2.2.2 Evaluation of the reference earthquake and earthquake hazard at the site

The estimation of the earthquake hazard is a precondition for the derivation of the earthquake load from the intensity possible (including peak ground acceleration (PGA) or velocity or deformation) and duration of the maximum vibrations. These values are important for the construction of buildings and also for the consideration of their effects on moving installations, e.g., elevators or cranes moving the nuclear waste containers.

Figure 2-5 gives the early development of the seismo-tectonic model (MS1). Here, only the surface geology is correlated with the maximum physical possible earthquake. Later, seismic zones were defined with a reference earthquake each. The latest versions were MS3 and MS4. The MS4 is shown in Figure 2-6 below.

---

[25] A decrease of 0.2 equates to a decrease in energy released by a factor of 2.

[26] Reproduced from Référentiel du Site 2010 Tome 3, Figure 28-2.

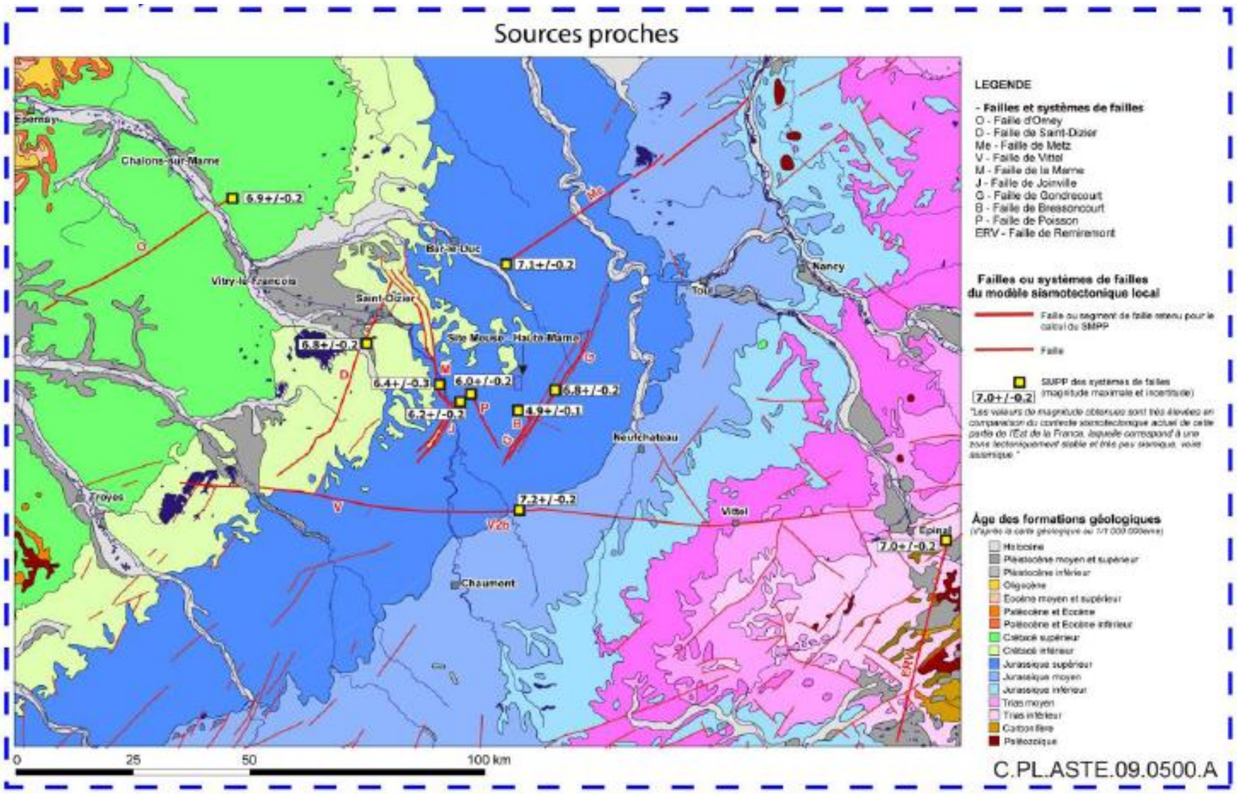


Figure 2-5: Seismo-tectonic zones at the local level with reference earthquake values for maximum possible earthquakes (Source: Référentiel du Site 2010 Tome 3, Figure 28-2 (p. 71))

Specifically, Figure 2-6 shows the regional seismo-tectonic zones with earthquake magnitudes based on historical earthquakes. It shows that the site is situated near the southeastern border of the seismo-tectonic unit *Paris Basin* in which the biggest magnitudes for SMS and SMPP are assumed to be M = 5.0 and 6.1, respectively. However, in this regional framework of zones, the Bure site is situated in the zone Vosges-Lorraine and the equivalent values are M = 4.8 and 6.1, resp. The neighboring zones show magnitudes up to M = 5.0 and 6.1 (Bourgogne-Morvan) respectively and M = 6.5 and 7.0, for SMS and SMPP respectively, (Epinal-Remiremont-Vesoul).

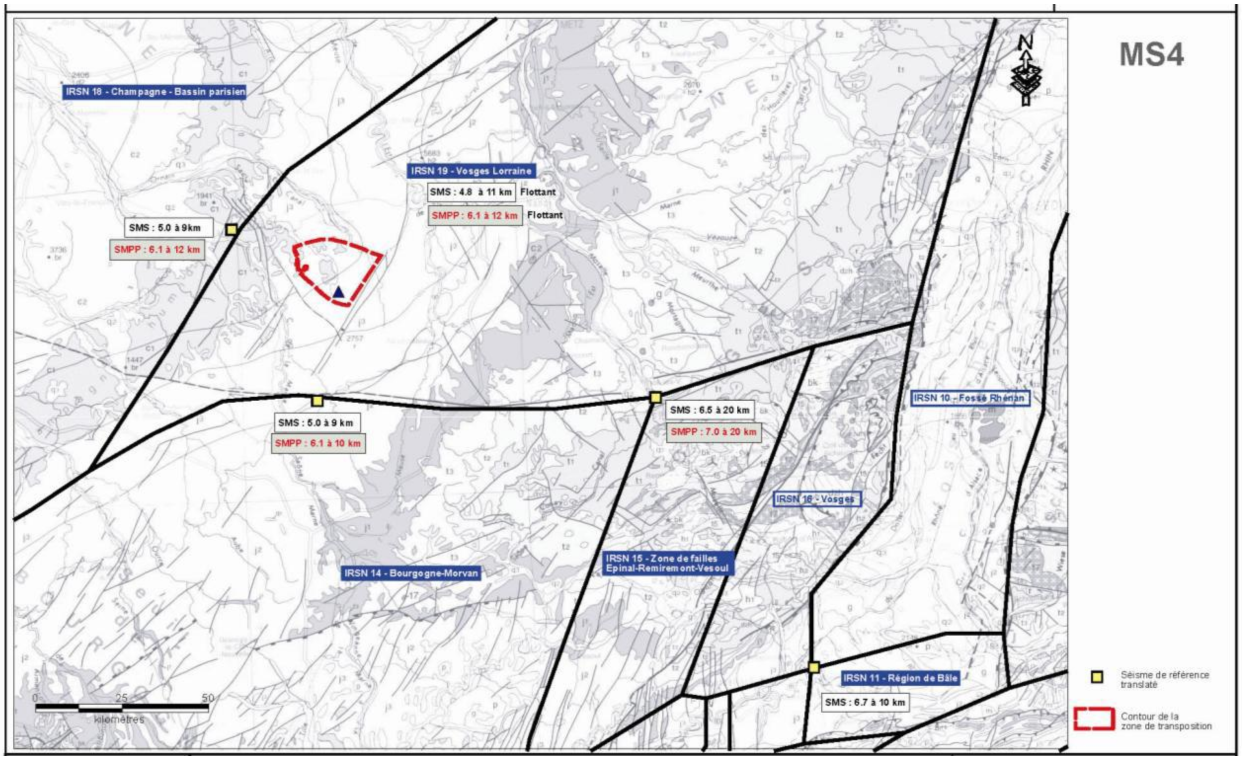


Figure 2-6. Seismo-tectonic model for determining reference values for SMS and SMPP by zone (Source: Référentiel du Site 2010 Tome 3, part of Figure 28-7 (p. 78))

In the framework of local faults, Andra shows the following SMS and SMPP values:[27]

- Marne fault: SMS 4.0 (depth 10 km); SMPP 6.1 (depth 10 km)
- Joinville fault: SMS 4.0 (depth 2 km); SMPP 5.2 (depth 2 km)
- Gondrecourt Fault: SMS 4.0 (depth 2 km; SMPP 5.2 (depth 2 km)
- Poisson fault: SMS 4.0 (depth 10 km); SMPP 6.1 (depth 10 km)
- Vittel system of faults: SMS 4.8 (11 km depth); SMPP 6.1 (10 km depth)
- Metz-Mayence-Hunsrück system of faults: SMS 5.8 (15 km depth), SMPP, 6.1 (15 km depth)

According to international practice, the earthquakes in the neighboring zones should be moved hypothetically to the border next to the site; if their effect on the site is bigger than the reference earthquake in the zone of the site it should be used as a reference for the Bure site. This may lead to bigger ground shaking at Bure being used for design purposes.

It would have been useful at this stage if Andra had compared the load and acceleration at the Bure site from the zonal analysis shown in Figure 2-6 above and also SMS values shown above.

The seismic zonation is the first step to evaluate the seismic hazard. The next is to determine the so-called site conditions. The local underground geomechanical properties determine the amplitude of the ground shaking (or resonance to the incoming seismic waves). Thus, they determine the response in the frequency range between 1 and 10 Hz. The response between 1

---

[27] Référentiel du Site 2010 Tome 3, Figure 28-6 (p. 77)

and 10 Hz depends on the soil class. Usually, typical soil-classes are used, e.g., for soft soil, medium soil, or hard rock.

The site response is also dependant on the frequency characteristics of incoming seismic waves: Local earthquakes contain higher frequencies than distant earthquakes. This is discussed in Figure 2-7 below.[28] This figure shows how the response spectrum at the Bure site was determined (here only the important result is included). SL is the spectrum of local earthquakes, and SR the one of regional ones. If one uses m/s^2 as the units for acceleration, one would find the curves in the area between 1 and 10, in which 10 m/sec^2 is approximately equal to the gravitation acceleration at the surface of the earth (1 g). In such a figure, the bulge would show the response of the site, and the constant acceleration above 10 Hz would show the magnitude of the seismic load. The safety rule requires Andra to consider frequencies in the range of 0.1 Hz to 34 Hz.[29]

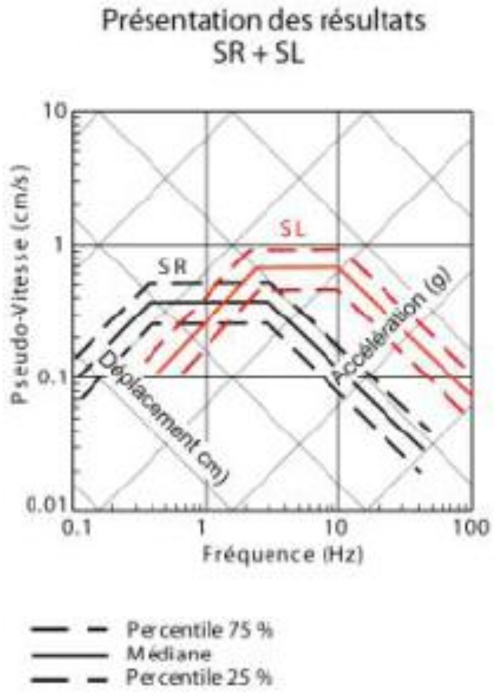


Figure 2-7. Response spectra for two kinds of earthquakes: SL – local, SR – regional. (Source: Référentiel du Site 2010 Tome 3, Figure 27-2 (p. 55))

We are unsure if a reference has been made to the site response; if not, we recommend that Andra do so. The maximum in the spectrum of pseudo-velocity between 1 and 10 Hz greatly depends on the geomechanical properties of the underground. The amplitude is bigger for soft underground rocks, like sedimentary rocks, and smaller for hard rock; the frequencies where the changes in pseudo-velocities occur may shift as well.

Further, the high-frequency (short period) value should be a constant indicating the seismic load without local amplification. The spectra given are velocity spectra which show neither the acceleration nor the seismic load. Hence the load is not clear from this graph. Later, Andra

---

[28] Référentiel du Site 2010 Tome 3, Figure 27-2 (p. 55)

[29] Safety rule as cited by Andra in Référentiel du Site 2010 Tome 3, p. 68.

recognizes that the velocity spectra do not show the local properties as clearly at the site, so Andra then uses acceleration, which is in accordance with the scientific standard:

> • Selecting the spectral acceleration values: maximum acceleration (PGA) and accelerations for the characteristic periods of the spectra: ≈ 0s, 0.2s, 0.5s and 2s [35].
> …
> • Locating areas where, on the surface, the movements are likely to be amplified because of the nature of the soils (lithology) and topography (slopes);
> • Quantifying the local amplifications where such areas are identified. [30]

The footnote 35, in the quote above, says:

> These items correspond to: the maximum acceleration (0s), the acceleration on the acceleration plateau of the spectra (0.2s), the acceleration of the descending branch of the spectrum (0.5s) and the part of the spectrum corresponding to movements of high frequencies (2s). [31]

Here, the term high frequency is misleading: a period of 0.5 s corresponds to a higher frequency (2 Hz) compared to a period of 2 s, which corresponds to 0.5 Hz. Thus, the highest frequencies are equivalent to very short periods (the shortest is mentioned to be ≈0 s, which is impossible to interpret in terms of frequency other than as an infinite frequency; we note that an acceleration at "infinite" frequency is required by the safety rule[32]). For practical purposes, the upper limit of frequency appears to be 34 Hz, which is required by rule; we presume that this is considered the functional equivalent of infinite frequency or zero period.

The discussion of the percentiles is as follows:

> The spectrum calculations of ground motions are described according to statistical quantities: median motions and 15% and 85% percentiles, to quantify the uncertainties. The computer codes used are Crisis® and Geosis®.[33]

The calculation is standard. It is important to mention that the 85th percentile value which means that about one standard deviation is the important one here. This value is used to be on the safe side since it ensures that nearly 85 percent of all earthquakes will be below the selected value.

Figure 2-8, shows a comparison of the expected surface acceleration to the one in the underground. The above ground acceleration is a factor of 1.5 greater than the underground acceleration. Here again, each of the two curves shows pseudo-velocity as a function of frequency. Given that the acceleration is the critical parameter in determining load, Andra should clearly describe how the values of 0.12 g and 0.19 g were derived.

---

[30] Référentiel du Site 2010 Tome 3, p. 60. Translated from the French.

[31] Référentiel du Site 2010 Tome 3, p. 60, note 35. Translated from the French.

[32] As quoted in Référentiel du Site 2010 Tome 3, p. 94. Also see Référentiel du Site 2010 Tome 3, p. 68.

[33] Référentiel du Site 2010 Tome 3, p. 57. Translated from the French.

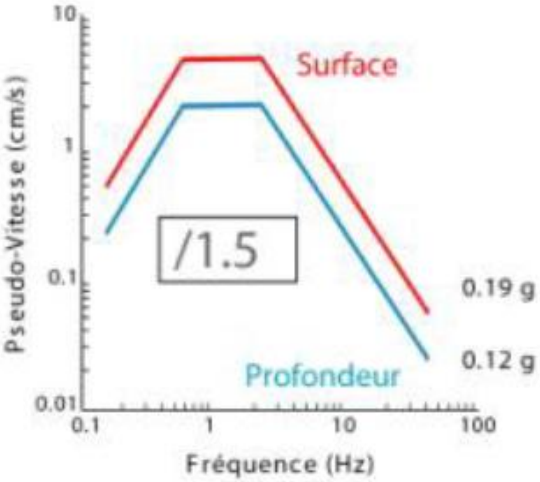


Figure 2-8. Comparison of surface versus underground vibrations for the velocity spectrum and the relation to acceleration (Source: Référentiel du Site 2010 Tome 3, part of Figure 27-5 (p 61))

In addition to the deterministic approach of seismic hazard assessment, Andra indicates that the probabilistic approach was also applied. Here, the so-called return-period is an important parameter that gives an estimate of the time between earthquakes of a specific strength (usually the strongest possible earthquake is used).

Here, different return periods are investigated: 1,000, 5,000, 10,000, 100,000 and 1 million years

> The annual probabilities of exceeding various levels of maximum ground acceleration are tested up to 10^{-6}, by performing calculations for return periods of: 1,000 years, 5,000 years, 10,000 years, 100,000, and 1,000,000 years. [34]

2.2.3 Evaluation of the seismic events

The reaction of the local site is derived from the attenuation law applied, which shows how much the seismic wave is damped along the way to the site. Thus, the damping is a function of the depth of the source and the structure / layering of the Earth's crust.

In Tables 2-1 and 2-2, reproduced from the Référentiel du Site,[35] the reference earthquakes for the Bure site are listed for the different seismic units and faults. But again, the offered results are not sufficiently explained: For instance, it is important to know why the uncertainties are so different (0.2 to 0.4). Here, it would be most important to see the specific data base, i.e., the specific list of earthquakes, that was used to determine the magnitude, depth, and location to be used in design.

Here we can read an estimation of the return period (page 85)

---

[34] Référentiel du Site 2010 Tome 3, p. 57. Translated from the French.

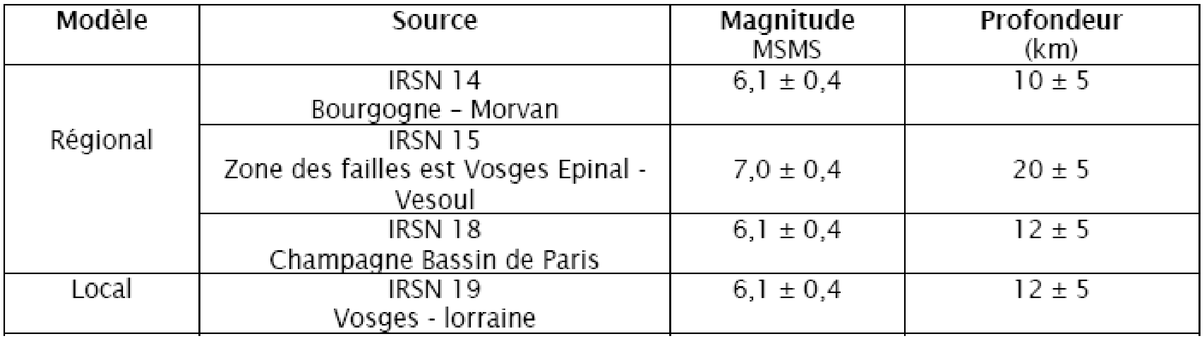
[35] Référentiel du Site 2010 Tome 3, Tableaux 28-5 (p.84) and. 28-6 (p. 85)

The sliding velocities would *a priori* be smaller for the active faults in the Vosges, which lack any indication of detectable deformation at the surface; at these velocities, earthquakes of 7.0 ± 0.4 magnitude could be generated, with a return period ranging between 10,000 years and 250,000 years;[36]

2.2.4 Determination of the maximum ground shaking possible at the Bure site

Table 2-1 gives the maximum earthquake magnitudes for the region as well as local sources; again, the meaning of the magnitude is not mentioned – it could be the local magnitude ML.

Table 2-1. SMPP Values used for the MS4 model used in 2008



Modèle	Source	Magnitude MSMS	Profondeur (km)
Régional	IRSN 14 Bourgogne – Morvan	6,1 ± 0,4	10 ± 5
	IRSN 15 Zone des failles est Vosges Epinal - Vesoul	7,0 ± 0,4	20 ± 5
	IRSN 18 Champagne Bassin de Paris	6,1 ± 0,4	12 ± 5
Local	IRSN 19 Vosges - lorraine	6,1 ± 0,4	12 ± 5

(Source: Référentiel du Site 2010 Tome 3, Tableau 28-4 (p. 83))

This points to the assumption of a local earthquake with magnitude 6.1 ± 0.4 at a depth of about 12 km. Under normal conditions such an earthquake would cause ground shaking of the intensity I > VIII at the epicenter using the simple rule-of-thumb formula, which applies at 10 kilometers depth:

$$I_0 = 1.5 M_L - 1.0\ (\pm 0.6) \quad or \quad M_L = 0.67 I_0 + 0.67_{+/-0.4}$$

Where M_L is the local (Richter) magnitude of an earthquake in a depth of 10 km, and

I_0 is the intensity at the epicenter.

More sophisticated discussions of this relation were already introduced by Gutenberg & Richter (1956) who developed empirical formulas, as well as by Ambraseys (1985) and Gutdeutsch et al. (2002), who discussed several details of the relationship between different magnitudes and intensity.

We note that Tome 3 also gives an SMPP magnitude of 5.2 +/- 0.2.[37] In the case of the smaller magnitude a focal depth of only 2 km is assumed which would cause a very strong vibration at the surface, especially because the distance is only 6 km. All this is not well discussed for its implications for design of the underground facilities and post-closure period evaluation.

---

[36] Référentiel du Site 2010 Tome 3, p. 85. Translated from the French.

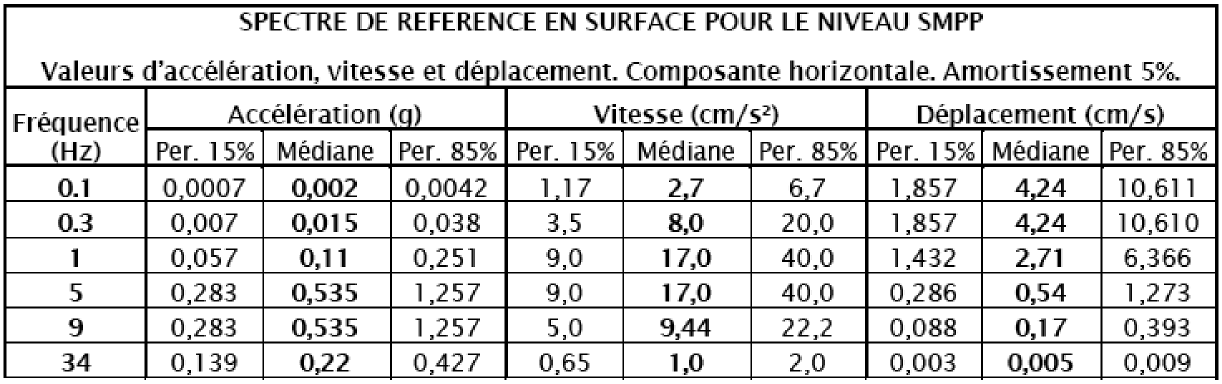
[37] Référentiel du Site 2010 Tome 3, Tableau 29-3 (p. 82)

2.2.5 Site response to earthquakes

To design site facilities, it is important to estimate the effect of the maximum earthquake which is physically possible, at the surface as well as at the underground level of the laboratory. For the operational period, Andra has derived an acceleration of 0.23g at 9 Hz frequency for the underground laboratory and most of the transposition zone.[38] This is presumably to be used in the design of the surface facilities.

The acceleration, velocity and displacement for SMPP earthquakes to be used for post closure design are much larger, as would be expected. The spectrum of the reference earthquake at the surface is given in Table 2-2, reproduced below, as well as for the acceleration as for velocity and displacement. As can be seen, the calculated effect between the frequencies 5 and 9 Hz is quite large: an acceleration of more than 1.25 g.

Table 2-2. Characteristics of SMPP reference spectrum on the surface, calculated for the site of the underground laboratory



SPECTRE DE REFERENCE EN SURFACE POUR LE NIVEAU SMPP

Valeurs d'accélération, vitesse et déplacement. Composante horizontale. Amortissement 5%.

Fréquence (Hz)	Accélération (g)			Vitesse (cm/s²)			Déplacement (cm/s)		
	Per. 15%	Médiane	Per. 85%	Per. 15%	Médiane	Per. 85%	Per. 15%	Médiane	Per. 85%
0.1	0,0007	**0,002**	0,0042	1,17	**2,7**	6,7	1,857	**4,24**	10,611
0.3	0,007	**0,015**	0,038	3,5	**8,0**	20,0	1,857	**4,24**	10,610
1	0,057	**0,11**	0,251	9,0	**17,0**	40,0	1,432	**2,71**	6,366
5	0,283	**0,535**	1,257	9,0	**17,0**	40,0	0,286	**0,54**	1,273
9	0,283	**0,535**	1,257	5,0	**9,44**	22,2	0,088	**0,17**	0,393
34	0,139	**0,22**	0,427	0,65	**1,0**	2,0	0,003	**0,005**	0,009

(Source: Référentiel du Site 2010 Tome 3, Tableau 29-4 (p. 103))

The spectrum for the site of the underground laboratory (see Table 2-3) shows similar properties; the maximum acceleration is reduced to a little more than 0.8 g, which is reasonable.

We note that there are mistakes that should not occur in an official technical report. First, in both tables[39] *the velocity is cited with the dimension cm/s² (instead of cm/s) and the displacement with cm/s (instead of simply cm).* Second, long periods correspond to low frequencies (and not to high frequencies), and vice versa. This error can be seen in the quote below:[40]

> T = 0s (acceleration at very low spectra frequencies),
> T = 0,2s (acceleration at peak Ŕ maximum – of the spectra),
> T = 0,5s (acceleration on the descending part of the spectra),
> T = 2s (acceleration at the highest frequencies of the spectra).

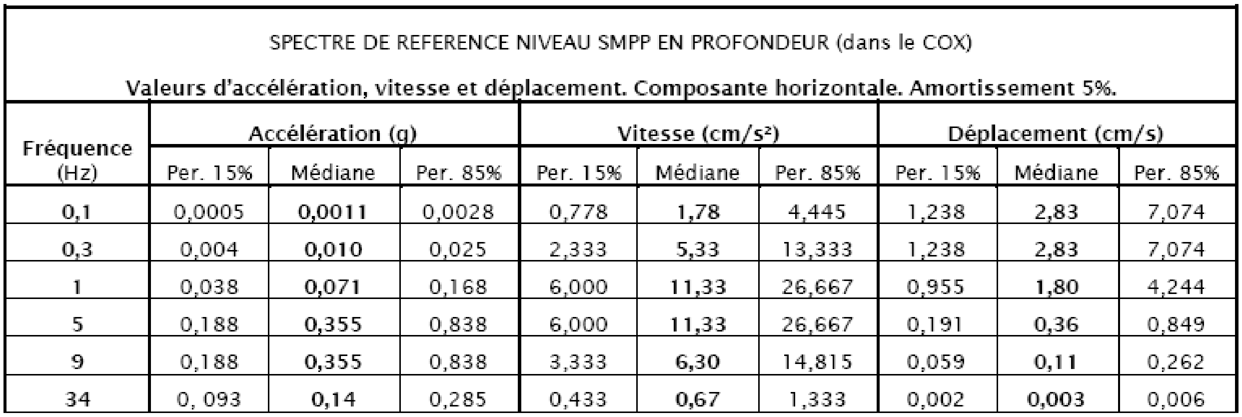
Table 2-3. Spectral features at depth in the host layer; postclosure period of storage, for the site of the underground laboratory.

---

[38] Référentiel du Site 2010 Tome 3, Tableau 29-1 and associated text pp. 94-95

[39] Référentiel du Site 2010 Tome 3, Tableaux 29-4 (p. 103) et 29-5 (p. 105)

[40] See, for example, Référentiel du Site 2010 Tome 3, p. 103. Translated from the French.



SPECTRE DE REFERENCE NIVEAU SMPP EN PROFONDEUR (dans le COX)

Valeurs d'accélération, vitesse et déplacement. Composante horizontale. Amortissement 5%.

Fréquence (Hz)	**Accélération (g)**			**Vitesse (cm/s²)**			**Déplacement (cm/s)**		
	Per. 15%	Médiane	Per. 85%	Per. 15%	Médiane	Per. 85%	Per. 15%	Médiane	Per. 85%
0,1	0,0005	**0,0011**	0,0028	0,778	**1,78**	4,445	1,238	**2,83**	7,074
0,3	0,004	**0,010**	0,025	2,333	**5,33**	13,333	1,238	**2,83**	7,074
1	0,038	**0,071**	0,168	6,000	**11,33**	26,667	0,955	**1,80**	4,244
5	0,188	**0,355**	0,838	6,000	**11,33**	26,667	0,191	**0,36**	0,849
9	0,188	**0,355**	0,838	3,333	**6,30**	14,815	0,059	**0,11**	0,262
34	0, 093	**0,14**	0,285	0,433	**0,67**	1,333	0,002	**0,003**	0,006

(Source: Référentiel du Site 2010 Tome 3, Tableau 29-5 (p. 105))

2.3 References

Ambraseys 1985	N. Ambraseys. "Intensity-attenuation and magnitude-intensity relationships for Northwest European earthquakes," *Earthquake Engineering and Structural Dynamics* 13 (1985): 733–778.
Andra Cartographie 2001	Andra. *Site Meuse/Haute-Marne: Cartographie géologique et structurale de l'environnement régional du site. Volume 1. Texte. Volume 2. Figures et planches hors texte. Volume 3. Fiches de sites micro tectoniques*. (D RP 0G2R 00-003/A) [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, Avril 2001. Running title: D RP 0G2R 00-003/A A1-2.
Andra Sismique	Andra. *Laboratoire de Recherche Souterrain Meuse / Haute-Marne, Lot 1 Sismique 3D, Rapport de Synthèse*. (B RP 0ANT 00-073/A) [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, 29 Janvier 2001. Figures in companion volume.
Andra Site Est 1998	Andra. *Site Est: Actualisation de l'analyse sismotectonique, zonage et evaluation de l'aléa sismique regional sur le Site de l'Est de la France*. (D RP 0ANT 98-044/A). [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, Décembre 1998.
Andra Sûreté 2010	Andra. *Options de sûreté du stockage en formation géologique profonde*. (C.NT.ASSN.09.0029.B) [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, 26 Février 2010. Running title: JALON 2009 HA-MAVL.
Andra ZT 2009	Andra. *Synthèse du programme de reconnaissance de la zone de transposition 2007-2008: Centre de Meuse/Haute-Marne*. (D.RP.ALS.08.1356.B) [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, 21 Juillet 2009. Running title: JALON 2009 HA-MAVL.
Dossier 2001 Argile	Andra. *Dossier 2001 Argile sur l'avancement des études & recherché relatives à la faisabilité d'un stockage de déchets à haute activité et à vie longue en formation géologique profonde - Rapport de synthèse*. [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, Décembre 2001. Running title: *Dossier de synthèse 2001*. Includes both Partie A and B.
Dossier 2005 Argile, Synthesis	Andra. *Dossier 2005 Argile: Synthesis: Evaluation of the feasibility of a geological repository in an argillaceous formation, Meuse/Haute-Marne site*. 2nd ed. (Report Series) (266 VA) [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, December 2005. On the Web at http://www.andra.fr/download/andra-international-en/document/editions/266va.pdf
Giardini et al. 2004	Domenico Giardini, Stefan Wiemer, Donat Fäh and Nicolas Deichmann, et al. *Seismic Hazard Assessment of Switzerland, 2004*. Vers. 1.1. Zürich: Swiss Seismological Service, ETH Zurich, November 25, 2004. On the Web at http://www.seismoatschool.ethz.ch/Hazard_report_2004.pdf.

Gutdeutsch, Kaiser, and Jentzsch 2002	Rolf Gutdeutsch, Diethelm Kaiser, and Gerhard Jentzsch. “Estimation of earthquake magnitudes from epicentral intensities and other focal parameters in Central and Southern Europe,” *Geophysical Journal International* 151(3) (2002): 824-834.
Gutenberg and Richter 1956	B. Gutenberg and C.F. Richter. “Earthquake magnitude, intensity, energy, and acceleration (Second Paper), *Bulletin of the Seismological Society of America* 46 (1956): 105-145.
Référentiel du Site 2010	Andra. *Référentiel du Site Meuse/Haute-Marne*. (C.RP.ADS.A09.0007.B) [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, 29 Janvier 2010. Running title: Jalon 2009 HA-MAVL. “Document interne.”

Chapter 3: Characteristics and properties of the host and surrounding formations in the Transposition Zone affecting the contaminant transport in geologic media and long-term repository performance

Strengths

1. Experimental and in situ research: Extensive research was conducted by Andra in laboratory conditions and in situ to characterize the geologic media within the Transposition Zone. A number of experiments conducted to obtain the transport properties of argillites required state of the art techniques to overcome the difficulties related to the low permeability, high sorption capacity, anionic exclusion, and other argillite specific factors.

2. Use of complementary data: The experience and the data acquired at similar clay sites were used to complement and corroborate the experimental data obtained for the Callovo-Oxfordian argillites. This effort resulted in an outstanding collection of the site-specific data documented in *Dossier 2005 Argile, Référentiel du Site 2010,* and numerous reports and journal articles.

Findings

1. Use of data in the conceptual model: Most of the issues and concerns are related to the way the existing data were used to justify the conceptual model of the site, to model the transport processes in the Callovo-Oxfordian formation, and to perform the safety analysis. The applicability of the models and approaches used by Andra and their transferability to the ZIRA can be only demonstrated by including the actual variability of the argillite properties in the process models and by performing a probabilistic safety analysis using the observed distribution of the transport parameters. Andra has not performed such an analysis.

2. Heterogeneity in the Callovo-Oxfordian formation: The existing data show great horizontal and vertical variability in the mineralogical composition and pore water composition of the Callovo-Oxfordian formation in the Transposition Zone. This variability results in noticeable differences in the transport properties, such as total porosity, kinematic porosity, anion accessible porosity, effective diffusion coefficients of cations and anions, and permeability of the argillites at the different locations and depths. The permeability and diffusion also exhibit anisotropy. The transport properties may also be affected by the micro-fractures discovered in the upper sequence of the Callovo-Oxfordian formation. Despite the heterogeneity, Andra relies on the homogeneity and isotropy of the Callovo-Oxfordian formation in their evaluations of the long-term repository performance.

3. Heterogeneity within the ZIRA: Two noticeably different areas were identified in the north-east and south-west of the Transposition Zone with the ZIRA located in between these two areas. This indicates heterogeneity within the ZIRA.

4. Inadequate evaluation of parameter variability: Andra uses average transport properties in the normal evolution scenario and minimum or maximum values in the sensitivity analyses. The average parameters may not represent the effective properties of the heterogeneous and anisotropic argillites. In the sensitivity studies only one parameter was changed while the other parameters were fixed at their average values. The situation in which multiple parameters would be set to their minimum or maximum (or 95th percentile) values was not considered. As a result the potential impacts of the parameter variability were not evaluated.

5. Average transport parameters: The average transport parameters used by Andra were derived for the overall Transposition Zone. The average (and effective) transport parameters may be different if only the ZIRA is considered. In particular, the diffusion coefficients and the vertical hydraulic conductivity might be higher and this may lead to the higher average rates of the diffusional and advective transport. Further, the effect of the heterogeneity in the ZIRA on transport remains to be determined.

6. Diffusive and Advective transport: The existing data (particularly, the natural tracer data) provide evidence of advective transport through the Callovo-Oxfordian argillites. Andra assumes that diffusive transport will dominate flow even though the data and an analysis of Peclet numbers indicates that both diffusive and advective transport may occur with significant probability. This presents a great concern because the advective transport in Andra estimates of the argillite retention properties is either not considered (normal evolution scenario) or greatly underestimated (sensitivity studies).

7. Inadequate evaluation of uncertainties: A simplified probabilistic safety analysis performed with the parameter ranges consistent with the ones defined by Andra indicates that these uncertainties in the input parameters result in the uncertainty in the total maximum dose of 5 orders of magnitude. The potential range in the total maximum dose defined by Andra as one order of magnitude (or 2 times when the proposed repository is located at the URL site) might be underestimated.

Recommendations

1. Andra should reevaluate its assumption of predominantly diffusive flow by taking better account of tracer data and by estimating a range of Peclet number values (instead of a single value) based on the variation in parameters.

2. It is essential for Andra to determine the nature of the heterogeneity in the ZIRA indicated by data from boreholes that are on the perimeter of the ZIRA.

3. Andra has stated that it will review the scenarios is Dossier 2005 Argile as well as the parameters used in performance assessment. Andra should perform a probabilistic risk assessment using the full range of parameter values indicated by the data, rather than just a limit sensitivity analysis. It would be highly desirable to have a source term that accurately represents in total quantity and type total wastes that would actually be disposed of if the repository is licensed. Failing that, a penalizing assumption should be made, for the source term, including appropriate assumptions about potential spent fuel disposal that updates the S2 scenario used in Dossier 2005 Argile.

4. Andra should conduct an extensive external review of its safety evaluation analysis, including software, input data, and methodology.

3.1 Introduction

Extensive research was performed by Andra and by other organizations in cooperation with Andra in the Bure Underground Research Laboratory (URL) and on the site to define the characteristics and properties of the host and surrounding formations within the Transposition Zone (TZ) and to characterize the associated variabilities and uncertainties. The major results of this research, based on all the work done up to March of 2009, are documented in *Référentiel du Site 2010*. The details of the specific studies are presented in a number of scientific reports and publications referenced in the *Référentiel du Site 2010*.

The characteristics and properties of the host and surrounding formations were used to develop a base case (or normal evolution scenario) conceptual model of the geologic media within the Transposition Zone.[41] Alternative (or altered) conceptual models were also developed to incorporate the conceptual uncertainties not represented in the normal evolution scenario. The base case conceptual model provided a basis for a number of the models simulating the transport of contaminants in the different repository compartments and in the geologic media. It also provided a basis for the long-term safety-assessment.

The conclusions about the repository suitability and robustness versus the objective of long-term confinement of the radioactive waste with respect to the biosphere made by Andra in *Dossier 2005 Argile* are largely based on the integration of scientific knowledge and the management of uncertainties related to the characteristics and properties of the host and surrounding formations. These conclusions, as well as surface considerations, led to the selection of the zone of interest for the future site characterization (la Zone d'intérêt pour la recherche approfondie or ZIRA).

Selecting the ZIRA implies that the variability and uncertainties associated with the processes and parameters within the Transposition Zone were adequately characterized and addressed in the process models and safety analysis. *Dossier 2005 Argile*, *Référentiel du Site 2010*, and a number of the related publications were reviewed to evaluate these conclusions. The results of this independent evaluation are presented in the following discussion.

Note that due to the short time frame and budget constraints only the issues that were believed to have the greatest radiological impacts were reviewed. This includes the analysis of the transport properties of the Callovo-Oxfordian formation, normal evolution scenario, and safety assessment methodology.

The following issues of less importance were either not reviewed or had a limited review:

- Sorption properties of non-conservative radionuclides and toxic contaminants.
- The transport properties of the adjacently formations.
- Flow models of the adjacent carbonate formations.
- Exposure parameters.
- Altered scenarios.

---

[41] Dossier 2005 Argile, Safety Evaluation

3.2 Characterization of Geologic Media in the Transposition Zone

Two types of geologic media can be defined with regard to the repository design and performance. The first type represents the host geologic medium and the second type represents the adjacent media.

The host medium is the geologic formation that contains the repository and represents the major geologic barrier. This medium plays an essential role in the long-term repository performance. As stated in *Dossier 2005 Argile*: "*While the barriers in the confinement system play complementary roles, the geological barrier is assigned an essential role especially in the long term*."[42] The role of the geologic barrier in designing a deep repository is in "*preventing the dissemination of radionuclides contained in the waste, or slowing it down to a minimum (no water flow, reducing environment).*"[43] Consequently, the major goal of the host rock characterization is to define its ability to retain the radionuclides and toxic contaminants. As it is specified in *Dossier 2005 Argile*, "*these properties must be appraised accurately and guaranteed over very long time scales (from one thousand years to several hundred thousand years).*"[44]

The adjacent media include the pathways that connect the contaminant fluxes exiting the host rock with the points at which the exposure to a member of the critical group occurs. The role of these media is in delaying and dispersing the contaminants and not in retaining them. The characterization of their properties has to be sufficient to define these capabilities.

The important processes and properties of the host rock are the ones that significantly affect the time of contaminant arrival at the formation boundaries (top and bottom), the maximum contaminant flux, and the total mass over a 1,000,000 year period. These criteria are used by Andra as supplemental indicators. Similarly, the processes and properties of the adjacent formations affect the contaminant concentrations in the exposure points. Therefore, it is essential to review Andra's performance assessment to evaluate whether the properties that it ascribes to the ZIRA and its approach to modeling of the geologic barrier is sufficient to demonstrate that radiation protection norms will be met.

The role of the geologic medium processes and properties in the long-term repository performance can be only evaluated based on the safety analysis in which the uncertainties in the host and adjacent formations parameters are properly incorporated. The important parameters are the ones that have the greatest impacts on the uncertainty in the performance measure (dose). Consequently, the adequate characterization of the spatial and temporal variability and uncertainties is one of the main goals of the parameter characterization.

The discussion of the processes and parameters related to the geologic media in the Transposition Zone and ZIRA is provided below for the host formation (Section 3.2.1) and adjacent formations (Section 3.2.2). The discussion of how these parameters affect the transport in the geologic media and the long-term repository performance is provided in Section 3.2.3.

---

[42] Dossier 2005 Argile, Synthesis p. 56

[43] Dossier 2005 Argile, Synthesis p. 56

[44] Dossier 2005 Argile, Synthesis p. 56

3.2.1 Host Rock of the Callovo-Oxfordian Formation

Andra description of the Callovo-Oxfordian formation in the Transposition Zone is as follows:

> *…a homogeneous, hardly permeable stratum with its top located at a depth varying from 420 metres (corresponding to the laboratory site) to more than 600 metres in the direction of the dip and its thickness also progressively varying from 130 metres to the South to 160 metres to the North of the zone*".[45]

Andra considers the host rock of the Callovo-Oxfordian formation as "*an essential component of the system, to the extent that it contributes to all of the functions that have been defined.*"[46.] The safety functions referred to in this statement are the following:

- preventing water circulation
- limiting the release of radionuclides and immobilizing them in the repository
- delaying and attenuating the migration of radionuclides

Preventing water circulation function *"is provided by the choice of a rock, the Callovo-Oxfordian, which has very low permeability, is homogeneous enough, and which also has very low internal hydraulic gradients*."[47] This also implies that there are no conductive fractures and/or faults that may represent fast paths for advective flow. "*The general contention that fractures in argillaceous media are infrequent and/or hydraulically insignificant is one of the main arguments for considering these rocks for waste isolation*."[48]

Limiting the release rate of radionuclides function is provided "*by imposing favorable physico-chemical conditions. The rock helps to maintain a pH close to neutrality and reducing conditions that are suitable for the control of releases, especially for vitrified wastes. The solubility of many elements is low under such conditions. Its low porosity also helps limit the risks of colloidal transport*."[49]

Delaying and attenuating the migration of radionuclides function is provided by*)* "*low diffusion rates, and the high sorption capacities of the argillites.*"[50]

Andra's conclusion about the Callovo-Oxfordian formation is as follows:

> *The function analysis conducted shows that the Callovo-Oxfordian is a particularly important component, whose characteristics ensure a good level of safety function performances, even in the event of mediocre operation of other*

---

[45] Dossier 2005 Argile, Safety Evaluation p. 79
[46] Dossier 2005 Argile, Safety Evaluation p. 649 (in Section 8.1.1)
[47] Dossier 2005 Argile, Safety Evaluation p. 127
[48] Mazurek et al. 2008 p. S101
[49] Dossier 2005 Argile, Safety Evaluation p. 649
[50] Dossier 2005 Argile, Safety Evaluation p. 649

> *components (defective containers, inefficient seals) or even of degraded properties of the geological medium itself.*[51]

In summary, in their evaluation of the host rock Andra specifically relies on the following properties of the Callovo-Oxfordian formation:

- Homogeneity (including absence of conductive fractures and faults)
- Low permeability
- Low hydraulic gradient
- Low effective diffusion
- High radionuclide absorption

Based on the research conducted in the Underground Laboratory and in the Transposition Zone the following conclusions are made by Andra regarding these major properties:

- *"[t]he rock's properties are now well-known because of a major characterization program in bore-holes and in the laboratory"*
- *"the main properties do not have an uncertainty margin of more than a factor of 10."*[52]

Andra's conclusions about host rock properties important to performance are as follows:

(1) "T*he transport of solutes in the Callovo-Oxfordian layer takes place mostly by diffusion.*"[53] This conclusion was further supported by modeling, based on which Andra stated that "*the diffusive and advective flow calculations, taken from results of numerical simulations, confirms this dominance of diffusive flow, to almost two orders of magnitude.*"[54] These modeling results were considered by Andra as bounding (conservative) because they were obtained with a conservative hydraulic gradient, which is "*an ascending, maximum, vertical hydraulic gradient corresponding to a specific location in the transposition zone and to the one million-year Hydrogeological model (0.4 m/m*)."[55] Note that the other modeling parameters affecting transport in the host formation were specified at their expected (not conservative) values.

(2) *"Four elements (iodine^{129}, chlorine^{36}, selenium^{79} and calcium^{41}) still present a flow at the top of the Callovo-Oxfordian. However, calcium^{41} and selenium ^{79} are already very strongly attenuated.*"[56] This conclusion is based on modeling 15 elements (^{129}I, ^{107}Pd, ^{135}Cs, ^{10}Be, ^{93}Zr (^{93}Nb), ^{36}Cl, ^{99}Tc, ^{41}Ca, ^{126}Sn, ^{59}Ni, ^{79}Se, ^{94}Nb, ^{14}C, ^{93}Mo, and ^{166}Ho) "*with a half-life of more than 1000 years and presenting, a priori, the most penalising behaviours.*"[57] Complementary analyses (transport calculations) conducted by Andra "*have shown that radionuclides not selected do not effectively contribute to the impact.*"[58]

---

[51] Dossier 2005 Argile, Safety Evaluation p. 264
[52] Dossier 2005 Argile, Safety Evaluation p. 649
[53] Dossier 2005 Argile, Synthesis p. 175
[54] Dossier 2005 Argile, Safety Evaluation p. 267
[55] Dossier 2005 Argile, Safety Evaluation p. 267
[56] Dossier 2005 Argile, Synthesis p. 212
[57] Dossier 2005 Argile, Synthesis p. 197
[58] Dossier 2005 Argile, Synthesis p. 197

(3) *"For the toxic chemicals associated with the waste and with the repository components, a few chemical elements, seeming the most significant ones, were considered: boron, nickel, antimony and selenium."*[59]

The review of the host rock transport properties is provided in Section 3.2.1.1.

3.2.1.1 Review of the Host Rock Transport Properties

3.2.1.1.1 Absence of Conductive Fractures and Faults

Realizing the great potential impacts of fault and fractures on the hydrogeologic properties of the host rock, Andra has conducted extensive geophysical studies complemented by observations in the boreholes and shafts within the Transposition Zone. Andra made the following conclusions based on these studies:

> "*To date, no fault has been identified in the Callovo-Oxfordian and its surrounding formations over an area of 250 km^2 towards north and north-west of the laboratory. The only known faults are located outside of that area, the Marne faults (NNW direction) and the Gondrecourt graben (NE direction) which form the sector boundaries towards west, south and east*."[60]
>
> "*The presence of vertical faults with a throw greater than a few metres has been ruled out as a result of geological mapping and seismic-reflection campaigns (2-metre detection threshold using 3D seismic imaging fine processing techniques). Smaller faults, referred to as secondary ones, where they exist, are limited in terms of extension (a few hundred metres extension maximum)*."[61]

Based on these conclusions the possibility of a fast radionuclide transport with the advective flow along the faults and fractures in the Callovo-Oxfordian formation is not considered either in the base case scenario or alternative scenarios. While there is some basis for this in research in the underground laboratory, there is some uncertainty as to how it might impact a repository located within the ZIRA.

There are two concerns related to these conclusions based on the studies reported in *Référentiel du Site 2010.*

The first concern is related to the faults uncovered by the recent 2007-2008 2D seismic studies in the north and north-west part of the Transposition Zone and in vicinity of its western boundary. The extent of these faults is on the order of a few kilometers with the vertical throw of up to 20 m in the deep part. As it was pointed out in *Référentiel du Site 2010*, the orientation of these faults was hard to define because in many cases a fault would only be identified based on a single seismic profile.[62] The locations of the new faults are shown in the *Figures 3-1* and 3-2 reproduced from *Référentiel du Site 2010*. A portion of one of these faults is located in the

---

[59] Dossier 2005 Argile, Synthesis p. 197

[60] Dossier 2005 Argile, Synthesis p. 88

[61] Dossier 2005 Argile, Synthesis p. 88

[62] Référentiel du Site 2010, Tome 1 Section 9.2.6 (p. 210)

ZIRA.[63] Note that the vertical cross section for this fault is not provided. The potential impact of these faults on the host rock properties within the Transposition Zone and ZIRA were not considered in *Référentiel du Site 2010.* During a meeting at Bure on 16 February 2011 to discuss the findings of the IEER team, Andra informed IEER that the fault that is partly located in the ZIRA is in the Dogger formation, well below the Callovo-Oxfordian and provided the publication to IEER.[64] As a result, the concern raised by IEER during the presentation of the report to the CLIS on 14 February 2011 has been addressed.

---

[63] The ZIRA is not shown in the figure, but we checked by overlaying maps that this is the case.

[64] Andra Campagne Sisimique 2008, Figure 3.5 (pdf p. 46)

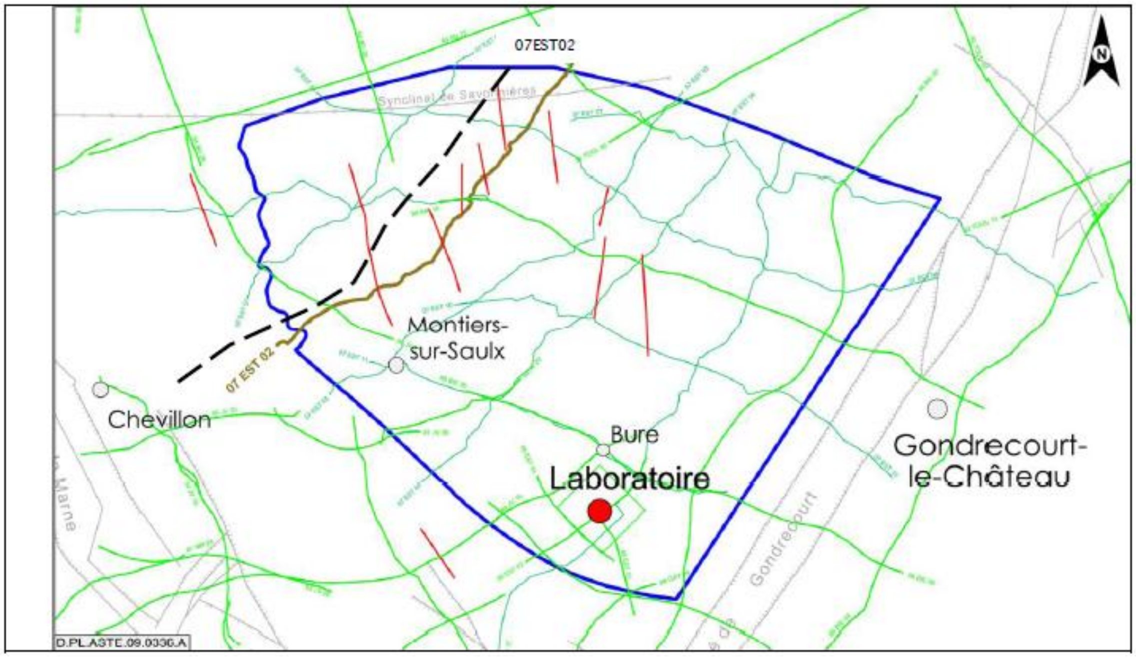


Figure 3-1 Location of Faults Uncovered by the Recent (2007-2008) 2D Seismic Studies (Source: Référentiel du Site 2010, Tome 1 Figure 9-14 (p. 212))

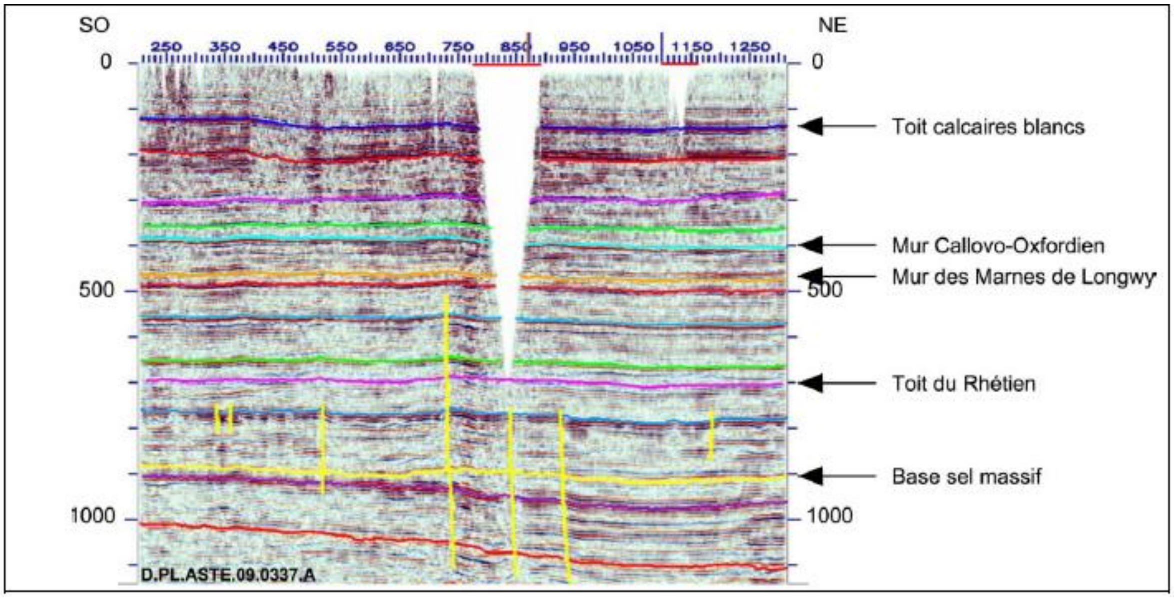


Figure 3-2 Geometry of the Deep Faults Located along the Seismic Profile 07EST02 (the location of this profile is shown in Figure 3-1) (Source: Référentiel du Site 2010, Tome 1 Figure 9-15 (p. 212))

The second concern is related to the microfractures observed in the boreholes EST211, EST207, EST209, and EST361 and in the main and auxiliary shafts. These microfractures are believed to be pressure fractures.[65] The microfractures had an extent in the order of a few meters or smaller and were subvertical.

---

[65] Référentiel du Site 2010, Tome 1 Section 9.4.3.2 (pp. 226-228)

The frequency of fractures is higher in the borehole EST211 than in the other boreholes. However, the microfractures were observed within the same depth interval in all the boreholes and shafts. This suggests[66] that the microfractured layer may have an extent on the order of tens meters to a few kilometers.

Most of the joints were discovered in the upper argillite sequence with the most carbonate content. As it is suggested by Andra, there is a positive correlation between the number of fractures and the carbonate content. The distribution of fractures is shown in the Figure 3-3 reproduced from *Référentiel du Site 2010*:[67]

> *The identified structures correspond mainly to joints, tension joints, and a few sub-vertical stylolitic joints. The two, metric to sub-metric, normal play microfaults, observed at a depth of about 451 meters are probably due to compaction and did not affect the geometry of the sedimentary units.*
>
> *Moreover, the observed joints are present in the upper Callovian-Oxfordian horizons which contain the most carbonate, suggesting a relationship between the frequency of fracturing and clay content (Figure 9-27) [i.e., Figure 3-3]. A layer of tension joints, filled with calcite is observed at the same depths in the EST211 and EST361 boreholes, it is found again in the main and auxiliary shafts (434-440 meters). Thus, it is likely that the diametric spacing between the few existing structures near the carbonated wall rocks, becomes progressively hectometric to kilometric in the more argillaceous formation.*[68]

Andra stresses that the major conceptual uncertainty related to fractures is in quantifying the proportion of open fractures and fractures filled with calcite:

> *…the main uncertainty arises from the distinction between fractures that are really open from those that are filled with calcite.* [69]

Andra did not develop a conceptual representation of the microfractured layer either within the Transposition Zone or ZIRA. In fact, Andra points out that it is difficult to quantify the frequency of these fractures and assumes that they have no impact of the host rock properties:

> *Therefore, it is difficult to quantify the spacing between the microfractures. One can assume that it is on the order of 100 meters or more without consequences on the properties of the argillite formation of the Callovo-Oxfordian,* [70]

There appears to be a basis for assuming that these microfractures would not have signficant effects on performance. During the 16 February meeting with IEER, Andra stated that it had

---

[66] Referentiel du Site 2010, Tome 1 Section 9.4.3.2 (pp. 226-228)

[67] Référentiel du Site 2010, Tome 1 p. 228

[68] Référentiel du Site 2010, Tome 1, p. 228. Translated from the French.

[69] Référentiel du Site 2010, Tome 1 p. 239 in Section 9.5.2. Translated from the French.

[70] Référentiel du Site 2010, Tome 1 p. 242 in Section 9.5.3. Translated from the French.

found that all microfractures were plugged. If this is turns out to be the case in the ZIRA as well, then the concern about the spacing of the microfractures would be alleviated.

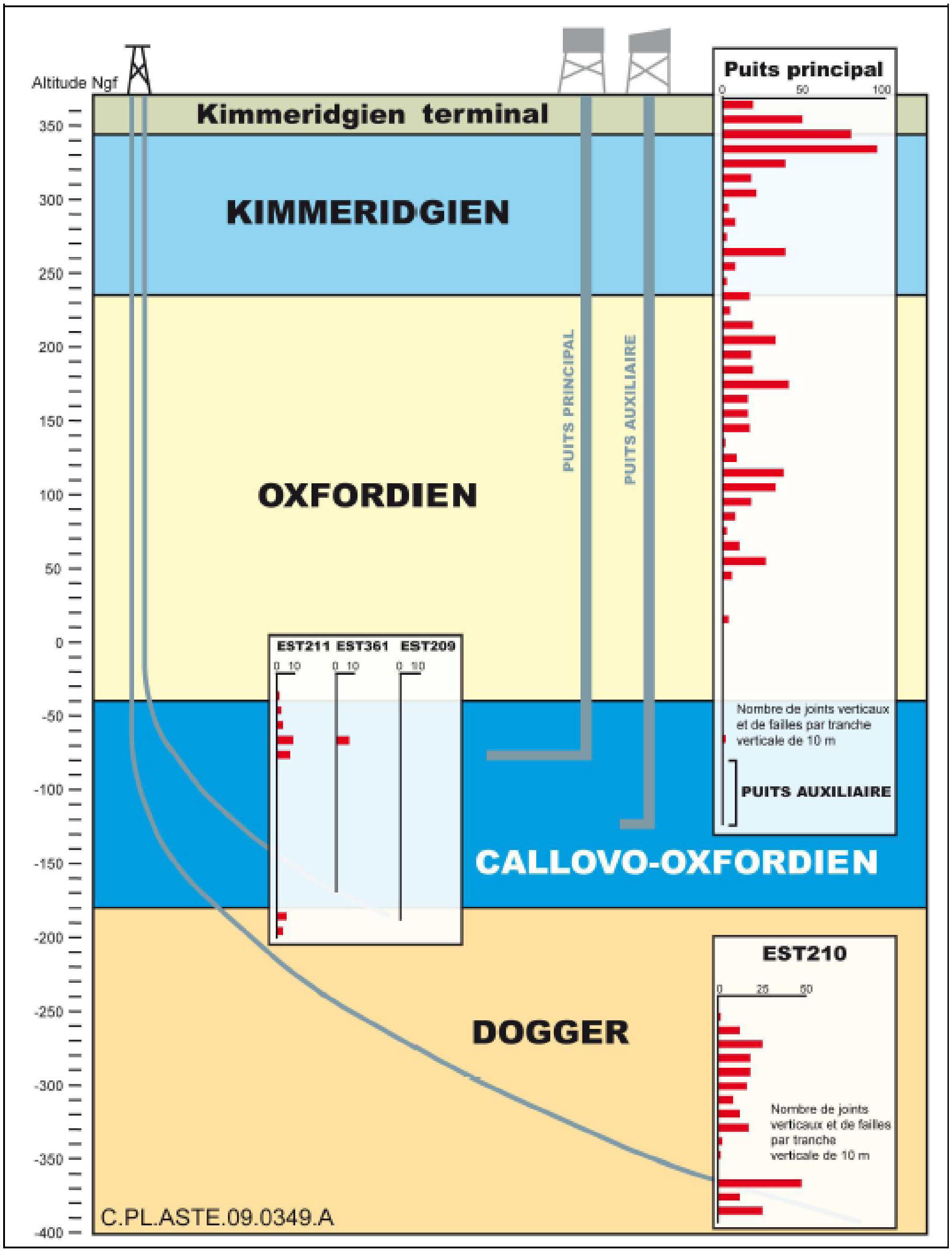


Figure 3-3. Fracture Frequency in the Boreholes and Shafts (Source: Référentiel du Site 2010, Tome 1, Tome 1 Figure 9-27 (p. 230))

3.2.1.1.2 Homogeneity

As discussed above, the host formation is assumed to be homogeneous. This assumption extends to the chemical composition of the interstitial water, which "*is considered homogeneous over the* [Callovo-Oxfordian] *formation's entire thickness, in consistency with its global lithological* *homogeneity*."[71] Based on this, Andra assumes that the formation's transport properties are homogeneous as well.

> *The « expected » variability is covered by representing the host formation as a homogeneous and uniform medium, and by the definition of intervals of variation (definition of a « phenomenological » and a « conservative » value) for all the parameters included in the SEN [Normal Evolution Scenario].When a sufficient number of measurements exist, the « phenomenological » value is used as a reference and the « conservative » value is used in sensitivity analyses ; if not, the conservative value is taken into account.*[72]

Andra used the expected (or nominal) values of the corresponding parameters in the normal evolution scenario and performed a few sensitivity analyses.

> *In order to complete the development of the normal evolution scenario, other calculations are also performed; namely sensitivity analyses conducted on the safety model to test parameter sets or models different from those selected as most representative. The approach may consist of selecting extreme values for certain parameters, corresponding to highly penalising situations, or also more favourable values.*[73]

The parameters considered in the sensitivity analyses are summarized in Table 5.5-17.[74] The hydraulic conductivity of the Callovo-Oxfordian formation considered in the sensitivity analysis was only one order of magnitude higher than in the nominal scenario. Note that this parameter defines the rate of transport (this is especially significant for non sorbing radionuclides) through the argillites.

Multiple lines of evidence contradict Andra's assumption of homogeneity and suggest that the host formation is heterogeneous in vertical cross section and laterally within the Transposition Zone and the ZIRA. Both, mineralogical composition and pore water composition change vertically and horizontally. These two characteristics affect the argillite transport properties such as porosity, permeability, diffusion, and sorption.

Extensive research has been done to date to study the properties of argillous formations. One important conclusion based on these studies is that "[*i*]*n argillaceous formations, the microscopic structure governs many macroscopic properties, including, among others, transport and geomechanical properties.*"[75] Consequently, "*good knowledge of mineralogy, of diagenetic evolution and of tectonic, burial and thermal history is essential for the assessment of transferability.*"[76]

The heterogeneity in mineralogical composition and pore water composition is discussed below. The resulting heterogeneity in the transport properties is described in the following sections.

---

[71] Dossier 2005 Argile, Safety Evaluation Section 2.2.2.4 (p. 82)
[72] Dossier 2005 Argile, Safety Evaluation Section 6.2.1.1 (p. 363)
[73] Dossier 2005 Argile, Synthesis p. 192
[74] Dossier 2005 Argile, Safety Evaluation p. 305
[75] Mazurek et al. 2008 p. S97
[76] Mazurek et al. 2008 p. S98

Mineralogical Composition

A detailed site-specific analysis of the mineralogical composition of the Callovo-Oxfordian argillites considered in a context of sedimentary and paleo-geographic history of the area is provided in *Section 10* of the *Référentiel du Site 2010*. This analysis provides both a description of the vertical and horizontal heterogeneity of the Callovo-Oxfordian formation and discusses the main reasons that caused it. The important conclusion based on this analysis is summarized below.

The mineralogical composition of the Callovo-Oxfordian formation is heterogeneous in vertical cross section. The following description of this heterogeneity is provided in *Dossier 2005 Argile*:

> *Vertically, the proportions of the main mineralogical phases vary and are structured into three sedimentary sequences. The upper sequence is characterized by higher carbonate content.*[77]

The thickness of the upper sequence in the Transposition Zone[78] increases from north-east (8 m) to south-west (20 m). The thickness of the middle sequence in the Transposition Zone[79] decreases from north-east (110 m) to south-west (70 m). The thickness of the lower sequence in the Transposition Zone[80] decreases from north (48 m) to south-west (32 m).

The mineralogical composition of the three sequences based on the samples from the different depth intervals in the different boreholes is presented in Figure 3-4 below. As can be seen from this figure the mineralogical composition has substantial variability within all three sequences both, vertically (different depth intervals in a borehole) and laterally (different boreholes).

The statement made in *Référentiel du Site 2010* acknowledges noticeable mineralogical variability only in the upper section and the lateral trend indicating enrichment in carbonates. Also acknowledged is the elevated content in clay in the middle sequence in the north-eastern part of the transposition zone.

However, in contrast to the variability in the middle and lower sequences that can clearly be seen in Figure 3-4 above, the variability of the mineralogical composition of the middle and lower sequences is described as small:[81]

> *The superposition of the mineralogical compositions of the EST413, EST423, and EST441 boreholes on those of previous boreholes clearly shows the small mineralogical variability for the middle and lower layers. For the upper layer, the observed spreading on the ternary diagram illustrate the carbonate enrichment and the alternation between marl and limestones (Figure 10-27)* [i.e., Figure 3-4]"

---

[77] Dossier 2005 Argile, Safety Evaluation p. 79
[78] Référentiel du Site 2010, Tome 1 Figure 10-9 (p. 269)
[79] Référentiel du Site 2010, Tome 1 Figure 10-8 (p. 268)
[80] Référentiel du Site 2010, Tome 1 Figure 10-4 (p. 264)
[81] Référentiel du Site 2010, Tome 1 p. 291

and

During the acceleration phase of the sea level drop of the middle layer, the logs show a more rigid behavior in the boreholes in the North East of the transposition zone, to be attributed to the higher silt content.[82]

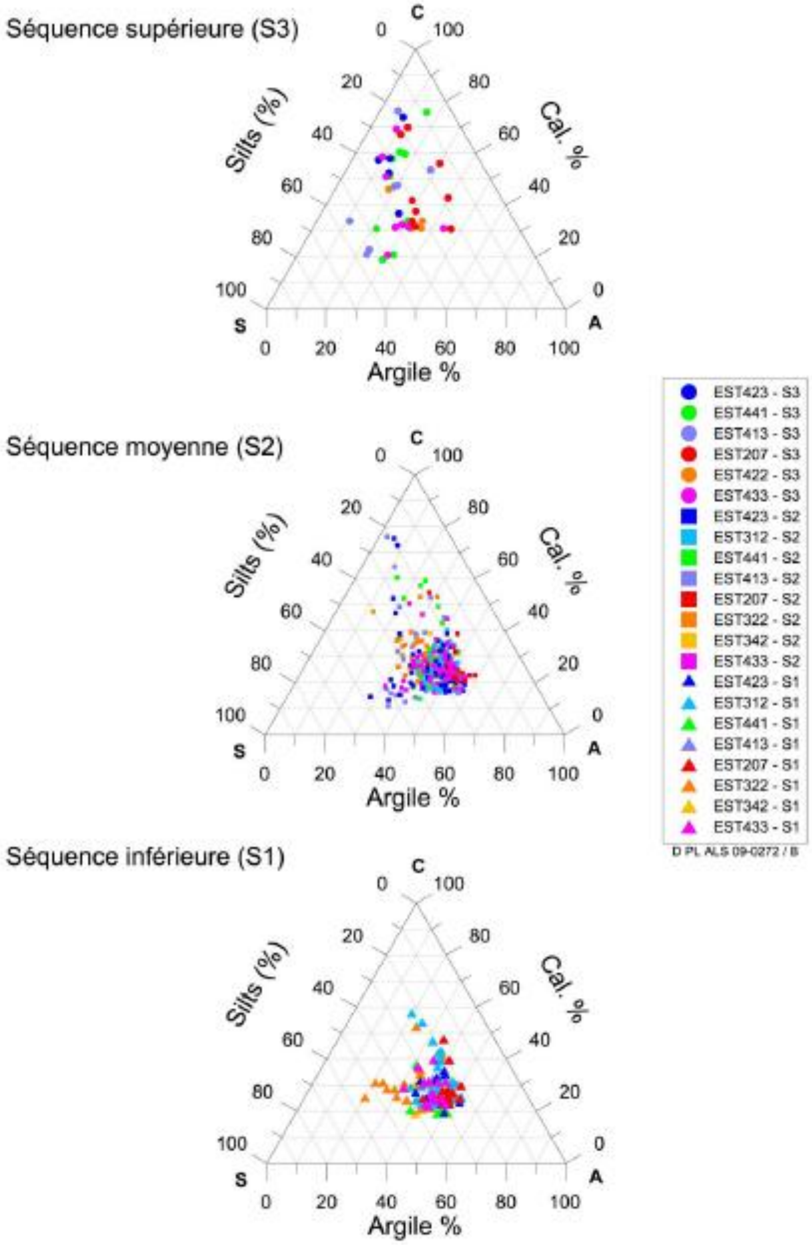


Figure 3-4. Mineral Composition of Three Lithological Sequences of the Callovo-Oxfordian Formation (based on the borehole logs) (Source: Référentiel du Site 2010, Tome 1Figure 10-27 (p. 294))
NOTE: S1, S2, and S3 are lower, middle, and upper sequences respectively.

---

[82] Référentiel du Site 2010, Tome 1 p. 270 in Section 10.1.1.4. Translated from the French.

Andra explains the mineralogical variability by a combination of two factors (besides the variations in depositional facies): (1) possible existence of the sedimentary gaps related to the changes in paleo-geographic depositional conditions and (2) to the development of the local depressions due to the lateral variations in tectonic displacements.[83]

Finally, Figure 3-5, reproduced below, demonstrates the vertical and horizontal heterogeneity of the Callovo-Oxfordian formation as a function of the different sedimentary facies within the Transposition Zone.

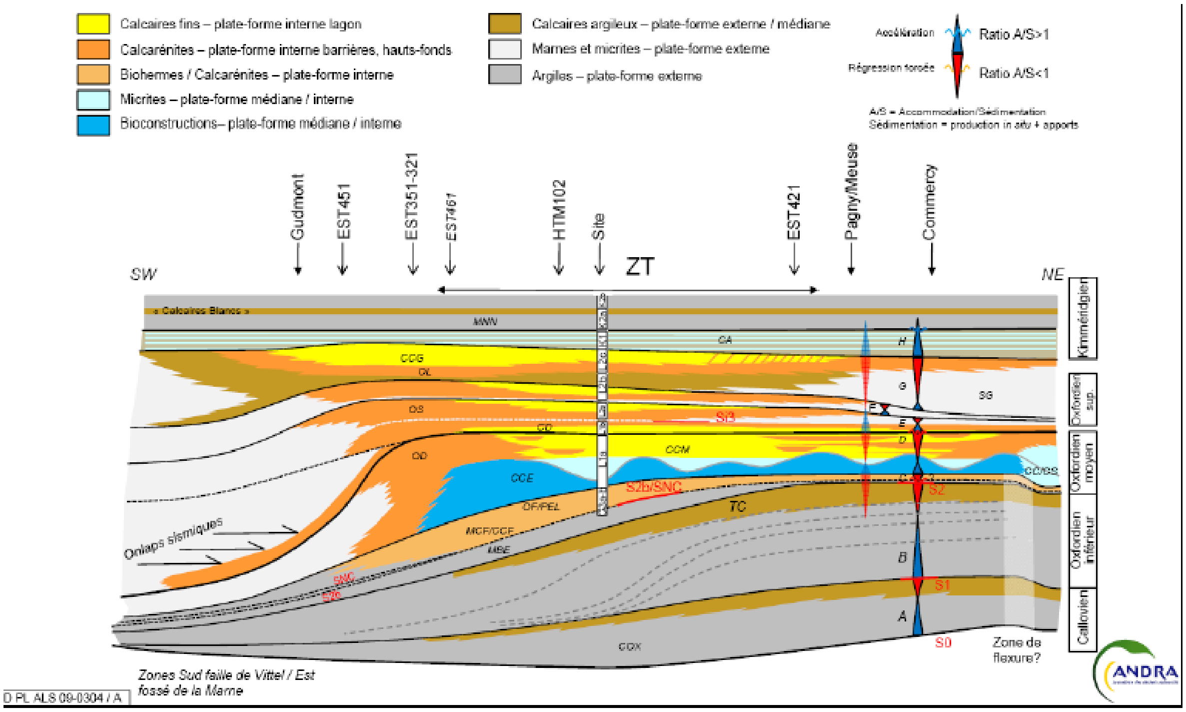


Figure 3-5. Stratigraphic Model of the Callovo-Oxfordian and Oxfordian Formations. (Source: Référentiel du Site 2010, Tome 1 Figure 10-40 (p. 314))

Pore Water Composition

The geochemical characteristics of pore water in the Callovo-Oxfordian formation are considered in detail in *Chapter 13* of the *Référentiel du Site 2010.* This chapter also discusses a geochemical model developed to simulate the pore water composition. The important conclusions based on this analysis are summarized below.

The original marine water contained in the pore space of the Callovo-Oxfordian argillites was substantially replaced by the infiltration water.[84] This process has gradually changed the original pore water composition and resulted in the composition currently observed at the site.

The chloride concentrations change significantly within the Transposition Zone. Figure 3-6 shows that the chloride concentrations are significantly higher in the boreholes located in the

---

[83] Référentiel du Site 2010, Tome 1 p. 270 in Section 10.1.1.4
[84] Référentiel du Site 2010, Tome 1 p. 462 in Section 13.3.1

north-east part of the Transposition Zone (boreholes EST312, EST413, and EST423) than in the boreholes located in the west and south-west part (boreholes EST443, EST433, and EST207/209).[85]

Also, as can be seen from Table 3-1, the porosity accessible to chloride is 2 times smaller in EST423 than the mean value. The difference in chloride concentrations within the Transposition Zone results in the related difference in the ionic strength. The ionic strength changes from 0.17 M in the north-east to 0.07 M in the south-west.[86]

The variation in concentrations of the exchangeable cations is minor laterally, but is significant in the vertical cross section. The ratio of the Cation Exchange Capacity (CEC) and content in clay minerals is different for the upper and the lower sequences.[87]

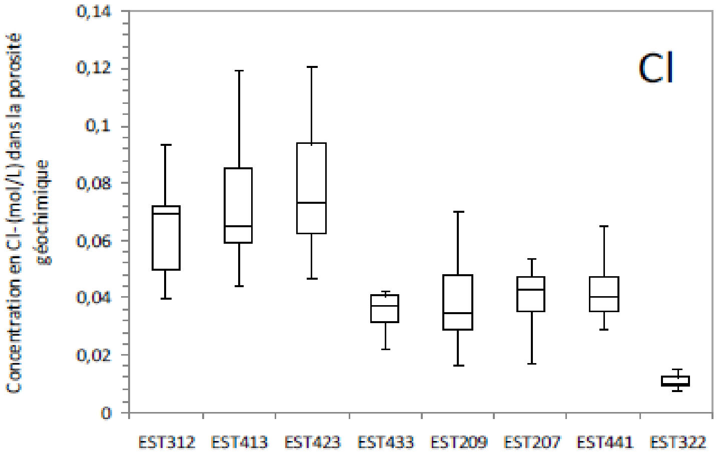


Figure 3-6. Median, 25th Percentile, 75th Percentile, Minimum, and Maximum Chloride Concentrations in Solution in the Different Boreholes within the Transposition Zone (+EST322) (Source: Référentiel du Site 2010, Tome 1 Figure 13-6 (p. 435))

The pore water composition with regard to major constituents is different in the north-east and south-west areas of the Transposition Zone[88] The water composition in boreholes EST423 and EST322, which represent the extreme values, will be taken as representative values for the variability of pore water composition.[89]

The locations of the wells are shown in Figure 3-7.

---

[85] Référentiel du Site 2010, Tome 1 Section 13.1.3.2 (pp. 432-437)

[86] Référentiel du Site 2010, Tome 1 p. 485 in Section 14.3.1.2

[87] Référentiel du Site 2010, Tome 1 Section 13.1.3.2 (pp. 432-437)

[88] Référentiel du Site 2010, Tome 1 Tableau 13-5 (p. 438)

[89] Référentiel du Site 2010, Tome 1 Section 13.1.4 (pp.438-439)

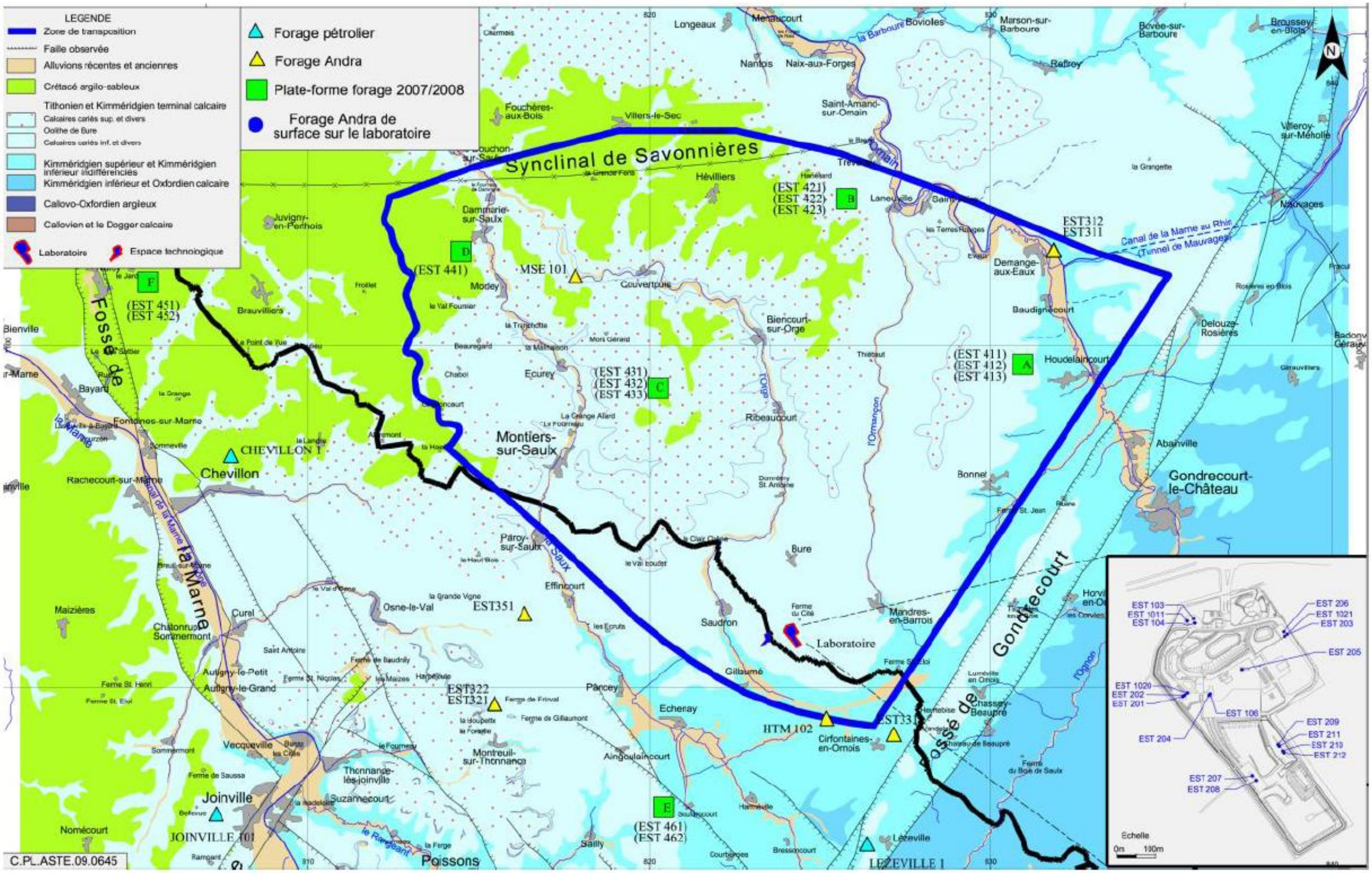


Figure 3-7. Location map of major deep boreholes from which water was sampled (Source: Référentiel du Site 2010, Tome 1 Figure 13-10 (p. 440))

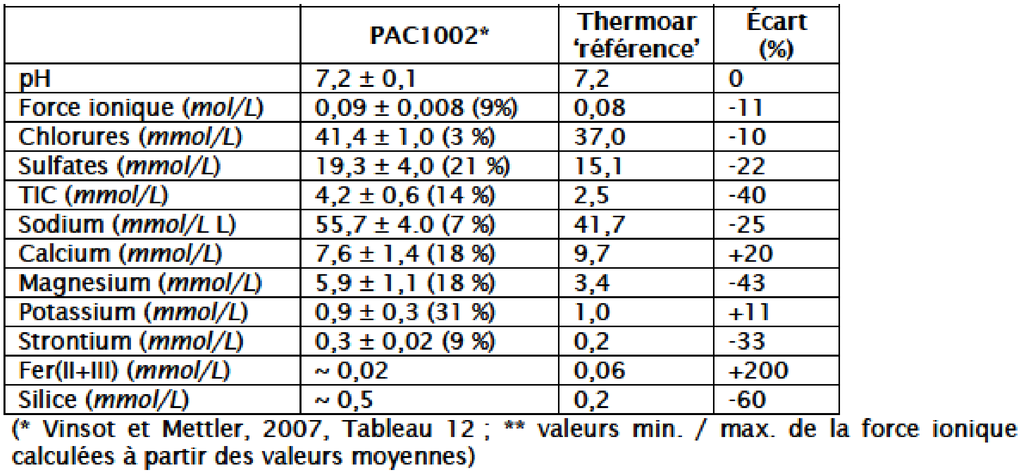
The variability was also observed in the concentrations of other constituents within the Transposition Zone. For example, the preliminary data collected on helium indicate the spatial variability in its concentration in the Transposition Zone.[90]

Geochemical modeling was performed to simulate the observed pore water composition. The concentrations of the major constituents predicted by modeling and those observed (PAC1002 experiment) are summarized in Table 3-1. As can be seen from this table, the calculated composition is somewhat different from the measured one.

In summary, pore water composition changes laterally and in vertical cross section within the Transposition Zone. There are two distinctive areas, located in the north-east and south-west parts of the Transposition Zone. The boundary between these two areas is probably located somewhere within the ZIRA.

The pore water composition has the same trend (north-east to south-west) as the mineral composition. The mineral composition affects the transport properties of the argillites. The difference in transport properties affects the diffusion and advection processes, which, in turn, affect the pore water composition.

Table 3-1. Chemical Composition Predicted by the Model and Measured Concentrations of the Major Constituents and pH in PAC1002 Experiment.



	PAC1002*	**Thermoar 'référence'**	**Écart (%)**
pH	7,2 ± 0,1	7,2	0
Force ionique (*mol/L*)	0,09 ± 0,008 (9%)	0,08	-11
Chlorures (*mmol/L*)	41,4 ± 1,0 (3 %)	37,0	-10
Sulfates (*mmol/L*)	19,3 ± 4,0 (21 %)	15,1	-22
TIC (*mmol/L*)	4,2 ± 0,6 (14 %)	2,5	-40
Sodium (*mmol/L* L)	55,7 ± 4.0 (7 %)	41,7	-25
Calcium (*mmol/L*)	7,6 ± 1,4 (18 %)	9,7	+20
Magnesium (*mmol/L*)	5,9 ± 1,1 (18 %)	3,4	-43
Potassium (*mmol/L*)	0,9 ± 0,3 (31 %)	1,0	+11
Strontium (*mmol/L*)	0,3 ± 0,02 (9 %)	0,2	-33
Fer(II+III) (*mmol/L*)	~ 0,02	0,06	+200
Silice (*mmol/L*)	~ 0,5	0,2	-60

(* Vinsot et Mettler, 2007, Tableau 12 ; ** valeurs min. / max. de la force ionique calculées à partir des valeurs moyennes)

(Source: Référentiel du Site 2010, Tome 1 Tableau 13-3 (p. 428 dans la Section 13.1.2.5))

3.2.1.1.3 Porosity

A few types of porosity are discussed in this section. The term total porosity refers to the total volume of voids in a rock sample. The term effective porosity (or kinematic porosity) refers to the fraction of the total porosity in which fluid flow may effectively take place. Kinematic porosity excludes dead-end pores and bound water.[91] The term anion/cation accessible porosity refers to the fraction of the total porosity that is accessible to anions/cations.

---

[90] Référentiel du Site 2010, Tome 1 Section 13.3.3 (pp. 468-469)

[91] Référentiel du Site 2010, Tome 1 p. 375

The total porosity of argillites for cations in the Transposition Zone considered by Andra in the safety analysis is from 10 to 21 % with mean value of 18%.[92]

The clay particles in argillites have a permanent electric charge. As a result, the proportion of bound water in contact with these particles is very high (approximately 50% of the water contained in the whole porosity) and kinematic porosity is significantly lower than the total porosity. The kinematic porosity used in the normal evolution scenario was 9%.[93]

The same effect (electrical charge) affects the pore volume accessible to the negatively charged particles (anions). Consequently, the anion accessible porosity may be significantly lower than the total porosity. The experimental results for the anions give the values of accessible porosity which vary from 4 to 7%[94] (with the mean value of 5%).

The anion accessible porosity is equal to or smaller than the kinematic porosity.[95] This means that the anion exclusion layer is equal to or greater than the bound water layer.

Most of the pore space is accessible to the positively charged particles (cations). The normal evolution scenario assumed that the cation accessible porosity is the same as the total porosity. The same range of 10% to 21% and the mean value of 18% as for the total porosity were used.

As regards uncertainties, Andra has stated that "*the uncertainties in the porosity values for the argillites are largely covered in the SEN* [Scénario d'évolution normale] *both in the reference calculations and the sensitivity studies*."[96]

Characteristics of the pore space, such as pore size and geometry, of the Callovo-Oxfordian formation are considered in detail in *Chapter 12* of the *Référentiel du Site (2010).* The porosity accessible to anions is discussed in Chapter 13. The experimental data provided in these sections were reviewed to evaluate Andra's assumptions concerning the homogeneity of the porosity values and ranges considered.

Total Porosity

The total porosity of argillites varies significantly both, laterally and in the vertical cross section. According to Andra, in the vertical cross section the total porosity ranges from 5% to 23%. Units C2d and C2c exhibit greater variability in the total porosity values relative to units C2b1, C2b2, and C2a.[97]

The total porosity is mainly controlled by the content of clay minerals. The macroporosity decreases and the mesoporosity increases with increasing of clay minerals. The low porosity

---

[92] Dossier 2005 Argile, Safety Evaluation p. 372
[93] Dossier 2005 Argile, Safety Evaluation p. 237 and 372
[94] Dossier 2005 Argile, Safety Evaluation p. 372
[95] Référentiel du Site 2010, Tome 1 Section 15.1 (pp. 516-517)
[96] Dossier 2005 Argile, Safety Evaluation p. 372
[97] Référentiel du Site 2010, Tome 1 Tableau 12-2 (p. 388) and Figures 12-4 and 12-5 (pp. 385 and 386)

zones (<12%) are located within the units C2c and C2d and at the bottom of unit C2b1. These units have content of the clay minerals less than 40%. The high porosity zones (>18%) are associated with the units with a higher clay mineral content of close to 50%.[98]

The mineralogical composition of argillites plays the major role because the total porosity is largely associated with the clay minerals (microporosity and mesoporosity). The porosity of silicates and carbonates (macroporosity) is very low.[99]

According to Andra. within the Transposition Zone the total porosity increases]from east to west with the minimal values measured in boreholes EST441 and EST322 and maximum values measured in boreholes EST312 and EST413 and at the URL.[100]

Andra notes the following regarding the textural heterogeneity of argillites in the Callovo-Oxfordian:

> *Within the Callovo-Oxfordian, the argilite exhibits textural heterogeneities on the decimetric to micrometric scale whose geometry mainly depends on the content proportion of clay minerals. The most heterogeneous rocks are those that have a small proportion of clay minerals.* [101]

The total porosity probability distributions obtained for the different locations are shown in the figure below reproduced from Figure 3-8. *As can be seen from this figure, the distributions are noticeably different at the different locations, especially in the upper value tails*. The distribution obtained for the URL is especially different from the other locations.

---

[98] Référentiel du Site 2010, Tome 1 Section 12.3.1 (pp. 383-388)
[99] Référentiel du Site 2010, Tome 1 Section 12.3.3.1 (pp. 391-393)
[100] Référentiel du Site 2010, Tome 1 Section 12.3.1 (pp. 383-388)
[101] Référentiel du Site 2010, Tome 1 p. 398 in Section 12.3.4.1. Translated from the French.

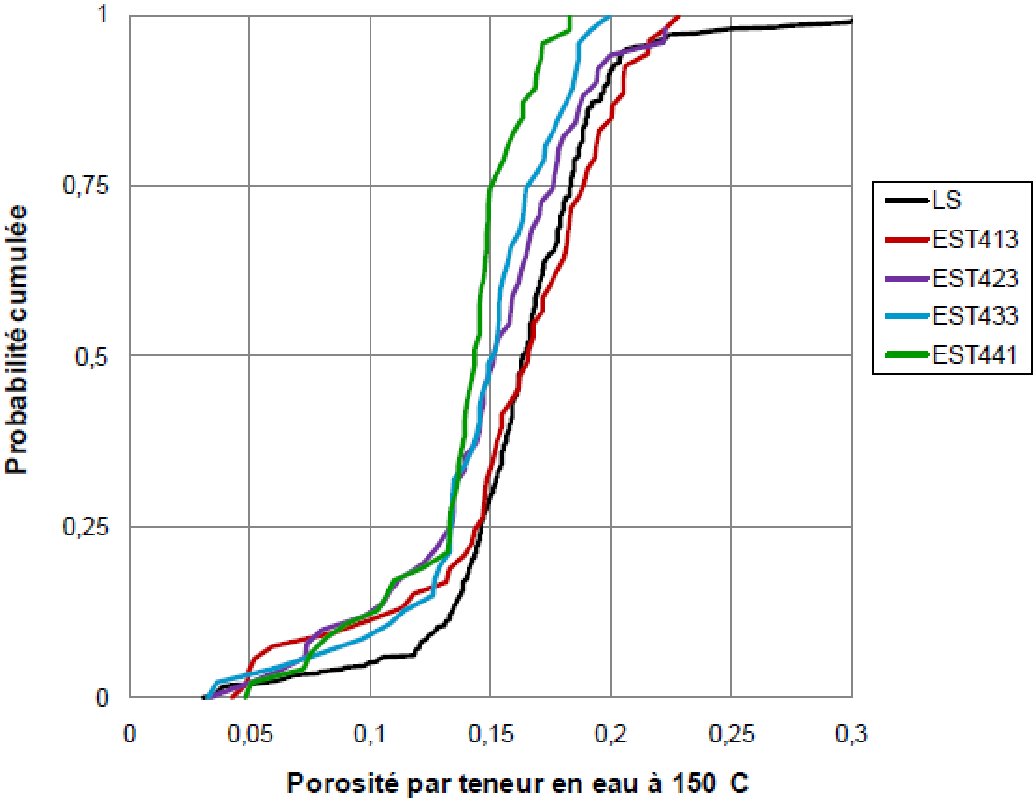


Figure 3-8. Cumulative Probability Distribution of Porosity of the Callovo-Oxfordian Samples from the Underground Laboratory and Transposition Zone (Boreholes EST413, EST423, EST433, and EST441) (Source: Référentiel du Site 2010, Tome 1 Figure 12-14 (p. 399)) NOTE: the porosity values were obtained from the water content measurement at 1500C and assuming grain density of 2.69 g/cm^3)

Kinematic Porosity

As was estimated in *Référentiel du Site 2010,* the volume of the bound water ranged from 30% to 80% of the total pore volume.[102] It is reasonable to assume that there is a correlation between the fraction of bound water (fraction of kinematic porosity) and the clay mineral content. The fraction of kinematic porosity should be greater when the clay mineral content is low because the effect of the electric charge will be smaller.

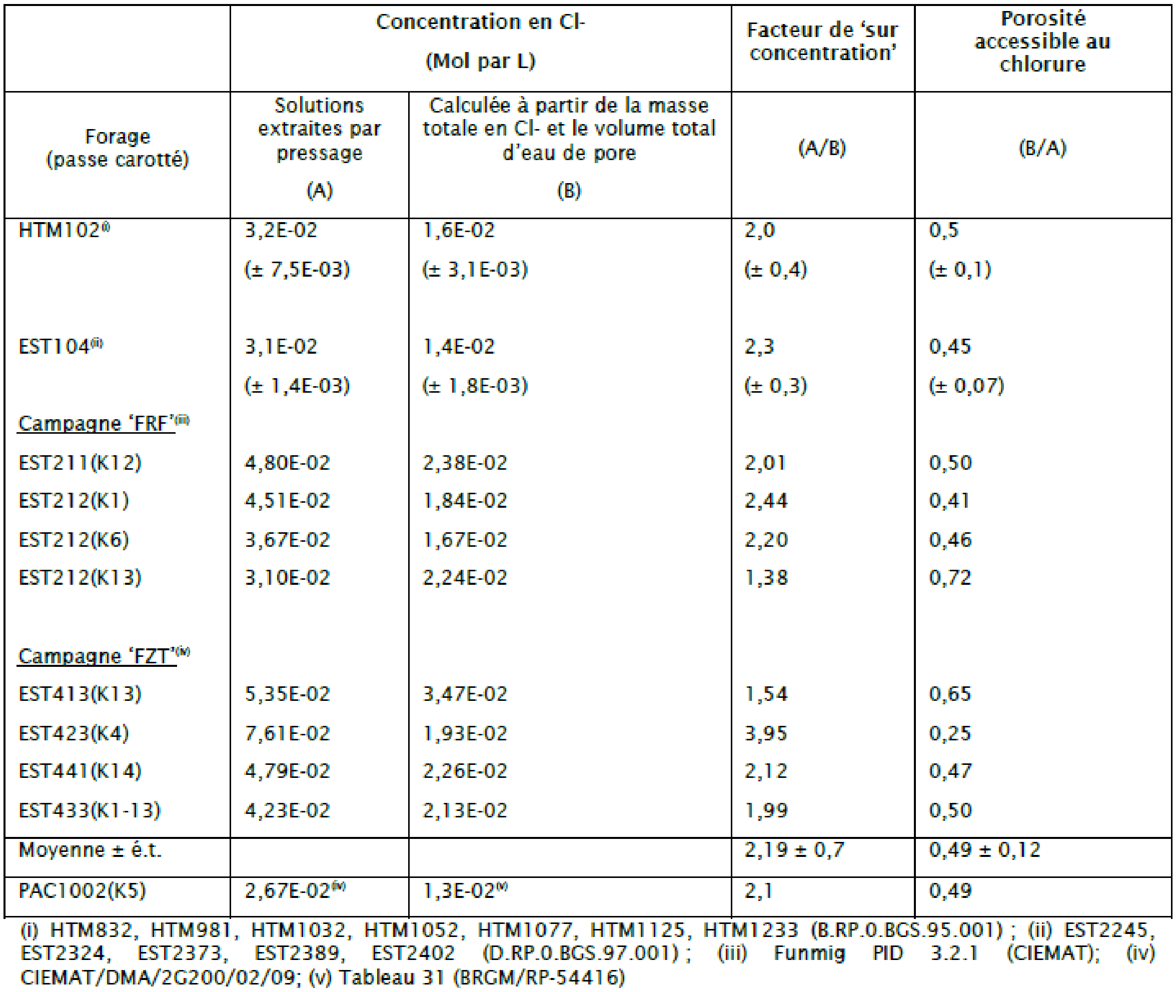
Anion Accessible Porosity

The data on the anion accessible porosity are summarized in Table 3-2. Chloride data are the most appropriate to determine the anion accessible porosity because it is a non-sorbing species as opposed to iodine that might experience weak sorption.

---

[102] Référentiel du Site 2010, Tome 1 Section 13.1.2.2 (pp. 422-424)

Table 3-2. Estimation of the Equivalent Pore Volume based on (1) Chloride Concentrations in the Pore Water Squeezed from the Samples and (2) Chloride Concentrations Calculated Based on the Total Mass of Chloride and the Volume of the Pore Water.



	Concentration en Cl- (Mol par L)		Facteur de 'sur concentration'	Porosité accessible au chlorure
Forage (passe carotté)	Solutions extraites par pressage (A)	Calculée à partir de la masse totale en Cl- et le volume total d'eau de pore (B)	(A/B)	(B/A)
HTM102[(i)]	3,2E-02 (± 7,5E-03)	1,6E-02 (± 3,1E-03)	2,0 (± 0,4)	0,5 (± 0,1)
EST104[(ii)]	3,1E-02 (± 1,4E-03)	1,4E-02 (± 1,8E-03)	2,3 (± 0,3)	0,45 (± 0,07)
<u>Campagne 'FRF'</u>[(iii)]				
EST211(K12)	4,80E-02	2,38E-02	2,01	0,50
EST212(K1)	4,51E-02	1,84E-02	2,44	0,41
EST212(K6)	3,67E-02	1,67E-02	2,20	0,46
EST212(K13)	3,10E-02	2,24E-02	1,38	0,72
<u>Campagne 'FZT'</u>[(iv)]				
EST413(K13)	5,35E-02	3,47E-02	1,54	0,65
EST423(K4)	7,61E-02	1,93E-02	3,95	0,25
EST441(K14)	4,79E-02	2,26E-02	2,12	0,47
EST433(K1-13)	4,23E-02	2,13E-02	1,99	0,50
Moyenne ± é.t.			2,19 ± 0,7	0,49 ± 0,12
PAC1002(K5)	2,67E-02[(iv)]	1,3E-02[(v)]	2,1	0,49

(i) HTM832, HTM981, HTM1032, HTM1052, HTM1077, HTM1125, HTM1233 (B.RP.0.BGS.95.001) ; (ii) EST2245, EST2324, EST2373, EST2389, EST2402 (D.RP.0.BGS.97.001) ; (iii) Funmig PID 3.2.1 (CIEMAT); (iv) CIEMAT/DMA/2G200/02/09; (v) Tableau 31 (BRGM/RP-54416)

(Source: Référentiel du Site 2010, Tome 1 Tableau 13-1 (Section 13.1.2.2 (p. 424))

As can be seen from this table, the fraction of the anion accessible porosity ranges from 0.25 to 0.72, which is very similar to the fraction of kinematic porosity. As in the case of kinematic porosity, it is reasonable to assume that the fraction of anion accessible porosity should be greater when the clay mineral content is low because the effect of the electric charge will be smaller.

<u>Conclusions</u>

The total porosity values vary significantly laterally and vertically. The variability is especially large for the upper argillite sequence with the higher carbonate content. The total porosity is largely controlled by the content of the clay mineral. The total porosity is larger for the layer with high clay content and lower for the layers with low clay mineral content. The total porosity range is from 5% to 23% (30% at the URL site), which is significantly larger than the range considered in the Andra sensitivity analysis (10% to 21%).

The fractions of kinematic porosity and anion accessible porosity are very similar and range from 0.2 to 0.72 of the total porosity. The kinematic porosity and anion accessible porosity should be correlated with the clay mineral content. The range defined without this correlation, based on the minimum and maximum values of total porosity and kinematic/accessible porosity fraction (1% to 17%), would not be representative of the existing conditions.

An example of kinematic (anion accessible) porosity distribution is shown in Figure 3-9. The results shown in this figure are based on 100 Monte Carlo realizations. This distribution was calculated using the following input parameters:

- Total porosity cumulative probability distribution was defined based on EST413 data
- Kinematic (anion accessible) porosity fractional distribution was defined as a uniform one with minimum of 0.2 and maximum 0.72
- A moderately strong negative correlation (correlation coefficient of -0.8) between the total porosity and kinematic (anion accessible) porosity fraction was used. The correlation coefficient value of -0.8 was used as an illustrative value to represent a relatively strong anti-correlation (no actual data were available).

The possible range of the kinematic (anion accessible) porosity based on this example is from 2.3% to 10.5%, with a median value of slightly over 6%.

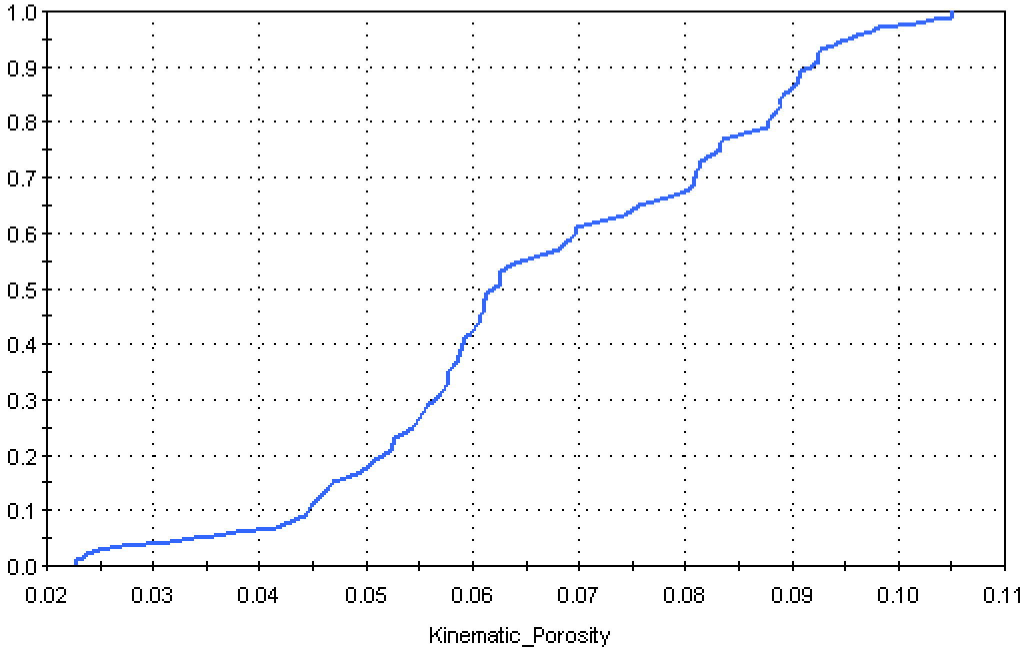


Figure 3-9. Cumulative Probability Function for Kinematic Porosity (Source: E. Kalinina)

The obtained range is in good agreement with the data in *Référentiel du Site 2010* , according to which the anion accessible porosity ranges from 3.3% to 8.9% with a mean of 6%.[103] Yet, in its

---

[103] Référentiel du Site 2010, Tome 1 Section 14.3.1.6, Tableau 14-3

safety analysis Andra used a much narrower range for The nominal value for the anion accessible porosity is 5%.[104] The nominal value for kinematic porosity is 9%. Experimental data suggest that the kinematic and anion accessible porosity values are very similar. Consequently, the same mean values and ranges should be applied to both parameters.

Based on the data provided above, the mean value for both, accessible porosity and kinematic porosity should be 6%. The anion accessible porosity considered in the sensitivity analysis was 4%.[105] The kinematic porosity was not considered in the sensitivity analysis. Consequently, the actual range in the accessible and kinematic porosity values was not studied.

3.2.1.1.4 Permeability

The horizontal and vertical hydraulic conductivities were used as a measure of the permeability of the Callovo-Oxfordian argillites. The values assumed by Andra in the normal evolution scenario were: $5x10^{-14}$ m/s for vertical permeability and $5x10^{-13}$ m/s for horizontal permeability.[106] A sensitivity study was conducted with the horizontal and vertical permeability values of $5x10^{-12}$ m/s and $5x10^{-13}$ m/s, respectively.

The permeability of the Callovo-Oxfordian argillites is considered in detail in *Chapter 15* of the *Référentiel du Site 2010*. The experimental data provided in this chapter were reviewed to evaluate the credibility of the assumptions concerning the homogeneity of the permeability values and ranges considered.

The hydraulic conductivity values obtained in the different in situ experiments (long-term pressure observations) are summarized in Figure 3-10. As can be seen from this figure, the hydraulic conductivity varies in vertical cross section. The hydraulic conductivity of the upper sequence is about one order of magnitude lower than the hydraulic conductivity of the middle and lower sequences of the Callovo-Oxfordian formation.

The hydraulic conductivity ranges from about $7x10^{-14}$ m/sec to $1x10^{-11}$ m/sec based on the data presented in Figure 3-10.[107] These data probably represent the horizontal hydraulic conductivity. The large values measured in the boreholes MSE101 and HTM102 in 1994-1995 were explained in *Référentiel du Site 2010* as less reliable due to the short duration of the tests and possibly disturbed conditions created by the drilling of the boreholes.[108]

---

[104] Dossier 2005 Argile, Safety Evaluation p. 237
[105] Dossier 2005 Argile, Safety Evaluation p. 240
[106] Dossier 2005 Argile, Safety Evaluation p. 237
[107] Référentiel du Site 2010, Tome 1 Figure 15-21 (p. 544)
[108] Référentiel du Site 2010, Tome 1 p. 545 in Section 15.2.2.1

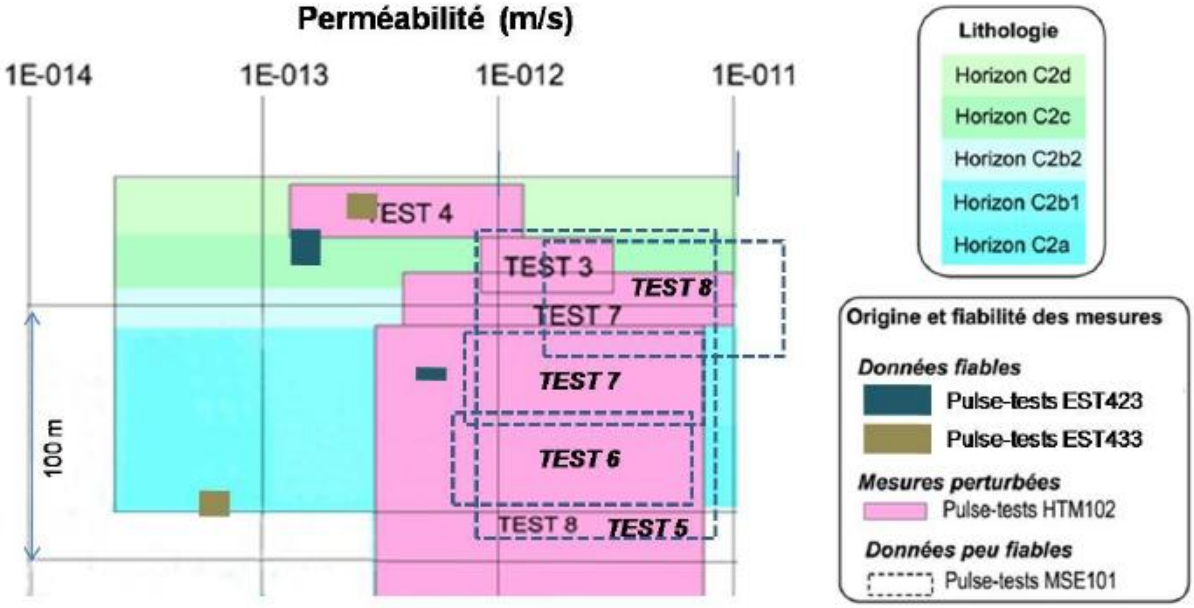


Figure 3-10 Permeability of Callovo-Oxfordian Argillites Based on In Situ Measurements within the Study Area.(Source: Référentiel du Site 2010, Tome 1 Figure 15-21 (p. 544))

The vertical and horizontal hydraulic conductivity data that were considered to be reliable are summarized in Figure 3-11. Both horizontal and vertical hydraulic conductivity values of the middle and lower sequence range from $2x10^{-14}$ m/sec to $2x10^{-12}$ m/sec. The vertical hydraulic conductivity appears to be slightly lower when the same depth interval is considered. This is consistent with the conclusion made in *Référentiel du Site 2010* that the anisotropy in permeability (ratio of horizontal to vertical hydraulic conductivity) is relatively small (around 2 to 3).[109]

Because the advective flow in the Callovo-Oxfordian formation is vertical, the rate of this flow depends on the vertical hydraulic conductivity. Thus, it is important to use the observed range in the vertical hydraulic conductivity to represent its variability ($2x10^{-14}$ m/sec to $2x10^{-12}$ m/sec).

The approach taken by Andra was to take the range in the horizontal hydraulic conductivity and derive the corresponding range in the vertical hydraulic conductivity using the anisotropy factor of 10. This approach underestimates the vertical hydraulic conductivity because the assumed anisotropy is much higher than was observed. Also, the horizontal hydraulic conductivity range was narrowed down to $5x10^{-14}$ m/sec to $5x10^{-13}$ m/sec based on the statement that most of the values fall into this range.[110]

As a result, the values for vertical conductivity used it the normal evolution scenario are lower than they should be based on the experimental data; similarly, the factor of ten used in the sensitivity analysis is noticeably narrower than indicated by the data.

---

[109] Référentiel du Site 2010, Tome 1 Section 15.3.2.1 (pp. 539-545)
[110] Référentiel du Site 2010, Tome 1 Section 15.3.2.2 (pp. 545-550)

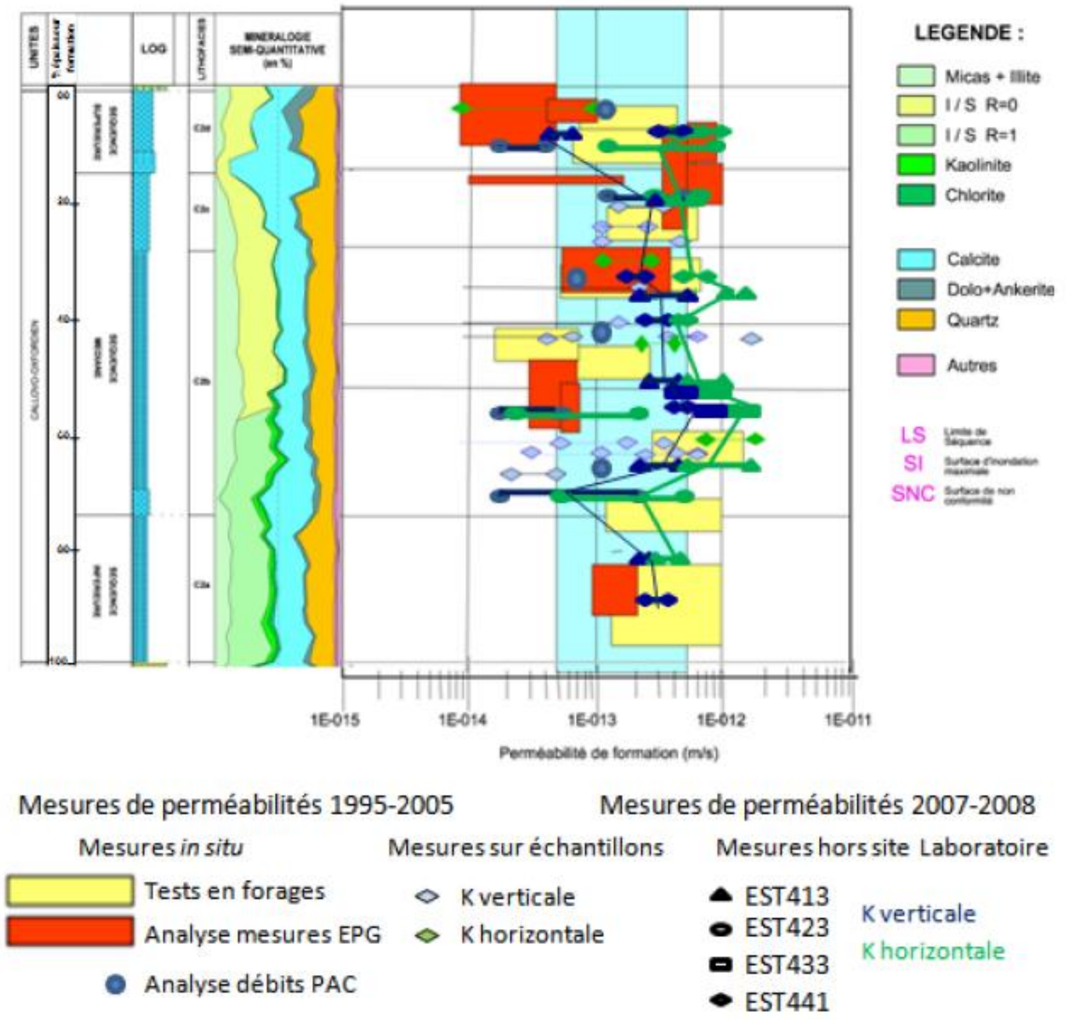


Figure 3-11. Summary of the Permeability Measurements in the Callovo-Oxfordian Formation (Source: Référentiel du Site 2010, Tome 1 Figure 15-28 (p. 551))

The comparison of the site data with the other clay sites around the world is presented in Figure 3-12. As can be seen from this figure, the variability of permeability within the Transposition Zone (number 16 in the figure] as represented by Andra is significantly smaller than at most other clay sites shown in the figure. This is most likely due to the fact that the actual variability was not sufficiently characterized.

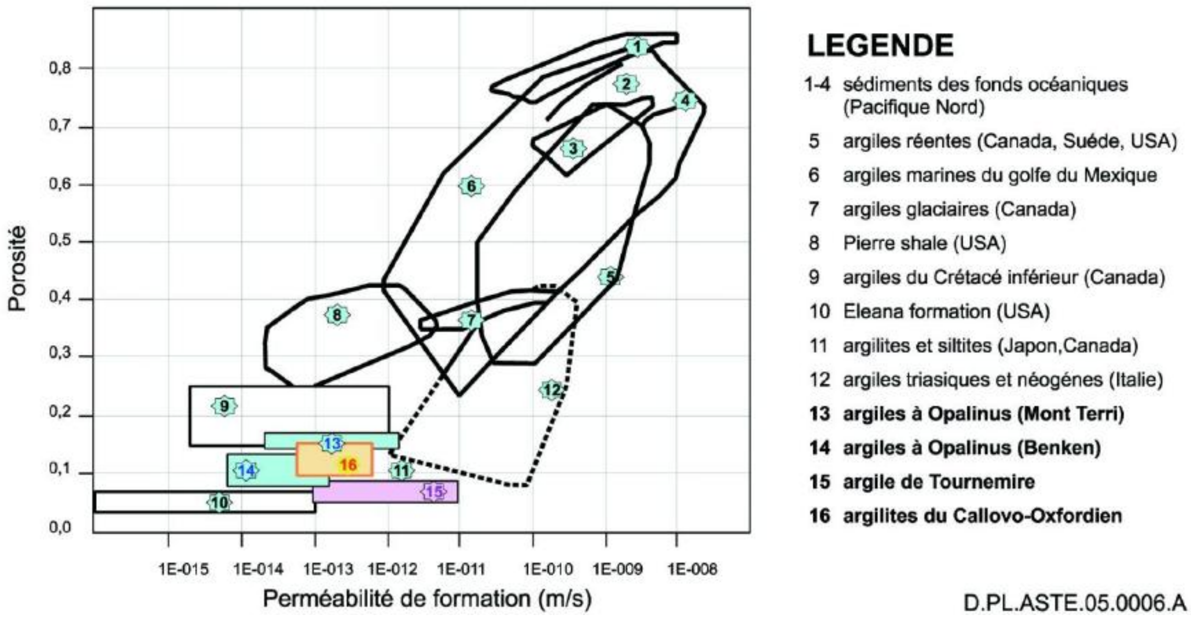


Figure 3-12. Summary of Permeability Measurements Obtained for the Different Argillous Formations and at the Different Sites around the World (Source: Référentiel du Site 2010, Tome 1 Figure 15-29 (p. 552))

3.2.1.1.5 Hydraulic Gradient

The ascending hydraulic gradient assumed by Andra is 0.2 m/m in the model for the current time and 0.4 m/m for the one million year model. The descending hydraulic gradient is -0.2 m/m for both present day and one million year model. Andra further infers that "*no source of uncertainty concerning the value of the gradient is sufficiently great to cause it to be called into question*".[111]

The hydraulic gradient in the Callovo-Oxfordian formation affects the vertical advective flow through the argillites. The advective flow rate is directly proportional to the hydraulic gradient and hydraulic conductivity. A number of tests were performed to define the permeability values of the argillites (Section 3.2.1.1.4). The hydraulic gradient estimates indicated by the data in *Chapter 15* of the *Référentiel du Site 2010* are significantly more uncertain than the fixed values used by Andra in the safety analysis cited above. More research is needed for determining suitable ranges for vertical hydraulic gradient in different parts of the site. The reasons for the variation of this parameter also bear further scrutiny.

The uncertainties in hydraulic gradient are associated with a number of factors. First, the measurements revealed an overpressure in the Callovo-Oxfordian formation relative to the formations surrounding it on the order of +20 m to +30 m with regard to Oxfordian formation and +40 m to +50 m with regard to Dogger formation.[112] To date no plausible explanation of this phenomenon was provided. A number of hypotheses were proposed and then dismissed.[113]

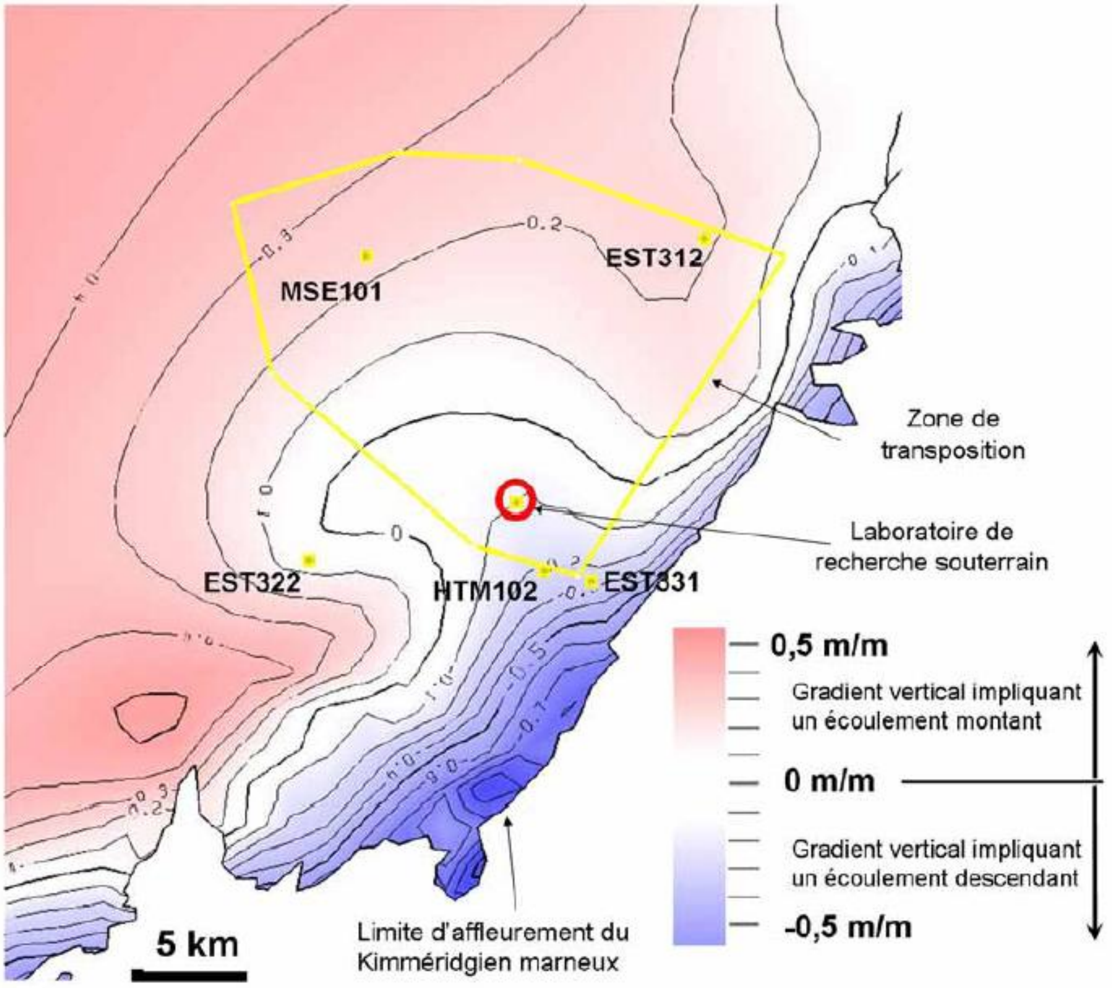
---

[111] Dossier 2005 Argile, Safety Evaluation p. 369
[112] Référentiel du Site 2010, Tome 1 Section 15.2.2.2 (pp. 527-532)
[113] Dossier 2005 Argile, Safety Evaluation p. 367

Eleven measurements of hydraulic heads are available for the Dogger formation and 13 are available for Oxfordian formation within the study area and many fewer for the Transposition Zone).[114]

The gradients in the Dogger formation are small in the north-east and large in the west. The reasons for these differences are not well known.[115]

As a result, the hydraulic gradient map shown in Figure 3-13 should be considered only as one of the many alternative representations.



Au sein de la zone de transposition, les champs de charge dans les encaissants déterminent un gradient vertical responsable d'un écoulement essentiellement montant au travers du Callovo-Oxfordien (en moyenne de 0,1 à 0,2 m/m)

Figure 3-13. Estimated Distribution of the Vertical Hydraulic Gradient in the Callovo-Oxfordian Formation Based on the Differences in the Hydraulic Heads in the Surrounding Formations (Source: Dossier 2005 Argile, Safety Evaluation Figure 6.2-4 (p. 369))

---

[114] Référentiel du Site 2010, Tome 1 Section 15.2.2.1 (pp. 520-527)

[115] Référentiel du Site 2010, Tome 1 Section 15.2.3.1 (pp. 532-534)

The representation in Figure 3-13 shows that hydraulic gradients are heterogeneous within the Transposition Zone. There is a strong ascending gradient in the north and north-west and a descending gradient in the south.

3.2.1.1.6 Effective Diffusion

The effective diffusion coefficient values were measured by performing diffusion tests both on core samples and in situ. The values used by Andra for the normal evolution scenario are $5x10^{-12}$ m^2/sec for anions and $2.5x10^{-10}$ m^2/sec for cations.[116] The sensitivity analysis considered effective diffusion coefficients that were a factor of two greater: $1x10^{-11}$ m^2/sec for anions and $5x10^{-10}$ m^2/sec for cations.[117]

Effective diffusion coefficients, along with the accessible porosity for anions and cations (discussed in Section 3.2.1.1.3) represent the most important parameters that affect the diffusional transport in the argillites. Diffusion is the major process that is relied on to satisfy the safety function defined as: "*delaying and attenuating the flow of radionuclides finally released by the wastes to the surrounding geological formations in space and time*".[118] Andra states that this function "*concerns spatial spreading, this consists of preventing the radionuclides from diffusing in privileged directions. This relies on the homogeneity of the Callovo-Oxfordian, and the absence of significant heterogeneity with respect to diffusion within the formation.*" [119]

An extensive research was conducted by Andra to determine diffusion coefficients. The summary of this research is documented in *Chapter 14* of the *Référentiel du Site 2010*. The experimental data provided in this section were reviewed to evaluate the credibility of the assumptions concerning the homogeneity of the porosity values and ranges considered.

The experiments conducted on the core samples demonstrated that there are 2 types of uncertainties related to the effective diffusion measurements:[120] (1) spatial heterogeneity of rocks and (2) experimental conditions.

The experiments also demonstrated that effective diffusion coefficients may change significantly even within the same core sample originating from the upper part of the Callovo-Oxfordian formation).[121] The diffusion coefficients measured in core samples from the different boreholes (from boreholes EST104, EST 205, and EST212) using tritiated water (HTO) are summarized in *Tableau 14-2* in *Référentiel du Site 2010*.[122]

The effective diffusion of anions is a function of the solution ionic strength. Most of the diffusion tests with chloride and iodide were conducted using solutions with the ionic strength of 0.05 M and 0.10 M.[123] These experiments provide the foundation of the analysis and

---

[116] Dossier 2005 Argile, Safety Evaluation p. 237

[117] Dossier 2005 Argile, Safety Evaluation p. 240

[118] Dossier 2005 Argile, Safety Evaluation p. 138

[119] Dossier 2005 Argile, Safety Evaluation p. 139

[120] Référentiel du Site 2010, Tome 1 Section 14.3.1.3 (p. 485)

[121] Référentiel du Site 2010, Tome 1 Section 14.3.1.3 (p. 485)

[122] Référentiel du Site 2010, Tome 1 Tableau 14-2 (p. 488)

[123] Référentiel du Site 2010, Tome 1 Section 14.3.1.6 (pp. 488-491)

conclusions regarding the diffusion of anions in the formation. Note that the ionic strength is up to 0.17 M in the north-east part of the Transposition Zone that also includes the ZIRA.

A few measurements were made to evaluate the impacts of the solution ionic strength on the chloride effective diffusion and accessible porosity. The solution ionic strength was up to 0.2 M. The results of these measurements are presented in Figure 3-14.

The conclusion made by Andra, based on this experiment, was that both the effective diffusion coefficient and accessible porosity increase by about factor of 2. Andra goes on to conclude that the pore diffusion (ratio of effective diffusion and accessible porosity) remains the same and therefore the effect on anion migration would be very small.[124]

However, this important conclusion of a small effect on anion migration is based on a few measurements and is not fully supported by the results in Figure 3-14 below. There is a large spread of the values for chloride effective diffusion coefficient for the solution ionic strength of 0.1M. Figure 3-14 shows that the increase in effective diffusion (the plot on the right of the figure) seems to be larger than an increase in accessible porosity (the plot on the left side). Thus, the effective diffusion of anions, as indicated by the ratio of effective diffusion to accessible porosity, might be higher in the north-east part of the Transposition Zone and possibly in northeast part of the ZIRA. More experimental research is indicated to clarify this issue and determine the variability in pore diffusion.

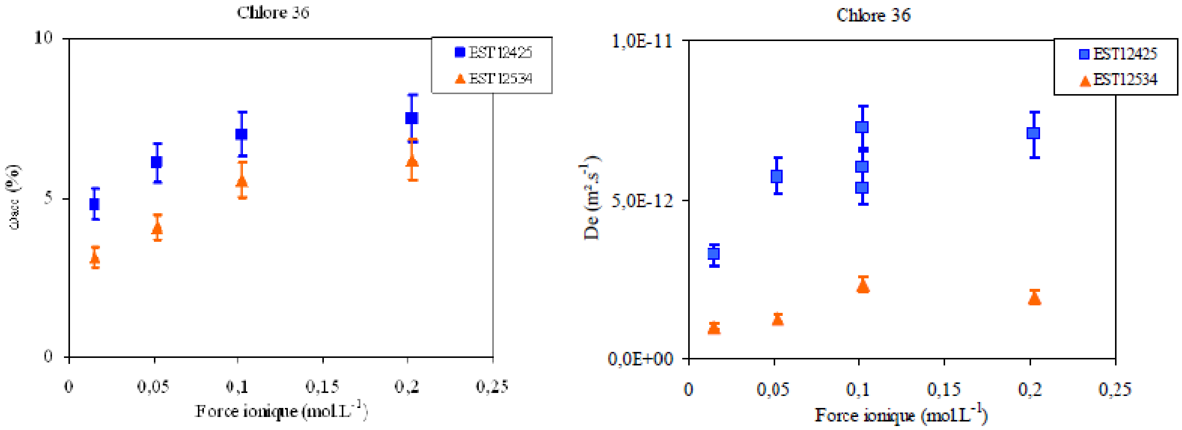


Figure 3-14. Chloride Diffusion as a Function of Ionic Force (Source: Référentiel du Site 2010, Tome 1 Figure 14-4 (p. 489))

The effective diffusion coefficients for chloride (solution ionic strength 0.1 M) are summarized in *Tableau 14-3* of *Référentiel du Site 2010.*[125] The diffusion coefficients range from 5x10^{-13} m^2/sec to 8.4x10^{-12} m^2/sec.

The mean value and the range of the effective diffusion coefficients for the cations were determined based on the core samples from the three different types of argillite samples from

---

[124] Référentiel du Site 2010, Tome 1 Section 14.3.1.6 (pp. 488-491)

[125] Référentiel du Site 2010, Tome 1 Tableau 14-3 (p. 490)

borehole EST205.[126] The samples from the other boreholes were not used to derive a range for the safety analysis. We could not find an explanation for the omission of these values.

The diffusion coefficient data based on the samples from the different boreholes are summarized in *Tableau 14-8* in *Référentiel du Site 2010.* The data for tritiated water and anions (chloride) are available for 8 boreholes and the data for cations (cesium) are available for 4 boreholes. The chloride effective diffusion coefficient in one of the samples from borehole EST413 (1.5×10^{-11} m^2/sec) is larger than the upper limit (1.0×10^{-11} m^2/sec) considered in Andra's sensitivity analysis. The average diffusion coefficient in this well is 8.8×10^{-12} m^2/sec, which is 1.75 times higher than the average considered in the normal evolution scenario. The borehole EST413 is located in the north-east of the Transposition Zone and just north of ZIRA.

The effective diffusion coefficients measured on the samples from the different boreholes are shown in the Figure 3-15 below (*Figure 14-7* in *Référentiel du Site 2010*) As can be seen from this figure, when multiple samples are available for the same well, they often show the considerable variability in the diffusion coefficients. Yet, Andra's conclusion regarding the vertical variability in effective diffusion coefficients based on the data in this figure, as reported in *Section 14.3.1.10* of the *Référentiel du Site 2010*,[127] is that the diffusion coefficients do not depend on depth and that this confirms the homogeneity of the Callovo-Oxfordian formation.

Andra's conclusion that diffusion coefficients are independent of depth contradicts all the other facts presented in Chapter 14 of the *Référentiel du Site 2010*, including the data shown in Figure 3-15 below. The data indicate that Callovo-Oxfordian formation is heterogeneous with regard to the diffusion coefficients. The effective diffusion coefficients vary significantly in a single borehole as a function of mineralogical composition and porosity (largely controlled by the content of clay minerals). The effective diffusion coefficients also between boreholes due to the differences in mineralogical composition and pore water composition; the latter is largely controlled by the ionic strength.

In addition to this heterogeneity, the diffusion is anisotropic as it is discussed in *Section 14.3.2* of *Référentiel du Site 2010.*

Two data sets on anisotropy are available. The first data set is for borehole EST104. The average anisotropy measured on the samples from this borehole was 1.56. The other set of data is related to the studies that were performed in support of Diffusion and Retention experiments. Based on these data anisotropy in diffusion coefficients was 1.9 for tritiated water and 1.3 for chloride.[128]

---

[126] Référentiel du Site 2010, Tome 1 Section 14.3.1.7 (pp. 492-493)

[127] Référentiel du Site 2010, Tome 1 Section 14.3.1.10 (pp. 496-498)

[128] Référentiel du Site 2010, Tome 1 Section 14.3.2 (pp. 498-507)

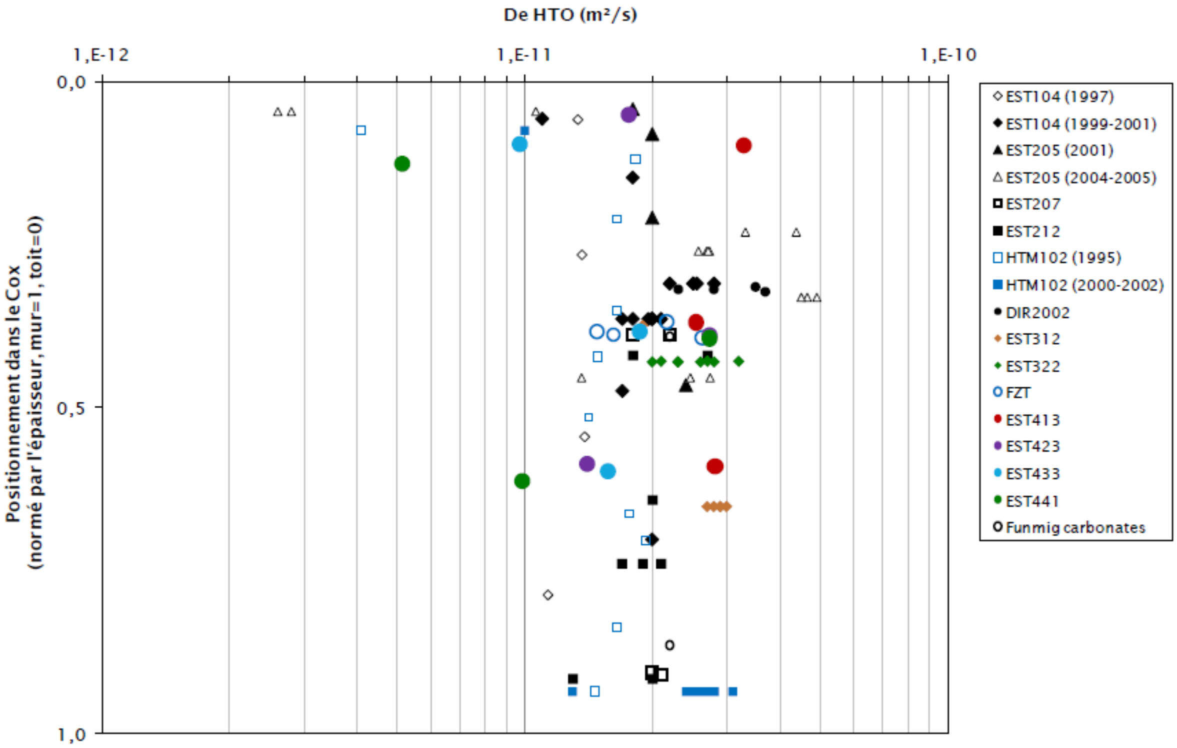


Figure 3-15. Diffusion Coefficients of the Tritiated Water in the Callovo-Oxfordian Formation as a Function of Sample Locations within the Formation (Source: Référentiel du Site 2010, Tome 1 Figure 14-7 (p. 497))

In summary, the Callovo-Oxfordian argillites exhibit vertical and horizontal heterogeneity and are anisotropic, with horizontal diffusion (parallel to stratification) being higher than the vertical one. Due to the limited amount of data it seems that the possible variability of the diffusion coefficients within the Transposition Zone and ZIRA was not totally captured. The upper effective diffusion coefficient value for anions considered in the sensitivity analysis is lower than the diffusion coefficient determined in one of the samples in borehole EST413 located in vicinity of ZIRA's north boundary.

3.2.1.1.7 Sorption

Limited information is presented in *Référentiel du Site 2010* and *Dossier 2005 Argile* concerning sorption and solubility data and identification of radionuclides and toxic constituents retained in the safety analysis. A significant effort would be required to locate and review these data and supporting analyses. This task is outside the scope of this report.

At this stage, it is reasonable to assume that the long-term performance of the repository will be mainly affected by the transport of two long-lived radionuclides with very low sorption capability and large solubility limits, such as *iodine-129* and *chlorine-36* and, to some extent, by *selenium-79 and calcium-41*. The effects of other radionuclides and toxic constituents will be either similar to these ones or attenuated to a different degree in accordance with their specific sorption and solubility properties.

3.2.1.2 Review of the Transport Processes in the Host Rock

Andra notes the importance of the transport through the host rock as follows:

> *Calculation highlights that the majority of the mass finally takes the transfer path through unaltered Callovo-Oxfordian….*
>
> *Nearly the entire released mass (99.999 %) exits by the top or the bottom of the Callovo-Oxfordian after having migrated by diffusion in unaltered Callovo-Oxfordian.* [129]

This is demonstrated in the Figure 3-16. As can be seen from this figure,[130] 99.99997% of the I-129 inventory is transported in the ambient Callovo-Oxfordian argillites. As was pointed out on many occasions in the previous sections, this makes the Callovo-Oxfordian formation the most important component on which Andra relies in its long-term repository safety evaluations.

Two major processes may affect the transport of conservative (nonsorbing and highly soluble) contaminants in the host rock: (1) advective transport in which dissolved species move with the flow of pore water and (2) diffusional transport in which the dissolved species move from the area with higher concentrations to the area with lower concentrations. Andra considers diffusion to be the predominant process:

> *Given the low permeability of the Callovo-Oxfordian formation ($5 \cdot 10^{-13}$ to $5 \cdot 10^{-14}$ m/s on average), these water flows are very low (a few hundredths of a millilitre per year and per m^2) as is their velocity (approximately a few centimetres per 100,000 years). In this context, the transport of solutes in the Callovo-Oxfordian layer takes place mostly by diffusion.*[131]

Andra incorporates the diffusion of contaminants through the host rock in the normal evolution scenario using the mean values for the transport parameters. This approach assumes that the host rock is homogeneous and isotropic and there is no preferential path and direction for diffusional transport.

The potential role of an advective transport component is evaluated in the sensitivity analysis by using vertical and horizontal hydraulic conductivity values that are one order of magnitude higher than in the normal evolution scenario. Based on this analysis Andra concluded that "*the transport mode is still diffusive without altering significantly flow at the host formation interface. We can therefore conclude that major safety margins are provided by the geological medium*" [132].

---

[129] Dossier 2005 Argile, Safety Evaluation p. 269
[130] Dossier 2005 Argile, Safety Evaluation Figure 5.5-4 (p. 270)
[131] Dossier 2005 Argile, Synthesis p. 175
[132] Dossier 2005 Argile, Synthesis p. 218

A detailed review of the transport parameters of the Callovo-Oxfordian formation is provided in Section 3.2.1.1 above. This section relies on that discussion in the analysis of the transport processes.

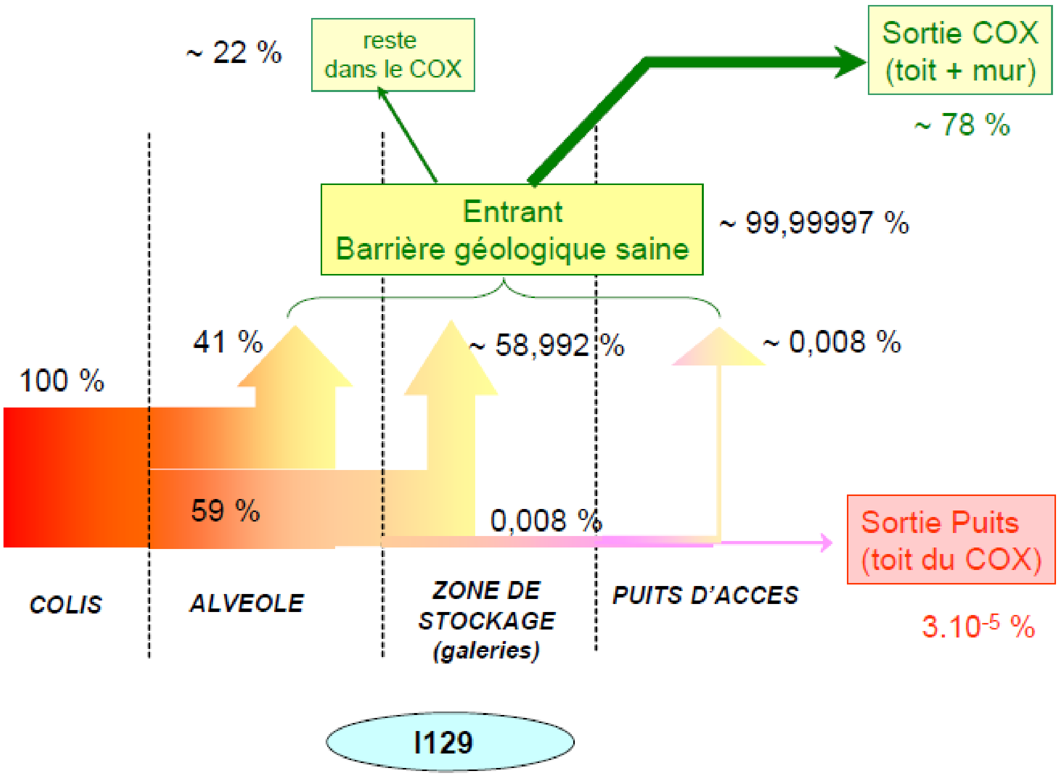


Figure 3-16. Distribution of I^{129} Mass in the Different Modeling Compartments in the CU1 Packages Normal Evolution Scenario) (COX = Callovo-Oxfordian) (Source: Dossier 2005 Argile, Safety Evaluation Figure 5.5-4 (p. 270))

The conclusion that diffusional transport is dominant is made by Andra based on its analysis of low permeability properties of the host rock. Andra corroborated this conclusion by (1) comparing diffusional transport times to the advection ones (simplified analysis involving calculating Peclet number) and (2) natural tracer data interpretation. These two issues are reviewed below.

3.2.1.2.1 Peclet Number

"A Peclet number is a dimensionless number that relates the effectiveness of mass transport by advection to the effectiveness of mass transport by either dispersion or diffusion."[133] This number may also be thought of as the ratio between the advective to diffusive time scales. Generally, the Peclet number smaller than 1 indicates that the diffusion (dispersion) is dominant. Peclet numbers in the range 1 – 10 correspond to systems in which diffusion and advection are

---

[133] Fetter 1993 p. 54

both important, and the values >10 relate to advection-dominated systems,[134] though the upper limit of 10 is rather subjective.

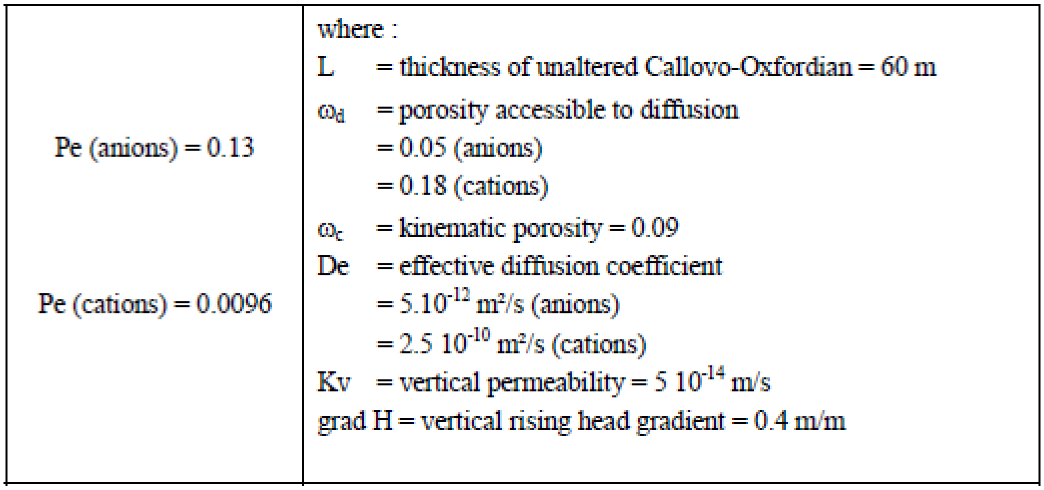
In the case of vertical advection and diffusion of a conservative anionic species (such as chloride), the Peclet number (*Pe*) can be expressed as:

$$Pe = \frac{vL}{D_p} \qquad v = \frac{k}{\varepsilon_k}\frac{dh}{dz} \qquad D_p = \frac{D_{eff}}{\varepsilon_{acc}} \quad , \qquad (1)$$

where *v* is the advective velocity, D_p is pore diffusion, *L* is the characteristic length of advection and diffusion, *dh/dz* (grad H in the table below) is the vertical hydraulic gradient, *k* (k_v in the table below*)* is the vertical hydraulic conductivity, ε_k *(*ω_c in the table below*)* is kinematic porosity, ε_{acc} (ω_d in the table below) is the anion accessible porosity, and D_{eff} (D_e in table below) is the anion effective diffusion coefficient. The values of these parameters are shown in Table 3-3.

Andra's estimate of the Peclet number for anionic species is 0.13. The transport parameters used in this estimate are summarized in Table 3-3. The corresponding conclusion is that diffusional transport is dominant.

Table 3-3. Calculation of Peclet numbers in the Callovo-Oxfordian



Pe (anions) = 0.13 Pe (cations) = 0.0096	where : L = thickness of unaltered Callovo-Oxfordian = 60 m ω_d = porosity accessible to diffusion = 0.05 (anions) = 0.18 (cations) ω_c = kinematic porosity = 0.09 De = effective diffusion coefficient = 5.10^{-12} m^2/s (anions) = $2.5\ 10^{-10}$ m^2/s (cations) Kv = vertical permeability = $5\ 10^{-14}$ m/s grad H = vertical rising head gradient = 0.4 m/m

(Source: Dossier 2005 Argile, Safety Evaluation Table 5.5-1 (p. 267))

All the parameter values used in calculating Peclet number correspond to the mean values, except the hydraulic gradient for which the maximum value (0.4 m/m) was used. No bounding or probabilistic estimates were provided to capture the transport parameter variability discussed in Section 3.2.1.1. Consequently, the applicability of this conclusion to the overall conditions within the Transposition Zone and ZIRA is not clear.

We performed simple calculations, as described below, to estimate a range of Peclet numbers that account for the variabilityof the parameters on which it depends. In these calculations a

---

[134] Mazurek et al. 2009 p 137

probability distribution was defined for each parameter in Equation (1). The result is a probability distribution was calculated for the Peclet number, instead of one deterministic value used by Andra. This distribution captures the range of possible flow regimes as indicated by the Peclet number and assigns a probability to them.

In the first set of calculations, transport parameter probability distributions were defined using the limits considered by Andra in the sensitivity analysis.

The following parameter probability distributions were used:

- Transport length (L): uniform distribution with minimum of 60 m and maximum of 75 m (based on the total Callovo-Oxfordian formation thickness within the Transposition Zone of 130 m to 160 m).
- Total porosity: average between the cumulative probability distribution defined in *Figure 12-14* in *Référentiel du Site 2010*.
- Fraction of kinematic porosity (with regard to total porosity): uniform distribution with minimum of 0.2 and maximum of 0.72.
- Fraction of accessible porosity (with regard to kinematic porosity): uniform distribution with minimum of 0.8 and maximum of 1.0.
- Vertical hydraulic conductivity (k): uniform distribution with minimum 5×10^{-15} m/sec and maximum 5×10^{-13} m/sec.
- Gradient (dh/dz): uniform distribution with minimum of 0.2 m/m and maximum 0.4 m/m.
- Anion diffusion coefficients (D_{eff}): uniform distribution with minimum 1.6×10^{-12} m^2/sec and maximum 1×10^{-11} m^2/sec.

The kinematic porosity (ε_k) was calculated as the product of total porosity and fraction of kinematic porosity assuming the correlation coefficient of -0.8.

The porosity accessible to anions (ε_{acc}) was calculated as the product of kinematic porosity and fraction of accessible porosity. This was done to account for the fact that the anion accessible porosity is equal to or slightly smaller than the kinematic porosity.

A moderate correlation (correlation coefficient of 0.5) was used between the total porosity and hydraulic conductivity. This allows for incorporating the observed relationship between these two parameters.

A moderately strong correlation of 0.8 was used between the effective diffusion coefficient and accessible porosity. This allows for incorporating the observed correlation between the effective diffusion and accessible porosity for anions.

The Monte Carlo analysis with 200 realizations was performed to calculate the Peclet number. The results of this analysis are shown in Figure 3-17 below.

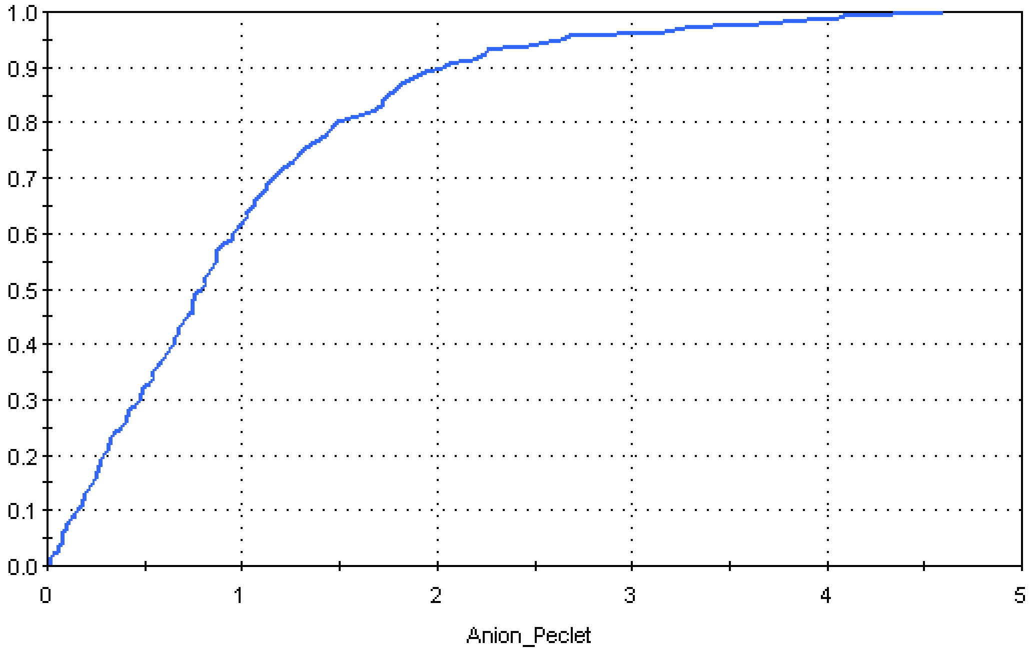


Figure 3-17. Peclet Number with Andra Defined Input Parameter Ranges (Source: E. Kalinina)

The median and mean Peclet numbers are 0.79 and 0.98 respectively. The range is from 0.016 to 4.6. This calculation shows that there is approximately a 40% probability that the advective and diffusional transport will be of the same order. If the correlations between the parameters are not used the larger Peclet numbers are calculated. Using Andra's parameter ranges does not indicate Peclet numbers high enough for a conclusion of dominant advective transport.

The second calculation was done to incorporate the actually observed ranges in the transport parameters. As discussed in Section 3.2.1.1 the ranges for some parameters were defined by Andra narrower than the observed variability and uncertainty. The following probability distributions were modified to take an account the actually observed ranges.

- Anion diffusion coefficients: uniform distribution with minimum $0.5\text{x}10^{-12}$ m^2/sec and maximum $1.5\text{x}10^{-11}$ m^2/sec.

The following new parameters were introduced:

- Horizontal hydraulic conductivity (k_h): uniform distribution with minimum $2\text{x}10^{-14}$ m/sec and maximum $2\text{x}10^{-12}$.
- Anisotropy in permeability: uniform distribution with minimum of 2 and maximum 4.

The vertical hydraulic conductivity was calculated as a ratio of horizontal hydraulic conductivity and anisotropy.

The results of this analysis are shown in Figure 3-18. The median and mean Peclet numbers are 0.78 and 1.37 respectively. The range is from 0.014 to 16. According to this calculation, the 40%

probability of some advective component remains, but now there is also a 1% probability of the dominant advective transport.

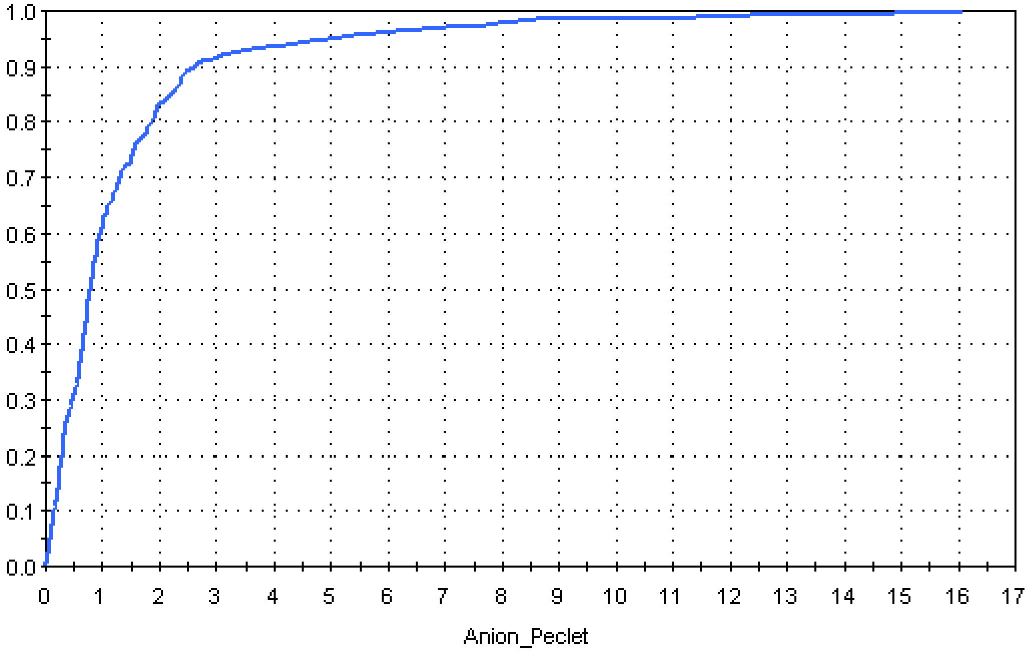


Figure 3-18. Peclet Number with Observed Input Parameter Ranges (Source: E. Kalinina)

A sensitivity analysis was done using the first calculation set-up only because it represents values used by Andra. This enables a direct comparison with Andra's analysis. The results are demonstrated in Figure 3-19 below. Based on this analysis the major parameters are effective diffusion and hydraulic conductivity.

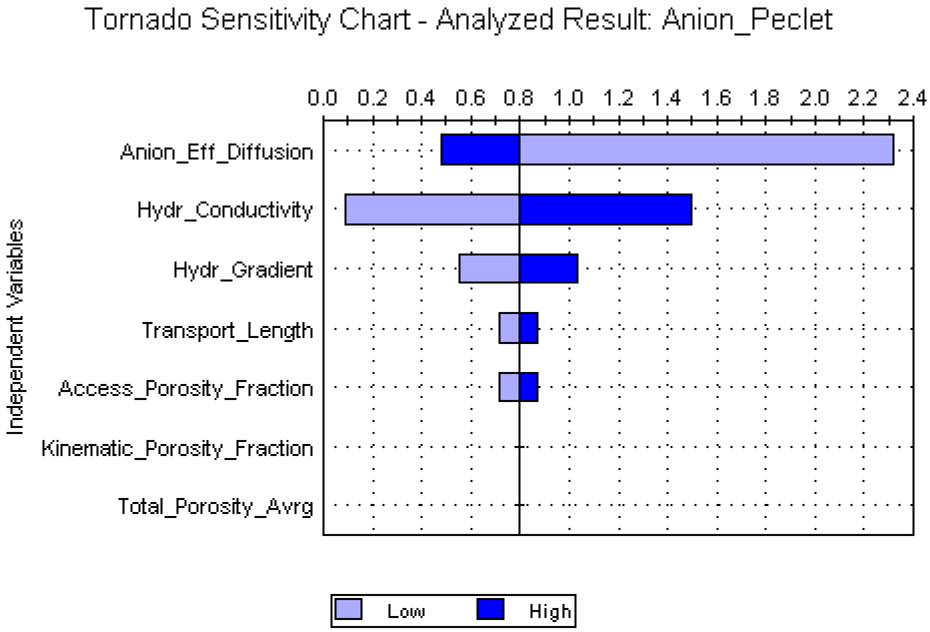


Figure 3-19. Sensitivity Chart for the Input Parameters Used in Peclet Number Calculations (Source: E. Kalinina)

The third calculation was done to introduce different probability distributions for the major parameters defined in the sensitivity analysis. A truncated lognormal probability distribution was used for horizontal hydraulic conductivity with a mean of $5x10^{-13}$ m/sec and minimum and maximum values the same as in the uniform distribution defined in the second calculation. A truncated normal distribution was used for the effective diffusion coefficient with a mean of $5.0x10^{-12}$ m^2/sec and minimum and maximum values the same as in the uniform distribution defined in the second calculation. The results are shown in Figure 3-20 below. The maximum Peclet number is noticeably lower, but the probability of the significant advective transport component is still 25%.

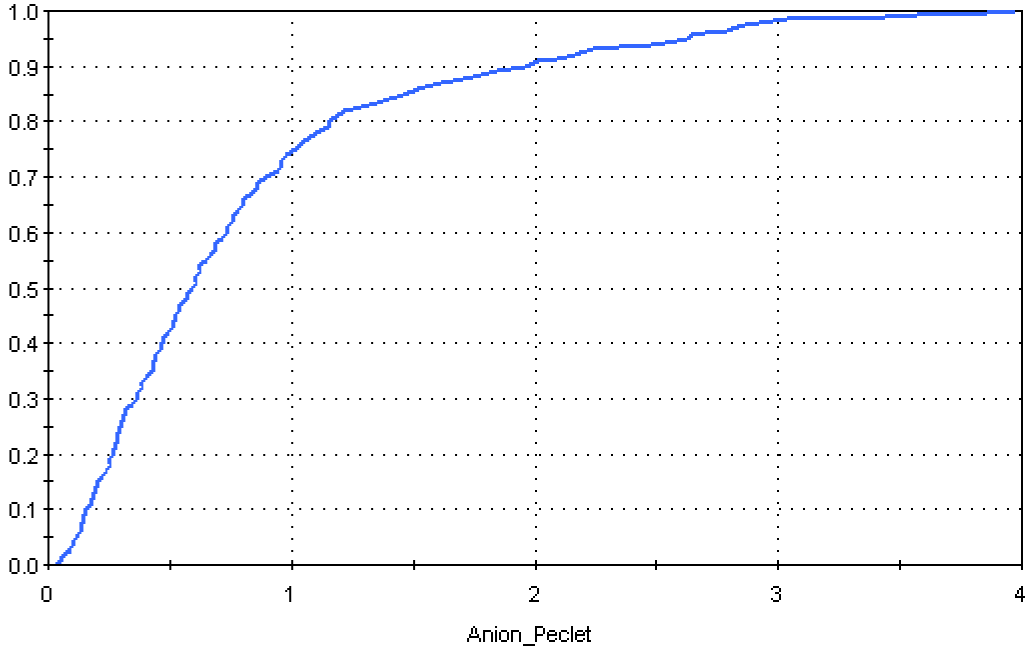


Figure 3-20. Cumulative Probability Distribution Function of Peclet Number for an Anionic Species (Source: E. Kalinina).

3.2.1.2.2 Natural Tracer Data Interpretation

Andra dedicated a significant effort to the natural tracers studies within the Transposition Zone due to the high importance of these data to corroborating the experimental results and especially to identifying major transport mechanisms in the host rock representative of the geological time scale. The current distribution of the natural tracers in the Callovo-Oxfordian formation is a result of the large scale transport processes that took place over millions of years and affected the overall argillite thickness. Consequently, these data may be used to estimate the significance of diffusional and advective transport through the host rock.

Andra concluded that the natural tracer distribution in the Callovo-Oxfordian formation can be explained by diffusion alone. This conclusion was used as an additional justification for assuming predominant diffusive transport in the host rock.

The summary of the natural tracer analysis is provided in *Section 14.5* of the *Référentiel du Site 2010.*[135] The details can be found in *Mazurek et al. 2009*. These data were reviewed and the results of this review are discussed below. The review concentrated on chloride data because chloride is a conservative tracer and because it was studied in a number of different experiments at the site.

Relatively good chloride data sets are available for borehole EST212 and HTM102. These data are presented in the Figures 3-21 and 3-22.

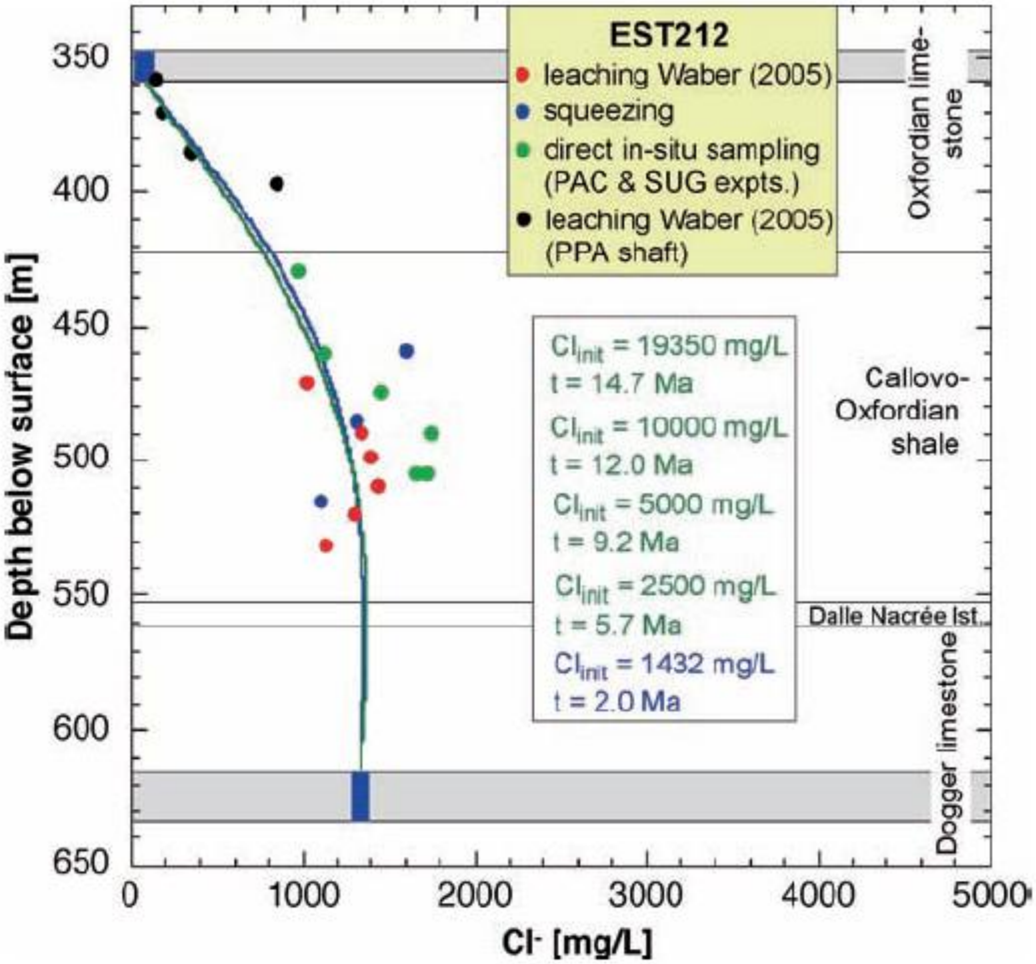


Figure 3-21. Model Predicted and Measured Chloride Concentrations in Borehole EST212 at the Bure URL Site (assuming a constant initial chloride concentration) (Source: Mazurek et al. 2009 Figure 5.1-2 (p. 153))

---

[135] Référentiel du Site 2010, Tome 1 Section 14.5 (p. 511)

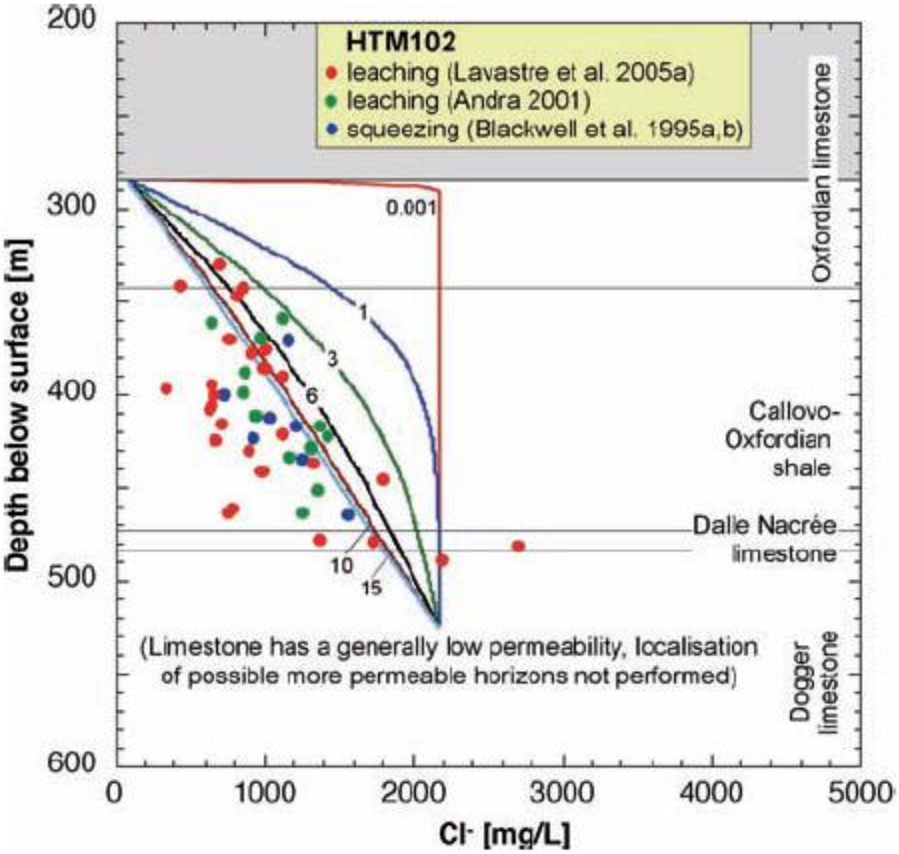


Figure 3-22. Model Predicted and Measured Chloride Concentrations in Borehole HTM102 at the Bure URL Site, 3 km Southeast of the Bure URL (Source: Mazurek et al. 2009 Figure 5.1-5 (p. 155))

The major modeling strategy used in *Mazurek et al.2009* for the interpretation of these data was simulating transient diffusional transport in the Callovo-Oxfordian formation with fixed concentration boundary conditions in the Oxfordian and Dogger formations. This approach has two considerable uncertainties. First, it requires the initial concentrations as the modeling input and these concentrations are undetermined. Second, the observed concentrations are compared to the concentrations calculated at the end of the evolution time, which is unknown. This is pointed out in *Mazurek et al.2009*

> *Because of the limited knowledge of the palaeo-hydrogeological evolution, a range of combinations of initial Cl^- concentrations and evolution times fit the data equally well, and so it is not possible to define a single base case.*[136]

In addition to the uncertainties related to the modeling approach, there is an uncertainty associated with a significant spread in the observed data.

A number of the base case modeling runs with the different initial conditions and evolution times were performed to fit the observed chloride concentration data. Based on these runs it was

---

[136] Mazurek et al. 2009 p. 152

concluded that the observed data can be well reproduced considering diffusion as the only transport process:[137]

> *All base cases consider diffusion as the only transport process – not by definition but due to the observation that adding advection does not improve the model fits to the data.*[138]

The conclusion suggests that a reasonable data fit can be obtained if both diffusion and advection are used in the simulation. A conclusion of diffusive flow alone is not wrong, but it unnecessarily and artificially constrains the possible interpretations of the data.

An estimate of an advective flow is available for the borehole EST211. The simulations for this borehole were performed for the two cases: (1) diffusion only and (2) diffusion and advection. Different advective velocities were used in the second case. These simulations showed that an equally good fit can be obtained in the first case and in the second case with the upward advective velocity equal to $1.1\text{x}10^{-13}$ m/sec assuming an initial chloride concentration of 2.15 g/L.[139] Using the higher initial concentration (5 g/L) showed that

> [*a*]*pproximate fits can be obtained for upward or downward Darcy fluxes of 2.0E-14 m/s, corresponding to an advection velocity of 2.2E-13 m/s in the Callovo-Oxfordian, with either a somewhat larger (upward advection, 5.5 Ma) or somewhat smaller (downward advection, 5.0 Ma) evolution time as compared to pure diffusion (5.3 Ma)*[140]

The following estimate is provided for the downward advective flow:

> *For downward advection, the definition of the maximum advection velocity that is still in broad agreement with the data is difficult due to the absence of data below the Callovo-Oxfordian shale and due to the unexplained high Cl^- value in the Dalle Nacrée. A flux corresponding to an advection velocity of 5.6E-12 m/s in the Callovo-Oxfordian can be tentatively considered as a maximum because the fit is becoming poor in both limbs of the profile at higher velocities*.[141]

Based on these estimates, the advective flow velocity ranges from $1.1\text{x}10^{-13}$ m/sec to of $5.6\text{x}10^{-12}$ m/sec. Using the thickness (250 m) and accessible porosity (0.05) data from *Mazurek et al.2009*, the resulting Peclet numbers are 0.27 (dominant diffusion) and 14.0 (dominant advection) respectively. This conclusion does not agree with the assumption of the dominant diffusion. It confirms that the transport properties of the host rock are heterogeneous and at some locations the diffusional transport may dominate while at other locations the advective component of transport may be comparable or greater than the diffusional one.

---

[137] Mazurek et al. 2009 Section 5.1.1 (pp. 151-155)
[138] Mazurek et al. 2009 p. 151
[139] Mazurek et al. 2009 Section 5.1.5 (pp. 162-164)
[140] Mazurek et al. 2009 p. 162
[141] Mazurek et al. 2009 p. 162

Note that Andra assumes[142] that the Darcy's velocity is a few cm in 100,000 yrs. Let us assume that a few cm is 3 cm. Then, the advective velocity is 1.05x10^{-13} m/sec (Darcy's velocity divided by kinematic porosity). Consequently, it would take a contaminant 1.8x10^{7} yrs to reach the top of the Callovo-Oxfordian formation. Now, let's consider the advective velocity of 5.6x10^{-12} m/sec, which is the upper limit derived from the natural tracer data. In this case it would take a contaminant 339,750 years to reach the top of the Callovo-Oxfordian formation. This time is comparable to the time when predicted diffusive flux at the top of the host rock reaches its maximum value (180,000 yrs to 465,000 yrs).[143] Hence, Andra's statement is optimistic in light of measured data.

An alternative approach can be considered to simulate the chloride data. This approach assumes that the observed chloride profiles are equilibrium profiles in which both advection and diffusion take place. This approach does not require the knowledge of the initial conditions and evolution time. Note, that the following conclusion was made in *Mazurek et al.2009* regarding the transient simulations:

> *Good and near-identical model fits can be obtained for a range of initial* Cl^- *contents and evolution times*.[144]

The absence of the dependence on the initial conditions and evolution time is an indication of the closeness to the equilibrium (or steady-state) conditions.

The following one-dimensional steady-state advective-diffusive transport equation in homogeneous and isotropic medium was considered:

$$D_p \frac{d^2C}{dz^2} - v \frac{dC}{dz} = 0 \qquad (2)^{145}$$

The boundary conditions at the top and at the bottom were defined as:

$$C=C_0 \text{ at } z=0 \quad \text{and} \quad C=C_1 \text{ at } z=L \qquad (3)^{146}$$

where

L is the distance between the top and bottom boundaries,
v is the vertical advective velocity, and
D_p is the pore diffusion coefficient.

Equation (2) with boundary conditions (3) has the following analytical solution:

$$\frac{C-C_0}{C_1-C_0} = \frac{\exp(\bar{v}_z \bar{z})-1}{\exp(\bar{v}_z)-1} \quad , \quad \bar{v}_z = \frac{Lv}{D_p} \quad , \quad \bar{z} = \frac{z}{L} \qquad (4)$$

---

[142] Dossier 2005 Argile, Synthesis p. 175
[143] Dossier 2005 Argile, Safety Evaluation Table 5.5-4 (p. 279)
[144] Mazurek et al. 2009 p. 165
[145] Williams 2006 Equation 1.49 (p. 22)
[146] Williams 2006 Equations 1.54 and 1.55 (p. 23)

As can be seen from Equation (4), the only parameter that can be estimated from the equilibrium concentration data is the ratio of advective velocity and pore diffusion coefficient. The higher this ratio, the more "curving" is observed. The positive ratio corresponds to the downward advection and the negative ratio corresponds to the upward advection. In the absence of advective transport (diffusional equilibrium profile) the concentrations represent a straight line.

This approach was used to interpret the data in boreholes EST212 and HTM102. The results are shown in Figures 3-23 and 3-24.

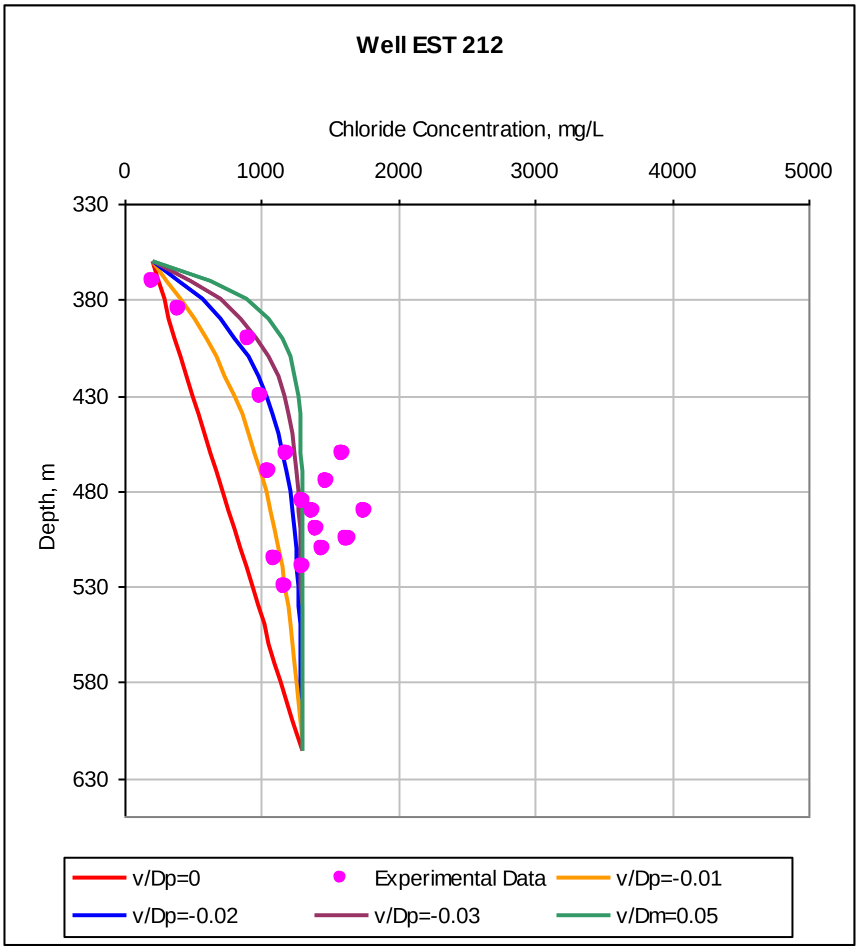


Figure 3-23. Calculated Chloride Concentrations for the Different Vertical Advective Transport Velocity to Pore Diffusion Coefficient Ratios compared to experimental data (Source: E. Kalinina)

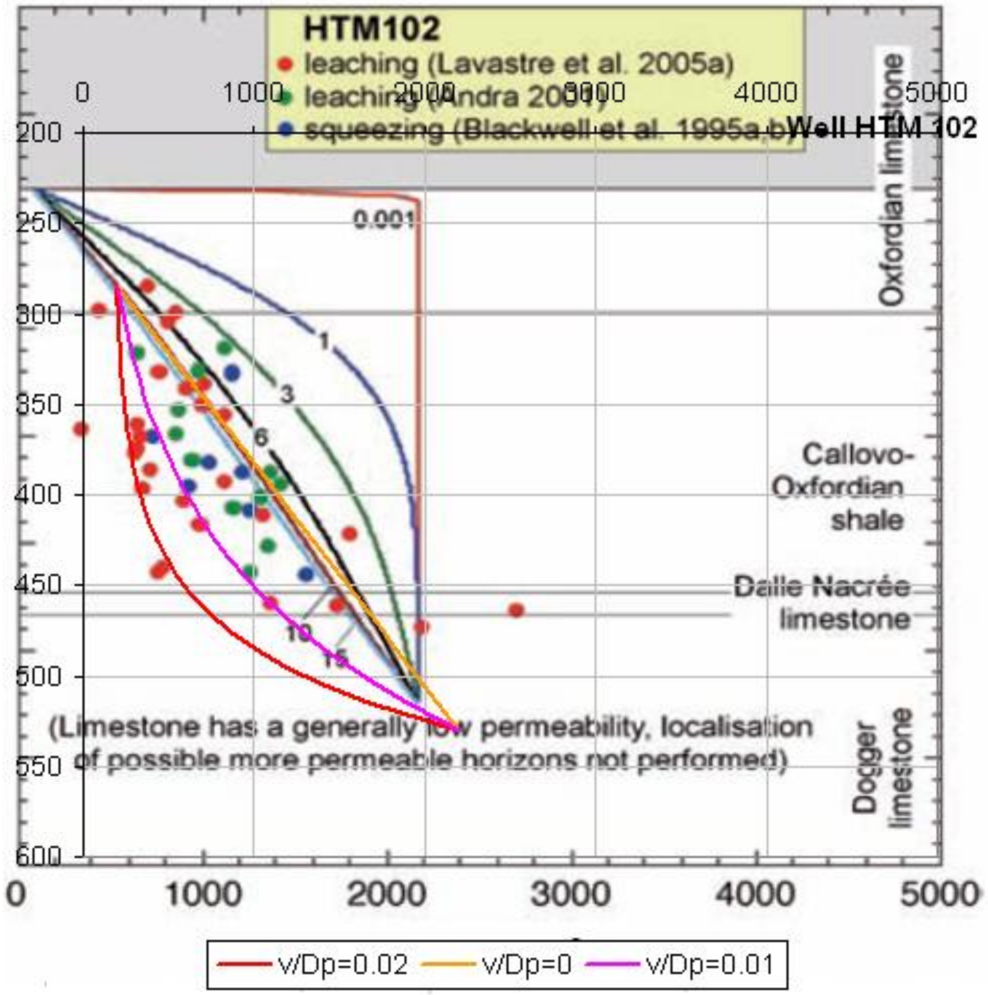


Figure 3-24. Calculated Chloride Concentrations for the Different ratios of Vertical Advective Transport Velocity (*v*) to Pore Diffusion Coefficient (D_p), plotted on the figure provided in Mazurek et al. 2009 (Figure 5.1-5, p. 155) (Source: E. Kalinina)

A few equilibrium profiles with the different v/D_p values were calculated for each borehole. Due to the spread in the concentration data the selection of the “best fit” is very subjective. The ratio of -0.02 was selected for borehole EST212 and the ratio of 0.01 was selected for borehole HTM102, though other interpretations are also possible.

The advective velocity and hydraulic conductivity can be estimated from the ratio v/D_p if the data on effective diffusion, ion accessible porosity, kinematic porosity, and vertical hydraulic gradient are available. Most of these data are available for borehole EST212. The average effective diffusion and accessible porosity values for this borehole are $6.1\text{x}10^{-12}$ m^2/sec and $0.1\text{x}10^{-12}$ m^2/sec respectively.[147] The kinematic porosity can be assumed to be the same as the accessible porosity. The hydraulic gradient was assumed to be 0.2 m/m. Based on these data the advective velocity is $6\text{x}10^{-13}$ m/sec and the hydraulic conductivity is $3\text{x}10^{-13}$ m/sec. The

---

[147] Référentiel du Site 2010, Tome 1 Tableau 14-8 (p. 496)

hydraulic conductivity value is within the range of the hydraulic conductivity data obtained for this borehole: $5x10^{-14}$ m/sec to $4x10^{-13}$ m/sec.[148]

No borehole specific data are available for borehole HTM102. The average effective diffusion, ion accessible porosity, and kinematic porosity values were used, which are $5.0x10^{-12}$ m^2/sec, 0.05, and 0.09 respectively. The hydraulic gradient was assumed to be 0.2 m/m. Based on these data the advective velocity is $1x10^{-12}$ m/sec and the hydraulic conductivity is $4.5x10^{-13}$ m/sec. The hydraulic conductivity range in borehole HTM102 is from $4x10^{-13}$ m/sec to $8x10^{-12}$ m/sec (Figure 3-10)[149] with lower values being most likely due to the disturbed conditions of this test.

In summary, the natural tracers data provide sufficient evidence that the advective transport may be comparable to the diffusional transport at some locations within the Transposition Zone. They also confirm that the transport processes have different magnitude and direction at the different locations, which appears to be mainly due to heterogeneity of the transport properties of the Callovo-Oxfordian formation.

3.2.2 Adjacent Formations

The contaminant fluxes exiting the top and the bottom of the host argillite rock are transported in the adjacent formations to the exposure points (water wells). The overlying formations include carbonate rocks of the Oxfordian, Kimmergian, and Barrois formations. The underlying formation consists of the Dogger carbonate rocks.

The carbonate formations are very heterogeneous. The intervals with the higher permeability values are considered as the advective transport zones. For example, there are 2 higher permeability intervals (also referred to as porous horizons) in the Oxfordian formation. The lower one has an average thickness of 50 m and the upper one of 5 m. One 5 m thick higher permeability interval is considered in the Dogger formation. Andra assumes that:

> "*in the calcareous Oxfordian and the Dogger formations, water flows are horizontal. Given the permeability of some levels of these formations (10^{-9} m/s to 10^{-8} m/s on average), solutes transport takes place there essentially by advection*."[150]

The Kimmergian formation is considered as the diffusion transport zone due to its low permeability. The Barrois formation is divided in two zones. The upper zone has high permeability because it is close to the surface and is affected by the karst processes.

It is reasonable to assume that most of the transport in the adjacent formations will be with the advective flow within the intervals with higher permeability. Due to relatively high permeability, the transport time to the exposure points will be significantly shorter than the transport time within the host rock. Because of this, the transport properties of these formations are only important because they define the flow paths from the repository footprints on the top and

---

[148] Référentiel du Site 2010. Tome 1 Figure 15-19 (p. 542)
[149] Référentiel du Site 2010. Tome 1 Figure 15-21 (p. 544)
[150] Dossier 2005 Argile, Synthesis p. 175

bottom of the host rock to the exposure points rather than for any significant additional delay they may introduce before the contaminants reach the human environment.

In the case when the flow paths point to the different locations, the contaminant mass is divided between these points and the total dose is "dispersed."[151] Figure 3-24 is an example of this case. In the case when all the flow paths points to the same location,[152] all the contaminant mass is captured at one exposure point, which results in the greater radiological impact.

The detailed hydrogeologic models of the adjacent formations are required to develop the corresponding flow fields. These flow fields can be used to delineate the flow paths. The flow paths will be different for the different locations within the Transposition Zone and ZIRA.[153]

As pointed out in Section 3.1, a significant effort would be required to review the adjacent formation hydrogeologic models and related data. Due to presumably lower importance of these formations to the evaluation of the radiological impact, we did not conduct this review.. An approach accounting in a simplified way for the advective transport in the Oxfordian formation is considered in Section 3.2.3.2 to check the credibility of the "lower importance" assumption.

3.2.3 Safety Assessment Analysis

The approach taken by Andra to safety assessment analysis is summarized in Section 3.2.3.1. The evaluation of this approach is considered in Section 3.2.3.2.

3.2.3.1 Summary of the Andra's Safety Evaluation Analysis

The safety assessment relies on knowledge of the properties and processes affecting the behavior of the different repository components. Based on this acquired knowledge the performance of the natural medium (geologic barrier) and engineered components (engineered barrier) is analyzed and compared to the long-term safety objectives. The long-term safety objective is expressed in the form of a radiological impact. According to the prescriptions of the International Commission on Radiological Protection (ICRP) and the recommendations of the basic safety rule RFS III.2.f,[154] radiological impact is measured based on the individual committed dose calculation for the critical group.

Andra's conclusion, based on the safety assessment, is that in the long term the repository performance is mainly defined by the performance of the geologic barrier and its components. The geologic barrier properties and processes within the Transposition Zone were discussed in Section 3.2.1 and 3.2.2. This section considers how these properties and processes and their associated uncertainties were propagated through the safety assessment model.

The following general approach to safety assessment was taken by Andra.

---

[151] Dossier 2005 Argile, Safety Evaluation Figure 5.5-16 (p. 290), is an example.

[152] Dossier 2005 Argile, Safety Evaluation Figure 5.5-74 (p. 340)

[153] Dossier 2005 Argile, Safety Evaluation Figures 5.5-16 (p. 290) and 5.5-74 (p. 340)

[154] RFS III.2.f

- The repository evolution is considered in a scenario context: "*This scenario constitutes the basis of a quantified assessment by means of safety calculations*."[155]
- Andra defines scenario as a set of conditions "*that is not intended to represent reality in the future, but rather to encompass the full range of probable situations likely to occur, with the assurance of representing a conservative and even penalizing view*."[156]
- Two types of scenarios were considered. The normal evolution scenario represents "*the situation deemed most probable or reflecting a repository behavior*".[157] The dose rate of 0.25 mSv per year is adopted as a reference threshold value in this scenario. Only the processes that have noticeable impacts on the repository performance are included in this scenario. These processes are selected based on results of the preliminary studies prior to the safety calculations. The normal evolution scenario "*is constructed so that the repository impact in a normal situation will be less than the evaluated one in the scenario*".[158]
- The altered scenarios represent the conditions corresponding to highly improbable situations. The calculated impact is considered as an absolute value as well as in terms of the scenario likelihood and the chronic or transient punctual character of the exposures. The dose exceeding the threshold value of 0.25 mSv per year is considered to be acceptable due to its low probability.[159]
- The radioactive impacts were evaluated at the locations (outlets) where radioactivity may reach the environment.[160] In defining the outlets it was assumed that the main radioactivity transport occurs via the water pathway. Consequently, the outlets may consist of rivers, aquifers, or water wells. These outlets were defined based on the analysis of the evolution of the geological medium and the radioactivity transport pathways from the repository.
- The possible uncertainties with regard to the process representation or physical parameter values were considered through sensitivity analyses. A number of these analyses were conducted on the safety model to test parameter sets or models different from those selected as most representative.[161]
- In the sensitivity analyses the models and parameters that best reflect the physical reality were distinguished from those intended to provide "conservative" or "penalizing" results depending on the degree of conservatism. Both the extreme values for certain parameters corresponding to highly penalizing situations and favorable values were considered. According to Andra, the purposes of the sensitivity analyses were to assess the respective importance of the various parameters and "*to measure the impact of these variations and determine whether a more in-depth study is required, either to increase safety margins or further reduce certain uncertainties*".[162]

---

[155] Dossier 2005 Argile, Synthesis Section 2.1 (p. 188)
[156] Dossier 2005 Argile, Synthesis Section 2.1 (p. 188)
[157] Dossier 2005 Argile, Synthesis p. 190 in Section 2.1.2
[158] Dossier 2005 Argile, Synthesis p. 191 in Section 2.1.3
[159] Dossier 2005 Argile, Synthesis Section 2.1.2
[160] Dossier 2005 Argile, Synthesis p. 190 in Section 2.1.2
[161] Dossier 2005 Argile, Synthesis Section 2.1.3
[162] Dossier 2005 Argile, Synthesis p. 192 in Section 2.1.3

In this section only the normal evolution scenario and related sensitivity analyses are reviewed because this scenario represents the most likely situation. We did not consider the altered evolution scenarios (container failure, seal failure, drilling an intrusive borehole) because of the two following reasons: (1) a significant additional effort would be required to review the completeness of all the situations, the issues related to scenario probabilities, and the modeling implementations and (2) these scenarios should have very low probability of occurrence and potentially low impacts on the repository performance (assuming that the scenario probabilities and parameters were defined adequately).

The normal evolution scenario implements the expected behavior of all the systems via considering the major processes related to the radionuclide release from the waste form, their transport in the engineered barrier (repository components) and in the host rock and adjacent formations, and their release at the exposure points assuming the expected (average) values for the modeling parameters.

The radiological impact is evaluated in the form of a total maximum dose to a critical group calculated during a one million year period based on the radionuclide concentrations in the water at the exposure locations and expected exposure parameters (e.g., a drinking water ingestion rate and others). The critical group in this scenario is defined as: "*a group of farmers living mainly from their own harvest and drinking water from their own wells: drinking water, irrigating a vegetable garden, watering and raising livestock from their own cereal harvest.*[163] *The individuals are all subject to uniform concentration, either directly in their drinking water or through contaminated food that they may consume.*"[164]

The exposure is assumed to be via using contaminated groundwater. The contaminated groundwater comes from the water wells installed in the carbonate rock intervals with higher hydraulic conductivity (porous horizons) in the surrounding formations. The water well is used by a critical group member for drinking purposes or agricultural use. The wells are placed as close as possible to the conventional repository site in zones with low water flows, and in most cases at depths of approximately 50 to 100 meters. In accordance with the basic safety rule RFS III.2.f, it was assumed that human behavior in the future will be generally the same as today (i.e., the exposure parameters, such as intake rates of water and food as well the types of food, remain the same over a one million year period).

During the IEER meeting with Andra on 16 February 2011, Andra provided a clarification concerning the exposure locations considered in the normal evolution scenario. IEER's original interpretation, explained above, was that Andra considered the groundwater use. Based on Andra's explanation, it became clear (and it was confirmed by Andra) that groundwater use was excluded from the safety analysis. Only the groundwater that discharges in specific locations was considered. Consequently, the estimated doses do not take in account the situation in which a member of a critical group would drill a well and would withdraw groundwater from the upper aquifer. Including groundwater use would significantly increase the dose estimates.

---

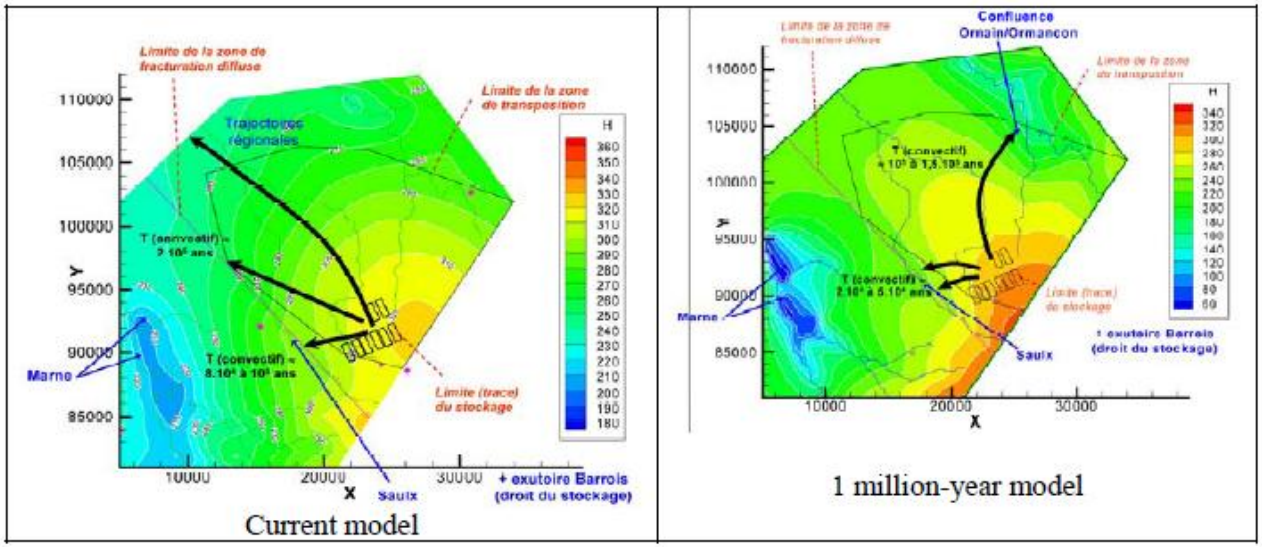
[163] Dossier 2005 Argile, Safety Evaluation p. 250

[164] Dossier 2005 Argile, Safety Evaluation p. 245

Two situations have been considered for the geologic medium. The first situation represents the current state of the geologic medium with corresponding flows in the various formations (current model). The second model represents the predicted state of the geologic medium at one million years (one million year model). It was assumed that the main factor that impacts the hydrogeologic conditions in one million year is surface erosion. As a result, the main difference between the two models is in the simulated flows in the carbonate formations overlying the Callovo-Oxfordian argillites. A set of the potential flow paths in the upper carbonate aquifers from the repository to the exposure locations was defined for each of two models. Note that these changes do not affect the flow in the Dogger aquifer, which remains the same in both cases.

During the IEER meeting with Andra on 16 February 2011, Andra explained that the Ornain outlet was defined based on the results of erosion simulations by the end of 1 million year period. That was the only location in which the groundwater discharges at the surface based on the modeling results. Taking in account a number of uncertainties related to a one million year period it is arguable that only one such location can be defined.

Three exposure locations were considered in the upper carbonate aquifers. Two locations are different in the current and one million year model. One location (Saulx outlet) remains the same. The locations and the flow paths used in these two models are shown in Figure 3-25.



Current model

1 million-year model

Figure 3-25. Results of the Sensitivity Analysis for the Normal Evolution Scenario: Current Hydrogeologic Conditions versus the Hydrogeologic Conditions at 1 Million Years (Source: Dossier 2005 Argile, Safety Evaluation Figure 5.5-16 (p. 290))

Two approaches were used to estimate contaminant concentrations at the exposure locations. In the first approach, the contaminant concentrations were calculated as a ratio of the contaminant flux and the well pumping rate (Ornain outlet in one million year model). In the second approach the maximum concentrations in the contaminant plume at the location of the well were used (Saulx outlet).

The same conventional water well outlet near the Saulx valley was selected as the exposure location in the Dogger aquifer in both models.

The contaminant concentrations in the overlying and underlying carbonate formations were calculated based on the contaminant fluxes exiting the top and the bottom of the Callovo-Oxfordian argillites. These contaminant fluxes were calculated from simulating radionuclide releases from the waste packages and their transport within the engineered structures and unaltered argillites.

A separate scenario was considered for each reference package (C, B, and CU). Each scenario incorporated package specific inventory, contaminant release model, and near-field thermal and chemical conditions. The total maximum dose was calculated for all of the C waste packages, all of the B waste packages, and all the spent fuel (CU) packages.

The following conclusions were made by Andra based on the results obtained from simulating normal evolution scenario.

- "*The hydraulic disturbance caused by the repository remains limited to the repository itself and the Callovo-Oxfordian formation on account of its low permeability. It disappears after approximately 100,000 years and a new state of hydraulic equilibrium is then established in the repository and the Callovo-Oxfordian layer*."[165]
- "*After total resaturation of the repository, vertically, the repository drains a small proportion of the flows through the Callovo-Oxfordian formation: a water flows appears along the repository engineered structures and the shafts (several tens to several hundreds of liters per year), far too little to transport solutes by advection. Diffusion is the dominant mechanism of solutes transport (radionuclides in particular) and everything is similar as in the initial state prior to the repository construction*." [166]
- Because the repository is located in the "*middle of the Callovo-Oxfordian formation, the distribution between the ascending and descending flows is nearly equivalent*."[167]
- *"… most of the mass is transferred into the Callovo-Oxfordian, which is therefore the privileged medium for transfer."*[168]
- "*The host formation, which is the main contributor of the « delaying and reducing the migration of radionuclides » function*." [169]
- "*only four elements (iodine 129, chlorine 36, selenium 79 and calcium 41) still present a flow at the top of the Callovo-Oxfordian. However, calcium 41 and selenium 79 are already very strongly attenuated*."[170]
- "*among the four previous elements, only iodine and chlorine have smaller attenuation coefficients, 65 to 75% for chlorine and 20 to 50% for iodine*." [171]
- "*After leaving the clay formation, non-attenuated elements penetrate the surrounding formations (Oxfordian above, Dogger below). The hydrogeological model can then be used*

---

[165] Dossier 2005 Argile, Synthesis p. 175
[166] Dossier 2005 Argile, Synthesis p. 177
[167] Dossier 2005 Argile, Safety Evaluation p. 276
[168] Dossier 2005 Argile, Synthesis p. 210
[169] Dossier 2005 Argile, Safety Evaluation p. 275
[170] Dossier 2005 Argile, Synthesis p. 212
[171] Dossier 2005 Argile, Synthesis p. 212

to assess the transfer time to the various outlets. These transfer times are short relative to those within the geological formation (about 50 000 years for the "one million years" model and 100 000 years for the current model, for the outlet closest to the Saulx river, which is the most penalizing)." [172]

- *"In the calcareous Oxfordian and the Dogger formations, water flows are horizontal. Given the permeability of some levels of these formations (10^{-9} m/s to 10^{-8} m/s on average), solutes transport takes place there essentially by advection*."[173]
- "*Characteristic migration times through advection in the Oxfordian limestone up to this outlet are effectively short in comparison with the migration time in the host formation, such that they do not bring about significant spread complementary to the appearance of maximum dose*." [174]
- *"In the Dogger formation, the radionuclides migrate horizontally towards the west-south-west at a very slow velocity up to a few kilometers over a time scale of a million years*."[175]
- "*In the Dogger, (see example in Figure 5.5-15) most of the mass migrates by diffusion towards the bottom. Molar flow analysis show that 0.03 % of the mass transits in the layer with strongest permeability (10^{-8} m/s) up to the level of the conventional outlet. This transmissive layer presents to small a thickness (5 meters), as compared to its immediate surrounding formations (terminal and basal Dogger) having lower permeability (10^{-10} m/s), to constitute a preferential drain of radionuclides*."[176]
- "*The essential contributors to the dose are iodine 129, chlorine 36 and selenium 79*." [177]

The results of the safety analysis for the one million year model are presented in *Dossier 2005 Argile, Safety Evaluation Volume, Tables 5.5-8* (Saulx outlet) and *5.5-9* (other outlets). The total maximum doses estimated at Saulx outlet are significantly higher than at two other outlets. They are 0.00047 mSv/yr (Total of B waste), 0.00083 mSv/yr (Total of C waste), and 0.02 mSv/yr (Total of spent fuel).

A contaminant plume for I-129 at the time close to the maximum concentration time is shown in Figure 3-26.

---

[172] Dossier 2005 Argile, Synthesis p. 212
[173] Dossier 2005 Argile, Synthesis p. 175
[174] Dossier 2005 Argile, Safety Evaluation p. 291
[175] Dossier 2005 Argile, Synthesis p. 187
[176] Dossier 2005 Argile, Safety Evaluation p. 288. Figure 5.5.15, cited in the quote is on p. 289.
[177] Dossier 2005 Argile, Synthesis p. 213

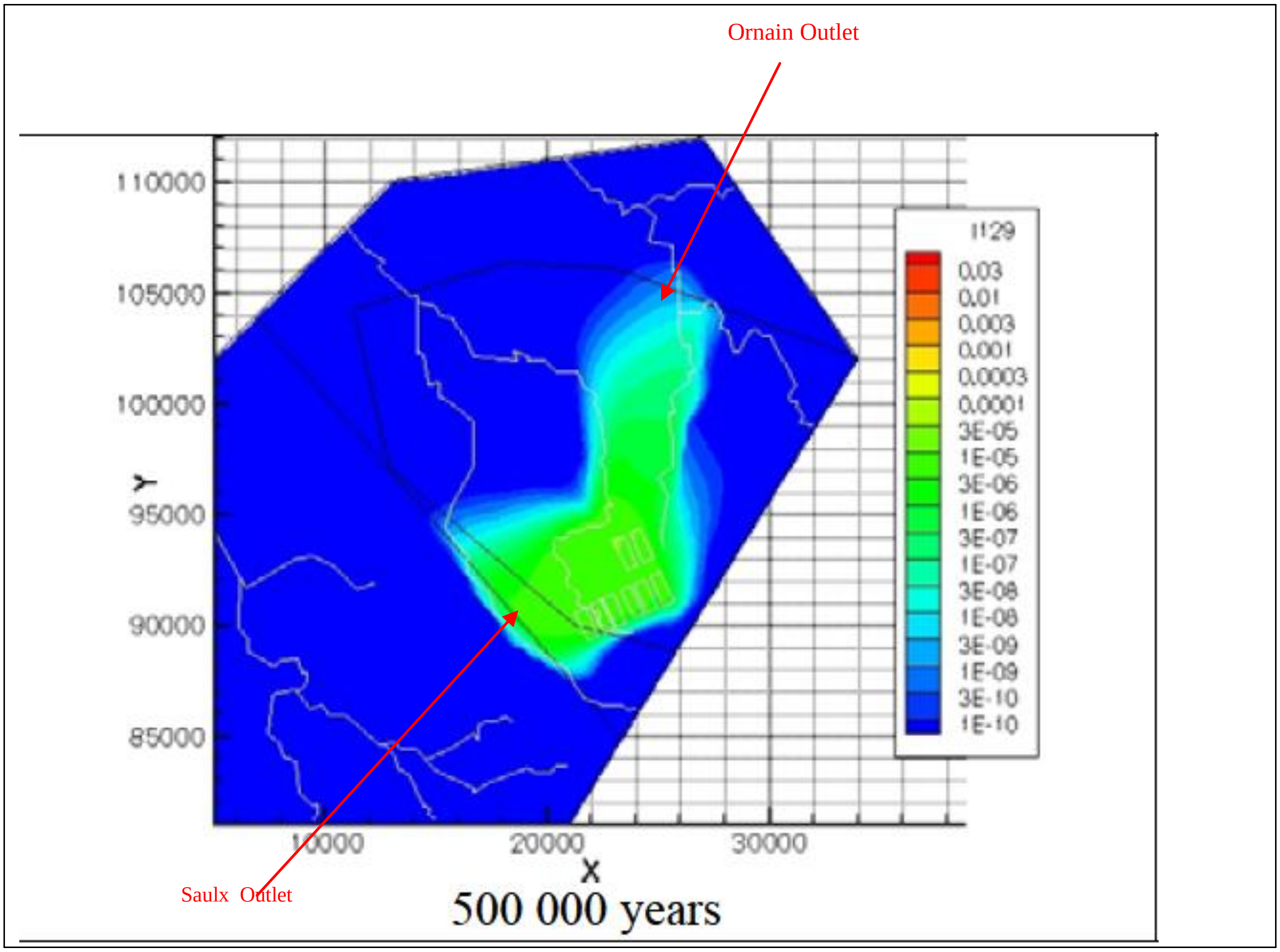


Figure 3-26. Normal Evolution Scenario, I-129 Plume at 50,000 yrs (Source: Dossier 2005 Argile, Safety Evaluation, detail of Figure 5.5-13 (p. .287))
Note: The outlets at Ornain and Saulx were added to this figure.

As it can be seen from Figure 3-26 above, the two major outlets are located on the edge of the contaminant plume. Note that "*Outlets are represented by water pumping operations at a level where an individual from a critical group collects radionuclide contaminated water for his drinking needs or agricultural operations.*"[178] These are two possible locations of these outlets. No current groundwater withdrawal occurs at these locations. Andra did not consider the potential location within the contaminant plume. The sensitivity analyses addressed the waste release models, engineered barrier parameters, and geologic barrier parameters. As it was explained above, Andra provided additional clarification concerning the exposure location. The new interpretation offered by Andra resulted even in greater concerns. These concerns as explained above are: (1) excluding groundwater use from the safety analysis and (2) not considering uncertainty in erosion over one million year period when defining the Ornain outlet location.

The sensitivity analyses of the models take into account the models for waste release, the parameters of the engineered barriers, and the parameters of the geological barrier.

---

[178] Dossier 2005 Argile, Safety Evaluation p. 243

Andra's major conclusion of the waste release and engineered barrier sensitivity analyses was that the potential impacts, based on considering conservative models and parameters, are very small.

The sensitivity analyses related to the geologic barrier addressed the parameters characterizing Callovo-Oxfordian argillites and the parameters and hydrogeologic models of the surrounding formations. The sensitivity analysis of the argillite properties considered the following cases:

1. Conservative Callovo-Oxfordian permeability (higher by a factor of 10),
2. Conservative transfer and retention parameters of the Callovo-Oxfordian : sorption, diffusion, and solubility limit for the Callovo-Oxfordian,
3. Less conservative argillites thickness of 160 m,
4. An iodine partition coefficient of 10^{-3} m^3/kg (the nominal value is zero),
5. Lower diffusion coefficients of the low-permeable layers of the overlying formations,
6. Different flow paths in the overlying formations.

Andra did the analysis varying only one parameter at a time. Only 2 of these analyses (retention properties of argillites and flow pathways in overlying formations were carried out to the total maximum dose evaluation. The other analyses only compared the fluxes exiting the Callovo-Oxfordian formation. No probabilistic assessment, with parameter distributions fully represented and varying at the same time in Monte Carlo realizations, was done.

The following conclusions were made by Andra based on the analyses that considered conservative parameters, i.e., parameters that would give higher dose estimates according to Andra:

- In the case of the higher argillite permeability the fluxes exiting the host rock increase by a factor of 2. "*The result can be explained by the fact that the transport conditions remain diffusive or co-dominant diffusive - advective. The study confirms that the dominant diffusion characteristic of the Callovo-Oxfordian is not drastically sensitive to the permeability of the host formation (see Figure 5.5-34), as long as it remains within values of less than* 10^{-12} *m/s*."[179]
- In the case of conservative retention parameters "*Degradation of argillites retention properties partly modifies the list of radionuclides attenuated by the formation, but does not cause any major dose evolution at the outlet*."[180] In terms of the total maximum dose "*for the spent fuels (CU1) which have the largest impact, the maximum dose at the Saulx outlet equals approximately 0.04 mSv/year at around 200,000 years, both in the 1 million year and in the current model*." .[181] This is 2 times higher than in the normal evolution scenario calculations.
- In the case of the lower diffusion coefficients of the low-permeable layers of the overlying formations "*The maximum dose at the Saulx and Ornain outlets drops by approximately 70*

---

[179] Dossier 2005 Argile, Safety Evaluation p. 306

[180] Dossier 2005 Argile, Synthesis p. 218

[181] Dossier 2005 Argile, Safety Evaluation p. 314

% and the occurrence of the dose maximum is delayed by about 170,000 additional years."[182]

- The greatest impact was estimated for the repository location shown in Figure 3-27. The total maximum dose for CU1 increased 10 times from 0.019 mSv/yr to 0.19 mSv/yr.

Note that the conclusions about *relative* magnitudes of doses should apply to all waste types based on Andra's conclusion that there is only "*a slightly higher attenuation for B waste concepts than for C waste and spent fuel concepts.*"[183]

In summary, the results presented in *Dossier 2005 Argile, Safety Evaluation* for the reference calculations and the sensitivity analyses indicate that an increase in the total maximum dose, using conservative parameters, is on an order of one magnitude or less.

Based on these sensitivity analyses results Andra infers: "*The conclusions of the safety analysis are relatively insensitive to the residual uncertainties*."[184]

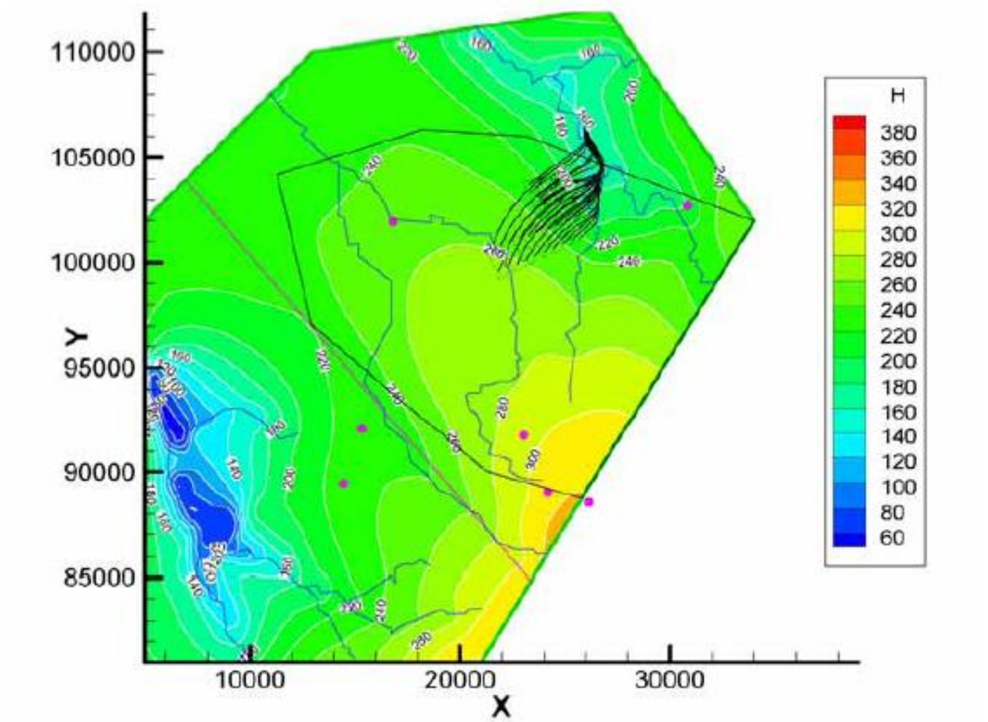


Figure 3-27. Normal Evolution Scenario – Sensitivity to the position of the repository - hydraulic pathways in the porous horizons Hp1-Hp4 – Position of the North repository (Source: Dossier 2005 Argile, Safety Evaluation Figure 5.5-74 (p. 340))

---

[182] Dossier 2005 Argile, Safety Evaluation p. 336

[183] Dossier 2005 Argile, Safety Evaluation p. 278

[184] Dossier 2005 Argile, Safety Evaluation p. 650

3.2.3.2 Safety Assessment Analysis Evaluation

The review of the safety analyses conducted by Andra and summarized in Section 3.2.3.1 brings up the following concerns:

- The normal evolution scenario and associated sensitivity analyses relies on the homogeneity and isotropy of the transport properties of the Callovo-Oxfordian formation while these properties are heterogeneous and anisotropic as discussed in detail in Section 3.2.1.
- The parameter ranges considered in the sensitivity analyses are more narrow than the parameter ranges actually observed (this is also discussed in Section 3.2.1). This especially concerns the vertical hydraulic conductivity of argillites. As a result, the predicted impact on the total dose is small (an order of magnitude or less).
- No sensitivity analyses were conducted to evaluate the impacts from the uncertainties in the exposure parameters (e.g., drinking water ingestion rate, well pumping rate, food consumption rates and other).
- Most of the sensitivity analyses are not carried out to the total dose calculations. As a result, adequate impact comparisons cannot be done.
- The potential impacts of the parameter and model uncertainties were evaluated through the sensitivity analyses and no probabilistic dose assessment was done. As a result, the estimated impact of an order of magnitude based on sensitivity studies may not be representative of the potential range.
- Only one sensitivity analysis considered the case in which all the flow paths from the repository lead to one exposure location. This case resulted in the highest total maximum dose. In all the other cases, the contaminant mass was divided between 3 different exposure locations, which resulted in “spreading” of the total dose with consequent lower values.
- The highest total maximum dose for the CU1 reference package of 0.19 mSv/yr was estimated for the case when the repository is located just north from the northern ZIRA boundary. This estimate may go up at least 2 times and exceed the regulatory limit of 0.25 mSv/yr if the conservative transport properties of the host rock are used instead of the average ones.
- The two major outlets considered in dose evaluation are located on the edge of the major contributor (I-129) plume, which may result in underestimating total doses.

The additional concerns, based on the IEER meeting with Andra on 16 February 2011, are: (1) excluding groundwater use from the safety analysis and (2) not considering uncertainty in erosion over one million year period when defining the Ornain outlet location.

A simple probabilistic safety assessment was performed to estimate a potential uncertainty in the total maximum dose. Note that the purpose of this assessment was to demonstrate the potential range in the maximum total dose estimates, not the actual dose. The increase in range of potential total dose – that is, a higher dose at the high end and a lower dose at the low end than estimated by Andra -- would apply relatively independent of scenario. Of course, the actual dose is dependent on the scenario, which defines the source term. We note that a definitive source term, including the amounts and types of waste, has not yet been defined for the proposed repository at Bure.

A simplified safety assessment model was developed using the conclusions made by Andra based on the normal evolution scenario simulations. The following assumptions were made:

- The reference package inventory includes 3 radionuclides: I-129, Cl-36, and Se-79. This is based on the conclusion that these three radionuclides are the major contributors to dose. These radionuclides were assumed to be non-sorbing and highly soluble.
- The reference package inventory is instantly dissolved in the pore water. This is based on the conclusion that the waste release model shows little impact. The time when this instantaneous dissolution occurs depends on the waste type.
- Only half of the radionuclide inventory transported towards the top of the host rock is considered. This is based on the dose results according to which the highest impact occurs in the overlying formations.
- The other half of the inventory travels to the bottom of the host rock and is not considered.
- The ranges in the host rock transport parameters were defined consistent with the ranges used by Andra in the sensitivity analyses.
- Two transport models in the host rock were considered – diffusive transport only and diffusive and advective transport. The fixed length of the transport path equal to 65 m was used in all the simulations (the distance from the middle part of the waste to the top of the host rock).
- The only exposure was assumed to be due to the consumption of drinking water. The other exposure pathways were not included. This assumption results in an underestimation of dose relative to the resident farmer scenario used by Andra and is made here only for simplicity.
- Two exposure scenarios were considered. In the first scenario the pumping well was placed above the repository in the overlying formation. The radionuclide flux exiting the top of the host rock was entirely captured by the well. No credit was taken for the radionuclide transport in the overlying formations. In the second scenario, the pumping well was placed at some distance from the repository and the advective transport in the overlying formation (within the porous interval with the higher permeability) toward this well was considered.
- The commonly accepted radionuclide dose conversion factors for internal radiation from ingestion were used to calculate the dose associated with each radionuclide: 7.46×10^{-8} Sv/Bq (2.76×10^{-4} mrem/pCi) for I-129; 2.35×10^{-9} Sv/Bq (8.7×10^{-6} mrem/pCi) for Se-79; , and 8.19×10^{-10} Sv/Bq (3.03×10^{-6} mrem/pCi) for Cl-36[185].

The parameter probability distributions used in this simplified safety assessment model are described below.

- Total porosity: uniform distribution with minimum of 0.14 and maximum of 0.18.
- Anion accessible porosity: uniform distribution with minimum of 0.07 and maximum of 0.09.
- Vertical hydraulic conductivity: truncated lognormal distribution with a mean of 1.0×10^{-13} m/sec, geometric standard deviation of 1.5, minimum of 5×10^{-14} m/sec, and maximum of 5×10^{-13} m/sec.

---

[185] RESRAD User's Manual 2001 Table D.1

- Vertical gradient between the Oxfordian and Dogger aquifers: uniform distribution with minimum of 0.05 m/m and maximum of 0.2 m/m.
- Anion diffusion coefficients: triangular distribution with the most likely value of $5.0\text{x}10^{-12}$ m^2/sec, , minimum of $5.0\text{x}10^{-13}$ m^2/sec, and maximum of $8\text{x}10^{-12}$ m^2/sec.
- Oxfordian hydraulic conductivity: lognormal distribution with mean value of $3.0\text{x}10^{-8}$ m/sec and and geometric standard deviation of 1.8.
- Transport path length in Oxfordian: uniform distribution with minimum of 2,000 m and maximum of 4,000 m.
- Horizontal gradient in Oxfordian formation: uniform distribution with minimum of 0.005 and maximum of 0.02.[186]
- Effective porosity of the Oxfordian formation (porous horizon): uniform distribution with minimum of 0.08 and maximum of 0.18
- Thickness of the high permeability layer: uniform distribution with minimum of 40 m and maximum of 60 m (average thickness is 50 m)[187], 25%-35% of the total thickness of Oxfordian formation.[188]
- Dispersivity in the Oxfordian formation: uniform distribution with minimum of 1 m and maximum of 10 m.[189]
- Drinking water ingestion rate: uniform distribution with minimum of 1.5 L/d and maximum of 2.5 L/d.
- Well pumping rate: uniform distribution with minimum of 75 L/min and maximum of 125 L/min. The mean pumping rate corresponds to the value of 100 L/min used by Andra.[190]

The Goldsim computer code[191]was used to implement this model. This code provides tools for probabilistic modeling of the major transport processes related to toxic and radioactive contaminants

The results of the simulations based on 25 realizations are presented in Figure 3-28. The mean total maximum doses are shown for the following three cases: (1) diffusion only, (2) diffusion and advection in Callovo-Oxfordian formation, and (3) diffusion and advection in Callovo-Oxfordian formation and advection in Oxfordian formation. As it can be seen from this figure, the difference in the total doses when both diffusion and advection are considered in Callovo-Oxfordian formation is about an order of magnitude as opposed to Andra estimate of 2 times.[192] The transport in Oxfordian formation results in smaller doses during the first 800,000 years compared to the diffusion and advection in COX, but the total maximum dose is similar. This is in line with Andra's conclusion concerning the lower importance of the transport parameters of the overlying formations. In all the simulations the major dose contributor was iodine-129. The contributions of selenium-79 and chlorine-36 to the total maximum dose are small.

---

[186] Référentiel du Site 2010, Tome 1 Section 15.2.2.1
[187] Dossier 2005 Argile, Safety Evaluation p. 242
[188] Référentiel du Site 2010, Tome 1 Section 12.4.1.2
[189] Référentiel du Site 2010, Tome 1 Tableau 15-6
[190] Dossier 2005 Argile, Safety Evaluation, p.246
[191] GoldSim User's Guide 2002
[192] Dossier 2005 Argile, Safety Evaluation p. 306

The mean total doses and the upper and lower limit doses are shown in Figure 3-29 below for the case of diffusion and advection in the COX formation. As can be seen in Figure 3-29, the uncertainties in the input parameters result in the uncertainty in the total maximum dose within 5 orders of magnitude. This is significantly larger uncertainty than estimated by Andra (one order of magnitude as discussed in details above in Section 3.2.3.1).

Specifically, Andra's range of uncertainty is a factor of 2 when the repository is at the lab and 10 when it is in the middle of the Transposition Zone, while our results indicate an uncertainty range of 5 orders of magnitude.

The difference in the maximum total dose between the "average deterministic" and the upper limit of the probabilistic simulation is about 2 orders of magnitude. This indicates that the results of sensitivity analyses (by an order of magnitude difference in the maximum total dose) do not reflect the potential range (2 orders of magnitude as shown in the simplified probabilistic assessment).

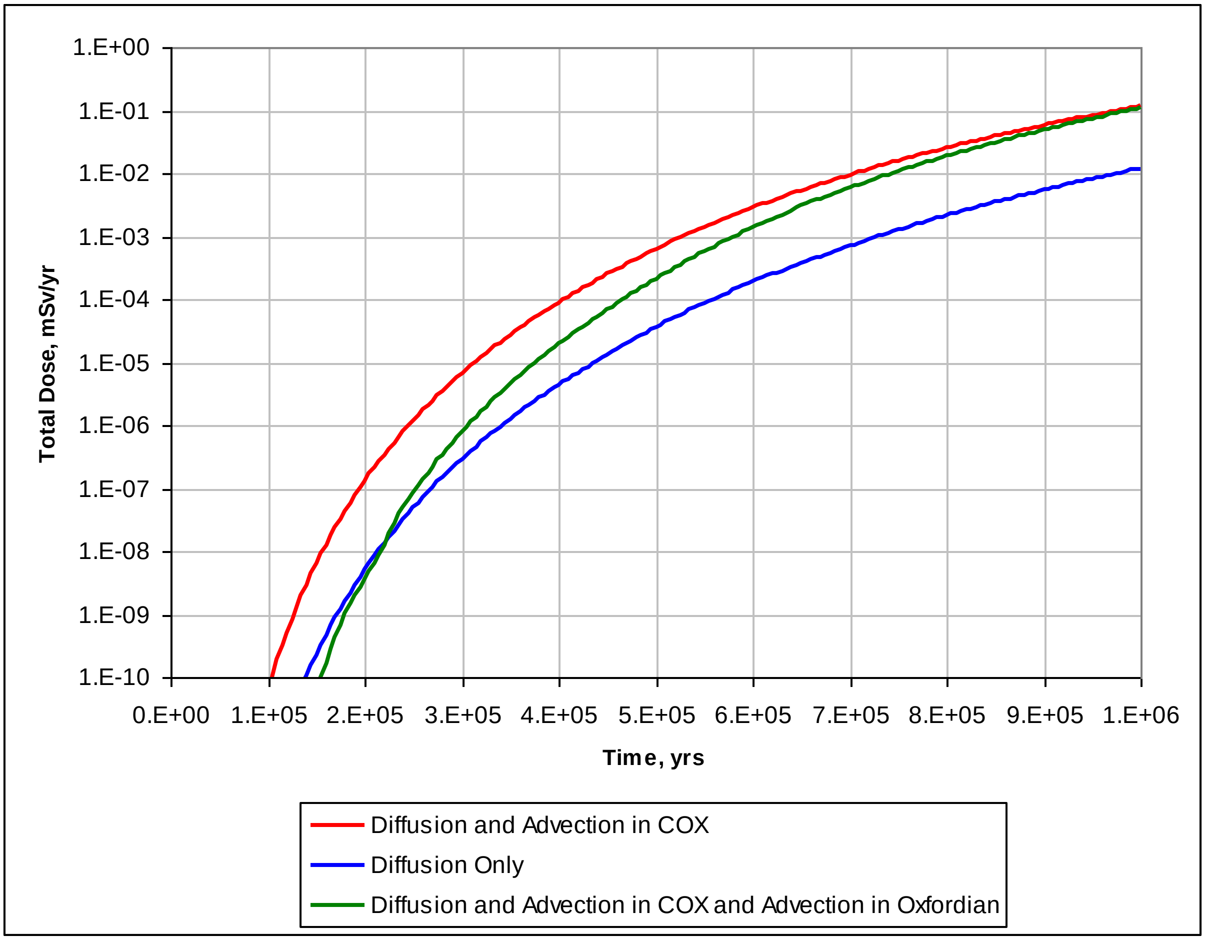


Figure 3-28. Mean Total Doses for the Different Conceptual Models (Source: E. Kalinina). Note: Doses are meant to show effect of assumptions about diffusive and advective flow and not necessarily estimates of outcomes.

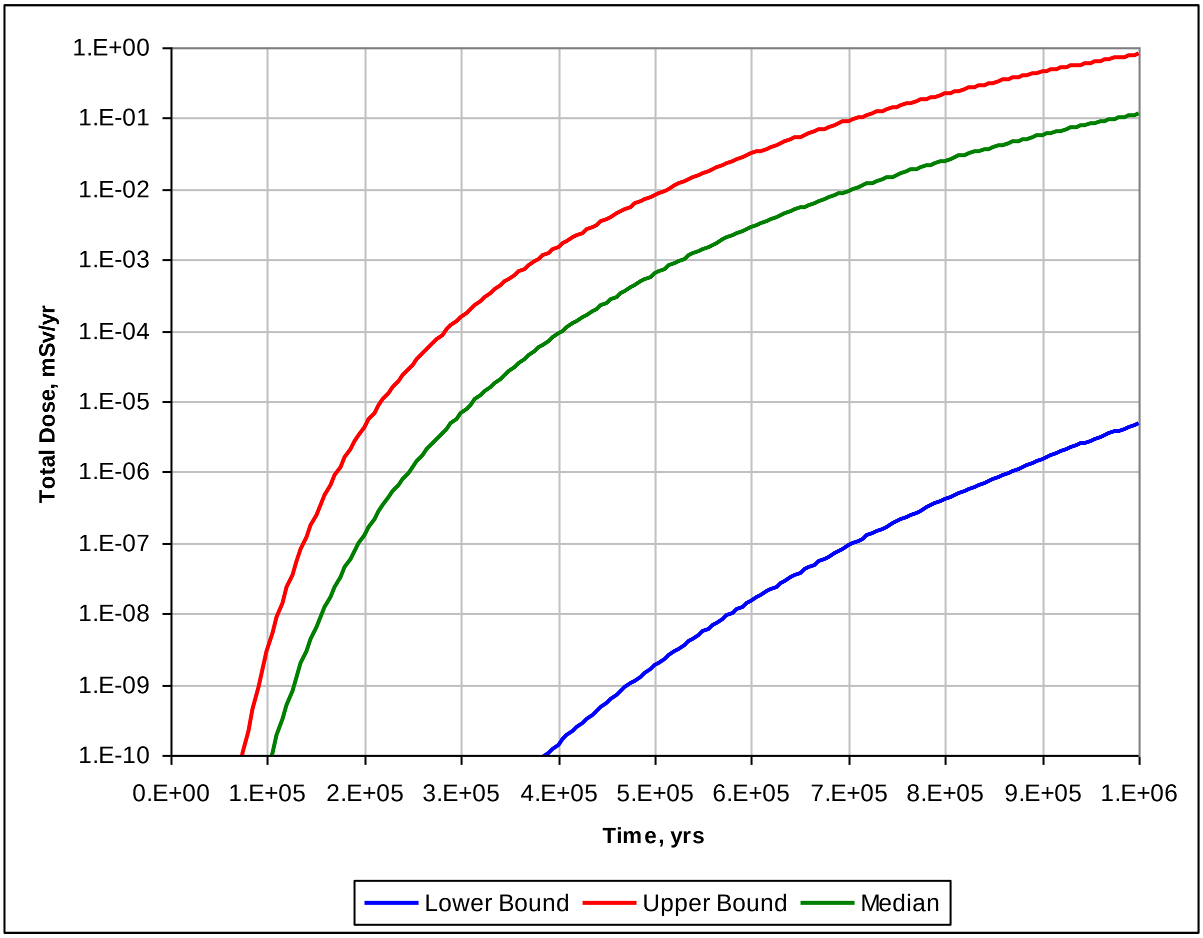


Figure 3-29. Uncertainty in the Total Doses for the Diffusion and Advection in Callovo-Oxfordien Conceptual Model (Source: E. Kalinina)
Note: Doses are meant to show range of uncertainty and not necessarily estimates of outcomes.

Note that the uncertainty range of 5 orders of magnitude is common for safety analyses. The total dose uncertainty estimated for the potential repository at the Yucca Mountain site is provided below to illustrate this statement. As it can be seen from this figure even larger uncertainty was estimated for the Yucca Mountain site.

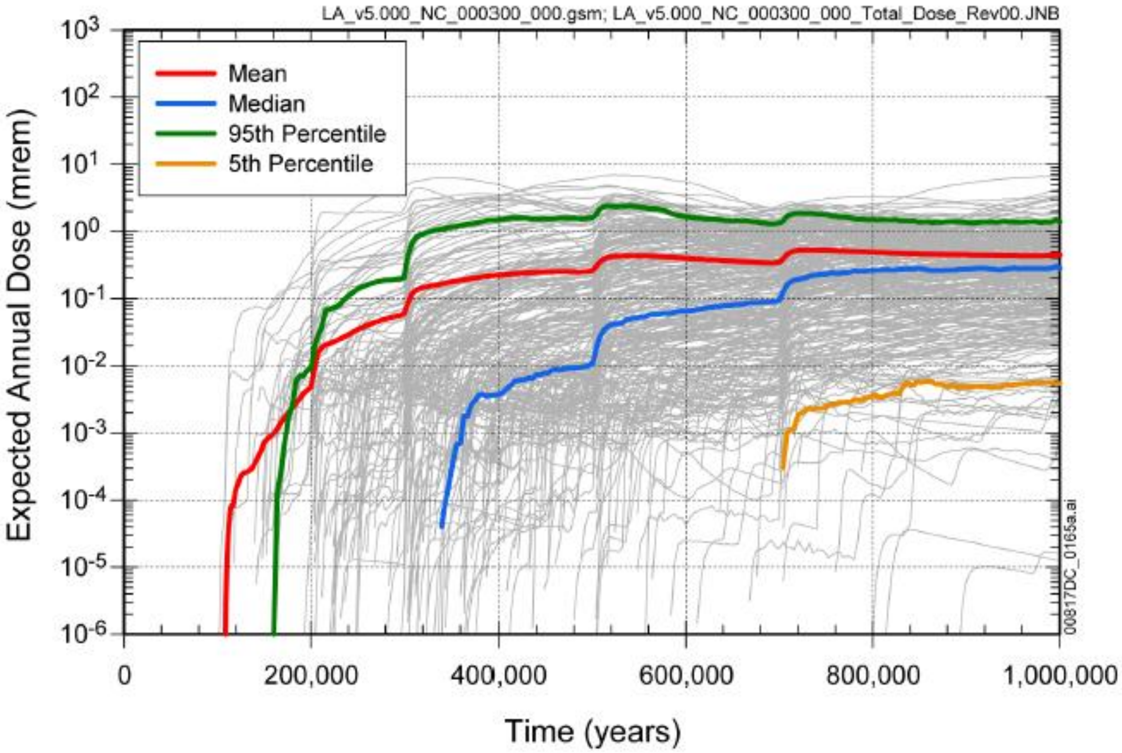


Figure 3-30. Example of Dose Estimate for the Yucca Mountain Site (Source: Sandia 2008 Figure ES-44 (p. FES-44))

The results of the sensitivity analysis performed with the simplified safety assessment model are presented in Figure 3-31 for the case of diffusional and advective transport in the Callovo-Oxfordian formation and advective transport in the Oxfordian formation. The most important parameters are the effective diffusion coefficient of anions, hydraulic conductivity of the Callovo-Oxfordian formation, and the vertical hydraulic gradient between the Oxfordian and Dogger formations.

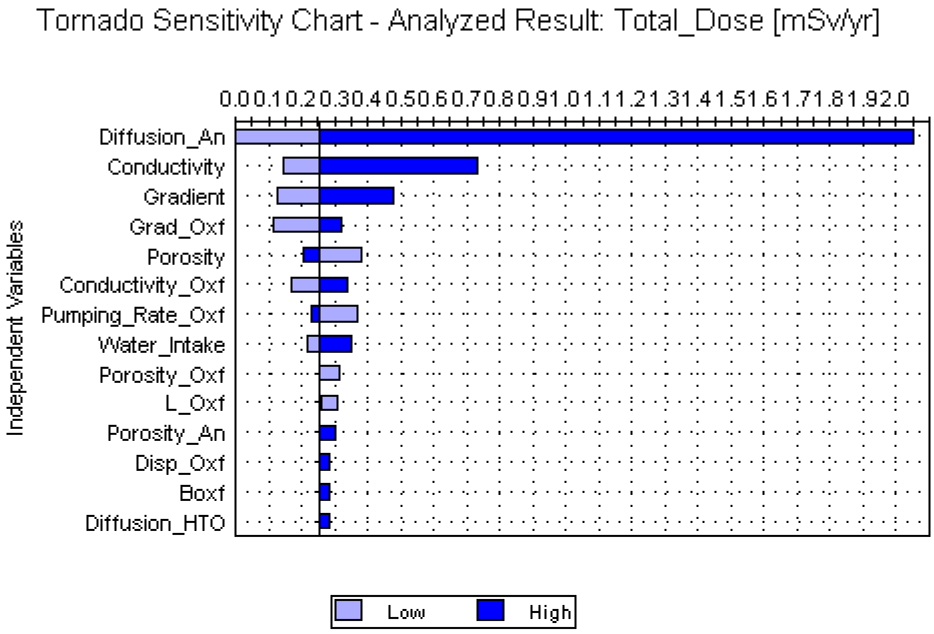


Figure 3-31. Results of the Sensitivity Analysis for the Advective-Diffusion Transport in Callovo-Oxfordian Formation and Advective Transport in Oxfordian Formation (Source: E. Kalinina)

NOTE:

Diffusion_An is the argillite effective diffusion coefficient for anions
Conductivity is the argillites hydraulic conductivity
Gradient is the vertical gradient between the Oxfordian and Dogger formations
Grad_Oxf is the horizontal gradient in Oxfordian formation
Porosity is the argillites total porosity
Conductivity_Oxf is the hydraulic conductivity of the Oxfordian carbonate rocks
Pumpin_Rate_Oxf is the well pumping rate
Water_Intake is the drinking water intake rate
Porosity_Oxf is the effective porosity of the Oxfordian carbonates
L_Oxf is the distance to the exposure point traveled in Oxfordian formation
Porosity_An is the porosity accessible to anions
Disp_Oxf is the dispersivity in Oxfordian formation
Boxf is the thickness of the high permeability layer in the Oxfordian formation
Diffusion_HTO is the effective diffusion coefficient of tritiated water.

3.3 Summary

Chapter 3 considers the issues that are believed to be the most important to the long-term repository safety: the transport properties and processes in the Callovo-Oxfordian formation and the safety analysis.

Dossier 2005 Argile, *Référentiel du Site 2010*, and a number of the related publications were reviewed to evaluate whether (1) the variability and uncertainties associated with the processes and parameters within the Transposition Zone were adequately characterized and fully addressed in the models and safety analyses and (2) the variability and uncertainties within the ZIRA are the same as in the Transposition Zone. The results of this independent review are summarized below.

3.3.1 Transport Properties of the Host Rock

The transport properties of the host rock are considered in Section 3.2.1.1. In its evaluation of the host rock Andra specifically relies on the homogeneity and isotropy of the transport properties of the Callovo-Oxfordian formation within the Transposition Zone and the ZIRA and on the absence of conducting faults and fractures (potential fast advective flow paths).

The main transport properties were reviewed to evaluate the credibility of these assumptions.

Absence of conducting faults and fractures (considered in Section 3.2.1.1.1)

A number of faults were uncovered by the recent 2007-2008 2D seismic studies in the north and north-west part of the Transposition Zone and in the vicinity of its western boundary. One of these faults is located within the ZIRA.[193] No data were provided by Andra to understand the potential role of these faults.

Multiple microfractures were observed in the boreholes EST211, EST207, EST209, and EST361 and in the main and auxiliary shafts. No attempt was made by Andra to develop a conceptual representation of the microfractured layer either within the Transposition Zone or the ZIRA. Andra points out that it is difficult to quantify the frequency of these fractures and assumes that they have no impact of the host rock properties.

These two issues were addressed based on IEER meeting with Andra on 16 February 2011.

Homogeneity and isotropy of the transport parameters

1. Mineralogical Composition (considered in Section 3.2.1.1.2)

The mineralogical composition is heterogeneous in vertical cross section. Three sequences were identified within the host rock. There is a lateral trend indicating enrichment in carbonates. There is an elevated content in clay in the middle sequence in the north-eastern part of the Transposition Zone.

The mineralogical variability is explained by the combination of two factors (besides the variations in depositional facies): (1) the possible existence of the sedimentary gaps related to the changes in paleo-geographic depositional conditions and (2) the development of the local depressions due to the lateral variations in the tectonic displacements.

2. Pore Water Composition (considered in Section 3.2.1.1.2)

---

[193] Réferentiel du Site 2010, Tome 1 Figure 9-14

The pore water composition has the same trend (north-east to south-west) as the mineral composition. The mineral composition affects the transport properties of the argillites. The difference in transport properties affects the diffusion and advection processes, which, in turn, affect the pore water composition.

In summary, the pore water composition changes laterally and in vertical cross section within the Transposition Zone There are two distinctive areas, located in the north-east and south-west parts of the Transposition Zone. The boundary between these two areas is probably located somewhere within the ZIRA.

3. Porosity (considered in Section 3.2.1.1.3)

The total porosity probability distributions obtained for the different experiments show that these distributions are noticeably different, especially in the upper values of the tails. The distribution obtained for the URL is especially different from the other locations.

The range defined by Andra for the anion accessible porosity is from 4% to 7% with a mean of 5%. This range is significantly narrower than it is should be based on the available data. Only a mean value of 9% was considered for the kinematic porosity. The range of values should have been considered.

4. Permeability (Hydraulic Conductivity) (considered Section 3.2.1.1.4)

The available data indicate that the hydraulic conductivity is heterogeneous and anisotropic (with the anisotropy factor of 2 to 4).

The approach taken by Andra was to take the range in the horizontal hydraulic conductivity and derive the corresponding range in the vertical hydraulic conductivity using the anisotropy factor of 10. This approach underestimates the vertical hydraulic conductivity because the assumed anisotropy is much higher than was observed. Also, the horizontal hydraulic conductivity range considered was $5x10^{-14}$ m/sec to $5x10^{-13}$ m/sec, which is noticeably narrower than the observed data range.

5. Hydraulic Gradient (considered in Section 3.2.1.1.5)

The hydraulic gradients are heterogeneous within the Transposition Zone and the ZIRA. There is a strong ascending gradient in the north and north-west and descending gradient in the south.

The hydraulic gradient estimates are very uncertain. The uncertainties are associated with a number of factors. First, the measurements revealed an overpressure in the Callovo-Oxfordian formation relative to the formations surrounding it on the order of +20 m to +30 m with regard to the Oxfordian formation and +40 m to +50 m with regard to the Dogger formation. To date no plausible explanation of this phenomenon has been provided.

Only 13 hydraulic head measurements are available in the Oxfordian formation and 11 in the Dogger formation. The gradients in the Dogger formation are small in the north-east and large in the west. The reasons for these differences are not known, so far as this review could determine.

6. Effective Diffusion (considered in Section 3.2.1.1.6)

Andra *"relies on the homogeneity of the Callovo-Oxfordian, and the absence of significant heterogeneity with respect to diffusion within the formation*" to justify diffusion in the vertical direction and thus *"preventing the radionuclides from diffusing in privileged directions."*[194]

The Callovo-Oxfordian argillites exhibit vertical and horizontal heterogeneity and are anisotropic with horizontal diffusion coefficients (parallel to stratification) higher than the vertical diffusion coefficients. The effective diffusion coefficients vary significantly in one borehole as a function of mineralogical composition and porosity (largely controlled by the content of clay minerals). The effective diffusion coefficients also vary in the different boreholes due to the differences in mineralogical composition and pore water composition (largely controlled by the ionic strength).

The average anisotropy measured on the samples from borehole EST104 was 1.56. Based on the studies that were performed in support of DIR [Diffusion and Retention] experiments, anisotropy in diffusion coefficients was 1.9 for tritiated water and 1.3 for chloride. Consequently, both sets of data show anisotropy.

The effective diffusion of anions is a function of the solution ionic strength. Most of the diffusion tests with chloride and iodide were conducted using solutions with the ionic strength of 0.05 M and 0.10 M while the ionic strength is up to 0.17 M in the north-east part of the Transposition Zone (and in vicinity of ZIRA's north boundary). Thus, the effective diffusion of anions might be higher in the north-east part of the Transposition Zone and the ZIRA.

Due to the limited amount of data it seems that the possible variability of the diffusion coefficients within the Transposition Zone and the ZIRA was not totally captured. The upper effective diffusion coefficient value for anions considered in the sensitivity analysis (1.0×10^{-11} m^2/sec) is lower than the diffusion coefficient determined in one of the samples in borehole EST413 located just north of the ZIRA (1.5×10^{-11} m^2/sec).

3.3.2 Transport Processes in the Host Rock

The transport properties of the host rock are considered in Section 3.2.1.2. Andra has concluded that diffusional transport is dominant. This conclusion is based on the low permeability of the host rock and corroborated by (1) comparing diffusional transport times to the advection ones (a simplified analysis involving calculating Peclet number) and (2) natural tracer data interpretation.

Andra estimated Peclet number of 0.13 (dominant diffusion) for anionic species using average transport parameter values. Simple probabilistic calculations with the parameter ranges

---

[194] Dossier 2005 Argile, Safety Evaluation p. 139

consistent with Andra's parameter ranges indicated that the Peclet numbers can be up to 16. This means that the possibility of advective-diffusive transport cannot be excluded.

Andra concluded that the natural tracer distribution in the Callovo-Oxfordian formation can be explained by diffusion alone. This conclusion was used as an additional justification for assuming predominant diffusive transport in the host rock. The upper bound of the advective velocity estimated from the natural tracer data is 5.6×10^{-12} m/sec. This is significantly higher than "*a few centimetres per 100,000 years*",[195] which is (assuming a "few" means "3" and kinematic porosity equal to 0.09) 1.05×10^{-13} m/sec. Note that it would take a contaminant 339,750 years to reach the top of the Callovo-Oxfordian formation in the case of velocity of 5.6×10^{-12} m/sec (this is comparable with the time of diffusion) and 1.8×10^{7} years in the case of "*a few centimetres per 100,000 years*".

The natural tracers data provide sufficient evidence that the advective transport may be comparable to the diffusional transport at some locations within the Transposition Zone. They also confirm that the transport processes have different magnitude and direction at the different locations, which is mainly due to heterogeneity of the transport properties of the Callovo-Oxfordian formation.

3.3.3 Safety Assessment Analysis

The safety assessment analysis is considered in Section 3.2.3.1. The review of the safety analysis conducted by Andra brings up the following concerns:

- The normal evolution scenario and associated sensitivity analyses relies on the homogeneity and isotropy of the transport properties of the Callovo-Oxfordian formation while these properties are in fact heterogeneous and anisotropic.
- The parameter ranges considered in the sensitivity analyses are narrower than the parameter ranges actually observed. This especially concerns the vertical hydraulic conductivity of argillites.
- No sensitivity analyses were conducted to evaluate the impacts from the uncertainties in the exposure parameters (e.g., drinking water ingestion rates, well pumping rates, food consumption rates and other).
- Most of the sensitivity analyses are not carried out to the total dose calculations. As a result, adequate impact comparisons cannot be done.
- The potential impacts of the parameter and model uncertainties were evaluated through the sensitivity analyses and no probabilistic dose assessment was done. As a result, the estimated impact, of an order of magnitude, based on sensitivity studies may not be representative of the potential range.
- Only one sensitivity analysis considered the case in which all the flow paths from the repository lead to one exposure location. This case resulted in the highest total maximum dose. In all the other cases, the contaminant mass was divided between 3 different exposure locations, which resulted in "spreading" of the total dose with consequent lower values.

---

[195] Dossier 2005 Argile, Synthesis p. 175

- The highest total maximum dose for the CU1 reference package of 0.19 mSv/yr was estimated for the case when the repository is located just north of the ZIRA. According to Andra, this estimate may go up at least 2 times and exceed the regulatory limit of 0.25 mSv/yr if the conservative transport properties of the host rock are used instead of the average ones. Note that these should apply to all types of wastes based on Andra's conclusion that there is only "*a slightly higher attenuation for B waste concepts than for C waste and spent fuel concepts.*"[196] However, there is a great need for a clear source term and an updated analysis that includes spent fuel disposal.
- The two major outlets considered in dose evaluation are located on the edge of the major contributor (I-129) plume, which may result in underestimation of total doses.

A simplified probabilistic safety analysis performed with the parameter ranges consistent with the ones defined by Andra indicates that these uncertainties in the input parameters result in the uncertainty in the total maximum dose of 5 orders of magnitude. The potential range in the total maximum dose defined by Andra as one order of magnitude (or 2 times when the proposed repository is located at the URL site) might be underestimated.

---

[196] Dossier 2005 Argile, Safety Evaluation p. 278

3.4 References

Andra Campagne Sismique 2008	Andra. *Lot M18-3: Campagne Sismique 2D et Activités Connexes Interprétation et Inversion des Données Sismiques 2D : Rapport Final.* Campagne de Reconnaissance de la Zone de Transposition 2007-2008, Laboratoire Souterrain de Meuse/Haute-Marne. (C.RP.0BEI.08.0001.A) [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, 29 Novembre 2008.
Andra Sûreté 2010	Andra. *Options de sûreté du stockage en formation géologique profonde.* (C.NT.ASSN.09.0029.B) [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, 26 Fevrier 2010. Running title: JALON 2009 HA-MAVL.
Dossier 2005 Argile, Safety Evaluation	Andra. *Dossier 2005 Argile: Tome: Safety Evaluation of a Geological Repository*. (Report Series) [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, December 2005. On the Web at http://www.andra.fr/download/andra-international-en/document/editions/270va.pdf.
Dossier 2005 Argile, Synthesis	Andra. *Dossier 2005 Argile: Synthesis: Evaluation of the feasibility of a geological repository in an argillaceous formation, Meuse/Haute-Marne site*. 2nd ed. (Report Series) [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, December 2005. On the Web at http://www.andra.fr/download/andra-international-en/document/editions/266va.pdf.
Fetter 1993	C.W. Fetter. *Contaminant Hydrogeology*. New York: Macmillan, 1993.
GoldSim User's Guide 2002	GoldSim. *GoldSim User's Guide.* [Issaquah, WA]: GoldSim Technology Group, 2002. On the Web at Later versions on the Web at http://www.goldsim.com/Web/Downloads/UserManuals.
Mazurek et al. 2008	Martin Mazurek, Andreas Gautschi, Paul Marschall, Georges Vigneron, Patrick Lebon, and Jacques Delay. "Transferability of Geoscientific Information from Various Sources (Study Sites, Underground Rock Laboratories, Natural Analogues) to Support Safety Cases for Radioactive Waste Repositories in Argillaceous Formations," *Physics and Chemistry of the Earth* 33 (2008): S95–S105. Supplement 1: Clays in Natural & Engineered Barriers for Radioactive Waste Confinement. Available for purchase on the Web or free at research libraries.
Mazurek et al. 2009	Martin Mazurek, Peter Alt-Epping, Adrian Bath, Thomas Gimmi, and H. Niklaus Waber, et al. *Natural Tracer Profiles Across Argillaceous Formations:The CLAYTRAC Project*. (NEA No. 6253) (Radioactive Waste Management). Paris, Nuclear Energy Agency, Organisation for Economic Co-operation and Development, 2009. Link on the Web at http://www.oecdbookshop.org/oecd/display.asp?k=5KSNXJV372NN&lang=en. Available at research libraries at http://www.sourceoecd.org/9789264060470.
Référentiel du Site 2010	Andra. *Référentiel du Site Meuse/Haute-Marne*. (C.RP.ADS.A09.0007.B) [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, 29 janvier 2010. Running title: Jalon 2009 HA-MAVL. "Document interne."

RESRAD User's Manual 2001	C. Yu, A.J. Zielen, J.-J. Cheng, D.J. LePoire, E. Gnanapragasam, S. Kamboj, J. Arnish, A. Wallo III, W.A. Williams, and H. Peterson. *User's Manual for RESRAD Version 6.* (ANL/EAD-4) Argonne, IL: Environmental Assessment Division, Argonne National Laboratory, July 2001. On the Web at http://web.ead.anl.gov/resrad/documents/resrad6.pdf.
RFS III.2.f	Règle Fondamental III.2.f - Règles fondamentals de sûreté relatives aux installations nucléaires de base autres que réacteurs, Règle No. III.2.f (10 juin 1991) – Stockage définitif de déchets radioactifs en formation géologique profonde. On the Web at http://www.andra.fr/download/andra-meuse-fr/document/rfs_iii_2_f.pdf.
Sandia 2008	Sandia National Laboratories. *Total System Performance Assessment Model/Analysis for the License Application. Volume I.* (MDL-WIS-PA-000005 REV00) Las Vegas, NV: U.S. Department of Energy, Office of Civilian Radioactive Waste Management, January 2008. Available at www.lsnnet.gov/under participant accession no. DOC.20080312.0001.
Williams 2006	Brian Williams. *Hydrobiological Modelling*. [Callaghan: Author at] University of Newcastle, NSW, Australia, 2006. On the Web at http://books.google.com/books?id=zN6cEKXL9aUC. Available at http://www.lulu.com/product/paperback/hydrobiological-modelling/1141455.

Chapter 4: Rock mechanics

As with other chapters, the observations and findings in this chapter are made with the caveat that they are based on reviews of summarizing documents. We recognize that we have not reviewed many of the more technical underlying documents that may have presented more convincing evidence for the findings below.

Strengths:

1. Quality of research: Andra has done impressive state of the art research on rock mechanics and rock engineering studies. All indications are that the research that led to the estimation of rock mechanical parameters in the underground laboratory and in the transposition zone is highly reliable, extensive, and designed to discover variations in the details of the rock composition.
2. Narrowing of transposition zone for ZIRA selection: The selection of the 100 km^2 from the 250 km^2 transposition zone within which to locate the ZIRA was based on sound scientific and technical considerations.
3. Modular design: We strongly endorse the conceptual modular design approach for the repository layout.
4. Planning for retrievability: We strongly concur with the emphasis in the planning and design on maintaining reversibility and retrievability, which is required under current law. Such planning is necessary because reversibility and retrievability will present complex and difficult challenges.

Findings:

1. Pervasive optimism: There is a pervasive optimism in Andra's the interpretation of complex phenomena with regard to repository performance that does not provide a realistic, and appropriately conservative, view of the evolution of the EDZ. The most striking example of this is the postulate that over a million years, the repository essentially behaves as an ideal fluid, which seems exceedingly optimistic.
2. Construction Impacts on the EDZ: There is relatively little discussion of the practical engineering aspects of repository development and construction, and of their implications with regard to long-term performance. Of particular concern in this regard is whether due attention is given to construction impacts on EDZ (Excavation Damaged Zone) development and its characteristics and properties. We note here that we had made extensive comments along these lines in the previous IEER report as well.[197]
3. Pros and cons of retrievability: The arguments in favor of possibly maintaining reversibility and retrievability for a very long time, e.g., multiple centuries, or even one century, may not be sufficient to balance the potential problems, such as potential deterioration of liners and surrounding rock that will occur over such long periods. To what extent any induced damage will be reversed after that according to Andra's optimistic picture of the post closure healing of the entire structure remains far from convincing. The risks of deterioration and damage raise the question of whether it would be better to consider minimizing any induced damage, e.g., by leaving any excavations open for no longer than absolutely necessary and justifiable.

---

[197] IEER 2005 Chapter 2

4. Borehole integrity issues: The IEER team observed marked "squaring" of some horizontal holes as well as shear displacement along some fractures in recently drilled horizontal cell emplacement holes (alvéole). While the evidence is admittedly anecdotal, such phenomena are not surprising in this type of rock mass. This raises concerns about analyses that assume that, following excavation, the shape of the emplacement holes will be truly circular and whether gaps can be sealed under the influence of an eventual redistributed of the *in situ* stresses and chemical healing.

5. Concrete liners: Of particular concern is the representation of the eventual softening and weakening of the concrete liners in numerical modeling exercises. This approach seems to allow for an exceedingly long life for concrete, even taking into account the presumably unusually favorable conditions under which this concrete will be operating (e.g., as compared to road tunnels or underground mines). This softening modeling at first glance seems inconsistent with the statements that it is expected that within a few millennia the liner will see renewed or re-activated fracturing.

6. Seal performance analysis: Andra's assumption that all modeling can be done as if the rock behaves as a continuum appears to be pervasive throughout seal performance analyses. Ease of numerical modeling should not take precedence over a realistic representation of observed phenomena. In other words, even if it is not possible to explicitly include all fractures or discontinuities in a numerical model, proper modeling of the observed behavior is essential in predicting the evolution of the repository.

Recommendations

1. Andra should make a reasonably conservative assumption about the post closure state of the EDZ. We would endorse an assumption that the EDZ does not fully repair itself to create in situ permeability and /or state of stress. In fact, it may be best to consider that the EDZ retains the worst state of estimated damage throughout the repository life.

2. Notwithstanding Andra's expectation that heterogeneities are unlikely, at this stage of the site characterization they cannot be excluded categorically. Hence, further efforts in assuring that no major surprises will be encountered later in this regard are highly desirable.

3. The observations of squaring and shear displacement along some fractures in recently drilled horizontal cell emplacement hole deserve close attention. They have obvious implications for EDZ geometry, liner loading, drift (tunnel) liner loading, void space created, and the formation of potential flowpaths. We have not seen any analysis by Andra of these phenomena.

4. In light of the fact that concrete inspection technologies are widely used and implemented in tunnels, we would strongly encourage Andra to commit more firmly and explicitly to concrete inspections for as long as access allows.

5. Deviatoric stress, saturation, and temperature all affect significantly the rate of creep. The interrelationship of these environmental factors and their effect on repository performance appears to have been treated rather qualitatively. A better integration of the combined influence of these factors is warranted to demonstrate the extent of benefits (and lack of adverse performance).

We wish to recognize up front to being truly impressed with the rock mechanics studies Andra has performed since our last review.[198] While the focus in this review report is rather on areas of concern and disagreement, we do not wish to leave an impression of negativism. The work performed, the research completed and in progress clearly and unmistakingly is at the leading edge of rock mechanics. This work is making a major contribution to rock mechanics and rock engineering, particularly in the difficult area of engineering in clayey, shaley materials that are a major challenge to the profession. Andra is making contributions in this arena that go well beyond the requirements of a French repository. As has long been recognized:

> Clay shales are often considered difficult materials with which to engineer. … The most problematic clay shales appear to be those which have low strength and a large proportion of the swelling clay – montmorillonite.[199]

A significant factor enhancing Andra's research standing, and the credibility of the program, is the numerous doctoral dissertations that the program has supported and continues to support. Especially helpful in this regard is the extensive bibliography provided in Andra[200], the very impressive survey and summary of four years of research. Conversely, it is a little bit surprising that not more of the publications, particularly journal publications that have resulted from this work, are referenced in many Andra documents. Here again, the credibility of all work and results invoked in Andra reports obviously can be strengthened by referenced peer reviewed publications that have accepted the work and the results. (Even in the research survey[201] the connection between the research summarized and the related publications frequently is not explicitly made, making it rather difficult for a reader the find the connections. Even more serious is that many of the references are given in an extremely condensed, cryptic, form, which makes it difficult and sometimes time-consuming to locate them).

While the fundamental research performed by Andra is outstanding and critical, in particular, in light of the time frames over which predictions or at least estimates are required, one apparent weakness of the program is that relatively little discussion is provided on the practical engineering aspects of repository development and construction, and of their implications with regard to long-term performance. Of particular concern in this regard is whether due attention is given to construction impacts on EDZ (Excavation Damaged Zone) development and its characteristics and properties. While it is recognized that considerable effort has been made on studying such effects, it is not entirely clear or convincing that the potential consequences of such effects are accounted for sufficiently and convincingly in the more theoretical analyses supporting performance assessments. There appears to be a significant disconnect between the field monitoring and mapping and the phenomenological analyses and performance assessments: the latter pervasively assume continuity, continuum mechanical behavior, even after the former have recognized fairly frequent and persistent fracturing. The justification for continuity, based on complete sealing and healing of fractures certainly needs more convincing evidence. We note

---

[198] IEER 2005

[199] This example is from Seedsman 1993 p. 164.

[200] Andra 2010c

[201] Andra 2010c

here that we had made extensive comments along these lines in the previous IEER report as well.[202]

Another important aspect of Andra's research that we wish to recognize very explicitly is the multiple international collaborations. It is clear that for a variety of reasons, notably efficient development of advanced methodologies, such collaborations are very valuable. Nevertheless, in this regard a problem arises: it is not always clear to what extent results from other laboratories and conditions truly are applicable to a potential repository in the ZIRA (la Zone d'intérêt pour la reconnaissance approfondie). It would be helpful if more frequent references could be made to studies that confirm the relevance of results obtained elsewhere to the Meuse/Haute-Marne site. This may be superfluous or redundant to insiders. To outside readers it often remains highly uncertain and unclear why results from Mont Terri, for example, should be so directly applicable to this site.

Also, in light of the vast amount of often very sophisticated work that has been performed over the last decade, and given the exceedingly short time that was allowed for this review, it is possible that some important references and/or information sources may have been missed, i.e., some of the topics that we have identified as perceived shortcomings may be based in part on an incomplete review. Nevertheless, a considerable amount of material has been reviewed, and it is hoped that no major sources have been overlooked.

4.1 Potential inhomogeneities in the mechanical properties in the transposition zone and their role in the selection of the ZIRA

A major concern in all sedimentary formations, certainly from a general rock engineering point of view, will be the risk of variations in the formations, and in particular the risk of unexpected significant changes in rock type, the "changed conditions" that so often lead to major problems, whether stability problems or construction difficulties, in underground construction and mining. For that reason we have looked rather carefully at the evidence Andra has gathered and presented to make the case that the host formation is uniform and homogeneous. We are particularly impressed with the comprehensive information that has been gathered about the sedimentary history and the geological development of the basin that has been presented in considerable detail, and leads to the strong conclusion that the presence of major heterogeneities seems rather unlikely.

We also find it very encouraging that Andra plans to continue research in this regard, as indicated in the GNR FORPRO-II (2010) research solicitation, although somewhat disconcerting that Andra believes some of this research to exceed the needs of its site selection.[203] It seems to us that the issue of homogeneity is so fundamental and essential that any further information that can be gathered to either strengthen the case for homogeneity or raise doubts about it deserves full and strong support. (It also is unfortunate that the web version of this solicitation does not include the references, many of which would appear to possibly have been of considerable value

---

[202] IEER 2005 Chapter 2

[203] GNR FORPRO-II 2010 Annexe 1

for this review.) Of particular concern would be highly localized variations in the lithology that may locally result in significant differences in isolation performance characteristics, be it permeability, diffusivity, thermal conductivity, and/or mechanical properties.[204]

Although not strictly an issue of inhomogeneity, according to the *Phenomenological Evolution of the Geological Repository*, "vertical variability in the mechanical properties is noted within the Callovo-Oxfordian layer," resulting in a division of the layer into "three distinctive mechanical zones."[205] If we understand it correctly, the ZIRA has been selected, at least in part, to allow emplacement of the entire repository within a particular zone (namely, Zone C) based on the depth from surface, and minimum required set-off distances from the top and bottom of the Callovo-Oxfordian host formation. Presumably, Zone C is selected because this zone most likely provides for the best performance in terms of waste containment and isolation. We concur that all the evidence adds up to a convincing case for the selection of the ZIRA as an optimal location for a repository, based on the information currently available, from the point of view of minimizing the risk of significant heterogeneities, minimizing rock mass damage (e.g., EDZ development), and waste isolation.

Notwithstanding the expectation that heterogeneities are unlikely, at this stage of the site characterization they cannot be excluded categorically (as pointed out, for example, by the Luxembourg review report of a potential Bure repository).[206] Hence, further efforts in assuring that no major surprises will be encountered later in this regard are highly desirable.

4.1.1 Differences and similarities between the discontinuities of the underground laboratory and those identified as part of the research in the transposition zone.

It appears that, conceptually, the major discontinuities of concern with regard to waste isolation, in its broadest sense, are secondary faults of modest extent and along which only minor displacement has taken place. Andra has recognized this potential problem, and has addressed it repeatedly, and continues to consider it as an issue that deserves high priority attention.

It is far less clear to us to what extent Andra has recognized and addressed the potential influence of bedding planes, e.g., of separation along bedding planes, being of concern with regard to waste isolation, and, most obviously, in terms of stability of excavations, especially drifts, and possibly most importantly, of emplacement boreholes, especially in light of the fact that the emplacement holes are horizontal. In the material we have reviewed we were unable to find where or to what extent Andra has addressed this issue. The reason for raising the question is primarily the well-established observations of failure around underground excavations in shaley formations, as illustrated very nicely in the classical pictures of Jacobi (1981) shown by Bock et al..[207] Similar examples, from many laboratory simulations as well as from numerous actual observations in tunnels and mines are widely available and well known; these problems are well recognized as being critical in many rock formations of this type, and hence always will be a

---

[204] Some of these issues are also discussed in Chapter 3 above and Chapter 5 below.

[205] Andra 2005e p. 345

[206] Groupe interministériel «Bure» 2010 p. 12

[207] Bock et al. 2010 Figure 2-7 (p. 40)

major source of concern. Of particular interest might be the extent to which, if any, overbreak associated with bedding planes might have been observed in any excavations, and especially around any horizontal boreholes. Presumably any observations of such occurrences would have been recorded somewhere in construction and/or observation reports. What remains unclear is to what extent, if any, such observations have been taken into account in phenomenological analyses, which largely assume perfectly circular holes in a continuum medium. Eventually, these bed separation and overbreak effects might affect long-term performance, both with regard to the stability (e.g., affecting retrievability) and overall large scale permeability (e.g., affecting the site's waste isolation capability.)

During our site visit (August 18, 2010) we observed a marked "squaring" on a recently drilled horizontal cell emplacement hole (alvéole), i.e., overbreak in the corners that resulted in an opening shape closer to a square rather than a circular hole. (Figure 4.1) Such overbreak is not uncommon in bedded shaley/clayey formations; in fact, it would almost be expected. We have not seen any discussion or any analysis of such observations in Andra documentation. We believe that this type of observation deserves close attention since it has obvious implications for EDZ geometry, liner loading, drift (tunnel) liner loading, void space created, and the formation of potential flowpaths. It also raises concerns about analyses that assume that, following excavation, the true physical shape of emplacement holes will be circular.

Figure 4.1. Fractures around a borehole drilled from a Bure laboratory gallery (Photograph by Arjun Makhijani, August 18, 2010. P1020429).

Figure 4.1 shows fractures around a borehole drilled from a Bure gallery wall. Shear displacement as well as opening up has taken place along some fractures, and block rotations result in large and variable apertures. It is difficult to accept that such gaps can be sealed under the influence of an eventually rebuilt normal stress. It also raises concerns about the validity of continuum models. While this 'evidence' admittedly is highly anecdotal, it is not at all surprising in this type of rock mass, and leaves questions as to whether such behaviors have been adequately addressed in the phenomenological analyses and observations made to date.

The problems of squaring and fractures around boreholes would be much more severe in case France decides to dispose of spent fuel (not required under current design criteria), since the required boreholes would be 3.3 meters in diameter, much larger than the boreholes so far drilled. In this context, it may be useful for Andra to consider whether vertical boreholes would reduce these problems.

It is not clear or convincing to us whether Andra has sufficiently recognized and accounted for any mechanical anisotropy, particularly on a macroscale, that might be associated with the bedded nature of the host formation. Again, this would be of particular concern with regard to stress concentrations around excavations, the potential impact of anisotropy on stress distributions, the impact of strength anisotropy, and the combined impact of anisotropy on the EDZ. We recognize that this anisotropy may not be, and probably is not, a decisive factor with respect to ZIRA selection. But, as pointed out by the CNE,[208] it almost certainly is a significant factor in the mechanical rock mass behavior of the host formation (as well as with respect to other behavioral aspects); it certainly deserves more attention than it appears to have received to date. Particularly noticeable in this regard is that both the thermal and the hydrological calculations and modeling explicitly account for anisotropy.

Given the frequently referenced observation of markedly directional fracture patterns around excavations, that, according to Andra, are reasonably representative of what might be observed at a Meuse/Haute-Marne repository, it is difficult to understand how a rock mass with such distinctly parallel fractures could remain isotropic.

Young et al. (2005), in their extensive studies (including those at Mont Terri) on seismic validation of thermo-mechanical modeling of rock damage around radioactive waste packages, emphasize the need to consider the pronounced anisotropy of the potential host rock formation.[209] Similarly, with respect to Mont Terri: "… the rock mass exhibits a high anisotropy, with a ratio of Young's Moduli in the order of 2.5."[210] The parallel discussion of modeling the Callovo-Oxfordian at Bure states that the anisotropy of this material is so weak that it can be modeled as an isotropic material.[211] We note that whereas comparisons with Mont Terri results are often cited by Andra in making its case, it is incumbent on Andra to also address certain ways in which findings at Mont Terri may not be applicable to the Bure site. It would be most helpful if Andra could provide convincing evidence, on a scale of the repository excavations, i.e., multiple meters, that the host rock can be treated, mechanically, as isotropic. Nevertheless, we recognize that this report is a nice illustration of the fact that Andra is at the leading edge of rock mechanics research, and most notably, in this particular case, of a sophisticated integration of seismic and numerical analysis, and of field data with laboratory data. The comprehensive integration, combined with multinational cooperation, is a good illustration of a most promising approach to address the remaining difficult problems to be dealt

---

[208] CNE 2010 Tome 1 p.11
[209] Young et al. 2005 p. 24
[210] Giot et al. 2006 p. 935
[211] Young et al. 2005 p. 32

with. Unfortunately, the study by Young et al. (2005), does not present any comparisons between numerical results and field observations. Was it beyond the scope of the project? While both of these publications are excellent examples of the outstanding rock mechanics research Andra is supporting, they leave the question as to how applicable Mont Terri results really are for Bure: how feasible, reliable, acceptable is it to apply results, observations, analyses, from a markedly anisotropic rock mass to one presumed to be mechanically essentially isotropic?

We recognize that considerable evidence with regard to anisotropy has been gathered on the small scale of typical standard rock mechanics tests.[212] It is less than convincing that arguments based on results from tests on such a scale can be extrapolated to the scale of the repository excavations. This is particularly true in light of the fact that there is at least some evidence suggesting that purely isotropic models may not suffice to mechanically model this rock mass.[213] While the anisotropy may be minor on the laboratory scale, it may deserve some more consideration and analysis to justify neglecting its impact entirely when extrapolating lab scale results to rock mass properties.

4.1.2 Possible differences in support requirements for the stability of excavations depending on ZIRA location selection, and whether these differences are important for the choice of the ZIRA

Andra has accounted for differences in support requirements in terms of depth of the formation available for repository candidate horizon, and has taken the step of limiting that depth. Andra repeatedly has emphasized the sensitivity of support requirements, e.g., concrete thickness requirements, as a function of depth. However, the emphasis has been mainly on construction and logistical implications of such requirements. It is neither clear nor obvious whether (or to what extent) Andra has addressed explicitly any implications with regard to waste isolation and/or reversibility in the context of depth of emplacement.

While the required concrete thicknesses (and volumes) have been given in multiple documents,[214] none of the ones we have seen include any detail about the analyses on which these thickness calculations were based, nor any reference(s) to a source for such information. Unfortunately, this is not an uncommon occurrence in Andra documents. We observe that Andra documents often tend to skip providing references to some key sources of critical information. While we recognize the demanding challenge of documenting such a massive effort, from a reviewer's viewpoint it would be most helpful if referencing were more extensive.

The issue of required (concrete) liner thickness is of particular concern because, as pointed out repeatedly by Andra itself, liner-ground interaction is likely to be a critical parameter with respect to EDZ development and control, and its characteristics and evolution over time. With respect to the concrete liner thicknesses listed in the references given in the previous paragraph, a possibly minor issue that may deserve clarification: it appears that some of the dimensions do not

---

[212] For instance, see Andra 2010a Tome 2 pp. 74-75, 83, 87, 93-94, and 139-140.

[213] For instance, see Andra 2010a Tome 2 p. 35, last bullet; p. 100, last paragraph; Figure 18-84 (p. 123). Although this figure is very difficult to read, even after considerable enlargement, and difficult to understand – given the lack of explanation (also missing is a reference to the source). Also see pp. 140and 186.

[214] For instance, see Andra 2009a p. 51; Andra 2009b slide 5; Andra, 2009c pp. 5-6.

add up: for example, at a depth of 485 m, a shaft with an internal diameter of 7.0 m and a concrete liner thickness of 0.60 m should, on the face of it require only an 8.20 m diameter excavation (rather than 8.60 m as stated by Andra). Is there another element involved here such as a construction safety liner element? For instance, could the extra thickness be the 20 cm shotcrete, mentioned in other documents[215] for the galleries? Again, particularly because of its critical importance with regard to eventual shaft sealing, a clearer and more precise and detailed description of these components and of their design and supporting analyses would be highly desirable.

While we find the many commitments by Andra towards monitoring of the repository evolution[216] highly commendable and encouraging, we consider the softness and ambiguity of a "maybe" commitment to concrete inspection and monitoring[217] rather disappointing. In light of the fact that such technologies are widely used and implemented in tunnels,[218] we would strongly encourage Andra to commit more firmly and explicitly to extensive continuing concrete inspections. Especially in light of the great longevity claimed by Andra for numerous critical concrete components, it would be extremely desirable to develop a data base, e.g., by the time of eventual closure of the repository, that gives ample observational evidence for the condition of those components at that time, and of their evolution over the time since their installation. (In addition, of course, such ongoing monitoring would provide confidence, e.g., with regard to retrievability, and with regard to the correctness of the phenomenological analyses that have predicted no changes for several hundreds of years, at least).

A similar problem is encountered with the statements, with respect to accounting for aging and weakening of protective materials[219] (presumably including concrete liners and steel supports?). Here also a reference to a more specific analysis document would have been most helpful. In addition, the implication that civil construction tunnels typically or usually are designed for a century lifetime,[220] with minimal maintenance, may be somewhat of an overstatement. At least the claim would certainly benefit from a reference to such design approaches. Similarly, it would be helpful to support the claim[221] that the long-term behavior of concrete and of steel is sufficiently well understood with a reference or references to the important research program that has been completed in this regard. The phrase "long-term" needs to be quantified if meaningful comparisons with existing civil structures are to be made.

Of particular concern is the representation of the eventual softening and weakening of the concrete liners in numerical modeling exercises.[222] This approach seems to allow for an exceedingly long life for concrete, even taking into account the presumed and unusually favorable conditions under which this concrete will be operating. Some justification, explanation of the logic behind this approach would be highly desirable. Moreover, this softening modeling

---

[215] For example, in Andra 2005b p. 17.
[216] For example, Andra 2010d p. 19.
[217] Andra 2010d p. 59, last sentence of text
[218] AFTES 2005; Haack et al. 1995
[219] Andra 2010b pp. 49, 253-254, 312, and 319
[220] Andra 2010b p. 253
[221] Andra 2010b p. 312, last paragraph
[222] For example, as described in Andra 2005a, Section 2.3.1.

at first glance seems at least somewhat inconsistent with the statements[223] that it is expected that within a few millennia the liner will see renewed or re-activated fracturing (presumably resulting in at least some stiffness (modulus) reduction).

A somewhat related concern, related in the sense that it may impact the EDZ development, is the argument[224] that the small extent of the alkaline disturbance and consequent softening will not enhance or allow further EDZ extension. If a soft layer with a thickness of 10 cm or so develops in between the stiff backfill core and the surrounding argillite, will this not allow further softening of the argillite?

We recognize the value of the important decision by Andra to limit the ZIRA site to areas where the potential repository depth does not exceed 600 m.

This conservative approach (e.g., compared to potential depths of up 1000 m for consideration in the German site selection criteria for shale/clay type potential host formations)[225] strikes us as a very prudent and wise decision, particularly with regard to EDZ development in general, and especially with regard to shaft and ramp EDZs.

Notwithstanding our recognition of the prudent Andra approach to minimize support requirements, we still have a number of concerns about Andra's approach to concrete liners, and in particular with regard to the long term performance of such liners. Our main reservations arise from the fact that we have seen virtually no data or analyses in support of the claims made for the long term performance of such liners and we recognize that some evidence probably is available in supporting documents, that we have not seen. Of particular concern are the longevity estimates of the concrete liners.[226] In the same document it is stated that fracturing of the liner is possible (likely?) within a few thousand years.[227] This seems rather inconsistent with a model in which the modulus starts decreasing only after 5,000 years. It is generally recognized and accepted that unreinforced concrete liners of underground excavations develop fractures soon after installation.[228] It is our strong impression that this fact does not seem to be recognized in Andra discussions of liner phenomenological behaviors. What is the modulus of a cracked liner? Is the likelihood that the liner is cracked recognized, acknowledged, accounted for in the degradation studies of such liners (which appear to assume a uniformly progressing degradation front, based on the assumption that the concrete liner is a uniform "uncracked", "unfractured" concrete mass, and not accounting, for example, for preferential fluid intrusion along cracks, fractures, or construction joints)?

A somewhat related concern, related to the long term behavior of concrete liners, is the impression we have that the shotcrete liner is not taken into account in desaturation calculations (important in terms of the stiffening up of the argillite as a result of desaturation). This assumption is stated explicitly in Massman et al. (2009), admittedly not a formal Andra

---

[223] Andra 2005b Section 3.3.3 (p. 37)
[224] Andra 2005b Section 3.3.3 (p. 37)
[225] BGR 2007
[226] For example, as presented in Andra 2005a Figure 2.3-1 (p. 16) and accompanying text.
[227] Andra 2005a p. 49
[228] For example, see AFTES 1998 Section 2.4 (p. 112)

document.[229] Shotcrete liners, both in underground construction and in mining, often are used to inhibit detrimental impacts on the rock walls resulting from contact with air. (For example, e.g., in the discussion of shotcrete: “Its first action …, is also, sometime, to protect against humidity variations.”)[230] While we recognize that the time frames of interest for a nuclear waste repository vastly exceed those for conventional mining and construction, our concern here is whether the calculated desaturation of the argillite (neglecting any “protective” effect of the shotcrete?), and its resulting stiffening, may result in underestimating of the creep loading of the liners, and, in particular, of the timing of such loading. Again, closely related, it is difficult to understand why the desaturation should proceed so quickly in lined, concreted or shotcreted, excavations.[231]

4.1.3 Adequacy of the research on the effect of deformation on the long term stability given the differences in depth and mechanical properties of rock in the transposition zone

It is very interesting and encouraging to read that extensive work has been done on the phenomenological development of the repository structures, and will continue to be done.[232] Unfortunately no citation is provided to the referenced APSS-Exploitation study, making it impossible to review any details in this regard.

It is very encouraging to see that Andra recognizes and acknowledges that the CNE approves of the emplacement of monitoring and surveillance instrumentation, and recommends a precise description of such a program.[233] While the commitment to such monitoring appears firm in principle[234] the somewhat more detailed description of the potential plans for implementing such a program,[235] leaves one with a feeling of great uncertainty: the commitment seems rather tentative, and far from precise and detailed. Of particular concern is the last sentence of this section, suggesting an extremely uncertain commitment to monitoring concrete. Given the extreme importance of concrete liners with regard to retrievability and with regard to controlling the EDZ, one would expect a firm commitment, without qualifications, towards ascertaining in situ the condition of the concrete liners, for as long as access allows, and remotely, for as long as practically feasible.

4.2 Comparison of the in situ stress state and pore pressure parameters between the underground laboratory and the ZIRA. Reliability of the research that led to the estimation of rock mechanical parameters in the ZIRA.

There are strong indications that the state of stress has been determined sufficiently to warrant concluding that the stress state in the ZIRA is known adequately. Presumably, as part of any

---

[229] Massman et al. 2009

[230] Duffaut 2003 p. 167 (quote translated from the French).. See also AFTES 2000 Section 2.1 (pp. 4-5)

[231] For example, see Andra 2005d pp. 54-55.

[232] Andra 2010d p. 18

[233] Andra 2010d p. 15

[234] Andra 2010d p. 19

[235] Andra 2010d Section 4.2.5 (p. 59)

actual repository development, further stress measurements will be made at the site to confirm or to modify this knowledge. Given that the stress state is a critical variable in repository layout and design, early determinations of this variable, i.e., very early on even during preliminary exploratory accessing of the ZIRA, should be considered a high priority. With regard to such measurements, it will be critically important for Andra to demonstrate that any exploratory holes drilled into or near the ZIRA location can and will be sealed, and hence – will not compromise the integrity of the host formation.

What becomes overwhelmingly clear from the extensive studies Andra has performed on this topic is that the pore pressure question remains an exceedingly difficult and complex one,[236] affecting numerous variables and, in turn, affected by numerous phenomena. All indications are, given the current state of the art, that the understanding of pore pressure phenomena gained to date will be transferable to the ZIRA. Presumably this topic will continue to be the subject of further in depth investigations, as seems to be necessary and appropriate.

All indications are that the research that led to the estimation of rock mechanical parameters in the underground laboratory and in the transposition zone is highly reliable, extensive, and closely related to variations in the details of the rock composition. This forms an excellent basis to estimate the rock mechanical properties in the ZIRA, and we expect that this work will continue, especially once rock from the ZIRA is available. Confirmation of the ZIRA properties obviously would be highly desirable, or, if significant differences in properties are discovered, a re-visit of the analyses and studies based on previous assumptions would become necessary.

4.3 Transferability of the research on seals in the underground laboratory to other parts of the transposition zone, including the ZIRA.

All indications are that Andra has a good preliminary understanding of the similarities and differences between the ZIRA and the underground laboratory, and hence is in a good position to reliably and credibly transfer results from the laboratory to the ZIRA, accounting for any and all significant differences.

Although not directly, or primarily, or exclusively related to the ZIRA, we wish to highlight some promising commitments, as well as some concerns about the sealing studies and analyses available to us.

We see great value in the proposed (or at least considered) seal test to be performed in the underground laboratory.[237] Although in principle we strongly endorse the consideration of finding methods for removing the concrete liner prior to sealing, we recognize that this is most likely to be an exceedingly challenging task, especially if it needs to be performed in such a way as to prevent further EDZ development and enhancement. Nevertheless, the benefits of removing concrete, with all its associated and related causes of potential detrimental effects and uncertainties, are so substantial and significant that we recognize this approach of removing the

---

[236] For example, see CNE 2010 pp. 10-11.

[237] Andra 2010b p. 334

liner, cutting slots, and filling the slots with clay seals as being a possibly beneficial one, although we may be less optimistic than Andra about its feasibility.

A subject of particular concern is the lack of accounting for fracturing observed during excavation. For example, Chapter 22 of *Référentiel du Site Meuse/Haute-Marne*[238] gives an impressive description of in situ observations of fracture developments during mining. Yet Chapter 23, the very next one, immediately starts with the assumption that all modeling can be done as if the rock is a continuum. And the latter assumption is pervasive throughout seal performance analyses. We note that ease of numerical modeling should not take precedence over a realistic representation of observed phenomena. In other words, even if it is not possible to explicitly include all fractures or discontinuities in a numerical model, proper modeling, including accounting for the influence of fractures and discontinuities, of the observed behavior is essential in predicting the evolution of the repository.

Many of the sealing analyses, including in particular the "failed seals scenario," treat the seal systems as homogeneous continua, with properties (e.g., "healed" fractures, joints) that appear to be based largely, if not exclusively, on laboratory studies on small samples, or at least a scale very small compared to the size of the excavations to be sealed.[239] Certain attributes and properties of some components of such 'failed' seals appear to have been selected highly optimistically. In situ evidence to demonstrate that such numbers are realistic would be exceedingly helpful. If evidence from other sites is invoked (e.g., Mont Terri, Tournemire), a convincing case needs to be presented that the information is indeed transferable.

Andra has given considerable thought to the transferability of data from other sites. For instance, Andra realizes that a larger variety of data can be transferred in early, preliminary stages of safety assessment than in later stages: [240]

> The more mature a safety case, the less information is used from elsewhere, and the more are external data, general observations and conclusions used as additional, independent lines of evidence.

We concur with this general approach. Andra is at a rather late stage in the development of its safety case, especially if the schedule for its license application (due by 2015) is not relaxed. Hence, appeal to data from other sites that are essential for making the safety case would be less and less appropriate, according to this line of thinking.

A particular concern with regard to "failed" seal scenario analyses is the apparently pervasive assumption of uniform hydraulic pore flow. Is there no risk of channeling? Is potential channeling accounted for implicitly or explicitly? This topic remains of considerable concern with respect to flow in rock masses, especially in fractured ones – unless and until it can be convincingly demonstrated that fracture healing, sealing, indeed will be as uniform, complete, and totally pervasive as assumed throughout the Andra literature on the subject. If channel flow

---

[238] Andra 2010a Tome 2

[239] Andra 2005i

[240] Mazurek et al. 2008 p. S99

does or could occur, the assumption of predominantly diffusive flow may need to be revisited; in other words, advective flow may have to be considered along with diffusive flow.

The fundamental concept of the proposed sealing approach is very good: multiple seals, to isolate various sections of the repository, as well as extensive shaft seals. The redundancy in the sealing committed to is indeed very attractive!

However, some of the sealing approaches leave unanswered concerns. One topic closely related to sealing, backfill performance, for example. Andra states repeatedly[241] that a 10 MPa modulus is sufficient to assure that the backfill will restrain argillite convergence sufficiently to prevent further enhancement of the EDZ. This is difficult to understand or accept, notably in light of the parallel statements that a stress of 10 to 12 MPa is likely to be the long term equilibrium stress. At such a stress state, would not the backfill allow very large inward displacements before providing sufficient reaction forces to constrain the argillite? For example, consider the example a solid cylinder with E = 10 MPa and gallery radius in Figure 6.1.22.[242]

A particular concern with regard to sealing performance is how rarely channeling is mentioned. In *Scellements et remblais des galeries et des puits d'un stockage en formation argileuse profonde* it is mentioned very briefly on page 75 and in slightly more detail on pages 95-96,[243] but is does not appear to be accounted for as a potentially serious problem or issue for seal performance.

4.4 The connection between rock mechanical aspects of the selection of the ZIRA and the adequacy of the seismic site investigations in the transposition zone

As of this writing the results of the 2010 3D seismic characterization campaign of the ZIRA are not yet available. The seismic investigations of the transposition zone, especially in combination with the sedimentological work, present a credible picture of uniformity, homogeneity, and continuity, with the variations, e.g., in mineral composition and related variations in rock properties as recognized in multiple Andra publications. Some uncertainty remains in particular with regard to the potential influence of small faults on excavation stability, EDZ, waste isolation performance, and the various aspects thereof (e.g., water and/or gas flow, heat flow, mechanical properties). It is important that the possible need to further characterize such faults, e.g., if they were to be encountered during repository development and construction, be recognized and addressed.[244]

---

[241] Andra 2005c

[242] Andra 2005c Figure 6.1.22 (p. 78)

[243] Andra 2005c pp. 75, 95-96

[244] See Chapters 2 and 3 for discussion of microfissures and heterogeneities.

4.5 Effect of the evolution of gas in the waste containers on stability of seals

It is recognized that Andra has devoted a considerable effort to investigating gas flow, its causes, mechanisms, and effects.[245] It nevertheless may deserve emphasizing that this topic is of particular concern with respect to the potential detrimental effects of gas pressures and flows on seal system components. Gas pressures in the EDZ may also oppose (or slow down) the resaturation of EDZ and the liner; therefore, a more quantitative analysis is recommended than a vague expectation that somehow the creep in the argillite will sufficiently offset the gas pressure.

4.6 Review of Andra's research on the requirement of reversibility over a long period of time (≥ 100 years).

It certainly is encouraging that Andra is committed to continuing research on the disturbances created by excavation on the host rock.[246] As pointed out, for example, by an international peer review group, "Considering a reversibility period of 200 to 300 years, there is limited experience for such long times regarding maintenance and repair of underground structures as well as of underground equipment. The same is true for observation and monitoring."[247]. We certainly consider it encouraging to read that "Andra has identified the needs in this area in its proposed Scientific and Technical Programme 2006-2010".[248]

It is encouraging that Andra recognizes and acknowledges the concern expressed by the CNE about the potential implications of leaving a repository open for an exceedingly long time (e.g., (well?) beyond 100 years).[249] It would be highly desirable that this issue be addressed more formally, and in more detail.

4.7 Are the geomechanical/geotechnical characteristics of the ZIRA determined by the seismic reconnaissance campaign in the transposition zone comparable to those in the laboratory?

All indications are, based on the earlier 2-D seismic analyses, but especially based on the extensive sedimentological and geological understanding of the site, that the geomechanical/geotechnical characteristics of the ZIRA are comparable to those in the laboratory. Presumably, additional information in this regard will become available with the results of the recent (2010) 3D seismic investigations focused on the ZIRA to complement the investigations centered on the underground laboratory done in 1999-2000. Presumably one may expect that one of the earlier activities in any ZIRA exploration will be to confirm any anticipated characteristics based on earlier work, or of establishing where modifications in the extrapolations of the anticipated characteristics might be required.

---

[245] Andra 2010a Chapitre 25

[246] Autorité Environnementale 2010 p. 7

[247] OECD 2006 p. 55

[248] OECD 2006 p. 55

[249] Andra 2010d p. 15, where a CNE report (CNE 2005) is quoted and referenced.

4.8 Performance of concrete liners and their interactions with EDZ

The performance of the liners is critical both during the operational phase and the post-closure phase. In addition, the reversibility requirements could only be satisfied if the liners maintain their integrity during the reversibility period.

In Dossier 2005 Argile the following statement is made:

> The argillite creep and swelling thus increase the loading on the ground support/liner, resulting in an increase in stresses in the liner until the concrete strength is reached after several thousand to 10,000 years, whereas its mechanical properties are not reduced by chemical degradation.[250]

Based on past experience and relevant published literature, it is to be expected that cracks will develop in the concrete liners, possibly within a few decades. For instance, according to a tunneling organization:

> A brickwork or plain concrete lining is often cracked. As soon as it is used, plain concrete tends to crack as a result of the shrinkage and stresses due to its own weight and rarely avoidable singularities such as the overbreaks producing major variations in the thickness of the lining.[251]

Thus, whether or not chemical degradation occurs, the mechanical properties of the liner are likely to degrade due to such cracks as well as due to other environmental factors. For example, concrete ageing, desaturation/resaturation cycle, gas pressure, and stressing/distressing due to variations in the creep rates of argillite will all tend to weaken the liner.

We also have a specific concern regarding the development of high tangential stresses in the concrete liners of galleries and Type B waste emplacement cells. Preliminary calculations for a thick, hollow cylinder (such as concrete liners in the galleries) show that a tangential stress of more than 60 MPa may develop in a 70-cm thick liner in a gallery with a diameter of 7 m at a formation depth of 490 m. This magnitude of stress is slightly higher than the strength of concrete adopted for the engineered structures.[252] Moreover, an emplacement depth that is greater than 490 m would mean a proportionately higher tangential stress in the liner. Accordingly, we recommend that the liner thickness design be carefully analyzed so as to allow a better margin of safety *vis a vis* the concrete strength.

Assertions are made by Andra that due to argillite creep and swelling clay seals, the permeability of the EDZ will be restored to within an order of magnitude of the rock mass permeability. Measurements in the Meuse/Haute-Marne URL show that argillite permeability increases by 3 to 5 orders of magnitude.[253] It is difficult to believe that loading/unloading of these fractures in the EDZ is an elastic process. In other words, it is doubtful that the permeability in the EDZ can be

---

[250] Andra 2005e p. 365

[251] AFTES 1998 Section 2.4 (p. 112)

[252] Andra 2005e p. 361

[253] Andra 2005e p. 350

substantially restored to approach its native value. What tests have been conducted (or designed) to demonstrate this near total healing of fractures?

The creep behavior of argillite is a complex function of at least three parameters that all vary, in space and time, in a repository environment. Specifically, tests show that deviatoric stress, saturation, and temperature all affect significantly the rate of creep.[254] The interrelationship of these environmental factors and their effect on repository performance appears to have been treated rather qualitatively. Further, regardless of the direction of variation in any of these parameters, a generally beneficial outcome is presumed by Andra. A better integration of the combined influence of these factors is warranted to demonstrate the extent of benefits (and lack of adverse performance). For example, the following quote illustrates the concern as well as the inconclusive nature of the assertions.

> "The rise in temperature has an antagonistic effect on the effect of desaturation, namely activating the argillite creep (Inset 8.3). Little is currently understood on the combination of these opposing effects, but for limited rises in temperature the effects of desaturation should remain dominant, namely slowing down the creep."[255]

The process of placing swelling clay seals includes cutting slots into the formation at selected intervals with the purpose of interrupting fluid flow along the liner/argillite interface. Portions of the concrete liner are removed to enable slot cutting at these intervals. However, the method of removing sections of the concrete liner is not mentioned. We are concerned that mechanical damage to the remainder of the liner is unavoidable under the proposed scheme. One option is to incorporate the slots (and the associated seals) at the same time the liner is installed to avoid removing sections of the liner.

4.9 Concluding comments and observations

Andra has accomplished a remarkable and impressive research effort in support of its Bure repository program. The broad range and in depth efforts are outstanding.

Nevertheless, some reservations remain. Probably the most serious one, overall, is a pervasive optimism in the interpretation of complex phenomena with regard to repository performance. The most striking example of this, repeated in multiple reports, is the postulate that the repository, over the very long term (in an engineering time frame, i.e., 1,000,000 years) and over the very short term (in a geological time frame, i.e., 1,000,000 years)[256] essentially behaves as an ideal fluid: all voids will be closed and sealed (including void space in primary waste packages, void space in waste emplacement packages, void space in disposal cells, void space in disturbed rock (fractured and microfractured), void space in seals, and all deviatoric stresses will vanish,

---

[254] Andra 2005e Inset 8.3 (p. 354)

[255] Andra 2005e Inset 8.5 (p. 360)

[256] The 1,000,000 year time frame can be seen for example in Andra 2005d Figure. 3.2.1 (p. 24), a figure that is very similar to many figures that illustrate characteristic times for various major processes. Other examples are Figures 3.2.1 (p. 26), 3.2.2 (p. 27), 5.1.1 (p. 57), and 5.1.2 (p. 58) of Andra 2005f. The million year time reference frame objective is stated as such in Andra 2005g, pp. 21 and 24, and even more explicitly, with explicit reference to international practice, on p. 186 of Andra 2005h.

i.e., the repository will essentially return to a pre-construction state with regard to waste isolation characteristics and behavior. This assumption of an eventual restoration of a seemingly undisturbed state, under isotropic stress, seems exceedingly optimistic. For example, the pre-construction state includes deviatoric stresses, as explicitly recognized by Andra, and repeatedly invoked in many of its repository design concepts. A reasonably conservative assumption, and one we endorse, would be to assume that the EDZ does not fully repair itself to create pre-construction unaltered in situ permeability and /or state of stress. In fact, it may be best, and certainly would seem more conservative, to consider that the EDZ retains the worst state of estimated damage throughout the repository life.

We wish to temper this observation by recognizing explicitly that most of our comments are based on reviews of summarizing documents. We recognize that we have not reviewed many of the more technical underlying documents that may present more convincing evidence for the above-questioned postulate.

We also wish to explicitly recognize that from this point of view the selection of the 100 km2 section within the transposition zone seems to be justified on the basis of sound scientific and technical criteria: a repository horizon with maximum clay content, at reasonably close to optimum depth, and in a centralized location within the host formation, i.e., with maximal confinement distances.[257]

We strongly endorse the conceptual modular design approach for the repository layout. Separating emplacement locations for various waste types by significant distances greatly enhances the credibility of the arguments in support of containment and isolation performance, even though it might incur a considerable additional cost. Moreover, the multiple sealing components to be emplaced in between the various modules greatly enhance confidence in the long term isolation of the wastes emplaced in these various modules, repository components.

We strongly concur with the emphasis in the planning and design on maintaining reversibility and retrievability. Conversely, we are less convinced that the arguments in favor of possibly maintaining reversibility and retrievability for a very long time, e.g., multiple centuries, or even one century, are sufficient to balance the potential detrimental, damaging, effects of leaving excavations open for that long, and to what extent any induced damage can be recovered after that. While Andra typically presents an extremely optimistic picture of the post closure healing of the entire structure, this approach remains far from convincing. The risks of deterioration and damage raises the question of whether it would be better to consider minimizing any induced damage, e.g., by leaving any excavations open for no longer than absolutely necessary and justifiable. We believe that this fundamental approach to repository planning deserves more study.

---

[257] The narrowing from 100 km^2 to the 30 km^2 ZIRA within it was done based on surface and social considerations.

4.10 References

AFTES 1998	Association Française des Tunnels et de l'Espace Souterrain. "L'utilisation du béton non armé en tunnel." [AFTES recommandation GT7R5F1] *Tunnels et Ouvrages Souterrains* Nº 149 (Septembre/Octobre 1998): pp. 387-395. Available at http://www.aftes.asso.fr/commande-recommandation.html. Approuveé du 7 avril 1998. English translation: Association Française des Tunnels et de l'Espace Souterrain. "The Use of Plain Concrete in Tunnels." [AFTES recommendation GT7R5A1] *Tunnels et Ouvrages Souterrains* Nº 158 (Mars/Avril 2000): pp. 110-118. Translated in 1999. Available at http://www.aftes.asso.fr/commande-recommandation.html.
AFTES 2000	Association Française des Tunnels et de l'Espace Souterrain. *AFTES Recommendations for the Design of Sprayed Concrete for Underground Support.* [AFTES recommendation GT20R1A1] Paris: AFTES, 2000. Available at http://www.aftes.asso.fr/commande-recommandation.html. Originally published as "Conception et dimensionnement du béton projeté utilisé en travaux souterrains," [Recommendation de l'AFTES GT20R1F1], *Tunnels et Ouvrages Souterrains* n°164 (2001).
AFTES 2005	Association Française des Tunnels et de l'Espace Souterrain. "Recommandations de l'AFTES relatives aux AFTES, 2005, Méthodes d'auscultation des ouvrages souterrains. [Recommendation de l'AFTES GT19R2F1] *Tunnels et Ouvrages Souterrains* - Nº 187 (Janvier/Février 2005). pp. 10-47. Available at http://www.aftes.asso.fr/commande-recommandation.html.
Andra 2005a	Andra. *Le Comportement Mécanique d'Alvéoles de Stockage de Déchets B dans le Temps: Site de Meuse/Haute-Marne*. (C.RP.ASMG.03.0110.B) [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, 2 Juin 2005.
Andra 2005b	Andra. *L'évolution phénoménologique des galeries d'un stockage et le comportement des radionucléides dans les galeries: Site de Meuse/Haute-Marne*. (C.NT.ASIT.04.0014.C) [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, 31 Mai 2005
Andra 2005c	Andra. *Scellements et remblais des galeries et des puits d'un stockage en formation argileuse profonde*: *Site de Meuse/Haute-Marne.* (C.NT.AHVL.04.0030.A). [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, 15 Juin 2005.
Andra 2005d	Andra. *Le Comportement Mécanique des Scellements de Puits dans le Temps*: *Site de Meuse/Haute-Marne.* (C.RP.ASMG.03.0112.A) [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, 16 Juin 2005.

Andra 2005e	Andra. *Dossier 2005 Argile, Tome: Phenomenological evolution of the geological repository*. (Report Series) (C RP ADS 04 0025 B) (269 VA) [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, December 2005. On the Web at http://www.andra.fr/download/andra-international-en/document/editions/269va.pdf.
Andra 2005f	Andra. *Le Comportement Mécanique d'Alvéoles de Stockage de Déchets C et de Combustibles Usés dans le Temps,: Site de Meuse/Haute-Marne.* (C.RP.ASMG.03.0109.B) [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, 3 Juin 2005.
Andra 2005g	Andra. *Andra research on the geological disposal for high-level-long lived radioactive waste: Results and perspectives*. (Report series) (265 VA). [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, Juin 2005 (April 2006 printing). On the Web at http://www.andra.fr/download/andra-international-en/document/editions/265.pdf.
Andra 2005h	Andra. *Dossier 2005 Argile: Synthesis: Evaluation of the feasibility of a geological repository in an argillaceous formation, Meuse/Haute-Marne site*. 2nd ed. (Report Series) (Andra 266 VA) [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, December 2005. On the Web at http://www.andra.fr/download/andra-international-en/document/editions/266va.pdf.
Andra 2005i	Andra. *Rapport de synthèse des calculs de sûreté du dossier argile 2005 – Scénario d'Evolution Altérée (S.E.A.)* "Défaut de scellement" - *Calculs de référence et de sensibilité – Schémas de calculs, hypothèses, données et résultats*" Andra C.RP.ACSS.05.0010, Mai 2005. [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, Décembre 2005.
Andra 2009a	Andra. *Stockage réversible profond: Proposition d'une zone d'intérêt pour la reconnaissance approfondie et de scénarios d'implantation en surface*. (C.RP.ADP.09.0035.A) [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, 30 Octobre 2009. Links on the Web at http://www.andra.fr/andra-meuse/pages/fr/menu18/la-demarche-d-implantation/2009---une-nouvelle-etape-vers-le-choix-du-site-6662.html. On the Web at http://www.andra.fr/download/andra-meuse-fr/document/proposition_zira_C-RP-ADP-09-0035A.pdf.
Andra 2009b	Andra. *Proposition de l'Andra: Démarche d'implantation du projet de centre de stockage géologique profond*. (C.TR.ADP.09.0038.A) [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, 9 Novembre 2009. On the Web at http://www.andra.fr/download/site-principal/document/actualites/ctradp090038-a.pdf.

Andra 2009c	Andra. *Réponses de l'Andra aux questions posées par la Commission «localisation» du Comité local d'information et de suivi*. (C.NT.ADP.09.0037.A) [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, 2 Novembre 2009. On the Web at www.clis-bure.com/pdf/commissions/reponse%20andra%20localisation.pdf.
Andra 2010a	Andra. *Référentiel du Site Meuse/Haute-Marne.* (C.RP.ADS.09.0007.B) [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, 29 Janvier 2010.
Andra 2010b	Andra. *Options de sûreté du stockage en formation géologique profonde.* (C.NT.ASSN.09.0029.B) [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, 26 Fevrier 2010. Running title: JALON 2009 HA-MAVL.
Andra 2010c	Andra. *2006-2009: 4 ans de recherches scientifiques à l'Andra pour les projects de stockage.* (383) [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, Juin 2010. On the Web at http://www.andra.fr/download/site-principal/document/editions/383.pdf. English summary is at http://www.andra.fr/download/andra-international-en/document/press_release/100625_4_years_of_scientific_research.pdf.
Andra 2010d	Andra. *Options de réversibilité du stockage en formation géologique profonde*. (C.NT.AHVL.09.0005.B) [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, 10 mars 2010.
Andra undated	Andra. *Scientific and Technical Programme HAVL – Argile (HLLL-Clay) 2006-2010* (draft, provisional version A, 96 pp.) [undated] (as referenced in OECD 2006 p. 71).
Autorité Environnementale 2010	Autorité Environnementale. *Avis délibéré de l'Autorité environnementale concernat le renouvellement de l'autorisation d'exploitation du laboratoire de recherche souterrain de l'ANDRA à Bure (Meuse)*. (Avis nº 2010-27) (Dossier SIGMANET nº007334-01). La Défense: AE, Conseil général de l'environnement et du développement durable, 22 Juilliet 2010. On the Web at http://portail.documentation.developpement-durable.gouv.fr/documents/cgedd/007334-01_avis-delibere_ae.pdf.
BGR 2007	Peer Hoth, Holger Wirth, Klaus Reinhold, Volkmar Bräuer, Paul Krull, and Hagen Feldrappe. *Final Disposal of Radioactive Wastes in Deep Geological Formations of Germany - Investigation and Evaluation of Argillaceous Rock Formations.* Berlin/Hannover: Bundesanstalt für Geowissenschaften und Rohstoffe, April 2007. Link on the Web at http://www.bgr.bund.de/cln_116/nn_335074/EN/Themen/Geotechnik/geotechnik__node__en.html?__nnn=truehttp://www.bgr.bund.de/nn_335086/EN/Themen/Geotechnik/Downloads/WasteDisposal__HostRockFormations__en,templateId=raw,property=publicationFile.pdf/WasteDisposal_HostRockFormations_en.pdf.

Bock et al. 2010	Helmut Bock, Helmut, Boris Dehandschutter, C. Derek Martin, Martin Mazurek, and Antoine de Haller, Frédérick Skoczylas, and Catherine Davy. *Self-sealing of Fractures in Argillaceous Formations in the Context of Geological Disposal of Radioactive Waste: Review and Synthesis*. (Radioactive Waste Management) (NEA No. 6184) Paris: Nuclear Energy Agency, Organisation for Economic Co-Operation and Development, 2010. On the Web at http://www.nea.fr/rwm/reports/2010/nea6184-self-sealing.pdf.
CNE 2005	CNE. *Rapport d'Evaluation N^o 11*. [Paris]: Commission nationale d'évaluation relative aux recherches sur la gestion des déchets radioactifs, Instituée par l'article L 542 du Code de l'environnement issu de la loi n° 91-1381 du 30 décembre 1991, Juin 2005. Link on the Web at http://www.ladocumentationfrancaise.fr/rapports-publics/054000461/index.shtml. On the Web at http://lesrapports.ladocumentationfrancaise.fr/BRP/054000461/0000.pdf.
CNE 2010	CNE. *Rapport d'Évaluation N^o 4*. [Paris]: Commission Nationale d'Évaluation des recherches et études relatives à la gestion des matières et des déchets radioactifs instituée par la loi n° 2006-739 du 28 juin 2006, Juin 2010. Link on the Web at http://www.ladocumentationfrancaise.fr/rapports-publics/104000323/index.shtml. On the Web at http://lesrapports.ladocumentationfrancaise.fr/BRP/104000323/0000.pdf.
Duffaut 2003	Pierre Duffaut, ed. *Manuel de mécanique des roches, Tome 2: Les applications*, par le Comité français de mécanique des roches. Paris: École des mines de Paris, 2003.
Giot et al. 2006	Richard Giot, Richard, Albert Giraud, and Françoise Homand. "Three-dimensional finite element modeling of stress relaxation tests in anisotropic clayey medium: direct problem and back analysis," *Geotechnical and Geological Engineering* 24 (2006): pp. 919-947.
GNR FORPRO-II 2010	GNR FORPRO-II. *Appel d'offres 2010-II*. [Paris?]: Groupement de Recherche CNRS – ANDRA (GNR FORPRO-II du programme interdisciplinaire PACEN). On the Web at webdr.dr2.cnrs.fr/IMG/pdf/Appel_d_offres_FORPRO_2010-II-1.pdf.
Groupe interministériel «Bure» 2010	Groupe interministériel «Bure». *Rapport de synthèse sur le projet français d'un stockage géologique de déchets nucléaires et ses implications pour le Luxembourg*. Luxembourg: Le Groupe, le 26 janvier 2010. On the Web at http://www.ms.public.lu/fr/activites/radioprotection/protect-popul-nucleaire/coop-nat-internationale/rp_rapport_groupe_bure_final.pdf.
Haack et al. 1995	A. Haack, J. Schreyer, and G. Jackel. "State-of-the-art of Non-destructive Testing Methods for Determining the State of a Tunnel Lining: Report to ITA Working Group on Maintenance and Repair of Underground Structures," *Tunnelling and Underground Space Technology* 10 (4) (1995): pp. 413-431.

IEER 2005	Institute for Energy and Environmental Research. *Examen critique du programme de recherche de l'ANDRA pour déterminer l'aptitude du site de Bure au confinement géologique des déchets à haute activité et à vie longue: Rapport final*, Préparé pour le Comité Local d'Information et de Suivi; Directeur du projet: Arjun Makhijani; Coordinatrice du projet: Annie Makhijani; Auteurs du rapport (par ordre alphabetique): Detlef Appel, Jaak Daemen, George Danko,Yuri Dublyansky, Rod Ewing, Gerhard Jentzsch, Horst Letz, Arjun Makhijani. Takoma Park, Maryland, IEER, 27 décembre 2004, avec corrections 11 janvier 2005. Links on the Web at http://www.ieer.org/reports/bure/1204index.html.
Jacobi 1981	O. Jacobi. *Praxis der Gebirgsbeherrschung.* 2nd ed. Essen: Glückauf, 1981.
Massman et al. 2009	Jobst Massman, Shin-ichi Uehara, Amel Rejeb, and Alain Millard. "Investigation of desaturation in an old tunnel and new galleries at an argillaceous site," *Environmental Geology* 57 (2009): pp. 1337-1345.
Mazurek et al. 2008	Martin Mazurek, Andreas Gautschi, Paul Marschall, Georges Vigneron, Patrick Lebon, and Jacques Delay. Transferability of Geoscientific Information from Various Sources (Study Sites, Underground Rock Laboratories, Natural Analogues) to Support Safety Cases for Radioactive Waste Repositories in Argillaceous Formations, *Physics and Chemistry of the Earth* 33 (2008): S95S105. Supplement 1: Clays in Natural & Engineered Barriers for Radioactive Waste Confinement. Available for purchase on the Web or free at research libraries.
OECD 2006	OECD. *Safety of Geological Disposal of High-level and Long-lived Radioactive Waste in France: An International Peer Review of the "Dossier 2005 Argile 2005" Concerning Disposal in the Callovo-Oxfordian Formation*. (Radioactive Waste Management) (NEA No. 6178) Paris: Nuclear Energy Agency, Organisation for Economic Co-Operation and Development. On the Web http://www.nea.fr/rwm/reports/2006/nea6178-argile.pdf.
Seedsman 1993	Ross W. Seedsman. "Characterizing Clay Shales." In *Comprehensive Rock Engineering, Volume 3: Rock Testing and Site Characterization*, John A. Hudson, Volume Editor and Editor-in-Chief, Chapter 7, pp. 151 – 165. Pergamon Press, Oxford, 1993.
Young et al. 2005	R.P. Young, D.S. Collins, J. Hazzard, A. Heath, W.S. Pettitt, C. Baker, D. Billaux, P. Cundall, D. Potyondy, F. Dedecker, C. Svemar, P. Lebon. *Seismic Validation of 3-D Thermo-mechanical Models for the Prediction of the Rock Damage around Radioactive Waste packages Packages in Geological Repositories – SAFETI , Final Report.* (EUR 21925) (Nuclear science and technology) [Brussels]: Directorate-General for Research, Euratom, European Commission, 2005. Link on the Web at http://cordis.europa.eu/search/index.cfm?fuseaction=lib.document&DOC_LANG_ID=EN&DOC_ID=78493291&pid=0&q=5DD13ACA4D98AD0663837EA4901FF055&type=adv.

Chapter 5: Thermal considerations

Strengths

1. The measurement methods used by Andra are credible and believed to be capable of evaluating thermal properties correctly, even in anisotropic rock, such as the sedimentary argillite with slightly lower heat conductivity in the normal direction to the bedding than in the parallel direction to that of the bedding.
2. Generally speaking, the thermal properties agree well from different measurement methods for various rock types along the sedimentary layers in most figures in the Dossier 2005 Argile documents. Especially important are the results for the Callovo-Oxfordian argillite, the material closest to the heat sources, which has the highest influence on the peak temperatures.
3. The anisotropy in the thermal conductivity of argillite is an important detail when performing predictive thermal calculations. Our analyses confirm that an "equivalent" isotropic value (e.g., geometric mean of the component values in different directions) may be used to produce an adequately "equivalent" thermal response.
4. The thermal model of the Dossier 2005 Argile for the argillite interface temperature around the CU1 package can be reasonably corroborated with alternative models, but there remain differences in the range of 10% to 15%.

Findings

1. The documentation of the thermal models regarding assumptions, conditions and input data is scattered beyond traceability and repeatability. The chain of traceability is broken in many places, discouraging transparency of the presentation of the results and findings.
2. Andra has used a rather high value for bentonite thermal conductivity on the assumption the initital saturation of the bentonite would be high and that it would resaturate to 100 percent. While these assumptions may be reasonable for vitrified waste disposal, they may not apply to spent fuel disposal, where a period of low saturation may occur in the first 100 years, indicating the need to use a lower value of bentonite thermal conductivity.
3. The thermal goal for the swelling clay buffer in the S2 scenario is slightly exceeded, using open literature data for thermal properties. We recognize that we have used a simplified, though realistic, model. It is critical for Andra to address and resolve this issue in detail (see recommendation below).
4. In spite of a very comprehensive summary of the thermal properties measurements, the choice of the flash method will keep the questions open for the validity of the conductivity results in non-isotropic media such as the Callovo-Oxfordian argillite.
5. Inconsistent heat conductivity values in subsequent documents in the Dossier 2005 Argile are a cause for some concern and need traceability and quality assurance checks, even if the discrepancies are small and are thought insignificant.

Recommendations

1. Thermal (and mechanical) design of the repository requires the specification of a source term. This includes a specification of how many of each type of waste package will be disposed of and the expected age and thermal characteristics of the packages. Most importantly, the current

uncertainty regarding whether unreprocessed spent fuel will be disposed of needs to be addressed and resolved.

2. We strongly recommend that Andra develop a plausible scenario that will include a substantial component of spent fuel disposal. This is necessary because scenario S2, from Dossier 2005 Argile, which assumes an end to reprocessing in 2010 is currently obsolete. We have performed illustrative temperature calculations involving a CU1 type of spent fuel package to show the importance of developing an updated version of the S2 scenario. We recognize that such a scenario is not presently required. However, unreprocessed spent fuel, including unreprocessed MOX spent fuel, will create more stressed thermal conditions as well as greater mining and mechanical challenges. Andra should develop a plausible updated S2 scenario or a modified S1b scenario and examine its thermal implications as well as its consequences for repository size.

5.1 Review of coupled thermal response of the proposed repository and thermal properties of the host formation

Radioactive decay of certain types of waste emplaced in the proposed repository will generate heat that will, in turn, heat the surrounding host rock resulting in a transient temperature change. A key design objective is to limit the increase in temperature such that the argillite temperature (or the buffer temperature, if applicable) remains below a prescribed limit. As the temperature of the argillite or the buffer approaches or exceeds 100 deg C, coupled processes may evolve and have a deleterious effect on repository performance. This review consists of a brief examination of Andra’s analyses and selected calculations. As appropriate, we have attempted to highlight potential concerns.

5.1.1 The emplacement scenarios

The proposed repository is needed to host various types of radioactive materials according to Dossier 2005 Argile:[258]

- Medium-level, B-type waste with negligible heat generation; [259]
- High-level, reprocessed, C-type waste with considerably high rate of heat generation depending on its age and composition;[260] and
- Although not envisioned by Andra under the present repository design, unreprocessed, CU-type spent nuclear fuel, with considerably higher volume and rate of heat generation.[261]

At present, Andra is not required to take into account direct disposal of unreprocessed spent fuel, but only Type B and Type C waste. Nonetheless, it has been recognized that both uranium and MOX spent fuel may need to be disposed of, depending on future policy decisions. We consider spent fuel disposal in this chapter in this context, especially since it may present some of the more difficult thermal issues.

---

[258] Dossier 2005 Argile, Synthesis p. 14

[259] Dossier 2005 Argile, Synthesis p. 46

[260] Dossier 2005 Argile, Synthesis p. 47

[261] Dossier 2005 Argile, Synthesis p. 47

Four scenarios, (1) through (4) are considered in Dossier 2005 Argile regarding the arrangement and composition of the disposal material:[262]

(1) **"Scenario S1a** assumes that all the spent fuel" generated by the French "power plants currently operating will be reprocessed (45000 MTHM, comprising 8000 MTHM of UOX1, 20500 MTHM of UOX2, 13000 MTHM of UOX3, 800 MTHM of URE and 2700 MTHM of MOX). This scenario deals with B- and C-type wastes only."

(2, 3) **Scenarios S1b and S1c** both assume that "the 42300 MTHM of UOX/URE are reprocessed. However, it is assumed that the MOX spent fuel (2700 MTHM) will not be reprocessed," requiring "direct disposal. In scenario S1b, the vitrified waste packages are assigned a higher" rate of heat generation "than current waste packages." "[I]n scenario S1c, their heat rating is equivalent to that of the current waste packages." This scenario deals with the disposal of B- and C-type wastes as well as with the direct disposal of CU-type spent nuclear fuel (SNF).

(4) **Scenario S2** assumes direct disposal of UOX and MOX spent fuel without reprocessing beyond 2010. Partial reprocessing of the UOX spent fuel is considered "until 2010 (8000 MTHM of UOX1 and 8,000 MTHM of UOX2)." Beyond 2010, direct disposal is assumed for "29000 MTHM with 12500 MTHM of UOX2, 14000 MTHM of UOX3, 500 MTHM of URE and 2000 MTHM of MOX." This scenario deals with the disposal of B- and C-type wastes as well as with SNF. We recognize that this scenario is obsolete since France continues to reprocess as 2011 begins. One of our recommendations is that it be updated.

In a 2009 update of the source term, Andra has described two basic scenarios. It also stated that an alternative scenario that includes spent fuel disposal "could be defined":

> - a baseline scenario "SB", with the addition of quantitative margins compared to the scenario of the nuclear operators. As a precaution, this scenario also includes wastes whose management has not yet been finalized;
> - a sizing scenario "SD". It adds space to the baseline, for certain kinds of waste, conventionally set to + 50%. This margin covers (i) the possibility license extension of the existing nuclear reactors, (ii) the operation and decommissioning of future facilities (prototype fourth-generation reactor for example), (iii) uncertainties in decommissioning operations.
>
> Furthermore, an alternate scenario "SA" could be defined to support exploratory studies on the direct disposal of unreprocessed spent fuel, under the PNGMDR [Plan national de gestion des matières et des déchets radioactifs]. These studies will aim to ensure that the proposed storage architecture does not present any unacceptable features if the reprocessing of spent fuel is abandoned.[263]

---

[262] Dossier 2005 Argile, Synthesis p. 44

[263] Andra 2009, Colis p. 14 Translated from the French

We recommend the development of an updated spent fuel scenario be defined as soon as possible.

The C-type nuclear waste as well as the CU-type SNF both produce substantial heat that has to be dissipated in the rock with moderate temperature difference between the emplacement cells and the ambient, far-field locations. The target is to keep the temperature in the rock below-boiling for the entire timespan of operation. Therefore, thermal considerations are part of the repository layout and the selection criteria of the heat-dissipation area, related to the size of the ZIRA.

5.2 Review of the thermal properties of the Callovo-Oxfordian host rock

How adequate is the experimental program in support of the repository design? Is the size of the repository that is now envisioned adequate and agreeable in view of the thermophysical properties available from laboratory and field measurements for the site and possible future changes in reprocessing policy? These questions may become critical regarding the size of the repository in case it becomes necessary to dispose SNF (i.e., CU1and CU2 waste types). A scoping calculation was made to investigate the sensitivity of target temperature to the thermal conductivity of the host rock, the prime parameter in the evolution of the temperature field under the heat load caused by radioactive decay.

We note that in the context of these calculations there is uncertainty about future reprocessing policy. While France continues to reprocess uranium spent fuel, there is no policy requiring reprocessing of MOX spent fuel. There is also a considerable backlog of unreprocessed uranium spent fuel from past power generation, since not all such spent fuel was reprocessed. For the moment, going forward, France plans to reprocess all uranium spent fuel, but it is uncertain how long this can be sustained if nuclear power grows or if financial pressures to reduce electricity costs become larger. We note that reprocessing light water reactor spent fuel is nearly two times more expensive than simply storing spent fuel on site.[264] We strongly recommend that Andra develop a plausible scenario that will include a substantial component of spent fuel disposal, as well as disposal of Type C and Type B waste. We have performed some illustrative temperature calculations involving a CU1 type of spent fuel package to illustrate the importance of developing an updated version of the S2 scenario.

5.2.1 Scoping calculation with an approximate, three-dimensional model for the CU1-type spent fuel package

The model input is based on Dossier 2005 Argile and other reference documents.[265] The geometrical arrangement of one CU1-type (long) package is shown in Figure 5-1. The model domain is bounded by adiabatic surfaces, assuming a repetition of the block in x and y directions. For a short study time period, this assumption is commonly accepted. Indeed, the maximum temperature will be reached in a few decades, during which the penetration depth of heat flow is only a few tens of meters, and the heat flow is quite localized in the vicinity of the package. It is believed that an adiabatic block of one package is a good approximation for numerous packages

---

[264] Von Hippel 2007 Slide 5

[265] Dossier 2005 Argile, Architecture, Plötze et al. 2007, and Tang et al. 2007

of the same kind in an infinitely repeated pattern in the horizontal plane. In fact, the adiabatic boundaries mean exactly that: a uniform, planar distribution of repeated heat sources. Unheated areas around the access and ventilation tunnels will have an unheated edge effect undoubtedly, but this effect will not be felt for decades, an assumption used in the scoping calculation.

The model input parameters are summarized in Table 5-1 below. The numerical code used in this study is NUFT,[266] a simpler-to-use version of the TOUGH model-family, assuming a conduction only model. The rockmass is assumed to be anisotropic in terms of thermal conductivity, λ_z=1.3 W/(mK) in vertical and $\lambda_x=\lambda_y$=1.9 W/(m-K) in horizontal directions, respectively. For comparison, an isotropic conduction model is also included assuming the average thermal conductivity of $\lambda_x=\lambda_y=\lambda_z$=1.6742 W/(m-K) in all directions, using the geometrical mean value of $\lambda_{avg}=(\lambda_x*\lambda_y*\lambda_z)^{0.333}$. A thermal conductivity of λ_{avg} =1.6742 W/(m-K) is quite possible to encounter with an uncertainty of +/-0.37 W/(m-K), an acceptable value in view of the spread of conductivities in many Andra documents.

The thermophysical properties of swelling clay for MX80 are listed in *La Charge thermique d'un stockage: Site de Meuse/Haute-Marne,* Table 3.4.1.[267] The thermal conductivity shows a strong variation with saturation, S, and formulated as follows:[268]

$$\lambda=\lambda_0 + (\lambda_s-\lambda_0)*S, \qquad (5\text{-}1)$$

where λ_0 is the thermal conductivity in the dry state (S=0)
λ_s is the thermal conductivity in the saturated state (S=1)

The problem with the tabulated conductivity values in *La Charge thermique d'un stockage: Site de Meuse/Haute-Marne,* Table 3.4.1, is that it is not realistic to use them in the de-saturated state of MX80 if the saturation is significantly lowered by heat and high temperature during the thermal period. Close to or above 90 ^oC temperature, the saturation may reduce from 80% to 20%, or 10%, or to near zero. Oven-dry condition for the MX80 may happen at the vicinity of the CU packages during the time period of the evolution of the maximum temperature. Using λ_s=1.5 at S=1 and λ=1.2 at S=0.8 in Equation 5-1), k_0 may be back-calculated as follows:

$$1.2= \lambda_0 + (1.5 - \lambda_0)*0.8 \qquad (5\text{-}2)$$

λ_0=0 is obtained from Equation (5-2), which is quite un-realistic, resulting in the following equation:

$$\lambda=1.5*S \qquad (5\text{-}3)$$

Equation. (5-3) gives a value of λ=0.3 W/(m-K) for 20% saturation which is not far from literature data on dry bentonite.[269] Instead of using this low value, the average thermophysical

---

[266] Nitao 2000
[267] Andra 2005, Thermique Table 3.4.1 (p. 29)
[268] Andra 2005, Thermique Section 3.4.1 (p. 29)
[269] Plötze et al. 2007; Tang et al. 2007

properties values for bentonite from the literature were used.[270] The most realistic value for thermal conductivity may be around 0.75 W/(m-K). Andra used a minimum value of 1.2W/(m-K) for bentonite thermal conductivity on the assumptions that (i) the initial saturation would be high (~70 to 80 percent), (ii) that the temperature would remain below 100 C throughout, and (iii) resaturation to 100 percent would occur without the temperature exceeding 100%.[271] These conditions may apply to HAVL waste. However, low saturation in the first 100 years may NOT apply to spent fuel disposal, as the calculations below indicate. We also examined the effect of using the high value of 1.2 W/(m-K) (at S=0.8) to compare with Andra's thermal model results. These values together with other properties are listed in Table 5-1.

Figure 5-2 shows the temperature results of the two models for 200 years after emplacement. The isotropic and the anisotropic model results differ by up to 8°C in the peak values, showing significant sensitivity to conductivities and to anisotropy. This is a significant point because it reinforces the need to use explicit anisotropic conductivity values whether or not spent fuel disposal is an issue. When using the more realistic bentonite conductivity of 0.75 W/(mK) in our model, additional disagreements of about 10°C are found between the results of the anisotropic and isotropic conductivity models, relative to the Andra temperature result.[272] It is not clear from the Andra documents whether an isotropic or anisotropic model was used for the reference studies. As illustrated, irrespective of this question, no agreement is reached.

Based on our simplified modeling exercise, it appears that the thermal goal of maximum 90°C at the package-swelling clay interface may not be met for the CU1-type packages for several decades. This would need to be verified, using more realistic models that include, as we did, anisotropy of thermal conductivity and a more realistic value of bentonite conductivity.

Better agreement may be reached with Andra temperature results if a conductivity value of $\lambda=1.2$ W/(m-K) is used for the buffer which is associated with 80% saturation, as shown in Figure 5-2.

---

[270] Plötze et al. 2007; Tang et al. 2007

[271] Andra has done considerable work on swelling argillite (Andra 2005, Materiaux), including research on thermal conductivity (see Andra 2005, Matériaux, Figure 4.2.1, for instance). Andra's choice of 1.2 W/(m-K) would be reasonable for high saturation that could accompany HAVL disposal. (See also Su 2006 pp. 69-74.) However, a lower value of thermal conductivity should be used for modeling spent fuel disposal. The data provided -- see Figure 4.2.1 -- and the data in the literature indicate that the value of 0.75 W/(m-K) that we have used more realistic for modeling spent fuel disposal. To our knowledge, Andra has not provided an indication of what value it would use for bentonite with should a low saturation.

[272] Dossier 2005 Argile, Architecture p. 151 and p.245

Table 5-1 Thermal model input parameters

Input Parameter	
Axial length of waste container	5.4 m
Diameter of waste container	1.25 m
Diameter of drift	3.3 m
Rockmass:	
Thermal conductivity (anisotropic)	λ_x=1.9, λ_y=1.9, λ_z= 1.3 W/(m-K)
Thermal conductivity (averaged)	λ_x=λ_y=λ_z=1.6742 W/(m-K)
Cp	1214 J/(kg-K)
Density	2390 kg/m^3
Bentonite/Swelling Clay:	
Thermal conductivity	0.75 and 1.2 W/(m-K)
Cp	1200 J/(kg-K)
Density	1600 kg/s
Waste Container:	
Thermal conductivity (effective)	50 W/(m-K)
Cp (effective)	250 J/(kg-K)
Density (effective)	8000 kg/m^3
Heat load at time of emplacement (CU1 long package with 4 assemblies)	1600 W/container (at emplacement after 60 years of aging)

Note: Cp is the specific heat at constant pressure.

Figure 5-3 shows the heat load variation with time of one CU1 package, based on the heat load data specified in Table 5-1. The decay heat characteristics follow that of Andra.[273]

---

[273] Dossier 2005 Argile, Architecture Figure 3.2.20 (p. 96)

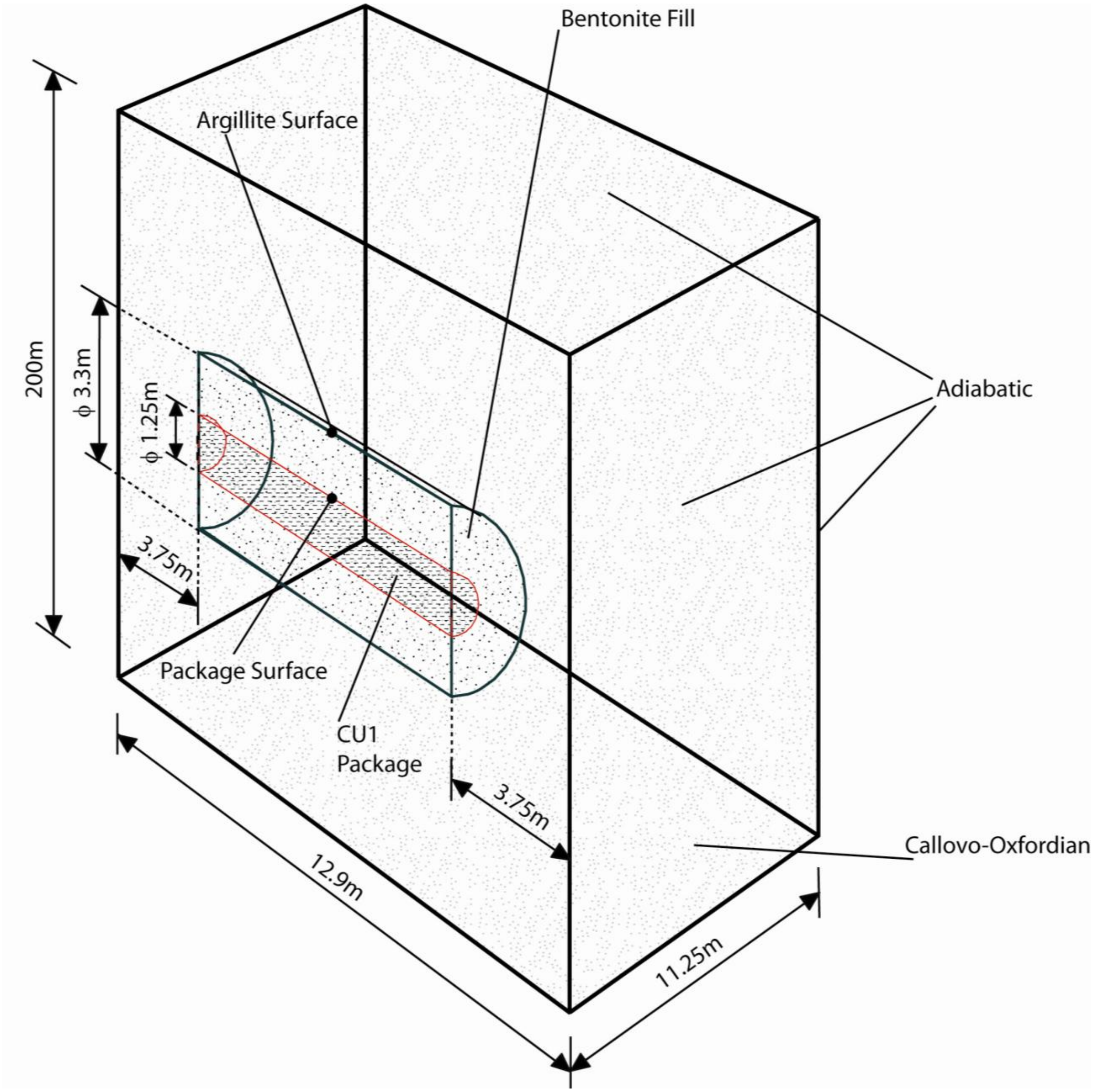


Figure 5-1. The model for a CU1 package (Source: G. Danko)

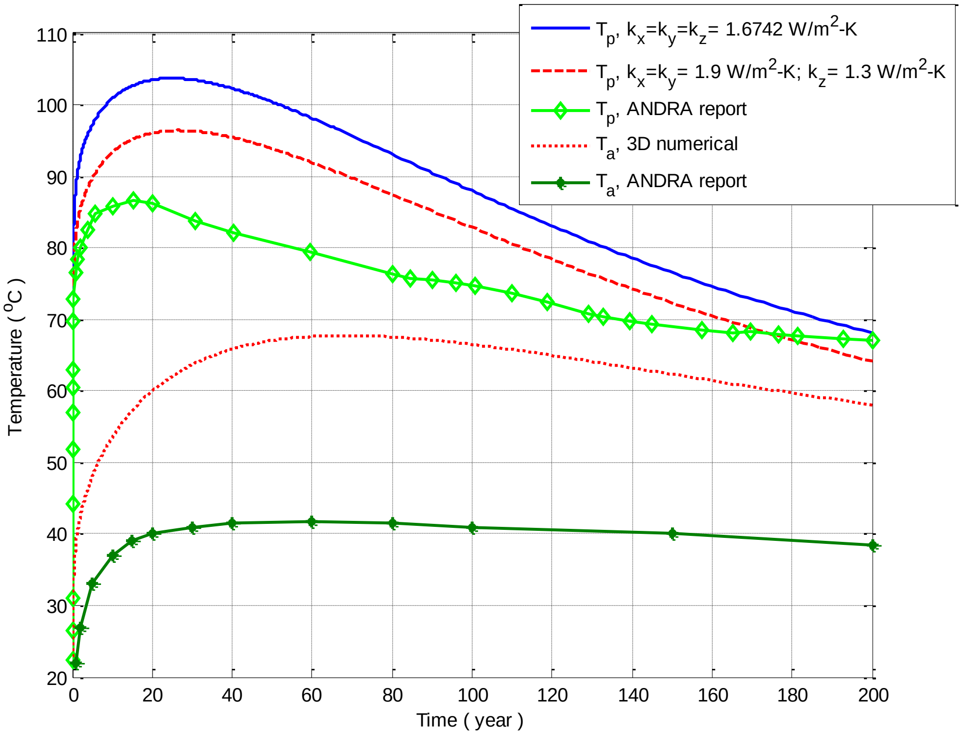


Figure 5-2. CU1 package surface (T_p) evolution over time using various input thermophysical properties for the argillite and the swelling clay (bentonite) (Source: G. Danko)
Note: The thermal conductivity is denoted by k instead of λ in the legend,

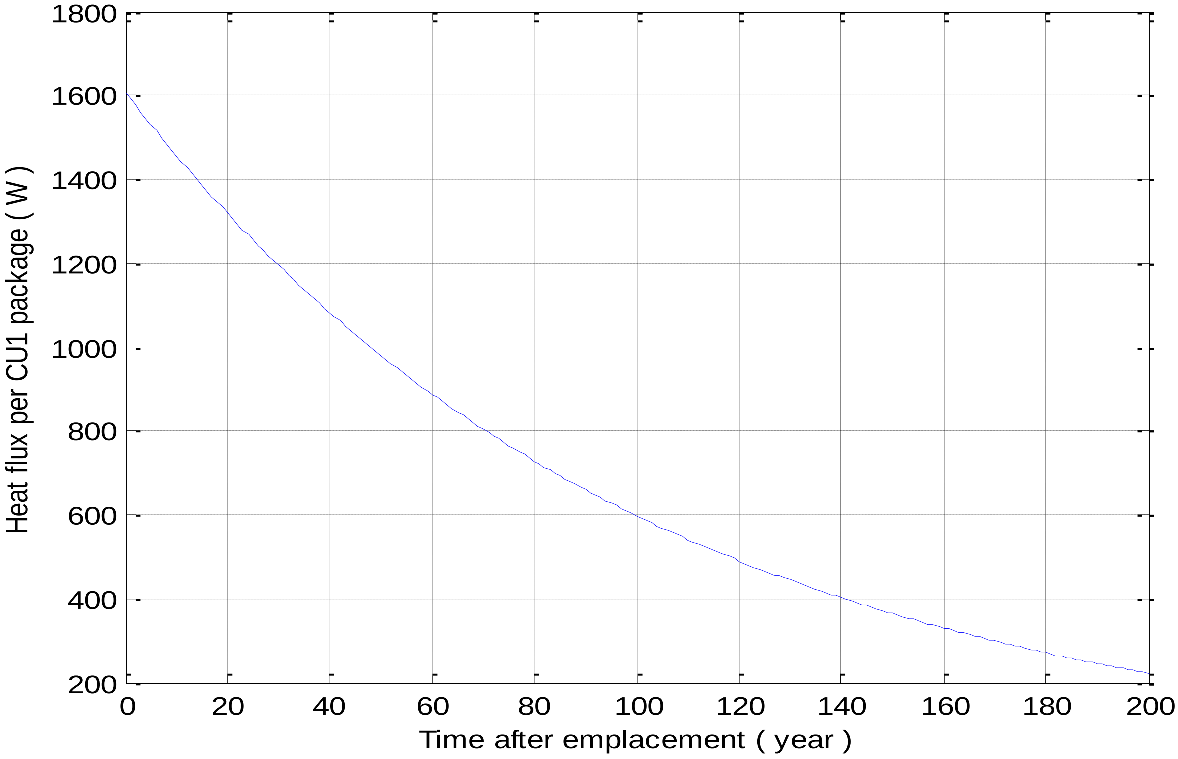


Figure 5-3. Heat load variation with time for the CU1 package (after Dossier 2005 Argile, Architecture Figure 3.2.20 (p. 96) (Source: G. Danko)

5.2.2. The thermal properties of the Callovo-Oxfordian host rock

The thermal properties of the rock within the ZIRA affect the emplacement density of the heat-generating waste. The thermal conductivity and diffusivity are prime variables of the time-dependent temperature evolution in the rock around the heat-generating waste packages. In general, a lower thermal conductivity of argillite would lead to a lower emplacement density for a given maximum target temperature in the host rock (or bentonite buffer). These properties are not known very precisely for the ZIRA or the bentonite. At this point, it is quite possible to have 10% to 20%, or even higher uncertainty in the thermal conductivity, considering the high variations in some of the preliminary estimates from laboratory measurements on rock samples, which are not necessarily taken from the actual area of the ZIRA. Will the size of the ZIRA be adequate if the thermal conductivity values measured during site characterization are at the lower end of the range and/or the highest possible target disposal capacity is demanded for the design?

A general observation may be made about a specific issue concerning the anisotropic nature of the host rock at the Bure site. It is important to use anisotropic thermal properties for correctly establishing peak temperature evolutions at specific target points such as the argillite or the swelling clay at the interface, during the thermal surge time period. As shown in Figure 5-2, the peak temperatures of the argillite are estimated at 96 ^{o}C and 104 ^{o}C for anisotropic and isotropic material properties, respectively, assuming a conductivity of 0.75 W/(m*K) for the bentonite fill in case of CU1 disposal. Therefore, averaging the heat conductivity of an anisotropic material makes numerical model results erroneous. Error may occur from using three-dimensional heat flow field in the thermal properties measurement without actually inverse-modeling the response function with an anisotropic model. Iteration is needed since finding three, directionally-specific values of a thermal property is an ambiguous task to solve from one resultant response function. Such a model with an iterative evaluation framework, however, is not described in the documents.

5.2.2.1 Review of the thermal properties measurement methods on samples

The importance of the thermal properties for the proposed site is well recognized by Andra, and a comprehensive review is provided in *Dossier 2005 Référentiel du Site Meuse/Haute-Marne, Tome 2*,[274] regarding the laboratory measurement methods on rock samples.[275] The methods for transient and steady-state measurement are briefly reviewed and referenced. The same techniques are documented by Andra in a more recent document in 2009. Reference is made to the sonic wave velocity measurements that can be empirically correlated with the thermal conductivity of the rock.[276]

The steady-state measurement directly yields thermal conductivity, λ, while the transient methods obtain thermal diffusivity first, which must be converted to conductivity from the formula $\lambda = \rho * c_p * a$, where ρ, c_p, and a are density, specific heat, and thermal diffusivity, respectively. Consequently, specific heat as well as density measurements are also involved in some of the heat conductivity evaluations. In case of sonic measurements, the conversion to heat conductivity involves empirical correlation equations specific to P (pressure) and S (shear) waves.

Verification exercises are cited for validation of the transient "flash" and the "divided bar" methods. Reasonable agreement is achieved between the results from different laboratories using the divided bar and the flash method. The differences with Pyrex and ceramic ranged from -6.9 and 12.5% except in one case. For the MeSy laboratory, the differences were up to 41.2%, [277] which were discarded without further investigation.

The methods used by Andra are credible and believed to be capable of evaluating thermal properties correctly, even in anisotropic rock, such as the sedimentary argillite with slightly lower heat conductivity in normal direction to the bedding than in the parallel direction to that of the bedding. Perhaps the "shock sensor ring" method[278] is a less capable technique in measuring specific, direction-dependent values of the thermal diffusivity in non-isotropic media. The circular heater generates a slightly semi-spherical temperature field in the sample material under the ring, integrating heat conduction in every direction. Due to the 3D heat flow in the sample,

---

[274] Référentiel du Site 2005 Tome 2 Chapitre 27
[275] Référentiel du Site 2005 Tome 2
[276] Référentiel du Site 2010 Tome 2 Chapitre 19
[277] Référentiel du Site 2005 Tome 2 Tableaux 27-1 and 27-2 (p. 219)
[278] Shown in Référentiel du Site 2010 Tome 2 Figure 19-2 (p. 168)

and an averaged result at the point-like sensor, this method will not be useful to clearly distinguish between heat conductivities in different directions.

Generally speaking, the thermal properties agree well from different measurement methods for various rock types along the sedimentary layers in some figures in the Dossier 2005 documents. Especially important are the results for the Callovo-Oxfordian argillite, the material closest to the heat sources and the highest in influence to the peak temperatures.

A closer look at the heat conductivity, λ (W/(mK)), the results for the argillite shown in Référentiel du Site 2005, Tome 2,[279] gives the following range of the results for the depth between 460 m and 510 m:[280]

From EST104 and HTM102 borehole core samples, analyzed by divided bar measurement

λ_{normal}: from ~ 1.1 to 1.6, with eight measurements below 1.3
$\lambda_{parallel}$: from ~ 1.4 to 2.2

From EST205 borehole log, sonic velocity-based measurements are:

$\lambda_{sonic\text{-}based}$: from ~ 1.2 to 1.4

These values agree very well with those used in the thermal models in the Dossier 2005 documents reviewed in the foregoing.

However, somewhat higher λ_{normal} values are reported from samples for EST104 borehole in the more recent Référentiel du Site 2010, showing all heat conductivity data together with in situ experimental results. The lowest λ_{normal} value discernable from samples there[281] is:

λ_{normal}: 1.22, with no other measurement result below 1.3

These are not quite the same as the results reported in 2005. However, a comparison is difficult because the earlier results cited above were for two boreholes, EST104 and HTM102, but the latter is not shown in the 2010 document. It would have been desirable to present the values in a manner that enabled direct comparison.

5.2.2.2 Review of the in situ thermal properties measurements

In situ measurements are important for checking the validity of extrapolating the results of the thermophysical properties obtained on laboratory-scale samples to large volumes of rock. Scaling effects, if any, may be obtained from such a comparison. Two in situ measurements are reported in Référentiel du Site 2005 and Référentiel du Site 2010: the TER experiments at the underground laboratory, and the REP measurements conducted during the construction of the shaft at the underground laboratory. Both measurements were carefully conducted and evaluated, corroborating the results of the measurements on laboratory samples. Therefore, scale

---

[279] Référentiel du Site 2005 Tome 2 Figures 27-4 and 27-5 (p. 225)
[280] Référentiel du Site 2005 Tome 2 p. 225
[281] Référentiel du Site 2010 Tome 2 Figure 19-5 (p. 174)

effects do not appear to be a factor for thermal conductivity values found in samples or rock mass at Bure.

The first report of the in situ heat conductivity measurements for the most critical argillite material is in Référentiel du Site 2005.[282] The values for the depth range between 460 m and 510 m from borehole EST 205 are:

λ_{normal}: 1.1, (two readings) and 1.35 (one reading)
$\lambda_{parallel}$: 2.0, (one reading)

The two lowest values for λ_{normal} are somewhat below the results from the sonic wave measurements from EST205 cited above.

However, a different relationship is shown in Figure 5-4 below:

---

[282] Référentiel du Site 2005, Tome 2 Figure 27-5 (p. 225). The samples were from borehole EST205.

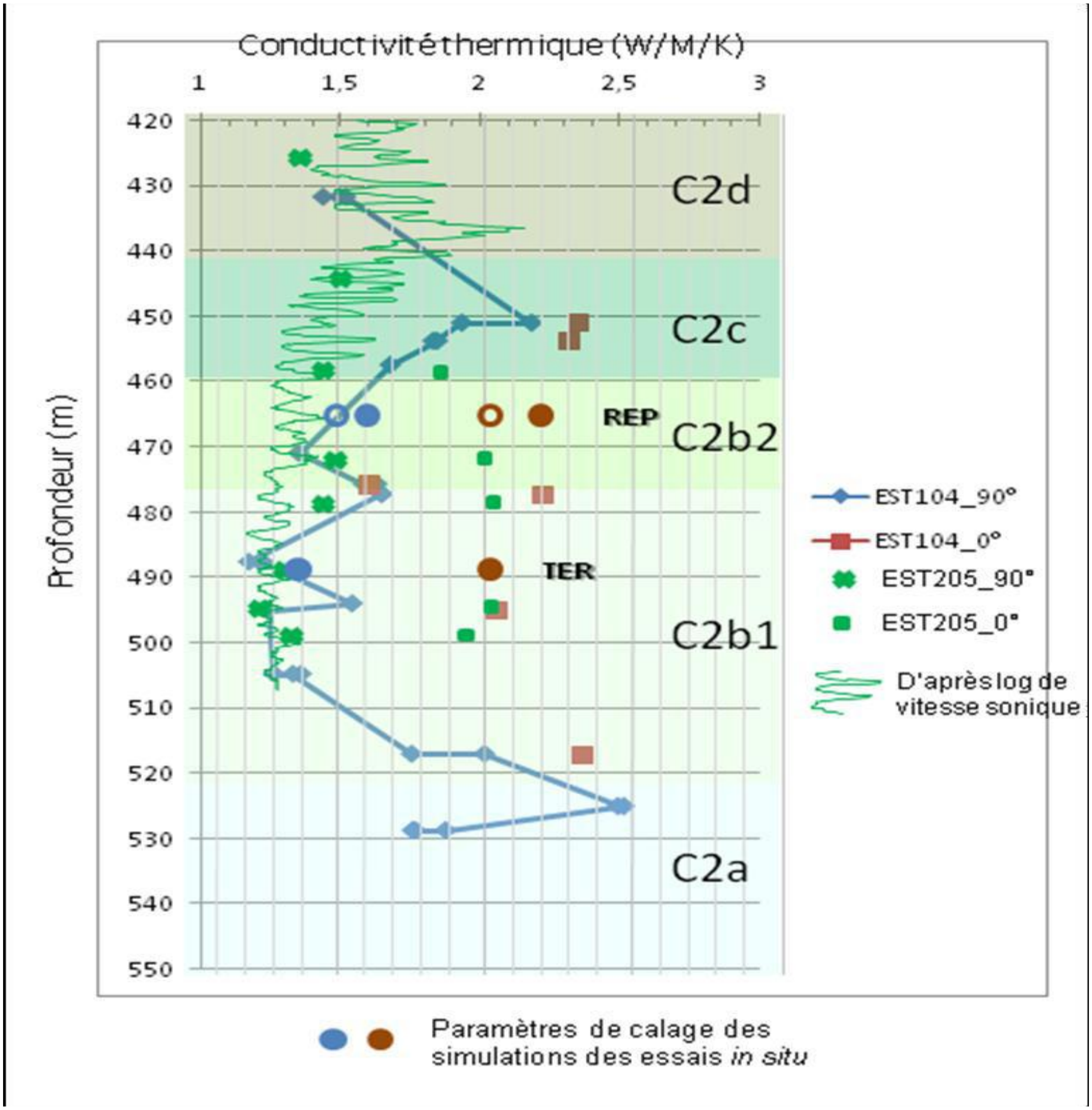


Figure 5-4. All thermal conductivity data obtained on the underground laboratory site. (Source: Référentiel du Site 2010, Tome 2 Figure 19-5 (p. 174))

The in situ measurement results are no longer lower than the values from the sonic curve that may be used as a reference guide. The discrepancy between the in situ results for $\lambda_{\text{perpendiculaire}}$ shown in Figure 27-5 of the 2005 report and Figure 19-5 of the 2010 report warrants explanation.

5.3 Review of the thermal models

5.3.1 Andra's thermal model in view of the scoping calculations in Section 5.2.1

Thermal models are predictive tools to support the conceptual design and the preparation for the site characterization program to confirm the site properties for the final design. The repository program by Andra uses credible, well-developed and tested thermal models for conceptual design. The models have the capacity of incorporating anisotropy, inhomogeneity, and variable saturation. Once the properties of the rock and the thermal load for the heat-generating waste packages are defined, the models will be fully capable of predicting the evolution of the temperature field in the emplacement zones, including interactions with the processes in the emplacement cells that may have hydrogen generation and a delayed re-saturation.

Andra continues improving the numerical models in the evaluation of the heat flow and its related coupled hydrologic, mechanical, and chemical effects. The recent application of the TOUGH model[283] evidences the continuing interest in model improvements. However, for the evaluation of the adequacy of the size of the ZIRA or sensitivity calculations of emplacement density, a much simpler modeling approach is sufficient. Andra presented such simplified, 2D and 3D studies, using the results from heat conduction-only models in the earlier documentations.[284]

The problem with the documentation of the results is its illustrative nature: it explains, rather than documents, sample model arrangements and representative temperature curves. The onus of understanding the technical and computational details is on the reader or reviewer. It is extremely difficult to trace the work in a reasonable amount of time and repeat it with the information given in the documents, stepping through the large set of nested loops of references. This should be given in one concise document which includes: (1) model description, conditions, assumptions; (2) geometry specification; (3) initial and boundary conditions specific to each task; (4) input properties for the material for each component.

The lack of traceability was one of the reasons for conducting an independent, simplified thermal calculation, described in Section 5.2.1. Discrepancies of about 20 ^{o}C are shown in Figure 5-2 in the package surface (T_b) and explained in the foregoing between the results of the scoping model and those from the Andra documents. Two further remarks are in order to explain the significance of those discrepancies.

Remark 1: Bentonite thermal conductivity uncertainties. The thermal model used by Andra and referenced in several figures[285] estimates the maximum bentonite temperature as being about 20^{o}C less relative to the scoping model of Section 5.2.1. This difference may be due to the difference in the thermal conductivity of the bentonite fill. Hence, the difference in package surface temperature may be regarded as a matter of different model assumptions.

---

[283] Pruess et al. 1999, Poppei et al. 2009, and Poller et al. 2009

[284] Dossier 2005 Argile, Architecture; Dossier 2005 Argile, Evolution; and Andra 2005, Thermique

[285] See, for instance, Dossier 2005 Argile, Architecture Figure 4.3.8 (p. 151) or Figure 5.3.15 (p. 245) for the CU1 (long) package.

Remark 2: Other model agreements or disagreements. The interface temperature (T_a) between the bentonite fill and the argillite host rock is not sensitive to the bentonite properties. Therefore, it may be a better choice for comparison between the scoping calculations of this review document and Andra's results. Figure 5-6 shows the argillite temperature, T_a, from the model calculation described in Section 5.2.1. A maximum of 67°C is reached at around 70 years after emplacement of the CU1 package subsequent to 60 years of aging. Andra's *La Charge thermique d'un stockage: Site de Meuse/Haute-Marne* shows a maximum of 42°C for the same argillite interface temperature reached at around 70 years,[286] which is believed to be a differential temperature over the ambient, initial temperature of 22°C. Adding the initial temperature of 22°C to Andra's predicted temperature change of 42°C gives a maximum temperature of 64°C. This is a discrepancy of only about 3°C for the maximum argillite interface temperature (T_a), a quite acceptable agreement.

A straightforward, simplified, 3D, analytical-numerical model is also used to corroborate the numerical model results of Section 5.2.1 for the argillite temperature, using a line-averaged heat load model.

5.3.2 Andra's thermal model in view of a simplified, analytical-numerical model

The objective of the simplified, analytical-numerical model is to further investigate the reasonability of the argillite temperature (T_a) evolution with time, a parameter believed to be only slightly affected by the thermophysical properties of the bentonite fill. The geometry of the simplified model is shown in Figure 5-5. Five drifts are modeled, all with line heat load, driven in an infinite, isotropic rock with averaged properties. The goal is to predict the temperature T_a at the drift wall at the center point of the arrangement. The simplified model applies an average argillite heat conductivity of λ =1.6742 W/(mK), and thermal diffusivity of a=5.7702*10^{-7} m^2/s, calculated from the properties in Table 5-1. Line heat load, an average of the dissipation of package over the 12.9 m length of an emplacement period gives 1,600/12.9=124.03 W/m at the time of the emplacement. Following the heat decay characteristics with a half-life of 70 years for the short time period of a few decades, the line-averaged heat load function in W/m is as follows: q(t)=124.03*exp(-t/100.99), where t is the time in year unit.

An analytical-numerical model can be constructed from Carslaw and Jaeger[287] for the temperature at the center of a 200 m long line load heater at the wall of a tunnel 3.3 m in diameter, driven in an infinite medium, using a solution for a point heat source and a double superposition in time and space. The time variable is used to account for the variation in heat load over time. The space variation is modeled by considering point sources over the length of 200 m and adding the resulting partial temperatures to the one at the center point on the tunnel wall. Two neighboring emplacement drifts on either side of the drift at the center, with inter-axial spacing of 22.5 m and 200 m in length are also included, shown in Figure 5-5. The neighboring drifts contribute to increasing the temperature at the center point; this effect is included by superposition to the center point temperature.

---

[286] Andra 2005, Thermique Figure 5.3.3 (p. 56)

[287] Carslaw and Jaeger 1959 p. 261

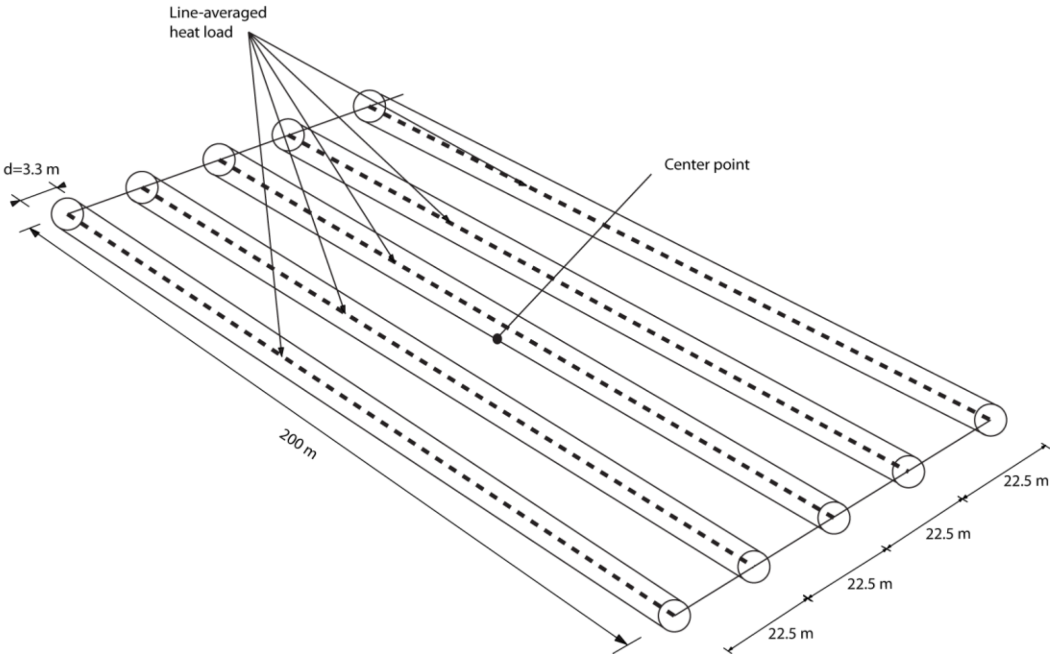


Figure 5-5. The geometry of the simplified, line-averaged heat load model (Source: G. Danko)

The line heat load of these two neighboring drifts adds a time-variable, incremental temperature of a few ^{o}C only to the argillite wall at the center point. However, there is no reason to model perfectly the emplacement footprint in this corroborating exercise and include more neighbor drifts and longer length of the line-load along the drifts. The temperature addition is small enough from the far-away heat sources at the beginning of the short time period of 100 years that captures the maximum temperature of the argillite around one CU1 package.

The result of the model for the argillite interface temperature is shown in our Figure 5-6 below together with that from Figure 5.3.3 of *La Charge thermique d'un stockage*.[288] The agreement between the temperatures from the analytical-numerical line-load model and that from the model in Section 5-2 above is very good and the differences are understandable in the first few decades, and still reasonable albeit gradually poorer with increasing time toward 100 years. The true 3D model with individual packages is supposed to give higher localized argillite temperature at short periods of time, while the simplified, line-averaged heat load model with a truncated heat load area is expected to yield lower argillite peak temperature with increasing time. Indeed, the maximum temperature at year 50 is about 66.5^{o}C, slightly lower than the 68^{o}C at year 70 from the numerical, heterogeneous 3D model, and much lower than the 72^{o}C from the numerical, homogeneous 3D model. The underestimation relative to the 3D numerical model with individual packages is an error, due to the line-load assumption, for the sake of simplicity and robustness.

The simplified model, however, corroborates the 3D model excellently at short time periods of a few decades, during which the penetration distance of noticeable heat flow is short. The models, presented as alternative, verification exercises, both show that the argillite temperature evolution

---

[288] Andra 2005, Thermique Figure 5.3.3 (p. 56)

agrees reasonably well with the results from the thermal model in Andra 2005, Thermique. Some difference, however, still remains in the shape of the temperature curves as shown in Figure 5-6. The temperature result from the Andra model also tends to be lower in the peak time period.

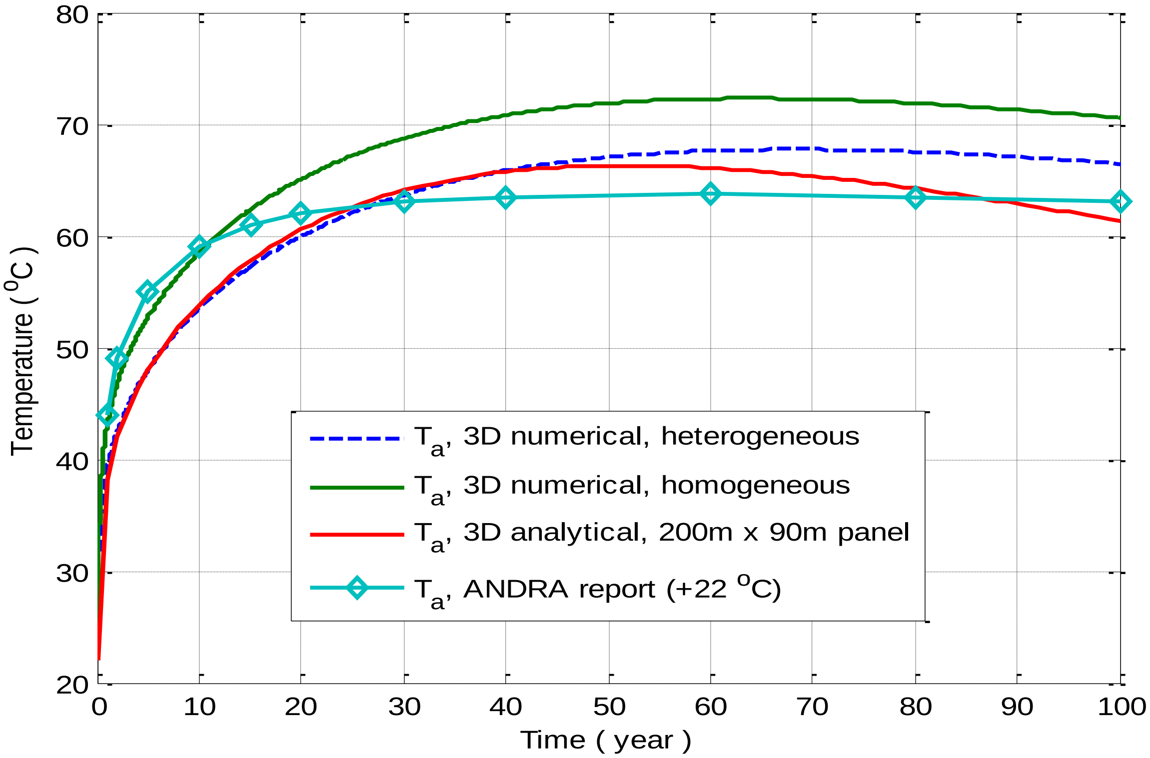


Figure 5-6. Argillite interface temperature from three models. (Source: G. Danko). The Andra curve is from Andra 2005, Thermique Figure 5.3.3 (p. 56).

The models in Sections 5.2.1 and 5.3.2 apply the argillite properties according to Andra specifications. The difference in the interface temperatures can be attributed only to differences in the thermal model, either in assumptions, condition, or input parameters. In sum, the thermal model of Andra 2005, Thermique for the argillite interface temperature around the CU1 package can be reasonably corroborated with alternative models, but there remain differences in the range of 10% to 15%.

In conclusion, it may be perfectly reasonable to accept from Andra illustrative study results to show the capabilities of their program; to agree that thermal sizing will be possible when it is needed; and to postpone the detailed evaluations until the actual design phase.

Clearly, a design cannot be accomplished until the source term is fully specified. This includes a specification of how many of each type of waste package will be disposed of and the expected age and thermal characteristics of the packages. Most importantly, the current uncertainty regarding whether unreprocessed spent fuel will be disposed of needs to be addressed and resolved.

5.4 Review of thermally-induced effects

Thermal convection is chosen for review as the most critical to the potential transport of radionuclides to the accessible environment. Although Andra's thermal analyses have shown compliance with specific temperature criteria, we believe there are factors that can result in potential violation of the maximum temperature criterion in the repository. For example, a relatively low thermal conductivity of the argillite (or the buffer, if applicable) in the emplacement horizon, a higher than anticipated emplacement density due to larger (or different) inventory, or rock inhomogeneities, can all cause a near-boiling temperature at the argillite interface. Higher localized temperatures and temperature variations in the horizontal plane may result in localized thermal convection during the time period of the thermal surge.

Figure 5-6 depicts the temperature evolution during the first 100 years of the thermal surge, and a discrepancy between the current analysis and the Andra result. Andra describes the expected thermally-induced convection.[289] The analysis assumes a lower temperature that may not be realistic for an S2 emplacement scenario. Therefore, the conclusion from that may not hold if a different input temperature is used.

There is another issue that brings into question the conclusion of the analysis given by Andra.[290] The application of one-dimensional scaling laws, such as represented by the Rayleigh (Ra) number for estimating thermo-convection lacks scientific reasoning since it is applied to the temperature field in a vertical direction only. In the horizontal direction, the temperature variation will generate buoyancy driving force for hydrothermal circulation, for which the critical Ra number established for vertical gradient is not applicable. Any Ra>0 calculated in the horizontal direction is believed to generate a non-zero vertical circulation, however small it may be, in a porous media.

---

[289] Andra 2005, Thermo-convection

[290] Andra 2005, Thermo-convection

5.5 References

Andra 2005, Matériaux	Andra. *Dossier 2005 : Référentiel des matériaux d'un stockage de déchets à haute activité et à vie longue. Tome 1 : Matériaux à base d'argile gonflantes*. (C.RP.ASCM.04.0015.A). [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, 17 mai 2005.
Andra 2005, Thermique	Andra. *La Charge thermique d'un stockage: Site de Meuse/Haute-Marne*. (C.NT.ASIT.03.118.C) [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, 14 juin 2005.
Andra 2005, Thermo-convection	Andra. *La thermo-convection dans la couche du Callovo-Oxfordien et les formations géologiques encaissantes sous l'effet de la charge thermique d'un stockage Site de Meuse / Haute-Marne*. (C.NT.ASTR.03.105.B) [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, 15 juin 2005.
Andra 2009, Colis	Andra. *Référentiel de connaissances et modèle d'inventaire des colis de déchets à haute activité et à moyenne activité à vie longue - Partie 1*. (C.RP.AHVL.09.0114.A) [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, novembre 2009. Running title: *JALON 2009 HA-MAVL*.
Carslaw and Jaeger 1959	H.S. Carslaw and J.C. Jaeger. *Conduction of Heat in Solids*. 2nd ed. Oxford: Clarendon Press, 1959.
Dossier 2005 Argile, Architecture	Andra. *Dossier 2005 Argile, Tome Architecture and management of a geological repository*. (C.RP.ADP.04.0001) (268 VA) [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, December 2005. On the Web at http://www.andra.fr/download/andra-international-en/document/editions/268va.pdf.
Dossier 2005 Argile, Evolution	*Dossier 2005 Argile*, *Tome: Phenomenological evolution of the geological repository*. (Report Series) (269 VA) [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, Décembre 2005.. On the Web at http://www.andra.fr/download/andra-international-en/document/editions/269va.pdf.
Dossier 2005 Argile, Synthesis	Andra. *Dossier 2005 Argile: Synthesis: Evaluation of the feasibility of a geological repository in an argillaceous formation, Meuse/Haute-Marne site*. 2nd ed. (Report Series) [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, December 2005. On the Web at http://www.andra.fr/download/andra-international-en/document/editions/266va.pdf.
Nitao 2000	J. Nitao. *NUFT, Flow and Transport code V3.0s.Software Configuration Management, Yucca Mountain Project – STN: 10088-3.0S-00*. [Livermore, CA: Lawrence Livermore National Laboratory, September 2000.
Plötze et al. 2007	Michael Plötze, Ueli Schärli, Andreas Koch, and Hanspeter Weber. "Thermophysical Properties of Bentonite." In *Proceedings of Clays in Natural & Engineered Barriers for Radioactive Waste Confinement*, 3rd International Meeting, 17.-20.9. 2007 Lille, 2007. Abstract Book, pp.579-580. On the Web at http://www.andra.fr/lille2007/abstract_lille2007/donnees/pdf/579_580_P_THME_19.pdf.

Poller et al. 2009	Andreas Poller, Carl Philipp Enssle, Gerhard Mayer, Jean Croisé, Jacques Wendling. "Repository-Scale Modeling of the Long-Term Hydraulic Perturbation Induced by Gas and Heat Generation in a Geological Repository For High and Intermediate Level Radioactive Waste—Methodology and Results." In *Proceedings, TOUGH Symposium 2009,* Lawrence Berkeley National Laboratory, Berkeley, California, September 14-16, 2009. On the Web at http://esd.lbl.gov/FILES/newsandevents/toughsymposium09/TOUGH Symposium 2009.zip (, under Nuclear Waste).
Poppei et al. 2009	Joachim Poppei**,** Gerhard Mayer, Nicolas Hubschwerlen, Pepin Guillaume, and Jacques Wendling. Estimation of Humidity During Tunnel Ventilation—Supported By TOUGH2 Calculations of Liquid, Vapor, and Heat Transport." In *Proceedings, TOUGH Symposium 2009,* Lawrence Berkeley National Laboratory, Berkeley, California, September 14-16, 2009. On the Web at http://esd.lbl.gov/FILES/newsandevents/toughsymposium09/TOUGH Symposium 2009.zip (under Nuclear Waste).
Pruess et al. 1999	Karsten Pruess, Curt Oldenburg, and George Moridis. *TOUGH2 User's Guide, Version 2.0*. (LBNL-43134) Berkeley, CA: Lawrence Berkeley National Laboratory, Earth Sciences Division, November 1999. On the Web at http://esd.lbl.gov/tough2/LBNL_43134.pdf.
Référentiel du Site 2005, Tome 2	Andra. *Dossier 2005 Référentiel du site Meuse/Haute-Marne. Tome 2: Caractérisation comportementale du milieu géologique sous perturbation*. (C.RP.ADS.04.0022B). [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, 15 décembre 2005.
Référentiel du Site 2010, Tome 2	Andra. *Référentiel du Site Meuse/Haute-Marne: Tome 2*. (C.RP.ADS.A09.0007.B) [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, 29 janvier 2010. Running title: Jalon 2009 HA-MAVL. "Document interne."
Su 2006	Kun Su. *Contribution à l'étude du comportement mécanique et thermo-hydro-mécanique des argilites du Callovo-Oxfordien : Application au stockage des déchets radioactifs*. [Lille] : L'université des sciences et technologies de Lille, 6 décembre 2005, copyright 2006. On the Web at https://iris.univ-lille1.fr/dspace/bitstream/1908/368/2/50376-2005-Su2.pdf. "Mémoire d'Habilitation à diriger des recherches de l'Université des sciences et technologies de Lille."
Tang et al. 2007	Anh-Minh Tang, Yu-Jun Cui, Trung-Tinh Le. A study on the thermal conductivity of compacted bentonites, *Applied Clay Science* 41 (2008) 181-189. Author's manuscript on the Web at http://hal.archives-ouvertes.fr/docs/00/33/70/24/PDF/Thermal_conductivity_ACS_2008_for_HAL.pdf . Journal = "DOI : 10.1016/j.clay.2007.11.001."

von Hippel 2007	Frank von Hippel. *Managing spent fuel in the United States: The illogic of reprocessing (report on www.fissilematerials.org)*. [Presented before the Panel on The U.S. and the Future of Reprocessing, 2007 Carnegie International Nonproliferation Conference, June 26, Ronald Reagan International Trade Center, Washington, DC. On the Web at http://carnegieendowment.org/files/FvHReprocPanelCarnegie26June07Rev.pdf.

Chapter 6: Comparison with other programs that have used underground research to select a ZIRA

Strengths

1. Andra has done extensive collaborative work with other repository programs and underground laboratories, notably those at Mol in Belgium and Mont Terri in Switzerland.
2. Andra has been a leader in much international collaborative work. For instance, it was the coordinator of the Engineering Studies and Demonstration of Repository Designs (ESDRED).
3. The international collaborative work has benefited both the work in France and in other countries and advanced the state of the art in a number of ways, such as development of techniques, equipment, and materials.

Findings

1. In some areas, such as sealing and thermal tests in full-scale boreholes, international collaborative programs are not a substitute for laboratory work at Bure even when the rock type is similar. The problems encountered with deformations in 0.7 m boreholes, for instance, had to be (and were) addressed in a site-specific way. Considerable site- specific work remains to be done at Bure along these lines.
2. While spent fuel disposal is not now mandated, research for its disposal has been suggested. The challenges of stabilizing 3.3m diameter boreholes are likely to be severe and need on-site research.

Recommendation

Andra should consider building an experimental area in the underground laboratory similar to the Aspö Prototype Repository in the Underground Laboratory to show, so far as is possible in an experiment lasting a few years, how the actual repository might work in practice, and to determine with greater realism some of the performance parameters that are specific to Bure, including the in situ performance of the HLW canisters under thermal stress.

6.1 Introduction

Besides France, numerous countries are interested in building a repository for their spent fuel or reprocessed high-level nuclear waste. It is more or less universally accepted that such a repository should be in a geological medium and located at a depth of several hundred meters in a suitable, stable formation. Whereas for many countries it is a future goal with no defined program in place, there are a few countries that have already embarked on a program of research and development that would presumably lead to site selection, site characterization, and a license application for submittal to an appropriate regulatory agency. Predictably, some programs are much further along than most others.

Until recently, the U.S. program for a commercial nuclear waste repository at the Yucca Mountain (Nevada) site was perhaps the farthest along, having submitted a license application to the U.S. Nuclear Regulatory Commission. The U.S. government has halted further evaluation of that site and appears unlikely to consider it further, though that halt is being contested in various ways. Nevertheless, important contributions have been made by that program to the international investigations for potential repository siting.

As of February 2011, the only functional deep geological repository for nuclear waste is one located in Carlsbad, New Mexico, in the U.S. It is restricted by law to disposal of transuranic waste[291] from the U.S. nuclear weapons program. It is situated in a bedded salt formation and hosts transuranic wastes from defense activities in the U.S.

Since the Andra repository program in France has opted for a site geology that is in a clay medium (argillite), our discussions will focus on other programs that are also pursuing a repository in clay formations; we understand, of course, that there are significant differences between various clay formations. For illustration purposes, we also will make periodic references to programs that are in non-clay media such as in salt or granite. Also, comparisons will be made among several European programs that appear to have made a serious commitment to an underground repository as well as significant contribution to the scientific and engineering knowledge base. For instance, underground research laboratories (URLs) in several countries have operated for numerous years. Most, if not all, have worked collaboratively and shared freely the successes and failures.

Over the last 10 years, numerous reports have been published reporting on the status of various repository programs around the globe. For instance, Witherspoon and Bodvarsson (2006) published a lengthy report that contained descriptions of programs in at least 24 countries.[292] Only a handful of these programs have made significant progress in terms of in situ investigations to guide site selection and to further the scientific knowledge base. A more recent comparison was published in a report to the U.S. Congress and the Secretary of Energy prepared by the Nuclear Waste Technical Review Board (2009).[293] This chapter briefly reviews selected national repository programs for high-level waste and spent fuel that have underground laboratories to provide a basis for comparison with Andra's program at its Bure URL. We are aware, of course, of Andra's participation in and collaboration with other national laboratory programs.

6.2 Six comparison programs

We have chosen six programs that currently have, or had in the past, or have future plans for an underground research laboratory with the purpose of characterizing a geological medium and/or gain fundamental understanding of processes expected to evolve during the life of a repository. Specifically, the following European countries are pursuing nuclear waste repository projects in a geologic medium for deep underground disposal.

1. Belgium
2. Finland

---

[291] Transuranic waste is defined in the United States as waste containing more than 100 nanocuries per gram (370 Bq/gram) of long-lived, alpha-emitting transuranic radionuclides.

[292] Witherspoon and Bodvarsson 2006

[293] NWTRB 2009 is the primary source for this chapter.

3. France
4. Germany
5. Sweden
6. Switzerland

The URL in Belgium is located at Mol and has operated for more than two decades. The facility is situated at a depth of 224 m below the surface in a Boom Clay formation. Mol is a part of an IAEA center of excellence network that has links with seven other URLs.[294] Whereas Belgium has not yet named a repository site, the tests and experiments in the URL have generated huge amounts of data that are of practical value to other repository programs in addition to Belgium's own. One large-scale in situ test that was conducted in two phases from 1996 through 2007 is known as the RESEAL II Test.[295]

It had multiple objectives including, but not limited to, the demonstration of technology, understanding the hydro-mechanical behavior of seals, and providing modeling parameters for numerical simulations. For instance, a major objective was to design, instrument, and "install a bentonite seal in a 2m diameter vertical shaft within the Boom Clay."[296] This test was conducted in an argillaceous medium and hence is of tremendous value to the French program. The results and experience of this test have been utilized extensively by Andra both in a numerical modeling context and in demonstrating the feasibility of such seals in argillite. Another experiment at Mol is investigating the performance of a glass material to be used as a matrix for encapsulating HLW according to information on the Mol website.[297]

Although the repository program in Finland selected a disposal site at Olkiluoto in year 2000 near the Olkiluoto Nuclear Power Plant, a "research" tunnel for the repository (known as ONKALO) is still under construction. This tunnel is being constructed in the Archean/Proterozoic bedrock estimated to be between 1.25 billion and 3.2 billion years old.[298] The NWTRB identifies it as "migmatite."[299] According to Encyclopedia Britannica (2010), migmatite is rock composed of a metamorphic host material that is streaked or veined with granite rock. Such rocks are usually gneissic (banded) and felsic rather than mafic in composition. Tunnel construction is being carried out in four phases. Phase 1 had a schedule to finish in 2009 the construction of a spiraling tunnel down to a depth of 420 m. In Phase 2, construction will continue to a final depth of 520 m. The curious thing to note about this program is that Posiva Oy (the company that is doing the construction at Olkiluoto) plans to submit a license application in 2012. This would seem to provide very little opportunity for conducting and interpreting the planned research prior to the application. Nevertheless, plans call for Phase 3 to begin in 2015; this is the phase in which the disposal facility is constructed. This is to be followed by Phase 4 (encapsulation and burial of waste) starting in 2020. There is close cooperation between the Finnish program and the Swedish program, which is utilizing a granite formation for disposal. The Finnish program is relying on the work done in the Swedish

---

[294] SCK-CEN 2011
[295] Van Geet et al. 2009
[296] Van Geet et al. 2009 p. 1
[297] See SCK-CEN Web Site, at http://www.sckcen.be/en.
[298] GTK 2010 Slide 5
[299] NWTRB 2009 p. 30

Äspö underground laboratory and canister design and is not developing an underground laboratory at a location completely separate from the repository. Work in tunnel excavation boreholes will complement the basis for its site characterization prior to license application. We have not investigated how Posiva plans to validate the Swedish corrosion and other on-site data for conditions that are specific to the Olkiluoto site (see further comment below).

The French program, of course, has chosen argillite as the geologic medium for disposal and the Andra URL is located at Bure at a depth of 490 m.[300] Andra has had and continues to have extensive collaborations among European programs. In particular, the URLs that are located in clayey media are the most relevant sources of knowledge and validation for Andra.

The German program has historically planned for a repository in salt. The program has faced technical and political challenges that provide lessons for other programs. The Gorleben site, though inactive today, has been investigated for its suitability to host nuclear waste since 1979. There was a moratorium placed on the project in 2000 which was lifted in 2010 for research.[301] However, a site for high-level radioactive waste disposal has not been selected. There is another research mine in Germany, Asse II, that is about 140 km from Gorleben. This is an old potash/salt mine that was used between 1965 and 1992 to carry out waste disposal exercises with the purpose of practicing and learning to manage nuclear waste disposal. One could think of that as a near full-scale experiment in a URL. However, it was not an experiment for high-level waste, because the waste disposed of there does not generate a significant amount of heat.[302] There is consideration being given to siting a German repository in a shale-clay type of formation; at this time we do not have concrete information on this pursuit.[303]

Arguably, the most advanced program for the construction of a spent fuel repository is the one in Sweden. It is in some ways the most relevant example as regards the kinds of work, including experiments, to be done in an underground laboratory prior to selection of a repository site for characterization. Of course, since the host rock and regulatory conditions for the Swedish program are different than the French program, many specifics would be different. For instance, French law requires reversibility for at least 100 years while Swedish law does not. The Swedish laboratory program is worth examining nonetheless, since the types of evaluation to be done, such as thermal testing, model validation using experimental results, etc. are generally the same independent of the rock type.

The Swedish program claims its national nuclear waste management policy is fully integrated (and “holistic”). The geologic medium is granite and a final site selection was made in 2009 for this repository. The Swedish program has operated at least two URLs for several years. The older of these two is the Stripa Project which has been in existence for more than 30 years.[304] The other URL facility is known as the Äspö Hard Rock Laboratory and it has operated for more than 15 years. It is located near the municipality of Oskarshamn. It is in a granitic formation at a depth of about 460 m and is considered by the Swedish Program to be “a dress rehearsal” for the

---

[300] Dossier 2005 Argile, Synthesis p.5
[301] BfS Gorleben 2010
[302] BfS Asse 2010 and BfS Repository 2011
[303] See, for example, BGR 2007.
[304] SKB 2009 p. 11

construction of an actual spent fuel repository.[305] Like the Finnish tunnel ONKALA, the Äspö tunnel is excavated with two spiral turns until it reaches its final depth.[306] Various tests and experiments are being conducted in branches and niches of this tunnel.

Aside from the fact no spent fuel is actually placed there, the Äspö Laboratory has had experience with all other engineered aspects including canisters, bentonite clay seals, tunnels, and emplacement holes. The Swedish concept relies primarily on the robustness of the copper canister that will be an overpack for the waste package that contains the spent fuel rods. The Swedish emplacement design requires copper canisters to be embedded in a buffer of bentonite clay. Notably, one of the tests at Äspö is the "Canister Retrieval Test" addressing the issue of retrievability.[307] We understand that the preference in the Swedish design is for vertical emplacement of the spent fuel canisters. Nevertheless, at Äspö they are testing the special equipment needed for boring of horizontal deposition holes and emplacement of canisters in those holes.[308] The utility of the Swedish retrievability experiment for Bure site is limited in that Andra is dealing with a much softer rock. For that reason, it is incumbent on Andra to conduct its own in situ retrieval exercise. One concern we have is about the deformation of the liner and/or the emplacement hole, making canister retrieval very problematic. For example, Figure 6-1 shows the damage (overbreak in the corners and "squaring" of the circular hole) in an experimental emplacement borehole at Bure.

---

[305] SKB 2008 pp. 3, 64
[306] SKB 2008 p. 19
[307] SKB 2008 pp. 5, 79-81
[308] SKB 2008 pp. 6, 86-88

Figure 6.1: Squaring of a horizontal borehole in ANDRA's underground laboratory at Bure. (Photo credit: Krishan Wahi, 18 August 2010)

The sixth (and last) on our list of European programs is the one in Switzerland. As with several others, the Swiss program has a URL; in fact, they have two: Mont Terri Rock Laboratory (Canton Jura) and the Grimsel Test site (Canton Bern). The laboratory at Mont Terri is in an Opalinus clay, whereas the one at Grimsel is in granite. Although a decision has not yet been made, it is likely that the repository site will be in a formation of Opalinus clay. This expectation is based on the recommendation by the National Cooperative for the Disposal of Radioactive Waste that three regions, all in Opalinus clay, be further explored. [309] Work has been ongoing at both laboratories for several years. The Mont Terri project is an "International Research project for the Hydrogeological, Geochemical and Geotechnical Characterisation of a Clay Formation (Opalinus Clay)."[310] With more than 25 years of research to date, the Grimsel Test Site has advanced techniques for site investigations, tested technologies for repository construction, developed and tested engineered barrier system. In addition, numerous data have been generated and shared with other programs to advance the art of numerical model simulations and safety analyses.

---

[309] NWTRB 2009 p. 46

[310] See the Grimsel Test Site Web page at http://www.grimsel.com and the Mont Terri Project Web page at http://www.mont-terri.ch.

In Table 6-1, a comparison of selected elements of the six programs briefly discussed above is provided. This is but one example of the vast amount of information available on each of the programs. Table 6-1 is meant to be indicative and a brief overview of schedules, rock types, and whether an underground laboratory programs exists. It is *not* an exhaustive list of the types of work being done in the various programs.

Table 6-1: COMPARISON OF UNDERGROUND NUCLEAR WASTE REPOSITORY PROGRAMS (Note 1)

Country	**Geological Environment(s) Studied**	**Status of Site-Selection**	**Indigenous URL**	**Retrievability Reversibility**	**Multi-Barrier Reliance**	**Waste Types / Waste Forms**	**Projected Date of License Application**	**Projected Start of Operations**
Belgium	Clay and Shale	No active siting process	Mol	no decision	undecided, but likely	HLW	not known	~ Year 2040
Finland	Migmatite	DECIDED, Migmatite	Under construction, Onkalo, same as repository location	not required	yes	SNF	2012	2020
France	Callovo-Oxfordian Argillite	Bure	Bure	required	yes	HLW, ILLW (and eventually SNF?)	2014	2025
Germany	Salt	Uncertain	Gorleben (but suspended)	none	yes	SNF, HLW, ILLW	not known	not projected
Sweden	Granite	Municipality of Östhammar	Äspö	none	Redundancy requirement. See Note 2	SNF	2011	2023
Switzerland	Opalinus Clay, (Granite)	Not Decided, likely in Opalinus clay	Mont Terri & Grimsel Site	required	yes	SNF, HLW	not known	No sooner than 2040

1. Main source of the information in this Table is NWTRB 2009. Also: Finnish Energy 2007, Andra 2010 p. 32.
2. The goal in the Swedish program is for each barrier to maintain safety, to the extent possible, despite the failure of other barriers. (NWTRB 2009 p. 46)

6.3 Andra collaboration – Mont Terri and Mol

Andra has collaborated with several other European programs to the mutual benefit of all participants. In particular, two of these programs are also dedicated to clayey media as is the case for the French program. Specifically, underground laboratories in Switzerland and Belgium have been conducting research for many years on characterizing the behavior of clay. The Mont Terri laboratory, located at a depth of ~300 m, is in Opalinus clay, which is similar to Bure argillite. Indeed, the underground laboratory at Bure is performing experiments that will undoubtedly benefit other national programs. Some of these collaborations are directed at development of new technology to be applied in the design and construction of underground repositories. A significant collaboration of this type was proposed to the European Commission in 2003, with the EC approving a contract in January of 2004. The project, titled ESDRED (Engineering Studies and Demonstrations of Repository Designs), began work in February 2004 and was completed in January 2009 (see Section 5 below).[311]

Many of the findings and experimental results of the work performed at Mont Terri have been used by Andra in its own predictive analyses reported in Dossier 2005 and other reports since then. In addition, some of the technology demonstrations and proof-of-principle construction techniques performed at Mont Terri have been heavily cited in Andra reports as evidence of their ability to design and build a safe repository in the ZIRA (within the transposition zone).[312] Andra has given considerable thought to the transfer of data from one site to another and recognizes that less data directly relevant to the safety case can be transferred at more mature stages of site investigation,[313] which is the case at present compared to 2005.

In a paper presented by Mr. J. Delay (Andra) at the TOPSEAL 2006 Conference, it is implied that large-scale seals would be tested at the Bure URL as part of the research phase starting in 2007. Specifically, the "Conclusions" section of this paper states, "The future work in the laboratory will include life-size construction of the different components of a disposal facility, such as the vaults or the sealing for vaults and drifts."[314] We have not been able to find any description of performance of such testing in Andra publications since 2006. For instance, the status report entitled "2006 – 2009: 4 ans de recherché scientifiques a l'Andra pour les projets de stockage" does not mention findings related to testing of seals or plugs a Bure.[315] It would be instructive to get information on such tests (if they have been conducted), particularly if results are available to review and compare to similar existing data from other URLs notably Mont Terri.

Another important Andra collaborator is the geological laboratory at Mol, Belgium, located in a "boom" clay formation at a depth of 224 m. Mol is also a part of IAEA "Centre of Excellence" network. The work at Mol has gone on for over two decades. An example of their work is

---

[311] ESDRED Leaflet 2009 p. 2

[312] For instance, Andra's confidence in the permeability measurements at Bure is based in part on similar results at Mont Terri. (Andra 2005c p. 126) Further, Delay 2006 notes that "[s]everal techniques and methodologies used at Bure URL had been previously developed at Mont Terri Rock laboratory."

[313] Mazurek et al. 2008 p. S99

[314] Delay 2006 p. 136

[315] Andra quatre ans 2010

investigating the performance of a glass material for embedding reprocessed high-level waste using real (or simulated) conditions of radiation and temperature. Other work is concerned with characterizing hydrogeological, geochemical, and coupled processes one would expect to occur in a repository.[316]

6.4 Some comparative comments

Andra has done much more work in the underground laboratory prior to beginning characterization of the repository location than certain other programs, such as the Finnish program, where the work is more or less simultaneous and no real separate underground laboratory is planned for construction. In addition to its own work at the Bure underground laboratory, Andra has had extensive collaboration with the Mont Terri program, where the rock type is similar to the Bure argillite, as a complement to its own work, as discussed above. Its target dates for a license application and the start of repository operation are a few years after those of the Finns, but much faster than the Swiss program.

On the other hand, it should be noted that Andra's program at Bure has so far been much less detailed than that of Sweden. The latter program, including drilling of full-scale emplacement holes, emplacement of full-scale canisters, and thermal testing with electrical heaters, has been part of the Äspö laboratory prior to the selection of the final repository location for characterization at Forsmark in 2009.[317] At the Bure laboratory, a successful emplacement hole, with a steel sleeve, was completed in 2010, after some initial borehole-wall stability problems and about a year after the selection of the ZIRA. The IEER team observed such problems during its visit to the site on August 18, 2010. As we will see below Andra has coordinated an international program, ESDRED, in which emplacement machinery was designed and tested. ESDRED is a critical piece of research and development in which Andra has been in the lead.[318] But in many cases, it is not an adequate substitute for in situ research.

While the rock type in Sweden is very different from that at Bure, the principles of the research and the essential elements that were done in the Äspö laboratory could usefully apply to Andra's work in the underground laboratory. Specifically, SKB (Svensk Kärnbränslehantering AB or Swedish Nuclear Fuel and Waste Management Company) has tested its entire concept in a Prototype Repository at Äspö beginning in 2001,[319] almost a decade before the selection of the repository location.[320] SKB describes the purposes of the Prototype Repository as follows:

> The execution of the Prototype Repository is a dress rehearsal of the actions needed to construct a final repository from detailed characterisation to resaturation of deposition holes and backfill of tunnels. The Prototype Repository

---

[316] For a description of work at Mol see the website of the laboratory at http://www.sckcen.be/en/Our-Research/Research-projects/NIRAS-ONDRAF-projects/Geological-disposal-R-D-for-the-geological-disposal-of-medium-and-high-level-waste-in-the-Boom-Clay.

[317] SKB 2008 and WNN 2009. Forsmark is in the municipality of Östhammar.

[318] A brief overview can be found in ESDRED Leaflet 2009.

[319] SKB 2008 p. 65

[320] While SKB's final repository location is not in the same location as its laboratory, it is in the same rock type so that the selection process is broadly comparable to the selection of the ZIRA.

> provides a demonstration of the integrated function of the repository and provides a full-scale reference for test of predictive models concerning individual components as well as the complete repository system. *The Prototype Repository should demonstrate that the important processes that take place in the engineered barriers and the host rock are sufficiently well underst*ood.[321]

The specific parameters studied in the Prototype Repository were:[322]

- Water uptake in buffer and backfill.
- Temperature distribution (canisters, buffer, backfill and rock).
- Displacement of canister.
- Swelling pressure and displacement in buffer and backfill.
- Stress and displacement in the near-field rock.
- Water pressure build up and pressure distribution in rock.
- Gas pressure in buffer and backfill.
- Chemical processes in rock, buffer and backfill.
- Bacterial growth and migration in buffer and backfill.

We understand that the work in the Bure underground laboratory will go on for several more decades in parallel with other aspects of the repository program. We also know that individual elements in the list above have been researched by Andra. However, it would have been advisable to have a comparable program that tests the entire concept of disposal in situ, even if not at full scale in terms of canister size, at the Bure laboratory prior to the selection of the ZIRA for characterization. While collaborative work with others can provide and has provided critical experience and information in proceeding with the investigations at Bure, it is not a substitute for critical in situ research in the underground laboratory. As noted above, Andra recognizes this in principle; nonetheless, it does not at present plan to construct a prototype repository to test the entire disposal concept in situ.

6.5 International project (ESDRED)

Andra participated in an international project set up to address, investigate, and solve specific engineering problems in repository design and operation. The program was called Engineering Studies and Demonstration of Repository Designs, or ESDRED, for short. Seven waste management agencies as well as some research and development organizations participated; it was coordinated by Andra.

A large number of experiments and design activities were a part of this international collaboration; final reports on various aspects of the project were published in 2009.[323] The four

---

[321] SKB 2008 p. 64. Emphasis added.

[322] SKB 2008 pp. 64-65

[323] The various reports are available on ESDRED's web site at http://www.esdred.info/proj_mod.htm.

main technical components of the ESDRED collaboration can be summarized as follows (though the work in each module was more complex and varied than depicted in this brief overview):[324]

- **Module 1** was oriented to demonstrating construction of bentonite rings as an engineered barrier, "backfilling of the annular gap between a waste canister and the disposal drift wall" with different types of materials, and development of "non-intrusive monitoring techniques." This module was a complement to the work done by Andra in the Bure underground laboratory.
- **Module 2** was oriented to the design, fabrication, and demonstration of equipment that will be used to transport smaller waste canisters (2 to 5.2 metric tons) and place them in horizontal or vertical disposal holes. Consideration of retrievability was part of this module.
- **Module 3** was concerned with design and demonstration of large equipment to place much heavier canisters (43 to 45 metric tons) in disposal tunnels as well as adaptation of these machines for placement of pre-assembled bentonite rings.
- **Module 4** consisted of formulating and testing sealing concrete plugs made of special low pH cement**.**

The above four modules are related to the technical objective of the program. Other objectives dealt with considerations related to European repository integration and to training and communications; these objectives are beyond the scope of the present study and are not considered here.

Many of these experiments have prepared the way for Andra and the other agencies participating in the project to implement an underground disposal program. Some of these activities like designing and testing large machines could not have been done or would have been very difficult to do in an underground laboratory that does not have full-scale tunnels. Various activities were aimed at repository activities in different host rock environments – various types of clay, including argillite and opalinite, as well as granite. The work done in the ESDRED project was a complement and to some extent a supplement to the activities in the underground laboratory at Bure. The complementary aspects included the development and testing of various types of cements and other materials as well of waste canister emplacement machines. The supplementary aspects included emplacement of canisters in test facilities and some tests of seals. Some of this work will be further pursued at the Bure underground laboratory, while other aspects presumably would be followed up during characterization in the ZIRA.

The activities, experience, and results of the ESDRED project provide parts of the basic research and development that needs to be done in the course of repository development. But it should be noted that the ESDRED project did not include in-situ testing of the packages in argillite. While there is much to learn from the extensive testing that has been done in the Aspö laboratory in Sweden, testing in the Bure laboratory under the rock conditions to be expected in the repository is highly desirable prior to extensive underground characterization in the ZIRA. Specifically, in-situ emplacement testing of a full-scale high-level waste canister and simulated thermal tests after sealing are important.

---

[324] ESDRED 2009 pp. 13-14. Bulleted text summarizes the source.

Of the experiments in the ESDRED program, Andra does not have an active counterpart at Bure for vertical borehole emplacement of high-level waste or spent fuel.[325] Specifically, as noted in Chapter IV, ensuring the stability of horizontal boreholes 3.3 meters in diameter that would be required for spent fuel disposal should that become necessary will present severe challenges in the Bure argllilite, if the difficulties already encountered with 0.7m boreholes are any guide. We recognize that Andra is not required to consider unreprocessed spent fuel at this stage. Yet the disposal of spent fuel (uranium spent fuel and/or MOX spent fuel) has not been ruled out. It will depend on reprocessing policy that is not within Andra's control. Since Andra has been asked to look at spent fuel disposal (though without a requirement to do so), it would be highly desirable to address the issue of large borehole stability as soon as possible. In this context, Andra should evaluate experimentally, in the Bure laboratory, whether vertical boreholes would be more suitable and to what extent they may or may not compromise the thickness requirement for the host rock in the ZIRA in case disposal of a significant large amount of spent fuel is needed.

---

[325] We note that a 12.3 meter long vertical bore hole was drilled in the Bure URL to conduct corrosion and other tests. However, this borehole was only 360 mm in diameter. (Andra quatre ans 2010 p. 45) A spent fuel borehole would be 3.3 m in diameter.

6.6 References

Andra 2010	Andra. *2009 Activity Report: Managing today to prepare for tomorrow*. (384-1-VA) [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, 2010. On the Web at http://www.andra.fr/download/andra-international-en/document/384-1-va.pdf..
Andra quatre ans 2010	Andra. *2006 – 2009: 4 ans de recherché scientifiques à l'Andra pour les projets de stockage*. (383) [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, Juin 2010. On the Web at http://www.andra.fr/download/site-principal/document/editions/383.pdf.
BfS Asse 2010	BfS. *Asse II. From salt dome to nuclear repository: The changeful history of the Asse II mine*. Salzgitter: Bundesamt für Strahlenschutz, 15/01/2010. On the Web at http://www.endlager-asse.de/cln_135/EN/2_WhatIs/B_History/_node.html.
BfS Gorleben 2010	BfS. *Introduction to the Gorleben site*. Salzgitter: Bundesamt für Strahlenschutz, 2010/11/19. On the Web at http://www.bfs.de/en/endlager/erkundungsbergwerk_gorleben/einfuehrung.html. BfS = Federal Office for Radiation Protection
BfS Repository 2011	BfS. *Disposal*. Salzgitter: Bundesamt für Strahlenschutz, 2011/01/24. On the Web at http://www.bfs.de/en/endlager.
BGR 2007	Peer Hoth, Holger Wirth, Klaus Reinhold, Volkmar Bräuer, Paul Krull, and Hagen Feldrappe. *Final Disposal of Radioactive Wastes in Deep Geological Formations of Germany - Investigation and Evaluation of Argillaceous Rock Formations*. Berlin/Hannover: Bundesanstalt für Geowissenschaften und Rohstoffe, April 2007. Link on the Web at http://www.bgr.bund.de/cln_116/nn_335074/EN/Themen/Geotechnik/geotechnik__node__en.html?__nnn=truehttp://www.bgr.bund.de/nn_335086/EN/Themen/Geotechnik/Downloads/WasteDisposal__HostRockFormations__en,templateId=raw,property=publicationFile.pdf/WasteDisposal_HostRockFormations_en.pdf.
Delay 2006	J. Delay. "Overview of Current and Planned Activities in the French Underground Research Laboratory at Bure," in *TOPSEAL 2006: Transactions*, International Topical Meeting, Olkiluoto Information Centre, Finland, 17-20 September 2006, (European Nuclear Society, Brussels, 2006). On the Web at http://www.euronuclear.org/events/topseal/transactions/TopSeal-Transactions.pdf.
Dossier 2005 Argile, Evolution	Andra. *Dossier 2005 Argile, Tome: Phenomenological evolution of the geological repository*. (Report Series) (C RP ADS 04 0025 B) (269 VA) [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, December 2005. On the Web at http://www.andra.fr/download/andra-international-en/document/editions/269va.pdf.

Dossier 2005 Argile, Synthesis	ANDRA. *Dossier 2005 Argile: Synthesis: Evaluation of the feasibility of a geological repository in an argillaceous formation, Meuse/Haute-Marne site*. 2nd ed. (Report Series) (Andra 266 VA) [Châtenay-Malabry]: Agence nationale pour la gestion des déchets radioactifs, December 2005. On the Web at http://www.andra.fr/download/andra-international-en/document/editions/266va.pdf.
Encyclopedia Britannica	Encyclopædia Britannica. "Migmatite," *Encyclopædia Britannica Online*. Chicago: EB, November 8, 2010. On the Web at http://www.britannica.com/EBchecked/topic/381818/migmatite.
ESDRED 2009	Integrated Project Coordinator. *Deliverable D6 of Module 6, WP4 Final Summary Report and Global Evaluation of the Project*. Author(s): IPC with contribution of all Contractors. [Châtenay-Malabry: Agence nationale pour la gestion des déchets radioactifs], ESDRED, 30 January 2009. On the Web at http://www.esdred.info/medias/Mod6-WP4-D6_FinalSummaryReport_Final30Jan09.pdf. Running title: *Mod6-WP4-D6 – Final Summary Report*.
ESDRED Leaflet 2009	Wolf K. Seidler. *Project Results Leaflet: Engineering Studies and Demonstration of Repository Designs*. Brussels: European Commission, Research Directorate-General, 27 January 2009. On the Web at http://www.esdred.info/medias/project-results-leaflet.pdf. Running title: Mod5-WP9-D12 – Project Results Leaflet.
ESDRED Web Site	Engineering Studies and Demonstration of Repository Designs. *ESDRED Project Results* [Web page]. [Châtenay-Malabry: Agence nationale pour la gestion des déchets radioactifs], ESDRED, viewed on November 8, 2010. On the Web at http://www.esdred.info/proj_mod.htm.
Finnish Energy 2007	Finnish Energy Industries. *Nuclear Waste Management in Finland*. Helsinki: Energiateollisuus ry, 2007. On the Web at http://www.energia.fi/en/publications/nuclear%20waste.pdf.
Grimsel Web Page	The Grimsel Test Site in Switzerland [Web page]. Wettingen: Nagra, viewed on January 20, 2011. On the Web at http://www.grimsel.com
GTK 2010	Timo Ruskeeniemi and Seppo Paulamäki. *Geological site selection process for the high-level nuclear waste repository in Finland*. [Presented before the] Blue Ribbon Commission for America's Nuclear Future, 21.10.2010, Crowne Plaza Hotel, Helsinki, Finland. [Helsinki?]: Geological Survey of Finland (GTK), 21 October 2010. On the Web at http://brc.gov/Disposal_SC/Finland_meeting_docs/Ruskeeniemi_BRC_21_10_2010.pdf.
Mazurek et al. 2008	Martin Mazurek, Andreas Gautschi, Paul Marschall, Georges Vigneron, Patrick Lebon, and Jacques Delay. "Transferability of Geoscientific Information from Various Sources (Study Sites, Underground Rock Laboratories, Natural Analogues) to Support Safety Cases for Radioactive Waste Repositories in Argillaceous Formations," *Physics and Chemistry of the Earth* 33 (2008): S95–S105. Supplement 1: Clays in Natural & Engineered Barriers for Radioactive Waste Confinement. Available for purchase on the Web or free at research libraries.

Mont Terri Web Site	*Mont Terri Project* [Web Site]. St-Ursanne, Switzerland: Swiss Federal Office of Topography, viewed January 20, 2011. On the Web at http://www.mont-terri.ch.
NWTRB 2009	United States. Nuclear Waste Technical Review Board. *Survey of National Programs for Managing High-Level Radioactive Waste and Spent Nuclear Fuel: A Report to Congress and the Secretary of Energy*. Arlington, VA: NWTRB, October 2009. On the Web at http://www.nwtrb.gov/reports/nwtrb%20sept%2009.pdf.
SCK-CEN 2011a	Belgian Nuclear Research Centre. *HADES - Underground laboratory*. Mol, Belgium: SCK-CEN, viewed January 20, 2011. On the Web at http://www.sckcen.be/en/Our-Research/Research-facilities/HADES-Underground-laboratory.
SCK-CEN 2011b	Belgian Nuclear Research Centre. *Geological disposal: R&D for the geological disposal of medium and high level waste in the Boom Clay*. Mol, Belgium: SCK-CEN, viewed February 4, 2011. On the Web at http://www.sckcen.be/en/Our-Research/Research-projects/NIRAS-ONDRAF-projects/Geological-disposal-R-D-for-the-geological-disposal-of-medium-and-high-level-waste-in-the-Boom-Clay
SCK-CEN Web Site	Belgian Nuclear Research Centre. [*SCK-CEN Web Site*]. Mol, Belgium: SCK-CEN, viewed January 2011. On the Web at http://www.sckcen.be/en.
SKB 2008	Svensk Kärnbränslehantering AB. *Äspö Hard Rock Laboratory: Annual report 2007*. (Technical Report TR-08-10) Stockholm: SKB, April 2008. On the Web at http://www.skb.se/upload/publications/pdf/TR-08-10webb.pdf. "Swedish Nuclear Fuel and Waste Management Co."
SKB 2009	Svensk Kärnbränslehantering AB. *Final repository for spent fuel in Forsmark – basis for decision and reasons for site selection*. (SKBdoc 1221293) Stockholm: SKB, June 2009. On the Web at http://www.skb.se/FileOrganizer/_Extranet/Engelska%20webben/Final%20repository%20for%20spent%20fuel%20in%20Forsmark%E2%80%93basis%20for%20decision.pdf. "This document is a translation of the report "Slutförvar för använt kärnbränsle i Forsmark – underlag och motiv för platsval", SKB document ID 1207622"
Van Geet et al. 2009	M. Van Geet, W. Bastiaens, G. Volckaert, E. Weetjens, X. Sillen, N. Maes, Ch. Imbert, P. Billaud, G. Touzé, M. Filippi, F. Plas, M.V. Villar, M. García-Gutiérrez, M. Mingarro, A. Gens, B. Vallejan**.** *RESEAL II: A large-scale in situ demonstration test for repository sealing in an argillaceous host rock – Phase II: Final report*. (EUR 24161 EN) (Nuclear science and technology) Luxembourg: European Commission, Directorate-General for Research, Nuclear Fission Safety, 2009. On the Web at upcommons.upc.edu/e-prints/bitstream/2117/9640/1/EUR%2024161%20EN_RESEAL%20II%20Final.pdf.

Witherspoon and Bodvarsson 2006	P.A. Witherspoon and G.S. Bodvarsson (eds.). 2006. *Geological Challenges in Radioactive Waste Isolation: Fourth Worldwide Review*. (LBNL-59808) Berkeley, Earth Science Division, Lawrence Berkeley National Laboratory, University of California, April 2006. On the Web at http://esd.lbl.gov/FILES/research/programs/new/lbnl-59808-wwr4.pdf.
WNN 2009	Forsmark for Swedish nuclear waste: Sweden's permanent disposal site for used nuclear fuel will be at Forsmark, the company responsible for building it announced today, *World Nuclear News*, 3 June 2009. On the Web at http://www.world-nuclear-news.org/print.aspx?id=25336. (Waste and Recycling)