

Radioactive Waste Management

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Safety of Geological Disposal of High-level and Long-lived Radioactive Waste in France

**An International Peer Review
of the “Dossier 2005 Argile”
Concerning Disposal in the
Callovo-Oxfordian Formation**

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FOREWORD

A major activity of the Nuclear Energy Agency (NEA) in the field of radioactive waste management is the organisation of independent, international peer reviews of national studies and projects. The peer reviews help national programmes assess accomplished work. The general comments expressed in these reviews are also of potential interest to other member countries.

The French Government requested that the NEA organise an international peer review of the *Dossier 2005 Argile* produced by the National Agency for Radioactive Waste Management (Andra). The scope and objectives of the review were laid out in the Terms of Reference (ToR). The peer review was to inform the French Government whether the *Dossier 2005 Argile* was: i) consistent with international practices and with other national disposal programmes, in particular those considering argillaceous formations, and ii) whether the future research needs were consistent with the available knowledge basis and priorities well-identified. The French authorities were particularly interested in receiving detailed recommendations for specific improvements, notably if the decision-making process led to a site-selection phase. According to the ToR, the NEA Secretariat established an international review team (IRT) made up of ten international specialists, including one member of the NEA Secretariat. The experts were chosen to bring complementary expertise to the review. This report presents the consensus view of the IRT. It is based on the *Dossier 2005 Argile* and supporting documents, on information provided by Andra in answers to questions raised by the IRT, and on direct interactions with staff from Andra during two working seminars in France.

In keeping with NEA procedures for independent reviews, neither the French Government nor Andra have commented on this report – Andra has only had the opportunity to check for factual correctness. The IRT has made its best effort to ensure that all information is accurate and takes responsibility for any factual inaccuracies.

Acknowledgements

All the members of the IRT would like to thank Andra staff for its hospitality during the brief visits to France, and for its excellent organisational support which facilitated the work of the IRT. The IRT would also like to thank the staff of Andra for the helpful and open way they responded to the review. Finally, the NEA acknowledges the many organisations that have made their experts available to carry out the review.

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HIGH-LEVEL FINDINGS AND CONCLUDING STATEMENT

Background

A review has been conducted of the documentation developed by Andra, collectively known as the *Dossier 2005 Argile*, by an international review team (IRT) of independent specialists covering all relevant aspects of research, safety assessment, and the geological sciences. As described below, the *Dossier* represents a key milestone in the programme of work, for which Andra is responsible, to assess the feasibility of the deep geological disposal of high-level and long-lived radioactive waste in France. This report presents the consensus view of the IRT. It is based on the documentation of the *Dossier 2005 Argile*, but it also draws importantly on information exchanged in writing with Andra in answers to questions raised by the review team, and on direct interactions with staff from Andra during two working seminars in France. Also, in order to fulfil its mandate, the IRT reviewed materials external to the *Dossier*, namely the document concerning the R&D Programme for a potential new phase of work in the period 2006-2010, in a draft, provisional version.

Andra hosted an orientation seminar for the IRT, with a visit to the Meuse/Haute-Marne Underground Research Laboratory (URL), in May 2005. The IRT members received the many documents composing the *Dossier 2005 Argile* and divided the main review responsibilities according to technical areas of expertise. The review was intended to focus primarily on the overall synthesis report and the three overview volumes (*tomes*) describing:

- the repository architecture and management (TAG);
- the repository phenomenology and its evolution (TEP), and
- the repository safety assessment (TES).

Numerous lower level documents were also reviewed, as found necessary by the IRT. Some had to be translated in English. In all, the IRT examined over 5 000 pages of text. The IRT used the specialist knowledge of its members and its collective understanding of international best practice to evaluate the information provided and to generate findings and recommendations.

The objectives and scope of the review are laid out in the Terms of reference (ToR). The IRT wishes to confirm that sufficient information was made available such that it was able to fulfil the ToR. In particular, the IRT was able to test the available knowledge and working methods.

This report documents the IRT main findings, and was written during the period 18 November to 20 December 2005. In keeping with NEA procedures for independent reviews, neither the French government nor Andra have commented on this report – Andra has only had the opportunity to check for factual correctness. The IRT has made its best effort to ensure that all information is accurate and takes responsibility for any factual inaccuracies.

High-level findings

The overall objective of the peer review was to inform the French government whether the *Dossier 2005 Argile* is: (i) consistent with international practices and with other national disposal programmes, in particular the ones considering argillaceous formations, and (ii) whether the future research needs are consistent with the available knowledge basis and if priorities are well identified.

Concerning the overall objective of the review: The IRT found Andra's scientific and technical programme to be fully consistent with international best practice and, in several areas, to be on the forefront for waste management programmes:

- Andra has made effective use of research programmes in other argillaceous formations, notably Opalinus Clay, to train its own experimental personnel and develop experimental techniques and equipment for use in the Meuse/Haute Marne URL;
- Andra has done a comprehensive job of identifying future research needs consistently with the available knowledge base, although prioritisation of those needs is not discussed in the relevant programmatic document. Relevant observations and recommendations are provided by the IRT in the body of the review, and
- Andra has made a visible and successful effort of responding to the findings of the international review of the earlier the *Dossier 2001 Argile*.

More specifically, the review was to check that the *Dossier 2005 Argile* is soundly based and competently implemented in terms of approach, methodology, and strategy. Specific elements of the review thus included:

The overall strategy for evaluating long-term safety: The IRT found Andra's overall strategy for evaluating long-term safety to be credible and comprehensive. It relies on the definition and handling of multiple safety functions and contains formalised ways of integrating phenomenology, science and safety – including the integration of teams and personnel – which significantly contribute to credibility and traceability. The strategy addresses ways both of achieving safety by guiding repository design and of evaluating safety by focusing on the safety assessment. In general, approaches relying on the definition of safety functions have the potential to overcome certain drawbacks of the multi-barrier approach. For this reason, they are now used by several other national programmes. Andra's approach is one of the most systematic ones internationally.

The scientific and technical credibility of the applied methodologies for long-term safety: The IRT found the safety-evaluation methodology to be sound. It contains the necessary elements and has been appropriately implemented in the *Dossier 2005*, as far as is evidenced by the review carried out by the IRT. Key elements of the methodology are: the definition of safety functions and their further analysis by means of a formalised method referred to as external and internal functional analysis (AFE/EFA, AFI/IFA); the formalised method of analysis of the temporal normal and altered evolutions of the system broken down into relevant spatial components that is referred to as phenomenological analysis of repository situations (APSS/PARS), which leads to numerical modelling; and an essentially *post hoc* verification and justification of the handling of uncertainties by means of the formalised qualitative safety analysis (AQS/QSA).

In the view of the IRT:

- the AFE/EFA and AFI/IFA method applied by Andra is an interesting contribution to the increasing use of functional approaches in safety assessments. Andra's method would benefit from being discussed and compared to others in an international context in order to better explore its advantages and limitations;
- the APSS/PARS provides a sound and original way of structuring processes and breaking them down in space and time. It also plays an important role as a tool for internal documentation and communication thus increasing traceability, and
- the AQS/QSA provides an effective means of uncertainty management. The IRT found the structured listing and handling of uncertainties, using standardised vocabulary and a table format, to be transparent and useful for its purposes. The AQS/QSA also seems useful for the identification of "coupled sensitivities" by means of qualitative tools. The IRT believes

that the AQS/QSA also has the potential to inform decisions concerning the repository design or the development of scenarios from first principles. This possibility could be further explored by Andra.

Overall, Andra has developed an original and credible methodology that approaches problems from diverse angles and uses expertise from different teams, thus decreasing bias. The methodology also contributes significantly to the traceability of information within Andra, and potentially also for regulatory review. Taken together, however, the methodology is somewhat complex and demanding to comprehend, as illustrated by the fact that some of its fundamental aspects had to be clarified at late stages of the review and by evaluating a number of lower level documents.

The credibility of the approach to reversibility: Andra was confronted with a requirement to develop a repository concept based on the principle of reversibility, with no specific standards or criteria stated as a basis for the design concept. The approach that it developed relies on progressive construction and progressive closure, with reversibility aspects evaluated at each step. In this concept, reversibility is seen as a means to provide the decision makers with more flexibility, so that any decision to move forward is not made, or perceived to be made, in haste. This graded reversibility concept was initially propounded by the French National Review Board (CNE) in its report on this subject of 1998. While conceptualising the facility, Andra chose not to specify any time for closure and, through an interactive process involving both design and safety assessment, developed a concept that they expect to be suited for both reversible and safe operation over a period of 200 to 300 years. The IRT considers that the design developed by Andra meets the requirement to demonstrate the principle of reversibility.

The IRT also investigated whether reversibility during the pre-closure phase was acquired at the cost of prejudicing long-term safety. The IRT was satisfied that this is not the case.

Finally, while recognising that a requirement for retrievability in the operating phase is stated in other countries and may be met by other designs than the one developed by Andra, the Andra concept is more geared than others to reversible operation of the repository over relatively large timescales. In response both to the sizeable inventory of the different types of waste to be disposed of and to the strategy to create waste emplacement zones that are independent of one another both during operation and after closure, the size and complexity of the repository facility are higher than in most other programmes. The IRT acknowledges the sophistication and uniqueness of the engineering approach developed by Andra. However, because of the long-term commitment

to reversible development and management of the facility, it cannot be said that all the operations will be simple. In particular there is a high requirement for precision engineering in connection with nuclear operations in underground conditions. Considerable demonstration work will be required to show that this can be delivered with the required reliability. The IRT was presented with a draft, provisional version of Andra's future scientific and technical programme that demonstrates that these requirements are understood and can be addressed.

The credibility of the scientific basis: the *Dossier 2005* Argile rests on a sound scientific basis. As in the previous review of the *Dossier 2001*, the IRT views this as being due, in considerable part, to Andra's commitment to involve the wider scientific community in its programme. Because of its importance and continued relevance, the finding of the *Dossier 2001* IRT is reproduced below:

Andra's links with public research institutions are very apparent through its policy supporting postgraduate and postdoctoral research, and its long-term contractual relationships with over 100 laboratories through partnership agreements that foster the formation of research groups or laboratory networks. The way Andra has established and sustained networks with the academic and research institutions in France promotes:

- *bringing together the best available teams and expertise;*
- *the development of innovative techniques and advances in fundamental understanding, and*
- *sharing of the objectives of the programme.*

These links provide a strong scientific foundation for the present work as well as for pursuing future activities.

The IRT did not conduct a detailed evaluation of calculations and individual parameter values used in the phenomenological modelling and in the safety analysis. Consistent with its Terms of reference for the review, the IRT examined, in depth, Andra's investigations in the areas of:

- Geology, hydrogeology, and transport in the Callovo-Oxfordian and surrounding formations:

The quality of the scientific foundations of the Andra programme regarding the characterisation of the host formation and its surroundings is regarded as high even in comparison with the good standard set in other national programmes.

The IRT notes that Andra has intensively pursued the characterisation of the Callovo-Oxfordian (COX) formation and its surrounding

formations, both at the site scale (Meuse/Haute-Marne URL and its immediate vicinity) and at the sector scale (transposition zone). This additional characterisation work has led to an impressive representation of the stratigraphy and hydraulic properties of the COX and its surrounding formations in complex 3-D models.

The IRT also notes positively the significant improvement of the confidence in the high performance of the COX as a barrier to the migration of radionuclides and other toxic chemicals towards the surroundings and the biosphere. This confidence has been gained by using multiple and complementary approaches combining laboratory experiments, preliminary results of *in situ* measurements at the Meuse/Haute-Marne URL, various modelling approaches, natural evidence (overpressurisation, elemental and isotopic natural profiles), analogies with the knowledge gained in relatively simpler engineered clay media (bentonite), and pore-space characterisation at the microscale.

The Synthesis and the TEP do not give enough credit to the high level of confidence gained by Andra concerning the retention of radionuclides in the COX. Consultation of lower level documents and Andra oral presentations during the peer review week were needed to build the IRT's own views and confidence. Overall, the IRT suggests that Andra significantly increase the visibility of the favourable retention characteristics of the COX and of their key role in ensuring long-term safety in future documentation. Recommendations as to the future R&D programme are provided in the text.

The IRT was surprised to learn that some of the boreholes drilled by Andra could not, by licensing conditions, be preserved as long-term monitoring wells, but instead had to be plugged and abandoned. Development of a long-term monitoring network on the sector scale will most likely be required for any future repository, and the information that could have been obtained in the period leading up to site selection and development, if these boreholes had been allowed to be retained as monitoring wells, would have been valuable. The result is likely to be significant additional work if new boreholes have to be drilled to complete a monitoring network, in line with international best practices.

- Waste package release models, including corrosion:

In many respects, the synthesis report on waste package release models is an excellent, comprehensive report. It illustrates a deep understanding of the processes associated with degradation of the various waste and presents conservative and best estimate models for radionuclide release. The analysis of dissolution processes for HLW glass

and Type-B waste and the resultant models are particularly impressive and are at the forefront of international studies.

In relation to the discussion of spent fuel processes and modelling, the discussion of processes is generally excellent, but there is insufficient referencing of studies that illustrate clearly that there is a dramatic effect of dissolved hydrogen in suppressing the dissolution rate of spent fuel. This tends to lend support to the extremely conservative oxidative model (complete dissolution in approximately 50 000 years) presently used for spent fuel dissolution, which would be difficult to justify otherwise.

Andra's rationale for using "corrosion-allowance" materials is acknowledged. Long-term behaviour of these materials is, in principle, more straightforward to predict compared to other alloys whose corrosion resistance rests on the stability of a highly protective surface layer. Other reasons include ease of fabricability (such as welding) and cost. Andra displays a state-of-the-art understanding of the corrosion mechanisms of interest to geologic disposal, including consideration of mechanical constraints, presence of hydrogen, and microbial attack.

- Gas issues:

Considering the absence of treatment of the gas issue in the *Dossier 2001 Argile*, the progress that has been made by Andra is very impressive. Not surprisingly, the analysis of gas production and transport issues appears to have been done after the design was completed, to confirm that gas does not lead to significant issues in long-term safety, thus results from the analysis are not fed back into the design process. There is thus a need to integrate gas into the design principles. Despite this observation, the IRT notes that Andra's gas analysis document shows an excellent understanding of the processes involved in gas production and transport in relation to the various repository components. The safety approach appears somewhat conservative, as the corrosion rates used are at the high end of measured experimental values and some potentially impact-reducing factors are not accounted for (prudently at present, as more needs to be done to confirm the importance of such processes). The modelling results obtained show that, with the present design, much of the gas moves along the liners and through the excavation disturbed zone (EDZ) into the tunnels adjacent to the cells and then escapes into the host rock. This suggests that, in order to increase confidence in the results, more data are required for modelling these pathways.

In regard to international practice, the gas production rate per unit of emplaced waste considerably exceeds that of other clay repository concepts, in particular because of the additional surface area of metal introduced with the emplacement cell liners. As gas production and transport in repositories is an important issue when communicating to non-specialists, much future intensive study and cooperation with other organisations is needed to ensure that the reasons for differences in approach are clearly understood and communicated. With respect to long-term safety, even if present gas production rates are considered, the tentative result that this will not jeopardise long-term safety appears reasonable. With respect to the need for future studies, it is acknowledged by Andra that large-scale studies of gas transport phenomena in the COX are required. In particular, two-phase transport models require validation and the threshold pressures for dilatancy and fracturing should be confirmed in future studies at the Meuse/Haute-Marne URL.

- Choice of architecture, engineering and repository management solutions:

The design elaborated and presented by Andra is a dead-end architecture, which meets the following objectives:

- the layout in a modular structure in order to accept different waste types and quantities at different times and in order for the different modules to be independent from one another from the point of view of long-term performance;
- the simultaneous construction of drifts and waste emplacement cells on the one hand with actual waste emplacement operation on the other hand, and
- meeting the requirement of reversibility while not overriding the ultimate objective of long-term safety after closure of the repository.

The IRT's review confirmed that the chosen architecture may be realised with presently available techniques. Some comments, however, are given to Andra for its later refinement and optimisation. Namely, realisation of the present design will be very demanding: the proposed mining and lining techniques require the highest working standards, especially taking into account the large numbers of different emplacement cells; and the proposed remotely handled waste-emplacement techniques require cleanliness in the underground repository similar to surface nuclear installations. The IRT therefore recommends introducing a strict quality management system (QMS) for underground construction. Also, mining experience would caution against cross-sections as large as more

than 100 m² (B-waste emplacement cells) because there is only limited experience in mining in clay formations like the COX at depths of about 500 m. The IRT sees the need for relevant demonstration tests.

Similarly, the proposed ventilation system is driven by the “dead-end architecture” to limit water flow in galleries, which results in the co-location of all four shafts in one position. The presently chosen co-location of the shafts should be re-evaluated considering operational and hydraulic factors. Testing of various aspects of the proposed ventilation system will also be needed. The IRT observes that many of these needs are addressed in Andra’s forward R&D document.

The clarity of the documentation: The IRT found the components of the *Dossier 2005 Argile* to display impressive readability as stand-alone documents. The documents are effective communication tools, facilitated by the abundance and quality of illustrations, the judicious inclusion of inserts that provide technical detail to the interested reader without breaking the flow of the narrative, and the overall quality of the writing. The synthesis document, in particular, is of high quality and is self-contained. Although the *Dossier 2005 Argile* is presented as having a hierarchical document structure, the IRT found that the different levels of documents do not form a strict hierarchy, and information in higher-level documents is not always detailed in the immediate lower level documents. For certain topics, the IRT had to review some of the more technically detailed documents in order to get the understanding and confidence in the approach and results required to meet its Terms of reference for the review. The detail of referencing could also be improved.

Concluding statement

The *Dossier 2005 Argile* successfully establishes confidence in the feasibility of constructing a repository in the Callovo-Oxfordian argillites in the region of the Meuse/Haute-Marne URL:

- the *Dossier* establishes a viable approach to achieving reversibility without compromising operational and post-closure safety;
- the scientific and technical basis is developed from first principles in a highly traceable manner;
- the safety evaluation method is sound and appropriately implemented;
- there is great confidence in the key safety function of the Callovo-Oxfordian, i.e., diffusion-controlled transport and radionuclide retention, and

- Andra appears to fully understand the mining and engineering challenges to be met, and to be capable of meeting those challenges;

The *Dossier 2005 Argile* should provide a relevant and important basis of information for the forthcoming discussions and decisions in France regarding the formulation of an updated national policy for the final management of high-level and long-lived radioactive waste.

1. INTRODUCTION

1.1 Background

Radioactive waste management has been a technical issue in France since 1960, when the first reactors were built and began operation. From the beginning, deep geological disposal has been considered as a potential solution to the long-term management of the waste. Construction of underground facilities for *in situ* characterisation of the potential host geology was envisioned as the best method of evaluating the feasibility of geological disposal.

Following unsuccessful attempts by the French Atomic Energy Commission (*Commissariat à l'énergie atomique* – CEA) to start preliminary geological surveys at four sites to assess different geological media (clay, granite, salt, schist), the French government decided in 1989 to involve the Parliament in the decision-making process, at first through hearings, and then through the passage of the *Law on Research in Radioactive Waste Management* at the end of 1991 (French Republic, 1992).

The *1991 Waste Act* defines the general frame of research and development and identifies three avenues of research concerning the management of high-level and long-lived radioactive waste, as well as a 2006 milestone for a parliamentary debate about future options for waste management. Within this legal frame, the French National Agency for Radioactive Waste Management (*Agence nationale pour la gestion des déchets radioactifs* – Andra) was created as an independent public body for radioactive waste management and made specifically responsible for the second avenue of research, “assessing the feasibility of the deep geological disposal of this radioactive waste, notably with underground laboratories”. Options for reversible or non-reversible disposal are to be studied under the *1991 Act*; however, in 1998, the French government indicated that emphasis should be given to a “logic of reversibility”.

The CEA is in charge of the two remaining R&D avenues foreseen by the *Waste Act*:

- partitioning and transmutation, and
- waste conditioning and long-term interim storage.

The *Waste Act* foresees a comprehensive assessment of all the avenues of research in 2006. To that effect, the *Act* also created an independent National Review Board (*Commission nationale d'évaluation* – CNE) to inform and advise the government on the interim progress at the technical and scientific levels.

In furtherance of the avenue of research related to deep geological disposal and URLs, a siting phase initiated in 1993 through a consultation mission led by MP Bataille identified four candidate sites: the Marcoule area in the Gard Department (clay formation), the area near La-Chapelle-Bâton in the Vienne Department (granitic formation beneath sedimentary layers), and two areas in Eastern France belonging to the Meuse and the Haute-Marne Departments (clay formation), joined in one single site in 1995. Beginning in 1994, Andra started preliminary geological and geophysical surveys (including 2-D seismic profiles) and drilled exploratory boreholes in these three different areas of France.

In 1996, three applications, backed by these preliminary studies, were filed by Andra to obtain construction and operating licences for underground laboratories so that *in situ* R&D programmes could be pursued. By the end of 1998, the French government took a twofold political decision concerning the Andra projects:

- it authorised the construction and operation of an URL at the Eastern site, and
- it did *not* authorise work at the other sites and started a new siting process with another consultation mission in order to find a new site with outcropping granite.

After the decree formalising the Eastern site decision (August 1999), Andra began its *in situ* R&D Programme for the Meuse and Haute-Marne area. In particular, it involved a 3-D seismic campaign and some additional boreholes aimed at characterising the geological formations to be investigated through the URL facility. The URL would be sited in the Callovo-Oxfordian argillite, the potential host formation for the repository. The construction of the URL, near the village of Bure, started in September 2000, after the authorisation to sink two shafts was granted by the government on 7 August 2000. The Callovo-Oxfordian argillite is a bedded, horizontal formation with a lateral extension of the order of tens of kilometres. It is 130 m thick at the URL site, and lies at an average depth of 500 m.

The Andra R&D programme for investigating the feasibility of deep geological disposal of high-level and long-lived radioactive waste in the Callovo-Oxfordian argillite of Eastern France is denominated *Projet HAVL*

Argile. To prepare for the 2006 comprehensive assessment by the French government and Parliament required by the *Waste Act*, Andra set out to produce an intermediate milestone report in 2001 for the *Projet HAVL Argile*, the *Dossier 2001 Argile* leading up to the final *Dossier 2005 Argile*, which is a conclusive study and is an essential input to the future political decision-making process in France, and is the object of the present international peer review.

The *Dossier 2001 Argile* methodology was submitted to peer review by an international team assembled under the aegis of the OECD/NEA in 2002/03 (NEA, 2003).

1.2 The *Dossier 2005 Argile*

As an input to the 2006 global assessment report to be produced by the National Review Board (CNE) for the decision-making bodies (government and Parliament), as required by the *Waste Act*, Andra has produced a feasibility report concerning geological disposal of high-level and long-lived radioactive waste¹ with a reversibility rationale in the Callovo-Oxfordian clay formation, the *Dossier 2005 Argile*. A similar report concerning the *Projet HAVL Granite*, based on data representative of French granitic formations but without any particular site identified, has also been produced.

The *Dossier 2005 Argile* compiles all acquired data (notably *in situ*) and knowledge leading up to Andra's conclusions on the feasibility of a repository in the Callovo-Oxfordian clay formation in the Meuse/Haute-Marne region. In particular, it takes stock of the lessons drawn from the 2001 Interim Report (*Dossier 2001 Argile*) and, notably, from its Peer Review carried out in 2003 under the aegis of the OECD/NEA.

In this context, the *Dossier 2005 Argile* has the status of a report providing conclusions for the decision-making process:

- it presents the knowledge and results in terms of local (on the Meuse/Haute-Marne URL Site) and regional geology, materials, waste inventory and radionuclides, impact on the biosphere, phenomenology, and modelling;

1. It is to be noted that spent fuel is not considered as waste in France. In fact, the policy for the back-end of the nuclear fuel cycle, as defined by EDF (the French utility), implements the reprocessing of the spent fuel, at the La Hague Plant. Andra included spent fuel in its analyses to cover possible evolutions in the present fuel cycle policy.

- it describes a possible design of the repository with its construction, operation, and closure with an underlying rationale of reversibility, while taking into account operational safety;
- it provides a comprehensive safety assessment containing the definition and breakdown of safety functions, the analysis of the potential temporal evolutions of the system which leads to numerical modelling, and a structured uncertainty management;
- it sets out the prospects for future complementary research and analytical work in the event that the government would approve a repository development project, and
- it provides one of the inputs for a global assessment report to be produced by the National Review Board (CNE) that will compile progress of research carried out so far in the three R&D avenues foreseen by the *Waste Act* of December 1991.

Thus, the *Dossier 2005 Argile* is conclusive and is an essential input to the future political decision-making process.

It must be observed, however, that while it does claim safety and engineering feasibility and, as such, paves the way to the decision-making process for siting, the *Dossier 2005 Argile* does not consider:

- optimisation, for instance, in terms of concepts, cost, and safety;
- the exact geographical layout (both at surface and underground), for instance, in terms of facility and building locations, access by road and transportation, and
- some scientific issues, for which a complete assessment has not yet been carried out but of which an appraisal is provided as a whole; this includes, for instance, long-term behaviour, which was assessed indirectly (via modelling and data acquired at sample level) since some experimental data acquired in the URL are from short-term experiments.

Most importantly, the *Dossier 2005 Argile* is neither part of a repository siting process in the Bure region nor part of a licensing process. Thus, it does not aim at establishing regulatory compliance.

The *Dossier 2005 Argile* comprises an overall synthesis document, three overview documents, and numerous supporting reports.

1.3 Organisation of the international peer review

It is the wish of the French government that the *Dossier 2005 Argile* be a widely-read and discussed document with the general aim of triggering debate and building confidence. Therefore, the French government considered it as essential to submit this important report to a review by an independent team of international experts. The useful contribution provided to national programmes by earlier NEA reviews, including the peer review of the *Dossier 2001 Argile*, led the French authorities to ask the NEA to carry out a peer review of Andra's new *Dossier 2005 Argile*.

The international review team (IRT) was assembled independently by the NEA. In order to preserve independence and avoid conflict of interest, the chosen experts could not be, and must not have been, involved (e.g., as consultants, experts, or contractors) in Andra activities directly contributing to the *Dossier 2005 Argile*. The peer review team was chosen to have a broad international composition. Team members were chosen to provide experience in long-term safety evaluations (including from the Nuclear Safety Authority side), clay formations, and engineering design and operational issues, as well as in key technical areas. Most of the IRT members also participated in the previous peer review of Andra's *Dossier 2001 Argile*. Appendix 1 to this report lists the IRT members and provides brief biographical sketches. A recent NEA document (NEA, 2005) provides information on the nature of NEA-organised peer reviews in the field of radioactive waste management. The general guidelines that the report describes were adhered to for the Andra peer review, as for others before.

1.4 Terms of reference

As laid out in the ToR, the peer review should inform French authorities (Ministry for Industry and Ministry for Research) whether the *Dossier 2005 Argile* is:

1. consistent with international practices and with other national disposal programs, in particular the ones considering argillaceous formations, and
2. whether the future research needs are consistent with the available knowledge basis and if priorities are well identified.

French authorities were particularly interested in the provision of detailed recommendations for specific improvements which could be brought in to that effect, notably if the decision-making process leads to a site-selection phase.

The general scope of the review was to check that the *Dossier* is soundly based and competently implemented in terms of approach, methodology and strategy. Specific elements of the review were:

- the overall strategy for evaluating long-term safety;
- the scientific and technical credibility of the applied methodologies for long-term safety;
- the credibility of the approach to reversibility;
- the well-foundedness, in terms of rationale, of the conclusions of the study, and
- the clarity of the documentation, through its structure and its synthesis.

It was expected that the reviewers would pay particular attention to such technical aspects as:

- the geological and hydrogeological modelling of the Callovo-Oxfordian and its surrounding formations (current and future expected situations);
- the scientific basis for the representation of processes and barrier functions (major phenomena, such as thermal, hydraulic, mechanical, chemical (THMC), in the repository at different timescales);
- the approach to gas production and its transfer;
- the clarity and traceability of the presentation of data, models, and arguments,
- the long-term safety analysis methodology, with a specific focus on the treatment of data and model uncertainties and on the derivation of scenarios, and
- the choice of the architecture and engineering and repository management solutions, with respect to the design requirements or system specifications.²

2. It is to be noted that the proposed repository architecture with its disposal concepts and related engineering options, notably in terms of operational safety, are not to be considered as optimised. These concepts are still optional at the present stage and were chosen through a preliminary first multi-attribute approach and are used as a base for the feasibility study.

Reference may be made, when pertinent, to the conclusions of the peer review of the earlier *Dossier 2001 Argile* carried out under the aegis of the OECD/NEA.

The ToR specified that the peer review should focus on four basic documents of the *Dossier 2005 Argile*:

- its synthesis report, and
- the three main overview volumes, each one addressing specific aspects of the feasibility study:
 - the repository architecture and management (TAG);
 - the repository phenomenology and its evolution (TEP), and
 - the repository safety assessment (TES).

The documents that were the subject of the review by the IRT are much more numerous and are listed in Appendix 2. In particular, in order to fulfil its mandate, the IRT reviewed materials external to the *Dossier*, namely the document concerning the R&D Programme [9]³ for a potential new phase of work in the period 2006-2010.⁴

1.5 Conduct of the review

The IRT met for the first time at Andra offices in Châtenay-Malabry and at the Meuse/Haute-Marne URL Site on 24-27 May 2005. During these four days, Andra staff presented an overview of the *Dossier 2005 Argile*. A representative of the French ministries also presented the government's view on the context of French studies on high-level, long-lived waste management and the purpose of the IRT review. The IRT also discussed the Terms of reference for the review, and the division of the work among the review team.

Lower-level documents were reviewed as found necessary by the IRT. A number of those had to be translated in English, the French version remaining the definitive reference in the case of mistranslation. In all, the IRT reviewed over 5 000 pages of text. In the process of the review, the IRT posed written questions to Andra, to which Andra also replied in writing. A one-week peer review seminar was held on 14-18 November 2005 at which the outstanding

3. Bracketed numbers (e.g., [7]) refer to reviewed documents listed in Appendix 2.

4. This post-2005 R&D Programme was presented to the IRT in a draft, provisional version.

questions identified by the IRT were discussed face to face with Andra personnel. The IRT is satisfied that it obtained all the information necessary to meet its peer review obligations.

1.6 Organisation of this report

Introductory material on the background, the *Dossier 2005 Argile*, ToR and the conduct of the review have been given in the preceding sections of this chapter.

Chapter 2 addresses the consistency of Andra's scientific programme with international best practices in general, and specifically with other national programmes dealing with argillaceous media. It also discusses the consistency of the future research areas identified by Andra with the available knowledge basis.

Chapter 3 is aimed at the more technically interested reader, and presents detailed observations on specific aspects of the *Dossier 2005 Argile*. Its subsections are organised around the different disciplines that contributed to the *Dossier 2005 Argile*, particularly those regarding the quality of the technical and scientific basis of the work undertaken.

Chapter 4 provides a high-level concluding statement that is considered important to providing the requested input to the forthcoming decision-making process.

The reference audience of this report is the French government. Other institutions, organisations, companies, and generally interested parties involved in waste management may also benefit from the report. The review presumes that the reader is generally familiar with the aims and content of the *Dossier 2005 Argile*, but not necessarily with all the details of the documentation.

2. DETAILED FINDINGS CONCERNING THE OVERALL OBJECTIVE OF THE REVIEW

The overall objective of the review was to “inform the French authorities whether the *Dossier 2005 Argile* is (i) consistent with international practices and with other national disposal programmes, in particular the ones considering argillaceous formations and (ii) whether future research needs are consistent with the available knowledge basis and if priorities are well identified.” Those issues are addressed in this chapter.

2.1 Consistency with international practices

The IRT found Andra’s scientific programme to be largely consistent with international best practice and, in several areas, to be on the forefront for waste management programmes.

The IRT believes Andra’s methodology for evaluating long-term safety to be in line with the state of the art. Andra developed its own ways of handling certain aspects, namely how phenomenological understanding is broken down in space and time by means of the APSS/PARS, how formal methods are being used for deriving safety (and other) functions, and how uncertainty management is verified *a posteriori* (AQS/QSA). In the view of the IRT, these aspects increase the credibility of the safety evaluation by approaching problems from diverse angles and using expertise from different teams, thus decreasing bias. They also contribute significantly to the traceability of information within Andra, and potentially also when being reviewed by regulators.

The IRT believes approaches based on the use of safety functions, such as the one chosen by Andra, to be consistent with international best practices. Andra’s way of handling safety functions is amongst the most systematic ones used internationally. Certain aspects, namely the rather formalised tools for breaking down the functions (the so-called functional analysis) which has been adapted from standard industrial methods, would benefit from being discussed and compared to others in an international context in order to better explore its advantages and limitations.

Andra's 3-D hydrogeological modelling, both at the basin and sector scales, is at the forefront of waste management programmes. Andra's core cataloguing, logging and testing programme sets a standard that few other programmes can match. Its understanding of the geologic history of the Meuse/Haute-Marne area is commensurate with the best practices of any other programme. However, the fact that, due to time constraints and associated licensing conditions, Andra was unable to convert all exploration and testing boreholes to long-term monitoring wells is unfortunate. The result is likely to be significant additional work if new boreholes have to be drilled to complete a monitoring network, in line with international best practices.

Because of the internationally accepted application of uranium (U) series methods to site characterisation, the IRT feels that such analysis should have been carried out earlier in the programme (in comparison with the efforts being made to use "exotic" isotopic profiles such as ^{81}Kr , ^{76}Li). However, the IRT commends Andra for recently applying U-series disequilibrium to several samples of COX claystone layers from two boreholes in the Meuse/Haute-Marne area and recommends that the method be used on a routine basis to ensure that secular equilibrium is preserved at all locations in the claystone. This would provide Andra with extensive "natural analogue" type evidence for demonstrating the immobility of waste-derived uranium at the Meuse/Haute-Marne Site.

The analysis of dissolution processes for HLW glass and Type-B waste and the resultant models are particularly impressive, and are at the forefront of international studies. The alternative conceptual models for glass dissolution are clearly outlined and their application to different glasses is quite sophisticated. The B2 (bitumen waste) degradation model clearly illustrates that much impressive underlying characterisation work has been done, coupled with sophisticated modelling. Overall, the investigations in these areas are advanced relative to other programmes.

2.2 Consistency with other national programmes considering argillaceous formations

The overall approach to safety and design

The overall safety and design approach is consistent with strategies followed in other clay-based national disposal programmes, especially regarding:

- the main reliance on the host formation for long-term safety (over the long term, the radionuclide retention in the COX overshadows all other barrier functions);

- the avoidance (or minimisation) of THMC perturbations of the host formation in order for the functions (diffusion-dominated transport, retention, stability, and buffering capacities) attributed to the COX to be ensured as expected; in this framework, the construction of the repository facility in the median plane of the formation to maximise the effective thickness of the COX is similar to other programmes, and
- modularity to reduce interactions between various parts of the repository facility and between various waste types. The IRT notes positively that Andra has applied the modularity approach in a more systematic way and has developed this concept more deeply than in other national programmes.

However, in the detailed implementation of this approach, some differences with other national programmes appear:

- the size, complexity, and length of operation (due notably to the reversibility provisions) of the repository facilities are much higher than in most other programmes. As a result, a long operational period will almost certainly increase the extent of perturbations, such as pyrite oxidation of the EDZ, induced in the COX, albeit by a small increment over and above the unavoidable early perturbations common to any other programme. This may delay the resaturation of the COX and hence the self-sealing of excavation-induced fractures and joints in the EDZ;
- the gas production rate per unit of emplaced waste considerably exceeds that of other clay repository concepts, in particular because of the additional surface area of metal introduced with the emplacement cell liners. As gas production and transport in repositories is an important communication issue, much future intensive study and co-operation with other organisations is needed to ensure that the reasons for differences in approach are clearly understood and communicated, and
- the complexity of underground operations appears to be greater than for concepts proposed in other clay repository programs, in particular the requirement for precision engineering in connection with nuclear operations in underground conditions. In particular, remote emplacement of spent fuel and HLW packages using a device that pushes the waste packages along a narrow diameter sleeve is a unique approach with many development challenges.

These differences are simply noted by the IRT; they should not pose any insurmountable difficulties.

Radionuclide migration and understanding of the COX

Regarding radionuclide migration, Andra has acquired a large set of batch sorption data over the period from 2001-2005, which is comparable to other national programmes. In parallel to these laboratory experiments, Andra has developed and will continue to develop a detailed characterisation at the nano-scale of COX pore structure as well as a more mechanistic understanding of the rock-water interactions. Andra's techniques and approaches are consistent with the most recent developments in these areas.

A characteristic of the *Dossier 2005 Argile* is the limited availability of information arising from long-term experiments at the Meuse/Haute-Marne URL. This is linked to the state of development of the Meuse/Haute-Marne URL at the time of the drafting of the report – and as such cannot be criticised.⁵ Most experiments were only started in 2004. The limited availability of information from the experiments at the Meuse/Haute-Marne URL has been compensated by, on the one hand, data acquired from boreholes and shaft sinking, on the other had by efficient “transfer” of knowledge from the Mont Terri project in the Opalinus clay in Switzerland to the Andra programme. The direct testing by Andra at Mont Terri of the experimental set-ups and their related interpretation tools that were planned to be used in the Meuse/Haute-Marne URL, as well as the efficient training of Andra's own experimental teams, have allowed Andra to rapidly optimise the use of the Meuse/Haute-Marne URL. Furthermore, Andra has taken care to justify the validity of the transfer by a systematic comparison of the COX at the Meuse/Haute-Marne Site and the Opalinus Clay at Mont Terri (*Analyse comparée des contextes géologiques et pétrographiques avec l'argile à Opalinus Mont Terri (Suisse), Annex to the Référentiel du site de Meuse/Haute-Marne*) [7].

A comparison covering other programmes and topics may further support Andra's case by helping to better understand specificities/differences of:

- the COX vis-à-vis other clay host formations, and
- Andra safety and design strategies compared to other programmes.

5. Andra informed the IRT that it will ensure that any new relevant information acquired in the URL will be included in the second version of the *Dossier 2005 Argile* being readied for publication by December 2005.

2.3 Consistency of future research needs with available knowledge

In general, Andra's proposed work programme is a well-planned, comprehensive blend of laboratory and *in situ* testing combined with appropriate modelling that should allow Andra to move successfully to site selection. Andra has done a comprehensive job of identifying future research needs consistent with available knowledge, although prioritisation of those needs is not discussed in the relevant scientific and technical programme document [9].

The proposed Scientific and Technical Programme HAVL – Argile 2006-2010 [9] establishes a permanent link between the “Already Acquired Knowledge” and the future “Projects” aimed at reducing the more important uncertainties or filling knowledge gaps. Recognising the draft, provisional nature of the document and its status as a planning document developed by Andra to ensure continuity of the scientific work, the document is confusing in parts and the IRT suggests that in its future development, attention is given to key areas:

- the numerous overlaps between the various sections (e.g., 4.4.1, 4.4.2.2, and 4.4.2.3 propose studying the pore structures and surface charge effects of the clay; the reader has to study numerous sections to get an overview of what is foreseen regarding natural organic matter and the assessment of its role on radionuclide mobility), and
- the mixture in the same subsection of discussion of the understanding of undisturbed COX and radionuclide transport therein, as well as of the effects of various perturbations (corrosion-induced hydrogen, cellulose degradation products etc.). This is rather confusing, especially because the rationale for considering specific perturbations is not always clear.

Considering the proposed work vis-à-vis the IRT recommendations given in Chapter 3, the following observations are noted:

- the work proposed on naturally occurring organic matter in the COX covers the possible influence of organic matter on fluid-rock equilibrium as well as on radionuclide speciation, complexation, and transport. That is of particular importance to support the preliminary observation of iodine retention in the COX. Hence, this work corresponds to the IRT recommendations;
- Andra also proposes to assess the role as complexing agent of the degradation products of organic matter present in the waste. This is of prime importance for some Type-B cemented waste which can contain cellulose. The rationale for focusing the work on exogenous organic ligands on the degradation products of cellulose, since several other waste types include organic matter, is explained on the basis that

Andra considers these products to be especially detrimental compared to the behaviour of other ligands in a cementitious system;

- Andra’s fundamental understanding of the host rock evolution and water-mineral interactions is already very developed. Andra will pursue this work (for example, through conceptual representation of the electrostatic double layer to better understand anionic exclusion, further characterisation of the pore space geometries and properties at nanometric scale, further understanding of COX diagenesis at mineral level, and isotopic analysis of neoformed mineral species). In accordance with the detailed characterisation work, Andra will seek to develop a mechanistic understanding of chemical retention mechanisms in the COX. For that purpose, Andra will take advantage of its current – and planned future – understanding of “simpler” media (in particular, the bentonite to be used as an engineered barrier). These endeavours are in the forefront from a scientific point of view. Andra’s participation in the EC FUNMIG project should allow a comparison of the various approaches to upscaling of transport parameters in clays;
- The IRT also positively notes:
 - the progressive integration of the *in situ* geochemical and diffusion data that are being gathered in the Meuse/Haute-Marne URL experiments (PAC: “water sampling for chemical and isotopic analysis”, DIR: “diffusion and retention in the argillites”) in order to support laboratory data;
 - the planned 2-D and 3-D seismic surveys over a wider area of the transposition zone;
 - the planned additional borehole drilling and testing and associated modelling aimed at developing a better understanding of the hydrodynamics of the Dogger and Oxfordian;
 - the verification that the retention parameters established for the Meuse/Haute-Marne site are valid for the whole transposition zone, and
 - the planned preliminary assessment of the retention capacity of the formations surrounding the COX (establishment of safety margins).
- In addition to DIR, it might be of interest, in order to further support diffusion-controlled transport through the COX, to carry out long-term (>10-year large-scale (decimetric to metric scale) *in situ* tracer experiments. To take full advantage of multiple lines of evidence, it would be advisable to use an experimental set-up that is different from the one used in DIR.

- The retention of radionuclides in the immediate proximity of the packages, and in the near-field in general, is usually (and conservatively) not considered. Andra plans extensive work on radionuclide behaviour in contact with (i) the metallic corrosion products of iron-based over-pack and the alteration products of the waste matrices, and (ii) concrete and aged concrete. With its planned work on this topic, Andra should be able to define a more realistic representation of radionuclide behaviour in the immediate proximity of the packages. This should build further quantitative confidence in the retention capacity of the immediate vicinity of degraded packages and is to be commended as it helps establish additional safety margins.
- The IRT could not determine how much work Andra is proposing in order to obtain better coverage of diffusion profiles for the transposition zone. The Scientific and Technical Programme 2006-2010 [9] suggests more data are to become available, but it does not state that more profiles will actually be obtained during the future work. Identifying the transposition zone as an area where diffusion through the COX is the only transport mechanism will be important for obtaining acceptance of a site.
- Andra should also seek to obtain a better understanding of the cause of over-pressurisation in the COX. Osmosis is mentioned in general as a topic of future research, but no specific plans are given.
- The IRT regrets the apparent absence of further work on the use of uranium concentration and isotopic ratios in groundwater to indicate redox conditions and natural mobility of uranium over a one-million-year timescale.
- The potential roles of microbial activity have not been fully explored to date, and the IRT agrees with Andra's proposed programme, both on micro-organisms introduced during operations and on those pre-existing in the COX, to address this topic.
- Andra should develop a method for integrating gas management into the repository design process in order to address this important aspect of future optimisation studies.
- The IRT found the plans to perform probabilistic calculations and global sensitivity analyses presented by Andra during the course of the review to have the essential elements of a probabilistic calculation. Also, the level of sophistication of the probabilistic approach seems appropriate for the problem at hand.

The IRT also makes the following observations and recommendations:

- The IRT notes that most international radioactive waste disposal programmes search out natural analogues to support and provide confidence in disposal at a particular site. The present and future use of natural analogues to support Andra's case is not greatly visible, either in the TEP or in the Scientific and Technical Programme 2006-2010 [9]. Andra has, however, participated in international natural analogue programmes. Andra should document further its position regarding the use (or not) of natural analogues.
- Andra should determine whether the oxidative perturbation originating from the release of nitrates from bituminous Type-B waste may extend outside the disposal cells and impact the COX.
- As part of its future programme, Andra should develop a sector-scale long-term hydrogeological monitoring well network. Such a network needs to be in place to develop baseline data some years before construction of a repository begins.
- The IRT suggests that future documentation should more prominently emphasise the favourable retention characteristics of the COX and their key role in ensuring long-term safety. This should include a clear exposition of the use of multiple lines of evidence in defining the sorption characteristics of the COX, and of the use of conservative assumptions.
- While Andra's current hydrogeological model is adequate to demonstrate that any radionuclide releases to the environment would be below levels of regulatory concern, confidence in the modelling could be enhanced by making it more realistic. Andra should consider directly embedding the sector hydrogeological model grid, in which hydraulic properties are based on Andra's field investigations, into the regional (basin) hydrogeological model to define the boundary conditions (both lateral and vertical) that will be used for the sector modelling. The calibration should attempt to match the observed piezometry with a higher level of accuracy than has been achieved thus far. Consideration should be given to a stochastic treatment of parameter uncertainty, creating multiple possible realisations of the permeability distribution for each important layer. Once acceptable calibrations are achieved, the revised sector model should be re-embedded in the regional model to verify that the boundary conditions used for the sector-scale modelling remain appropriate. Finally, multiple realisations of the Dogger and Oxfordian single-layer models should be created to generate distributions of potential travel paths and

travel times. These model results should be compared, at least in a general way, to observed geochemical variations in the Dogger and Oxfordian (e.g., Cl concentrations) as an additional way of demonstrating overall conceptual consistency.

3. DETAILED FINDINGS FROM THE REVIEW OF SPECIFIC TECHNICAL ASPECTS

The ToR identified specific, technical aspects of the *Dossier 2005 Argile* for review. The aspects that eventually received an appropriately detailed review were refined following discussions with Andra and French authorities during the first meeting in May 2005. The specific aspects reviewed hereafter are:

- the geological, hydrogeological, and transport modelling of the COX and its surrounding formations (current and future expected situations);
- the scientific basis for the representation of processes and barrier functions (major phenomena, such as THMC, and waste-package release models in the repository at different timescales);
- the approach to gas production and its transfer;
- the long-term safety analysis methodology, with a specific focus on the treatment of data and model uncertainties and on the derivation of scenarios, and
- the choice of the architecture and engineering and repository management solutions, with respect to the design requirements or system specifications.

3.1 Geology, hydrogeology and transport in the COX and surrounding formations

According to the results presented in the *Dossier 2001 Argile* and to the outcomes and recommendations of the 2003 NEA Peer Review, the focus of the 2005 review was primarily on transport mechanisms in the COX, and in particular the dominance of diffusion as a transport mechanism and the retention capacity of the clay, as well as on the hydrogeological modelling. The overall geological characterisation of the COX, of its past evolution (burial, diagenesis, etc.) and of its possible future evolution was already very detailed and well founded in the *Dossier 2001 Argile*. However, the performance of the COX as a barrier to radionuclide migration was poorly supported in that *Dossier 2001*.

Shortcomings in the hydrogeological modelling of the surrounding formations were also noted in the 2003 review.

The documentation presented in the TEP and the *Référentiel du site de Meuse/Haute-Marne* [7] is, from a geological sciences point of view, extensive and impressive. The quality of the scientific foundations of the Andra programme regarding the characterisation of the host formation and its surroundings is regarded as high even in comparison with the good standard set in other national programmes. The IRT particularly notes the important effort made by Andra to provide clear, graphic illustrations of the geological information and concepts in the TEP and the *Référentiel du site de Meuse/Haute-Marne*. Some shortcomings of the documentation are, however, highlighted below.

3.1.1 Major advances in knowledge since the Dossier 2001 Argile

The IRT notes that Andra has intensively pursued the characterisation of the COX formation and its surrounding formations, both at the site scale (Meuse/Haute-Marne URL and its immediate vicinity) and at the sector scale (transposition zone):

- new boreholes drilled over the sector scale (FSP) have allowed an improved characterisation of the hydraulic and chemical properties of the Dogger and Oxfordian formations, as well as a refinement of the transposition zone definition, and
- inclined boreholes (FRF) that were drilled at the Meuse/Haute-Marne Site were of high technological standards. They confirm the vertical and lateral lithological continuity and homogeneity of the COX at the site scale as well as the absence of potential water-conducting features in the COX at the Meuse/Haute-Marne Site.

This additional characterisation work has led to an impressive representation of the stratigraphy and hydraulic properties of the COX and its surrounding formations in complex 3-D model at both the basin and site scales.

The IRT also notes positively the significant improvement of the confidence in the high performance of the COX as a barrier to the migration of radionuclides and other toxic chemicals towards the surroundings and the biosphere. This confidence has been gained by using multiple and complementary approaches combining laboratory experiments, preliminary results of *in situ* measurements at the Meuse/Haute-Marne URL, various modelling approaches, natural evidence (overpressurisation, elemental and isotopic natural profiles), analogies with the knowledge gained in relatively simpler engineered clay media (bentonite), and pore-space characterisation at the microscale.

These advances in knowledge since the *Dossier 2001 Argile* are in accordance with the recommendations of the NEA Peer Review of 2003.

3.1.2 Confirmation of diffusion-controlled transport in the COX

A number of arguments and physical/chemical observations support or confirm the dominance of diffusion as the mechanism of solute transport in the COX. These aspects are summarised below.

3.1.2.1 Inclined boreholes

Since the *Dossier 2001 Argile*, many of the boreholes drilled at the Meuse/Haute-Marne Site have been inclined so that they penetrate the COX at a sub-horizontal angle, thus increasing their intersection with the horizontal layers of COX lithologies. These inclined boreholes have also been oriented with respect to the local stress field to provide the greatest likelihood of encountering any (near) vertical features (e.g., faults, fractures) that might be present and conduct water. The IRT supports the use of this technique, which has been developed by the petroleum industry, to provide the maximum amount of information on geologic structures. Results have shown that there is a remarkable lack of such water-conducting features in the COX, thus supporting the Andra arguments for the homogeneity and low permeability of the COX in the area of the Meuse/Haute-Marne URL.

3.1.2.2 Elemental and isotopic profiles

The demonstration that diffusion is the principal mechanism for solute transport through the COX is central to the disposal concept and important in ensuring long-term safety. Several profiles of conservative chemical elements (as ions) and isotopes have been shown to be useful in identifying diffusional transport in the COX. The principal parameter used was the Cl concentration of pore fluids in core samples taken from vertical boreholes through the COX. Progressive changes in Cl concentrations of pore fluids were found to fit a model describing diffusional transport through a low-permeability rock matrix. In the TEP, the evidence for this is presented as vertical Cl profiles for five boreholes. While three of the profiles clearly show diffusional control, ranging from about 4 000 mg/L in the Dogger to 1 000 mg/L in the Oxfordian, results for the two remaining boreholes show only minor changes in Cl concentration.

Low Cl concentrations of Dogger groundwaters in some places are not initially expected and could be interpreted as indicative of advective flow and dilution by recharge that enters the Dogger through fracturing to the south-west of the transposition zone. Andra argues that all the profiles of Cl concentration for pore fluids at each location, whether dilute or saline, are characteristic of diffusion-controlled processes, because the concentrations of Cl in fluids of the underlying Dogger formation are still higher than in the COX and the overlying Oxfordian. Andra attributes the dilute Dogger fluids to ingress of recharge waters at some time in the past (>40 000 years before present) although it is clear that the *high* Cl concentrations in the main recharge area (to the north) are inconsistent with the *low* concentrations found along the flow direction. The IRT believes that these anomalies can only be resolved by continued groundwater and pore fluid analysis from existing and new boreholes in the area, and by continued efforts to understand the sector-scale hydrodynamics of the Dogger.

Information on profiles of the isotopes ^{37}Cl and ^{18}O has also been obtained by Andra and is presented in the *Référentiel du site de Meuse/Haute-Marne* [7] and two lower level documents [13 and 25]. This additional information is helpful because it shows that diffusional profiles also exist for other conservative species in solution. The TEP deals only with Cl profiles without adequate explanation, and these results and their implications are understated in the TEP.

Finally, modelling of multiple diffusion profiles across the COX provides an elegant and innovative way of verifying the diffusional nature of solute transport in the COX, and the IRT encourages Andra to test more cores and obtain representative groundwater samples to act as “end-members” for the profiles.

3.1.2.3 Anion diffusion coefficients

Considerable investigation has been performed by Andra to determine the effects of the clay on ion retention of solutes diffusing through the COX. This work was performed partly to understand the hydraulic overpressure in the COX and also to examine the processes of ion exchange and, particularly, anion exclusion, a process by which anions are rejected from small pores due to interaction with the negatively charged clay surfaces. While anion exclusion satisfactorily accounts for the more rapid transport of anions through the clay compared with non-interactive species such as ^3H or the isotopes of oxygen and hydrogen in water, portions of the TEP (e.g., the insert 3.9) unintentionally give the incorrect impression that anions are significantly separated from cations whereas the observations are entirely consistent with the fundamental requirement for overall electroneutrality.

Determination of anion diffusion coefficients by laboratory tests on intact COX borehole core has been performed and a significant database has been obtained. Further confirmation of anion exclusion effects and differences in diffusion coefficients is being obtained at the field experiment scale, using specially drilled boreholes in the COX at the experimental level of the Meuse/Haute-Marne URL (-445 m). This experiment, known as the DIR (diffusion and retention), involves measuring the diffusion of radionuclides into the surrounding rock at the end of a borehole in the URL. Findings to date indicate that ion diffusion coefficients are comparable to those estimated from models based on the results of laboratory measurements. The IRT supports this comparative study, but advises a careful evaluation of the potential for advection of solutes, that may be induced by the test design and implementation, to interfere with evaluation of diffusional transport.

3.1.2.4 Uranium-series analysis

Further confirmation of slow fluid movement through the COX is obtained by the use of uranium-series disequilibrium methods in the analysis of whole rock from the Meuse/Haute-Marne area. Because the age of the COX greatly exceeds 2 million years, the measurement of rocks with $^{234}\text{U}/^{238}\text{U}$ activity ratios less than or greater than 1.00 would indicate that there had been loss or gain of either isotope (usually ^{234}U) within the last 2 million years. Alternatively, the finding of $^{234}\text{U}/^{238}\text{U}$ ratios with equilibrium values, in core samples from the COX, would indicate that uranium has not migrated through the COX. This provides additional support for the non-advective nature of transport through the COX.

Some previous work on U-series disequilibrium and its application to understanding U mobility was cited by Andra in the TEP for the Dogger limestones that underlie the COX at the Meuse/Haute-Marne Site [23]. Analyses show disequilibrium in the $^{234}\text{U}/^{238}\text{U}$ ratio in stylolitic discontinuities in the limestone with as much as 20% depletion in ^{234}U . In contrast, the adjacent limestones had ratios of up to 1.05. This type of analysis has also been applied by Andra to the COX claystones in a few samples from two boreholes [7] and all results were at secular equilibrium indicating the immobility of uranium in the samples analysed. Continued analyses of claystone samples are recommended to show that this condition can be extended to all parts of the transposition zone.

3.1.3 Confidence in the reference COX pore-fluid composition

Knowledge of the chemical composition of pore fluids in the COX and its relationship to transport properties is an important part of the characterisation studies at the Meuse/Haute-Marne Site. Since the compilation of the *Dossier*

2001 Argile, when little data on pore fluid composition were available, a considerable amount of data for the COX has been obtained by Andra. This is not apparent from the upper level documents (specifically the TEP), in which there is very little mention of pore fluid compositions. This initially gives the impression that such data are not available, but searching through level three and four documents (e.g., [21]) has shown that good efforts have been made to obtain this information.

Various techniques of extraction of pore fluids for analysis have been tested, including high-pressure squeezing, diffusion, and crush-leaching. Difficulties in sampling the pore water are caused by the very low hydraulic conductivity (10^{-13} to 10^{-14} m/s) of the claystone, the presence of reactive components such as secondary minerals and organics, and the gain or loss of gases. One technique that appears to yield reliable results with minimal sample disturbance is the method of advective displacement [22]. The application of this technique is a good example of collaborative work between different international groups, in this case, with the Swiss, working on the Opalinus clay.

The IRT notes that good progress has been made by Andra in determining pore fluid composition in the COX and further work is recommended to continue to define in more detail the variations in composition and their causes.

3.1.4 Radionuclide retention in the COX

A key function of the host formation is the retention, by various processes, of the radionuclides that may eventually escape the disposal facility. This function plays a major role in ensuring long-term safety.

The COX retention properties and the confidence Andra has gained in their characterisation are very superficially handled in the TEP: two pages without confidence statements regarding the quality of the presented solubilities and sorption coefficients (K_d). It is quite clear, however, after having checked Chapter 5: *Comportement des radionucléides et des toxiques chimiques dans le Callovo-Oxfordien – Site de Meuse/Haute-Marne* of the *Référentiel de comportement des radionucléides et des toxiques chimiques d'un stockage dans le Callovo-Oxfordien jusqu'à l'homme* [8], which was not specifically included in the initial IRT's ToR, that the acquisition of solubility and K_d values for radionuclides and other toxic chemical elements constitutes a major experimental and modelling effort that has been carried out by Andra since the *Dossier 2001 Argile*. This effort adequately supports the solubility and K_d values that have been used for the *Dossier 2005 Argile* safety calculations. It is also in accordance with one of the IRT recommendations of 2003.

Based on the above-mentioned documentation, the IRT finds:

- Andra has carried out impressive work on the characterisation of COX pore space, pore network, texture, and porosities at microscale in order to allow development of a sound basis for further understanding of water/rock interaction; this work is certainly “cutting edge”;
- Andra has adequately used multiple sources of information to support the choice of K_d values in addition to the batch sorption experiments in dispersed media, in particular:
 - a more mechanistic understanding of retention processes on pure clay mineral phases (illite or smectite) derived from its studies on sorption on bentonite, and
 - the analogy with the Opalinus clay in Switzerland. The relevance of the analogy with this formation is supported notably by a systematic comparison between the COX and the Opalinus clay documented in an Annex to the *Référentiel du site de Meuse/Haute-Marne* [7] (*Analyse comparée des contextes géologiques et pétrographiques avec l’argile à Opalinus du Mont Terri, Suisse*);
- the use, for batch experiments, of samples from various layers in the COX at the Meuse/Haute-Marne Site and from boreholes located throughout the transposition zone helps build confidence in the representativeness of the chosen K_d values;
- Andra has defined a reference geochemical composition of the COX pore fluids, the representative quality of which has been confirmed by multiple approaches (modelling, sampling, *in situ* PAC experiment at the Meuse/Haute-Marne Site). The availability of such a reference composition was of great help to support batch experiments and their interpretation, and
- also to be positively noted is the consideration of the dependency of sorption characteristics for some species (and of the related K_d values) on temperature and varying radionuclide concentrations as well as the coherent handling of K_d for radionuclides and toxic chemical elements.

On these bases, the IRT concludes that Andra has established sound confidence in the high retention capacity of the COX for most radionuclides, and especially for actinides.

The IRT emphasises the need for Andra to increase further the understanding of retention processes in the COX. In particular, the potential influence of naturally occurring organic matter in the overall migration behaviour is still to be

investigated and clarified. Despite the fact that Andra has extensively analysed organic matter to define palaeogeological conditions encountered by the COX during its geological evolution (e.g., maximal burial depth and temperature), the role of naturally-occurring organic matter in enhancing or reducing radionuclide mobility has not been considered explicitly up to now. It should, however, be acknowledged that the contribution of organic matter is implicitly included in the K_d values derived from batch sorption experiments. Such investigation may lead to better support for the effectiveness of iodine retention in the COX and support its consideration in safety calculations (as iodine has, up to now, been considered as a fully non-sorbing species).

Andra has planned, in its draft Scientific and Technical Programme 2006-2010 [9], relevant work on solid and dissolved organic matter that would answer the above recommendation (e.g., assessment of organic matter reactivity and ability to complex radionuclides and toxic chemicals, experimental determination of functional group types, reactivity and role in pH regulation of interstitial fluids, solubility and speciation of elements in solution).

The Synthesis and the TEP do not give enough credit to the high level of confidence gained by Andra concerning the retention of radionuclides in the COX. Consultation of lower level documents and Andra oral presentations during the peer review week were needed to build the IRT's own views and confidence. Overall, the IRT suggests that Andra significantly increase the visibility of the favourable retention characteristics of the COX and of their key role in ensuring long-term safety in future documentation.

Also, the difference between phenomenological observations and conservative K_d choices for safety calculation purposes should be acknowledged in the TEP. For instance, the chapter on the *Comportement des radionucléides et des toxiques chimiques dans le Callovo-Oxfordien – Site de Meuse/Haute-Marne* [8] discusses evidence of iodine retention in the COX while the TEP states that this element does not have any affinity for the COX, therefore justifying a zero K_d value. It would have been more accurate to state that considering the uncertainties regarding the efficiency and the understanding of iodine retention in the COX, a zero K_d value had been conservatively (and justifiably) chosen for safety calculation purposes.

3.1.5 Impact of geochemical perturbations on the COX

Andra has a good understanding of the limited extent of the most prominent geochemical perturbations that are induced by the repository on the COX (i.e., oxidation front and alkaline plume). Sound evidence is available that these perturbations are limited to the EDZ.

The potential for the COX sorption sites to become saturated by migrating species other than radionuclides (e.g., produced by the progressive degradation of the cement-based materials or by the corrosion of the metallic materials) has also been assessed. Such a competition for sorption sites – which could lead to the potential unavailability of sorption sites for migrating radionuclides – is very limited due to the significantly large surface area of the COX argillaceous minerals and will, in any case, be limited to the EDZ.

The impact of these geochemical perturbations on the retention properties of the COX is handled adequately and conservatively in the safety calculations as no retention properties are attributed to the COX fractured zone in the relevant sensitivity calculation.

The thermal degradation of the COX organic matter and its consequence on the retention characteristics of the formation should be better assessed. The organic matter naturally present in the COX is rather immature and, as such, can rapidly react and be degraded (oxidation, interaction with alkaline fluids, thermal stress).

The chemical perturbations are limited to the EDZ and well buffered by the COX mineralogy (e.g., calcite buffering of acidification created by organic matter oxidation). As such, they should not have any safety consequences (as a zero retention capacity is attributed to the fractured zone). However, the thermal load on the COX, even if limited (the maximum temperature in the clay remains below 90°C) and of rather short duration in the repository evolution (typically 10 000 years), will extend beyond the COX EDZ and may impact natural organic matter. Indeed, information from other programmes indicates that low activation energy (i.e., low thermal stress) is sufficient to degrade immature organic matter, with accompanying changes in structure and CO₂ releases.

The potential roles of microbial activity (micro-organisms introduced during repository operations or together with materials used in the construction, as well as pre-existing organisms in the COX) on radionuclide mobility in the COX were not fully considered in the *Dossier 2005 Argile*. The IRT was reassured that Andra will be considering both microbes introduced during operations and possibly existing microbes in the COX in its future R&D work.

3.1.6 Characterisation and modelling of the COX and the surrounding formations

Generally speaking, the hydrogeological setting in the Meuse/Haute-Marne area is favourable for repository development: e.g., a host formation in which diffusion is the dominant transport mechanism, poorly exploitable sur-

rounding aquifers due to their low permeabilities, the availability of other water resources, the high level of Cl in the Dogger. Andra has done an impressive job of representing the stratigraphy and hydraulic properties in a complex 3-D model using methods and technologies developed by the petroleum industry. In this regard, they are at the forefront of waste disposal programmes. Andra has used 3-D seismic surveys and the FSP and FRF drilling programmes to convincingly demonstrate layer continuity and low permeabilities in the COX, Dogger, and Oxfordian formations. The low permeability of the COX has also been substantiated by confirmation of the overpressurisation of that unit, including vertical pressure profiling.

Andra has used multiple lines of evidence to support the concept of extremely slow advective velocities in the COX, including:

- groundwater age dating;
- measured low permeabilities;
- results of numerical models, and
- demonstrated absence of faults and fractures at the site scale.

Andra has also appropriately used modelling to identify areas where additional boreholes and data are needed (e.g., to explain geochemical variations and heads).

However, neither the TEP nor any of the individual lower level documents reviewed by the IRT contained a complete, comprehensive explanation of the types, scales, and purposes of hydrogeological models developed by Andra. The information needed to understand what models had been developed and how they were related was isolated and disjointed. An extensive review of level three and level four documents was necessary for the IRT to develop an understanding of the generally excellent modelling that has been performed.

The IRT was surprised to learn that some of the boreholes drilled by Andra could not, by licensing conditions, be preserved as long-term monitoring wells, but instead had to be plugged and abandoned. Development of a long-term monitoring network on the sector scale will most likely be required for any future repository, and the information that could have been obtained in the period leading up to site selection and development, if these boreholes had been allowed to be retained as monitoring wells, would have been valuable. An unfortunate consequence of having to abandon these holes is that Andra's hydrogeological modelling must rely, in part, on an assumption that head measurements made at different times at different locations over the course of a number of years reflect the same system state.

3.1.7 Transposition zone

As noted in the 2003 Review, the definition of a “transposition zone” is very useful in building confidence in the applicability of the results acquired at the Meuse/Haute Marne Site for future potential siting exercises. The IRT notes an improvement in the delineation of the transposition zone since the *Dossier 2001 Argile*.

The IRT recommends that the definition and extent of the transposition zone should continue to be checked against new data. In particular, the positive results from the inclined boreholes at the Meuse/Haute-Marne Site should be extrapolated to the whole transposition zone via, e.g., correlation with additional high-resolution seismic surveys.

3.2 Scientific basis for the representation of processes and barrier functions

The scientific bases underlying the understanding of the major phenomena affecting the evolution of a repository and its geological environment are embedded in the TEP, as well as in several level three “reference” documents and level four technical documents.

Noting that geological and hydrogeological modelling of the COX and surrounding formations is reviewed in Section 3.1, this section focuses on the representation of the thermal, hydraulic, chemical, and mechanical processes that are relevant to describe the phenomenological evolution of the natural and engineered components acting as a multi-barrier system for the purpose of protecting man and the environment from the dissemination of radioactive elements.

Making the most of the geological medium, i.e., preservation of its favourable properties, drives the repository architecture and design, notably by limiting disturbances caused by (i) excavation work of the underground structures, (ii) materials introduced, and (iii) presence of waste, especially with regard to heat release. Concepts and architectures are therefore tested, whenever appropriate, by using the conceptual models presented in the TEP. The descriptions of the thermal, hydraulic, chemical, and mechanical processes are appropriately introduced one by one based on their relative influence on the development of other phenomena.

Andra made full use of today’s technological capabilities in modelling time-dependent heat transport throughout the various repository zones. The main uncertainties are related to uncertainty in the values of the input parameters (heat load, thermal conductivity, specific heat, etc.) and spatial representation of the repository (emplacement clearances, etc.). Thermal criteria are

chosen to be reasonably conservative with regard to the needs (i) to preserve the favourable properties of the geological medium, and (ii) to minimise the impact of uncertainties associated with modelling waste package degradation.

Andra's rationale for using "corrosion-allowance" materials is acknowledged. Long-term behaviour of these materials is, in principle, more straightforward to predict compared to other alloys whose corrosion resistance rests on the stability of a highly protective surface layer. Other reasons include ease of fabricability (such as welding) and cost. A significant body of knowledge exists on the corrosion behaviour of low- and non-alloy steels, which is well captured in the *Référentiel des matériaux d'un stockage de déchets à haute activité et à vie longue – Tome 3: Corrosion des matériaux métalliques*. [5] In particular, Chapters 2 through 4 dealing with the corrosion of low-alloy and non-alloy steels provides an excellent overview of the corrosion mechanisms of interest to geologic disposal, including consideration of mechanical constraints, presence of hydrogen, and microbial attack.

Consistent with the recommendations made in 2003 following the peer review of the *Dossier Argile 2001*, much progress has been made detailing the potential evolution of the overpack-clay system, specifically with regard to iron/clay interactions, as documented in Chapter 5 of the *Référentiel des matériaux d'un stockage de déchets à haute activité et à vie longue – Tome 1: Matériaux à base d'argiles gonflantes*. The discussion and conclusions regarding the extent of alteration of bentonite are reasonable and well justified, although the uncertainties regarding the extent of influence of released Fe(II) on the bentonite are perhaps larger than expressed. Nonetheless, these uncertainties do not have significant safety implications.

There is evidence (in particular in [19]) of a deep understanding of the processes associated with degradation of the various waste, enabling presentation of conservative and best estimate models for radionuclide release. The analysis of processes for HLW glass and Type-B waste and the resultant models are particularly impressive and are at the forefront of international studies. In these areas, the presentation clearly illustrates to the reader the present understanding of the materials and their behaviour.

In relation to the discussion of spent fuel processes and modelling, the discussion of processes is generally excellent, but there is insufficient referencing of studies that illustrate clearly that there is a dramatic effect of dissolved hydrogen in suppressing the dissolution rate of spent fuel. This tends to lend support to the extremely conservative oxidative model (complete dissolution in approximately 50 000 years) for spent fuel dissolution which would otherwise be difficult to justify. In particular, the IRT notes that several key journal papers

and reports (Röllin *et al.*, 2001; Spahiu *et al.*, 2000; King *et al.*, 1999; King and Shoesmith, 2004) confirming the impact of hydrogen are not referenced.⁶ There is considerable discussion of the prudent use of the oxidising radiolytic model, as opposed to the model (or dissolution rate) based on H₂ suppressing dissolution. The radiolytic model certainly overestimates dissolution rates and part of the justification for using it is that the permanent presence of H₂ cannot be demonstrated. Yet in the same report, it is acknowledged that the H₂ cannot diffuse away and this is apparent from both the TEP and the report on gas [10]. Since radiolysis is only significant in the first 100 000 years, when gas pressure in the emplacement cells is high, this discussion is contradictory.

The question of when there is sufficient understanding to use a “realistic” or “best-estimate” model in safety assessment versus when it is prudent to adopt a very conservative model is always difficult to assess. It is always true that if the latter illustrates that there is no safety issue, it may not be important. In this case, however, the use of the conservative model gives doses of 0.02 mSv, whereas a dose about an order of magnitude lower may result from using a model considering reducing conditions. Given that oxidising models for spent fuel dissolution have been repeatedly contradicted by experimental observations of low dissolution rates of spent fuel in the presence of hydrogen (including studies in which the CEA has recently participated), this is certainly an issue that deserves more scrutiny. This is clearly acknowledged by Andra, but its significance may be lost when viewing the dose rate results in the Synthesis Report, which could lead to misleading inferences with respect to relative doses from different waste types. It is recommended that Andra carefully evaluate the studies related to the effects of hydrogen on spent fuel dissolution to ensure a comprehensive assessment of all available data.

3.3 Approach to gas production and transfer

There are several processes in the Andra repository that lead to gas production (in particular, metal corrosion, radiolysis, and biodegradation of Type-B waste) and metal corrosion is acknowledged to be by far the most significant of these in terms of rates and total volumes of gas that will be produced. The repository design concept proposes use of considerable quantities of steel, in particular as liners for disposal cells for Type-C waste and spent fuel, which lead to significant hydrogen gas production. As the total production rate is proportional to the surface area of metal, the hydrogen production rate per unit area of emplaced waste exceeds that of other clay repository concepts by

6. Notably, the study of Röllin *et al.* (2001) shows a reduction of 4 orders of magnitude for 1 bar hydrogen as opposed to 0.2 bar oxygen.

more than a factor of 10. Because of the low permeability of the COX formation, gas accumulation occurs and a comprehensive analysis is required to determine if there are significant consequences with respect to safety. An evaluation of such processes was not included in the *Dossier 2001 Argile*, but the IRT notes that the progress since then has been impressive.

Not surprisingly, the analysis of gas production and transport issues appears to have been done after the design was completed, to confirm that gas does not lead to significant issues in long-term safety, thus results from the analysis are not fed back into the design process. There is a need to integrate gas into the design principles (it is presently not discussed as a design factor in the TAG, where it might be expected to be discussed under a heading such as “limiting disturbances to the host rock”), as the treatment of gas requires that it be fully incorporated from the beginning of the design process. An advantage of fully integrating gas management into the design process is that the issue of reducing gas production, including whether or not this should be an explicit goal of design optimisation, can be more thoroughly explored.

Despite this observation, the IRT notes that Andra’s gas analysis document shows an excellent understanding of the processes involved in gas production and transport in relation to the various repository components. It appears somewhat conservative, as the corrosion rates used are at the high end of measured experimental values and some potentially impact-reducing factors (e.g., low water inflow rates and reduction of gas pressure due to the consumption of water) are not accounted for (prudently at present, as more needs to be done to confirm the importance of such processes). As a tool for design, more realistic evaluation may ultimately need to be done. Nonetheless, there are findings from the analysis that are certainly relevant to design, e.g. Andra intends to look at the possibility of longer disposal cells, from which gas would partially escape directly into the rock and partially escape to the access tunnel. Pros and cons related to this need to be considered and the analysis tools available should permit this to be explored. The modelling results obtained show that, with the present design, much of the gas moves along the liners and through the EDZ into the tunnels adjacent to the cells and then escapes into the host rock. This suggests that, in order to have confidence in the results, more data are required for modelling these pathways.

With respect to long-term safety, even if present gas production rates are considered, the tentative result that this will not jeopardise long-term safety appears reasonable. With respect to future studies required, it is acknowledged by Andra that large-scale studies of gas transport phenomena in the COX are required. In particular, two-phase transport models require validation and the threshold pressures for dilatancy and fracturing should be confirmed in future studies at the Meuse/Haute-Marne URL.

3.4 Long-term safety analysis methodology

3.4.1 General

The methodology applied in the *Dossier 2005 Argile* contains the essential components that can, in one form or the other, be expected in an assessment of long-term safety. It contains:

1. a comprehensive description of the system to be analysed;
2. the definition and breakdown of the safety functions of the system;
3. an analysis of the temporal evolution of the system broken down into relevant spatial components in the APSS/PARS;
4. a structured derivation, from the understanding of safety functions and the temporal evolution of the system, of a normal evolution scenario (SEN/ NES) for the quantification of radiological consequences;
5. a definition of a limited number of stylised altered evolution scenarios (SEA/AES) based on regulatory requirements and on information from previous assessments;
6. derivation of models and data for consequence calculations;
7. consequence calculations for the normal and altered evolution scenarios,
8. deterministic sensitivity analyses for these scenarios, and
9. an essentially *post hoc* motivation/justification of the handling of uncertainties (AQS/QSA).

The above steps are informed by results from ongoing research and development work.

3.4.2 Functional analyses

The use of safety functions constitutes a key element in Andra's safety assessment methodology in the *Dossier 2005 Argile*. The IRT notes that, in general, function-based approaches are now being used in several national programmes and methods relying on the definition and handling of (multiple) safety functions have the potential of overcoming certain drawbacks of the multi-barrier approach. As evidenced in the *Dossier 2005 Argile*, for example, functions are useful both as a way of achieving safety (guiding design as an element in a safety strategy) and as a way of evaluating safety (focusing the assessment).

Andra's method for defining primary functions and breaking them down into sub-functions is derived from standard industrial methods. This has advantages, but it might be questioned whether the complexity introduced through these methods unnecessarily compromises transparency. The IRT also noted difficulties in obtaining a clear view of how functions were derived and of the definitions of these functions and of the constraints subsequently imposed when refining the analysis. Considering the key role the safety functions have in structuring the safety case, the description of the functional analysis appears at lower levels in the *Dossier 2005 Argile* [17, 18].

Andra's method is more formalised than several other "function approaches". In the view of the IRT, this contributes to the traceability of information within Andra, e.g., with respect to design decisions, scenario selection, transfer of information between teams, and decision-making in general, and potentially also when being reviewed by regulators.

In conclusion, the IRT finds that the method used by Andra is an interesting contribution to the increasing use of functional approaches in safety assessments. Andra's method would benefit from being discussed in an international context in order to better explore its advantages and limitations.

3.4.3 APSS/PARS (normal and altered evolution)

As in the *Dossier 2001 Argile*, Andra uses the so-called APSS/PARS method for the structuring of processes related to repository evolution and for breaking them down in space and time. The IRT finds the method sound for its purposes and thereby also an important tool for managing timescales. It also plays an important role as a tool for internal documentation and communication thus increasing traceability.

In line with the review findings on the *Dossier 2001 Argile*, the APSS/PARS in the *Dossier 2005 Argile* has improved in the senses that it *i)* also has brief variants for altered evolutions in the form of records of deviations from the base variant covering the normal evolution, and *ii)* has undergone a FEP check. The modifications of the APSS/PARS since the *Dossier 2001 Argile* resulted, amongst other things, in a separation of the APSS/PARS from the derivation of models and data. Andra's modifications are viewed as an improvement in the traceability of the overall approach to safety analysis.

As acknowledged by Andra, there is need for more consideration with regard to the questions whether, to what extent, and how altered evolution scenarios should be handled by the APSS/PARS method. Furthermore, the derivation of models is more developed and separated from the APSS/PARS

compared to the *Dossier 2001 Argile*. Model development and its underlying assumptions are clearly and traceably documented in a number of low-level documents, but the IRT found that general information on this issue needs to be reflected at a higher level of the *Dossier 2005 Argile* documentation.

In the view of the IRT, the APSS/PARS method can now be considered as a mature method for handling the normal evolution scenario.

3.4.4 The management of uncertainties

The handling of uncertainties is prominent throughout the TES. The safety functions aid in focusing the analysis and thereby also indirectly in the ranking of uncertainties. Uncertainties are identified in the APSS/PARS, and the APSS/PARS also aids in defining the bounds of the normal evolution domain, whereby uncertainties within the normal evolution can be separated from those related to altered evolutions. The deterministic sensitivity analyses provide an evaluation of the impact of uncertainties within each scenario. The so-called qualitative safety analysis, the AQS/QSA, is an instrument for verifying that all uncertainties have been appropriately handled in previous steps of the analysis, thereby justifying *post hoc*, e.g., the selection of altered evolution scenarios. It also led to the identification of a few additional calculation cases and has, in principle, the potential to inform design decisions and the derivation of additional scenarios.

In the view of the IRT, the uncertainty management in the *Dossier 2005 Argile* is well developed. More detailed comments on the AQS/QSA are given below.

3.4.5 Qualitative safety analysis (AQS/QSA)

The IRT notes that the so-called qualitative safety analysis (AQS/QSA) has undergone considerable development since the *Dossier 2001 Argile*. The automated failure mode analysis criticised in the IRT review of the *Dossier 2001 Argile* has now been replaced by a comprehensive method supporting uncertainty management.

More specifically, the *Dossier 2005 Argile* version of the AQS/QSA distinguishes the following types of uncertainties:

- uncertainties managed by design basis;
- uncertainties included in calculation hypotheses in the normal evolution scenario;

- uncertainties covered by an altered evolution scenario;
- uncertainties related to external events (handled in either the normal or altered evolution scenarios), and
- uncertainties mentioned for the record, with a motivation of why they are not further addressed in the *Dossier 2005 Argile*.

In the *Dossier 2005 Argile*, the AQS/QSA is essentially used as a *post hoc* evaluation of how the safety functions could become impaired and, thereby, a *post hoc* motivation/verification of the normal and altered evolution scenarios, calculation cases, and design measures. This use of the AQS/QSA is essential in particular for motivating the altered evolution scenarios that are to some extent stylised, since they were defined, based on regulatory requirements and on results of earlier assessments, rather than being derived directly from results obtained within the *Dossier 2005 Argile*.

The IRT found the structured listing and handling of uncertainties, using standardised vocabulary and a table format, to be transparent and useful for its purposes. The AQS/QSA also seems useful for the identification of “coupled sensitivities” by means of qualitative tools.

The *post hoc* application of the AQS/QSA in the *Dossier 2005 Argile* resulted essentially in a verification that all relevant uncertainties were treated appropriately, and only in a few cases led to the definition of additional calculation cases. The IRT, however, believes that the AQS/QSA also has the potential to inform decisions concerning the repository design or the development of scenarios from first principles. These possibilities could be further explored by Andra.

3.4.6 The management of different timescales

The methodology presented by Andra in the *Dossier 2005 Argile* explicitly addresses the issue of timescales. This is most notably introduced through the temporal discretisation in the APSS/PARS.

The handling of couplings in APSS/PARS, where relatively short time steps with addressing of THMC couplings in each step seems well founded and based on the physical nature of the processes involved.

Thus, the IRT finds that the methodology presented by Andra in the *Dossier 2005 Argile* has been demonstrated to be capable of managing different timescales relevant to deep geological disposal in accordance with the French Basic Safety Rule RFS III.2.f (*Direction de la sûreté des installations nucléaires*, 1991).

3.4.7 Sensitivity analyses

Sensitivity analyses are mainly handled through a number of deterministic calculation cases defined *a priori* which address sensitivities to deviations in base case parameter values both in the normal and altered evolution scenarios. These cases thus handle local sensitivities where one or a few parameters varied from a base case. The IRT found Andra's approach to deterministic sensitivity analyses to be adequate and addressing relevant properties of the analysed system. The IRT acknowledges the additional treatment of sensitivities by qualitative means (AQS/QSA).

During the course of the review, the IRT has learnt that Andra intends to perform probabilistic calculations allowing also so-called global sensitivity analyses, where sensitivities are examined in the overall framework of uncertainties, i.e., all possible parameter combinations given a correlated set of input data distributions are examined. The IRT found the plans presented by Andra to have the essential elements of a probabilistic calculation. Also, the level of sophistication of the probabilistic approach seems appropriate for the problem at hand.

3.4.8 Overall conclusions regarding safety assessment methodology

The IRT found the methodology for safety assessment used in the *Dossier 2005 Argile* to be sound and contain the elements required in a well-developed safety analysis.

The method has been appropriately implemented in the *Dossier 2005 Argile* as far as evidenced by the reviewing carried out by the IRT, including some documents at lower levels.

The method includes formalised ways of integrating phenomenology/science and safety, including the management of teams/personnel, which contribute significantly to credibility and traceability.

This is exemplified by the functional analysis through its impact on both design and safety analysis and by the AQS/QSA, through the way it enforces interaction between safety analysts and scientists.

In the view of the IRT, the methodology is somewhat complex and demanding to comprehend, illustrated, e.g., by the fact that some fundamental aspects of the methodology had to be clarified at late stages of the review.

The TES is well-structured and digestible. However, a certain amount of information which is, in the view of the IRT, essential for understanding

Andra's work and the methodology applied, is only documented in the lower level documents. This concerns in particular the functional analysis and the qualitative safety assessment. Some aspects of the overview of the methodology in the introductory chapter of the TES were found confusing in not appropriately reflecting, for example, the relationship between elements and the chronological order of the steps of the methodology as applied by Andra in its approach to safety assessment.

3.5 Choice of the architecture and engineering and repository management solutions

The design of the repository chosen by Andra was mainly influenced by four objectives:

- the repository has to be laid out in a modular structure in order to accept different waste types and quantities at different times;
- the repository concept must enable simultaneous construction of drifts and waste emplacement cells on the one hand with actual waste emplacement operation on the other hand;
- the design has to include the concept of reversibility with no explicit design criteria and/or timescale given to Andra, and
- safety of the repository is the overriding objective of the design.

The design elaborated and presented by Andra is a dead-end architecture that meets the aforementioned objectives.

The IRT's review confirmed that the chosen architecture can be realised with presently available techniques. Some comments, however, are given to Andra for its further refinement and optimisation of the repository's architecture.

The present design appears to be strongly influenced by civil engineering technologies for constructing tunnels, bridges, and dams with lifetimes of about 100 years. Mining experience would caution against cross-sections as large as more than 100 m² (B-waste emplacement cells) because there is only limited experience in mining in clay formations like the COX at depths of about 500 m.

The main design feature that is introduced in response to the requirement for reversibility is the use of stronger and thicker steel and/or concrete liners than would otherwise be necessary, to ensure the long-term mechanical stability of the openings. This is not seen as having significant implications for long-term safety. Clearly the thickness of the linings could be adjusted to match any

specific period less than 200 to 300 years for which the repository was planned to remain open in any future review of the approach to reversibility.

Realisation of the present design will be very demanding. The proposed mining and lining techniques require the highest working standards, especially taking into account the large number of different emplacement cells. The IRT therefore recommends introducing a strict quality management system (QMS) for underground construction. The proposed remotely handled waste-emplacement techniques require cleanliness in the underground repository similar to surface nuclear installations. The IRT sees the need for a relevant demonstration test.

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 technical equipment. The same is true for observation and monitoring. Andra has identified the needs in this area in its proposed Scientific and Technical Programme 2006-2010 [9].

The proposed ventilation system is driven by the “dead-end architecture” to limit water flow in galleries. This results in the co-location of all four shafts in one position. Also, ventilation of filled Type-B waste cells is not finally decided. The IRT has specific recommendations for a future optimisation of the ventilation system:

- the presently chosen co-location of the shafts should be re-evaluated considering operational and hydraulic factors; the IRT does not concur that arguments based on hydraulic driving forces between shafts provide compelling motivation for co-location of the shafts when the horizontal hydraulic gradients in the COX do not appear to be large enough to influence long-term safety even if shafts were located at either end of a repository;
- the ventilation of cells filled with Type-B waste (inflow around stacked containers, outflow through perforated wall and air ducts) should be tested with and without fans, and
- as mine ventilation systems try to avoid ducts and tubes, Andra should investigate/test alternative solutions to its approach.

4. CONCLUDING STATEMENT

The *Dossier 2005 Argile* successfully establishes confidence in the feasibility of constructing a repository in the Callovo-Oxfordian argillites in the region of the Meuse/Haute-Marne URL:

- the *Dossier* establishes a viable approach to achieving reversibility without compromising operational and post-closure safety;
- the scientific and technical basis is developed from first principles in a highly-traceable manner;
- the safety evaluation method is sound and appropriately implemented;
- there is great confidence in the key safety function of the Callovo-Oxfordian, i.e., diffusion-controlled transport and radionuclide retention, and
- Andra appears to fully understand the mining and engineering challenges to be met, and to be capable of meeting those challenges.

The *Dossier 2005 Argile* should provide a relevant and important basis of information for the forthcoming discussions and decisions in France regarding the formulation of an updated national policy for the final management of high-level and long-lived radioactive waste.

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Appendix 1

MEMBERS OF THE INTERNATIONAL REVIEW TEAM

Alan Hooper, *Chairman*

Alan Hooper is Chief Scientific Advisor at United Kingdom Nirex Limited, the UK organisation responsible for developing safe and publicly acceptable concepts for the long-term management of radioactive materials. He is responsible for advising on the overall science and engineering programme of Nirex and its key deliverables, and on communicating the programme to scientific institutions in the UK and internationally.

Alan Hooper was awarded a first class honours degree in chemistry from Nottingham University in 1968 and a Ph.D. for research into complex oxide systems by the same University in 1971. He worked in the Research Division of the Central Electricity Generating Board for 17 years, initially studying the safety of operation and maintenance of advanced power reactor systems. In 1980, he joined the Nuclear Decommissioning Project and was responsible for research into the safety implications of decommissioning strategies for the UK's first generation of gas-cooled Magnox reactors. From 1985 he was responsible for the specification and implementation of the research programme to support the retrieval and conditioning of the CEGB's intermediate-level waste for eventual geological disposal.

Since joining Nirex in 1988, Alan Hooper has held a number of senior management positions. He was responsible for the research and assessment programme for a number of years, and, for some time, for the specification and implementation of the site characterisation studies at Dounreay and Sellafield. He gave extensive evidence to the public inquiry into the siting of an underground "rock characterisation facility" at Sellafield and has also given evidence to various parliamentary select committees. He is the named inventor of the specially formulated backfill material proposed for use in the Nirex Phased Geological Repository Concept for intermediate-level waste.

Alan Hooper is currently a member of the UK delegation to the NEA Radioactive Waste Management Committee and its Integration Group for the

Safety Case, playing an active role in developing documents to explain the nature and purpose of the post-closure safety case for geological repositories, and associated confidence-building measures. Previously he was Chairman of NEA's Site Evaluation and Design of Experiments Co-ordinating Group for seven years, promoting initiatives such as The Clay Club, GEOTRAP Project, and workshops on specialist topics such as conceptual modelling. He has also chaired various technical specialist groups for the IAEA working on the scientific and technical basis for radioactive waste management and the associated safety requirements. He has served on various advisory groups to the British Geological Survey.

In 2002-2003, he led the international peer review of *Andra's Dossier 2001 Argile*.

Richard Beauheim

Richard Beauheim is a Principal Member of Technical Staff at Sandia National Laboratories, and is currently Lead Hydrologist for the Waste Isolation Pilot Plant (WIPP) in Carlsbad, New Mexico, USA. From 1984 to 1996, he was the Principal Investigator for the hydrogeological characterisation of the WIPP site. During preparation of the WIPP license application, he was responsible for integration and consistency of field information and performance assessment models. After the licensing of WIPP in 1998, he was responsible for the hydrology components of the WIPP monitoring system. He is now co-ordinating and directing hydrogeologic field studies and performance assessment activities related to the recertification of WIPP.

Richard Beauheim received his B.A. in anthropology from the University of Wisconsin-Madison, USA, in 1974. In 1980, he received M.S. degrees in geology and water-resources management from the same university. Prior to joining Sandia in 1984, he spent four years as a hydrogeological consultant to the mining and nuclear-waste industries. During this time, he was a member of the US Office of Nuclear Waste Isolation review team evaluating seven candidate salt sites for high-level radioactive waste repositories. Mr. Beauheim is the author of 25 journal and conference papers and over 30 technical reports. His particular technical expertise is in the areas of performance and interpretation of hydraulic and tracer tests and site characterisation.

In 2000-2001, Mr. Beauheim took a one-year leave of absence from Sandia to serve in the Radiation Protection and Waste Management Division of the NEA in Issy-les-Moulineaux, where he oversaw the completion of the GEOTRAP project and prepared a number of reports and documents related to

URLs and radioactive waste management. On behalf of Sandia and the WIPP project, he was actively involved in the INTRAVAL and GEOTRAP projects, and is currently on the Steering Groups of the NEA International Projects on Engineered Barrier Systems (EBS) and Approaches and Methods for Integrating Geologic Information in the Safety Case (AMIGO). In 2002-2003, he served on the International Review Team for Andra's *Dossier 2001 Argile*.

Melvyn Gascoyne

Mel Gascoyne has been a geochemical consultant since 1998. For 16 years prior to that, he was a Senior Scientist with Atomic Energy of Canada Limited, and Head of the Hydrogeochemistry Section of the Applied Geosciences Branch, at the Whiteshell Laboratories, Manitoba.

Mel Gascoyne was responsible for obtaining and interpreting geochemical data for the Canadian Nuclear Fuel Waste Management Programme for the characterisation of several crystalline rock formations in Canadian Shield. His particular areas of expertise include the use of naturally occurring stable and radioactive isotopes in groundwater to determine its residence time (age), sources of dissolved salts and geochemical evolution, and the application of uranium decay methods for dating fracture minerals and determining the timing of recent alteration.

Since leaving AECL, Mel Gascoyne formed Gascoyne GeoProjects Incorporated (GGP Inc.) and has performed consulting work for document review, report preparation, isotopic analysis of groundwaters for SKB (Sweden), POSIVA OY (Finland), Ontario Power Generation, AECL (Canada), the US Geological Survey (Denver), Duke Engineering (Canada), and NOVA Chemicals (Canada). He participated as well in the international peer review of the Yucca Mountain TSPA organised under the aegis of the NEA.

Mel Gascoyne obtained his B.A. (Honours) in Chemistry (1969) and M.Sc. in Environmental Sciences (1974) at the University of Lancaster, UK, followed by his Ph.D. in Geology at McMaster University, Hamilton, Ontario, Canada. After two years of post-doctoral work at McMaster, he joined AECL to work on geochemical aspects of nuclear waste disposal. He was a contributing author to the Environmental Impact Statement for nuclear waste disposal submitted to the Canadian federal government in 1995 and subsequently defended in public hearings.

Mel Gascoyne is the author of over 60 journal and conference papers and over 50 technical reports and QA documents for commercial projects. He has

been an Associate Editor of the journal *Applied Geochemistry* since 1988, Secretary of the International Association of Geochemistry and Cosmochemistry from 1992 to 2002, and member of the Board of Directors of the ISOTRACE Accelerator Mass Spectrometry facility, University of Toronto from 1997 to 2002.

Allan Hedin

Allan Hedin is a senior company specialist on safety assessments at the Swedish Nuclear Fuel and Waste Management Company (SKB). His responsibilities include the management of SKB's safety assessment projects for deep repositories for high-level waste.

Allan Hedin received a M.S. in Engineering Physics from the University of Uppsala in 1983 and a Ph.D. in Ion Physics from the same university in 1987. His thesis concerned theoretical and experimental work on interactions between fast heavy ions and solids with applications in mass spectrometric techniques. After four years of further academic research in the fields of laser-induced desorption and scanning tunnelling microscopy, he was employed by the Swedish National Chemicals Inspectorate in 1991 to work with risk assessments of chemical substances and products.

Allan Hedin has been working with SKB since 1994. He was originally employed to work with probabilistic radionuclide transport calculations and has gradually obtained more general responsibilities for safety assessment methodology issues. He has a particular interest in developing simplified mathematical models that capture the essential properties of more complex representations in the field of safety assessment. He was a senior author, editor and assistant project manager for SKB's latest safety assessment SR 97 and is now the manager for the safety assessments to be carried out during SKB's site investigation phase.

Allan Hedin was a member of NEA's former Performance Assessment Advisory Group (PAAG) and is currently a member of the Integration Group for the Safety Case (IGSC). He has taken active part in several international projects organised within PAAG and IGSC. He was responsible for reviewing the safety assessment methodology in the NEA international peer review of Andra's *Dossier 2001 Argile*.

Lawrence Johnson

Lawrence Johnson is senior scientist and R&D co-ordinator at Nagra (the Swiss National Cooperative for the Disposal of Radioactive Waste), where he has worked since 1999 on various aspects of engineered barriers performance, including waste form behaviour, canister design, bentonite properties, criticality assessment and development of models for near-field performance assessment. He is one of the principal authors of the Opalinus clay safety assessment study, a key component of Nagra's 2002 Entsorgungsnachweis Project.

Lawrence Johnson received a B.Sc. in Chemistry with Great Distinction from the University of Lethbridge in 1977 and joined AECL at Whiteshell Laboratories in 1978. After several years studying the dissolution of spent fuel and vitrified high-level waste, he became manager of engineered barrier studies in the Canadian Nuclear Fuel Waste Management Programme, leading the group responsible for research and development for engineered barriers for disposal of nuclear fuel, including engineering studies, as well as the development of a source-term model for spent fuel, corrosion models for nuclear fuel waste containers, transport models for clay-based buffer and backfill barriers, and integration of near-field models. In addition, he managed the studies of durability of spent fuel in interim wet and dry storage. He is senior author of two comprehensive performance assessment studies of engineered barriers, one detailing borehole emplacement of spent fuel in titanium containers and the other on in-room emplacement of copper containers. The two studies played a central role in the federal review of AECL's Environmental Impact Statement under the Environmental Assessment and Review Process conducted in 1994-1997. He is the author of over 80 reports and journal papers on spent fuel dissolution, spent fuel storage and near-field performance assessment.

In 1997, he was a member of the NEA International Review Group for the SKI SITE-94 performance assessment study, and during 1997-98 was a member of the USDOE Expert Panel on Waste Form Dissolution and Radionuclide Mobilization. In 2002-2003, he served on the International Review Team for Andra's *Dossier 2001 Argile*. He is presently a member of the International Scientific Advisory Board of the CEA PRECCI Programme.

Klaus Kühn

Klaus Kühn is a retired professor for radioactive waste management at the *Technische Universität* (TU) Clausthal. Simultaneously, he was director of the *Institut für Tieflagerung* (GSF) in Braunschweig. His main activities were all aspects of radioactive waste disposal in geological formations.

Klaus Kühn graduated in 1963 from the Clausthal School of Mines (now *Technische Universität Clausthal*) in Mining Engineering (Dipl.-Ing.). In 1968, he got his Ph.D. from the same university. He was the first scientific staff member of the GSF – *Institut für Tief Lagerung*, which was founded in 1965 on behalf of the federal government in Germany with the aim of performing research and development with regard to the disposal of radioactive waste. From 1973 until 1995 he served as director of that institute. In 1987 he was appointed Honorary Professor at the TU Clausthal.

He has been a member of numerous national and international committees. On the national scene, he was a member of the German *ReaktorSicherheitskommission* (RSK – Reactor Safety Commission) from 1983 until 1998. Between 1999 and 2002, he joined the AkEnd, an Advisory Committee to the government charged to formulate a set of scientific and social criteria in order to find new repository sites. For his outstanding service, he was decorated in September 1990 with the *Bundesverdienstkreuz* (Order of Merit) of the Federal Republic of Germany by the President. Most recently, he was appointed Honorary Member of the German Nuclear Society KTG (*Kerntechnische Gesellschaft*).

In the international arena, Klaus Kühn participated in, and/or chaired, several committees of the IAEA, OECD/NEA, and the European Commission. Among them was the joint NEA/IAEA-International Peer Review Group for the 1996 Performance Assessment of the US Waste Isolation Pilot Plant.

After his retirement in April 2003, Klaus Kühn is still consulting for GSF on the decommissioning of the Asse Research Mine. Besides that, he chairs the Scientific Advisory Board for the decommissioning activities of VKTA in Rossendorf/Dresden. He is a member of the Advisory Board of Nagra (Switzerland), of the International Technical Advisory Committee (ITAC) of NUMO (Japan), and of the Nuclear and Radiation Studies Board (NRSB) of the US National Academy of Sciences.

Philippe Lalieux

Philippe Lalieux is Manager of the HLW/MLW Disposal Programme at ONDRAF/NIRAS, the Belgian Agency for Radioactive Waste and Enriched Fissile Material. He is a geologist and geophysicist with more than 15 years' professional experience in the field of radioactive waste disposal.

He graduated from the University of Brussels (Belgium) in 1983 with a B.Sc. in Geological Sciences and obtained a Masters Degree (M.Sc.) in Geo-

physical Sciences from the same university in 1984. From 1986 to 1994, he was a staff member of ONDRAF/NIRAS. His responsibilities included the co-ordination and defence of the Safety Assessment and Feasibility Interim report (SAFIR) as well as the supervision of geoscientific characterisation of potential sites for deep and near-surface disposal, and natural analogue studies.

Philippe Lalieux joined the OECD/Nuclear Energy Agency Secretariat in 1995. He was in charge, within the Radiation Protection and Waste Management Division, of the Agency's programmes on deep disposal site characterisation and evaluation. In particular, he was responsible for the Scientific Secretariat of the Co-ordinating Group on Site Evaluation and Design of Experiments for Radioactive Waste Disposal (SEDE), the GEOTRAP Project on radionuclide transport in the geosphere, and the Clay Club. He was a member of the joint NEA/IAEA international peer review of the 1996 Performance Assessment of the US Waste Isolation Pilot Plant (WIPP) and of the NEA international peer review of the SKI SITE-94 Project (Sweden).

In 2000, he went back to ONDRAF/NIRAS to ensure the co-ordination, editing, and defence of the second Safety and Feasibility Interim Report (SAFIR 2), which provides a comprehensive assessment of the possibility to dispose of long-lived radioactive waste in poorly indurated clays in Belgium. The SAFIR 2 was presented to the authorities in 2001 and allowed ONDRAF/NIRAS to pursue R&D towards geological disposal in Belgium.

Since returning to ONDRAF/NIRAS, Philippe Lalieux has also chaired the NEA Working Group on the Characterisation, Understanding, and Performance of Argillaceous Rocks as Repository Host Formations (usually known as the "Clay Club"), as well as serving as a member of the NEA International Review Team of Andra's *Dossier 2001 Argile*. He is also a member of the Safety Committee of Posiva, the Finnish waste disposal company.

Albert Machiels

Albert Machiels is a Senior Technical Manager at the Electric Power Research Institute (EPRI), where he is responsible for several R&D programmes related to the back-end of the fuel cycle, materials corrosion, and advanced nuclear plants' systems. Present activities are focused on developing a better understanding of environmentally assisted corrosion (including stress corrosion cracking and irradiation-assisted stress corrosion cracking) and other materials degradation phenomena for application to light-water reactor primary and balance-of-plant systems and to spent fuel storage, transportation and disposal.

Albert Machiels holds *Ingénieur civil chimiste* and *Ingénieur en génie nucléaire* degrees from the University of Liège, Belgium; and an M.S. and a Ph.D. in Engineering from the University of California, Berkeley.

Before joining EPRI, he was an Associate Professor at the University of Illinois, Urbana-Champaign. Prior to moving to the USA, he spent four years at the University of Liège, Belgium, including one year at the EUROCHEMIC Reprocessing Plant, teaching and working on issues related to spent-fuel reprocessing.

Albert Machiels previously served as a member/reviewer in several panels on the “Scientific Needs of the Technology of Nuclear Waste Containment”, “Glass Leaching”, and “Engineered-Related Issues in the US Nuclear Waste Repository Program”. He also served as co-chairman for the Third International Symposium on Ceramics in Nuclear Waste Management”, American Ceramic Society, Chicago (1986) and as the US Technical Chairman for the International Topical Meeting on LWR Fuel Performance, American and European Nuclear Societies, France (1991). In 2002-2003, he served on the International Review Team for Andra’s *Dossier 2001 Argile*.

Claudio Pescatore

Claudio Pescatore holds a Ph.D. in nuclear engineering from the University of Illinois, Urbana-Champaign, USA. He has over 25 years’ experience in the field of nuclear waste covering storage and disposal of low-level waste, high-level waste, and spent-fuel.

Claudio Pescatore joined the Brookhaven National Laboratory in 1982 and was involved in the study of high-level waste and spent-fuel disposal concepts in basalt, salt, and tuff formations. His work covered reliability and modelling studies of waste package materials during storage and disposal, analyses of gaseous and aqueous pathways for radionuclide migration, and peer reviews of environmental impact assessment studies and site characterisation plans. At Brookhaven, he was group leader for Radioactive Waste Performance Assessment. Until 1995, he was also adjunct Professor of Marine Environmental Sciences at the University of New York, Stony Brook.

Claudio Pescatore joined the OECD/NEA in 1992 in the Division of Radioactive Waste Management and Radiation Protection, where he is the Deputy Head for Radioactive Waste Management. He has been at the centre of several recent international initiatives such as the ASARR and GEOTRAP projects, and the IPAG studies, and co-author of several NEA reports on the

status of and issues in radioactive waste management worldwide. This includes well-known forward-looking studies on reversibility and retrievability, stepwise decision-making, etc. He is a co-author of the NEA Confidence Document. He serves as the technical secretariat of several NEA committees: the Radioactive Waste Management Committee (RWMC), the RWMC Regulators' Forum, the Working Party on Decommissioning and Dismantling, and the Forum on Stakeholder Confidence. On behalf of the NEA, he has organised numerous international peer reviews of national safety studies. These include: SKI's Project-90 (Sweden); AECL's Environmental Impact Statement of the Disposal of Canada's Nuclear Fuel Waste; the 1996 Performance Assessment of the US Waste Isolation Pilot Plant (WIPP); SKI's SITE-94 project (Sweden); the Nirex methodology for scenario and conceptual model development (UK); the JNC's H-12 Project to establish the technical basis of HLW disposal in Japan; the SR 97 study by SKB (the Swedish spent fuel and waste management company); the USDOE Total System Performance Assessment of the Yucca Mountain Project; the SAFIR 2 report produced by the Belgian Agency for Radioactive Waste and Fissile Materials (ONDRAF/NIRAS); the *Dossier 2001 Argile* by Andra (the French Agency for Radioactive Waste Management); and the Safety Report of the *Entsorgungsnachweis* of Nagra (Swiss National Co-operative for Radioactive Waste).

Klaus-Jürgen Röhlig

Klaus-Jürgen Röhlig graduated as a mathematician in 1985 at the Mining Academy (*Bergakademie*) in Freiberg, Saxony. In 1989, he received his Ph.D. degree (Dr. rer. nat.) in the field of mathematical bifurcation theory and its application to fluid flow problems from the Mining Academy.

From 1989 to 1991, Klaus-Jürgen Röhlig was employed by the *Institut für Energetik* (IfE), Leipzig, Saxony. He developed and applied computer codes for the numerical simulation of fluid flow and contaminant transport. During this time, he became increasingly involved in environmental questions and, amongst others, in the field of radioactive waste management.

In 1991, Klaus-Jürgen Röhlig joined the *Gesellschaft für Anlagen- und Reaktorsicherheit* (GRS) mbH in Cologne (Köln), initially working on hydrogeological modelling and on numerical simulation of fluid flow and contaminant migration in the near-field and the far-field of final repositories for radioactive waste. During the following years, the scope of his work broadened towards other fields linked to the post-closure safety case for radioactive waste repositories such as the methodology of safety cases and safety assessments, scenario development, quality assurance for computer codes used in assess-

ments, and probabilistic methods. He is especially interested in the utilisation of geostatistical methods for probabilistic safety assessments. Being the project manager for the technical advice to the German regulator BMU (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety) in the field of post-closure Safety Cases, he is involved in the development of safety criteria and regulatory guidelines for radioactive waste disposal.

Klaus-Jürgen Röhlig worked in NEA's Performance Assessment Advisory Group (PAAG) and is now a member of the Integration Group for the Safety Case of Radioactive Waste Repositories (IGSC). He was and is involved in several activities of these groups such as PSAG, IPAG, and GEOTRAP. He chairs the Steering Group of the OECD/NEA International Project on Approaches and Methods for Integrating Geologic Information in the Safety Case (AMIGO). In 2000, he served as a consultant at NEA Headquarters in Issy-les-Moulineaux.

He participated in the NEA-organised peer review of Andra's *Dossier 2001 Argile* and, in 2004, was a member of the international review team that examined, on behalf of SKI/SSI, the interim report of SKB's SR-Can.

Appendix 2
DOCUMENTS REVIEWED

The main documents reviewed were:

- [1] *Synthesis Report, Evaluation of the Feasibility of a Geological Repository, Meuse/Haute-Marne Site* (175 p.; in English and French).
- [2] *Phenomenological Evolution of the Geological Repository* (TEP; C.RP.ADS.04.0025, 520 p.) (in English and French).
- [3] *Assessment of Geological Repository Safety* (TES; C.RP.ADSQ.05.0018, 705 p.).
- [4] *Architecture and Management of a Geological Disposal System* (TAG; C.RP.ADP.04.0001, 483 p.).
- [5] *Référentiel des matériaux d'un stockage de déchets à haute activité et à vie longue* (C.RP.ASCM.04.0015.A).
- [6] *Référentiel de connaissance et modèle d'inventaire des colis de déchets à haute activité et à vie longue* (C.RP.AHVL.04.0006.A, 364 p.).
- [7] *Référentiel du site de Meuse/Haute-Marne* (C.RP.ADS.04.0022.A), including: Annexe « Analyse comparée des contextes géologiques et pétrographiques avec l'argile à Opalinus (Mont Terri, Suisse) ».
- [8] *Référentiel de comportement des radionucléides et des toxiques chimiques d'un stockage dans le Callovo-Oxfordien jusqu'à l'homme, Site de Meuse/Haute-Marne* (C.RP.ASTR.04.0032.A) with particular emphasis on Chapter 5: « Comportement des radionucléides et des toxiques chimiques dans le Callovo-Oxfordien ».
- [9] *Scientific and Technical Programme HAVL – Argile (HLLL – Clay) 2006-2010* (draft, provisional version A, 96 p.).

Reviewed Level 4 and 5 documents in English included:

- [10] *Gas Production and Transfer in the Repository and in the Callovo-Oxfordian Layer – Relation to the Hydraulic Transient, Meuse/Haute-Marne Site* (C.NT.ASCM.03.0042B, 51 p.).
- [11] *The Corrosion of Metal Disposal Components: (Over)packs of Vitrified Waste Packages and Spent Fuel and Metal Infrastructures, Meuse/Haute-Marne Site* (C.NT.ASCM.03.0046C, 65 p.).
- [12] *Geological and Hydrogeologic Models of the Formations Surrounding the Callovo-Oxfordian Layer in Their Initial State, Meuse/Haute-Marne Site* (C.NT.ASMG.03.0108B, 83 p.).
- [13] *Model of Flow and Solute Transport in the Callovo-Oxfordian (Sound and Disturbed), Meuse/Haute-Marne Site* (C.NT.ASTR.03.0022B, 66 p.).
- [14] *Geological Model of the Callovo-Oxfordian Formation in Initial State, Meuse/Haute-Marne Site* (C.NT.ASMG.03.0101C, 44 p.).
- [15] *The “Phenomenological” Conceptualisation of the Normal Evolution Scenario (NES): Proposals, Meuse/Haute-Marne Site* (C.NT.ASIT.03.0128B, 214 p.).
- [16] *Qualitative Long-term Safety Analysis of a Deep Clay Formation Repository, Meuse/Haute-Marne Site* (C.NT.AMES.04.0049A, 590 p.).
- [17] *Internal Functional Analysis of a Deep Clay Repository in Post-closure Phase, Meuse/Haute-Marne Site* (C.RP.AHVL.01.031D, 68 p.).
- [18] *External Functional Analysis of a Repository in a Deep Clay Formation, Meuse/Haute-Marne Site* (C.RP.AHVL.00.140D, 55 p.).
- [19] *Synthesis of Waste Package Release Models, Meuse/Haute-Marne Site* (C.NT.ASCM.03.0045B, 122 p.).
- [20] *Chemical Evolution of Swelling Clay Based Structures in a Repository: Disposal Cells for C Wastes and Spent Fuels, Drift and Shaft Seals, Meuse/Haute-Marne Site* (C.NT.ASCM.03.043B, 64 p.).
- [21] *The Chemistry of Interstitial Water in the Callovo-Oxfordian Layer in Its Initial State (Meuse/Haute-Marne Site)* (C.NT.ASTR.03.023C, 50 p.).
- [22] *Porewater Chemistry, Porosity and Hydraulic Conductivity of Callovo-Oxfordian Claystone at the EST-322 Deep Drilling Site Sampled by the Method of Advective Displacement – Laboratoire*

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- [23] C. Hillaire-Marcel, J.-L. Michelot, R. Doucelance, B. Ghaleb, and S. Buschaert, “ $^{234}\text{U}/^{238}\text{U}$ Disequilibrium Along Stylolitic Discontinuities in Deep Mesozoic Limestone Formations of the Eastern Paris Basin: Evidence for Discrete Uranium Mobility Over the Last 1-2 Million Years”, in *Hydrogeology and Earth System Science*, Vol. 8, No. 1, 2004, p. 35-46.

Reviewed Level 4 and 5 documents in French included:

- [24] *L'Architecture des calculs de sûreté pour le Dossier Argile 2005, Site de Meuse/Haute-Marne* (C.NT.ACSS.03.113B, 67 p.).
- [25] V. Lavastre, *Événements sédimentaires, diagénétiques et post-diagénétiques dans la formation argileuse du Callovo-Oxfordian (Bassin de Paris, France) : Enregistrement isotopique des minéraux et de l'eau porale*. Thèse de doctorat de l'Université de Paris VII, Rapport FORPRO 2002/13Th, Paris, France, 195 p.

Andra also made other supporting documents available in French as requested by the IRT. The review also drew on information given in answers to questions from the IRT, and the extensive discussions with Andra staff (see Section 1.4).

Appendix 3
LIST OF ACRONYMS

French acronym	French	English	English acronym
AEN	<i>Agence pour l'énergie nucléaire</i>	Nuclear Energy Agency	NEA
AFE	<i>analyse fonctionnelle externe</i>	external functional analysis	EFA
AFI	<i>analyse fonctionnelle interne</i>	internal functional analysis	IFA
Andra	<i>Agence nationale pour la gestion des déchets radioactifs</i>	French National Agency for Radioactive Waste Management	Andra
APSS	<i>analyse phénoménologique des situations de stockage</i>	phenomenological analysis of repository situations	PARS
AQS	<i>analyse qualitative de sûreté</i>	qualitative safety analysis	QSA
ASN	<i>Autorité de sûreté nucléaire</i>	Nuclear Safety Authority	
CEA	<i>Commissariat à l'énergie atomique</i>	French Atomic Energy Commission	CEA
CNE	<i>Commission nationale d'évaluation</i>	National Review Board	
COX	<i>argilites du Callovo-Oxfordien</i>	Callovo-Oxfordian argillites	COX
EDZ	<i>zone perturbée (par l'excavation)</i>	excavation disturbed zone	EDZ
FEP	<i>caractéristiques, événements et processus</i>	features, events, and processes	FEP
GPD	<i>Groupe permanent des déchets auprès de l'Autorité</i>	Standing Group on Waste of the French Nuclear Safety	

	<i>de sûreté nucléaire</i>	Authority	
GRI	Groupe de revue international	International Review Team	IRT
HAVL	<i>[déchets à] haute activité et à vie longue</i>	high-level long-lived [waste]	LL-HLW (or HLLLW)
LRS	<i>laboratoire de recherche souterrain</i>	underground research laboratory	URL
RFS III.2.f	<i>Règle fondamentale de sûreté III.2.f</i>	Basic Safety Rule III.2.f	
SEA	<i>scénario d'évolution altérée</i>	altered evolution scenario	AES
SEN	<i>scénario d'évolution normale</i>	normal evolution scenario	NES
TAG	<i>Tome: Architecture et gestion du stockage</i>	Volume: Repository architecture and management	TAG
TEP	<i>Tome: Phénoménologie et évolution du stockage</i>	Volume: Repository phenomenology and its evolution	TEP
TES	<i>Tome: Évaluation de sûreté du stockage</i>	Volume: Repository safety assessment	TES
THMCR	<i>[phénomènes] thermiques, hydrauliques, mécaniques, chimiques, radiologiques</i>	thermal, hydraulic, mechanical, chemical, radiological [phenomena]	THMCR
R-D	<i>recherche et développement</i>	research and development	R&D
	<i>mandat</i>	Terms of reference	ToR

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