Unclassified **NEA/RWM/IGSC(2008)2**

Organisation de Coopération et de Développement Économiques
Organisation for Economic Co-operation and Development **23-Jul-2008**

English - Or. English

NUCLEAR ENERGY AGENCY
RADIOACTIVE WASTE MANAGEMENT COMMITTEE

Integration Group for the Safety Case (IGSC)

The Evolving Roles of Geoscience in the Safety Case: Responses to the AMIGO Questionnaire

A report of the NEA Working Group on Approaches and Methods for Integrating Geological Information in the Safety Case (AMIGO)

JT03249160

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Foreword

In the late 1990s, geoscience research and development for long-term radioactive waste management was largely focused on establishing a basis to understand and simulate radionuclide transport in the geosphere at time frames relevant to repository safety. International forums organized by the OECD/NEA included GEOTRAP (International Project on the Transport of Radionuclides in Geologic, Heterogeneous Media) whose aim was to exchange information, ideas and opinions on topics related to sub-surface radionuclide transport. GEOTRAP was succeeded in 2001 by AMIGO (Approaches and Methods for Integrating Geologic Information in the Safety Case), which was designed to examine international experience with respect to the broader contributions of geoscience to a repository safety case.

The safety of a deep geologic repository for long-term radioactive waste management typically requires an assessment of performance at times on the order of 1 000 000 years. At such time frames, a safety case needs to assemble and present evidence describing the evolution of the geosphere and multiple barrier systems of the repository that instils confidence in the understanding of processes and mechanisms that govern long-term performance. During the last decade considerable international experience has accumulated in the process of safety case development and the effective and multiple roles of geoscience in contributing to improved confidence and assurance in predictions of repository performance. These contributions include the rationalization of a site-specific descriptive site model(s) to aid safety assessment and engineering design functions; the integration of multi-disciplinary site characterisation data and generic knowledge to describe potential evolutions of the geosphere and the repository system as a whole; and the investigation of geoscience analogues that provide a complementary means to convey expectations for near- and far-field integrity and long-term evolution. In these roles, the contributions of geoscience can complement and influence the communication, understanding and acceptance of a repository concept and/or safety case.

A key goal of the AMIGO project is to foster awareness of geoscience and its continuing role in the development of a repository safety case. As part of this effort, AMIGO undertook to document current international experience with respect to the practical usage, communication and management of geoscientific data and information that underpin an explanation of the geosphere and its evolution germane to assessing repository concept performance and safety. This report summarizes the responses from 17 AMIGO participants, including both implementing organizations and regulatory agencies, to a questionnaire that examined the current status and role of geoscience in contributing to a repository safety case. It presents examples of important contributions, discusses challenges that include effective communication of the science and the collaborative effort of different geoscience disciplines, and explores where geoscience might play a further role in studies of long-term safety.

Acknowledgements

The NEA wishes to express its appreciation to all participants in the AMIGO project, and especially to those people who responded to the questionnaire on behalf of the following organisations:

Belgium:	AVN, ONDRAF/NIRAS, SCK•CEN
Canada:	Ontario Power Generation
Czech Republic:	RAWRA
Finland:	Posiva
France:	Andra, IRSN
Germany:	BfS, BGR, GRS-Braunschweig
Hungary:	PURAM
Japan:	JAEA
Sweden:	SKB, SKI
Switzerland:	HSK, Nagra
United Kingdom:	Environment Agency, Nirex (now NDA)
United States:	US DOE - WIPP

The questionnaire is the driving force behind this report. The thoughtful and balanced contributions in response to the questionnaire were essential in exposing and explaining many important points.

NEA also acknowledges the members of the AMIGO steering group (and to their respective organisations) throughout the tenure of this questionnaire development and reporting, for their efforts in initiating and directing the preparation of this report:

Klaus-Jürgen Röhlig,	Chair (GRS Köln, now Clausthal Technical University)

Johan Andersson	(Streamflow AB)
Rick Beauheim	(SNL)
Gérard Bruno	(past member, on behalf of IRSN; now EC, DG-TREN)
Ann Dierckx	(past member, ONDRAF/NIRAS)
Betsy Forinash	(NEA)
Erik Frank	(HSK)
Andreas Gautschi	(past member, Nagra)
Mark Jensen	(Ontario Power Generation)
Patrick Lebon	(Andra)
Christophe Serres	(IRSN)
Sylvie Voinis	(past member, formerly NEA, now Andra) and

finally, special recognition is due to the lead authors for this report, Bruce Goodwin (GEAC) and Mark Jensen (OPG). Their analysis gave shape to the mass of questionnaire responses, and without their perseverance this report would not exist. The secretariat also appreciates those steering group members and questionnaire respondents whose thoughtful reviews and comments contributed to the final product.

Executive Summary

The OECD/NEA Approaches and Methods for Integrating Geologic Information in the Safety Case (AMIGO) project was initiated in 2003. The purpose of the project was to provide a forum for the exchange of international information and experience on the use of geoscience information in the development of a safety case for a deep geologic repository.

During the last decade considerable experience has been gained internationally with the collection, synthesis and presentation of multi-disciplinary geoscience data to describe existing site-specific conditions and the evolution and integrity of the far-field with important relevance to repository design and safety. This report summarizes the results of a questionnaire circulated to AMIGO participants to capture elements of that practical experience and to collect together current geoscience knowledge and reasoning that supports a safety case. The information is pertinent to long-term radioactive waste management programs which must consider safety over time frames extending up to 10^6 years. Specific goals of the AMIGO questionnaire were to:

i) collect examples of geoscientific lines-of-evidence that directly support or convey confidence in the performance of the repository in varied geologic settings;

ii) consider techniques used for effective communication of geoscientific reasoning and perspectives that support the safety case for a deep geological repository;

iii) identify methods and procedures that provide the geoscientific basis for the safety case, notably the geosynthesis or integration of multi-disciplinary geoscientific information and approaches that can constrain non-uniqueness and uncertainty in the description of the geosphere; and

iv) explore methods related to planning and organizing, to improve the manner in which geoscience information is collected and communicated.

Participants in the questionnaire came from 17 organisations representing both implementing organizations and regulatory agencies from 12 countries, and also representing abroad cross section of national programs with a variety of repository concepts in different host rocks and at different stages of development, from conceptual studies to repository siting and licensing. Their responses have been structured into two primary sections in the report.

The first section summarizes the geoscience reasoning and use of multiple lines of evidence underlying quantitative and qualitative arguments related to the long-term behaviour of the geosphere and how it might influence repository performance. Over 30 examples are documented that cover experience and practice in sedimentary and crystalline settings. While the majority of the examples are drawn from implementing bodies, others represent regulatory remarks or observations on the usage of geoscientific arguments. The topics are site-specific and wide ranging, and include groundwater age and residence times, long-term climate perturbations, sorption and matrix diffusion, diffusion dominant transport regimes, preferential groundwater pathways, depth of recharge penetration, geomechanical stability, self-sealing properties, seismicity, erosion and uplift. Taken together, these examples reveal a commonality in international programs toward the combination of multi-disciplinary evidence to constrain or bound interpretation of geosphere behaviour and to better explain concepts of repository isolation and safety. The examples serve the safety case directly, for example by providing information or data for models used in quantitative evaluation of safety, or indirectly, for example by providing evidence to support model assumptions concerning issues such as site stability.

The second section summarizes responses to a group of questions that examined the emerging role of geosynthesis and challenges associated with communication and management issues. Geosynthesis is the reasoned integration of available geoscience information to construct a comprehensive understanding of the geosphere, often documented in a dedicated volume or part of a safety case. The information can be qualitative and quantitative, and typically derives from many disciplines such as geochemistry, geophysics, hydrogeology, lithology, paleohydrogeology, isotopic analysis, tectonics, structural geology, climate change and glaciation. Paleohydrogeologic arguments are particularly important in discerning the past and concluding or extrapolating about the future stability of the geosphere. This understanding leads to a “conceptual model” of the geosphere, and includes information on uncertainties – using different lines of reasoning to constrain possibilities. The model supplies the specialized information and data sets pertaining to the geosphere that are needed for the safety assessment and for the design of the engineered barriers. An important outcome from geosynthesis is its contributions to support the safety case with evidence on the potential significance of key processes and mechanisms. The examples described in the first section of this report are largely the products of geosynthesis.

An important challenge for geoscientists is how they express their confidence in their geosynthesis and conceptual model. Several questions and responses examined practical international experience in methods for the communication of geoscientific information to a broad range of audiences that include peers and non-technical stakeholder groups. Another challenge is the management of the diverse range of geoscience activities, which must be integrated during geosynthesis. For example, a common potential bottleneck which must be resolved involves communication and sharing of data between physically separated teams.

The responses to the questionnaire generally represent a snapshot in time on how geoscience has been applied to explore and bound an understanding of the geosphere, including past evolution and expected future evolution, to better demonstrate confidence in predictions of geosphere performance and long-term safety. It is evident that geoscience provides essential contributions to understanding and communicating the role of the far-field in a repository concept and to the development of technically defensible estimates of repository environmental performance.

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1. Introduction

1.1 Background and Goals

AMIGO is an acronym for the NEA/OECD project on the topic of "Approaches and Methods for Integrating Geological Information into the Safety Case". It grew out of the GEOTRAP project (NEA 2002) which was mostly focussed on understanding and modelling radionuclide transport in heterogeneous geologic media for use in developing a safety case. In comparison, the scope of the AMIGO project is broader, both in terms of the geoscience disciplines that could be involved and their range of application. For instance, AMIGO topics include development of an understanding of how geologic features can influence the modelling of radionuclide transport, and thus how geoscience provides input to safety assessment calculations and to the safety case in general (NEA, 2004; 2007).

AMIGO was undertaken to advance the understanding of geoscientific methods and approaches applied to support a safety case for the disposal of radioactive waste in a deep geologic repository. The deep geologic repository concept involves passive safety of radioactive waste disposal by means of multiple safety functions. Passive means the disposal system should not require further human intervention once decommissioned. Multiple safety functions are ensured over the time scales required "*by means of multiple barriers whose performance is achieved by diverse physical and chemical processes. The overall performance of the geological disposal system shall not be unduly dependent on a single barrier or function*" (IAEA 2006).

These barriers are often categorized as engineered and geologic. The engineered barrier system includes the waste form and the design and contents of the repository, while the geologic barrier system pertains to the containment and isolation offered by the enclosing geologic setting. The engineered and geologic barrier systems are meant to work together to provide safety: site selection processes help identify a satisfactory geologic setting barrier which often provides conditions that ensure the safety functions of the engineered barriers, and best engineering practises further fortify the overall safety of the disposal system.

In this report, we use the definition of 'safety case' developed by the NEA (see Box 1). A sub-entity called the safety assessment means a systematic, usually quantitative, analysis of "*the hazards associated with the facility and the ability of the site and the design of the facility to provide for the safety functions and to meet technical requirements*" (IAEA, 2006).

Typically the results of a safety assessment are an important element of the safety case, but there are other noteworthy elements. For example, recently finalised safety cases contain sections on engineering feasibility and on management issues and compilations of knowledge about relevant processes and even a volume dedicated to geosynthesis. See, for example, entries in References Associated with Recent Safety Cases, and in particular ANDRA (2005a to d) and Nagra (2002b). Other safety cases, currently in progress, make substantial use of geosynthesis, such as the studies by SKB in Sweden and Posiva in Finland to support their work leading to license applications for deep geological repositories.

These considerations highlight a crucial point: an understanding of the current state and future evolution of the geosphere is a fundamental prerequisite to demonstrate confidence in the expected performance of a deep geologic repository. In fact, the strength of the safety case for such a repository will be closely related to our understanding of the geosphere and acceptance of the repository will depend on our ability to communicate our confidence in that understanding to all stakeholders. Geoscience is uniquely poised in this regard. Through the process called geosynthesis (Box 1), geoscience generates information that can be projected with confidence far into the future, and thereby offers insight into the potential performance of a deep geologic repository over the very long time frames relevant to repository safety. Thus geoscience and geosynthesis can make important contributions to the safety case in general and to the safety assessment in particular.

Definitions

A **safety case** is a collection of arguments at a given stage of repository development, in support of the long-term safety of the repository. A safety case comprises the findings of a safety assessment and a statement of confidence in these findings. It should acknowledge the existence of any unresolved issues and provide guidance for work to resolve these issues in future development stages (NEA 1992).

Geosynthesis is the reasoned integration of all relevant geoscience information to construct a comprehensive understanding of the geosphere (conceptual model of the geosphere). The geoscience information can be qualitative and quantitative, and involve disciplines such as geochemistry, geophysics, hydrogeology, lithology, paleohydrogeology, isotopic analysis, tectonics, structural geology, climate change and glaciation. Geosynthesis in support of a deep geological repository should yield a model from which predicted geosphere behaviour and performance can be extracted with some measure of confidence. In the early stages of a study, when limited information is available, geosynthesis might support several feasible conceptual models. The arrival of further information helps to resolve non-uniqueness and uncertainty.

Box 1

The field of geoscience as related to long-term radioactive waste management has made considerable advances in the last decade. A key aspect of these advances has derived from a better appreciation of the complexity in the subsurface, whether crystalline or sedimentary, and an acknowledgement for the need to constrain interpretations of geosphere behaviour and performance. Complexity in the subsurface, which can vary extensively for different sites, has been influenced by its evolution over geologic time and space. This evolution continues to occur, and the physical and chemical characterization of such environs will always be associated with a degree of uncertainty that influences the understanding and confidence in the predicted behaviour and performance of the geosphere at the spatial and temporal scales necessary to demonstrate safety. In part, this uncertainty arises due to limitations in the ability to make direct and complete measurements of the geosphere that represent more than a narrow time slice within a slowly evolving system. Despite such limitations, a reasoned geoscience basis can be assembled to develop an understanding of current and historical behaviour and potential future evolution. This understanding will never be complete or precise, but can be sufficiently bound to minimize the ambiguities, constrain non-uniqueness and define degrees of certainty.

The considered method to resolve these challenges involves geosynthesis, the assembly and integration of multi-disciplinary geoscience data. Geosynthesis yields several important products (see Box 2). It is used to construct a site-specific conceptual description of the geosphere, also called the geosphere model, that is consistent with and justified by the available information. It does so by combining qualitative and quantitative data and reasoned arguments. The coincidence or constancy in interpretation of independent multidisciplinary data provides a rationale to constrain uncertainty and to place boundaries on the geosphere model.

Main outcomes of geoscience and geosynthesis

- provide the required understanding to develop a coherent, logical and defensible geosphere model that describes how the geosphere acts today and how it will evolve over time scales relevant to repository safety;
- constrain uncertainties in that understanding based on different lines of reasoning that eliminate some possibilities and reinforce others;
- supply the specialized information and data sets pertaining to the geosphere that are needed for the safety assessment and for the design of the engineered barriers; and
- contribute complementary evidence to support the safety case, notably on the potential significance of key processes and mechanisms.

Box 2

Note that geosynthesis does not lead immediately to a unique, definitive geosphere model. Instead, geosynthesis and the geosphere model advance iteratively throughout the various stages of a repository site investigation. At each stage, geosynthesis has access to more data and information that can be used to extend the model, to eliminate ambiguities and uncertainties, and to confirm model veracity. Geoscience and geosynthesis therefore ultimately underpin the geosphere model, and the model provides summary descriptions of geosphere evolution over time scales germane to safety. The model can then be used to supply information and data needed to perform safety assessments and to design the engineered components of the deep geologic repository. For example, the traditional needs for safety assessment include data for rock porosity, permeability and groundwater velocities to help predict radionuclide movement and discharge locations, while facility design engineers need information on rock strength, location of faults and composition of infiltrating groundwaters to map out emplacement areas and devise suitable containment materials. Other geoscience information, such as an understanding of the current and predicted geochemical environment, can be vital to both safety assessment and engineering design.

In addition, geosynthesis and geoscience can support a safety case by contributing alternative or complementary evidence regarding the significance of key processes that might affect site stability, isolation and containment properties, radionuclide release and mobility in the sub-surface, and other issues relevant to safety. For example, the geosynthesis of a particular site might lead to important conclusions pertaining to mechanisms affecting radionuclide transport or the potential extent of erosion, while geoscience studies of a natural analogue might shed light on the likelihood of geochemical transformations or the effect of isotopic exchange.

This report documents some collective experiences of the AMIGO participants. It provides a snapshot of the evolving role of geoscience in the preparation and communication of a safety case for long-lived radioactive waste in a deep geologic repository, with extra emphasis on geoscience-based “complementary evidence” that could appear in a safety case. Its specific goals, summarized in Box 3, are as follows.

Goals of This Report

1. Describe examples of geoscience lines-of-reasoning that support a safety case.
2. Examine current geoscience R&D aimed at integrating multidisciplinary studies
3. Foster awareness and advance further development of geoscience support for the safety case, especially related to communicating confidence in understanding geosphere behaviour and performance.

Box 3

- Describe geoscience support for the safety case. We document numerous examples where geoscience supports a safety case. Many of the examples serve a dual purpose: they support safety assessment in a direct fashion by providing information or data for models, and more indirectly by providing evidence for the applicability of model assumptions such as the dominance of diffusive transport or the long-term stability of a site. Other examples may provide additional and complementary lines of reasoning to underpin a key assumption or prediction, such as supplementary arguments that re-enforce the role of diffusion or site stability. We are particularly interested in examples that appear most relevant to effective communication of confidence in the geosphere model and consequent implications on the performance of the geosphere as it relates to repository safety. We also wish to examine how easily these examples can be explained to audiences ranging from peers to a non-technical community. While these examples are frequently applicable only to a specific site and concept, they do offer illustrations of the potential potency of geoscience support for a safety case.
- Outline current geoscience research relevant to safety case development. We examine influential elements of current geoscience R&D related to integration of multi-disciplinary studies that include hydrogeology, geochemistry, paleohydrogeology, mineralogy, geophysics, geomechanics, geostatistics, remote sensing, natural analogues, numerical analysis, climate change and isotope analysis. While many of the details in these efforts are very much site- and concept-specific, there is generic interest and value in studying how these disciplines act together through the process of geosynthesis to construct a conceptual model of the geosphere that covers past, present and future evolution, and that constrains uncertainty and non-uniqueness affecting reliable predictions of geosphere performance.
- Foster awareness of geoscience support for the safety case. Our ultimate goal is to foster awareness and advance further development of geoscience support for the safety case. To that end, we examine planning and organizing issues related to geoscience activities, especially the integration and presentation of geoscience results and the potential for collaborative efforts that could aid in communicating confidence in predicted geosphere behaviour and barrier performance over long times.

Most of the details in this report are aimed at members of the radioactive waste management community, and especially those who may be charged with preparing or reviewing a safety case and the geoscientists who are conducting the R&D. Hopefully the results herein will reinforce their perception of the importance for further geoscience research, notably collaborative multidisciplinary efforts that are aimed at producing independent reasoning to support the safety case. We trust that they will also be persuaded as to the importance of communication of their results to widespread audiences, and not just to their peer groups.

We are also confident that this summary report will be of interest to other research personnel who wish to learn more on the current breadth of geoscience reasoning in support of the safety case, and to gain a better understanding of the degree of confidence attached to a geoscience-based argument.

1.2 Report Source Material and Outline

The observations described herein derive largely from a questionnaire developed and distributed by the AMIGO Steering Group to participants at the AMIGO workshops and their colleagues within the international radioactive waste management community. Table 1 identifies the 17 organisations that responded to the questionnaire. The questionnaire itself, reproduced in Appendix A, was designed to collect descriptions of:

1. geoscientific reasoning, or examples of geoscientific lines-of-evidence that directly support or convey confidence in the performance of a deep geologic repository;
2. communication techniques used for effective communication of geoscientific reasoning and perspectives that support the safety case for a deep geologic repository;
3. geoscience contributions to the safety case through methods and procedures that provide a scientific basis for the safety case, notably the integration of multi-disciplinary geoscientific information and approaches that can constrain geosphere non-uniqueness and uncertainty; and
4. managing geoscience contributions, or strategies for planning and organizing to improve the manner in which geoscience information is collected and communicated

The questions were intended to be generic and apply to any type of host geosphere and engage both implementing organizations (proponents) and those responsible for technical approval of a safety case (regulators). Moreover, the respondents were reminded that the thrust of the questionnaire was on how geoscience provides overall support to a safety case, and not restricted to geoscience data that might be supplied to safety assessment models.

Responses obtained to the questionnaire represent a broad cross-section of experience from programs at different stages of development: some programs are at or near a siting stage whereas others are involved with research of a more generic nature. Moreover, programs differ with regards to the relevant characteristics of the geosphere and its perceived barrier role relative to the engineered systems, the breadth and scope of data needed to characterize the geosphere, the concept-specific assessment methodology, and regulatory information requirements and expectations. As a consequence, the questionnaire responses are diverse, but at the same time reveal the utility of geoscience information with indication on how that utility has broadened and progressed in recent years.

A preliminary compilation and evaluation of responses resulted in a first draft which was reviewed by members of the AMIGO Steering Group[1]. A revised draft was then sent to all questionnaire respondents for more detailed comment and correction. Thus this report represents an extensive collection of geoscience knowledge, has been thoroughly vetted and has met with general consensus.

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[1] Klaus-Jürgen Röhlig (GRS Köln, now Clausthal Technical University, chair), Johan Andersson (Streamflow AB), Rick Beauheim (SNL), Gérard Bruno (IRSN), Andreas Gautschi (Nagra), Mark Jensen (OPG), Patrick Lebon (Andra), Sylvie Voinis (formerly NEA, now Andra) and Betsy Forinash (NEA)

Table 1: **Participating Organizations and Their Recent Studies**

Organization	**Proponent or Regulator**	**Recent Safety Cases** (Additional documents are noted in the References)
ANDRA (F)	P	Dossier 2005 (Andra 2005)
AVN (B)	R	SAFIR II (ONDRAF/NIRAS 2001)
BGR, GRS and BfS (D)	P	Morsleben, Konrad and Gorleben (BGR-GRS-BfS 1992-2005)
EA (UK)	R	Nirex GPA (Nirex 1997-2003)
HSK (CH)	R	Review of Opalinus Clay, Kristalin-I (HSK 2004-2006)
IRSN (F)	R	IRSN draft review of Dossier 2005 (IRSN 2006)
JAEA (J)	P	Projects H12 and H15 (JNC 2000-2004)
Nagra (CH)	P	Opalinus Clay Project (Nagra 2004)
Nirex2 (UK)	P	Nirex 97, GPA (Nirex 1997-2003)
ONDRAF/NIRAS (B)	P	SAFIR II (ONDRAF/NIRAS 2001)
OPG (CDN)	P	Third Case Study (OPG 1999-2006)
Posiva (FIN)	P	TILA-99 (Posiva 1999-2005)
PURAM (H)	P	Boda Claystone Formation and Bátaapáti site PURAM (2004)
RAWRA (CZ)	P	Reference conceptual design RAWRA (1999-2002)
SKB (S)	P	SR-Can, SR 97 (SKB 1992-2006)
SKI (S)	R	SR-Can, SR 97 (SSI/SKI 1995-2005)
WIPP (USA)	P	WIPP Certification (US DOE 1996-2004)

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2. In 2007, the role previously undertaken by Nirex in the UK become the responsibility of the newly-formed Nuclear Decommissioning Authority Radioactive Waste Management Directorate (NDA RWMD).

The core of this report has two sections concerned with the current status of geoscience and its evolving role in the safety case for a deep geologic repository.

1. Examples of geoscience support for a safety case (Section 2). Many of these examples are taken from recent national safety cases.
2. Technical issues affecting the successful development of geoscience support (Section 3). These issues are mostly related to the unique combination of geoscience expertise that must be focussed, integrated and communicated. We examine challenges that pertain to the underlying science, including management approaches that facilitate resolution of technical issues, and challenges involved with the effective communication of the scientific results.

2. Geoscience Contributions to the Safety Case

2.1 Introduction

The respondents supplied more than 30 illustrative examples of how geoscience has been applied to explore and bound an understanding of geosphere evolution as relevant to a safety case in a deep geologic repository. Most of the examples came from the proponents but a few regulators had their own examples or salient comments on what they believed constitute good examples. Other regulators specifically commended the use of such examples in safety studies, as implied in the following comment from the UK EA:

> *We would expect to see geoscience information used in support of the safety case. It is up to the proponent of a deep repository to identify the appropriate arguments that can be made for a specific site and to use them in support of a safety case. However, we would be very cautious about a safety case that relies on the geosphere barrier… if good independent geoscientific arguments were not available to build confidence in the models that would be used.*

For a deep geologic repository, a host geosphere may contribute to the safety case in a variety of ways. The following two attributes are amongst the most common and both are inherently significant. These safety-related attributes provide a convenient grouping scheme for the examples that follow of potential geoscience contributions to a safety case.

1. **Stability:** provides a physical and chemical environment that is expected to endure, more or less unchanged, for very long time frames, or an environment sufficiently well understood that its evolution over long time frames is reliably predictable. This environment is expected to be reasonably resilient to internal and external perturbations at time frames pertinent to repository safety. Examples in this group would be geoscience evidence that deep groundwater has been unaffected by climate change for long time frames and evidence that the proposed repository is completely surrounded by very old, saline groundwater.

2. **Barrier Function:** contributes to mechanisms and processes that prevent, delay or attenuate radionuclide release and migration. Examples include evidence that fluid flow to and from a repository area is limited or restricted, that radionuclide transport is dominated by diffusion, and that radionuclides tend to sorb strongly onto available mineral surfaces or have solubility constraints.

These two categories are not always independent as stability often implies a delay barrier and vice versa. There are also other attributes of the geosphere that can be beneficial. For example, a strong argument for deep geological disposal involves isolation: the depth itself implies a lower likelihood of future contact by humans (deliberate or accidental) with the hazardous material, and this function can be enhanced by positioning the repository away from, or otherwise isolating it from exploitable resources. Yet another important attribute is related to predictability: a particular host geosphere may be amenable to characterization because its rock types, groundwater flow paths, paleohistory etc. have favourable predictive characteristics, such that uncertainties are more easily constrained and enhanced confidence can be attached to the conceptual model.

Each of the following examples is briefly described with an emphasis on illustrating the multiple and often independent lines of geoscience evidence that have been drawn together to provide understanding with greater defence in depth. More details can be found in the supplied references. Although each example can be specific to a particular site, rock type or disposal concept, they all have merit in illustrating the potential role of geoscience to:

- instil confidence in the understanding of far-field processes and mechanisms influencing a multi-barrier design concept for a deep geologic repository,
- provide site-specific evidence for expected long-term geosphere barrier performance, and
- contribute support to the safety case.

Most respondents indicated that their examples could be easily explained to their peers and the scientific community as a whole, and that communication is much more challenging when dealing with non-technical and public communities. A few exceptions are noted below.

2.2 Providing a Stable Environment

A deep geological repository can provide an enduring stable environment for the repository contents. That is, the geologic setting might support the presence of chemical and physical conditions that are relatively unchanging for very long time frames, because of the properties of the host rock at the repository depth, local and regional rates of groundwater movement, geochemical conditions in and near the repository, mechanical properties of the repository openings within its rock horizon, the unlikelihood or uneventful impact of perturbations such as seismic and volcanic activity, glacial episodes or other geological events and processes, and long-term processes primarily affecting the surface environment such as uplift, erosion and climate change. Stable conditions are important because greater confidence can be attached to a safety case in which the deep environment is relatively unchanging compared to an environment with indeterminate and uncertain future physical and chemical conditions. Furthermore, it is more feasible to make long-standing engineering choices for a well-characterized and stable environment.

The following discussion considers nine headings (see Box 4) that best fit into the ‘stability’ category. For simplicity, we have gathered together related examples under some headings, and included several salient submissions which provide guidance or advice as opposed to examples. The first three headings pertain to the properties of the deep geosphere and consider the significance of the age of brine groundwaters, the implications of widespread homogeneous low permeabilities and the distinctive geology of a salt dome. The fourth example pertains more to the ‘near field’ geosphere immediately surrounding a potential deep geologic repository and specifically to the swelling and plastic properties of clay. Examples 5 through 8 deal with the potential effects of specific external perturbations: climate change, geochemical transformations, groundwater penetration and seismicity. The last example is actually an advisory concerned with bedrock stability, and, with some consideration of the previous examples, points to generic guidance available from geoscience to help with repository siting.

2.2.1 Example 1: Age of deep brine groundwaters

A "desk study" funded by Nirex (see Bath (2004), Jackson (2004) and Bath and Jackson (2004) within the associated references for Nirex (1997-2004)) provided confidence in understanding the long-term stability and isolation capacity of hypersaline groundwater. It examined historical data from investigations of the Sellafield site[3] and considered

- geochemical data and interpretation concerning the distribution, composition, origin and age of the brine;
- geochemical evidence that has a bearing on understanding the hydrodynamic stability of the brine, noting that it has been investigated in a zone where there are quite sharp changes in physical and chemical groundwater conditions over rather short distances;
- the simplified hypothesis that this brine is 'very old and virtually immobile'; and
- physical hydrogeology and numerical modelling, basinal geology, structure and rock properties, and mineralogy integrated with geochemistry to develop an understanding of the behaviour of the groundwater system in the study region in terms of its evolution to present day, and its potential future behaviour.

The conclusions indicate that these brine groundwaters have a large coherent extent. More importantly, the conclusions include a very powerful statement.

> *Integrated interpretation of various strands of geochemical/isotopic data strongly indicates that the water in the brine is at least 1.6 million years old, i.e. prior to the Quaternary period. Palaeohydrogeological considerations suggest that it most probably originated as meteoric infiltration to groundwater during the Tertiary period (between 1.6 and 65 million years ago).*

The study provides confidence in understanding the long-term stability and isolation capacity of hypersaline groundwaters. Although the example pertains to a geological system dominated by fracture flow, the methodology might find application in other host media.

2.2.2 Example 2: Low permeability over a large region

The Dossier 2005 studies of the Callovo-Oxfordian formation (Andra 2005) provide confidence in the understanding of diffusion-dominated transport within a large area of the Callovo-Oxfordian formation. In particular, the studies indicate that there exists a very large area (approximately 250 km^2) of this formation with well established geometrical continuity and weak lateral mineralogical variability, and radionuclide transport within the formation is dominated by diffusion. The evidence includes:

- well-known paleogeographical conditions during deposition,
- detailed lithostratigraphic and sequential analyses of well data,
- observed weak lateral mineralogical variability,

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[3] The Sellafield dataset was gathered as part of the Nirex investigations of the Longlands Farm site that ceased in 1997. The use of Sellafield data in this "desk study" is simply an artefact of it being a convenient dataset that was readily available, and in no way is intended to pre-judge or affect any activities of the on-going UK Managing Radioactive Waste Safety (MRWS) programme.

- absence of observed major tectonic features within the area of interest (different stress states reactivate the same major faults but those faults are located outside the region of interest), and
- major differences in groundwater composition and hydraulic head of surrounding aquifers which support the notion that the Callovo-Oxfordian formation is a (relatively) impermeable barrier.

The studies also provide input to and support the results of safety assessment modelling and offer an independent qualitative argument for safety. Moreover, the example has strong links with other geoscience results, such as the effects of climate change (see Example 5).

2.2.3 *Example 3: Integrity of a salt dome*

Multiple lines of evidence provide confidence in understanding the plastic behaviour and dissolution properties of rock salt and, in particular, indicate that the Gorleben salt dome is effectively protected from penetration by fluids. An important implication is that the Gorleben dome will maintain its integrity over geological time frames (see the Gorleben citations with BfS-BGR-GRS (1992-2005)).

- One main line of evidence shows that the inner rock salt of the dome has not interacted with external water for more than $2x10^8$ years (the time of deposition), and that peripheral salt dissolution is limited to a few tens of metres of soluble potash seams. These results are based on investigations in the Gorleben salt dome and other salt formations such as the study of brine and gas inclusions and bromine concentration profiles.
- The second main line of evidence is based on observations of very low water content and the plastic behaviour of the salt rock. This last characteristic means that any voids and fissures will be reduced and closed, and is based on results of several laboratory and in-situ studies and the investigation of the self-sealing process in the excavation disturbed zone of a 90-year old drift in a salt mine.
- Other observations, such as basaltic intrusion into in a salt formation, show that high temperatures have low impact on the rock salt stability. Furthermore, subrosion rates of the Gorleben salt dome are less than 40 m in 10^6 years. Even under the conditions of a strong subglacial erosion event, only a very minor part of the salt dome was affected and, by far, the major part of the salt dome remained as an integer barrier.

This example also has implications for an assessment of physical and chemical stability from external perturbations.

2.2.4 *Example 4: Self-sealing characteristics of clay*

The recent safety case on the Opalinus Clay (Nagra 2002-2004) includes studies of the excavation damaged zone (EDZ) surrounding the underground openings of a potential repository. These studies support the notion that a potential repository in the Opalinus Clay can be effectively isolated, in the sense that construction of the tunnels does not result in favoured groundwater flow pathways. The EDZ forms during construction and gives rise to an increase of several orders of magnitude in the transmissivity of the clay near a tunnel compared with the undisturbed clay. The result could be a preferential transport pathway for groundwater and radionuclides, which could potentially short-circuit all or parts of the geologic barrier. However, the EDZ is expected to reconsolidate and self-seal after repository closure, based on:

- empirical evidence from various structural, hydrogeological and mineralogical studies in northern Switzerland;
- several laboratory experiments within the Mont Terri Project, including a long-term in situ study;
- crosshole tests which indicate that the interconnectedness of the EDZ fracture network is partially restricted;
- observation of tightness of natural fractures/fracture zones in tunnels where overburden exceeds 200 m; and
- theoretical considerations in the Kozeny-Carman porosity-permeability relationship.

Furthermore, reductions in transmissivity can be expected from the swelling pressure of the bentonite clay used to backfill emplacement tunnels. These studies also enhance confidence in modelling and provide input and support the results of safety assessments. One of the more important results of these studies is they offer an independent qualitative argument for safety.

2.2.5 Example 5: Climate change including glaciation

Many examples touch on glaciation and climate change but just three contributions are included here. The first gives the viewpoint of a regulator and the second involves studies of climate change and accompanying erosion on the European continent. The third example deals with the Canadian Shield and is concerned with how fractures might form and their influence on deep groundwater flow.

Comments from the IRSN point to the necessity (in France) to consider the effects of glaciation on a potential site, and to demonstrate that safety is not compromised. Studies should include the effects of glacial loading and permafrost (depth and extent) on the site itself and effects on groundwater flow. The results are expected to lend confidence to the expectations that erosion will not significantly affect the host rock and that mass transport will be dominated by diffusion.

The Dossier 2005 studies (Andra 2005) have led to the conclusion that climatic evolution over the next million years will not affect the stability of the Callovo-Oxfordian formation. Moreover, they support arguments that the present-day state of the Callovo-Oxfordian is representative of conditions expected for the next 10^6 years and longer, especially with regards to the influence of glaciation and climate change. The implication is that the low permeability of the formation (see Example 2) is long lasting. Their reasoning is based on a number of observations.

- The mechanisms for climate change (mostly glaciation) are well known and the potential effects of anthropogenic disruption of CO_2 appear to be mostly on the magnitude of glacial maxima within about the next $6x10^5$ years. The region has already experienced many glacial cycles and it has been observed that the impact of permafrost is limited to the surface and near surface. Thus permafrost will not affect (directly) the deep Callovo-Oxfordian formation.
- Although permafrost may impose transient effects on groundwater composition in the aquifer formations that bound the Callovo-Oxfordian, the geochemical environment in the Callovo-Oxfordian itself (which has low permeability) will not be affected. This deduction is supported by the lack of traces from previous glaciations.

- The main erosion process over the next 10^6 years will be the incision of valleys and formation of flood plains, which generally evolve quickly within a few millennia during glacial retreat. These processes have occurred many times in the past and are expected to have no effects on the Callovo-Oxfordian formation in the area of interest.

These studies most pertain to arguments for a stable repository environment, unaffected by perturbations of the climate. In addition, they provide a base for the evaluation of the effects of erosion (see Example 8) and support arguments for isolation and delay. Finally, the results contribute to considerations concerning uncertainties in travel time in the overlying aquifer formations.

A group of integrated studies conducted by OPG (OPG 1999-2006) provide confidence in understanding the likelihood of future fracture generation and how their interconnectivity influences deep groundwater movement. Within the Lac du Bonnet batholith, fractures and fracture interconnectivity at depth (>300m) are thought to have been generated early in the batholith's history. It is hypothesized that the extent and geometry of the fractures and fracture zones will remain unchanged over the next million years. These conclusions are based on studies such as:

- geologic history and tectonics, for example knowledge of thermal chronology which puts into geologic context the nature and timing of the events that lead to fracturing and the likelihood of such events affecting future fracture propagation and/or re-juventation potentially influencing repository - far-field performance;
- paleohydrogeologic studies of fracture infill mineralogy (i.e. mode of occurrence, paragenesis);
- fracture hierarchy studies with specific relevance to shallow sub-horizontal unmineralized exfoliation fractures; and
- regional apatite fission track thermochronology studies.

The results provide qualitative evidence concerning the stability of these features and information on groundwater circulation, and notably the potential for penetration by future glacial meltwaters into the deep fracture networks. Moreover, linking fracture network hierarchy and age with knowledge of geologic events and glacial cycles during the Quaternary that affect surface boundary conditions leads to a more complete understanding of the likelihood of how structural discontinuities may affect far-field performance. This understanding could underpin safety assessment assumptions regarding flow system geometry, and contribute support to the notion that the geosphere is very capable of withstanding significant external perturbation.

2.2.6 Example 6: Deep geochemical transformations

Seven submissions are included here. The first describes the value of research directions at the JAEA. Examples from Andra, Nagra and ONDRAF/NIRAS are concerned with sedimentary host rocks, and examples from SKB and OPG deal with crystalline settings.

The JAEA acknowledges that a key component of the safety case will be the ability of the geosphere to provide favourable conditions, which ensure the engineered barriers function as planned (JNC 2000-2004). Favourable conditions are envisioned to include groundwaters that are reducing, neutral to slightly alkaline, and a host rock that is mechanically stable and in which groundwater fluxes are low. Geochemical, hydrological and mechanical data from in situ measurements at depth will play a part in repository design and safety assessment, but support should be provided from other lines of argument, such as arguments based on qualitative study of groundwater evolution and groundwater age. The JAEA also notes that natural analogue studies of bentonite and volcanic glass can provide useful evidence on the longevity of engineered barrier components. Thus their research plans are aimed at improving confidence in the modelling effort as well as providing alternative lines of support, with expectations that the results can be readily communicated to both technical and non-technical audiences.

Studies of the Callovo-Oxfordian formation in France provide support for the stability of the near-field in terms of the expected limited groundwater and radionuclide movement near a potential repository. The studies have included consideration of mineralogical transformations that might be induced by the introduction of alkaline cement-based fluids (Andra 2005). Observations have been assembled from

- experiments performed in surface and underground research laboratories (i.e. Mont Terri);
- studies of natural analogues, particularly at the Maqarin and Khushaym Matruck sites in Jordan; and
- research conducted as part of the European ECOCLAY I and II projects, and as part of the CNRS/Andra research group (FORPRO).

The results indicate that any interactions do not significantly modify migration processes at the formation scale and have limited perturbation on the swelling clays that form part of the engineered barrier system. The predicted effects after 10^6 years are that mineralogical and chemical transformations will have a maximum extent of the order of metres in the excavation damaged zone surrounding a repository opening, and up to 1.8 m in the bentonite seals. Moreover, these potential chemical interactions would only involve a small portion of the total volume of materials that are closely contacted by the cement fluids. This example supports process understanding and justifies the fact that the alkaline disturbance associated with cement fluids is not explicitly represented in the overall safety calculation. In particular, any potential changes would not give cause to adjust the conservative data now used to represent hydraulic, transport and retardation parameters.

Two examples by Nagra (2002-2004) provide support for a favourable and stable geochemical environment in the Opalinus Clay. Their study results include the following lines of evidence.

- Pore waters have hydrochemical and isotopic signatures consistent with very old, practically stagnant formation waters.
- There is no formation pore fluid isotopic evidence for influence by Quaternary glaciation cycles.
- Electrochemically reducing conditions are strongly buffered by pyrite and organic matter.
- Carbon dioxide partial pressures are within the world-wide trend of waters in sedimentary basins.
- Model predictions based on natural tracer profiles and the regional hydrogeological situation suggest only minor salinity reduction over 10^6 years.
- The increased temperature effects (about 95^oC and lasting up to several thousand years) induced by the radioactive waste will not have a significant impact on the minerals and organic matter in the Opalinus Clay, based on evidence from the geological history of the formation.

These related examples provide confidence in modelling efforts and qualitative arguments that support the notion of a repository geologic setting that is resilient to external perturbation and has remained stable for geologic periods of interest to demonstrating repository performance and safety.

An example provided by ONDRAF/NIRAS concludes that the Boom Clay has a stable mineralogical and geochemical composition. The Boom Clay formation is under study as the reference formation for methodological research in Belgium, and is characterized as a tectonically and seismically stable regime in the study area. The present-day mineral assemblage is considered to represent largely the mineral assemblage of the Boom Clay shortly after deposition (30 Ma ago), based on the following evidence.

- A study of the heavy mineral composition, clay mineralogy and chemistry of various mineral phases indicate a clear detrital origin for most minerals.
- There are few diagenetic minerals (all related to early diagenesis) and no evidence of important mineral transformations.
- Organic matter shows a low level of maturity.
- The stable isotopes of some carbonates (both fossil shells and diagenetic carbonate phases) all point to a marine origin, with no indication of mineral transformations or recrystallisation.
- U-Th series disequilibrium studies also point to a geologically stable system.

This example has implications concerning future behaviour of the Boom Clay, and in particular on isolation from humans and protection from external perturbations. Moreover, the example supports results from safety assessment modelling and can be readily explained to a broad range of audiences, including the general public.

A topic of interest to SKB (and Posiva) concerns the paleohydrogeology of the deep saline groundwaters in the Fennoscandian Shield, and a growing volume of studies provide confidence in understanding chemical processes that might have deleterious effects on two important engineered barriers: the canister and bentonite. The main concerns are that highly saline groundwaters (> 100 g/L total dissolved solids) in the repository system might lead to deterioration of the bentonite buffer and, if combined with high groundwater sulphate levels, could promote canister corrosion through the production of sulphides from microbial activity.

- Paleohydrogeochemical evidence shows that Fennoscandia has been subject to repeated fluctuations of groundwater salinity during glacial events, associated with downward propagating freeze-out processes and potential upsurging of deeper saline groundwaters (both during permafrost), and ingress of fresh, brackish or saline waters (during glacial retreat). The majority of paleohydrogeochemical evidence indicates the most important process at potential repository depths is the ingress of brackish marine waters. Greater salinities may have occurred locally during permafrost conditions, but these have been efficiently flushed from the bedrock.
- Since ingress and flushing out of brackish groundwaters, and permafrost effects, appear to be mostly restricted to the higher permeability rock volumes, the low permeable rock volumes which will host the repository largely will have been spared any major changes in groundwater salinity that are not likely to exceed 100 g/L total dissolved solids, the cut-off considered critical for bentonite-based buffer and backfill.

There remains a possibility that highly saline pore water in the rock matrix of the low permeable repository host rock may contact the engineered barriers through diffusion. Nevertheless, the overall paleohydrogeologic implication for the Fennoscandian Shield is that, at the depths of a potential repository, future salinity levels are expected to remain below 100 g/L total dissolved solids. This example and the underlying studies support the notion of a stable chemical environment at depth, provide input and support the results of safety assessments, and also serve as an independent qualitative argument for safety.

Studies on a granite batholith on the Canadian Shield have demonstrated the stability of the hydrogeologic system at depth using several isotopic, chemical and microthermometric techniques applied to secondary mineral phases and mineral alteration products of weathering, such as calcite, hematite, chlorite and clays. The evidence includes:

- saline waters in fracture zones of characteristic shield-type composition (~50 g/L, Ca-Na-Cl);
- oxygen and hydrogen isotopic composition of chlorite and illite in sealed fractures are consistent with ancient formation;
- active, recent isotopic exchange with Pleistocene groundwaters is seen only in illite and kaolinite in permeable fracture zones;
- carbon and oxygen isotopic composition of calcites in sealed and open fractures shows hydrothermal (i.e. ancient) origins supported by microthermometry of fluid inclusions which shows high salinities and, in some cases, three phases, indicating temperatures at time of formation above 100°C; and
- secular radioactive equilibrium in some fracture zone calcites indicates ages greater than 1 Ma.

This example also supports the notion that the deep hydrogeologic system is not connected to the surface environment.

2.2.7 *Example 7. Depth of penetration of groundwaters containing dissolved oxygen*

The issue of deep penetration of groundwaters is important to many programs and has been a factor in Examples 5 and 6 above. The issue is examined here from a different perspective. One submission points out why deep penetration could be significant and three further submissions provide useful evidence.

Comments from the SKI (SSI/SKI 1996-2005) point out the significance of reducing electrochemical conditions at the repository depth. These conditions will:

> *significantly enhance the expected longevity of copper-steel canisters and thus limit release of radionuclides into the near-field. Demonstration that reducing conditions will be maintained over the expected range of evolving surface climate conditions thus substantially enhances confidence in the ability of the engineered barrier system to contain radionuclides.*

Further comments give examples of studies that would enhance confidence in the capacity of the geosphere to maintain poised reducing conditions:

- geochemical measurements taken during site investigations that show an absence of oxidizing conditions in groundwater samples representing waters that originated under the range of past surface-climate conditions and that can be expected to recur in the future;
- the absence of mineral assemblages that would indicate past occurrence of oxidizing conditions at repository depth;
- supporting hydrogeochemical models that reproduce current conditions and that show dissolved oxygen is consumed before reaching the repository horizon, even under expected high-gradient conditions such as passage of a glacial front; and
- transport models and experimental data showing that, even if oxidizing conditions could occur in groundwater at the repository horizon over relatively brief periods during future glacial cycles, the redox front would not reach the canister surface.

These comprehensive studies would support understanding in coupled groundwater flow and geochemistry as part of the overall site understanding and can be useful in safety assessment and in offering an independent qualitative argument for safety.

Some detailed results from related studies are described by SKB (1992-2006) and Posiva (1999-2005), and indicate that the infiltration to repository depths of dilute glacial melt or meteoric recharge is unlikely. An example from Posiva, dealing with reducing geochemical conditions deep in the bedrock, shows the following.

- At Olkiluoto, there is abundant pyrite and methane available to buffer oxygen and reduce sulphate present in infiltrating meteoric and sea waters. These processes take place mainly at rather shallow depths.
- High methane concentrations are observed in gas samples from the deep bedrock, which have been interpreted to occur as a result of persistent reducing conditions.
- In deep bedrock, groundwater samples have low oxygen and sulphide content and there are no signs of oxidation observed in fracture minerals.

Similar findings have been made by SKB at their sites. These conditions are favourable for maintaining the integrity of the iron-copper canister.

An example from Nirex (1997-2004) complements the results described in Example 1 and provides further confidence in understanding the long-term stability and isolation capability of hypersaline groundwater. The example describes previous investigations that were recently extended as part of the PADAMOT (Palaeohydrogeological Data Analysis and Model Testing) project. The studies examined the mineralogical and geochemical evidence for the stability of the deep geosphere, and have confirmed two main points.

- The interface between shallow freshwaters and deeper saline waters has remained relatively constant over at least the Quaternary, based on studies of the crystal form of calcite whose morphological variation correlates with salinity.
- Despite some evidence that glacially derived water may have penetrated along discrete pathways to depth, there is no evidence that paleo-redox conditions have been oxidising at depth during this time. This study is based on trace element and isotopic analysis of concentric growth bands of Quaternary age calcite crystals.

This example (together with information outlined in Example 1) shows the resilience of the geosphere to changes in groundwater salinity. It also describes an approach to understanding redox stability associated with glaciation. Finally, this example can also provide influential qualitative arguments for safety through developing and presenting reasoned arguments on the insensitivity of the groundwater regime to external perturbations.

OPG has carried out studies that support the contention that oxidizing waters from the surface have not reached repository depths in fractured crystalline rocks of the Lac du Bonnet batholith on the Canadian Shield during past glacial cycles. The implication is that electrochemical conditions would remain reducing for millions of years at a deep repository in a similar geological environment.

- Mineral geochemistry studies have employed techniques of increasing spatial resolution to search for mineralogical indicators of active groundwater flow and the past presence of oxygen at various depths in the batholith. These methods range from bulk rock analyses, isotopic techniques and optical petrography down to micro- and nanometre scale mineralogical investigations using analytical transmission electron microscopy. The oxidation reactions of interest occur in response to the diffusion of oxygen into the rock matrix along mineral grain boundaries. The nanometre scale of investigation is well suited for investigating this process, but oxidative mineral weathering products have not been found at depths below 65 m.
- In contrast to the ‘negative’ results at depth, several lines of evidence support geologically recent fracture flow and low-temperature oxidation at shallow depths, such as the presence of secondary mineral products of weathered iron-bearing biotite, oxidized rims on sulphide mineral grains, and precipitated ferric iron minerals, such as goethite, in fractures.
- Reactive transport modelling is being applied to study the key processes and parameters affecting potential oxygenated surface water infiltration into discrete fractures and fracture zones. The modelling integrates advective transport in fractures, diffusive transport in the adjacent rock matrix, and key reactions between the infiltrating water and reduced minerals that are known to occur in the Canadian Shield rocks (e.g. chlorite and biotite). Infiltrating water is assumed to be influenced by glaciation-deglaciation which results in periods of increased recharge rates and elevated dissolved oxygen. With a parameter set considered representative of Canadian Shield conditions, it is shown that oxygen diffusion into the rock matrix and consumption by reduced iron minerals limit the depth of dissolved oxygen migration to less than 100 m during a simulated period of glacial meltwater production of 10 000 years. The results of an uncertainty analysis indicate that the most influential factors controlling dissolved O_2 ingress in a single fracture are the flow velocity in the fracture, the fracture aperture size, and the biotite reaction rate. This project has integrated several types of existing geoscience information, including mineralogy (for initial composition of fractures and matrix), hydrogeology (fracture velocities), solute transport (matrix diffusion coefficients), and long-term climate change modelling (for duration of glacial periods).

This example combines several different studies to gain a better understanding of the far-field attenuation of oxygenated water infiltration via fractures, and provides a clearer indication of which parameters could be better constrained when moving to site-specific characterization.

2.2.8 Example 8: Seismicity, uplift and erosion and related processes

Three examples are included in this category, although other examples have touched on one or more of the defining topics. The first example provides some detail on research underway at the

JAEA, notably on volcanic activity. The next two examples describe recent studies from Switzerland and France.

The JAEA notes that the *"long-term stability of the geological environment is one of the key components of the safety case ... to ensure that neither natural phenomena nor human intrusion will significantly degrade the repository or the surrounding rocks"*. Information is required on geoscience topics that include volcanic activity, faulting and fault movement, uplift and subsidence and the effects of climate change – notably sea-level changes. Studies on the first of these topics have led to the following information.

- Volcanic activity is unevenly distributed in Japan and there are large areas where volcanic activity has not occurred for many millions of years.
- Detailed case studies have been undertaken to clarify the ages of volcanic rocks and to acquire information on the properties of rocks and groundwater surrounding volcanoes and to better understand, for example, the effects of volcanic activity on the geological environment
- Sophisticated seismic and electromagnetic exploration techniques are available which could be used during site investigation to confirm the absence of deep underground magma.

These particular studies are providing information that constrains the occurrence of volcanism in time and space, and bounds its plausible regional influence on geosphere and repository performance.

The recent safety case for the Opalinus Clay (Nagra 2002-2004) documents multiple lines of evidence that provide support for stability of the geosphere for up to 10^6 years. The evidence includes the following.

- The potential siting area (Zürcher Weinland) has low seismicity.
- Expected depths of erosion will not be an important factor, even at maximum rates for 10^6 years.
- Magmatic activity is not expected, based on the absence of heat flow anomalies and significant discharge of deep groundwaters.

This example also implies isolation of a deep repository. It provides a qualitative argument for safety and the concepts are readily explained to all levels of audiences.

The Dossier 2005 results (Andra 2005) include support for the notion that the geosphere will provide a stable environment in the sense that perturbations caused by erosion are not expected to be important. In particular, Andra concludes that erosion processes (geomorphological evolution) are well understood and will not affect the stability of the Callovo-Oxfordian formation over the next 10^6 years.

- Erosion rates and uplift of the region are available from paleogeologic studies, and erosion rates are not notably affected by different hypotheses for evolution of the climate.
- Most erosion takes place as valley incisions when deglaciation occurs, while erosion of limestone plateaus and clay/marly depressions is weak. These generalizations permit prediction of 'maximum possible erosion' over the next 10^6 years and the impacts on various strata.

- The major impact of landscape evolution will be on the overlying formation resulting in significant changes in the hydraulic field, while the underlying strata are only weakly impacted.
- Concerning the Dogger limestones (the underlying formation), due to the distance of the zone from outcrops and the depth of the formation, modelling confirms that the impact of erosion remains weak. It does not change the direction of flow or the hydraulic gradient inside the formation.
- The main effect on the Callovo-Oxfordian is a two-fold (approximately) increase in the vertical hydraulic gradient after 10^6 years. This change is sufficiently minor that it would not alter the current regime, in which diffusion is the dominant mass transfer mechanism.

2.2.9 Example 9: Mechanical stability of the host rock

The single submission placed into this category is in the nature of an advisory from SKI (SSI/SKI 1996-2005) on the effect of evidence for bedrock stability. This evidence could significantly simplify the engineered barrier system with regards to the importance of mechanical failure scenarios. Confidence in understanding the regional tectonic framework and active faulting in the region could derive from:

- a plate-tectonics and faulting framework within which past occurrences of earthquakes and any seismic gaps in the region are well understood;
- the absence of neotectonic features such as recent offsets or indications of sediment liquefaction;
- seismic monitoring data which confirm the understanding of deformation in the region;
- geologic evidence for reactivation along existing faults as opposed to the formation of new faults; and
- confirmation of field methods that preclude locating waste packages close to existing critical faults that might be reactivated under future stress perturbations.

The last factor is described as a *"remaining challenge"* in leading to confidence in the stability of the bedrock near a repository, and it is clear that a mechanically stable geologic setting would provide a qualitative argument for safety. (SKB advises that they have carried out several studies addressing the potential for seismic events and their potential impacts as part of the ongoing work in preparation for a license application.)

This more generic example, and consideration of the previous examples, point out a role for geoscience to guide site selection through the conception of criteria for site exclusion and site inclusion. An exclusion criterion might preclude or tend to preclude a site based on characteristics judged to have the potential for severe, negative impacts on future performance. Examples of possible exclusion criteria could include a history of significant uplift or erosion over a large area, the presence of active fault zones in the repository area, seismic activity exceeding specified levels, a high likelihood of future volcanism and the occurrence of young groundwaters at depth. Conversely, an inclusion criterion would tend to support a site based on traits deemed to be beneficial. For example, beneficial properties could include the presence of a thick zone of impermeable rock surrounding the repository, a suitable host rock that has a very large areal extent and the absence of any known mineral resources in the vicinity.

2.3 Barriers to Prevent, Delay and Attenuate Release and Movement

The concept for deep geological disposal of radioactive waste envisions a set of multiple safety functions that act independently, as much as possible, to provide safety over long time scales. The geosphere can provide effective barriers to delay and attenuate the release and migration of radionuclides that eventually escape from the disposal vault. The barriers can be based on processes that include diffusion-limited transport and very slow groundwater rates of movement (or the absence of flow and transport processes), small porosities or permeabilities, sorption processes, the presence of geochemical fronts or gradients and groundwater geochemistry that promotes sorption and precipitation. The geosphere can also contribute to the effectiveness of the engineered barriers to prevent the release of radionuclides. Examples include prolonged performance of copper containers in low-sulphide groundwaters, longer lasting iron containers in electrochemically reducing groundwaters and the slow alteration of bentonite to illite in low-potassium groundwaters.

More than 10 examples have been placed in this category. They have been assembled under a smaller number of headings (see Box 5) although, as before, many examples overlap into other headings and even into examples described in Section 2.2.

Examples of the Barrier Function

10. *Preferential groundwater flow pathways*
11. *Advective or diffusion-dominated transport*
12. *Sorption and matrix diffusion*

Box 5

2.3.1 Example 10: Preferential groundwater flow pathways

This topic is concerned with the existence or formation of groundwater flow pathways which could potentially circumvent the ability of a geosphere to delay radionuclide transport. Many previous examples have touched on this topic, notably Examples 4 and 5. The examples here include advisory comments from a regulator and experience from three programs at different stages of development.

Comments from the IRSN were concerned with confidence in understanding the groundwater flow system, including its potential evolution with time and consequently its effect on radionuclide movement. It would be important to establish whether diffusion or advection processes would dominate radionuclide transport. Gaining this information would include recognition of existing fractures and faults in argillaceous and granite host media, information on which are conducting structures, and the understanding to estimate radionuclide transport processes (compare with the GEOTRAP experience). Finally, the safety case would require an ability to enhance safety through efficient sealing practices or the existence of sufficiently large homogenous blocks in the case of granite formations. IRSN expressed the opinion that adequate understanding can certainly provide a qualitative argument for safety, but it involves a significant challenge in convincing both technical and non-technical communities.

An important conclusion from Dossier 2005 (Andra 2005) is:

> *Fracturation at different scales does not generate preferential pathways through the Callovo-Oxfordian. Radioactive nuclides transport remains diffusion dominated.*

This significant result is based on a number of integrated studies.

- *In situ* investigations at the Meuse/Haute-Marne Underground Research Laboratory (MHM URL) – cored directional wells and observations during shaft sinking and gallery excavation – have not encountered any tectonic features. This is consistent with results of the 3D seismic geophysical survey of the site of the MHM URL.
- Hydraulic testing of natural faults performed in the Mont-Terri laboratory show that hydraulic conductivities of faults are similar to undisturbed rock. Other testing on major faults in various argillaceous media show a maximum increase of about two orders of magnitude compared with the undisturbed rock, but such faults are not found in the region of interest (see Example 2).
- The presence of septaria structures observed in the MHM URL are clearly related to early diagenesis processes and are indications of no further circulation of aggressive external fluids.
- At a larger scale, all data sets on natural tracers (Cl, δ^{37}Cl, δ^{18}O, δH, He, …) are consistent and indicate that mass exchange between the surrounding limestone formations occurs via diffusion dominant processes across the argillites.

These results, in combination with Examples 2 and 6, and other studies, support the notion that the Callovo-Oxfordian provides a diffusion-dominated host rock over a large region, and supports understanding of mass transport at far-field and near-field scales. The absence of impact of fracturing on the diffusive-dominant regime inside the Callovo-Oxfordian contributes to fulfilling the main long-term safety functions assigned to the geological repository: *"resisting the circulation of water"* and *"delaying and reducing the migration of radioactive nuclides"*.

The Radioactive Waste Repository Authority of the Czech Republic (RAWRA) is currently in the screening stage of siting, and has recently completed comparative studies to improve their confidence in understanding near-field and far-field migration, and to help identify parameters of the near- and far-field that require further R&D. Near-field robustness for a reference design of a deep geologic repository examined the effects on radionuclide migration of the thickness of bentonite blocks and radionuclide solubility, distribution coefficients and diffusion coefficients. Far-field robustness examined the effects of changes in geological and hydrogeological parameters related to pressure, amplitude and direction of the groundwater flow. The donation definition was used to evaluate model transport and spatial distribution for various distribution and diffusion coefficients over 10^6 years. The results will provide input to safety assessment and provide a qualitative argument for safety that is expected to be readily explained to both scientists and the public. RAWRA also notes that more study, and collaborative work, is required. Revisions to the reference conceptual design (RAWRA 1999, rev. 2002), including a safety case on a hypothetical granite host site, were initiated in 2008 and will be completed in 2011.

PURAM (2004) is currently studying disposal concepts for a L/ILW repository in fractured granite near Bátaapáti and a HLW repository in the consolidated Boda Claystone Formation (BAF) situated in SE Transdanubia. Recent studies of the groundwater flow pattern at the Bátaapáti site, using large-scale interference tests and the spatial distribution of water ages, suggest the hydrogeological regime is more complex than envisioned in earlier explorations. The results suggest a very distinct compartmentalisation characteristic which is believed to be the consequence of some gouge zones with extensive and massive alteration and clay mineralisation. These zones have been penetrated by inclined boreholes and access tunnels and are believed to be the major barriers for advective transport of radionuclides. Thus these zones will play an essential role in the long-term safety of the repository, and further study is needed to detail their extent, distribution and transport properties.

2.3.2 *Example 11: Advective or diffusion dominated transport*

The examples included here are advisory comments from a regulator and experience from four relatively mature programs. Several examples are concerned with diffusion-dominated media and all examples support geosphere stability.

The Swiss Federal Nuclear Safety Inspectorate (HSK) discussed two examples that deal with barriers to delay radionuclide transport and the effect on groundwater movement and radionuclide transport. They point out that very low hydraulic conductivity and low diffusivity enhance both the protective capability of the geosphere for the engineered barriers (providing a low water exchange rate and therefore stable chemistry) and the retarding efficiency for the radionuclides that are released from the engineered barriers. HSK notes that support for a diffusion-dominated regime is provided by, for example, observations of the spatial distribution of isotope ratios, and state:

> *The example refers to the measured data in clay host rock, interpreted using a conceptual model for the hydrogeologic history of the site. Independently of any further data on the hydraulic head regime, it leads to the understanding that solute transport must be diffusion dominated and extremely slow.*

In their studies of the Boom Clay, ONDRAF/NIRAS has concluded that diffusion is the dominant transport mechanism within the clay. This conclusion is based on multiple lines of evidence for the very low hydraulic conductivity in the Boom Clay host rock and the diffusion-dominated transport of radionuclides.

- *In situ* and laboratory hydraulic testing at scales from a few centimetres to a few metres show that the hydraulic conductivity in the Boom Clay host rock is very small, (approximately $2x10^{-12}$ m/s).
- Piezometric observations indicate that the hydraulic gradient over the Boom Clay Formation is about 0.02 to 0.04 m/m but the corresponding water flow in the clay is negligible; consequently diffusion is the dominant transport mechanism.
- *In situ* and laboratory migration experiments provide characteristic diffusion profiles.
- Tests of the porosity/conductivity relationship show consistency with clay formations investigated worldwide.
- Natural discontinuities are nearly absent in the Boom Clay and are not found at the Mol site.
- Discontinuities (fractures and fissures) induced during the excavation of the galleries are self-sealing.

(See also Nagra's work discussed in the next paragraph.) The evidence provides confidence in understanding how radionuclides would move in the Boom Clay, and provides quantitative and qualitative arguments for safety. It is expected that this example can be readily explained to the general public.

In their recent safety case for a potential repository in the Opalinus Clay, Nagra developed multiple lines of evidence for the very low hydraulic conductivity and groundwater flow in the rock and concluded that (i) radionuclide transport is diffusion-dominated; and (ii) faults do not act as preferential pathways. Their evidence is based on:

- *In situ* and laboratory hydraulic testing;
- concentration profiles of numerous elements and isotopes in pore water which suggest a diffusion-dominated system;
- tests for consistency with the porosity/hydraulic conductivity relationship for clay formations investigated world-wide;
- the composition of illite/smectite mixed layer minerals in the host rock in comparison with experience from the hydrocarbon industry;
- the existence of hydraulic overpressures, which are interpreted as relics of burial history or as a result of the compressive stress field, but can only be understood if the hydraulic conductivity is even smaller that those derived from hydraulic tests;
- hydraulic testing of natural faults which show hydraulic conductivities similar to undisturbed rock;
- the absence of anomalies in natural tracer profiles crossing faults; and
- the absence of mineral veins and alterations, suggesting that there was no significant water flow through natural discontinuities in the past.

The example provides a qualitative argument for safety that is founded on transparent multiple lines of complementary reasoning supporting phenomenological understanding.

The GRS provided an example that provides confidence in understanding density-driven flow and diffusion, with multiple lines of evidence supporting very low groundwater flow velocities and diffusion-dominated transport processes in the host formation (iron oolite) and the overlying strata at the site of the planned Konrad repository. Evidence for very long travel times and a high isolation potential derive from the following observations.

- The geological setting includes a host rock overlain by about 500 m of very low-permeable claystone and almost no (at most locally) increased permeability of fracture zones and faults.
- Chemical analyses of water samples show a linear vertical increase in total dissolved solids and in relevant ion ratios with indications that the composition in the mine results from a two-component mixture of residual brine from deep lying bedded evaporites and a more dilute Na-Cl brine, and a linear depth-dependent trend in salinity with horizontal stratification independent of the vertical sequence of aquifers and aquitards;
- Isotopic content of the formation waters show a stable isotope composition of formation waters such as that of basinal brines to the right of the meteoric water line, a high content of noble gases and ^{14}C concentrations below detection limit; and
- Model calculations with variable density show an almost linear increase in salinity and density with depth, very low flow velocities with almost horizontal flow in aquifers and vertical flow in aquitards, a high probability of large convection cells, and indications that diffusion is the dominate process.

Taken together, these observations provide strong evidence of very long groundwater transit times and indications of a stable (and isolated) system.

Posiva completed the TILA-99 safety assessment and supporting geoscience studies over the past decade and more recent geoscience studies are related to the potential repository site at Olkiluoto (Posiva 1999-2005). Past and current studies of the Olkiluoto site continue to provide confidence in understanding advective transport processes and limits in mass transfer. In the KBS3 concept, the major role of the geosphere is to limit and retard inflow to the repository and subsequent release of radionuclides. It follows that a low rate of deep groundwater flow is significant, and recent supportive evidence includes the following.

- Extensive hydraulic testing at the Olkiluoto site shows that the hydraulic conductivity and number of conductive fractures of the sparsely fractured rock decreases with depth. There exist very few highly transmissive local features outside a few hydrogeological zones. This general view of the hydrogeological characteristics of the site has withstood the arrival of new data.
- The high salinity of the deep groundwater can be interpreted as an isolated system in which the deep groundwaters do not mix with near surface groundwaters.

The results also offer a qualitative argument for safety which can be explained to the scientists and public. In addition, the first point hints at the value of an iterative approach which uses "new" data to test and calibrate as part of model development. Finally, Posiva notes that *"more work on discrete fracture network [DFN] modelling and model development as well as site characterisation is required to fully describe water flow in fracture scale at the site".* Similar studies, including the development of DFN models, have been conducted by SKB (see, for example, SKB 2005a, 2006),

2.3.3 Example 12: Sorption and matrix diffusion

One of the more traditional roles of the geosphere has been retardation of radionuclide transport through the effect of sorption. The process is usually characterized using an element-specific distribution coefficient which appears in the mass transport equations. The first two of the following submissions are from a program mostly involved with conceptual studies and from a program that has advanced to evaluation of potential sites. Despite this disparity, the two programs offer similar views. The next two submissions are concerned with retention for two specific elements: strontium and uranium. A final example examines a related geosphere retardation mechanism: diffusion of radionuclides into the rock matrix.

A submission from the JAEA notes that retardation in the geosphere is an important component of their safety case. Most deep groundwaters are expected to have very slow velocities, and thus radionuclides that may be released from the repository would have very low transport rates. These rates are further attenuated through interactions between the radionuclides and minerals present along the transport pathways in the rock. Information required to quantify the performance of the geosphere includes groundwater flow rates, micro-pore structure, matrix diffusion properties (depth of diffusion, flow-wetted surface and mineralogy) and the water-conducting features or flow pathways. The concentration of natural colloids and colloid filtration by the geosphere are also important to the performance of the geosphere. The JAEA looks to in situ experiments and natural analogue studies to provide such information, and suggests that such approaches provide opportunities to aid in explaining concepts to scientists and the public.

An example from SKB (1992-2006) is aimed at increasing confidence in their understanding of radionuclide retardation through analyses of fracture wall rock mineralisation to identify immobilization processes at fracture surfaces. They note that present-day hydraulically active fractures often represent ancient fluid pathways through the rock mass and normally have a complex geological history of mineralisation. The main control on radionuclide retardation along these pathways will be the post-secondary fracture minerals that coat fracture surfaces, together with coatings encountered by matrix diffusion into the rock matrix. Studies of elemental association with different mineral phases, using sequential extraction of separated mineral fractions which are then compared to background values derived from the surrounding host rock, have shown that calcite, iron oxyhydroxides and clay phases are common in the Fennoscandian Shield and significantly retard the transport of radionuclides and other trace elements. These minerals are consequently considered important for safety studies.

- Calcite is a sink for rare earth elements via sorption and co-precipitation processes. Its behaviour in active hydraulic systems (rapid precipitation/dissolution) may lead to significant redistribution of these bound elements in the near- and far-field. Biogenic-mediated processes may also be an important factor in the formation of calcite, especially at the geosphere/biosphere interface where mobilised radionuclides may be entrapped by the precipitating calcite.
- Iron oxyhydroxides selectively retard various radionuclides, rare earth elements and other trace elements through sorption and co-precipitation. The effectiveness of the amorphous Fe-oxyhydroxides might be expected to decrease as they age and begin to crystallise to higher forms such as goethite and hematite, accompanied by the release of previously bound nuclides. However, some studies show that the affinity to scavenge and retain uranium appears to increase with aging and increasing crystallinity. Biogenic activity is considered to be a major process at shallow depths (i.e. at the geosphere/biosphere interface), and in the repository confines during the construction and post-closure phases, leading to the precipitation of Fe-oxyhydroxides. In addition, the iron oxides produced from corrosion of the steel canister can give rise to a growing retardation capacity in the near-field.
- Clays can play a critical role in radionuclide transport because of their high sorptive capacity and large surface area. Clays are also relatively stable since clay alteration is a relatively slow geochemical process. Thus clays found in the far-field and bentonite clay emplaced in the repository will have long-lasting effects on radionuclide retardation.

SKB indicates that a well founded and balanced knowledge basis is crucial to understanding phenomenological processes and building confidence in issues that influence long-term repository performance.

ONDRAF/NIRAS has considered two potential mechanisms, ion exchange and solubility, to explain the observed behaviour of strontium concentrations in the Boom Clay. From a broad range of field and laboratory data collected under different geochemical conditions, their model was used to predict the observed variation in strontium content stemming from pore waters squeezed from Boom Clay samples that suffered from oxidation. They concluded that measured strontium concentrations are solubility controlled instead of ion exchange (sorption) controlled. The model uses $SrCO_3$ as the solubility limiting phase, and strontium concentrations are regulated by the dissolution of $SrCO_3$ and the concurrent dissolution of $CaCO_3$ as the clay samples are oxidized. Their more general conclusion is: if a radionuclide has a stable isotope in the host formation whose concentration is solubility limited, retardation of this radioisotope will likely be controlled by isotopic exchange but not by sorption.

Another example from ONDRAF/NIRAS examined the behaviour of natural uranium in the Boom Clay for use as a natural analogue for uranium in the radioactive waste. The average concentration of (natural) uranium in the Boom Clay is 4.6 μg/g. Generally, the concentration profiles for a whole spectrum of naturally occurring trace elements and isotopes are quite flat in the Boom Clay underneath Mol. However, uranium shows a characteristic concentration peak of significant amplitude at the base of the Putte Member and is associated with organic matter, carbonates, pyrite, and U-bearing heavy minerals (zircon, apatite). The uranium enrichment is interpreted to be primary in origin (enrichment during deposition) and not the result of later enrichment, based on the favorable geochemical conditions during deposition and results from uranium-series disequilibrium studies. The study results conclude that uranium has been immobile over geological time scales because:

- the uranium peak is still present after 30 Ma; and
- transport calculations have indicated that diffusion tends to flatten any concentration profile over geological time scales. The fact that the uranium peak is still present suggests a very high retention and very low effective diffusion rate of uranium in the Boom Clay.

This 'natural evidence' provides qualitative evidence of the long-term effectiveness of the Boom Clay as a barrier with a very high retention of uranium. The evidence also provides additional support for the conclusion that diffusion is the dominant transport mechanism within the Boom Clay (see Example 11). This example offers a qualitative argument for safety that can be readily explained to the public.

Finally, comments from the SKI (SSI/SKI 1996-2005) point out the significance of confidence in understanding matrix diffusion. This process has the potential for significant radionuclide retention in the far field, acting to delay and decrease radionuclide releases into the biosphere. In addition, the peak doses are smaller because the arrival of radionuclides is dispersed in time. SKI further points out confidence in understanding matrix diffusion could be enhanced through the following research activities.

- Mineralogical and isotopic studies of alteration zones adjoining fractures or other geologic evidence to show that matrix diffusion has occurred over relevant time scales in the bedrock adjacent to fractures that act as flow paths.
- Natural and/or bomb-pulse tracer profiles showing that matrix diffusion has limited penetration of isotopes into the rock adjoining major flowing features.
- Long-term laboratory and in situ diffusion measurements on similar rocks, showing the potential for matrix diffusion to occur under representative conditions.
- Supporting hydrogeochemical models incorporating matrix diffusion which can reproduce current distributions of groundwater isotopic composition and conservative ions, and which have been verified against in situ tracer migration experiments.
- Demonstration of field methods for detecting potential fast paths in the vicinity of deposition holes.

3. Enhancing the Role of Geoscience: Successes and Challenges

The breadth of the above examples illustrates the potential for geoscience to make valuable contributions to the safety case for a deep geological repository. Each example provides more detailed understanding to support some key element necessary for repository safety. In addition, geoscience provides an essential contribution to the safety case through the highly specialized data and models essential for quantifying estimates of performance and for facility design and construction. All of these contributions have been and are becoming more influential because of geosynthesis, which uses reasoned arguments to integrate a growing collection of observations and evidence arriving from many geoscience disciplines.

This section examines further the role of geosynthesis in a safety case, to better reveal what endeavours are most successful and what challenges must be faced, in terms of the science itself and in terms of related communication and management issues. The discussion is based on responses to questions in the AMIGO questionnaire that had a similar focus. The questions and responses are not itemized directly here, but instead we have assimilated and summarized the salient findings.

3.1 Geosynthesis and Related Scientific Issues

An improved appreciation and understanding of the complexity in the subsurface has led to the requirement to constrain interpretations of geosphere performance and bound uncertainty through reasoned integration of multi-disciplinary data sets. Complexity is largely a site-specific issue representing cumulative effects that have occurred over geologic time and that have been influenced by the surroundings. The pragmatic process of geosynthesis combines qualitative and quantitative reasoning to demonstrate and instil confidence in an understanding of site-specific characteristics and performance at time scales relevant to repository safety.

Information of value may arise from surface characterisation studies and an underground rock laboratory at a specific site, and from more generic sources such as geoscience observations from other regions possessing similar topography and rock types. The data may be quantitative but require scaling or interpretation, such as in situ and natural tracer testing, or the data may be qualitative in nature such as observations from some natural analogues. The many sources of information must be assembled to build a consistent description or model of the geosphere that presents the paleohistory or past evolution of the site with emphasis on perturbations that may have occurred in the ‘recent’ past; the relevant properties of the site (geophysical, geochemical and hydraulic), before any construction or related activities occur; consideration of nearby valuable mineral and other resources that are currently being exploited or that might be exploited and that could impinge on isolation or stability; the likelihood and magnitude of future perturbations and disruptions that could be caused by repository construction and operation (and which could be used to guide these activities to minimize deleterious impacts); and knowledge on the future natural evolution of the site, accounting for natural perturbations such as climate evolution and erosion and uplift.

This information will inevitably be associated with some degree of uncertainty because of the spatial extent of the deep geologic repository system and the long time frames of relevance. Uncertainty influences the understanding and confidence in the past and future evolution of the geosphere and thence the predicted performance of the repository. Additional information is needed to constrain or limit uncertainty wherever possible, and to ensure that the model (or models) of the geosphere are coherent and consistent with all available independent multi-disciplinary information. One of the more convincing models would be one which includes coincidence or constancy in interpretation of all information:

> *“to show consistency between interpretations of independent sources of information.... Confidence in the overall understanding of a system is enhanced when multiple lines of evidence converge on a single conceptual model” (NEA 2002).*

The questionnaire had several questions directed at current trends and development related to geosynthesis, with an aim to improve the use of geoscience information in the safety case and the ability to communicate concepts of repository performance to broad stakeholder audiences. Several important observations follow.

3.1.1 *Information Supporting a Stable Environment*

A clear majority of the responses indicated that information on the past stability of the geosphere is extremely important because *"knowledge of the past is ... the key to the future"* (ONDRAS/NIRAF response). Statements concerning paleogeology, paleohydrogeology and paleogeochemistry can be powerful, and statements concerning future stability can be reinforced by examining the likelihood and effects of possible disturbances, including earthquakes, uplift and subsidence, erosion and burial, volcanism, major fault movements and climate change with both anthropogenic and natural causes. Important implications can also be drawn from factors such as the time of formation and extent of diagenetic evolution of a host sedimentary rock or similar information on minerals formed in fracture zones of crystalline rocks.

A few responses commented on the potential value of natural analogues, such as evidence that the geological environment can provide an environment that is stable and that endures for very long periods of time. Another less frequent response noted the importance of favourable information on the long-term isolation potential of the host media, such as evidence for limited ingress and movement of groundwater, long groundwater residence times, the presence of a benign geochemical environment that is well poised and buffered, and the ability of a system to 'self-seal'.

Several respondents provided examples of information that is known to be unfavourable or that has the potential to be unfavourable, based on current observations or deriving from unresolved uncertainties. All such examples were concerned with site-specific issues and (as it turns out) none were fatal to a safety case. Most importantly however, is that geoscience effort had occurred to identify, research and resolve these potential problems. More generally, the role of geoscience in supporting a safety case must include the consideration and examination of information that may weaken the case so that an informed, balanced and objective decision can be made.

3.1.2 *Managing Geoscience Uncertainty*

The management of uncertainties, including uncertainty assessment, is crucial for qualitative and quantitative estimates of impact that span millions of years, as well as the broader process of reducing, avoiding, or mitigating uncertainties by, for example, selecting more robust designs and focussing future R&D efforts. Several respondents implied that the manner in which uncertainties are managed is more important than the uncertainties themselves. It is certainly clear that the proper identification and treatment of uncertainties is essential to build confidence in the safety case.

To this end, there is a need for thorough documentation of the source and treatment of uncertainties. For example, documentation of parameter uncertainty is invariably a painstaking process, starting from the acquisition and interpretation of raw data and proceeding through rescaling, extrapolation or other transformations to yield a discrete value, probability density function or qualitative approximation which can then be used in a safety assessment or to support a qualitative argument in the safety case. The documentation must also be traceable, meaning that it is easy to follow the steps between the raw data and the final application. Andra notes for Dossier 2005 that *"each technical document has its own chapter on uncertainties, indicating how they are managed. This provides the basis of the analysis for the higher level* *documents."* Similarly, recent geosynthesis documents prepared by both SKB and Posiva include chapters devoted to assessing confidence and uncertainty which provide integrated feedback to the continued site investigations (e.g. SKB 2005a, 2006 and Posiva 2005a).

From the perspective of safety assessment, there is uncertainty regarding scenarios, alternative models and parameter values. That is, there may be a need to define different scenarios to evaluate multiple distinct possible futures, each scenario may be described by more than one viable conceptual model, and each conceptual model might take in a large number of parameters which are characterized by a range of feasible but uncertain values.

Scenarios

This endeavor often starts from the international FEP database (NEA 1992, 2001, 2003) and is a first step (but frequently informal) in geosynthesis at a particular site. It typically leads, with crucial input from the geoscientists, to the identification of potentially important scenarios. For example, the study of glaciation, glacial rebound, ocean transgression and related outcomes warrants a dedicated study in many national programs. Nagra describes the identification and subsequent study of plausible and unlikely 'what-if' scenarios to illustrate robustness, and the role of conservative 'reserve FEPs' (see Schneider et al. in NEA 2004).

Conceptual models

Credible predictions of future flow and transport need the understanding and associated data to foretell how the disposal system will evolve, taking into consideration transient and slow acting processes. That understanding and data must derive from a precise description of the system as it currently exists, based on a sound understanding of its geohistory. For instance, several investigations are now underway to uncover how glaciation and climate change have acted in the past to produce the current state, so that predictions can be made on the response to future glacial cycles (see, for example, Peltier in NEA 2007). It is also important to have knowledge of the uncertainties in these predictions, with the expectation that these uncertainties tend to increase at longer prediction times.

The construction of conceptual models requires expert judgment and may involve a large group of specialists in the wide range of geological processes that are involved. Uncertainty in process such as evolution of the groundwater flow system may require collaborative studies of alternative models and assumptions. ONDRAF/NIRAS describes an approach using two different but complementary conceptual models, sometimes using very conservative parameter values, to asses the potential impact of uncertainty associated with the interaction of specific radionuclides with organic material in the Boom Clay.

Several conceptual models may be required for a safety study of a particular geologic setting, depending on the specific objectives of the safety case and the nature of residual uncertainty. A reasonable expectation is that a conceptual model will evolve from its predecessor as the geoscience research program advances, and that eventually only one conceptual model will remain after various other conceptual models become subsumed or are discarded.

A general summary of the responses is that a safety case should not be based on a single conceptual model unless that model has been thoroughly tested and reviewed within the program and by independent scientists and the regulators. Additional specific comments are as follows.

- Regulators for WIPP formally require a peer review of each of their 24 conceptual models *"to gain consensus within and outside the project"* . The US DOE is also required *"to address all peer panel concerns such that the conceptual models passed peer review or were deemed to be inconsequential to repository performance."*
- For development of the Safety and Feasibility Case 1, ONDRAF/NIRAS envision a first relatively long period (2004-2011) of strong interaction between groups responsible for design, R&D and safety assessments, which leads to a definition and a common understanding of the scenarios linked to conceptual models. The ensuing second relatively short period (2011-2013) for conducting and documenting the formal safety assessments builds on the scenarios and the conceptual models from the first period. Interactions with the safety authorities is seen to be ongoing, but ONDRAF/NIRAS maintains responsibility for how and to what extent they take into account any comments made by the authorities.
- Andra has developed a reference model which represents the expected evolution of the system through a consensus involving an integration team made up of multidisciplinary experts and specialists. They also have altered evolution models, such as one that represent seal failure.
- The BfS-BGR-GRS experience is quite varied. The safety case for the ERAM (Endlager für radioaktive Abfälle Morsleben) site has four groups of scenarios, with the most important (brine intrusion) modelled using two different concepts. The two concepts lead to comparable results, currently undergoing regulator review. For Konrad, the focus was on understanding the groundwater flow field, using 2- and 3-dimensional models to identify three representative flow paths for radionuclide transport, the use of a porous medium model and an alternative 'fracture model'. There were also intensive interactions between the proponent and the licensing authority and its experts; for example the experts were called upon to confirm the modelling results. At the Gorleben site, there is no radionuclide transport in the 'normal' evolution scenario and so no transport modelling is needed. Nevertheless, modelling of thermo-mechanical processes is needed for the 'normal' evolution scenario to evince the continued integrity of the salt barrier. Transport modelling has instead examined the brine intrusion scenario, involving a hydraulic connection from the overburden to the repository and considered to be 'worst case' in terms of its consequences. A subrosion scenario, which presumes dissolution of the salt dome down to the repository horizon over a time frame of about 10^6 years, was considered earlier, but can be excluded on the basis of exploration results at the Gorleben site.
- Nagra has developed several different conceptual models to deal with possible evolutions of the system. These models were developed iteratively and involved the safety assessment team and the geoscience team. There was no pressure to achieve consensus, but instead *"management forced all scientists involved* to *give the full spectrum of possibilities, not just one single answer. This should ensure that the uncertainties are fully covered in the assessment."*
- In contrast, conceptual models for the Nirex 97 studies involved "a team of experts working together to reach a consensus position that accurately reflected the known facts and that was in accord with expert opinion."

Parameters and data

Data may come from laboratory experiments, field tests, site investigation, literature research and natural analogues. It often requires interpretation and manipulation (e.g. upscaling, interpolation, extrapolation) prior to application in a numerical model. Data collection must also include uncertainties and, where possible, the source or cause of the uncertainty (e.g. measurement errors, extrapolation errors, spatial variability). Uncertainty in parameter values requires additional expert input, frequently involving personnel with experience in both numerical analysis and geoscience. This effort might include the definition of particular limiting values, such as best and worst case, best estimate, mean value and conservative or pessimistic value, and the definition of statistical distributions (probability density functions) that describe the likelihood associated with each feasible parameter value. In addition, parameter uncertainty frequently involves expert intervention, for example in upscaling laboratory data and in statistical tests to ensure the data are representative. Several national programs have developed strict procedures to ensure these activities are correctly and consistently applied. For example, the SKB describes protocols that formally question whether (i) all data are considered, understood and have known accuracy and bias, (ii) the source and cause of uncertainties in the models is known, along with the potential for alternative interpretations and whether further characterization would reduce uncertainty, (iii) the data shows consistency between disciplines, (iv) there is consistency with understanding of past evolution, and (v) there is an evolution of the data compared with previous model versions. The answers undergo review at a workshop involving experts from all disciplines. SKB also uses a standardized procedure to assess uncertainty in all data, including a summary of decisions such as conditions of use and correlations with other parameters.

3.1.3 The Value of Paleohydrogeologic Support

The AMIGO questionnaire included an unambiguous question on paleohydrogeology: Do paleohydrogeologic arguments provide convincing support for expectations concerning long-term flow system evolution? Responses to this question were uniformly positive. For example, comments from members of regulatory groups indicate that paleohydrogeologic arguments *"can provide an important contribution to a safety case"* (UK EA), make for *"understanding and in some cases even validating ground water flow models"* (HSK) and are *"viewed as an important part of demonstrating site understanding which will be useful for confidence-building"* (SKI).

Comments from the proponents were even more motivated: *"palaeohydrogeological arguments and data are also the only available information with respect to long-term system behavior ... [including] the past long-term stability of the system"* (BfS-BGR-GRS); *"one of key elements is evaluation of long-term topographical change, which ... influences hydraulic gradients and might also affect water pathways"* (JAEA); and *"differentiated groundwater chemistry and old groundwater ages defined by environmental isotopes are a convincing proof for slow groundwater movement and long-time stability of the hydrogeological system"* (PURAM).

Several examples in Section 2 make extensive use of paleohydrogeologic arguments, including Example 10 (Andra), Example 11 (Nagra and ONDRAF/NIRAS) and Examples 1 and 7 (Nirex). A few additional examples, some of work in progress, were cited in responses to this question.

- Geochemical evaluations of the Oxfordian limestones in the overburden demonstrate that the last cementation (which blocks porosity in the granular facies) was linked to an inflow of meteoric water, which may have been facilitated locally by fault movement, particularly during the Oligocene which was a period of distension as suggested by the isotopic signature of some fracture filling. Nevertheless, this fault contribution is limited in time and space, and in particular, can only be envisaged during periods of tectonic extension, which means prior to the Miocene (-23 Ma) and are not expected in the future (Andra).

- The salt content, density distribution and isotopes in the groundwater offer a potential approach to the validation of groundwater models, for example at the Gorleben site. In this approach, the actual salinity distribution, including isotope data, will be used as a target for time-dependent modeling of the transient flow system, and thus describe the evolution of the flow system. It is expected that this work will increase confidence in modelling capabilities over very long time scales (in the past) with implications on extrapolations into the future (Bfs-BGR-GRS).
- Site investigations on the Fennoscandian Shield indicate that the hydrogeochemical evolution of groundwater is strongly dependent on flow, transport and water rock interactions driven by the past and present climate; for example, it is thought that the Forsmark and Olkiluoto sites have been greatly influenced by the most recent glaciation. This process is continuous and leads to a complex groundwater composition caused by the mixing of brine, glacial, marine and meteoric waters and interactions with minerals contacted over long time periods. The mixing at depth in the bedrock depends also on the hydraulic character of the fracture zones. Interpretation of the observed data can contribute to the development of an interdisciplinary model of a site, lead to an improved understanding of the hydrogeological performance of the site and to increased confidence in predictions of future performance (POSIVA and SKB).
- Studies of fracture infilling minerals and groundwater isotopes can provide insight into the paleohydrogeology of a site. For example, calcite and iron oxyhydroxides are sensitive to past changes in groundwater conditions, and can provide information on fluctuations in the interface between saline and fresh waters and variations in redox states. Models that have successfully explained the past evolution of a system to its current state can be used with more confidence to predict future conditions (SKB).

3.1.4 The Effect of Regulatory Guidance and Regulations

While there appears to be a commonality in the underlying objectives of the various national regulations, there are many differences in the manner in which they are applied and enforced. Some examples follow.

- Belgium does not yet have a regulatory framework, although there is draft guidance on requirements for selection of the host formation and site, and for site characterisation.
- Finland has regulatory guidance and regulations. The Radiation and Nuclear Safety Authority in Finland (STUK) and its international advisory group recurrently review updated versions of the main reports of the Posiva safety case. The comments from STUK are addressed in subsequent versions, and have affected the R&D plans. Current issues are discussed at semi-annual meetings between Posiva and STUK.
- France has rules regarding technical requirements for site selection, site exploration and investigations to be carried out at the underground laboratories, and essential criteria pertaining to a potential site, such as stability of the geosphere over a reasonable period of time and a hydrogeology characterized by a very low permeability and a low hydraulic gradient. Andra undergoes audits several times per year on their program results and plans. They must also seek regulatory approval of specific project checkpoints, such as those described in Dossier 2001 and Dossier 2005, before proceeding to the next phase.
- Germany has limited regulatory guidance pertaining to a dose limit for safety and recommendations for construction of a repository. This situation led to comprehensive discussions between the implementer (BfS), the licensing authority, and their experts during

the licensing process for the Konrad site, and subsequently to modifications of the safety assessment requirements (such as a longer cut-off time for modelling).

- Hungary has a Ministerial 'Decree on General Research Aspects for Geological Site Suitability of Nuclear Facilities and Radioactive Waste Disposal Facilities' that prescribes the methodology and geological requirements of site selection and characterization, the essential elements of quality assurance and control, the general geological and mining requirements, and details of the licensing procedure.
- Japan has no safety regulations in place, although the Nuclear Safety Commission of Japan (NSC) has published requirements related to favourable conditions for geologic disposal (NSC 2002).
- Sweden has two main reviewers of the SKB reports: the Swedish Radiation Protection Institute (SSI) and the Swedish Nuclear Power Inspectorate (SKI). The SSI and SKI, with their international expert review teams called OVERSITE and INSITE, are currently reviewing ongoing site investigations, and reviews of the safety case are expected in the future. Comments from the regulatory bodies are discussed at biannual meetings. One outcome of these meetings is a formal 'Tracking Issues List' which identifies and follows progress on issues.
- Switzerland has regulatory guidance such as documents prepared by HSK describing requirements for site characterization and for safety. Nagra has actively responded to these guidance documents.
- The UK has no prescriptive regulations concerning the development and preparation of a safety case, although the UK EA expects to influence the program development through review of the proponents work. There is regulatory guidance, such as the document 'Guidance on Requirements for Authorisation' which includes a set of four principles and eleven requirements covering all aspects of the design, construction, operation and closure of a deep waste repository in the context of long-term safety. The Nirex 97 study focussed on a dose constraint pertaining to the first few hundred years and a risk limit for longer time frames, and interactions with the regulators is ongoing. More recently, the Environment Agency of England & Wales and the Environment and Heritage Service (now the Northern Ireland Environment Agency) have issued, for public consultation, a draft document on "Deep Geological Disposal Facilities on Land for Radioactive Wastes: Guidance on Requirements for Authorisation". Along with the Scottish Environmental Protection Agency, these organisations have also issued, again for public consultation, a related draft document on "Near-surface Disposal Facilities on Land for Solid Radioactive Wastes: Guidance on Requirements for Authorisation".
- The USA has both generic requirements (US EPA 1993) and WIPP-specific criteria (US EPA 1996a) for radioactive waste disposal. This last document has detailed requirements related to the description of the natural and engineered features that could affect performance, which must include information on location and physical setting, geology, geophysics, hydrogeology, hydrology and geochemistry, the presence and characteristics of potential waste transport pathways, and the projected geophysical, hydrogeologic and geochemical conditions caused by the presence of the waste. There is also a 'guidance' document (US EPA 1996b) which has served as a checklist to ensure that essential information required by the regulations are contained within the WIPP Compliance Certification Application (US DOE 1996) and the Compliance Recertification Application (US DOE 2004).

3.2 Geoscience Communication Issues

A safety case for long-term management of radioactive waste in a deep geologic repository requires a unique application of geoscientific skills and knowledge combined with communication proficiency. For example, the safety case must deal with the uncertainties inherent in the long-term performance of the deep geologic repository, which must involve the successful integration of multi-disciplinary data sets and the construction of a comprehensive conceptual model(s) of the geosphere. Communication plays a pivotal role in describing to others how the uncertainties have been resolved and why this leads to confidence in the legitimacy of the safety case.

Communication goes beyond the preparation of reports and the presentation of site-specific data. A credible safety case must be transparent and easy to follow, and so must the foundation provided by the underlying geoscience. Practical approaches that enable broader audience awareness and understanding have become essential. The audience includes all stakeholders, including not just peers and colleagues but also academia, decision-makers and the public.

An important aspect of communication is decisions related to the collection of data that may be best used to enhance understanding in the temporal and spatial evolution of the geosphere. Perhaps more importantly, the data must also make clear what confidence levels can be associated with that understanding and why predictions of long-term performance and safety are credible. Such decisions make use of knowledge obtained through past experience with site characterization methods, geosynthesis and preparation of the safety case. Further focus for site characterization may be derived from knowledge of those processes and mechanisms that most influence reasons for confidence in long-term geosphere performance, such as the isolation, stability and barrier properties of a deep geologic repository.

Finally, experience with geoscience can be tempered with experience in communicating to highlight what science is needed and how it is best imparted. For example, the application of scientific visualisation technology is a relatively new approach that promotes sharing geometrically complex geoscientific data and realisations in time and space. It is of value to experts in the various geoscience disciplines to ensure that their independently developed data sets are complete and free of unexplained inconsistencies, especially when integrated with other data sets. That is, scientific visualisation can serve as a convincing data quality assurance tool to geoscience experts. For the non-technical stakeholders, scientific visualisation holds promise as a compelling communication aid.

The questionnaire requested knowledge and experience on communication issues between groups responsible for site characterisation, repository design and safety assessment, between geoscience experts associated with the proponents and the regulators, and between the waste management team and other project stakeholders including members of the public. A summary of many important responses follows.

3.2.1 The Role of Peer Review

Peer review is a regulatory requirement for conceptual models used at the WIPP. No similar regulatory requirement was noted for other national programs, but a fair summary is that regulatory bodies "*strongly encourage a proponent to seek appropriate expert peer review nationally and internationally"* (UK EA response) and the proponents find "*application of peer review is a live and accepted practice of ... waste management*" (PURAM response). Many research organisations routinely organize formal and informal internal peer reviews or make use of external agencies to conduct peer reviews of selected topics. The NEA has been very productive in recent years in managing international peer reviews of safety cases and related matters at the request of member countries. Most national programs also encourage publication of scientific work in international journals and presentations at international symposia.

Peer review is not regarded as a substitute for thorough examination by regulatory or safety authorities, nor for internal and external audits. Nonetheless, all responses concurred that peer reviews are helpful and useful. They have and are being used to provide decisive comments on all elements of waste management programs, such as the adequacy and interpretation of data and information used in the decision-making at the end of each major phase, including planning and conducting site investigation, planning of the repository layout, construction, operation, closure, and decommissioning, and for major activities and products such as geosynthesis, safety assessment, identification of scenarios, development of conceptual models and the preparation and organization of documentation. Peer reviews also play an important role in building confidence when it can be shown that there exists expert scrutiny of key issues.

All types of peer review are potentially useful in the sense that different reviewers, such as academics and national and international colleagues, have different objectives and offer different perspectives. For example, international colleagues might be in a position to offer pragmatic experience from their own programs whereas an academic might be more inclined to analyse the fundamental science. The technical judgement of academics is seen to be especially credible, in Japan and other countries, for basic issues such as the long-term stability of the geologic environment and for more specific scientific issues such as evolution of the climate.

3.2.2 Using and Presenting Geoscience Information

A collection of questions was concerned with how geoscience information has been used in feasibility studies, application for a construction license and other phases, and what geoscience information is of most concern to the stakeholders including the public community. The questions also solicited experience on methods seen to be most effective in presenting key information. Not surprisingly, the resulting responses were very broad, partly reflecting the different levels of development of the various national programs. Most responses identified similar phases of geoscience work, such as conceptual (or desk) studies, site screening (or exploration), preliminary (or feasibility) studies, detailed site investigation (which may lead to an underground research laboratory), and construction studies. Most responses also alluded to the perceived importance of the geosphere to safety, which then highlights the need for detailed and focused geoscience information. Obviously, the actual information needed is strongly dependent on the type of host rock and its surroundings and the safety concept under consideration. For example, important information relating to a repository in rock salt includes the internal geological structure of the salt dome and the creeping behaviour of salt, whereas a repository in crystalline rock is more concerned with fracture networks, hydrology and retardation effects.

The different phases of a project impose different uses and presentation of geoscience information. For example, the main source and use of geoscience information during conceptual studies might be evidence from literature surveys and case studies to establish that suitable geological environments likely exist. Information from site selection might be used to demonstrate that, for preliminary investigation areas, there are no unacceptable features, events or processes that would preclude siting of a successful repository or, from a positive viewpoint, that observed features, events and processes are deemed to be favourable. Subsequent phases require more of an integrated multidisciplinary approach and eventually lead to a conceptual model that amalgamates all available information. These subsequent phases will have regional information, but there is increasingly more detail at a local scale such as from an underground research laboratory.

Communication of geoscience information involves many potential audiences such as personnel responsible for safety assessment and for repository design, regulators and specialists in other fields of geoscience and engineering. The public constitutes another important stakeholder in many countries and special attention is required to ensure that qualitative and quantitative geoscientific concepts surrounding or supporting notions of repository performance are couched in terms that are broadly understandable or intuitive. The following selected comments point to the geoscience issues of most interest to regulators and other stakeholders including the public community.

- In Belgium, ONDRAF/NIRAS notes that *"geoscience communication issues are part of [their] global communication strategy … . They are not dealt with in a distinct way but are just one of the items that are tackled in the various initiatives in order to inform the public about the radwaste management in general."* (See examples that follow.)
- In Finland, Posiva remarks that the issues of most concern to the regulators include the presence of saline groundwater and groundwater flow and the way it is modelled, together with existing and future geochemical conditions. This contrasts with the public community which is mainly concerned with canister integrity over long periods of time.
- In France, IRSN advises that the regulators are largely concerned with the "essential" and "important" criteria contained in their Basic Safety Rule (BSR) documents. The former include stability of the geological formations over reasonable periods of time (at least 10^4 years), the hydrogeology of the site which should be characterized by a very low permeability and a low hydraulic gradient, and the identification and characterisation of fractures and faults in the site. Important criteria include favourable mechanical and thermal properties and favourable geochemical conditions. Based on their experiences, Andra indicates that local communities are mainly interested in the seismicity of the area, the continuity and homogeneity of the geological barrier, and the travel time of radionuclides from repository to surface.
- In Germany, BfS-BGR-GRS report that the regulators and technically oriented stakeholders appreciate a full range of information, from the precise site description to the release scenarios and consequence assessments. In contrast, the public is more interested in the resulting consequences. For a repository in a salt dome, *"the proof of its isolation potential ... is ... of relevance to the public. For the Konrad repository, information relating to the verification of very low groundwater flow and transport rates ... is of great interest."*
- In Japan, the situation appears to be clear: *"of all geoscience information, that relevant to long-term stability of the geological environment is of most concern to the regulators and stakeholders (including the general public) because it is well known that Japan is located in a tectonically active zone. ... siting factors at early stages focus on information that can be used to avoid unsuitable areas in terms of long-term stability of the geological environments."*
- In Sweden, six feasibility studies were carried out in local municipalities judged to be potentially suitable for a repository and where the municipality accepted the SKB presence. Of these, SKB selected two municipalities for surface-based investigations (including drilling deep boreholes), starting in 2002. Since then, *"extended consultations"* have been held with stakeholders in the concerned Municipalities of Oskarshamn and Östhammar and

the regulators, SKI and SSI. Issues raised during these meetings are important for *"the ongoing preparatory work for the license applications since the meetings reveal issues of potential concern to the ultimate decision makers."* For the most part, these concerns involve few geoscientific issues. Geoscientific discussions with the regulator are mostly covered in other fora (see section 3.1.4 above).

- In Switzerland, geoscience discussions between implementer and regulator started early, during the site screening and selection phase. Nagra suggests that reports related to safety assessment are not widely read outside the international safety assessment community and within the country are typically read only by the regulator and its consultants. The regulator is interested in topics such as repository gas release, the role of the EDZ with respect to radionuclide transport and the role of glacial erosion. Activities such as seismic surveys and drilling attract the attention of public and media and historical experience shows that the general public more readily understands geology than safety analysis models. Nagra further states that the public is interested in their ability to predict geological long-term evolution, seismic effects and partly glacial erosion. HSK notes similar interest for the public but adds that the public understands and views as important the tightness (low hydraulic conductivity) of the host rock.
- In the USA, the WIPP's many stakeholders include the EPA, state organizations, various public interest groups, citizens, independent technical organizations, and tribal representatives, with wide-ranging concerns such as hydrologic transport pathways and the influences of karstic features, sink holes, retardation mechanisms on radionuclide transport, postulated human intrusion scenarios, the performance of the engineered barrier, and the possible existence of a pressurized brine pocket below the disposal facility.

Considerations making for effective communication include the following.

- Andra describes the production of a series of reports during their progression from early to more advanced phases, with a growing volume of information: for example the *"core documents"* represent about 100 pages in the *"Mémoire géologique"* in 1996, followed by 700 to 800 pages in Dossier 2001 and more than 3000 pages in Dossier 2005. The latter document is structured into several volumes. The upper level documents describe the initial state and expected evolution of the repository, the repository design, the safety study, and a summary document that includes material aimed at the general public. Lower level documents (about 10 000 pages long) contain more of the detailed geotechnical information. Andra's main challenge has been to ensure consistency within and between the various levels of documentation.
- The JAEA states an effective method to present key information is to explain how such information is related to, and used for, repository safety assessment. They indicate that animation has been seen to be an efficient tool to visualise possible future evolution. Finally, effective oral presentation/explanation by qualified experts seems the most efficient communication tool with the general public.
- ONDRAF/NIRAS gave several examples of their geoscience communication initiatives. ISOTOPOLIS is the ONDRAF/NIRAS information center for young people and anyone else with an interest in radioactive waste issues, including the fate of such waste in Belgium. The exhibition in the EURIDICE demonstration hall at the nuclear site of Mol-Dessel provides information concerning the technical feasibility of disposing of radioactive waste in deep clay layers. There are also 'local partnerships' with the municipalities of Mol, Dessel and Fleurus/Farciennes, and geoscientific publications, meant for a scientific

educated public. Of special interest was the video entitled "Traces of the Future" which was developed in collaboration with other national programs and released about ten years ago.

- Posiva indicates that effective arguments for the public are based on the facts that the Finnish bedrock is old, the bedrock conditions are stable, and the geological history is well known, and thus future can be predicted.
- Puram suggests geoinformation management has benefited as tasks are mandated to the Hungarian Geological Survey, which is a well-regarded, independent and neutral agency.

3.2.3 Integrating Geoscience with the Safety Case

All deep geologic repository concepts regard the geosphere as an important or even the most important factor contributing to safety and thus information on the geosphere can be crucial in the safety case. It is not surprising to find that the nature of the crucial information is dependent on the host rock, but there are notable commonalities.

- Evidence of Long-term Stability. Most responses mention directly or allude to the need for evidence on long-term stability, taking into consideration potential external perturbations and effects associated with the excavated repository. For repositories in salt, the most crucial information is related to isolation. Information on stability and isolation generally requires a good understanding of the past geological evolution of the site, preferably combining observations from many geoscience disciplines.
- Mass Transport Properties. One important factor identified by many respondents is related to groundwater transport properties, including the flow geometry and geologic structures, hydraulic gradient, hydraulic conductivity, retardation and matrix diffusion. For some host rocks, the presence of saline groundwater and sulphides can be very important.
- Predictability. A factor less often mentioned in the responses has to do with predictability. AVN notes that the extent of homogeneity is important as it affects characterization and can enhance confidence in predictive results. Nirex states that information crucial to the safety case includes arguments for the predictability of groundwater flow and composition.
- Mechanical Stability. Several other factors were only mentioned infrequently, such as the mechanical stability of the excavation, absence of nearby resources, geochemistry of the host rock, geochemical and other processes that could affect the evolution of engineered barriers.

Finally, IRSN notes that there is an iterative process: geoscience is "injected" into the safety case, safety is evaluated, and feedback to and from design and engineering results in the need to collect better or more data whose status might now be deemed crucial.

In most deep geologic repository programs, geoscience experts take an active role in the planning and preparation of the safety case. Early specialist input involves considerations as to their ability to characterize the rock to a degree that is sufficient to support decision making. Later input includes development of the underlying conceptual model(s) of the geosphere for the safety case, selection of suitable data and help with uncertainty and sensitivity analyses. As part of the iterative and feedback process noted above, geoscientists propose further R&D studies, typically aimed at reducing uncertainties and re-affirming a conceptual model. Finally, many programs employ geoscientists to contribute to a robust repository design, including many of the associated engineered barriers. Several respondents remarked that they made use of a designated project team to coordinate geoscience and other input into the safety case.

Each national program appears to have several ways in which proponents and regulators share concerns and plans. In Belgium, information on the development of the Safety and Feasibility Case 1 is passed to the safety authorities by ONDRAF/NIRAS who are fully responsible for taking into account any subsequent comments from these authorities. In France, the IRSN, ASN and Andra have defined a stepwise assessment process regarding the feasibility of a deep geological repository in the clay formation investigated through the Bure underground research laboratory. The process is aimed at tackling the main key safety questions related to the collection of basic data, the preliminary design, the research programme, the understanding and modelling of hydraulic patterns and geomechanical and geochemical interactions. A preliminary safety report titled "Dossier 2001" was also produced to adjust the safety methods developed by Andra as well as the clarity of the safety case to help guide the final "Dossier 2005 argile". From 2000 to 2005, a total of nine reviews had been performed by IRSN and debated with Andra and ASN. In Germany there were many meetings involving BfS (implementer), BGR (responsible for creating the geoscience information base) and GRS (responsible for safety assessments). In Finland, Sweden and Switzerland, regular meetings are held between the proponents (Posiva, SKB and Nagra) and the regulatory authorities (STUK, SKI and SSI, HSK). Finally, the long-running US WIPP has involved experts from the National Academy of Sciences, the Department of Energy and its precursors, the Nuclear Regulatory Commission, the Army Corps of Engineers, the National Geodetic Society, the National Laboratories, the Environmental Protection Agency, the US Geological Survey, and many other U.S. and international scientific organizations. The WIPP response could not identify any single method that promotes interaction between the various experts, except for the necessity to communicate ideas and develop consensus within the regulatory requirements.

3.2.4 *The Influence of Site Characterization Studies*

Most responses to questions on the role of site characterization studies expressed a common theme: site characterisation feeds development of the conceptual model, repository siting and design, and the safety case including safety assessment. Moreover, this work is highly interactive and iterative: for example, the results of design and safety assessment serve, in part, to redefine specifications for site characterisation. An important objective of iterations (between and within project phases) is to reduce uncertainty and thereby develop a better fit of the repository design with the host rock and improve confidence in the demonstration of safety. These cycles must eventually end, at least within each step of repository development. For their next development step, involving site selection and preparation of a license application to start construction of the repository for spent nuclear fuel, SKB remarks that, *"site investigations should continue until the reliability of the site description has reached such a level that the* body *of data for safety assessment and repository engineering is sufficient, or until the body of data shows that the site does not satisfy the requirements."*

There are numerous technical outcomes from site characterisation that are especially important, although most are specific to a particular site. An outcome important for most deep geologic repository concepts would be the repository layout with respect to distance from active faults. A more specific example might be one cited by Nagra for the Opalinus Clay, where "*tunnel orientation is adapted to stress field ... bentonite emplacement density is adjusted so that swelling pressure at full saturation and after tunnel convergence balances the external stress field".*

Only a few responses discussed how site characterisation could influence a strategy for communicating safety and for conducting the safety assessment. The essential element appears to be information from site characterisation that supports safety functions. Factors dealing with the notion of geosphere stability are seen to be most important by some respondents, followed by information supporting the influence of different barriers. However, it is not just the data that are important, but also an adequate understanding of the relevant processes that have and will affect the general geologic evolution of the site. Other information important to safety assessment includes the potential for nearby ore resources with respect to assertions regarding isolation.

3.3 Geoscience Management Issues

It is clear that geoscience contributions to the safety case involve many specialist disciplines. This is particularly true for a site characterisation program which may include paleohydrogeologic studies of fracture infill mineralogy and paragenesis to assess redox front movement; apatite Fission Track Thermochronology and other methods to estimate formation depth of burial and uplift; derivation of parameters in the laboratory and field to predict radionuclide transport in the scales needed by safety assessment; hydraulic well testing in deep boreholes to derive permeability field distributions for fracture and matrix continua; characterisation of matrix pore fluid elemental and isotopic compositions to assess groundwater origin and residence time; assembly of geologic models of sedimentary basin formation and tectonic evolution to determine effects on clay properties and geologic structure; measurement of deep stress-strain relationships needed for repository construction and to establish criteria for designing mechanically stable engineered barriers; predictive estimates of how climate change during the Quaternary has affected surface thermal, mechanical and hydraulic boundary condition; and development of numerical flow systems simulations to understand groundwater flow dynamics at regional and local scales in media such as heterogeneous rock with variable salinity. Many of these examples also possess an inherent and valuable predictive element; for example, conclusions regarding past movement of redox fronts can be very constructive if they offer insight into future behaviour.

Pragmatic experience has shown that management of these diverse activities must be carefully orchestrated. An illustrative example follows from reflections on the development of a FEPs catalogue for argillaceous media, in which 59 geosphere FEPs important to safety were identified, along with their current status of knowledge, research and linkages to safety assessment and the safety case (NEA, 2003). The authors concluded that there were three main technical challenges:

1. bridging the wide scientific spectrum between the disciplines typically involved in geoscience studies;
2. integration of information from varied sources; and
3. establishing a strong link between data acquisition, process understanding and the application in safety assessment.

One commonality of each of these challenges is the need for decisive leadership and management.

The AMIGO questionnaire sought experience with methods to improve planning and organizing of geoscience information for a safety case. The questions were concerned with current methods of managing geoscience information and potential improvements in its collection and distribution. In particular, the intent of the questions was to examine ways to integrate results more effectively and to provide those results to other stakeholders in a timely fashion.

3.3.1 Multi-disciplinary Geoscience Databases

Questions on the management of large multi-disciplinary geoscience databases, including accessibility and bottlenecks, were posed for a number of reasons, but notably because the volume of geoscience information increases at very rapid rates as a program matures. At the same time, there is a need to ensure that all geoscientists, and experts in safety assessment and repository design, have access to the identical information. This would ensure, amongst other accomplishments, that research studies of gas transport and radionuclide retardation in some region of rock would both be using the same set of properties for that rock, with no ambiguities or disharmonious assumptions. Moreover, this condition would apply during the entire program, including the first and last safety assessment which could be conducted more than a century apart.

Almost all national programs have installed a central, dedicated database to hold their data, or they have plans to do so. The database is commonly available via the internet or intranet and ideally provides a single and thus consistent source of data for all specialists. Generally the database consists of the raw data from site characterisation activities, coupled with reports describing the methodology, uncertainties and so forth. Most organizations also have or intend to include results from the integration steps whereby geosynthesis combines different types of data to construct the conceptual model and to provide information and data for safety assessment and repository design. In addition, a traceable history and summary of actions, decisions, monumental meetings, results and other important knowledge is frequently stored in this central or a closely related database. The few exceptions where no central database exists are for special cases, such as a case where data can only be extracted manually from archives and those archives are not centrally located or publicly accessible, or a case where several independent databases have been in place for lengthy periods.

The most critical difficulty noted is ensuring that the various data sets are consistent and meet the needs and expectations of different users. This requires not just the essential data, but also precise definitions of terms, statements on uncertainty (quantified if possible), adherence to quality assurance procedures for validation and verification and a summary indication that the data have been reviewed and approved for use, perhaps with qualifications. It also applies to all data, except that there is an extra need to document in detail the means by which integrated or processed data have been created. Other difficulties are associated with the collection of some data, such as archived data that are privately owned or are withheld because of official concerns; the rapidly increasing volume of data which strains quality assurance, and notably could limit adequate peer review checks because of the unavailability of qualified reviewers; issues related to continuity, such as the loss of key staff which could result in data that are lost or not readily interpreted; and the question of unassigned responsibility, where some key process (verification for example) or some important class of data has not been assigned to be the mandate of some specific person or group.

A useful database system also requires some important technical elements, such as a robust design, suitable storage formats, ready retrievability and versatile access methods, safeguarded update rights, version control (reproducibility) and audit trail (traceability and update responsibilities), backup capability, and a secure and controlled environment for storage and maintenance that is capable of guaranteed preservation for perhaps hundreds of years.

3.3.2 Setting Research Priorities

Many national programs have periodic reviews of progress and can adjust priorities frequently. The makeup of the review team is crucial, and Nagra notes that most of their examples of multiple lines of evidence *"were driven by the continuous collaboration and discussions between geoscience and safety assessment groups."* Another imperative source of review comments, with a strong influence on priority setting, is often provided by the regulators and their consultants. In Sweden, SKB (with general input from SKI) distinguishes between generic research issues and more specific issues. The former are typically identified in a three-yearly Research, Development and Demonstration programme while the latter typically arise from on-going assessments and site investigations.

The reasons for setting or re-setting priorities appear to be made on a case-by-case basis and using expert judgement that would take into consideration the perceived importance and likelihood of success. 'Importance' depends on factors such as which safety function is at question, and is often relative to the particular objectives of the current phase of a project which may be directed at a constrained decision. The 'likelihood of success' may also be relative: for example, more resources may be assigned to a proposal expected to produce results affecting the next decision.

The following two examples are from Andra and GRS. The study of fractures in the Callovo-Oxfordian formation (see Examples 2 and 10) has clearly influenced the Andra program. It has been a priority since 1994 and progressed from regional surface-based studies to more detailed local seismic studies, construction of the underground research laboratory starting in 1999, and continuing currently with in situ shafts and galleries within the formation. The study of erosion (see Example 8) also went through a series of prioritized phases. In Germany, the priorities differed for the different sites. For example, at the Konrad mine, the main concern was information on the groundwater velocities, and studies began early during site investigation and have continued through the licensing procedure. For Gorleben, a main objective was to understand the evolution of the salt dome and to demonstrate its isolation capability. Many time-consuming studies resulted, including several that were driven by safety assessment to learn more about the creep behaviour of rock salt.

3.3.3 Effective Presentation Methods

The importance of communication is indisputable. It must be focussed as implied by the IRSN: *"presenting geoscience is not a goal in itself but presenting geoscience and the way it acts towards safety is essential"* and by the JAEA: *"extensive knowledge underpinning the safety case would be no use if it could not be easily accessed and understood by stakeholders."*

It is also unquestionable that effective communication requires different approaches for different audiences. The technical community, including regulatory authorities, must have access to a full set of technical information that may extend downwards to the raw data and a systematic examination of minutia. Their needs can often be met with scientific documents and discussions. In contrast, most non-technical laypeople and the general public have neither the expertise nor inclination to deal with such detail and must receive their information through other means. The responses to this question identified a large number of examples of different methods and tools used to present geoscience information. These examples are shown in Table 2, which also identifies whether the example appears to be most suitable for technical or more general (non-technical) audiences, or both.

Table 2. **Examples of communication approaches and tools**

Communication example	**Audience type** **Technical**	 **General**
Publications – journal articles, safety case documents etc.	yes	no
Publications – pamphlets, brochures etc. with simple explanations and attractive pictures, graphics	no	yes
Workshops, conferences, symposia	yes	no
Community meetings	no	yes
Oral presentations developed for conferences, work shops	yes	no
Oral presentations customized for clarity	no	yes
3-D visual or 'virtual reality' presentations	yes	yes
Internet – access to information	yes	yes
Tours of facilities (URLs, rock outcrops, wells, …)	yes	yes
Exhibitions of rock samples, models, simulations, analogues, mock-ups (or real versions) of the canister and fuel elements, transport casks and trucks/ships, …	no	yes
Travelling exhibitions ("road show") and visitor's centres	no	yes
Public outreach program, public 'hot line', formal public hearings	no	yes
Geoscience events targeting groups such as pupils, students and teachers; for example game shows	no	yes
Graphical/artistic presentations	no	yes
DVDs, movies, 'cartoon' animations of key processes	no	yes
Geoscientific articles in daily/weekly newspapers	no	yes
Notion of the 'pillars of safety'	yes	yes
Examples in Section 2	yes	yes for many
Natural analogues	yes	yes
Comparisons with dose, risk limits etc.	yes	no
Comparisons with naturally-occurring radiation levels and other natural performance indicators	no	yes
Cultural programs organized by the national RWM company to deepen relations with local communities	no	yes

The internet was frequently cited as an effective tool to reach out to different audiences, using dedicated web pages for different potential sites and with customized levels of detail. To enhance dialogue with the public, the web site should include frequently asked questions (FAQs) and a "contact us" option.

Clearly the requirements of technical communications command the expertise of the geoscientist, perhaps with extra training in speaking, graphics preparation and other interaction skills. For more general communication, the two main options might be to make use of public relations experts who have been given a geoscience background, or to make use of geoscience experts who have been given public communication training. Whenever this issue was mentioned in the responses, the recommendation was quite clear: the most credible person is the well-trained geoscientist. For example, Andra states *"one major point is the positive impact, frequently express[ed] by member of the public, of the presence of scientists"* at events such as site visits and exhibitions. Nagra further cautions that public relations experts can stumble because of the *"unexpected awkward question expected from a wider public."*

3.3.4 Engaging Outside Experts

It is certainly desirable to engage outside experts and most radioactive waste management organizations do so with external contracts requiring special expertise in the geosciences and related disciplines such as material science and environmental science. Most organizations have established expert groups for consultation purposes, such as Geological Commission on Radioactive Waste Disposal (KNE) for HSK and the OVERSITE and INSITE teams for SKI and SSI. Another effective way to attract external experts is through the development of personal networks of contacts. This is achieved by encouraging personnel to participate in areas outside of the waste management area, such as scientific conferences and workshops, topical presentations at universities, and the preparation of scientific papers for journals devoted to general scientific and engineering disciplines.

Outside experts are typically associated with research institutes and universities and the largest part of the contracts with universities support postgraduate and postdoctoral research. The nature of the contract work is varied: some experts are chosen to provide specialized advice or laboratory and field procedures while others provide critical review of key issues that make up the safety case. Some of these experts may lack a complete understanding about what is important in the overall safety case, and it can be advantageous to enlist their further assistance by putting into context how their detailed contributions fit into a safety case.

Finally, it is important to recognize that the period from construction to decommissioning of deep geologic repositories for radioactive waste will typically take many decades, and perhaps not start for several decades in many countries. Thus, it may be important to engage not just graduate students, but also undergraduates and conceivably younger students—those who will become the "experts" of the future.

4. Summary

4.1 Geoscience Lines-of-Reasoning

The examples described in Section 2 provide strong confirmation that geoscience can make consequential contributions to the safety case. No one example 'proves' that safety is assured, but each example supports some key element or component of the repository safety concept or safety case, such as evidence that a salt dome has been isolated from fluids for millions of years, that oxidizing waters from the surface have not reached repository depths in fractured crystalline rocks, or that radionuclide transport has remained diffusion-dominated, at time frames relevant to safety, in the Opalinus Clay and similar formations. Furthermore, experience has demonstrated that such arguments can provide a more intuitive basis to explain site-specific reasoning to both scientific and non-technical audiences. The overall outcome has been an enhanced confidence in different safety cases.

The examples given are not exhaustive and there are other studies that could potentially serve well. For instance:

- the lack of occurrence of natural mineral resources or nearby deep recharge or discharge zones of groundwater could support the notion that the location would have a low intrusion likelihood (i.e. remain isolated);
- there are many studies of natural analogues that support the stability and barrier functions, such as the comprehensive studies of radionuclide migration at Oklo;
- there are other important elements of deep geological disposal that could be supported by geoscience, notably the notion of predictability for issues such as groundwater movement and composition: arguments for safety could be enhanced for a geosphere that possesses more predictable attributes.

In addition, while most examples are specific to a particular site or concept, many can be transferred to broader applications in certain instances. For example, the geoscience evidence gathered that supports diffusion dominated transport in clay might spawn similar studies for other host rocks.

4.2 Geosynthesis

An overview observation from the examples in Section 2 suggests that the most effective examples involve elements of geosynthesis. That is, some key element of the safety case is supported not by a single geoscience observation, but by a number of observations from different disciplines that coalesce to a single important conclusion. This observation actually highlights the power of geosynthesis: the integration of independent geoscientific information provides an effective and scientifically defensible approach to increase confidence and bound uncertainty in geosphere performance.

One of the most important outcomes from geosynthesis at a potential repository site is information with regard to the past and future stability of the geosphere, for which paleohydrogeologic arguments are vital. Geosynthesis is substantially strengthened when it combines all qualitative and quantitative sources of information and data, and does not disregard or omit anything that could hint at defects or deficiencies in understanding. One of the greatest challenges to geosynthesis is the identification and treatment of uncertainties.

With regards to geoscience communication, most responses indicate that geoscience experts take an active role in the planning and preparation of the safety case and other activities dependent on geoscience information such site selection and repository design. These activities require close communication and cooperation, frequently with multidisciplinary teams. For the safety case especially, geoscience communications that supports the safety functions are vital. Several ancillary messages can also be drawn from the responses. The IRSN response notes that *"... presenting geoscience is not a goal in itself but presenting geoscience and the way it acts towards safety is essential"*, implying that geoscientists must be prepared to talk not just to their peers, but to members responsible for preparing the safety case and even to a broader group of stakeholders.

In the topic of geoscience management, most respondents appear to utilize a top-down management structure and assign responsibility for various issues to technically competent teams. Potential bottlenecks include communication issues between physically separated teams and the availability of adequately qualified staff. Geosynthesis involves many disciplines and the staffing may come from many sources, but notably from academia. Some unique management issues to be considered include the continuity of staff, especially graduate students and establishing lines of communication between different groups, such as academics and consulting companies. Finally, a comment from Nagra provides the following caution.

> *"Geoscientific R&D programmes should be developed on the basis of practical experience from a peer reviewed safety case. The R&D programme should emphasise and justify the specific needs for the improvement of the geoscientific data base and for a better understanding of safety-relevant processes. However, there is also a need to maintain sufficient "width" in the programme to be prepared for the unexpected. Thus, it may not be appropriate to focus on just those issues that were important in the last PA."*

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INTRODUCTION TO THE AMIGO QUESTIONNAIRE

Introduction

AMIGO is the OECD/NEA international project on “Approaches and Methods for Integrating Geological Information in the Safety Case”. Its primary focus is on the effective use of geoscience information to support a safety case for a deep geological repository designed for disposal of radioactive waste. More specifically, it relates to the development of the geoscientific understanding of long-term geosphere barrier performance, which is typically drawn from the assembly or synthesis of multi-disciplinary data to justify a site-specific conceptual and quantitative description of the geosphere (geosphere model). The geosphere model evolves iteratively throughout the various stages of a repository site investigation, at each stage becoming more detailed and able to exploit more data that extends its development or re-affirms its veracity. The model ultimately underpins explanations of geosphere performance over time scales relevant to repository safety and illustrates the importance of the geosphere barrier as a natural component of the disposal system.

For a deep geological repository, the strength of the safety case is closely related to our understanding of the behaviour and evolution of the geosphere, and our ability to communicate our confidence in that understanding. The basic purpose behind this questionnaire is to examine how geoscience information contributes to the safety case, and how these contributions are evolving in significance.

Background and Scope

Over the past decade, the international geoscience community has gained considerable practical experience associated with planning and coordination of site characterization programs, integration of independent data sets to enhance notions of safety and longevity, communication of a deep geological repository safety case and meeting the needs and expectations of various external reviewers. The main focus of this AMIGO questionnaire is to capture examples of practical experience that contribute to the acceptance of a safety case. The information desired will be pertinent to long-term performance of radioactive waste repositories with a timeframe extending to 10^6 years.

Another objective of the questionnaire is to examine present day and state-of-the-art experience in methods and tools to communicate understanding of site-specific geosphere stability and resilience, and to explore how that knowledge can convey confidence and assurance in the predicted capacity of the deep geological repository to achieve passive waste isolation and safety.

Within this framework, specific goals for this questionnaire are to:

1) collect examples of geoscientific lines-of-evidence that directly support or convey confidence in the performance of the repository in varied geologic settings;
2) consider techniques used for effective communication of geoscientific reasoning and perspectives that support the safety case for a deep geological repository;
3) identify methods and procedures that provide the geoscientific basis for the safety case, notably the geosynthesis or integration of multi-disciplinary geoscientific information and approaches that can constrain geosphere non-uniqueness and uncertainty; and
4) explore methods related to planning and organizing, to improve the manner in which geoscience information is collected and communicated.

This questionnaire is designed to capture generic and specific undertakings during geoscience investigations for a deep geological repository within sedimentary (clay, carbonate, evaporite) and crystalline settings. In addition, many of the questions that follow are directed at implementing organizations (proponents), but we also desire critical insight from those who are responsible for technical approval of a safety case (the regulators). Thus many questions come with revised wording *[italicized within square brackets]* to solicit input from the regulators.

We anticipate that numerous examples will illustrate that significant advances have already been made and that geoscience contributions are further evolving. We plan to compile the questionnaire responses into an AMIGO report that will provide guidance and serve as a reference on how geoscience can strengthen a safety case. In addition, we expect that this compendium will broaden awareness and knowledge beyond geoscience audiences in two key areas. It will describe the current geoscientific understanding of the ability of the geosphere to isolate radioactive waste over long time frames, and current confidence (and limitations) in that understanding.

Questionnaire Instructions

The questionnaire is comprised of six sections.

- Part 1 ascertains background information on studies related to the safety case of a deep geological repository.
- Part 2 requests information on specific examples of how geoscience information has contributed (or will contribute) to a safety case. Two examples are attached to the end of the questionnaire. Please use extra pages and enter all examples that you feel can illustrate this aspect of a safety case. Regulator's comments on known examples would be very pertinent!
- Parts 3 to 5 are more subjective and solicit comments on practical experiences related to communication, the use of geoscience information in the safety case, and management practices.
- Part 6 is for your additional thoughts and ideas that could be of potential interest to the compendium. Also use this section to document any cited references.

In all parts, please limit written responses to a paragraph or less and attach informative pictures and figures if available. During the review and analysis of responses, we may appeal for additional information to expound on some issues.

Finally, please note that the thrust of this questionnaire is not on geoscience data that might be supplied to safety assessment models. Rather, the emphasis is on how geoscience provides overall support to a safety case. For example, in Part 2, topics of interest include geoscience evidence related to:

- the existence of diffusion-limited geosphere transport regimes;
- the presence and longevity of reducing electrochemical environments, including limits to the depth of penetration by oxygenated surface water and infiltration of oxidizing agents;
- the occurrence of retarding processes such as sorption and precipitation;
- the understanding of particular processes offered by studies of natural analogues such as Oklo;
- the significance of groundwater composition such as high salinity or isotope markers to the interpretation of groundwater residence times and groundwater flow system dynamics and evolution; and
- the degree of physical and chemical geosphere stability, including the effects of external processes such as seismic events, erosion and long-term climate change in addition to internal processes associated with the presence of the repository and its contents.

AMIGO Questionnaire
The Role of Geoscience in the Safety Case
For a Deep Geological Repository

Part 1. Identification of Respondent and Recent Studies

Name: ______________________________

Title and affiliation: ______________________________

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Has your organization prepared *[reviewed]*

y/n	a safety case?
y/n	a safety assessment?
y/n	related geoscience studies?

y/n	over the past two years?
y/n	over two to five years?
y/n	longer ago than five to 10 years?

Please identify the most recent studies (provide full citations in Part 6___________________

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Were the studies

y/n	generic or conceptual in nature?
y/n	linked to a specific deep geological repository and site?
y/n	aimed at some other purpose (please specify)? ______________________________

Did they include geoscience information to support or investigate *(select all that apply)*:

y/n	models and data used in a safety or performance assessment?
y/n	results of a safety or performance assessment?
y/n	siting of a potential deep geological repository?
y/n	design options or host rock options?
y/n	a safety case developed (for example) as part of a licence submission?
y/n	some other topic or issue (please specify)? ______________________________

Do these studies envision that the main roles or functions of the geosphere are to *(select all that apply)*:

y/n	provide a stable chemical and physical environment for the engineered barriers?
y/n	delay or retard radionuclide transport?
y/n	dilute and/or disperse radionuclide concentrations?

y/n	provide isolation from humans?
y/n	protect the repository and its contents from external perturbations?
y/n	other (please specify) ____

Please briefly describe the geological media and main features of the engineered barriers.

____

____

Does your organization plan to prepare *[review]* a safety case in the near future (Y/N)?

If Yes, what is the expected completion date? ______________________________

To the best of your knowledge, will this future study be

y/n	generic or conceptual in nature?
y/n	linked to a specific deep geological repository and site?
y/n	aimed at some other purpose (please specify)? ____

To the best of your knowledge, will this study include geoscience information to support or investigate *(select all that apply)*:

y/n	models and data used in a safety or performance assessment?
y/n	results of a safety or performance assessment?
y/n	siting of a potential deep geological repository?
y/n	design options or host rock options?
y/n	a safety case developed (for example) as part of a licence submission?
y/n	some other topic or issue (please specify)? ____

Please briefly describe the geological media and main features of the engineered barriers if different from above.

____

____

Part 2. Examples of Geoscience Contributions (Existing or Potential)

Briefly describe *[evaluate]* existing or potential examples that typically support a key element of a safety case. An example outline might be as follows: *"The longevity of engineered barriers is significantly enhanced under reducing electrochemical conditions, and geoscience evidence supports the contention that oxidizing groundwater could not reach a disposal vault during glacial cycles."* Consider specific process and events and their implications, such as how gravity and density gradients influence groundwater residence times and flow paths, how anomalously high hydraulic heads relate to regional scale flow properties, how rates of erosion and uplift might ensure isolation, how zones of diffusive control affect transport times, and how different observations might provide evidence for long-term stability of crucial geosphere properties. Perhaps reflect on various geoscience sub-disciplines, such as structural geology, geochemistry, paleohydrology and isotope systematics, to reveal how they contribute or might contribute to key issues in a safety case. Natural analogues such as Oklo, copper artefacts and studies of permafrost, may provide extraordinary examples. You may have built upon and re-used an example at different stages in your studies, and it would be very informative to describe how the understanding has evolved (question 5.2 below might be helpful). *(Please provide a brief outline how each example can support or build confidence in some key element of an existing or planned safety case, and then check all options that apply. Please try to provide 3 to 5 significant examples, using extra copies of these two pages.)*

Outline:

This example (select all that apply)	Definitely	With Effort	Not Relevant
applies to most other media	☐	☐	☐
applies to different disposal concepts	☐	☐	☐
applies to any engineered barrier system (EBS)	☐	☐	☐
supports issues regarding:			
…a stable chemical or physical EBS environment	☐	☐	☐
…delay or retardation in the geosphere	☐	☐	☐
…dilution or dispersion of radionulcides	☐	☐	☐
…isolation from humans	☐	☐	☐
…protection from external perturbations	☐	☐	☐
…other (please specify)			
provides confidence that we understand some process	☐	☐	☐
if so, name the process			
lends confidence to modelling or scenarios	☐	☐	☐
supplies input to safety assessment modelling	☐	☐	☐
supports results from safety assessment modelling	☐	☐	☐
offers qualitative argument(s) for safety	☐	☐	☐
can be easily explained to any scientist	☐	☐	☐
can be easily explained to the general public	☐	☐	☐
shows promise but requires more study	☐	☐	☐
would or does benefit from collaborative development	☐	☐	☐

(Please add any other comments that you feel are important. For instance, if this example pertains to a particular process, identify the process and give more information on the role of this example, such as whether it supports process understanding, input for models or verification or validation of model results, and whether this support focussed on the process level or has implications on a system-wide level.)

Comments: ______________________________

Part 3. Geoscience Communication Issues

In this section, we explore communication issues that may involve:

- members of the site characterisation group;
- groups responsible for site characterisation, repository design and safety assessment;
- geoscience experts associated with the proponents and the regulators, and
- geoscience experts and other project stakeholders including members of the public.

We are particularly interested in practical experiences found useful in gaining consensus on geoscience issues related to repository safety. We also wish to examine how geoscience evidence supporting the safety case is assembled so as to promote effective communication. Assembly includes demonstration of traceability and showing how raw site characterisation data is logically connected to the safety conclusion(s). Please consider the following questions and comment on as many as possible.

3.1 What role has peer review played during, for example, site investigation? Is this activity seen to be helpful? Are all forms of peer review equally useful (e.g. from regulators and academics, and at national or international venues)? Are there specific regulatory requirements concerned with peer (or other) review?

3.2 How has geoscience information influenced the presentation *[regulatory acceptance]* of the safety case? For example, consider geoscience support for results of a safety assessment, documentation of alternative lines of argument, implementation of modeling approaches and codes, and long-term indicators of safety and performance.

3.3 How do you deal with *[rate the treatment of]* uncertainty in topics such as evolution of the groundwater flow system? How do you then describe the methodology chosen and your confidence in its utility? What method(s) are most effective in managing uncertainty and in describing that management?

3.4 How has geoscience information been used in various phases, such as a feasibility study or application for a construction license? What geoscience information is of most concern to the regulators and other stakeholders? What method(s) are most effective in presenting key information related, for example, to site suitability? What geoscience information is of most concern to the public community (perhaps near a potential host site) and what communication methods are most effective?

3.5 Is some geoscience information seen to be crucial in the safety case? To what extent do geoscience experts contribute to planning and guiding the safety case? More generally, what opportunities exist for interaction and discussion between experts in different specialities (safety assessment, geoscience, site selection, repository design, conceptual model development and the safety case)? How do proponents and regulators share their concerns and plans?

3.6 What is *[should be]* the role of site characterisation studies? For instance, how do these studies influence (i) repository siting and design, (ii) development of a strategy for communicating safety concepts and (iii) approaches to conducting the safety assessment? More generally, how do you use information generated from the interpretation of a specific site?

Part 4. The Safety Case

We are concerned here with methods to improve the use of geoscience information in the safety case. Consider how we currently make use of geoscience information and speculate on what changes might improve our capabilities. For example, how do we go about integrating results from different disciplines, and how we interact with personnel involved with safety assessment, repository design and development of engineered barriers? Please consider the following questions and comment on as many as possible.

4.1 Has some particular set of geoscience information been most effective in arguing that the geosphere will provide a stable and benign environment for millennia? Has other information proven to be detrimental? Consider, for example, arguments related to the permanence of electrochemical conditions, the likelihood of fracture propagation and rejuvenation, the stability of flow system properties, and the occurrence of very long groundwater residence times in a diffusion dominated regime.

4.2 What approaches have been found to deal effectively with geoscience uncertainty, considering the realities and limitations of site characterisation data? How do *[should]* these uncertainties influence development of the conceptual model (or models) that represents the disposal system? Consider issues such as data scaling, presumed time independence of parameters related to flow and transport, future site evolution including glaciation and isostatic rebound, and the effects of model and parameter abstraction.

4.3 What essential understanding is needed to permit realistic predictions of groundwater flow and mass transport over millennia? How do we collect the required information and data, and how is it then used? What compromises our use of collected information and data? For instance, what accuracy can we attach to predictions of groundwater flow hundreds of years from now? What criteria are used to select a small set of alternative models (or constrain predictive outcomes) and what are the consequences? What drives model simplification and what is the penalty? How have these conflicts been balanced in the selection of modeling approaches and computer software? *[Are these controversial land sometimes conflicting issues handled adequately and transparently?]*

4.4 Do paleohydrogeologic arguments provide convincing support for expectations concerning long-term flow system evolution? Examples may include fracture fluid mixing, fracture infill morphology and paragenesis, fracture mineral-water reaction and spatial distribution of environmental isotopes.

4.5 How has consensus been achieved in the conceptual model that represents the disposal system? Is there a single model or several alternatives? How are regulator concerns made known and addressed?

4.6 What has been the effect of regulatory guidance and regulations *[how have you developed regulatory guidance and regulations that reflect]* on the site characterisation plan, the approach to predictive numerical modeling, documentation to support the repository safety case, geoscience activities and so forth?

Part 5. Management Issues

We are concerned here with methods to improve planning and organizing of geoscience information for a safety case. Consider how we currently manage geoscience information and what changes might improve the way in which it is collected and distributed. For example, how can we more effectively integrate results from different geoscience disciplines and provide those results in a timely fashion to other stakeholders? Please consider the following questions and comment on as many as possible.

5.1 What approaches have been applied in the management of large multi-disciplinary geoscience databases and how has such information been made accessible to site characterisation, safety assessment and repository engineering functions? What difficulties exist, where are the bottlenecks and how can they be resolved?

5.2 How and when are resources best prioritized? For instance, consider the examples described in Part 2 or any other examples that pertain to this issue. At what stage in your programme was the example researched? Did an issue arising from a safety assessment, site characterization studies or some other source steer the example? Has a particular issue evolved through different stages in your programme?

5.3 What methods do you find most useful in presenting geoscience information? What tools exist to reach a wide range of audiences? For example, what methods work best for presentations to members of the public?

5.4 How do we engage and focus experts outside of the nuclear waste management community? For instance, how can we solicit critical review from petroleum geologists and how might we encourage research by graduate students?

Part 6. Other Comments and References

Please comment on any other thoughts that might help or encourage the use of geological information in the safety case. For example, have we exhausted the use of observations over the geological time scale in supporting the extrapolation of laboratory results for all engineered barriers and other components of the repository?

Please also provide here the details of any references cited in previous section.

Other comments: ____
____
____