

Radioactive Waste Management

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Geoscientific Information in the Radioactive Waste Management Safety Case

Main Messages from the AMIGO Project

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Foreword

Radioactive waste is associated with all phases of the nuclear fuel cycle as well as the use of radioactive materials in industrial, medical, defence and research applications. The most hazardous and long-lived wastes, such as spent nuclear fuel and high-level waste from fuel reprocessing, must be contained and isolated for thousands of years. Disposal of these wastes in engineered facilities deep underground – geological repositories – in suitable geological formations is being investigated worldwide as the reference solution.

The safety of disposal is evaluated and documented in a “safety case”. The latter presents the underlying evidence and methods that give confidence in the quality of the disposal concept, the safety of the facility, the reliability of scientific and institutional processes, and the results of analyses and calculations. The NEA Integration Group for the Safety Case (IGSC), builds and documents the technical and scientific basis for safety cases as a platform for dialogue amongst technical experts and as a tool for decision-making.

For deep geological disposal, studies of the geosphere form a principal component of the safety case. Geoscientific information is unique in that it can offer evidence and lines of reasoning that span geological timescales (i.e. millennia and longer). It may involve diverse information from many sub-disciplines, such as geophysics, hydrogeology, geochemistry and palaeohydrogeology. Another important characteristic of geoscientific information in the context of radioactive waste disposal is that the level of information and understanding evolves over repository development. During the initial stages of planning for a repository, geoscientific information may be limited and provisional, primarily because data are often sparse or are generic if no specific site has been selected. At these stages, the safety case is therefore also limited. More data are collected during subsequent stages, such as during repository siting and construction, and the iterative improvements in the breadth and depth of information lead to a better understanding of the geosphere and its evolution, contributing to a more comprehensive safety case. Based on the data available, including that of a geoscientific nature, the safety case may support a decision to proceed to site selection, repository construction, repository operation and, eventually, to closure of the disposal facility.

To gain a perspective on the application of geoscientific information in safety cases, the IGSC sponsored the Approaches and Methods for Integrating Geological Information in the Safety Case (AMIGO) project. It focused on the collection and integration of all types of geological information in repository

siting and design, performance assessment models and the overall safety case for deep disposal of radioactive waste. The project grew out of a series of international exchange projects on modelling radionuclide transport. It integrated and built on their results to provide a broader view on the use of geological information, not only in modelling but in the context of the overall safety case. The AMIGO project has demonstrated that geoscientific data and understanding serve numerous roles in the safety case, and thus contribute substantially to decision-making during the stepwise development of geological repositories. Important progress has been made in how such information is integrated and applied.

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Klaus-Jürgen Röhlig	Chair of the Steering Committee, formerly GRS-Köln, now Clausthal University of Technology, Germany
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Patrick Lebon.....	Andra, France
Christophe Serres	IRSN, France
Sylvie Voinis.....	Formerly OECD/NEA, now Andra, France

Special thanks are also due to the Technical Programme Committee of the 3rd AMIGO workshop:¹ firstly because their contributions were unfortunately not acknowledged in the workshop proceedings, but primarily because the discussions and concluding session of that workshop proved especially valuable in distilling the main messages and legacy of the overall project.

Last, but not least, the IGSC acknowledges the leaders and participants of all the AMIGO workshops and the questionnaire. Clearly the project – much less this document – would not have been possible without their thoughtful contributions over the years.

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1. Sylvie Voinis (Andra) served as the chair of the Technical Programme Committee. Other members included: Jean-Claude Duplessy (Centre national de la recherche scientifique, France), Betsy Forinash (OECD/NEA), Erik Frank (ENSI), Lise Griffault and Patrick Lebon (both Andra), Christophe Serres (IRSN), Jan-Olof Selroos (SKB) and Paul Smith (SAM Ltd.).

Table of contents

Foreword	3
Acknowledgements	5
Overview of findings	9
Context and motivation for the AMIGO project	9
Roles of geoscientific information in the safety case	10
Trends and recent advances	11
The importance of integration	12
The value of information exchange	13
Background information and discussion of key points	15
Background and goals of the AMIGO project	15
The role and functions of geoscience in safety concepts for geological disposal	16
The role of geoscientific information in repository development and safety cases	18
Arguments and evidence for safety	21
The collection of geoscientific information and its transferability	23
Integrating and managing geoscientific evidence for use in a safety case	31
Links between geoscientific information and repository engineering	35
Conclusions	37
References	39
Appendices	
A. Background and objectives of the AMIGO project	43
B. Outcomes of the AMIGO workshops and questionnaire	49

Overview of findings

Context and motivation for the AMIGO project

Before the start of the AMIGO project, there was concern, as evidenced in the project's foundation document (NEA, 2002) and outlined in Appendix A of this report that insufficient use was being made of geoscientific information in the development of safety cases. Indeed, it was felt that safety concepts had tended to undervalue the fundamental contribution to safety offered by the geosphere – or at least, had failed to capture these contributions in safety cases. Thus, the important role of the deep geological environment in contributing to the isolation of the waste, and its role in ensuring both suitable and stable conditions for the engineered barriers, may have been underrepresented or taken for granted when presenting a safety case.

Furthermore, at that time, there were considered to be several issues that complicated the representation of the geosphere in safety cases (see Appendix A). One issue was that many repository programmes focused geological investigations and modelling almost exclusively on hydrogeological aspects directly related to radionuclide transport, with little (or uneven) attention to other aspects of the geological system. Another issue was the challenge of achieving effective coordination between site characterisation and geoscientific investigations, on the one hand, and the needs of modelling and performance assessment, on the other. The ability to achieve a direct link between these activities was made more difficult, for example, by the fact that the parameters and site properties in safety assessment are often not directly measurable and also that they must be extrapolated into additional dimensions or to significantly different spatial scales. An attendant challenge was communication between site characterisation and safety assessment personnel and, more generally, the integration of data and work of the various disciplines (including among geological sub-disciplines). The AMIGO project was designed to address directly both the role of the geosphere and the practical challenges identified regarding its representation in safety cases.

The AMIGO project consisted of a series of three workshops and an extensive questionnaire, as described in more detail in Appendices A and B. The outcomes of these workshops and the responses to the questionnaire show that considerable progress has been made since 2002 in defining the roles of geoscientific information in safety cases. Concepts such as safety functions and the geosynthesis² have provided useful mechanisms to prioritise and synthesise

2. The terms *geosynthesis* and *site descriptive model* (SDM) are defined and discussed in more detail in the section on Integrating and managing geoscientific information for use in a safety case.

relevant information, and to convey their significance to the overall safety of a disposal system. There are practical challenges in interpreting and applying geoscientific information in safety cases, and various tool and approaches (among them, again, the concepts of safety functions and geosynthesis) have been developed to address these. This section presents the conclusions and provides perspectives on the role and practical application of geoscientific information in the safety case.

Roles of geoscientific information in the safety case

The importance of geoscientific information in site selection is self-evident and has long been recognised [i.e. in the work of the NEA SEDE (the Co-ordinating Group for Site Evaluation and Design of Experiments for Radioactive Waste Disposal) pre-2000]. More recently, there has been a growing recognition of the broader role of geoscientific information in safety assessment, as well as in the broader safety case, and the attendant need to properly integrate such information (as evidenced, indeed, by the formation of the IGSC from SEDE and PAAG (the Performance Assessment Advisory Group), previously separate NEA groups devoted to site characterisation and performance assessment (PA), respectively).

- Geoscientific evidence has a number of important roles in a safety case. Chief among these is that it provides the basis for establishing the values (including their range and uncertainties) of key parameters in performance assessment. However, the scope of site characterisation and the importance of geoscientific understanding reach well beyond the data needs strictly for performance assessment.
- Geoscientific evidence provides the basis of understanding the geosphere at the temporal and spatial scales relevant to repository safety – both how the geosphere could have evolved to its present state, as well as its potential future evolution. The demonstration of this understanding, as well as the investment in research that is implied, is itself a significant contribution to building confidence in the safety case.
- Geoscientific evidence contributes to setting the boundaries and priorities for performance and safety assessment, by identifying and confirming relevant processes and events, aiding in the formulation of conceptual models, supporting decisions on acceptable simplifications in modelling, etc.
- Geoscientific evidence provides qualitative and complementary evidence (e.g. the age of groundwater) to support statements made regarding the significance of processes affecting the stability of a site, the isolation of the waste, the containment properties of the geosphere, radionuclide release and mobility in the sub-surface, and other issues relevant to the safety functions.

Trends and recent advances

The collection, interpretation and communication of geoscientific information are all important aspects of its application in safety cases. Related to these aspects, there have been notable technological advances and methodological tools developed during the last decades, as described below. Of course, not all aspects are fully resolved; practical challenges and debate remain in some areas related to, e.g. the use of natural analogues and the communication of geoscientific information to less technical audiences (i.e. the general public). Examples of advances recently made include:

- The use of multiple lines of evidence is no longer only a high-level managerial aspiration; it is applied in practice and accepted as a sensible approach to the use of geoscientific information. An example is a recent French safety case, which presents evidence for diffusion-dominated transport in argillaceous formations (Smith *et al.* in Andra, 2005a).
- The use of what has been termed soft data is an example of multiple lines of evidence that seems to be playing an ever increasing role. Such data are, actually, specific and often rather specialised pieces of evidence that can provide convincing support regarding a site's long-term stability and suitability for the disposal of radioactive waste. The evidence may be derived from a proposed disposal site or from a similar geological environment (there are several examples of the use of such evidence in NEA, 2009a). An important use of "soft data" is in assessing the relevance of specific processes and phenomena, by providing insights into the conditions under which they occur as well as on their potential effects. That is, they can be seen as analogues for potentially important processes, especially those that cannot be observed directly at a potential disposal site because of the timeframes under consideration or due to other factors. An example to illustrate the use of such soft data is from the Opalinus Clay in Switzerland: an extensive hydrogeological database – part of which derives from strongly-tectonised geological environments – suggests that advective transport through faults and fractures in the Opalinus Clay at depths greater than 200 metres is insignificant. This conclusion is also supported by independent evidence from clay porewater hydro-chemical and isotopic data. The lack of hydrochemical anomalies and extensive mineral veining suggest that there was also no significant palaeoflow through such faults and fractures. These observations can only be reconciled with a strong self-healing capacity of the clay, and it is concluded that reactivated existing faults or newly-induced fractures will not act as pathways for significant fluid flow at anytime, due to self-healing processes (Gautschi in NEA, 2001 and Nagra, 2002a and 2002b).
- The increasing role of palaeogeoscientific information (which can often be linked to the "soft data" referred to above), together with the aim of using such evidence to extrapolate into the future, to increase confidence in the performance of the geosphere and in the models developed.

- An increasing understanding and a more systematic approach to the subject of the transferability of data, techniques and conclusions, e.g. concerning individual parameters, investigation techniques and data evaluation methods, process understanding and conceptual models. Such transferability has been especially marked in the investigation of argillaceous formations (e.g. Mazurek et al. in NEA, 2007 and Mazurek et al., 2008), as well as in crystalline geological environments and rock types (see e.g. SKB, 2006a,b).
- In the late phase of the AMIGO project, there was an increasing awareness of the need to account for engineering feasibility and to ensure compatibility with engineered components when addressing geoscientific questions.

The importance of integration

The key to the effective implementation of all these recent trends is the integration of geoscientific information, not only in the development of a safety case but also in the overall process of repository development. The following important points can be noted:

- There are increasing links and iterative feedback between site characterisation, engineering design and safety assessment. This reflects the increasing emphasis in safety cases on repository layout and engineering feasibility. These developments have implications for the types of data required from geoscientific investigations and for the manner in which such data are integrated and used.
- New tools and methods have emerged in recent safety cases to aid in the prioritisation of geoscientific investigations and in the integration of geoscientific information. Some of the most important in this regard are safety functions (though, of course, these were not derived from geoscientific work and their application is not restricted to geoscientific areas of the safety case) and the development of a geosynthesis or a site descriptive model (SDM).³ A safety function may be seen as a means by which a repository component contributes to safety (although exact definitions vary between programmes; NEA, 2009c). An example of a high-level safety function is “Delaying and attenuating the migration of radionuclides”. This relates to the sub-function “delaying the migration of the radioactive elements by diffusion/retention in the host formation”, which in turn relies *inter alia* on the “absence of significant

3. A geosynthesis is a report or a set of reports and files containing a geoscientific explanation of the overall understanding of site characteristics, attributes and evolution (past and future) as they relate to demonstrating (i.e. building confidence in) long-term repository performance and safety. A geosynthesis includes models (e.g. descriptive, mathematical, conceptual, site) and accounts for uncertainties and alternative geoscientific interpretations of the available evidence, as is described in more detail in the section on “Integrating and managing geoscientific data for use in a safety case.” An SDM is similar to a geosynthesis, but is not synonymous, and the difference between these two terms is also discussed in that section of the document.

heterogeneity with respect to diffusion” (from Andra). Safety functions related to the geosphere may be defined or evaluated in terms of, for example: the geological and mechanical predictability of the host formation, the predictability of groundwater flow, the retention properties with regard to any released radionuclides, the predictability of the composition of the groundwater and the absence of resources in the host rock (and its immediate vicinity). Tables 1 and 2 describe examples of safety functions. The concept of a geosynthesis has also been extensively discussed. This is perhaps the most useful concept to have evolved and allows best use to be made of geoscientific information in a safety case in encouraging, and indeed requiring, that a proper integration of such information takes place.

In recognition of the importance of such integration, some national programmes, including those of Andra, Nagra, Posiva and SKB, have even adapted their organisational structures and used other management tools to improve communication and foster mutual understanding among different disciplines and teams. These approaches support coherence, for example, between the needs of safety assessment and the priorities for geoscientific investigations.

The value of information exchange

One of the objectives of the AMIGO project has been to foster information exchange among international radioactive waste management geoscience programmes, as well as with academic, regulatory and implementing bodies. The following conclusions can be drawn, some of which, in particular those regarding the interactions between the implementers and the regulators, have previously been emphasised in the key messages from the GEOTRAP project (NEA, 2002):

- Making geoscientific datasets available in the open literature to foster their use in new research may be of benefit to geoscientific work programmes.
- An external steering group, a periodic programme peer review, or both, can provide the means to ensure the relevance of the geoscientific work being carried out by a programme.
- Effective interactions between regulators and implementers are essential to facilitate the review processes and to build confidence in the results of the safety assessment. The regulator should establish a clear and comprehensive set of regulations, and provide guidance and direction on critical issues. The implementer should openly communicate research results and fully document the assessment of safety and his supporting scientific bases. This documentation must include elements of quality assurance, describing (for example) the process and results that involve collection, interpretation and application of geoscience data in the safety assessment and the safety case.

- There is a role for both formal (public) and two-way interactions between the regulators and implementers. A mechanism to resolve issues should be prescribed.

These findings are discussed in more detail in succeeding sections of this document.

Background information and discussion of key points

Background and goals of the AMIGO project

History and motivation for the AMIGO project

International geoscientific projects on radioactive waste disposal in the 1980s focused on the development and validation of models of flow and radionuclide transport. Drawing on the lessons learnt from these projects, the IGSC predecessors – the SEDE (Co-ordinating Group on Site Evaluation and Design of Experiments for Radioactive Waste Disposal) and the PAAG (Performance Assessment Advisory Group) – initiated the GEOTRAP project: Radionuclide Migration in Heterogeneous Geologic Media (1996-2001). This project took a broader view of the topic of radionuclide migration; beyond model development and validation, it also assessed the practical approaches available to address modelling challenges and knowledge gaps, as well as considering the feasibility of international co-operative projects.

The OECD/NEA project on the topic of “Approaches and Methods for Integrating Geological Information into the Safety Case”, known as “AMIGO”, grew out of the GEOTRAP project (NEA, 2002) and provided an even broader scope, both in terms of the geoscientific disciplines that could be involved and their range of application. For instance, AMIGO topics include developing an understanding of how geological 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).

Scope and objectives of the AMIGO project

AMIGO emphasised the collection and integration of all types of geological information and their role in the overall safety case. The objectives of AMIGO were defined as follows (NEA, 2002):

- To understand the state-of-the-art and to identify means of improving geosphere support to the development of a repository safety case.
- To contribute to the development of methods for geosphere representation in the repository safety case.
- To define terminology for communication and interaction between site characterisation and safety assessment groups in support of the repository safety case.

- To clarify the role and application of geoscientific information and evidence applied in the repository safety case.
- To clarify the relationship and information requirements for site characterisation and safety assessment modelling.
- To foster information exchange between international radioactive waste management geoscience programmes, as well as between academic, regulatory and implementing bodies.

Structure of the AMIGO project

The AMIGO project was structured as a series of workshops, beginning in 2003:

- The first AMIGO workshop, “Geological Disposal: Building Confidence Using Multiple Lines of Evidence” took place in 2003 in Yverdon-les-Bains, Switzerland.
- The second AMIGO workshop, “Linkage of Geoscientific Arguments and Evidence in Supporting the Safety Case” took place in Toronto, Canada in 2005.
- The third and final AMIGO workshop, “Approaches and Challenges for the Use of Geological Information in the Safety Case” was held in Nancy, France in 2008.

The technical papers, along with a summary of the discussions and conclusions of each workshop, have been published as NEA reports (NEA, 2004b, 2007, 2009b). An important part of each of the workshops was the presentation, by the respective host organisation, of their safety case, with specific reference to the use made of geosphere information, both for providing details to other participants and in providing an opportunity for the host organisation to obtain feedback on their work. In addition to the workshops, an AMIGO questionnaire was developed to compile practical examples of national experience related to the key topics and challenges and a report published that summarised the questionnaire responses: “The Evolving Role of Geoscience in the Safety Case: Responses to the AMIGO Questionnaire” (NEA, 2008).

More detailed background of the AMIGO project can be found in Appendix A. The outcomes of the three AMIGO workshops and the questionnaire are presented in Appendix B.

The role and functions of geoscience in safety concepts for geological disposal

In qualitative terms, the role of the geosphere (and, by implication, of geoscientific information) is similar in all disposal concepts for long-lived waste. The geosphere provides long-term safety by:

- Isolating the waste from the human environment and decreasing the likelihood of inadvertent or accidental human intrusion.

- Providing a stable and favourable chemical and physical environment at depth, thereby protecting the waste and the engineered barriers from various external phenomena (such as long-term climate change and erosion), and thus supporting long-term containment of the waste.
- Preventing, delaying, and/or attenuating radionuclide release and migration (although the contribution that the geosphere makes to any specific disposal concept varies, depending on the role that it plays), thereby contributing to the multi-barrier concept.

These are often referred to as safety functions (as discussed above).

Potential host formations for geological repositories (and the geological environments in which they lie) are chosen in particular for their long-term stability, for their ability to accommodate the waste disposal facility, for their ability to prevent or attenuate potential releases of radioactivity and for their buffering capacity with respect to external and internal perturbations. Natural hazards are also considered in the choice of a site for a potential disposal facility. It is recognised that the host rocks that are of interest for radioactive waste disposal, at depths of more than a few hundred metres, are unlikely to be in physical or chemical equilibrium. The concept of geosphere stability in maintaining stable chemical and physical environments at depth does not imply, therefore, that steady-state conditions prevail over very long periods of time. The concept of such stability does imply, however, that the changes that occur in the geological system do so to an extent and at such a rate that their effects are unlikely to compromise the short- or long-term safety of the disposal system.⁴

All repository programmes for long-lived wastes attach a high weight to the geosphere for the first two of the safety functions listed above. The third function is also a high priority for all programmes. However, the degree to which it is expected to be fulfilled by the geosphere – compared to contributions from waste containers and other engineered components of the repository – can vary, depending on geological, regulatory and programmatic considerations. Regardless of the details of the disposal concept, the geosphere is usually considered to be an essential component of the multi-barrier system at long times in the future, at least to the degree of providing redundancy for the primary features providing containment and preventing radionuclide releases from the waste. The role of the geosphere is, thus, broadly similar in all geological disposal concepts, even if the relative roles of the geological and engineered aspects of the disposal system vary between concepts (and between different stages of a given programme). Indeed, the characteristics and the confidence in the geosphere as a barrier are important factors that influence the design of the engineered barriers to ensure long-term safety.

4. This subject is extensively discussed in the two reports produced as part of the NEA Geosphere Stability project, see NEA (2004a, 2009a).

The role of geoscientific information in repository development and safety cases

An understanding of the current state and future evolution of the geosphere is a fundamental prerequisite in demonstrating confidence in the expected performance of a geological repository. In fact, the strength of the safety case for a repository is closely related to the understanding of the geosphere, and acceptance of the repository depends partly on the ability to communicate confidence in that understanding to all stakeholders. The importance of this point is emphasised throughout this report.

A safety case is typically presented at specific points in the stepwise process of repository development. Throughout repository development and implementation, a safety case matures and is progressively refined through an iterative process, with feedback between key programme components including site characterisation, engineering design and performance assessment modelling. Both the scope of information and the way it is used evolve as the safety case matures. Geological information is used in a variety of ways by waste management programmes, including:

- In site selection, to test whether general exclusion criteria are met, and to demonstrate whether the extent of a suitable host rock is sufficient, both to host a repository and to provide flexibility with respect to repository location.
- In engineering design, to adapt the design and repository layout, such that the engineered barriers function adequately in, and are protected by, the selected geological environment.
- In providing support for safety assessment – geological data provide parameter values for models, support model assumptions and can discriminate between model concepts.
- Complementary or multiple lines of evidence that provide indirect or qualitative support and otherwise build confidence in safety, stability or other key features addressed in the safety case (e.g. for long-term geological stability).

The specific use of geological information depends on the stage of planning or implementation that a programme has reached. A safety case at an early stage of repository development may use limited or quite generic geoscience data, often based on open scientific literature. Even at very early stages of planning, some general requirements of the geosphere and of geological characterisation can be defined (for example, as criteria to identify candidate sites), based on considerations of long-term safety and engineering feasibility. In terms of long-term safety, it may be adequate at this early stage to show that a site meets general requirements or exclusion criteria. At a later stage, the safety case is more detailed and would be expected to incorporate significantly more (and more detailed) geoscientific information, especially site-specific data collected through the site characterisation programme, including both surface-based and sometimes underground tests and investigations.

Table 1 shows the favourable characteristics of the geosphere that could be cited in a safety case, using the example of the Opalinus Clay in Switzerland, as presented at the AMIGO 1 workshop (Gautschi et al., in NEA, 2004b). Although these characteristics were developed for the Opalinus Clay, they are generally applicable to any geological environment.

Table 1. Favourable characteristics of the geosphere that could be cited in a safety case, using the example of the Opalinus Clay in Switzerland, as presented at the AMIGO 1 workshop (Gautschi et al. in NEA, 2004b)⁵

Long-term geological stability, implying, for example, a low rate of uplift and erosion and an insensitivity of the geochemical and hydrogeological environment to geological and climatic changes.

Favourable physical, chemical and structural properties, including thickness of the host formation, low rates of groundwater movement, a geochemical environment that is beneficial in terms of radionuclide retention and protection of the engineered barrier system, and rock mechanical properties that support the feasibility of construction (although not strictly part of the safety case, engineering feasibility is relevant in that the system described in the safety case must be one that can be realised in practice).

Sufficient lateral extent, which gives flexibility in the location and layout of the repository.

Absence of, low likelihood of, or insensitivity to detrimental phenomena and perturbations, including climatic and geological events and processes, perturbations caused by the repository itself (gases, chemical alterations), and future human intrusion.

Explorability, or the ability to characterise the rock at any stage of the project to a degree that is adequate to support a decision to proceed (or not) to the next stage (e.g. site characterisation from the surface can provide sufficient evidence to support the decision to proceed with further characterisation from underground tunnels); and

Predictability, meaning that the range of possible geological evolution scenarios is sufficiently limited over the time scale for which the geological environment plays a role in the safety case (perhaps, for example, a million years).

Once a site, or several alternative sites, has been selected, the focus of geoscientific work tends to be on developing confidence in the description or conceptual model of the site and on a detailed characterisation of the properties of the site. In general, the aim is to reach a point where:

- A stable “site model” is established. That is, the model does not change fundamentally as new and more detailed information is acquired, and thus confidence in the use of, and results from, the model increases incrementally through repository development. For there to be sufficient confidence in such a “site model” it must be consistent with a broad range of measurements from a variety of sources.

5. The statement in this table under *Favourable physical, chemical and structural properties* (“although not strictly part of the safety case, engineering feasibility is relevant in that the system described in the safety case must be one that can be realised in practice”) is a direct quote from Nagra (2002b). Recent developments, as described in this report, suggest that there is now a much closer relationship between engineering design and feasibility and the development of a safety case.

- The information required for detailed safety assessment (e.g. in support of a licence application) is available, including the quantification of uncertainties.
- The uncertainties do not compromise confidence in safety.

All available information must, as far as possible, be synthesised in a consistent description, or conceptual model, of the site (also known as a geosynthesis). This includes relevant data from a wide range of characterisation techniques, taking account of both site-specific and more generic information, for example from generic rock laboratories and natural analogues. There may also be “soft data”, such as natural tracer profiles, which are quantitative but provide only indirect information or constraints on the characteristics and evolution of the site. The site model should address the geological evolution of a site, its current undisturbed characteristics, the likely disturbance caused by repository construction and its post-closure evolution. As the understanding of a site evolves, priorities tend to shift from developing a general understanding towards a better characterisation of those phenomena that are judged to have the most potential to affect the performance of the repository. Over time, scenarios of most concern are identified, and data collection activities are focused on providing the information needed to evaluate them. Such descriptions or conceptual models are used for exploring design options and for safety assessment studies, as well as for planning possible further site investigations.

Another element of developing a convincing safety case is in building confidence using multiple lines of evidence. As noted above, the synthesis of geoscientific understanding contributes to safety assessments by providing a basis for model parameters and model assumptions used in calculations of disposal system performance. This subject is considered in more detail later in this report. Confidence is favoured when the conceptual site model can be shown to be consistent with a broad range of measurements and observations from a range of sources, including laboratory and in situ field experiments and observations of analogous natural systems. Geological evidence can be used to support the realism or the conservatism of parameter values and model assumptions. Similarly, multiple lines of evidence can support key assumptions in the site model itself regarding site characteristics and their long-term evolution.

Finally, geoscientific information can be used to support qualitative arguments to foster confidence in long-term safety. In terms of the geosphere, these can include evidence for the strength of geological disposal as a waste management option – based on, for example, natural analogues and the favourable properties of the chosen disposal system, i.e. diffusion-dominated transport in the host rock. It is interesting to note that the degree to which information from natural analogues has been integrated in safety cases has been, however, limited. These analogues are viewed by some as still under-utilised with respect to their potential to communicate safety cases to wider (including non-technical) audiences; on the other hand, arguments based on natural analogues are not always simple and readily accessible to such audiences. Furthermore, as well as analogues that provide clear support for

safety assessment hypotheses and the safety case, there may be other “negative analogues” that need to be explained in order that they do not undermine safety case arguments.⁶

This consideration of the favourable characteristics of the geosphere provides a link with another NEA project, entitled “Stability and buffering capacity of the geosphere for long-term isolation of radioactive waste”, also referred as the Geosphere Stability project, which was initially proposed by the NEA Clay Club and was initiated in 2002.⁷ Two workshops were held, the first on clay host rocks (NEA, 2004a) and the second on crystalline rocks (NEA, 2009a). The conclusions from the geosphere stability project emphasise the importance attached to the concept of geosphere stability, in all potential disposal environments, and address this stability in relation to its importance in the development of a convincing safety case and also on its effect on the location and layout of a repository. The increasing realisation of the importance that should be attached to the stability of the geosphere, and in understanding its stability, in safety cases is itself a good example of the evolution of the role of geoscience in radioactive waste management.

Arguments and evidence for safety

For any particular type of geological environment and disposal concept, there are arguments and evidence for safety, which can be divided into those that support isolation of the waste or those that support its retention within the near-field of the repository and the surrounding geosphere. The applicability of the arguments that can be employed is likely to change as different time frames are considered. When considering them it is, of course, necessary to take into account the field evidence that might provide support; and conversely, the types of field evidence that might be found to counter them. In presenting these arguments in a safety case, it is important to decide which key messages are likely to provide the greatest promise in terms of their scientific credibility.

The discussion at the AMIGO 2 workshop (NEA, 2007) concluded that the status of such geoscientific arguments could be best expressed in terms of five categories of key importance to the geosphere-related safety functions, which can be linked to the application of geoscientific information in a safety case, as outlined in Tables 1 and 2:

- The ease of understanding and modelling of groundwater flow.
- The retention of any released radionuclides.

-
6. The potential problem of the transferability of geological data, including analogue data, between sites and different geological environments, is discussed below in the section entitled “The collection of geoscientific information and its transferability”.
 7. For the Geosphere Stability project, the stability of a crystalline rock was broadly defined as the presence of THMC (Thermal-Hydrogeological-Mechanical-Chemical) conditions considered favourable for the safety of a nuclear waste repository. Stability, in this sense, does not imply that steady-state conditions exist; the geosphere is constantly evolving, although in many cases rather slowly, and such evolution is perfectly acceptable for safe geological disposal. What is important is that we understand this evolution.

- The predictability of the composition of the groundwater.
- The geological and mechanical predictability of the host formation.
- The absence of resources in the host rock (and its immediate vicinity).

For each of these categories, the workshop identified the reasoning and arguments that could be developed in their support, the ways in which they could be applied in each of the host rocks or geological environments of interest, and their applicability in different time frames. In addition, it also identified field and other evidence that would tend to negate these arguments and developed the key messages that would contribute most to the scientific credibility of a safety case.

The AMIGO 2 workshop also established the following conclusions regarding the use of geoscientific arguments for, and indicators of, safety:

- The most important geoscientific argument is a clear understanding of the past geological history of the site and the geological environment in which it is located. Such an understanding should be consistent with what is known about similar geological environments and should have a broad consensus among independent experts.
- Most geoscientific evidence for safety is based on a chain of arguments that, together, are stronger and more powerful than any individual argument.
- The goal of geoscientific investigations should be a level of predictability that could be considered as being “reasonable”. As long as it is possible to supply well-reasoned bounds on the future evolution of a site, a safety case could be made and defended – thus implying that a detailed description of such an evolution is unnecessary and may anyway be impossible to achieve.
- The same type of argument is generally applicable to all host rocks and geological environments, although the strength of the argument, the ease with which it can be made and the time scale of its validity might vary. Such arguments are usually best suited to systems that are geologically simple – this is directly related to the requirement of *explorability* and to other favourable characteristics of the geosphere (see Table 1).

It was also concluded that sharing experiences from different programmes is a crucial form of peer review and will lead to improved geoscientific arguments.

The last bullet point regarding geological simplicity is important from several standpoints, which are significant in the development of a convincing safety case:

- It will be considerably easier to demonstrate sufficient confidence in the properties and future performance of the geosphere if the geological environment (and, by association, the hydrogeological and hydro-geochemical environments) is relatively simple.

- There are two main reasons for this: firstly, it will be easier to obtain the necessary information for demonstrating such confidence (vis. the *explorability* of Nagra, as explained in Table 1); and secondly, there are likely to be fewer alternative conceptual models of the geosphere and fewer uncertainties associated with its properties and characteristics – the geosynthesis will therefore be easier to prepare and, in turn, is likely to be more convincing.
- The resulting reduction in uncertainty in geosphere properties and performance will make it easier to make a convincing safety case. This will be especially so in disposal concepts where the geosphere plays a more dominant role than the EBS in determining long-term safety.

Table 2 shows how specific types of geoscientific information are applied to demonstrate the various safety functions of the geosphere.⁸ Some information, although available, is not widely used or is considered inappropriate for safety cases; this is also indicated. The table is, of necessity, somewhat generalised but, where possible, examples from national programmes are provided as illustrations. The terms *qualitatively* and *quantitatively* are used in the table to distinguish how data are used in the safety case. Data that are used *quantitatively* provide direct evidence for a process or event, and may be used directly in a model, for example. Data that are used *qualitatively* supply supporting or complementary evidence regarding a process or event, but would not be used directly as input to a model.

The collection of geoscientific information and its transferability

One of the main objects of a site characterisation programme is to provide evidence for the safety case, and it is thus evident that performance assessment should have a considerable influence on the scope and content of such a programme. In practice, however, such a direct link may be hard to achieve.

The parameters and site properties used in safety assessments are almost never directly measurable, except perhaps for some of the geometrical properties of a site, e.g. the boundaries of a formation. The inclusion of such geometrical elements may be applicable only in sedimentary environments in which the geological structure is simple, so that they can be measured directly, possibly with great accuracy.

Such parameters and site properties are otherwise derived from a long chain of observations, the interpretation of data, the construction of models, and the integration of separate models. In addition, measurements are only able to cover a small portion of the volume of the geosphere that needs to be modelled and the majority of site properties vary in space, and also possibly in time. Their extrapolation into three dimensions thus requires additional assumptions to be made and associated modelling to take place before PA-type assessment modelling is possible. In addition, as already discussed above, the

8. How geoscientific information is structured for use in a safety case is discussed later in this report.

Table 2. Specific types of geoscientific information used in safety cases

This table describes how some specific types of geoscientific information are used in safety cases to demonstrate the various safety functions of the geosphere: isolation of the waste, acting as a transport barrier to radionuclide migration, and in demonstrating the long-term stability and predictability of the geosphere. The use of the terms *quantitatively* and *qualitatively* is explained in the text.

Type of information	Isolation of the waste	Transport barrier
Isotope signatures	Information not currently used or considered to be inappropriate for use.	Quantitatively
Groundwater composition	Quantitatively and qualitatively	Quantitatively and qualitatively
Natural fluxes	Qualitatively	Quantitatively (in theory, but not often in practice) and qualitatively
Temperature	Information not currently used or considered to be inappropriate for use.	Qualitatively and quantitatively
Fracture infills	Quantitatively and qualitatively	Quantitatively and qualitatively
Structural geology	Quantitatively and qualitatively	Quantitatively and qualitatively
Geomorphology	Quantitatively (where uplift is of significance) and qualitatively	Quantitatively and qualitatively
In situ experiments	Information not currently used or considered to be inappropriate for use.	Quantitatively and qualitatively

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Long-term stability and predictability	Comments and examples
Qualitatively and quantitatively, (depends on relevance for constraining models)	Used effectively and efficiently. Of particular interest in argillaceous rocks, e.g. preservation of diffusion profiles. Useful in detailed reconstructions of past conditions, e.g. from fracture minerals
Quantitatively and qualitatively	Groundwater composition is a key input for assessing EBS evolution and stability, as well as for the parameters used in migration modelling. Preservation of stratified groundwater types, even at sites subjected to past thick ice sheets, e.g. Olkiluoto, Finland, suggests that the hydrogeological and hydrogeochemical systems are well-buffered.
Qualitatively	Under-used, theoretically interesting but potential somewhat unclear. Natural analogues based on uranium deposits, for example, can be used to represent the long-term behaviour of radioactive waste repositories or the processes that influence their radioactive contents.
Qualitatively and quantitatively	Temperature distributions are needed as initial conditions for assessing the thermal evolution of the site. Temperature profiles may also be used e.g. to justify assessed values of thermal conductivity (e.g. by SKB in SKB, 2008).
Quantitatively and qualitatively	Can provide useful information for palaeohydrogeological reconstruction (e.g. Sellafield) and indicate lack of fluid movement (e.g. Boom Clay, Callovo-Oxfordian clay).
Quantitatively and qualitatively	Generally used effectively and efficiently. Absolute requirement in all geological environments – perhaps of greatest significance in crystalline rocks, where deformation zones are ubiquitous and have major control on hydrogeological system, repository layout, etc.
Quantitatively and qualitatively	Used – still under development. Of greatest significance in areas with marked topography and/or where uplift is significant in safety case (e.g. Japan, Switzerland). Also of significance for coastal sites, especially in relation to future biospheres.
Semi-quantitatively and qualitatively	Have been used effectively and efficiently in all geological environments. Can be used in a quantitative or semi-quantitative manner, with regard to long-term stability and predictability, when considering convergence measurements made in a URL over many years – although this may be applicable only to weaker repository host rocks.

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Type of information	Isolation of the waste	Transport barrier
Natural analogues	Qualitatively	Quantitatively and qualitatively
Alternative conceptual and numerical models	Quantitatively	Quantitatively

provision of geoscientific data for performance assessment is only a part of the requirements imposed on a site characterisation programme; the majority of the data collected is unlikely to be used, either directly or indirectly, in performance assessment, but may well be used in developing a comprehensive understanding of the site and the area in which it lies, as part of the safety case. An additional important requirement for data is for the engineering design of the repository. In fact, even during the AMIGO project, the significance of obtaining data relevant to repository engineering has noticeably increased, as the appreciation of the importance of integrating the requirements of the engineering aspects of waste disposal with that of geoscience has grown.

The application of geoscience in the field of radioactive waste management has made considerable advances in the last decade. These advances derive largely from a better appreciation and understanding of the complexity of geological systems, along with assessments of the significance (or not) of such complexity in specific geological environments; and an acknowledgement of the need to constrain interpretations of geosphere behaviour and performance. The complexity of the geosphere will have been influenced by its evolution, perhaps over many aeons – an evolution which continues now and into the future. The physical and chemical characterisation of the geosphere will always be associated with a degree of uncertainty, which influences the understanding and confidence in its predicted behaviour and performance at the spatial and temporal scales necessary to demonstrate safety for geological disposal. In part, this uncertainty arises due to the inability to make direct and complete measurements of the geosphere that represent more than a narrow interval within a slowly-evolving system. Despite such limitations, a reasoned geoscientific understanding of its current and historical behaviour and potential future evolution can be developed. This understanding will never be complete or precise, but can be sufficiently bounded to minimise any ambiguities and to define the degrees of uncertainty.

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Long-term stability and predictability	Comments and examples
Quantitatively	Generally under-used, although often stated that they are of potential use. The use of information from natural analogues in a safety case is often restricted to a specific process, or part of the system, for which a basis of transferability can be demonstrated (e.g. the interaction of hyperalkaline water with the rock matrix – e.g. Maqarin, Jordan).
Quantitatively	Used effectively and efficiently – the use of alternative conceptual models tends to decrease as a programme progresses, as the collection of extensive data limits the possibilities to a preferred model, e.g. the single geological model for Olkiluoto.

The majority of the site investigation techniques have been available for many years, but there have been major advances in some techniques over the last decade, in particular in the area of geophysics, especially seismic, which allows the definition of structures at depths of several hundred metres and greater, with a resolution of potentially only a few metres under suitable conditions (e.g. Davies *et al.*, 2004). Over the past few years, the use of such techniques has been extended from dominantly sedimentary environments [for example their use in investigating the Opalinus Clay, see Nagra (2002a) and NEA (2004b)] to crystalline rocks [e.g. the investigations by SKB (e.g. Cosma *et al.*, 2003) or by Posiva at Olkiluoto (Cosma *et al.*, 2008)]. There has also been increasing use made in site characterisation in radioactive waste disposal programmes of experience gained in the hydrocarbons industry and in academia. This has possibly been of most significance in the investigation of sedimentary environments, where the transfer of experience on subjects such as basin evolution and diagenetic changes has been greater than in crystalline rocks.

Another area of transfer has been in the management and organisation of large multidisciplinary site characterisation datasets and associated simulation programs, the use of which in sedimentary rocks was discussed above. In crystalline rock environments, and particularly in more complex tectonic and volcanic terrains, there has been more cross-fertilisation from academia and from other areas of research, such as seismic risk, than in sedimentary environments, as can be seen in NEA (2009a) regarding the stability and buffering capacity of geological systems.

The demands imposed by the requirements of the safety case have required that considerable effort has had to be put into the measurement of certain parameters, such as the chemistry of pore waters, the hydraulic conductivity of individual fractures, or the in situ thermal conductivity, well beyond what is normally required in site investigation programmes in other

fields, such as mineral assessment.⁹ For the most part, suitable techniques already exist for measuring these parameters, further practice in their application is, however, required, so that they are used as efficiently as possible. This is particularly the case when a repository development programme has reached the stage of underground construction, for example the construction of the ONKALO at Olkiluoto in Finland or the Gorleben investigation mine in Germany. There are, for example, practical constraints that limit the opportunities for the collection of geological data during construction that need to be understood, so that greatest use can be made of such construction activities in obtaining data over considerably larger volumes of the rock mass than is possible from surface-based boreholes alone (*e.g.* Posiva, 2009).

The conclusions of AMIGO 2 emphasised the importance of three elements of a site characterisation programme:

- An external steering group, a periodic programme peer review, or both, can provide the means of ensuring the relevance of the geoscientific work being carried out by a programme. Regulatory authorities may also participate in the decision-making process to define future investigations and experimental work.
- Confidence in geoscientific data for a potential host site enhances the ability of regulators to make a credible and defensible licensing decision. Effective interactions between regulators and implementers are thus essential and there are good examples of such profitable interaction in several waste management programmes.
- Making geoscientific datasets available in the open literature, to foster their use in new research, may be of benefit. The release of such data is likely to encourage co-operative ventures between the disposal programme and industry or academia. The use of such data in areas outside the radioactive waste disposal programme itself has obvious implications in terms of the management of such data sets and their release.

9. There are numerous reports available from current and past site characterisation programmes for radioactive waste disposal which describe the use of the many techniques that are necessary to adequately investigate the geological environment. In crystalline rocks, probably the greatest number of such reports is available from SKB and Posiva, whilst in sedimentary environments there are numerous reports from Andra and Nagra. Reports from the Yucca Mountain investigations are perhaps of greater relevance to more tectonically-active environments, such as those in Japan. Investigations in evaporites, such as at the WIPP, illustrate the influence of investigation techniques developed for the hydrocarbon industry in such characterisation programmes, *e.g.* Beauheim *et al.* in NEA (2007), as well as the possibilities of underground investigations by means of mapping, drilling and electromagnetic reflection measurements (Bornemann *et al.*, 2008). There are also interesting parallels between the disposal of radioactive waste and the disposal of CO₂, as evidenced by Whittaker in NEA (2007), but also more recently in Bachu and McEwen (in press, expected 2009).

What has become apparent over the last decade in particular, is the need to design a site characterisation programme that is properly integrated – that is, there is good integration between the geological, hydrogeological, hydro-geochemical and geotechnical parts of the programme. This integration is particularly important when considering the modelling that needs to take place and the subsequent use of these modelling data in the safety case – a subject that is discussed in more detail below.

Transferability of data from other sites, laboratories and URLs

The transfer of data and other information between sites can be an important element in making best use of the information available on a specific rock type or geological environment. There are important implications regarding the applicability of transferring data from other disposal programmes, laboratories, and generic and other site-specific URLs to potential disposal sites in similar geological environments. Such transfer is, however, relatively common and there are numerous examples of its application in all the types of geological environments of interest to radioactive waste disposal. This subject is discussed with reference to argillaceous host rocks and to Andra and Nagra programmes, in particular, by Mazurek *et al.* (NEA, 2007) and Mazurek *et al.* (2008).

As discussed by Mazurek *et al.* (NEA, 2007), there are various levels on which information can be transferred, with regard to: individual parameters, investigation techniques and data evaluation methods, process understanding, conceptual models, and high-level conclusions (*e.g.* engineering feasibility, safety aspects).

In argillaceous systems, the microscopic structure governs many macroscopic properties, including the transport and geomechanical properties, and is essentially determined by the properties of the clay mineral platelets. This type of microstructure is common to all argillaceous systems and is the fundamental basis of transferability among different sites and formations. Some differences occur among argillaceous formations, however, which are mainly due to factors such as variations in the degree of compaction (and therefore porosity) and the degree of diagenetic cementation, and a good knowledge of these and other characteristics of argillaceous rocks is necessary for a proper transferability of data to be possible.

In crystalline rocks, such differences are of a different form and are related more perhaps to factors such as the tectonic history and maximum metamorphic grades of the sites than to their specific rock types. For example, the Äspö URL in Sweden is considered as being an applicable URL for any potential disposal site in the Fennoscandian Precambrian shield; and data from Äspö could be considered to be equally applicable to a crystalline environment in Japan in much younger rocks.

In evaporites, in particular rock salt, there is probably a greater general applicability of information and data from one site to another, as there perhaps fewer significant differences between evaporite formations. There are, however, features of considerable importance in evaporites for ensuring confinement by the host rock (the central safety function), such as the number and size of brine inclusions or the geometry of anhydrite bodies, which can only be investigated at the particular site under consideration.

The reasons vary for wanting to transfer features, processes, data and understanding between sites. National disposal programmes can be at quite different stages of development and also may pursue different strategies in developing a safety case. There are, therefore, several different motivations for the transfer of information among formations and sites:

- Information from other sites can be used to fill current gaps in a specific national programme in order to obtain data for a preliminary safety case. For example, the basis for extrapolating laboratory measurements to in situ conditions can be justified if both laboratory and in situ data are available in other programmes. An example of this is the NEA Clay Club catalogue of characteristics (Boisson, 2005) or the catalogue of features, events and processes for argillaceous systems (FEPCAT, Mazurek *et al.*, 2003).
- Information from other sites is taken to demonstrate that the investigated formation or site is not unusual, but has features which are in line with other equivalent formations or geological environments. If independent programmes converge towards consistent data sets and conclusions, confidence is built in the national programme. Examples could be of the form of demonstrations of the self-sealing properties of rock salt or clays, or the maintenance of reducing conditions at depth, even during glacial periods, in crystalline rocks.
- The identification of evident differences can be used to guide future research. Dedicated investigation techniques can be developed and evaluated in URLs and then used for site characterisation elsewhere: an example could be the development of geotechnical equipment and testing techniques.
- Conceptual models on different levels (individual features and processes, their coupling and their safety relevance) can be transferred from other, similar sites or URLs. Examples include the identification of relevant transport processes in the geosphere and the role of natural and induced fractures on flow and transport.
- Transfer of information on engineering aspects of waste disposal could be of equal, or perhaps even greater, importance than that associated with increasing knowledge in natural processes. For example, information on construction techniques, geotechnical modelling and repository layout and design could be transferred between sites.

Transfer occurs at different levels, depending on the degree of development of the safety case and on the extent of analogy that can be made between the sites and formations concerned. In the early stages of safety case development, information could be transferred from other sites to fill gaps in the site characterisation and to obtain a data set needed for a preliminary safety case. At this stage, the basis of transferability may not be well elaborated. In mature safety cases, the role of information transfer is less in supplying missing data, but in contributing to process understanding and confidence building, for example by means of establishing empirical relationships that include information from diverse sites and settings.

Integrating and managing geoscientific evidence for use in a safety case

As discussed above, the benefit of assembling, interpreting and modelling geoscientific data in a structured and integrated manner has become particularly apparent over the last two decades. This structured approach was perhaps first used by Nagra, in their development of the safety case for the Opalinus Clay (Nagra, 2002b), but has been subsequently employed by other waste management organisations, such as Andra, NUMO, NWMO, SKB and Posiva. It is the integration of such geoscientific data that has proved to be of greatest significance and thus the need for efficient and successful integration is paramount, a subject that is highlighted in all four AMIGO reports (NEA, 2004b, 2007, 2008, 2009b).

Geosynthesis and site descriptive model (SDM)

The safety case for a geological repository is designed to convey reasoned and complementary arguments to illustrate and instil confidence in estimates of long-term performance. The long-term safety inherent in the geological repository concept relies, in part, on the long-term stability of the surrounding geosphere and in the multi-barriers, which are designed to immobilise the waste and to retard contaminant migration. An important element of the safety case is the derivation of an integrated model of the geosphere, which is known as a *geosynthesis*, a term first used by Nagra, but now in more common parlance, e.g. by NUMO and NWMO, and which is likely to include not only the site itself, but also the surrounding geological environment.

This geosynthesis represents the integration of site-specific, multi-disciplinary data into an internally consistent understanding or realisation of the geological environment and its evolution; with the term *geosphere* incorporating all aspects of the geology, hydrogeology, hydrogeochemistry, etc. of the geological environment. A geosynthesis can be defined, therefore, as a report or a set of reports and files containing a geoscientific explanation of the overall understanding of site characteristics, attributes and evolution (past and future) as they relate to demonstrating (i.e. build confidence in) long-term repository performance and safety. A geosynthesis includes models (e.g. descriptive, mathematical, conceptual, site) and accounts for uncertainties and alternative geoscientific interpretations of the available evidence.

Ultimately, the geosynthesis provides the scientific basis for communicating confidence and understanding in the long-term performance and stability of the geosphere and thus provides a holistic understanding of a site. It also serves as a technical basis for rationalising safety assessment analyses and for developing complementary geological arguments that support the repository safety case. Although the implementer typically compiles the geosynthesis, which necessarily requires an extensive amount of work, the regulator may choose to conduct an independent geological, hydrogeological and geochemical interpretation of the implementer's geological database, and is likely to comment on the adequacy of and scientific justification for the geosynthesis (Bluth, in NEA, 2004b).

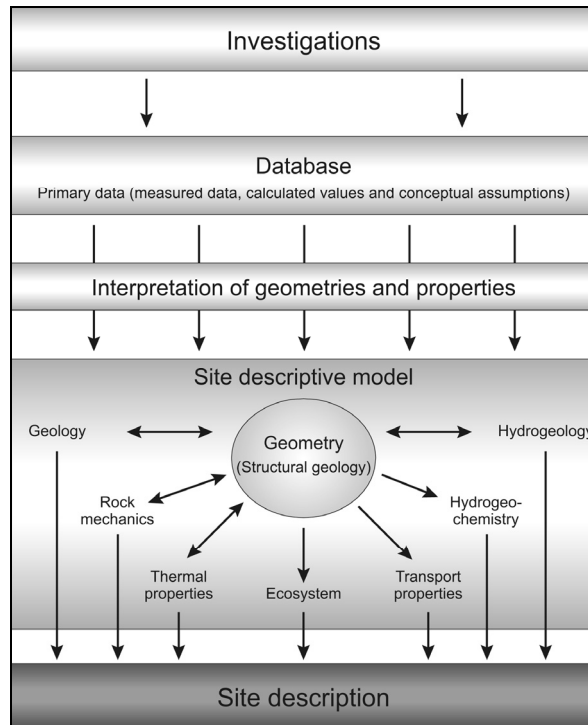
Other terms are also used to refer to the integration of the geological data for a site – for example both Posiva and SKB use the term Site Descriptive Model (SDM), *e.g.* SKB (2008) which, although similar to a geosynthesis, is not entirely synonymous (Figure 1). One important difference is that SDMs are deliberately separate from the safety assessment itself, with separate reports describing the data that are used in the safety case modelling and the future evolution of the site. Other waste management organisations take a yet different approach in presenting the relevant information, *e.g.* Andra’s Dossier Argile (Andra, 2005b).¹⁰

The geosynthesis thus takes the SDM a step further by illustrating the site’s past evolution, its present state and likely future evolution – with a specific reference to the repository safety case. It does so by, for example, i) illustrating multiple lines of reasoning which provide supporting evidence for understanding the site’s evolution; ii) placing constraints on far-field barrier performance/integrity using, for example, site analogues (*e.g.* anomalous hydraulic heads; the maximum depth of glacial recharge, etc.); and iii) providing a document that demonstrates thoroughness in the assessment and the influence of uncertainties on predictions. Although there are differences in the approach taken by waste management organisations in presenting the geological data, the importance of developing an integrated description or model of the geosphere is nevertheless universally appreciated.

There is now a trend, as noted at the AMIGO 3 workshop (NEA, 2009b), towards maintaining a clear separation between the development of a geosynthesis (or, in particular, an SDM), which aims to be as realistic as possible, and a safety assessment, in which, if the aim is the demonstration of compliance, a deliberately conservative bias is often introduced, generally as a means of dealing with certain poorly-understood phenomena and poorly-quantifiable uncertainties, or a lack of suitably realistic models or databases. For example, the reports prepared by Andra for Dossier 2005 Argile (*e.g.* Lebon in NEA, 2009b) included two documents – one focusing on geoscientific information and another providing the justification for safety assessment modelling assumptions. It should be noted that conservatism is not always easy to define in safety assessment; models and databases may be used in more than one application in a safety assessment, and a model that is conservative for one application may not necessarily be conservative for another. The challenge in defining “conservative” may be even more difficult in the context of a geosynthesis, which is one of the main reasons why SKB, for example, separates the SDM from the future predictions of site evolution. The latter is, instead, presented in the safety assessment.

10. Andra have two documents that present the type of information that would be contained in a geosynthesis or an SDM. These documents are: (i) A Site Reference Document, which is a synthesis of raw data acquisition and interpretation, with a discussion of uncertainties of all kinds (*e.g.* ranges of porosity and permeability, uncertainties associated with head values, etc.) and (ii) A Conceptual Model Document, which is a short presentation of conceptual and phenomenological models (supported by measured values, results of modelling, lines of arguments) which form the basis for the description of the evolution of the repository.

Figure 1. Illustration of the development of an integrated site description, referred to as a site descriptive model (SDM) by SKB and Posiva (from SKB)



The development of a geosynthesis provides a structured framework in which confidence in geosphere understanding is gained. The model is developed through an iterative process, in which geological, hydrogeological, geochemical, palaeohydrogeological, geophysical and geomechanical data from successive and increasingly more detailed investigations are combined to test and revise the model, as required. The geosynthesis serves a number of purposes including: i) the development of hypotheses that aid in the co-ordination and planning of site characterisation activities to strengthen the understanding of the geosphere and its evolution; ii) a systematic method for identifying and articulating alternative geological arguments which support long-term geosphere stability; and iii) the development of a transparent and logical scientific basis to substantiate and underpin flow and transport or other modelling. The methods employed to organise and structure the geoscientific evidence in order to make it of greatest use for the safety case are discussed below.

Interdisciplinary communication and data integration

In order to carry out such work, it is necessary to have a system that permits the efficient communication of information and ideas between the different disciplines and ensures that there is sufficient integration of the various types of data. There is an increasing level of experience in using a *multidisciplinary integrated safety team* (or *safety case team*) as an important approach for ensuring

the necessary integration between safety assessment, engineering (design), site characterisation and R&D, whilst keeping a holistic view and maintaining a proper safety culture, as described in more detail in the report on the NEA INTESC initiative (NEA, 2009c).

A number of problems have, in the past, limited the effective use of data from site characterisation in safety cases. For example, because the focus of safety assessments has often been on “hard” outputs, such as estimated doses, there has been a tendency for site characterisation data to be incompletely integrated with associated evidence that does not directly aid such calculations, even if the data could contribute other important lines of evidence in the safety case. On the other hand, site characterisation programmes have sometimes tended to be driven by the managerial and practical aspects of accomplishing field operations, resulting in the needs of safety assessment not being fully met. Such problem areas have, thankfully, largely been resolved by a better integration of site characterisation and safety assessment in the majority of disposal programmes, with the use of a geosynthesis or SDM playing an important role in linking the two activities.

There are different ways of actually achieving the necessary integration, and various views on how it should be organised, with the result that several, rather similar, management structures can be appropriate, as outlined in the INTESC report (NEA, 2009c). Extensive experience over many years and via the work of many implementing and regulatory organisations has demonstrated that the use of an integrated multidisciplinary group is one appropriate and efficient method of synthesising existing geological information and developing confidence in a site description or conceptual model. Such a group, *e.g.* Posiva’s Olkiluoto Modelling Task Force (OMTF) and the other parallel and similar groups within Posiva, are able to check whether all relevant data are being used, whether all relevant sources of uncertainty are being addressed and whether all suggested alternatives make sense and the potential for additional alternatives has been explored. Such groups need to contain representatives of the safety case team, so that there is cross-fertilisation of ideas between the site characterisation and modelling team and the performance assessment. There are now several specific examples of this approach in the development of geosyntheses/SDMs, *e.g.* Nagra, Andra, NUMO, SKB, Posiva, etc., and it has become very apparent over the last decade that without such a multidisciplinary team, or one of the similar management structures described in the INTESC report (NEA, 2009c), it will not be possible to carry out the necessary integration and provide the safety case with the geoscientific information required.

Transparency and traceability

The processes by which information from site characterisation is selected and applied in a safety assessment require proper documentation, justification and cross-referencing in order to ensure traceability of analyses presented in a safety case. Geoscientific information provides not only parameter values for safety assessment models, but also supporting evidence for model assumptions, such as the homogeneity and time invariance of some geological processes and features. The important role of FEP catalogues in this regard was

noted at the AMIGO 3 workshop, a good example being FEPCAT, which was developed for argillaceous rocks by the NEA Clay Club (Mazurek et al., 2003), as has been alluded to earlier in this report.

The need for traceability has to be managed early in a project to avoid the task becoming too onerous. Information is best organised in quality-assured databases, with controlled procedures for entering and retrieving data and procedures for qualifying “external data”, e.g. from hydrocarbon wells, whose quality cannot easily be checked. Such procedures are especially important given the very long duration of a repository development project. An appropriate records management system can help in maintaining corporate memory of all relevant information, ensure the traceability of knowledge as a programme progresses through successive stages, and assist future personnel engaged in the project to fully understand past work. This, in turn, should minimise the possibility of the unnecessary repetition of such work.

Other aspects of managing geoscientific information in safety cases

Presentations from, for example, Nadeau et al. (NEA, 2004b) and discussion at the AMIGO 1 workshop emphasised the fact that radioactive waste management programmes can usefully draw on experience from the hydrocarbon and other industries and from academia in managing and organising large geological datasets from multidisciplinary sources and in developing related conceptual models of interest for the geological environment being investigated. In a sedimentary environment, conceptual models of processes, such as diagenetic change and basin evolution, could be of interest; in crystalline rocks, the aspects of interest might be the structural evolution of deformation zones. For example, a basin model was used to reproduce geological, physical and chemical processes occurring in the course of the 248 million year evolution of the Paris Basin to explain the present-day hydraulic properties at the regional scale (Violette et al., in NEA, 2004b). The model is constrained by different types of quantitative and qualitative information, originating from different scientific disciplines that include geology, palynology (pollen analysis for the reconstruction of past climates), hydrogeochemistry, rock mechanics, hydrogeology and climatology.

Links between geoscientific information and repository engineering

At a certain stage in a repository development programme, the safety concept and repository design must be adapted to site-specific conditions, which are characterised in increasing detail in a step-wise manner as a programme proceeds. The repository design and layout may, therefore, be fully specified only at a relatively late stage and are likely to be modified as additional information is obtained about the host rock. The safety case is developed in parallel with the results of the site characterisation programme, and may also be updated even after repository operations have begun, as further geoscientific information becomes available from the monitoring programme, for example, on the impact of repository construction and operation.

At each stage, the impact of uncertainties in geoscientific data is explored through qualitative and quantitative safety analyses, and is taken into account in design measures to make the repository robust with respect to the more

significant events, processes and uncertainties. Papers presented at the AMIGO 3 workshop and discussion in the Working Groups provide examples from programmes at different stages of development of how the availability of geoscientific data is taken into account in the safety concept, the repository design and the safety case (NEA, 2009b).

The process of adapting a repository design to increasing amounts of site-specific information can be guided by preferences, guidelines or criteria that indicate, for example, the conditions that must be met for a particular volume of rock to be suitable for emplacing a waste package. The role of geoscientific data and the associated preferences, guidelines or criteria in the design process will vary according to the stage reached in repository planning and implementation. Such data may be used at early stages to define, for example, a tentative repository layout, based on information obtained from surface-based investigations. At later stages, they may be used in support of decisions such as to construct a tunnel, to bore a specific deposition hole, or to use the hole for waste emplacement.

Posiva, for example, are in the process of developing Rock Suitability Criteria (RSC) that will determine the location, length and orientation of deposition tunnels and the locations of disposal holes in the floors of such tunnels (Posiva, 2008) and SKB are carrying out similar work. This work has evolved from Posiva's earlier programme of host rock classification, as described by Andersson et al. (in NEA, 2009b), which has been tested during the construction of the ONKALO at Olkiluoto. Andersson et al. (op cit.) also refer to the development of deposition hole rejection criteria by SKB, based on the potential for earthquake-induced slip on long fractures intersecting deposition holes.

Such programmes have been set up to define the performance targets for the host rock and to develop the criteria for accepting certain volumes of rock for disposal, including the acceptance criteria for the deposition holes (for the disposal concepts referred to above), and similar programmes have been developed for locating modules for different types of waste in Andra's disposal concept (e.g. Andra, 2005b). The criteria to be developed and applied are designed to cover the requirements arising from both long-term safety and design. As a result of applying such criteria, estimates of the expected conditions around such deposition holes, or modules, will be achieved, along with the probabilities of deviations, for example those caused by disruptive events, e.g. earthquakes. Repositories employing different repository designs and disposal concepts from those of SKB and Posiva, in crystalline rocks, and by Andra, in clay, may have different performance targets for the host rock and different types of geological constraints and FEPs to consider, but the process of developing such criteria is likely to be similar.

All waste management organisations are, thus, following similar paths with respect to repository layout and design, although tempered by the site-specific geological conditions that result in designs that can show a considerable variability. There is thus a strong link between the collection and integration of geoscientific data, the design of repositories and the engineering features within them, and the development of safety cases.

Conclusions

As explained above and in Appendix A, before the start of the AMIGO project there was concern that insufficient use was being made of geoscientific information in the development of safety cases and that safety concepts had tended to undervalue the fundamental contribution to safety offered by the geosphere. There were also considered to be additional issues that complicated the representation of the geosphere in safety cases.

The importance of geoscientific information in site selection is self-evident and has long been recognised. However, there has been a growing recognition of the broader role of geoscientific information in safety assessment, as evidenced by several NEA projects and reinforced by the AMIGO project. Geoscientific evidence has a number of important roles in a safety case. Chief among these is that it provides the basis for establishing the values of key parameters in performance assessment. However, the scope of site characterisation and the importance of geoscientific understanding reach well beyond the strict data needs for performance assessment, as has been outlined above in this report.

The AMIGO project highlighted advances that have been made in the way that geoscientific data are collected and used in the development of safety cases. In particular, there has been an increasing awareness of the need to account for engineering feasibility and to ensure compatibility with engineered components when addressing geoscientific questions. Above all, however, the key to the effective application of geoscientific information is its integration in the development of a safety case and also in the overall process of repository development. This is perhaps the area in which the greatest strides have been made in the efficient use of geoscientific data – and this subject was discussed continuously and its importance emphasised throughout the AMIGO project. In fact, the desire for a high degree of integration of geoscientific data in the development of a safety case continues to motivate projects in the IGSC programme of work; high value is placed on geoscientific understanding and information, but the emphasis in coming years is on, for example, technical issues that affect or involve both the geosphere and the engineered components of a repository.

One of the objectives of the AMIGO project was to foster information exchange between international radioactive waste management geoscience programmes, as well as between academic, regulatory and implementing bodies. It was successful in this regard, in particular regarding the interactions between the implementers and the regulators, something that had earlier been one of the key messages from the GEOTRAP project (NEA, 2002).

With the completion of three key projects concerned with central aspects and important pillars of the safety case, namely the engineered barrier systems (EBS) project, the Geosphere Stability project and the AMIGO project, that have achieved their respective objectives, the IGSC is now orientating its work towards cross-cutting issues and themes concerned with integration in repository development and the safety case. By doing so, it is building upon the experience gained and the conclusions drawn from these projects and is focusing its work on the challenge of designing and building a repository in a geologically stable environment and in demonstrating its safety, using evidence derived from geoscience and other scientific and technical fields.

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Appendix A

Background and objectives of the AMIGO project

Background and history of the AMIGO project

International projects on this theme began in the 1980s as individual countries came to appreciate the benefits of sharing experiences and comparing approaches to modelling radionuclide transport. Relevant projects under aegis of the NEA include INTRACOIN (1981-1984), HYDROCOIN (1984-1987) and INTRAVAL (1987-1993).

These projects focused on the development and validation of models of flow and radionuclide transport. The projects concluded that the validation of models applied to natural systems over the timeframes for disposal was not achievable, at least not in the strict sense of the term. Another important lesson learnt was that the variety of information relevant to radionuclide transport needs to be properly integrated, which in turn requires effective communication between the people involved in modelling and those collecting data or using the results of modelling. It was also appreciated that calculating the migration of radionuclides was not, in itself, sufficient for developing a safety case, which comprises the full and integrated technical basis in support of long-term safety of a waste disposal system.

Drawing on these lessons learnt, the IGSC predecessor groups – SEDE (Co-ordinating Group on Site Evaluation and Design of Experiments for Radioactive Waste Disposal) and PAAG (Performance Assessment Advisory Group) – initiated the GEOTRAP project: Radionuclide Migration in Heterogeneous Geologic Media (1996-2001). This project took a broader view of the topic of radionuclide migration. Beyond model development and validation, it also assessed the practical approaches available in addressing modelling challenges and gaps in knowledge, as well as considering the feasibility of international co-operative projects.

Five key messages resulting from the GEOTRAP project were considered as being “guiding messages for the future”, applicable beyond radionuclide transport to virtually all aspects of a radioactive waste repository programme (NEA, 2002). These messages can be summarised as:

- The personnel responsible for site characterisation and those responsible for performance assessment should be in close communication at all stages in the development of a safety case. Site characterisation specialists must understand how data and conceptual

models are being used in assessing the evolution of the geosphere and disposal system, including the limitations of PA models and the specific data needed. Performance assessors, in turn, must understand the methods used for developing conceptual models of the geosphere and the applicability of data, including what data are possible (or not) to collect and the contexts in which data can be considered valid.

- Site characterisation is crucial to developing a comprehensive understanding of the geological setting and overall disposal system. This understanding goes beyond what would be required to implement performance assessment models, which are necessarily simplified. Indeed, site characterisation informs and justifies decisions on model abstraction and simplification; it also is used to identify the operative processes and quantify important parameters in PA. The implication is that site characterisation activities cannot be guided solely by the needs of performance assessment.
- Improving the integration, quantitatively and qualitatively, of different types of data is important to improve confidence in the overall system understanding. Quantitatively, laboratory and field data can be used to reduce the number of free parameters in models of other experiments. In addition, data from experiments or observations at various scales can be extrapolated and combined in larger-scale PA models. “Qualitative” integration is important to show consistency between multiple lines of evidence, such as when interpretations of independent sources of information converge on a single conceptual model.
- Significant benefits can be obtained by drawing on the knowledge of specialists in others fields of science and engineering beyond radioactive waste disposal. Such knowledge could include theoretical understanding, experimental techniques, field experience/evidence related to specific processes, or techniques for integrating data from diverse sources. These other technical communities may also provide opportunities for broader-based peer review.
- Communication between implementers and regulators at all stages of the process of repository development is extremely important. Communication can allow the regulator to gain information and provide feedback on the technical direction being pursued by the implementer, as well as understanding the limitations of the data and models. At the same time, the implementer can gain an improved understanding of the expectations of the regulator and modify its programme as appropriate.

These lessons provided the genesis for the IGSC AMIGO project on “Approaches and Methods for Integrating Geological Information in the Safety Case”.

Scope and objectives of the AMIGO project

AMIGO emphasised the collection and integration of all types of geological information and their role in the overall safety case. Thus, from its inception, it aimed for a broad view of both the information considered and the applications in the context of geological repositories. For example, the project addressed the application of geosciences in repository siting and design, in performance assessment (PA) models and in providing other evidence supporting confidence in safety.

The objectives of AMIGO were defined as follows (NEA, 2002):

- To understand the state-of-the-art and to identify means of improving geosphere support to the development of a repository safety case.
- To contribute to the development of methods for geosphere representation in the repository safety case.
- To define terminology for communication and interaction between site characterisation and safety assessment groups in support of the repository safety case.
- To clarify the role and application of geoscientific information and evidence applied in the repository safety case.
- To clarify the relationship and information requirements for site characterisation and safety assessment modelling.
- To foster information exchange between international radioactive waste management geoscience programmes, as well as between academic, regulatory and implementing bodies.

The AMIGO project was structured as a series of workshops, beginning in 2003. Related to the objectives above, some key challenges were identified as topics to be addressed in the workshops (NEA, 2002):

- The role of the geosphere and its representation in the safety concept and safety case.
- The capabilities of site characterisation relative to the needs of the safety case and PA.
- Procedures for integrating and taking into account all kinds of available information.

The relevance of each of these topics is described below in more detail. An emphasis was placed on practical experience and approaches to address these topics. Also importantly, the project aimed to involve practitioners in both site characterisation and safety assessment with experience in a range of host rock environments.

The role of the geosphere and its representation in the safety concept and safety case

At the time when AMIGO was initiated, the IGSC expressed a concern that safety concepts for geological repositories had tended to down-value the fundamental contribution to safety offered by the geosphere. Traditionally, retention had been the main safety function attributed to the geosphere. However, it was felt that the deep geological environment played an equally important role in contributing to the isolation of the waste; this role of ensuring suitable and stable conditions for the engineered barriers may have been underrepresented or taken for granted when presenting a safety case.

The role of the geosphere in a safety case is clearly related to the ability to represent it in a well-supported manner for the relevant temporal and spatial scales. Several issues complicated the representation of the geosphere in safety cases, for example, how to assemble and present the understanding of the site and how to assess the influence of repository construction and the evolution of the engineered barriers on the geosphere.

A related issue was that in many repository programmes, site investigations and PA modelling focussed on that part of the hydrogeological system thought capable of transporting radionuclides to the biosphere, with other parts of the system being characterised to lesser degrees. It was appreciated at the time, however, that determining what degree of characterisation was required of these supposedly less important parts of the system was a nontrivial, and sometimes non-intuitive, task.

Capabilities of site characterisation relative to the needs of the safety case and PA modelling

One of the main objects of a site investigation programme is to obtain evidence that can be used in modelling disposal system evolution. It is, thus, evident that performance assessment should have a considerable impact on the scope and content of such a programme; in practice, however, the IGSC acknowledged that such a direct link is hard to achieve.

The parameters and site properties used in safety assessments are almost never directly measurable, except in specific situations mentioned in this report. Typically, they are derived in a process that starts with observation and measurement and includes data interpretation and the eventual construction of a model, which itself is likely to have to be integrated with other related models. Their extrapolation into three dimensions also requires additional assumptions and associated modelling, before PA-type assessment modelling is possible.

A further issue identified was the potential difficulties in communication between site characterisation and safety assessment personnel. An efficient working relationship is necessary, so that both groups understand what is required to develop a well-supported and persuasive safety case.

Procedures for integrating and taking into account all kinds of available information

Site characterisation encompasses a wide range of disciplines, activities and measurement techniques, the results of which are used by a variety of users. There is a need, therefore, for a flexible, but secure, data management system that should document and store data and interpretations, but also provide accessibility of relevant aspects of these data sets for various users. In formulating the AMIGO project, it was recognised that such site characterisation databases and geological visualisation systems needed to be complemented by other tools that could incorporate soft information or represent confidence, for example. Of special interest in this regard are, for example, tools and procedures for developing confidence in the geological model – traceability, hypothesis testing and consistency between disciplines – and the use of multiple lines of evidence, e.g. palaeohydrogeological information.

Structure of the AMIGO project

As noted above, the AMIGO project was structured as a series of workshops, beginning in 2003:

- The first AMIGO workshop, “Geological Disposal: Building Confidence Using Multiple Lines of Evidence” took place in 2003 in Yverdon-les-Bains, Switzerland.
- The second AMIGO workshop, “Linkage of Geoscientific Arguments and Evidence in Supporting the Safety Case” took place in Toronto, Canada in 2005.
- The third and final AMIGO workshop, “Approaches and Challenges for the Use of Geological Information in the Safety Case” was held in Nancy, France in 2008

The technical papers, along with a summary of the discussions and conclusions of each workshop, have been published as NEA reports (NEA, 2004b, 2007, 2009b). In addition to the workshops, an AMIGO questionnaire was developed to compile practical examples of national experience related to the key topics and challenges. The questionnaire aimed to collect descriptions of national experience in applying geoscientific arguments and evidence in safety cases and a report was published that summarised the questionnaire responses: “The Evolving Role of Geoscience in the Safety Case: Responses to the AMIGO Questionnaire” (NEA, 2008). The outcomes of these three workshops and the questionnaire are presented in Appendix B.

Appendix B

Outcomes of the AMIGO workshops and questionnaire

Short summaries and the main conclusions from the three AMIGO workshops and the AMIGO questionnaire are presented below. Many of these conclusions form the basis of the main part of the document.

The first AMIGO workshop: “Geological Disposal: Building Confidence Using Multiple Lines of Evidence”

The first workshop was held in Switzerland in 2003. The topics at AMIGO-1 included the role of the geosphere in disposal concepts, the synthesis of geological information in conceptual models, and the types of safety case arguments that can be derived (or based upon) geological information. Nagra (the Swiss National Cooperative for the Disposal of Radioactive Waste), one of the host organisations, gave a detailed presentation of geoscientific evidence in its recently completed safety case for the opalinus clay. In addition to information on national waste management programmes, the workshop also included presentations on geological research and investigations related to basin modelling and the oil industry. Three working groups considered: (i) the roles of the geosphere in the safety case, (ii) the multiple lines of evidence involved in safety case arguments and (iii) practical guidelines for managing the interaction between different teams in order to build a safety case.

The workshop resulted in the following recommendations:

- Greater efforts may be needed to explain the role and strength of the geosphere – and, thus, the concept of geological disposal itself – to a wider audience.
- Radioactive waste management programmes can usefully consider geophysical techniques and interpretative methods that were developed and originally applied by the hydrocarbon industry and in academia. Experience managing large datasets covering multidisciplinary sources, and in developing associated conceptual models, might also be transferable.
- Better use could be made of some types of geoscientific information, particularly from natural analogues. Although natural analogues cannot generally be used on their own to provide, for example, parameter values for safety assessment models, they can be used to

identify relevant processes and to constrain or provide complementary evidence supporting the selection of parameter values.

- Making geoscientific datasets available in the open literature, to foster their use in new research, may be of benefit.
- An external steering group, a periodic programme peer review, or both, can provide the means of ensuring the relevance of the geoscientific work being carried out by a programme. Regulatory authorities may also participate in the decision-making process to define future investigations and experimental work.

The recent development of radioactive waste disposal programmes illustrates the lessons learnt from programmes such as AMIGO as, since the AMIGO project started, the cross-fertilisation of ideas from other industries has influenced the design and operation of more recent and current site investigation and safety cases.

Second AMIGO workshop: “Linkage of Geoscientific Arguments and Evidence in Supporting the Safety Case”

The second AMIGO workshop was held in Canada in 2005. The workshop expanded upon the AMIGO-1 deliberations to examine how geoscience information and evidence are linked to create a unified and consistent description of the geosphere (often referred to as a *geosynthesis* or *site descriptive model (SDM)*) to support a safety case. It also examined the extrapolation and transfer of geoscientific information in time and space, and some practicalities of collecting, linking, and communicating this information.

The host organisations, including Ontario Power Generation (OPG) and the Canadian Nuclear Safety Commission (CNSC), described geoscience research undertaken within the Canadian Deep Geologic Repository Technology Program and relevant regulatory guidance being developed. Four working groups considered the topics: (i) geoscience indicators for safety, (ii) communication of geoscience safety arguments, (iii) the realities of site investigation and (iv) the assembly and integration of geoscience knowledge and arguments.

The conclusions and recommendations from the AMIGO-2 workshop, including working group discussions, were:

- Presenting geoscience investigation results is not a goal in itself; it is indispensable to present the understanding of the results and explain how they affect safety. Geoscience evidence and arguments can be related to key safety functions served by the geological host formation (these are discussed in greater detail in the section on “Arguments and indicators of safety”).
- Confidence in geoscientific data for a potential host site enhances the ability of regulators to make a credible and defensible licensing decision. Effective interactions between regulators and implementers are essential.

- The transfer of data and information from underground research laboratories (URLs), analogues and other sites is a valuable means of filling gaps in the data, of increasing the level of understanding, and of promoting the development of investigative tools and the identification of model requirements. The transfer of such data must follow a pre-defined and logical structure.
- Uncertainty is likely to be most effectively reduced or constrained by using arguments based on multiple lines of evidence and studies of the past evolution of a site. Such arguments can only take place efficiently in fora that allow multidisciplinary discussions and reviews.

The third AMIGO workshop: “Approaches and Challenges for the Use of Geological Information in the Safety Case”

The third AMIGO workshop took place in France in April 2008. The workshop continued the themes of the first two AMIGO workshops, and also considered the links and feedback, in developing a safety case, among site characterisation; the safety concept; engineering aspects of repository design, construction and operation; and safety assessment (NEA, 2009b). It also took account of the outcomes of the AMIGO questionnaire initiative (NEA, 2008) (see following section of this report). Detailed presentations were provided on the collection and application of geosciences data by the French agencies Andra (National Radioactive Waste Management Agency) and IRSN (Institute for Radiation Protection and Nuclear Safety).

The workshop highlighted specific examples of how geoscientific evidence and arguments are increasingly being incorporated in safety assessments and in safety cases. This has been achieved by, notably, the emergence of geosynthesis as a platform to synthesise wide-ranging information and consolidate understanding; and by more effective communication between the geoscientists and safety assessors. Examples were also given of how the safety concept and repository design are adapted to site-specific conditions, guided, for example, by safety-related criteria on the properties of the host rock that make it suitable for repository construction or waste emplacement. There is thus a strong link between the safety concept and associated repository design on the one hand, and site characterisation on the other.

The general conclusions of AMIGO-3 overlap to a large extent with those of previous workshops in the AMIGO and earlier GEOTRAP projects. In particular, all the workshops indicated the need for multidisciplinary integration in order to plan site investigations, synthesise geological information and use this information in safety cases. AMIGO-3 provided practical and encouraging examples of progress in achieving integration in practice in several national programmes. These included the increasing use of integration groups to identify and address gaps in knowledge and understanding and the development of project tools and methods to support integration, such as the phenomenological analysis of repository situations (PARS/APSS) developed by Andra and the safety function approach applied by SKB, the Swedish Nuclear Fuel and Waste Management Company.

A recurring theme at the AMIGO-3 workshop was, indeed, the use of safety functions, “safety statements” or similar concepts to organise geoscientific information according to its safety relevance and to prioritise R&D and site characterisation work to address knowledge gaps or uncertainties in safety cases. The “language” of safety functions can provide a valuable tool for communicating between safety assessors, geoscientists and also stakeholders. At Andra, for example, safety functions and associated indicators have been developed collaboratively by designers, safety assessors and scientists. Similarly, the safety statements used by ONDRAF/NIRAS (Belgian Agency for Radioactive Waste and Enriched Fissile Materials) were developed collaboratively by safety assessors and geoscientists. It was noted, however, that the primary aim of R&D and site characterisation work is to understand the site and its evolution in the presence of a repository; care should be taken that investigations are not unduly biased by assumptions regarding the expected function of the geosphere in the safety concept and safety case.

Responses to the AMIGO questionnaire

As described earlier, an AMIGO questionnaire was developed following the AMIGO-2 workshop (see NEA, 2007 and NEA, 2008). The questionnaire aimed to collect descriptions of national experience in applying geoscientific arguments and evidence in safety cases. This includes, for example:

- How geosciences investigations are planned.
- How multidisciplinary information is integrated.
- What approaches are used to constrain uncertainty.
- What techniques are applied to communicate the interpretation and understanding of the synthesised results.

The questionnaire also gathered practical examples of specific geoscientific lines of evidence that directly support or convey confidence in the repository performance for various national safety concepts and geological settings. The questions were intended to apply to any type of geological environment. Moreover, the questionnaire emphasised how geoscientific information provides overall support to a safety case, and was not restricted to geoscientific data that might be supplied for use in safety assessment models.

Responses to the questionnaire came from 17 organisations, representing both implementing and regulatory agencies from 12 national programmes covering a range of repository concepts in different host rocks and at various stages of development. The conclusions related to two main topics (NEA, 2008):

- Geoscientific lines of reasoning
 - The national examples showed that geoscientific information can make consequential contributions to a safety case. No single argument can prove definitively that safety is assured, but a range of geoscientific evidence and reasoning are used to support some key aspects of the repository safety concept or safety case. Furthermore, experience demonstrated that such evidence can provide a more intuitive basis for explaining and demonstrating

- site-specific, long-term safety to both scientific and non-technical audiences.
- While most examples are specific to a particular site or disposal concept, many are more broadly applicable.
- Geosynthesis
 - The results highlighted the power of a geosynthesis or other similar site descriptive model: the integration of independent geoscientific information provides an effective and scientifically-defensible approach for increasing confidence in the performance of the geosphere. That is, key elements of the safety case may be supported by a number of observations from different disciplines that coalesce to a single important conclusion.
 - 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 in the development of a geosynthesis is the identification and treatment of uncertainties.
 - One of the most important products of such an approach at a potential repository site is information regarding the past and future stability of the geosphere, for which palaeohydrogeological arguments are likely to prove of great importance.¹¹

Like the workshops, the questionnaire results reinforced the importance of good communication and co-operation between geoscientists and performance assessment personnel.

11. The subject of geosphere stability is discussed in more detail in the two reports produced as part of the Geosphere Stability project (NEA, 2004a, 2009a). As discussed elsewhere in this report, there is thus a strong link between the NEA AMIGO and Geosphere Stability projects.

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