INTRODUCTION

AMIGO and its objectives

The OECD/NEA Integration Group for the Safety Case (IGSC) is a technical advisory body to the OECD/NEA Radioactive Waste Management Committee. The IGSC brings together national programmes that are investigating the deep geological disposal of long-lived and high-level radioactive waste, and its focus is on the science and technology underlying long-term repository safety and on methods to improve confidence in repository safety cases. A repository "safety case" is defined as a synthesis of evidence, analyses and arguments that quantify and substantiate a claim that the repository is safe. It typically provides a comprehensive and specialised assessment of the expected long-term safety and potential impacts of a radioactive waste repository.

For deep geological disposal, studies of the geosphere form a principal component of the safety case. Accordingly, the IGSC has sponsored the AMIGO programme,[1] an OECD/NEA international project on Approaches and Methods for Integrating Geological Information in the Safety Case. AMIGO is concerned with the collection and integration of geoscience evidence, analyses and arguments that contribute to an understanding of long-term safety. The project is devoted to the exchange of information and in-depth discussions 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.

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 paleohydrogeology. 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 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 related to geoscience, the safety case may support a decision to proceed to site selection, to construction, to an operational stage and, eventually, to closure of the disposal facility.

The objectives of the AMIGO project are:

- To understand the state of the art and identify means to improve the ways in which safety cases are supported by geological information.
- To contribute to the development of methods for representing the geosphere in safety cases.

1. AMIGO foundation document. Mode of Operation of Work of AMIGO: OECD/NEA International Project on Approaches and Methods for Integrating Geologic Information in the Safety Case. NEA report NEA/RWM/IGSC(2002)9, April 2003.

- To define terminology for communication and interaction between groups engaged in site characterisation and safety assessment in support of safety cases.
- To clarify the role and application of geoscientific information and evidence applied in safety cases.
- To clarify the relationship between 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 is structured as a series of workshops. Together with the results of a detailed AMIGO questionnaire (see the section entitled, "AMIGO questionnaire"), the outcomes of the workshops provide guidance on how geological information can be collected, synthesised and applied to reach conclusions and to build confidence in safety cases for deep geological disposal.

A significant part of the agenda of each workshop has been a session devoted to the presentation of a recently completed safety case, together with supporting geoscientific evidence, by the host (or co-host) organisation. There have been two main benefits of these presentations: (i) they have triggered discussions at the workshops by giving detailed insight into a specific safety case and (ii) they have provided the opportunity for the host organisation to expose its work to informal review and discussion. Other sessions in each workshop have included keynote presentations from workers outside the field of radioactive waste management, oral contributions and posters giving examples of other safety cases or of ongoing efforts in safety assessment, and working group sessions for intensive discussions on the main workshop themes.

This document summarises the third and last workshop of the AMIGO series, held at the *École des Mines*, Nancy, France, on 15-17 April 2008, and hosted by the French National Agency for Radioactive Waste Management (Andra).

Previous AMIGO workshops and the AMIGO questionnaire

AMIGO-1 Workshop: Geological Disposal: Building Confidence Using Multiple Lines of Evidence

The first workshop, AMIGO-1, was held at Yverdon-les-Bains, Switzerland, on 3-5 June 2003, and was hosted by the Swiss National Cooperative for the Disposal of Radioactive Waste (Nagra), the Swiss Federal Nuclear Safety Inspectorate (HSK) and the University of Bern. The workshop focused on building confidence in analyses and arguments that support the safety case, including the use of multiple lines of evidence. A safety case for the disposal of spent fuel, high-level vitrified waste, and long-lived intermediate-level waste in the Opalinus Clay formation of northeast Switzerland was presented in detail by Nagra. The topics addressed 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.

The following recommendations were made in the workshop synthesis.

- Greater efforts may be needed to explain the role and strength of the geosphere, and thus of the concept of geological disposal itself, to a wider audience.
- Radioactive waste management programmes can usefully consider new and innovative geophysical techniques and interpretative methods developed and applied by the hydrocarbon industry and from academia. For example, the growing importance of 3-D seismic methods was noted at the workshop.

- Radioactive waste management programmes can also usefully draw on experience from the hydrocarbon industry and from academia in managing and organising large geological datasets from multi-disciplinary sources, and developing conceptual models.
- Better use could be made of some types of geoscientific information, particularly that from natural analogues. Although natural analogues cannot generally be used on their own to provide, say, 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. Other "multiple lines of evidence" should also be fully explored.
- 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 means to ensure the relevance of the geoscientific work being carried out by a programme. The licensing authorities may also participate in the decision making process for future investigations and experimental work.

It was also noted that the description or conceptual model of the site is sometimes presented in the form of a "geosynthesis" document, which forms part of the overall documentation of a safety case and includes a thorough description of the inter-disciplinary analysis and interpretation work underpinning its findings. The construction of a geosynthesis was examined in more detail at the AMIGO-2 workshop.

AMIGO-2 Workshop: Linkage of Geoscientific Arguments and Evidence in Supporting the Safety Case

AMIGO-2 was held in Toronto, Canada, on 22-25 September 2005 and was hosted by Ontario Power Generation (OPG) and the Canadian Nuclear Safety Commission (CNSC). The workshop expanded upon the AMIGO-1 deliberations to examine how geoscience arguments and evidence are assembled and linked to create a unified and consistent description of the geosphere (i.e. a geosynthesis) in support of 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. At the workshop, OPG gave a detailed account of the geoscience research undertaken within the Canadian Deep Geologic Repository Technology Program and CNSC described geoscience and related topics in the context of a forthcoming Canadian regulatory guide for assessing the long-term safety of radioactive waste management.[2]

Recommendations made in the workshop synthesis were as follows:

- All (geoscientific) studies require thorough documentation that meets stringent requirements for transparency, clarity, quality control and quality assurance.
- The uniqueness issue can be very problematic. Generally, uncertainties can be reduced with more data and better understanding. However, it may not be possible to eliminate outright all feasible options and it would then be prudent to examine systematically such options in the safety case. Often simple scoping studies might suffice to show that many options need not be carried forward because, for example, they do not lead to or imply any significant impact in the repository evolution or performance.

2. This document has since been issued as "Assessing the Long Term Safety of Radioactive Waste Management," Regulatory Guide G-320, Canadian Nuclear Safety Commission, December 2006. See: www.nuclearsafety.gc.ca/pubs_catalogue/uploads/G-320_Final_e.pdf.

- An explanation of current groundwater composition requires an integration of hydrochemistry and hydrogeology within a context of past geological events. It must also deal with uncertainties, notably those associated with system heterogeneity and the initial and boundary conditions. The benefits of this "geohistory" approach include prediction of future groundwater evolution and conclusions on potential groundwater residence time.
- Transferability of data and information from other sites, laboratories and analogues is a valuable means to fill gaps in data and understanding (especially at early states), to confirm important observations and conclusions, and to promote development of investigative tools and identification of model requirements.
- The transfer of data should not be *ad hoc* but follow a predefined logical structure. Uncertainties arising from the transfer of data and information are best minimised if there exists a fundamental basis that allows valid transfers. That is, the transfer of data and information must be justified using basic scientific arguments; these arguments may differ for different types of host rocks. In the case of argillaceous rocks, transfer is most transparent for parameters and features that do not depend on formation properties and physical states; more difficult but still feasible for parameters and features that depend on a limited number of formation properties (mineralogy and porosity); and difficult to impossible when physical states are dissimilar. Well-reasoned scientific arguments can likely be developed for other sedimentary rocks and for crystalline rocks.
- Effective interactions between regulators and implementers are essential to facilitate the review processes and to build confidence in the predicted outcomes 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 safety case and supporting documents. This documentation must include elements of quality assurance, describing (for example) the process and results that involve collection, processing 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.
- There are numerous similarities in the geoscience programmes for nuclear waste disposal and for geosequestration of CO_2. There is an opportunity for cross-pollination of information and tools, and certainly for knowledgeable critical review.

The following additional recommendations were made by the AMIGO-2 working groups:

- A useful geoscience focus for demonstrating safety is on the following five broad topics: (i) groundwater flow predictability, (ii) retention of potentially released radionuclides, (iii) predictability of groundwater composition, (iv) mechanical and geological predictability of the host formation, and (v) absence of resources in the host rock. These categories influence the three main roles of the geosphere, which are (1) to provide isolation from the human environment, (2) to prevent, delay and attenuate radionuclide release and (3) to provide a stable chemical and physical environment that is insulated against external perturbations. The most important geoscience argument is a clear understanding of the past geological history at the particular site; this should be consistent with a global understanding of geological evolution and have a broad consensus among independent experts.
- Uncertainty might be effectively reduced or constrained using arguments that are based on multiple lines of evidence and studies of past evolution of the site. These outcomes will require multidisciplinary discussions and review.

Members of the AMIGO Steering Group and the AMIGO-2 Scientific Programme Committee also made several recommendations that were considered during the planning for AMIGO-3, the final workshop of the AMIGO series.

The AMIGO questionnaire

Within the framework of AMIGO, the OECD/NEA undertook to document the current experience in international programmes related to the practical usage and application of geoscientific information that complements analyses of repository safety and that helps convey those notions. The starting point was a questionnaire circulated to national organisations that examined various aspects of geoscience related to approaches to integrate results from different geoscience disciplines and to constrain the understanding of far-field evolution. The key goals of the questionnaire were to:

- Collect examples of geoscientific lines-of-evidence that directly support or convey confidence in the performance of the repository in varied geologic settings.
- Consider techniques used for effective communication of geoscientific reasoning and perspectives that support the safety case for a deep geological repository.
- Identify methods and procedures that provide the geoscientific basis for the safety case, notably the geosynthesis or integration of multi-disciplinary geoscientific information and approaches that can constrain non-uniqueness and uncertainty in the description of the geosphere.
- Explore methods related to planning and organising, to improve the manner in which geoscientific information is collected and communicated.

In total, 17 participating organisations responded to the questionnaire, representing both implementing organisations and regulatory agencies from 12 countries. The responses also reflected a broad cross section of national programmes with a variety of repository concepts in various host rocks and at different stages of development, from conceptual studies to repository siting and licensing.

An overview of responses to the AMIGO Questionnaire was presented at AMIGO-3 in a paper by Jensen and Goodwin. The responses and conclusions drawn from them are described in more detail in a recent NEA publication.[3] An important outcome of the questionnaire was that it provided numerous examples of geoscientific support for site-specific repository concepts in sedimentary and crystalline settings. More than 30 examples were highlighted of the use of geoscientific information that provides supporting evidence to underpin notions of long-term geosphere stability and, barrier performance and safety functions.

As an example of observations and evidence for stability, the self-sealing capacity of the Opalinus Clay in Switzerland following excavation disturbance is supported by:

- Empirical evidence from various structural, hydrogeological and mineralogical studies in northern Switzerland.
- Several laboratory experiments within the Mont Terri Project, including a long-term *in situ* study.
- Crosshole tests which indicate that the interconnectedness of the excavation disturbed zone (EDZ) fracture network is partially restricted.
- Observation of tightness of natural fractures/fracture zones in tunnels where overburden exceeds 200 m.
- Theoretical considerations of the Kozeny-Carman porosity-permeability relationship.

3. The Evolving Roles of Geoscience in the Safety Case: Responses to the AMIGO Questionnaire. A report of the NEA Working Group on Approaches and Methods for Integrating Geological Information in the Safety Case (AMIGO). NEA/RWM/IGSC(2008)2.

These observations and evidence have been used by Nagra to support the notion that a potential repository in the Opalinus Clay can be effectively isolated in the sense that construction of the tunnels does not result in favoured groundwater flow pathways along the EDZ.

As an example of observations and evidence supporting barrier performance, the assumption by Andra that fracturation at different scales does not generate preferential pathways through the French Callovo-Oxfordian argillite (COX) and that radionuclide transport through the COX is diffusion dominated is supported by:

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

The questionnaire also sought out experience related to the communication and management of multi-disciplinary geoscience work programmes that support the repository safety case. The results of the questionnaire provide a broad cross section of experience and provide a snapshot of current practice and future challenges in enhancing the role of geoscience in safety case development. This experience coupled with lessons learnt demonstrates the utility of multi-disciplinary geoscience studies and reasoning in developing convincing and complementary arguments for conveying an understanding of long-term geosphere barrier performance.

Aims and structure of the AMIGO-3 Workshop

The third workshop, “Approaches and Challenges for the use of Geological Information in the Safety Case”, provided a logical continuation of the themes covered by the first two AMIGO workshops. It focused on complementary topics with regard to both the earlier workshops as well as on the outcomes of the AMIGO questionnaire initiative. In recognition of the rapidly increasing interest in repository programmes regarding questions related to the connections between the safety case and design, engineering and construction issues, and its relationship to geoscientific investigations, the workshop also considered the links to repository design.

As in previous AMIGO workshops, Workshop Session I was devoted to the presentation of a recently completed safety case, together with supporting geoscientific evidence, by the co-host organisation, Andra and the French technical support organisation, IRSN. The safety case, “Dossier 2005 Argile”, addresses the disposal of high-level and long-lived radioactive waste in a clay formation, based in particular on work conducted on the site of the Meuse/Haute-Marne Underground Laboratory. The papers presented in this session were as follows:

- **Lebon, P.** Overview of the Disposal Feasibility Assessment in Meuse/Haute-Marne: From the Preliminary Geoscientific Survey to the Safety Case.

- **Plas F. and Vigneron, G.** Integration of the Geoscientific Data in the Safety Case: Methodology and Organization, Justification of the Processes and Models, Choice of the Data.
- **Rocher M., Dehoyos A. and Cushing M.** Dealing with Geological Discontinuities in Safety Assessment: the Approach of the French Technical Support Organisation.
- **Cahen B. and Voinis S.** From the Feasibility Assessment to the Licensing Application: Organisation of the Safety Case: Interactive Development of Engineering/PA/Knowledge Management, Key Issues Addressed to Geosciences.
- **Labalette T. and Landais P.** From the Feasibility Assessment to the Licensing Application: Organisation of the Data Acquisition and Connection to New Safety Rules: Dealing with Metrological Limits, Uncertainties, and Project Milestones.

Session II consisted of four further presentations from other programmes directly related to the themes of the workshop:

- **Andersson J., Gunnarson D., Hedin A., Hellä P., Ikonen A., Munier R., Selroos J.-O. and Wikström L.** Application of Host Rock Classification and Acceptance Criteria for Repository Layout and the Safety Case.
- **Rahn M., Frank E., Altorfer F. and Wanner H.** The Regulatory Perspective: Role of Regulatory Review of the Safety Case and Feedback to Site Investigation.
- **Hatanaka K., Osawa H. and Umeki H.** Geosynthesis: Testing a Safety Case Methodology at Generic Japanese URLs.
- **Beauheim R. I.** Collection and Integration of Geoscience Information to Revise the WIPP Hydrology Conceptual Model.

An overview of responses to the AMIGO questionnaire:

- **Jensen M. and Goodwin B.** Overview of Responses to the AMIGO Questionnaire on the Use of Geoscience in Safety Cases.

A keynote presentation from outside the field of radioactive waste management addressed the issue of modelling global climate changes:

- **Duplessy J-C.** Integrating Components of the Earth System to Model Global Climate Changes.

More technical papers on selected topics were presented in a poster session:

- **Fedor F., Feurer V., Geiger J., Menyhei L. and Szikszai Z.** Management of Mission-Critical Information in Bátaapáti LLW/ILW Project, S-Hungary.
- **Nagy Z.** Aging of Information – A New Source of Uncertainties?
- **De Hoyos A., Viennot P., Ledoux E., Certes C., Rocher M., Gros J-C. and Bodilis S.** *Thermohaline Modeling of the Paris Basin Hydrogeological System.*
- **Geier, J and Lindgren G.** Application of a Discrete-feature Model to Assess Geological Uncertainties in a Regulatory Context.
- **Niizato T., Yasue K.I., Kurikami H., Kawamura M. and Ohi T.** Synthesizing Geoscientific Data into a Site model for Performance Assessment: A Study of the Long-term Evolution of the Geological Environments in and around the Horonobe URL, Hokkaido, Northern Japan.

- **Saegusa H., Osawa H., Onoe H., Takeuchi S. and Takeuchi R.** Stepwise Hydrogeological Characterisation Utilising a Geosynthesis Methodology - A Case Study from the Mizunami Underground Research Laboratory Project.
- **Cushing M., Revil A., Gélis C., Jougnot D., Lemeille F., Cabrera J., De Hoyos A. and Rocher M.** Resistivity Survey Aiming at Identifying Hydrogeologically Active Zones in Limestone and Clay Formations: Application to The Tournemire Experimental Station (Aveyron, France).
- **Smith P., Dierckx A., Capouet M. and Van Geet M.** Safety Statements as a Tool to Incorporate Geoscience in the Safety and Feasibility Case.
- **Rocher M., De Hoyos A., Pellegrini D., Cushing M. and Cabrera J.** Some Considerations from IRSN on the Survey of Hydrogeologically Active Faults Located in the Vicinity of an Underground Radioactive Waste Repository.

The Working Group Sessions addressed three topics:

Topic 1: What are the processes by which information from site characterisation is selected and applied in safety assessment (i.e. scenario development and modelling)?

Topic 2: How are the uncertainties in geological data and scaling issues dealt with in repository design and the safety case? (i.e. modelling)

Topic 3: How does (and to what extent) the development of the repository design and of the safety case influence site characterisation and R&D priorities? (Information flow back from the safety case)

These topics were addressed by four working groups (Working Groups A-D; see Appendix A), with each working group assigned two topics. Further presentations were made to the working groups in order to stimulate discussion:

- **Fedor F., Kovács L., Benkovics I. and Szűcs, I.** The New Conceptual Model in Boda HLW/SF Project, S-Hungary.
- **Kurikami H. and Hyodo H.** Lessons Learnt from Staged Dry Run of Performance Assessment and Repository Design.
- **Mohanty S., Wittmeyer G., Peters G. and Whaley S.** Role of Independent Studies to Address Uncertainty and Their Impacts on Regulatory Interactions.

The workshop concluded with presentations of the main findings of the working groups and a final overall discussion.

In all, more than 50 individuals representing 16 national programmes and international organisations participated in AMIGO-3. Participating organisations at the workshop ranged in maturity from those that are still at a generic stage with no selected host rock to those that are more advanced, including those at the stage of repository operation.

Structure of this document

This document summarises the discussions and conclusions of the AMIGO-3 Workshop. A synthesis of workshop discussions is provided in the following section. The synthesis is structured along the main themes around which the workshop was organised. These themes, which correspond approximately to those topics addressed by the working groups, are:

- Has geoscientific information been effectively integrated and addressed in safety cases?

- To what extent (and how) does geoscientific data influence the development of the safety concept, the repository design, and the safety case?
- To what extent (and how) does the development of the safety case influence R&D priorities and site investigation or other geoscience activities?

The synthesis summarises the views expressed and the examples described in the various presentations, posters and workshop discussions. A summary of workshop outcomes is also provided.

More detailed supporting information is described in several Appendices. Appendix A provides a detailed summary of the discussions and conclusions of each working group related to the main workshop themes. Appendix B lists the workshop participants. The supporting papers for posters and oral presentations can be found in Appendix C.