WORKSHOP SYNTHESIS: MAIN THEMES OF AMIGO-3

The main themes of the workshop, which include the topics covered both by the plenary sessions and Working Group sessions, can be stated as follows:

- 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 following synthesis summarises the main points raised on these themes in the course of the workshop.

Theme 1: Has geoscientific information been effectively integrated and addressed in safety cases?

It is generally acknowledged that geoscientific information plays a fundamental role in safety assessments. It is also increasingly used in the wider context of the safety case to provide evidence and arguments for the intrinsically favourable properties of a site, including its long-term stability. The importance of geoscience to both safety assessment and the safety case was already noted in AMIGO-2. AMIGO-3, however, showed that geoscientific input to the safety case is continuing to evolve and is becoming more significant. No single geoscientific argument “proves” safety, but rather each supports some key element of the safety case and provides enhanced confidence in the safety case. The workshop provided several specific examples of how geoscience is integrated in safety assessment and in the safety case, some of which came from papers prepared specifically for the AMIGO-3 workshop, while others came from the responses to the AMIGO questionnaire on the use of geoscience in safety cases, which were summarised at workshop in an overview paper by Jensen and Goodwin. Further examples came from the discussions of Working Groups A, B and D regarding the processes by which information from site characterisation is selected and applied in safety assessment.

Observations and examples from workshop presentations and papers

The geoscientific information that supports a safety case is highly diverse and is used in a range of different ways. Information includes that from boreholes, geophysics (including 2-D and 3-D seismics), underground rock laboratories, other (surface) laboratories, modelling and literature. Data is used in safety assessments in the development of scenarios, in the choice and justification of modelling assumptions, including the justification of the conservatism of simplifying assumptions where there is uncertainty, and in the selection of parameter values and ranges. Moreover, there are numerous implicit assumptions underlying assessment calculations (e.g. about the stability of the hydrogeological system to be modelled) that need to be justified by geoscientific evidence.

In the safety assessment for Andra Dossier 2005 Argile, Plas and Vigneron gave examples of how:

- Understanding of geological structure, surface topography and groundwater flow was used to identify potential radionuclide migration pathways from the host formation (the Callovo-Oxfordian argillite, or COX) to the biosphere.
- Measurements of diffusion coefficients in the host formation indicated that the COX may be treated as homogeneous porous medium for the purposes of transport pathways.
- Understanding of the thermal evolution of the COX and surrounding formations in the presence of the repository supported the safety assessment assumption that the heat output from the repository has no safety-relevant effects on the geosphere.

In the wider context of the safety case, it was observed at AMIGO-3 (and also at AMIGO-2) that paleohydrogeological arguments are particularly valuable in that they can add to the understanding of some of the most critical processes and mechanisms. It was, however, noted that some geoscientific evidence has not, as yet, been effectively integrated into safety cases, including, for example, diagenetic evidence from a site. It was also observed that many geoscientific arguments have the potential to reach non-technical audiences, and that particularly observations from nature, including natural analogues and site-specific observations, could be better used to communicate the favourable qualities of a site to a range of stakeholders. Arguments should not, however, be over-simplified, as this could undermine the credibility of a safety case.

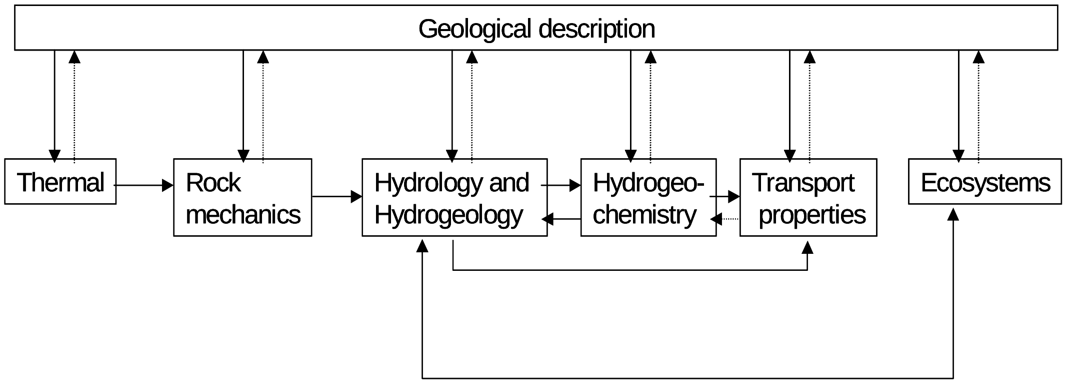
The argumentation for safety is made more powerful by integrating observations from different disciplines that coalesce to a single important conclusion regarding the properties or evolution of the site. Thus, the various types of data from field investigations and associated laboratory studies are brought together to develop an overall description of the site, termed a geosynthesis (or, in the Swedish and Finnish programmes, a site descriptive model).

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

Figure 1 shows an example from Andersson *et al.* of the various elements that are brought together in a geosynthesis, and the relationships between these elements. The result is typically a description of the present state, which describes the characteristics of the rocks from the regional scale to the centimetre scale or smaller, as well as ongoing processes, allowing assessment of the potential disturbances due to repository construction, operation and closure, and the long-term evolution of the geological environment.

The integration process should ensure, as far as possible, completeness in the information that it includes, consistency between information of different types, and should include an assessment of all relevant uncertainties. Several examples were given at the workshop of methods of working and project tools to support these aims. Integration groups are increasingly used, as described, for example, in Cahen and Voinis and in Plas and Vigneron. These consist of specialists in different disciplines, including, for example, those indicated in Figure 1, as well as in safety assessment, engineering and design. The multi-disciplinary nature of the groups fosters dialogue between these disciplines. Their tasks include identifying and addressing gaps in knowledge and understanding, and organising larger or more specialised groups for the development of models and databases for safety assessment, including the identification of uncertainties and the conduct of preparatory calculations.

Figure 1. **Example of the various elements that are brought together in a geosynthesis ("geological description"), and the relationships between these elements** (after Andersson *et al.)*



A geosynthesis will include a range of geological, hydrogeological and other phenomenological models. The development and application of these models serves as a tool to integrate site investigation results, evaluate the impact of uncertainties, provide datasets for safety assessment and design studies and prioritise issues for further investigation (see, e.g. the case study from the Mizunami Underground Research Laboratory Project (Saegusa *et al.*]).

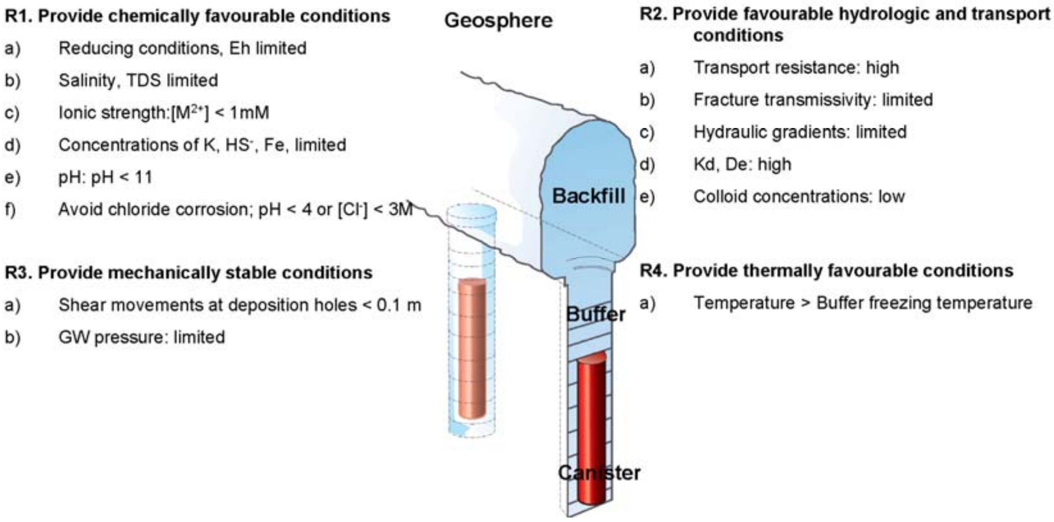
Other project tools and methods described at the workshop that support the integration of geoscientific information in the safety case include:

- The phenomenological analysis of repository situations (PARS/APSS) (Cahen and Voinis, Plas and Vigneron and Labalette and Landais), the aim of which is to integrate multi-disciplinary geoscientific and other data to provide a consistent description of how phenomena may evolve and influence each other in time and space, including both expected and less likely situations.
- Qualitative Safety Assessment (QAS) (Cahen and Voinis, Plas and Vigneron and Labalette and Landais), which involves analysing the effects of uncertainties and risks on the safety functions and on the evolution of the repository, specifying the limits of the normal evolution range, describing situations that can diverge from normal evolution and defining altered evolution scenarios to cover these situations.
- Knowledge management tools to support the reporting, storage and usage of large amounts of information and reports generated in the course of the LLW/ILW Project in Hungary **(**Fedor *et al.* [poster presentation]).
- The development of data flow diagrams and process diagrams that trace the flow of information from their acquisition through to their final use in design studies and in the safety case (Niizato *et al.*).
- Organising geoscientific and other information according to its relevance to a hierarchy of "safety statements", at the highest level of which are statements concerning the evolution of repository safety functions (Smith *et al.*).

- The development of safety function indicator criteria, which are criteria on observable or calculable system parameters that indicate the conditions under which the safety functions of the repository components are expected to be provided, and those under which they could be significantly perturbed (Andersson *et al.*).

SKB safety functions, safety function indicators and associated criteria for the geosphere are illustrated in Figure 2.

Figure 2. **SKB safety functions, safety function indicators and associated criteria for the geosphere** (after Andersson *et al.)*



A specific issue to be considered is the age of the information used, and its relationship to confidence in that information. A safety case compiled at the advanced stages of a programme may make use of information acquired at much earlier stages of a programme, and that programme may span several decades. However, this requires that compilers of the safety case retain an adequate level of confidence in this information. Nagy described the potential decrease in the confidence in information over time, and how such a decrease can be reduced or avoided. This issue was also addressed in the working group discussions (below).

There was some discussion of the role of natural analogues compared with site-specific geoscientific information. A distinction was suggested between "process analogues", which support arguments for which direct evidence may not be available at a site (e.g. uranium deposits giving evidence for the limited mobility of uranium under certain conditions), and "site analogues", which are believed to closely resemble a site in that they share most or all of its relevant properties. An example of a site analogue is the Mont Terri rock laboratory as a site analogue for the Opalinus Clay in the Zürcher Weinland of Northern Switzerland, which has been studied by Nagra as a potential host rock for a geological repository for spent fuel, vitrified high-level waste and long-lived intermediate-level waste. Rocher *et al.* also discussed the Tournemire Toarcian clay formation as an analogue for the Callovo-Oxfordian argillite (COX), which has been used by IRSN in its studies of the tectonic fracturing of clay, carried out in its preparation for review of "Dossier 2005 Argile". Due, for example, to possible differences in burial history (and seismotectonic context) compared with the COX. IRSN does not use the studies at the Tournemire site to draw definitive conclusions on the characteristics of the COX; it recognises that these can only be obtained using site-specific studies. Rather, such studies are used draw the attention of Andra, the implementer, to particular processes that may require further investigation and tools that may be helpful to perform such investigations.

There is an apparent trend towards maintaining a clear separation between the development of a geosynthesis, which aims to be as realistic as possible, and safety assessment, in which, if the aim is compliance demonstration, a deliberate conservative bias is often introduced, generally as a means of dealing with certain poorly understood phenomena and poorly quantifiable uncertainties, or a lack of suitable realistic models or databases. Conservatism may, in any case, not be an easy concept to define, at least for some of the models and databases within a geosynthesis. These 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.

Nevertheless, some differences were apparent from the discussions in the scope of the geosynthesis documents prepared by different organisations. The Nagra geosynthesis prepared for the Swiss Project Opalinus Clay, for example, included, in a single document, not only pure geoscientific data and understanding, but also recommended input data for safety assessment, involving a degree of abstraction for safety assessment modelling purposes. On the other hand, the link between the Site Descriptive Model prepared by SKB for the Swedish SR-Can safety assessment and the safety assessment itself was provided by a dedicated data report, thus maintaining a clear separation between geoscience and safety assessment modelling. Similarly, as described in the paper and oral presentation by Lebon, the geosynthesis prepared by Andra for the French "Dossier 2005 Argile" included two documents – one focussing on geoscientific information and another providing the justification for safety assessment modelling assumptions.

Working group discussions on the processes by which information from site characterisation is selected and applied in safety assessment

Working Groups A, B and D discussed this topic. The working groups considered how safety assessors need to identify and address those geological features, events and processes that are safety relevant. The identification of such features, events and processes is iterative, and involves both the safety assessors themselves and site characterisation experts. The report of Working Group B gives some examples of how new findings can emerge during site characterisation that lead to the consideration of new processes. However, irrespective of the direct needs of the safety case, a comprehensive understanding of a site needs to be developed, which may exceed the understanding directly required to address safety and feasibility questions.

The processes by which information from site characterisation is selected and applied in 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 features. The important role of FEP catalogues was also noted by Working Group A. The FEPCAT catalogue can, in particular, be used to relate site-specific geoscience attributes that influence far-field performance and their relative importance with respect to assessment of mass transport and long-term barrier integrity (erosion, palaeohydrogeology, mineral diagenesis, fault sealing etc). FEPCAT was developed by the NEA Working Group on the Characterisation, the Understanding and the Performance of Argillaceous Rocks as Repository Host Formations (known as "Clay Club").

A distinction was drawn by Working Group D between "hard" information, which can be measured and used as input data for safety assessment calculations, and "soft" information, such as sedimentation facies or paleohydrogeological information, which is not directly used in the safety assessment but is important in the wider context of the safety case (e.g. to provide arguments for the old age of the groundwater or for the long-term stability of a site). The groups discussed the roles of natural analogues and how information from studies of palaeogeology, paleohydrogeology, and paleohydrogeochemistry can support safety assessment by serving as a basis for extrapolation in time. It was noted that a safety case can sometimes use observations from nature that indicate potential reactions of a geological environment to disturbances caused by the repository, by using information about disturbances that occurred in the past (e.g. basaltic intrusions at the Gorleben salt dome, which show that highly elevated temperatures caused only limited alterations in sodium-rich rock salt).

Uncertainties in the information from site characterisation propagate via a chain of arguments, simplifying assumptions etc. to the models and data used in safety assessment calculations. These uncertainties, their propagation and their impact on assessment results also need to be acknowledged and documented in a safety case. Tools such as the safety function indicator criteria used by SKB and Posiva, the ONDRAF/NIRAS safety statements and the sensitivity analyses used generally in safety assessments were acknowledged by the working groups as valuable means to indentify those areas where uncertainty reduction is a priority for the safety case. The Andra PARS methodology also identifies uncertainty reduction is a priority, although this is a “by-product” of its application and not a main objective.

It was noted that the need for traceability has to be managed early in a project to avoid the task becoming too onerous, as mentioned by Working Group D. 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 to maintain memory of all relevant information, ensure traceability of knowledge as a programme progresses through successive stages and assist future personnel engaged in the project to understand past work fully. This, in turn, should minimise the possibility of unnecessary repetition of past work.

Working Group B noted a number of problem areas that 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” output such as estimated doses, there has been incomplete integration of site characterisation data and evidence that do not directly inform such calculations, even if the data could contribute other important lines of evidence in the safety case. Furthermore, site characterisation programmes have sometimes tended to be driven by the managerial and practical aspects of accomplishing field operations, resulting in safety assessment needs not being fully met. Such problem areas have largely been resolved by better integration of site characterisation and safety assessment in most disposal programmes, with geosynthesis playing an important role in linking the two activities. A detailed description of working group discussions is provided in Appendix A.

Theme 2: To what extent (and how) does geoscientific data influence the development of the safety concept, the repository design, and the safety case?

At a certain stage in a repository development programme, the safety concept and repository design must be adapted to site-specific conditions. These conditions are characterised in increasing detail in a step-wise manner as a programme proceeds, and the design and layout may, therefore, be fully specified only at a relatively later programme stage, and may to some extent be adapted to additional information about the rock as it is acquired. The safety case is developed in parallel with, and consistent with the results of, site characterisation, and may also, in some cases, be updated after repository operations have begun, as further geoscientific information becomes available from the monitoring programme, for example, on the impact of construction and operation on groundwater flow and geochemistry. 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 uncertainties. The workshop papers provided examples from programmes at different stages of how the availability of geoscientific data is taken into account in the safety concept, the repository design, and the safety case. Working Groups A, C and D also considered the issue of how uncertainties in geological data and scaling issues are dealt with in repository design and in the safety case.

Observations and examples from workshop presentations and papers

The Japanese high-level waste programme is still at a generic study stage. Japan has an "open solicitation" approach to site selection, and is currently awaiting one or more volunteer host communities. In the interim, NUMO is conducting a dry run based on a hypothetical site to gain experience in how the geoscientific information that will be acquired in the course of different programme stages (literature survey, preliminary investigation from the surface and detailed investigation from underground) will be used in safety assessment and can guide repository layout studies, including what is the critical information to be sought at each stage (Kurikami and Hyodo).

By contrast, site characterisation for the Waste Isolation Pilot Plant (WIPP) in New Mexico, USA, began over 30 years ago. The facility was certified for disposal of transuranic and mixed waste in 1998 and has been in operation since 1999. A periodic update of the license application is, however, required by the WIPP regulator, the Environmental Protection Agency (EPA). As described in Beauheim, the hydrological conceptual model has been revised in response to the findings of geoscientific investigations conducted since the original 1996 licence application. For example, monitoring of water levels and rainfall at high temporal resolution has shown that water levels in the Culebra Dolomite are much more affected by rainfall than previously believed. A revised model has been developed to account for such observations. The model is more complete and comprehensive than that developed for the original licence application, but the changes implemented have no impact on WIPP compliance with regulations. However, because of all the changes made to the Culebra model, EPA has requested a peer review of the Culebra conceptual model, which is scheduled for August 2008. The peer-reviewed model will be used in future recertification applications to authorise continued operation of the disposal facility.

The process of adapting a repository design to increasing amounts of site-specific information can be guided by 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. Figure 3 illustrates how the role of geoscientific data and associated criteria in the design process will vary according to the stage reached in repository planning and implementation. As described in Andersson *et al.*, they 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 to construct a tunnel, to bore a specific deposition hole, and to use the hole for waste emplacement.

In the Swedish and Finnish programmes, criteria on the host rock are derived from the general safety functions that the host rock should provide. The criteria, which are defined in terms of observable properties of the host rock, are still under discussion. They are site and concept specific and are expected to be closely related to the safety function indicator criteria described in the previous section. The specific example of how observations of fracture intersections with underground excavations and more general understanding related to earthquakes influence the development of both repository design and safety assessment is described in detail in Andersson *et al.* In terms of design, such observations and understanding are expected to allow the location of deposition holes in the Swedish/Finnish KBS-3V repository concept to be chosen so as to reduce (but not entirely exclude) the possibility of canister shear failure due to secondary movements on fractures in the event of a large earthquake. In terms of safety assessment, they provide a basis for the rate at which it is assumed that canisters in a repository undergo such failures in the event that some fractures with the potential to undergo significant shear movements are not identified and avoided by design. The example illustrates how such criteria may need to strike a balance, being, on the one hand, sufficient to reduce the likelihood or severity of some adverse phenomena, and, on the other hand, not overly restrictive, which could otherwise make identifying and selecting a suitable host rock volume difficult or impossible.

Figure 3. **Illustration of how the role of geoscientific data and associated criteria in the design process will vary according to the stage reached in repository planning and implementation** (after Anderson *et al.*)

Before construction	**During construction**			
	Pilot hole for disposal tunnel	**Disposal tunnel**	**Pilot hole for deposition hole**	**Deposition hole**
Aims • Define suitable volumes for disposal • Estimate number of potential canister positions within these volumes	**Aims** • Estimate number of potential canister positions within the tunnel	**Aims** • Locate potential canister positions within the tunnel	**Aims** • Confirm the suitability of deposition hole	**Aims** • Confirm the suitability of deposition hole
Available information • Site characterisation data • Site models	**Available information** • Pilot hole data • Site models	**Available information** • Tunnel data • Site models	**Available information** • Pilot hole data • Site models	**Available information** • Deposition hole data • Site models
Results • Repository layout • Possible conditions at deposition holes for safety analysis	**Results** • Decision on construct the tunnel • Estimate of canister positions	**Results** • Potential canister positions	**Results** • Decision to bore the deposition hole	**Results** • Decision on use of the deposition hole

Working group discussions on how uncertainties in geological data and scaling issues are dealt with in repository design and in the safety case

Working Groups A, C and D discussed this topic. The working groups considered how the management of uncertainties in geoscientific and other data can include:

- Reducing uncertainties by further R&D and site characterisation.
- Avoiding or mitigating them, e.g. by appropriate siting and design choices.
- Analysing their significance by means of safety assessment.

The working groups agreed that a range of approaches for handling uncertainties can have a role in a safety case, including probabilistic and stochastic approaches, as well as deterministic calculations, for handling of data uncertainties and the application of alternative models where more than one model is consistent with available understanding. Conservatism is also widely used, although Working Group D noted some limitations and difficulties, such as the fact that a particular assumption may be conservative with respect to some safety-relevant processes, but not to others, so that the overall conservatism of the assumption may not be ensured. Probabilistic and deterministic approaches can be used together in a complementary fashion,[1] although there is a tendency to shift from a deterministic towards a more probabilistic approach as information is acquired and the basis for probability density function (PDF) becomes better justified. Working Group A also noted that it can be beneficial, even at an early, generic stage of a programme, to use probabilistic calculations to analyse parameter sensitivity and identify favourable characteristics for a repository location or to determine where 'real' knowledge of parameter values is most crucial as an input to research or site investigation programmes. Working Group C suggested that it could be useful to split up the post-closure period into discrete time intervals,

1. This was also pointed out at the NEA workshop on the management of uncertainty in safety cases and the role of risk (NEA/RWM/IGSC(2004)15.

during which may differ the significance and likelihood of uncertain processes and events that could influence evolution and performance, although it also noted that the applicability of this approach needs to be judged on a case-by-case basis. Working Group C also discussed the use of “what-if?” scenarios or assessment cases, particularly to deal with situations where expert opinion is divided as to whether, say, a specific type of geological feature could exist or a process or event could take place. The working group noted the need for a clear structure and presentation of the rationale behind such scenarios in the safety case. The relative importance of the approaches chosen for handling uncertainties and, in particular, of probabilistic compared with deterministic modelling may also be conditioned by the regulatory framework (in particular, whether or not a risk target is specified) and may be the subject of dialogue between the implementer and regulator.

One specific source of uncertainty is the temporal and spatial scaling that is required so that data measured in small-scale or short-term experiments can be applied in safety assessments. Both require proper justification in terms of the methods or assumptions used. Temporal scaling can be challenging in view of the long timescales covered by safety cases, although repository sites are generally chosen such that most rock properties change very slowly. Working Group A gave several examples of natural safety indicators that can be used to justify and strengthen certain aspects of the safety case related to long timescales, and also emphasised the use of site-specific multiple lines of evidence in this context. These examples include groundwater age and travel times through the geosphere to the biosphere, the spatial distribution of hydraulic properties such as over- and under-pressurisation, location of recharge and discharge areas and hydraulic gradients, groundwater composition and isotope signatures. The issue of spatial scaling is related to the treatment of spatial heterogeneity in safety assessment. Working Group A noted that spatial heterogeneity needs to be represented only to the extent that it is important in understanding the performance of a repository system.

The working groups gave some specific examples of how geological features and uncertainties have affected the choice of site (although the range and number of options available depends on the national programme), repository concept (particularly the emphasis on the engineered versus the geological barrier), construction techniques and the adaptation of repository layout according to local characteristics of the rock. An example is the use of drilling rather than blasting for tunnelling to avoid or limit the development of an excavation disturbed zone (EDZ), the characteristics of which may be highly uncertain. Design changes to mitigate one source of uncertainty can sometimes give rise to additional processes and hence to other additional uncertainties; for example, the proposed use of low pH grouts to avoid degradation of a bentonite buffer means that uncertainties related to the impact of superplasticisers[2] on the natural and engineered barriers needs to be considered. The working groups also noted that a key aim in both site characterisation and repository design is to avoid, or at least reduce as far as practicable given the competing needs for thorough characterisation, engineering feasibility etc., perturbations to favourable characteristics of the rock, and that those perturbations that are unavoidable need to be addressed in the safety case. Working Group C noted that, in view of the uncertainties in the characteristics of a site that may exist throughout a programme, it is in the interests of the implementer to maintain some flexibility in repository design for as long as possible.

Theme 3: To what extent (and how) does the development of the safety case influence R&D priorities and site investigation or other geoscience activities?

As programmes progress, any important gaps or weaknesses in the safety case must by identified, prioritised and addressed in the subsequent R&D programme (see, e.g. Cahen and Voinis and Plas and Vigneron). There is also an increasing emphasis on specifying the repository layout and ensuring

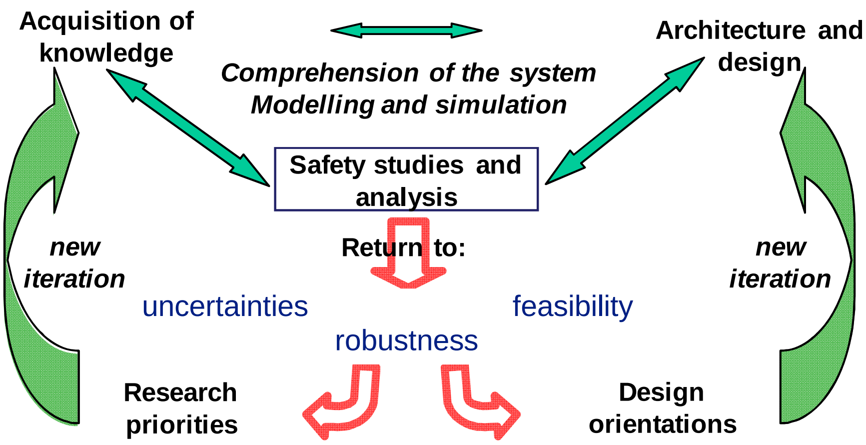
2. Superplasticers are chemical admixtures that can be added to cement to improve workability. [http://en.wikipedia.org/wiki/Concrete#Workability].

engineering feasibility. These developments have implications for the types of data required from geoscientific investigations. The workshop papers provided examples of the feedback from safety assessment calculations and the compilation of safety cases to site investigation. Working Groups B and C also considered how, and to what extent, the development of the repository design and the safety case influence site characterisation and R&D priorities.

Observations and examples from workshop presentations and papers

All programmes adopt an iterative approach to safety studies and analysis, design and the acquisition of knowledge, with safety studies and analysis playing a driving role (see, e.g. Figure 4). This iterative approach can also include the iterative development of acceptance criteria to guide repository design. As the process proceeds, requirements initially defined may need to be revised. Safety assessment calculations may, for example, reveal a need to make the criteria stricter, e.g. because of an unacceptably high likelihood of detrimental effects from geological phenomena on the engineered barrier system (Andersson *et al.*). On the other hand, some less essential criteria may be relaxed if they are found to prohibit repository implementation, provided operational and long-term safety can be shown not to be compromised.

Figure 4. **The role of safety studies and analysis in the iterative approach**
(after Lebon, Plas and Vigneron and Cahen and Voinis)



Andra disposal feasibility assessment for the Meuse/Haute-Marne potential siting area in France consisted of three phases of iterative knowledge acquisition, design development and safety studies, with project milestones in 1996 (URL licensing application), 2001 (intermediate report) and 2005 (feasibility assessment – "Dossier 2005 Argile") (Lebon). At each milestone, research priorities (including priorities in site investigation) and design issues to be addressed in the next phase were identified both by the implementer and by the safety authority in its review of the safety studies.

At the end of the first phase, safety assessment results indicated that diffusion-dominated transport in the Callovo-Oxfordian argillite (COX) provides a powerful radionuclide transport barrier, but confidence in this finding would be enhanced if the transport significance of the discrete fractures that certainly exist in this formation could be clarified. Thus, in subsequent phases leading up to the production of "Dossier 2005 Argile", the emphasis has been on understanding the site-specific properties of the host rock, including, in the most recent phase (2002-2005), an extensive programme of studies in an underground rock laboratory (URL).

The importance of the possible existence of structures that may exist in the COX, and their role in groundwater flow and radionuclide transport, has also been identified by IRSN, and has been addressed in studies to prepare for its review of “Dossier 2005 Argile” (Rocher *et al.* [2 papers]). IRSN developed its own geological and hydrogeological model of the Meuse/Haute-Marne area and found that consistency of the model with available hydraulic head and salinity measurements requires the explicit representation of water-conducting features in the model (De Hoyos *et al.*). IRSN also conducted a modelling to examine the effects of the existence of a hypothetical water-conducting fault on the performance of the geosphere barrier, and, in view of the uncertainties in this study, concluded that improvements in detection techniques for such features would improve confidence in a safety case. IRSN is currently testing various methods to detect hydrogeologically active faults in limestone at its Tournemire station that are complementary to the more standard methods of geological and geophysical surveys (e.g. electrical resistivity tomography, ERT [Cushing *et al.*]).

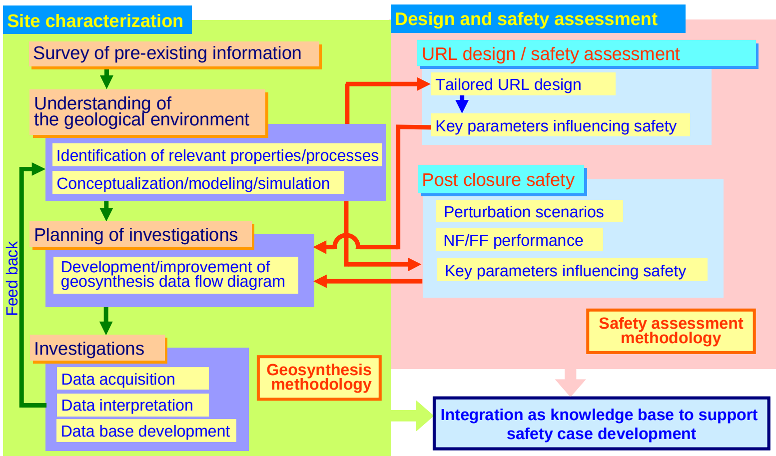
The iterative process illustrated in Figure 4 is continuing beyond the “Dossier 2005 Argile”. Open questions identified by Andra in studies that support this safety case identified the need for better understanding of some aspects of system evolution in preparation for a license application foreseen for 2015 [Cahen and Voinis] and [Labalette and Landais]. The sedimentation history of the site has, for example, been identified as a key issue for further study. In “Dossier 2005 Argile”, the interpretations of classical well logs suggest the possible occurrence of sedimentation hiatus, with potential consequences for the safety-relevant properties of the host formation. Other uncertainties related to long-term safety that will also need to be addressed include those associated gas migration pathways, the chemical perturbations undergone by the host formation due to the exogenous materials placed within it, the impact of the duration of operating phase on the properties of the formation and the effects of complexants in waste packages on radionuclide transport. The review of the assessment by the French national review board (CNE) and the safety authority (ASN), though favourable, also identified a need for more realistic modelling of some aspects of system evolution in future assessments, including, for example, the saturation of the repository and the migration properties of the excavation disturbed zone (EDZ).

These open questions and the modelling needs have influenced the organisation of the research programme that was set up by Andra in early 2007 to support a move from feasibility studies to studies supporting licensing. Remaining uncertainties are being addressed, for example, by conducting more detailed site characterisation (e.g. the use of FMI – fullbore formation micro-imaging – to examine the deposition history of the site at a higher resolution than was possible with classical well logs), experiments over longer periods of time, and complex, integrated experiments addressing the interactions of several system components. The further consolidation of existing and future THMC data acquired within the Meuse/Haute-Marne URL from diffusion, thermal, retention and other experiment remains a challenging issue for the future. The results of “Dossier 2005 Argile” and the recommendations of reviewers are leading Andra to re-evaluate certain aspects of repository design. A strategy will also need to be developed to manage the balance between operational risks related to accidental situations identified in “Dossier 2005 Argile”– such as the risk of explosion due to the accumulation of radiolytic hydrogen gas – and post-closure perturbations and events, such the impact of gas production on hydraulic evolution. An overall objective of these studies is to anticipate questions from scientific reviewers and other stakeholders, even if these questions are not always significant for repository safety. The studies must address significant challenges (e.g. limited experimental time frames, the issue of the how well complex experiments represent real systems and how to integrate the results in a safety case). Confidence in the safety case must be built on a sound scientific basis that addresses all relevant issues, and the more difficult issues may necessitate sophisticated approaches and complex experiments.

Several examples were given of how safety assessment modelling can be used to identify geoscientific information requirements. An example from the Andra programme is the issue of the safety-relevance of the degradation of repository shaft seals. The function of the seals is to prevent water circulation in the repository tunnel system. However, modelling studies show that failure of the seals, while increasing water flows, does not significantly influence the radiological consequences of the repository, since the Callovo-Oxfordian argillite remains the dominant transport pathway. It was pointed out, however, that issues for the next phase of R&D and site characterisation are identified not only from the results of such sensitivity and uncertainty analyses, but also from other activities involved in preparing for and carrying out a safety assessment and compiling a safety case. For example, the consideration of features, events and processes (FEPs) included in, and excluded from, safety assessment models may indicate where information on a FEP (or the interaction between FEPs) is insufficient to include it in quantitative modelling at a given programme phase.

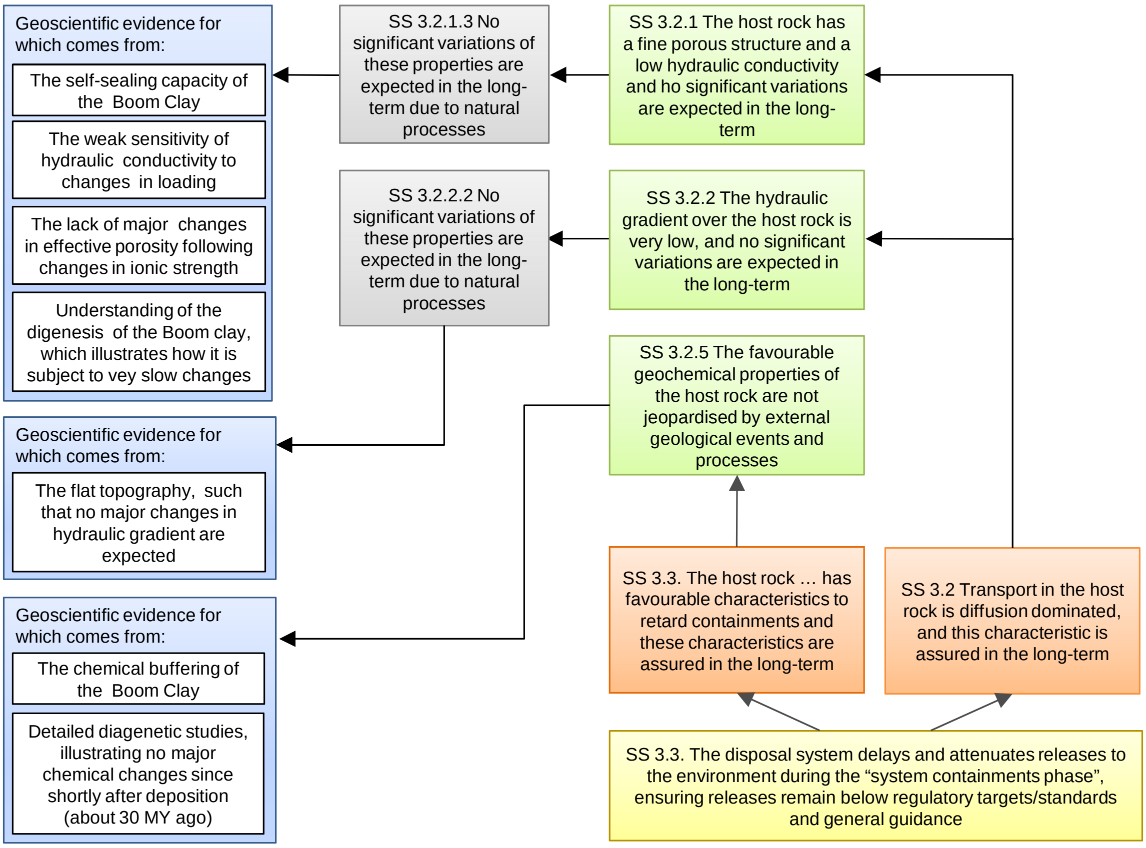
Various structured methods for identifying information requirements were described at the workshop. In Hungary, a generic conceptual model of radionuclide transport through multiple barriers, which includes its links to safety assessment, the availability of information and the social and technological environment, is being used to guide data acquisition at different programme stages (Fedor *et al.*). In Japan, an iterative approach to site characterisation based on data flow diagrams is being investigated (Hatanaka *et al.*). In this approach, links between site characterisation, repository design and the safety case are used to identify critical properties of, and processes in, the geological environment. The diagrams, based on the conceptual framework shown in Figure 5, are used to map geoscientific investigation techniques onto the data identified as critical for safety case and repository design. Site characterisation proceeds in a step-wise manner, with geosynthesis and safety assessment providing guidance for proceeding from one step to the next. The approach was found to provide a practical tool for planning site investigations for Japanese generic URL projects at Mizunami and Horonobe and analysing the results. Another example is the systematic organisation of geoscientific and other information according to its relevance to a hierarchy of "safety statements", as presented in Smith *et al.* and illustrated in Figure 6. The assessment of these statements in term of the adequacy of the underlying scientific support for the statement in the context a safety case allows information and knowledge gaps to be identified and filled by R&D and site characterisation work.

Figure 5. **Conceptual data flow diagram and framework for safety case development**
(after Hatanaka *et al.*)



Examples from the French programme of how the review of a safety case can influence R&D and site characterisation priorities have been mentioned above. An additional example,, mentioned previously, is the continuing site characterisation studies carried out at WIPP and the development of a revised hydrological model, as mentioned above and described in more detail by Beauheim, were requested by the WIPP regulator in response to inconsistencies between the predictions of the original hydrological model of the WIPP site and ongoing monitoring of the Culebra Dolomite. The EPA made a number of specific requests regarding the types of information to be acquired, including the installation of new wells to understand why heads in the Culebra where observed to be rising, in contradiction to the original hydraulic model.

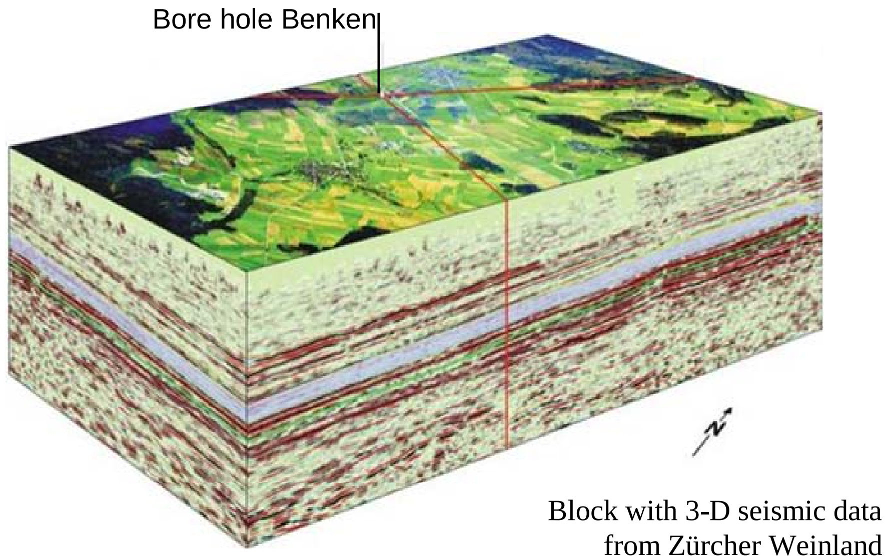
Figure 6. **Example of geoscientific evidence underpinning ONDRAF/NIRAS safety statements** (after Smith *et al.*)



Regulators may carry out their own analyses of geoscientific information in support of their review of safety cases. Mohanty *et al.* described how the United States Nuclear Regulatory Commission (NRC) and the Centre for Nuclear Waste Regulatory Analyses (CNWRA) are conducting confirmatory studies and technical analyses of the proposed Yucca Mountain Repository, independent of those of the implementer (the United States Department of Energy – DOE) to support their review of DOE activities. These studies, among other things, clarify the effects of geoscientific uncertainties on safety assessment results, and indicate how uncertainties might be reduced through specific investigations or mitigated by design. The Swedish regulatory authorities developed a discrete-feature model of the Swedish bedrock, independent of that of the implementer, to integrate various type of geoscientific information in support of their review of the SR-Can safety assessment. In particular, the model provided independent estimates of key parameters, such as the spatial variability of the flow of water around canister positions (Geier and Lindgren).

The review of a safety case may also influence the site selection process, as has been the case, for example, in Switzerland with the review of Project Gewähr 1985 and the more recent Project Opalinus Clay. Project Gewähr 1985 included a safety assessment of a repository for vitrified high-level waste in crystalline basement under sedimentary cover. As described in Rahn *et al.*, however, the regulatory review highlighted the difficulties in characterising this host rock and demonstrating the existence of suitable rock volumes for waste disposal. This resulted in the implementer subsequently focussing on sedimentary host rocks in an area of simple geology, giving good possibilities for site characterisation using surface-based methods (i.e. 2-D and 3-D reflection seismic measurements, see Figure 7). Explorability is now one of criteria to be applied in the site selection process in Switzerland, implementation of which has recently commenced. The shift in focus to disposal in sedimentary rocks also affected the FEPs that had to be considered in the more recent Project Opalinus Clay safety case (e.g. a greater emphasis on the issue of repository-generated gas), and lead to the establishment of the URL at Mont Terri, Switzerland. The Swiss implementer and the Swiss regulatory authority participate independently in experiments conducted at this international URL. Rahn *et al.* also illustrated how safety assessment calculations and, in particular, calculations of dose for a reference case and from parameter variations, can provide input to the site selection processes. It was noted in the discussions that calculated dose is determined not only by the features of a site, but also the features of the chosen design, which will be adapted to conditions at a site. The process is therefore to be seen as one not simply of site selections, but rather of site and design selection.

Figure 7. **3-D seismic data for the Zürcher Weinland showing the lateral homogeneity and hence good spatial explorability of the bedrock**
(after the oral presentation by Rahn *et al*., and based on a figure from Nagra NTB 02-05).



Working group discussions on how, and to what extent, the development of the repository design and the safety case influence site characterisation and R&D priorities

Working groups B and C discussed this topic. Working Group C considered how site characterisation and R&D priorities are guided by an iterative cycle of review that aims to ensure consistency between these priorities and the chosen safety strategy and design, in the light of safety assessment findings and the evidence, arguments and analyses presented in a safety case. It was felt that regulators or technical support organisations are well-served by developing independent experimental and modelling capabilities in order to assess the site characterisation and R&D programme proposed by the implementer.

It was noted by Working Group B that qualitative and quantitative site understanding is an essential component of the safety case. Thus, for example, site characterisation will typically consider not only the properties of the rock units that provide confinement in safety assessment calculations, but also the adjacent formations and wider geological system. The extent to which this is done varies between programmes, often reflecting differences in both the safety concept and the regulatory context. Moreover, the finite resources available to programmes mean that it is necessary to prioritise site characterisation activities to some extent according to the needs of safety assessors and repository designers. Safety assessment needs are oriented around site- and design-specific geosphere safety functions and associated criteria, and these provide a valuable tool to support prioritisation.

The reports of the working groups provide several specific examples of how site characterisation has been affected by the needs of safety assessment and design and, in the case of Working Group B, some counter-examples of where changes in design or the needs of safety assessors have had little or no implications for site characterisation. An example of the former given by Working Group C was the decision by IRSN to update its groundwater model to include salinity, which led to the gathering of additional data on salinity concentrations in the Parisian Basin (see the paper by De Hoyos *et al.*).

Working Group B noted that enhanced numerical modelling capabilities allow more complexity to be introduced in process and safety assessment modelling, with implications for degree to which data for site characterisation can be directly used. The report of Working Group B also lists some examples of emerging technologies that allow more detailed characterisation of the site at different stages of site investigation.