Radioactive Waste Management

Geological Disposal: Building Confidence Using Multiple Lines of Evidence

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NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

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EXECUTIVE SUMMARY

The role of the geosphere in the safety case for a deep geological repository is related to its safety-relevant characteristics, the possible ways in which the repository will affect these characteristics, and their long-term evolution. It is also related to the ease with which they can be determined and represented in a well-supported fashion in the safety case. The description of the geosphere used in developing the safety case generally draws on wide-ranging, site-specific and more generic geological information, which must be integrated in a coherent picture or conceptual model of the current, undisturbed characteristics of the site, as well as past and ongoing processes and disturbances caused (or likely to be caused) by repository construction, operation, post-closure and long-term evolution.

The integration of wide-ranging information from multi-disciplinary sources is a complex task. This has provided the motivation for establishing AMIGO, an OECD/NEA international project on "Approaches and Methods for Integrating Geological Information in the Safety Case". AMIGO is structured as a series of bi-annual topical workshops involving site characterisation and safety assessment practitioners with experience in both sedimentary and crystalline rock settings.

These proceedings summarise the first workshop of the series, which was intended to serve as a pilot for subsequent workshops. This workshop included the detailed presentation of a recently completed safety case, together with supporting geoscientific evidence, by the co-host organisation, Nagra. It also included invited keynote presentations, oral contributions giving examples of other safety cases or of ongoing efforts in safety assessment, a poster session and discussions in working groups. The main themes addressed were:

- the role of the geosphere in disposal concepts;
- the ways in which geological information is used by waste management programmes, and the way in which usage changes as a programme progresses;
- the synthesis of wide-ranging geoscientific information into a consistent site description or conceptual model;
- the development of arguments for the long-term safety of disposal systems;
- the use of multiple lines of evidence to build confidence in the geoscientific understanding that underlies the safety case; and
- the integration of the work of geoscientists and safety assessors.

These proceedings describe the issues discussed during the workshop sessions and present a number of broad recommendations. One of the key conclusions is that radioactive waste management programmes can usefully consider new and innovative geophysical techniques and interpretative methods developed and applied by the hydrocarbon industry and academia, as well as draw on their experience in managing and organising large geological datasets from multi-disciplinary sources and developing conceptual models. Another conclusion is that greater efforts may be needed in the future to explain the role and strength of the geosphere, and thus of the concept of geological disposal itself, to a wider audience.

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Special thanks are also due to:

- The Workshop Steering Group,[1] which is responsible for the management of the AMIGO workshop series as a whole, and which set the general objectives for the first workshop.
- The Scientific Programme Committee,[2] which was responsible for the detailed planning of the first workshop, and defined the lists of issues to be considered during the plenary and working group sessions.
- The working group chairpersons and rapporteurs, who led and summarised the debates that took place in the three working groups.
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The proceedings were prepared by Paul Smith (SAM Ltd., UK) and reviewed by the Steering Group and the Scientific Programme Committee.

1. Klaus-Jürgen Röhlig (GRS Köln, chair), Johan Andersson (Streamflow AB), Rick Beauheim (SNL), Gérard Bruno (IRSN), Andreas Gautschi (NAGRA), Mark Jensen (OPG), Patrick Lebon (ANDRA), Sylvie Voinis (NEA);

2. Rick Beauheim (SNL, Chairman and member of AMIGO Steering Group), Andreas Gautschi (Nagra), Erik Frank (HSK), Martin Mazurek (University of Bern), Horst-Jürgen Herbert (GRS), Bruce Goodwin (GEA/OPG), Jan-Olof Selroos (SKB), Emmanuel Mouche (CEA, France), Paul Smith (SAM Ltd., as consultant), and Sylvie Voinis (NEA, France).

TABLE OF CONTENT

OVERALL SYNTHESIS

1. INTRODUCTION

1.1 AMIGO and its objectives

AMIGO is an OECD/NEA international project on the topic of "Approaches and Methods for Integrating Geological Information in the Safety Case". The term *safety case* here refers to the post-closure safety case for a geological repository for long-lived radioactive waste, and is defined as a synthesis of evidence, analyses and arguments that quantify and substantiate a claim that the repository is safe. Geological or geoscientific information includes the various types of geophysical, hydrogeological, geochemical and structural information that can contribute to the safety case. The safety case is generally updated periodically throughout the step-wise process of repository siting, planning, construction, operation, as well as prior to closure, and becomes more rigorous over time, as increasing amounts of geological and other data become available, until, for a well-chosen site and design, a point is reached at which the safety case is adequate for repository licensing.

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;
- 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; and
- to foster information exchange between international radioactive waste management geoscience programmes, as well as between academic, regulatory and implementing bodies.

AMIGO is structured as a series of workshops. This document summarises the first workshop of the AMIGO series, held at Yverdon-les-Bains, Switzerland, on 3-5 June 2003, and 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.

1.2 Aims and structure of the first AMIGO workshop

The first workshop was intended as a pilot for subsequent workshops in the AMIGO series. The focus of the workshop was on "building confidence (in analyses and arguments that support the safety case) using multiple lines of evidence", but other themes within the overall scope of AMIGO were also discussed, such as the integration of the work of geoscientists and safety assessors.

Workshop Session I was devoted to the presentation of a recently completed safety case, together with supporting geoscientific evidence, by the co-host organisation, Nagra. The safety case addressed the disposal of spent fuel, high-level vitrified waste, and long-lived intermediate-level waste in the Opalinus Clay formation of Northeast Switzerland [1-6]. Session II consisted of invited keynote presentations from workers outside the field of radioactive waste management [7-9]. Session III consisted of oral contributions giving examples of other safety cases or of ongoing efforts in safety assessment [10-17]. More technical papers on selected topics were presented in a poster session [18-21].

The Working Group Sessions addressed three topics in parallel meetings:

A. Role(s) of the geosphere in the safety case;

B. Multiple lines of evidence involved in safety case arguments; and

C. Practical guidelines for managing the interaction between different teams in order to build a safety case.

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

Following the workshop, each of the working groups produced a written synthesis of its discussions. These syntheses are appended to the present document.

1.3 Structure of this document

The main themes addressed by the workshop, which include the topics covered by the Working Group Sessions, can be stated as follows:

(i) the role of the geosphere in disposal concepts;

(ii) the ways in which geological information is used by waste management programmes, and the way in which usage changes as a programme progresses;

(iii) the synthesis of wide ranging geoscientific information into a consistent site description or conceptual model;

(iv) the development of arguments for the long-term safety of disposal systems;

(v) the use of multiple lines of evidence to build confidence in the geoscientific understanding that underlies the safety case; and

(vi) the integration of the work of geoscientists and safety assessors.

The views expressed on these issues in the presentations and workshop discussions are summarised in Sections 2.1 to 2.6 of this document. A summary and set of recommendations from the workshop are presented in Section 3.

2. MAIN THEMES OF THE WORKSHOP

2.1 The role of the geosphere in the disposal concept

The role of the geosphere in disposal concepts for long-lived wastes was discussed by Working Group A, and also, to some extent, by Working Group B. In qualitative terms, the role of the geosphere is similar in all disposal concepts for long-lived waste and is to provide both security and long-term safety by:

- isolating the waste from the human environment and decreasing the likelihood of inadvertent or accidental human intrusion;
- *maintaining a stable chemical and physical environment* and thus protecting the waste from various external phenomena, such as climatic events, climate change and erosion; and
- *contributing to the multi-barrier concept* which provides multiple features and processes to prevent, delay and attenuate radionuclide release and migration.

All repository programmes for long-lived wastes attach a high weight to the first two of these functions. The weight attached to the third function can vary, depending on geological, regulatory and programmatic considerations, as discussed by Working Group A. The geosphere is, however, usually considered to be an essential component of the multi-barrier system at long times and for high-level waste, regardless of the details of the disposal concept. For instance, as noted in [14], the RFS III-2f French rule specifies that the main barrier is the geological one, particularly in the long term.

The situation may be different for shorter-lived waste disposal at shallower depths. In the case of the Drigg disposal facility in the United Kingdom, for example, the long-term safety case is founded more on the low concentrations of radionuclides in the waste form than on the protection offered by shallow disposal. This is because of the limited longevity of near-surface engineered barriers and the uncertainty and possible large impact of surface environmental processes, such as climate and sea level change [21].

2.2 The use of geological information in waste management programmes

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 that the extent of suitable host rock is large enough to host a repository and gives flexibility with respect to repository location;
- in engineering design to determine whether engineered barriers function adequately in, and are protected by, the selected geological environment; and

- in providing support for safety assessment and for the safety case – geological data provide parameter values for models, support model assumptions and can discriminate between model concepts; geological information can also be used to provide more indirect support of the safety case through multiple lines of evidence (e.g. for long-term geological stability - further examples are discussed below).

The specific use of geological information typically depends on the stage of planning or implementation that a programme has reached. Programmes represented at the workshop included those with a selected site or potential site, such as the host organisation, Nagra, which has proposed that future investigations relating to deep geological disposal should focus on the Opalinus Clay of the Zürcher Weinland of Northeastern Switzerland.[1] Other programmes are in a site selection phase or in a generic study phase with no candidate sites and one or more potential host rock types.

For countries with no candidate sites, considerations of long-term safety and engineering feasibility can be used to define some general requirements on the geosphere and on geological characterisation. 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 relating to, for example, rates of uplift and erosion, proximity to major fault zones and active volcanoes, groundwater flow (permeability, hydraulic gradients), mechanical, geochemical and thermal properties, minimum depth and potential impacts of glaciation. Other important factors include societal acceptance and surface impact. Having selected a site, an engineering concept is developed to complement the geological characteristics, such that an adequate level of safety is provided by the combination of natural and engineered barriers and safety functions.

For programmes in a site selection phase, the focus tends to be on developing consistent descriptions or conceptual models of candidate sites, integrating or synthesising wide-ranging information from a variety of geoscientific investigation techniques, and allowing for alternative conceptual models where these cannot be excluded by the available information. The synthesis of geological information is discussed in the next section.

For programmes with a selected site, the focus of geoscientific work tends to be on developing confidence in the description or conceptual model of the site, and on detailed characterisation of the properties of the site through, for example, additional reconnaissance. In general, the aim is to reach a point where:

- a stable conceptual 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 conceptual model increases;
- the information required for detailed safety assessment (e.g. in support of a license application) is available, including the quantification of uncertainties; and
- the uncertainties do not compromise the safety case.

As the understanding of a site evolves, priorities tend to shift from developing a general understanding towards 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

1. Licensing and possible implementation of a repository at this site still lie far in the future, and are not expected before 2020 at the earliest [1].

identified, and data-collection activities are focused on providing the information needed to evaluate them.

The workshop included presentations from two programmes with operational facilities: the Waste Isolation Pilot Plant (WIPP) in the USA [15] and the Drigg facility for low-level waste in the UK [21]. In these cases, monitoring programmes, either ongoing or planned, are aimed at building confidence in the developers' understanding of the evolution of the site by comparing monitoring observations with model predictions. For instance, at WIPP, data are now being collected to resolve conceptual model issues raised by monitoring data, and to provide data needed for numerical representation of the revised conceptual models.

It was noted that, at any stage in a programme, an external steering group, a periodic programme peer review, or both, can overview and provide authoritative insight on the relevance of the geoscientific work being carried out. The licensing authorities may also participate in the decision making process for future investigations and experimental work. Furthermore, making geoscientific datasets available in the open literature to foster their use in new research may be of benefit to geoscientific work programmes.

2.3 Synthesis of geological information

Geoscientific data relevant to a site may be available from a wide range of characterisation techniques, and include 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. All this information must, as far as possible, be synthesised in a consistent description, or conceptual model of:

- the historical evolution of the site;
- the current, undisturbed characteristics of the site, i.e. structural, thermal, hydraulic, mechanical and chemical properties;
- disturbances caused (or likely to be caused) by repository construction and operation, such as excavation-disturbed zones (EDZs) and gas pressure build-up in the near field; and
- possibilities for post-closure evolution, taking into account potential external disturbances such as glaciation effects..

Such descriptions or conceptual models are used for exploring design options and for safety assessment studies, as well as for further planning of the site investigations.

Historical evolution is relevant in that possibilities for the future evolution of a site are generally identified based on an understanding of the past. Ideally, extrapolations are made from a long period of time in the geological past to a shorter period in the future. "Natural experiments", such as the development of concentration profiles of isotopes and elements in the Opalinus Clay pore water [3], are thus valuable in that they provide information over long timescales in the past - hundreds of thousands to millions of years – as well as significant spatial scales – hundreds of metres or more. Other examples given at the workshop of the importance of understanding the historical evolution of the site also come from the Opalinus Clay project [5], as well as from the ANDRA "Dossier 2001 Argile" [14], in both of which studies of geological history have been carried out to confirm geodynamic stability and to reconstruct the diagenetic evolution of the sedimentary sequence. Such data are used as an input for assessing the future evolution of the geological medium and to help define the transport model for radionuclides. In Canada, paleohydrogeologic studies have been carried out in which constrained thermodynamic analyses coupled with field studies to characterise the paragenesis of fracture infill mineralogy have provided evidence that constrains the possible depth of penetration by oxygenated water during glaciations [17].

Several presentations discussed the practical measures adopted to interpret and integrate geoscientific information. Interpretation and integration can be aided by Geological Information System (GIS) technologies and emerging Virtual Reality Technologies. A particular methodology, described in [20], integrates geological information into a conceptual site model based on Evidential Support Logic (ESL), which is a generic mathematical concept based on evidence theory.

Integrated multi-disciplinary groups (see also Section 2.6) are frequently established to synthesise existing geological information and to develop confidence in a site description or conceptual model by checking whether:

- all relevant data are used;
- all relevant sources of uncertainty are addressed; and
- all suggested alternatives make sense and the potential for additional alternatives has been explored.

General guidance regarding the organisation of interdisciplinary discussions and multidisciplinary groups is given in the report of Working Group C.

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 multi-disciplinary sources [9], and developing related conceptual models for topics such as diagenetic change [7] and sedimentary basin evolution. For example, a basin model has been 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 [8]. 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), rock and water geochemistry, rock mechanics, hydrogeology and climatology.

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. Although the implementer typically compiles the geosynthesis, the regulator may choose to conduct an independent geological and hydrogeological interpretation of the implementer's geological database. This was the case for the Konrad, facility in Germany, where the regulator independently derived geological and hydrogeological models to better understand the findings of the implementer's safety assessment [10, 11].

2.4 Developing arguments for safety

Various types of argument that can be developed in a safety case are discussed in [6]. They include arguments for:

- the strength of geological disposal as a waste management option, evidence for which can be drawn, for example, from natural analogues;
- the favourable properties of the chosen disposal system (see Box 1);
- the good scientific understanding that is available for the chosen system, supported, where possible, by multiple lines of evidence (see Section 2.5); and
- calculations of disposal system performance, expressed in terms of a range of safety or performance indicators, that illustrate radiological consequences, taking into account uncertainties in the properties and evolution of the system.

There may be features and processes of the geological environment and other parts of the disposal system that are considered likely to occur and to be beneficial to safety, but are deliberately (and conservatively) excluded in the analyses of system performance, because the level of scientific understanding is insufficient to support quantitative modelling, or because suitable models, codes and databases are unavailable. These are sometimes termed *reserve FEPs*, an example of which is the possibility of long-term immobilisation processes (precipitation/coprecipitation) in the Opalinus Clay [6]. The presence of reserve FEPs constitutes an additional qualitative argument for safety, since it indicates that the actual performance of the disposal system will, in reality, be more favourable than that indicated by the analysis of assessment cases.

In addition to more plausible cases or scenarios, hypothetical or highly unlikely "what if?" cases are sometimes evaluated to illustrate the robustness of the disposal system. An example is the effect of water-conducting fault zones in the Opalinus Clay [3]. All investigations carried out in boreholes and tunnels indicate that the hydraulic conductivity of fault zones is the same as the undisturbed rock for overburdens greater than 200 m due to the self-sealing capacity of Opalinus Clay. Nonetheless, the existence of more conductive zones cannot currently be completely excluded. The result that the inclusion of such features in calculations of performance does not lead to unacceptable consequences illustrates the robustness of the disposal system, and thus enhances the safety case.

System performance is generally quantified in terms of the safety indicators of dose and risk. Other indicators can be used in a complementary manner, as discussed in [12] in the context of the Boom Clay, Belgium. Complementary indicators include the fraction of the radionuclides that decay before they can reach the aquifer and radionuclide fluxes and concentrations arising from the repository. These can each be compared to naturally occurring fluxes or concentrations.

Box 1. **Favourable characteristics of the geosphere that can be cited in a safety case – example from Nagra [3]**

- *long-term geological stability*, implying, for example, a low rate of uplift and erosion and 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).

2.5 Building confidence using multiple lines of evidence

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. Confidence in these contributions is favoured when the conceptual site model is consistent with a broad range of measurements and observations, including hydraulic measurements, measurements of pore water composition, the distribution of natural tracers, various laboratory and *in situ* field experiments and observations of analogous natural systems.

Geological evidence can support either the realism or the conservatism of parameter values or model assumptions. For example, in the safety case for the Konrad repository in Germany [10], evidence for the age of groundwater, as well as the observation of increasing salinity with depth, suggests that hydrogeological calculations, which neglected the stabilising effects of the salinity stratification, err on the side of conservatism.

The synthesis of geoscientific understanding can also contribute to the safety case in a more general sense. For instance, it can provide multiple lines of evidence to support key assumptions regarding the presumed properties of a site and its long-term evolution, and also the projected performance of important elements of the multi-barrier system.

The report of Working Group B and the presentations at the workshop included several examples of the use of multiple lines of evidence to support key safety-relevant properties of repository sites. These multiple lines of evidence relate, for example, to groundwater flow rates or groundwater travel times, diffusion properties, sorption properties and the stability of geochemical conditions within a host rock.

In the case of the Opalinus Clay in Switzerland, key safety-relevant properties that are supported by multiple lines of evidence are given in Box 2.

Box 2. **Key safety-relevant properties of the Opalinus Clay that are supported by multiple lines of evidence (based on [3-5])**

Low rate of uplift and erosion, consistent evidence for which comes from:

- basin modelling (burial history) of the Zürcher Weinland, which takes into account stratigraphic evidence, apatite fission track analysis, organic matter maturity studies and investigations of diagenetic cements and their fluid inclusions;
- geomorphological studies of the elevation and age of river terraces in Northern Switzerland, from which the rates of linear erosion since the time of deposition can be evaluated, as well as an evaluation of erosion rate from the assumption that the pre-glacial landscape was a peneplain whose elevation corresponds to present day hill and mountain peaks; and
- geodetic studies using precision levelling, which is available over a period of almost 100 years, relative to a point where the crystalline basement is exposed.

Low hydraulic conductivity and groundwater flow in the bulk rock, evidence for which comes from:

- *in situ* and laboratory hydraulic testing;
- tests for consistency with the porosity/conductivity relationship for clay formations investigated world-wide;
- the existence of hydraulic overpressures, which are interpreted as relics of burial history or as a result of the compressive stress field, but can only be understood if the hydraulic conductivity is even smaller that those derived from hydraulic tests; and
- concentration profiles of numerous elements and isotopes in pore water which suggest a diffusion dominated system.

Self-sealing capacity, evidence for which comes from:

- *in situ* experiments of artificially induced fractures at the Mont Terri Rock Laboratory; and
- the absence of mineral veins and alterations, suggesting that there was not significant water flow through natural discontinuities in the past.

As a further example, evidence for the dominance of diffusion over advection as a transport process in the Boom Clay, Belgium, has been obtained from large scale *in situ* tests, and from paleohydrogeological studies, including the behaviour and migration of naturally occurring radionuclides [12]. Support for the long-term geochemical stability of the Boom Clay comes from studies of natural tracers, and from the observation that the transition from marine to fresh water about 2 million years ago did not result in major changes. The future Belgian programme foresees reinforcing these arguments with additional studies of natural tracers.

2.6 Integrating the work of geoscientists and safety assessors

The acquisition and processing of geological information by a repository programme should be focussed primarily on programme needs. Since programme needs evolve as a programme progresses, the focus of geoscientific work must be periodically reviewed. Site characterisation thus proceeds iteratively with the development of the safety case and of repository design, and interdisciplinary communication is of key importance to success in all of these areas. Effective communication between geoscientists and safety assessors is also essential to:

- ensure the integration into the safety case of all relevant information produced in the R&D and site characterisation programmes,
- give researchers a broader picture, so that they can see how their results contribute to safety case arguments and so that they can, if necessary, intervene to correct misunderstandings promptly and effectively, and
- promote understanding and support of the safety case by all the participants.

The workshop noted the role that can be played by informal communication and technical seminars involving programme geoscientists, safety assessors and repository designers, and it was recognised that communication between different project groups cannot be expected to occur without, to some extent, being "forced" by programme managers. Examples of measures presented at the workshop to foster integration are summarised in Box 3.

Box 3. **Examples of measures to foster integration of the work of geoscientists and safety assessors**

Belgium [12]:

A new reporting procedure is being formalised, in which every report will be accompanied by a short "integration module". Assigned persons, called "integrators" will place the reported research into its broader framework and indicate its importance in the overall safety case. In addition, interfaces between the various scientific and technological disciplines involved in the programme are identified, and responsibility is assigned for the transfer of information across each of these interfaces, as well as the interface with the "outside world", including regulators and general stakeholders.

USA (WIPP) [15]:

For the WIPP license submittal application, a formal procedure was developed to ensure that "Principal Investigators" (PIs) and safety assessors worked in an integrated fashion. Working from the information provided by PIs, safety assessors would describe the models they could use to represent various processes, and the data that would be required for each. The PIs would then approve the use of the recommended model, or suggest an alternative, and provide the data needed with qualifications on its use. Finally, both the safety assessors and the PIs would sign a form summarising this information. Currently at WIPP, a hierarchy of Analysis Plans and Test Plans is used to ensure integration. No data collection or analysis activity is performed outside of this umbrella of plans.

Spain [16]:

In the 2003 safety assessment for clay, efforts have been made to involve R&D and site characterisation staff directly in the safety assessment by setting up "Integration Thematic Groups" (GTIs) to establish detailed and coherent work programmes and timetables, with each GTI coordinated by an ENRESA manager.

Canada [17]:

Geoscientific studies in three diverse topics have been coordinated to develop a detailed understanding of flow domain stability as it relates to redox front migration and flow system dynamics. The topics involve development of a constrained Laurentide ice-sheet model, consideration of paleohydrogeological evidence from the Whiteshell Research Area (WRA) and application of 3-dimensional numerical methods to predict long-term groundwater flow system dynamics as affected by glacial and peri-glacial conditions.

Japan [19]:

In Japan, the development of the "JNC Geologic Disposal Technical Information Integration System (JGIS)" aims to facilitate integration and sharing of the technical information among site investigation, repository design and safety assessment teams.

The hydrocarbon industry [9]

A case study of the Norman Wells field was presented to highlight the workflow and data integration steps associated with characterisation and modelling of a complex hydrocarbon reservoir. The involvement of reservoir and simulation engineers in the planning and implementation of the geologic-modelling project was particularly important and allowed for the integration of production and performance data early in the reservoir characterisation workflow.

3. SUMMARY AND RECOMMENDATIONS

3.1 Summary

Participants to this first AMIGO workshop were generally in accord with the following points.

- The role of the geosphere in disposal concepts for long-lived wastes is to provide both security and long-term safety by isolating the waste from the human environment and from various external phenomena, and by constituting an important element of the multi-barrier system that serves to prevent, delay and attenuate radionuclide release and migration.
- Favourable characteristics of the geosphere that can be cited in a safety case include a range of beneficial physical, chemical and structural properties, sufficient thickness and lateral extent of the host formation, absence of, low likelihood of, or insensitivity to detrimental phenomena and perturbations, explorability and, most importantly, long-term stability and predictability.
- The geosphere is generally regarded to be an essential component of the multi-barrier system at long times and for high-level wastes, regardless of the details of the disposal concept.
- Geological suitability is only one of several factors that must be taken into account in site selection. Having selected a site, an engineering concept must be developed to complement the geological characteristics, such that an adequate level of safety is provided by the combination of natural and engineered barriers and safety functions.
- As the understanding of a selected site evolves, priorities in geoscientific work tend to shift from developing a general understanding towards better characterisation of those phenomena that are judged to have the most potential to affect the performance of the repository.
- Geoscience information can have two distinct and important functions in a safety case. The first is to provide information on model parameters and model assumptions used in calculations of disposal system performance. The second is to provide multiple lines of evidence that support key assumptions on the properties of a site and the projected performance of the multi-barrier system, especially over very long time frames.
- The conceptual model of a site generally includes a description of the past history, the current, undisturbed characteristics, the ongoing hydrogeological, geochemical and other processes and disturbances that are naturally occurring, or are caused (or likely to be caused) by repository construction, operation, and post-closure evolution, and potential external disturbances such as glaciation effects.
- The description of the site is the result of a synthesis of wide-ranging site-specific and more generic geological information. Interpretation and integration of these data can be

aided by Geological Information System (GIS) technologies and emerging Virtual Reality Technologies.

- Integrated multi-disciplinary groups are the favoured approach to the synthesis of existing geological information and to the development of confidence in a site description and conceptual model.
- Arguments that can be developed in a safety case include those for (i), the strength of geological disposal as a waste management option, (ii), the favourable properties of the chosen disposal system, (iii), the good scientific understanding that is available for the chosen system, and (iv), acceptable disposal system performance, expressed in terms of a range of safety and performance indicators.
- Confidence in the quality of geoscientific understanding is favoured where a site model is consistent with a broad range of measurements and observations and where multiple lines of evidence exist to support key assumptions regarding the properties and projected performance of a site.
- Measures are being implemented in several repository programmes to foster communication between programme geoscientists, safety assessors and repository designers, the benefits of which include the efficient management of resources by focussing the acquisition and processing of geological information on programme needs.

3.2 Recommendations

- 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.

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PART A

WORKING GROUPS SESSIONS

CONCLUSIONS OF WORKING GROUP A

ROLES OF THE GEOSPHERE IN THE SAFETY CASE

Chair*:* A. Hautojarvi (Posiva Oy, Finland)
Rapporteur: P. A. Smith (SAMt, UK)

Participants

G. DE MARSILY (Université Pierre et Marie Curie, France), J. ASTUDILLO (ENRESA, Spain), A. DIERCKX (ONDRAF, Belgium), E. FRANK (HSK, Switzerland), R. GIL DE MINGO (NSC, Spain), L. GRIFFAULT (Andra, France), S. LEI, J. MARIVOET (SCK•CEN, Belgium), P. MARSCHALL (Nagra, Swtizerland), L. NACHMILNER (RAWRA, Czech Republic), P. NADEAU (STATOIL ASA, Norway), K-J. RÖHLIG (GRS, Germany), K. SCHELKES (BGR, Germany), J. WOLLRATH (BfS, Germany)

1. Introduction

The working group was set six questions by the AMIGO Programme Committee. This report considers these questions one by one and summarises relevant points made in the course of the discussions. Discussions of the working group were, however, neither limited to, nor exclusively structured around these questions, and additional points are noted in the conclusions at the end of this report.

2. What role does the geosphere take in safety cases?

The role of the geosphere in the context of geological disposal was seen as to provide both security and long-term safety from the potential hazard associated with radioactive waste. The various safety functions that the geosphere can provide were discussed. These include:

Isolation of the waste from the human environment and from various external phenomena

Placing it in a repository located deep underground, with all access routes backfilled and sealed, isolates it from the human environment and thus reduces the likelihood of any undesirable intrusion and misapplication of the materials. The waste is also isolated from various surface phenomena such as climatic events and climate change, erosion and other geomorphological processes.

Providing a barrier to radionuclide release and migration

The slow groundwater movement and geochemical retardation and immobilisation that occur in a well chosen host rock ensure long travel times and consequent radioactive decay for most radionuclides should they be released from a repository. The geosphere can also provide a spreading of released radionuclides in time and space by, for example, diffusion, hydrodynamic dispersion, dilution and (in the case of the Yucca Mountain Project) favouring a distribution of waste package failure times by the heterogeneity of water flow. These processes all serve to reduce the concentrations that might occur in the surface environment.

It was emphasised that the geosphere is just one component of a multi-barrier system that also includes various engineered barriers. The function of the geosphere in providing a suitable physical and chemical environment for the engineered barriers was also discussed. It was pointed out, however, that this should not be seen as a "role" of the geosphere, in that a geosphere is not typically chosen with this function in mind. Rather, the engineered barriers are designed such that they function adequately in a given suitable geological environment.

3. How does the role of the geosphere vary among disposal concepts

Participants felt that, in qualitative terms, the role of the geosphere is similar in all geological disposal concepts, and is as described in Section 2. What varies between concepts (and between different stages of a given programme) is the *confidence* that can be placed in the geosphere barrier, and the emphasis that should be placed on the geosphere in a safety case, compared to that placed on the engineered barriers. Indeed, confidence in the geosphere as a barrier largely determines how robustly designed the engineered barriers need to be.

The emphasis placed on the geosphere can depend on:

- the properties of the potential host rocks that are available – some programmes have access to a wide range of potential rock types, whereas other may effectively have only one or two;
- the waste type to be disposed and the possibility of co-disposal of more than one waste type – the waste type or types are relevant because of the radionuclides inventories (some of which may include long-lived, poorly sorbing constituents such as ^{129}I), as well as the inherent stability of the waste form and the envisaged packaging;
- the stage reached in repository planning and development – in particular, the availability of information on geosphere characteristics at a given stage and the maturity of the design of the engineered barrier system;
- regulatory requirements (e.g. in terms of the timeframes to be considered) and the demands of the public.

Uncertainties in the evolution and performance of all repository barriers generally increase with time. In the case of the geosphere, however, which is generally selected with a view to its long-term stability, geological sciences can often predict evolution over timescales of hundreds of thousands or even millions of years. In general, therefore, the geosphere is the most important barrier at long times, regardless of the details of the disposal concept. Indeed, in France, regulations state that in the long-term, only the geological barrier can be relied upon to provide safety.

4. How can safety assessment be used to define requirements on the geosphere?

In general, safety assessment does not place very specific requirements on the characteristics of the geosphere (although it can be used to place requirements on – or at least guide – site characterisation – see Section 6, below). At the earliest stages of site selection, requirements derived from safety considerations can, however, take the form of general exclusion criteria relating to rate of uplift, proximity to major fault zones, proximity to active volcanoes, etc.

The arguments for safety derived through the process of safety assessment and to which the properties of the geosphere can contribute relate to:

- the quality of the system, as illustrated by means of analyses of system evolution and performance;
- the quality of the analyses; and
- the confidence that any remaining issues can be adequately addressed, for example by more refined site characterisation.

These aspects of safety assessment place a number of different general requirements, or at least suggest a number of desirable properties, on the geosphere. These include:

- long transport times, long-term stability and robustness (insensitivity to perturbing phenomena and uncertainties), which are aspects of the quality of the system;
- good general understanding, good quality data, predictability in time and well-defined residual uncertainties, which promote the quality of the analyses; and
- explorability (i.e. spatial predictability), which contributes to confidence in the characterisation of the system even at the early stages of a site characterisation programme – explorability may be key to site selection where several otherwise suitable sites are available.

These aspects are, of course, interrelated. Predictability in time is, for example, favoured by long-term stability and the number of issues to be addressed is likely to be less for a more robust system.

5. What is the influence of repository construction on geosphere performance?

It was agreed that the most important phenomena related to repository construction (and, more generally, simply the presence of the repository) from the point of view of long-term safety are those that could result in long-lasting or irreversible changes in the properties of the geosphere. The working group identified as particular areas of concern:

- rock mechanical effects – i.e. the excavation disturbed zones around underground tunnels, including the possibility of self-healing of clays and salt;
- geochemical disturbances – including oxidation fronts, microbial effects, colloids (most relevant in the case of fractured hard rocks) and high-pH plumes in the case of repositories that include cementitious materials;
- repository induced gases – gases from, e.g. the corrosion of metallic components, which can convey certain radionuclides as volatile species and can potentially build up to pressures where they might cause fracturing of the rock; and
- connected pathways for groundwater movement – provided by the repository tunnels, shafts, and their associated disturbed zones.

It is largely a matter for repository design to avoid influences that could compromise safety, e.g. by appropriate excavation techniques, the avoidance of materials that could cause problematic geochemical disturbances and gas generation, design of repository seals to relieve gas pressure build up while still providing a barrier to groundwater movement.

6. What is needed (link to site characterisation) to make the safety case?

The demands on the safety case as a support for decision-making increase as a repository programme progresses, with the highest demands placed on a case that supports licensing. In order to meet these increasing demands, the safety case generally becomes more rigorous over time, as increasing amounts of information become available.

The following is a partial list of the types of information that a safety case generally requires:

- the undisturbed thermal, hydraulic, mechanical and chemical properties of the rock;
- evidence for geological stability and the maintenance of an adequate overburden over the timescales of concern;
- understanding of phenomena arising from the presence of the engineered barrier system (see Section 5, above);
- understanding of the impact of climatic and geological phenomena on the undisturbed rock properties;
- understanding of potential radionuclide transport mechanisms and data for specific transport models;
- evidence for the absence of economically viable natural resources (this may be a regulatory requirement for a suitable site); and
- measurements of natural radionuclide fluxes and concentrations (as "yardsticks" for comparison if such fluxes and concentrations are to be used as safety indicators complementary to dose and risk).

Where possible, multiple lines of evidence for key safety-relevant phenomena and parameters are sought.

At the earliest stages of repository siting, it may be adequate to show that a site meets general requirements in terms of rate of uplift, proximity to major fault zones, proximity to active volcanoes, etc. During initial site characterisation, the emphasis in site characterisation may be on determining which phenomena are most relevant to safety, and on determining which scenarios need to be considered in safety assessment and which can be excluded. At later stages if underground characterisation of an actual site (e.g. using an underground rock laboratory), the emphasis may be on determining specific parameters to support modelling studies for a licence application.

Thus, the specification of requirements for the safety case from site characterisation is an iterative process that takes place throughout repository planning, and demands a high degree of interdisciplinary communication between safety assessors and geological scientists. Detailed safety assessment requirements (in terms, say, of numbers for model parameters) are likely to emerge only after a more general understanding of the site and of relevant phenomena has been developed by safety assessors and geological scientists working together.

7. Are some data currently under utilised?

It was noted that data are used in a number of ways in a safety case, and that the ways in which data are used can vary as a programme progresses. Data are not only used to provide parameter values for models. They are also used to give support for particular model assumptions and to discriminate between model concepts. The working group identified some areas where data could be more fully used in safety assessment models if they could be shown to be adequately reliable or if adequate models were available – safety assessment models typically incorporate numerous simplifications, including, for example, the treatment of sorption as a linear, equilibrium process and the treatment of the rock matrix (between fractures) as a homogeneous medium.

It was also noted that examples of under-utilised data are found in other areas where the geosciences are applied, and, in particular, the hydrocarbon industry. These include the data from around 10 000 reservoirs in the Gulf of Mexico (Seni *et al*. 1997), which have never been systematically analysed or integrated into geological models for basin scale fluid flow, although their usefulness in quantifying fluid migration in geological systems has been illustrated in the work of Nadeau *et al*., 2001.

8. Conclusions

The following overall conclusions were drawn from the working group discussions:

- Repository programmes have different geological, regulatory and programmatic settings and thus attach different weights to the safety functions provided by the geosphere.
- All programmes attach a high weight to the role of the geosphere in isolating the waste from the human environment and from various external phenomena.
- Stability, robustness and predictability are key geosphere qualities in all disposal concepts.
- A convincing safety case requires (and geological characterisation aims to achieve) a good general scientific understanding of the geosphere, its evolution and its interaction with the repository – safety assessment can be used to define some general requirements on the geosphere and on geological characterisation.
- The full range of repository-induced and external disturbances need to be taken into account when developing a safety case – long-term or irreversible disturbances are of primary importance.
- The development of the safety case proceeds iteratively with site characterisation, and interdisciplinary communication is of key importance to the success of both.

Finally, it was felt that greater efforts are needed to explain both the role and the strength of the geosphere to a wider audience.

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CONCLUSIONS OF WORKING GROUP B

MULTIPLE LINES OF EVIDENCE INVOLVED IN SAFETY CASE ARGUMENTS

Chair: Simon NORRIS (UK Nirex Ltd, UK)
Rapporteur: Emmanuel MOUCHE (CEA, France)

Participants

B. GOODWIN (GEA, Canada), K-H. HELLMUTH (STUK, Finland), P. Jürgen LARUE (GRS, Germany), C. LEAN (BNFL, UK), N. MAES (SCK•CEN, Belgium), M. MAZUREK (University of Bern, Switzerland), T. SEO (NUMO, Japan), M. STIGSSON (SKB, Sweden)

The characterisation of a potential repository site and the development of related conceptual and numerical models are generally recognised as complex undertakings, that are a necessary part of developing a Safety Case for the long-term management of radioactive waste. A key challenge in this process is the co-ordinated collection, interpretation, analysis and integration of a range of data and knowledge, to demonstrate an adequate understanding of a site and its acceptability for purpose. Given the complexity of this challenge, multiple lines of evidence[1] – both site-specific and analogous – should be utilised as part of the repository Safety Case. These aim to corroborate the understanding of the site, as captured in the conceptual and numerical models, and therefore to assist in building confidence in and support for the Safety Case.

This Working Group was tasked with addressing "Multiple lines of evidence involved in Safety Case arguments". Responses to the series of questions posed prior to the AMIGO meeting are detailed herein. The Group's deliberations provide useful insights as well as valuable input for consideration at future AMIGO workshops.

Question 1: In what field do you see the lines of evidence?

Lines of evidence can be provided by many scientific disciplines, e.g. hydrogeochemistry, hydrogeology, mineralogy, geology, geomorphology, geophysics. Information can be qualitative or quantitative, and can be specific to a particular site and concept, or applicable by analogy to a number of sites and concepts.

1. Multiple lines of evidence are here taken to be various data, information and understanding of natural systems, either site-specific or derived from appropriate analogues, that are inherent parts of a Safety Case. Multiple lines of evidence complement conceptual, qualitative and quantitative models and their bases, and build confidence in their applicability and appropriate consideration of near-field and geosphere processes, and in their ability to describe potential future effects.

Question 2: At what stage in the making of your Safety Case (e.g. conceptualisation, model abstraction, formulation of arguments for safety) do the lines of evidence come into play?

Multiple lines of evidence have an important role at all stages of developing and making a Safety Case. For example, in developing a model (conceptual or numerical) of a new site as part of preparatory work for a Safety Case, the personnel involved use their scientific experience to integrate data and understanding that are inherently multiple lines of evidence. Sources of data and understanding derive from, for example, literature surveys, non-intrusive and intrusive site investigations. Site-specific data need to be demonstrably understood, and related numerical models to be used in a Safety Case need to be tested against site-specific and analogous lines of evidence, independent of the development of the model. Note that models could show both agreement and disagreement with such lines of evidence – the latter would be indicative of the need for further developments in understanding. Multiple lines of evidence could be used, for example, to:

- Identify relevant processes and their couplings.
- Constrain parameter values.
- Assist in the screening of FEPs (Features, Events & Processes), i.e. to identify relevant and less relevant FEPs for a particular repository site and design.

Additionally, a regulator might use multiple lines of evidence when evaluating a Safety Case, or might even define requirements for their use.

Question 3: What parameters/processes/issues can be supported by multiple lines of evidence?

Question 4: What are the specific lines of evidence for each of the parameters/processes/issues?

The applicability of multiple lines of evidence is wide ranging (spatially and temporally), at both the microscopic scale (e.g. fracture infill geochemistry) and site scale (e.g. structural geology), and for a wide range of parameters, processes and issues.[2] In fact, many parameters, processes and issues can be supported by multiple lines of evidence, and exceptions are likely to be rare. It is anticipated that specific parameters/processes/issues and their supporting multiple lines of evidence could be logically ordered in the form of, for example, tables or flowcharts, to aid Safety Case presentation. Specific examples of the use of multiple lines of evidence are given in the next section.

Question 5: How are the lines of evidence used in the Safety Case (explicitly, numerically, qualitatively, etc)?

Question 6: Which are the most effective and efficiently used lines of evidence?

2. Given the huge range of possible parameters, processes and issues, and the limited time available to the Working Group, it was not considered fruitful to address these questions in any greater detail.

Question 7: What data and potential lines of evidence for safety are currently under-utilised?

In developing a response to these questions, the Working Group decided to base its thoughts around a few crucial functions that any repository disposal system must perform to achieve long-term security and safety. Borrowing from Nagra literature [1], these are termed safety functions, and include:

- Isolation from the human environment ("Isolation").
- Factors that need to be considered when addressing the isolation of a potential repository site include containment, depth of burial, fault frequency, recharge/discharge, neotectonics, stress field, formation thickness, natural resources, properties of the host formation and waste packaging.
- Attenuation of releases to the environment ("Transport Barrier").
- Factors that need to be considered when addressing geosphere radionuclide transport at a potential repository site include diffusion, dispersion, advection, retention processes (e.g. sorption), transport times, porosity/permeability, geochemical fronts and gradients, mineralogy, waste packaging and buffer capacity.
- Long-term confinement and radioactive decay within the disposal system ("Long-term stability and predictability").
- Factors that need to be considered when addressing the long-term stability and predictability of a potential repository site include tectonics, seismicity, climate change, erosion and deposition; uplift and subsidence history, volcanism and subduction events, the groundwater cycle, geochemistry, diagenesis and geomechanics.

Based on a qualitative discussion and on insight from quantitative analyses, key features and phenomena contributing to these safety functions are identified in [1]; these are termed "pillars of safety". Although such "pillars of safety" as detailed in [1] are focussed on the Opalinus Clay Safety Case, the Working Group considered this nomenclature to be a powerful aid to communication.

Building on the above and considering Questions 5-7, the Working Group developed the Table below, entitled "*Use of Multiple Lines of Evidence in Assessing Role of Geosphere in Safety Case Arguments*":

- Column A lists information that potentially could be used as multiple lines of evidence in Safety Case arguments.
- Columns B - D detail whether these multiple lines of evidence are used currently in Safety Cases in support of the safety functions "*Isolation*", "*Transport Barrier*" and "*Long Term Stability/Predictability*", and if so, whether the information is used qualitatively or quantitatively.
- Column E provides commentary on the state of utilisation of the potential multiple line of evidence in current Safety Case work.

The information listed in Column A of the Table is not biased to any one particular deep repository concept, but rather presents a "shopping list" of potential lines of evidence that could be considered in developing a repository Safety Case. It is anticipated that certain of these multiple lines of evidence would, for example, be more applicable in an argillaceous host rock, while others might be more readily applied in a crystalline host rock.

Examples of use of multiple lines of evidence

On the basis of the understanding captured in the table, the Working Group developed a few examples of the type of multiple lines of evidence that could be drawn upon to help justify and strengthen certain aspects of a Safety Case. Examples include the following:

- Multiple lines of evidence for "*groundwater flow – groundwater travel time*" could draw on information from:
  - Groundwater age and travel times through the geosphere to the biosphere.
  - Spatial distribution of hydraulic properties such as over- and under-pressurisation, location of recharge and discharge areas, and hydraulic gradients.
  - Spatial distribution of groundwater composition, including variations in total dissolved solids and the presence of main and trace ionic species and isotopes.
- Multiple lines of evidence for "*radionuclide migration in the geosphere*" could draw on information from:
  - Groundwater composition and isotope signatures.
  - Rock/water interactions and their influence on, for example groundwater composition, isotope signatures and fracture infill.
  - Rates of release of natural radionuclides from geological formations to the biosphere.
  - Natural analogue studies, such as those at Oklo and Cigar Lake.
- Multiple lines of evidence for "*erosion rate*" could draw on information from:
  - Basin modelling, to assist in identifying, for instance, important features of structural geology.
  - Geomorphology.
  - Climate modelling and its effects on groundwater composition and natural fluxes.
  - Geodesy, providing information on e.g. structural geology.
  - Ecology and geography, providing insight into natural fluxes and geomorphology.
- Multiple lines of evidence for "geochemical stability in host rock" could draw on information from:
  - Palaeohydrogeology, providing information on natural fluxes and fracture infill.
  - Fracture infill.
  - Buffer capacity, providing information on e.g. groundwater composition.

Conclusions

Multiple lines of evidence are used throughout the process of making a Safety Case. The Table presents a first pass at collecting together examples that could potentially be used as multiple lines of evidence in a Safety Case. It is organised in terms of three key safety functions "*Isolation*", "*Transport Barrier*" and "*Long Term Stability and Predictability*". Comment is made on how the Working Group considered such multiple lines of evidence are used presently, identifying certain multiple lines of evidence that are used effectively and efficiently, and other that are under-used. The

Working Group suggests that this information could be built upon and extended at a subsequent AMIGO workshop – a possible way to facilitate this could be a preceding questionnaire, with responses subsequently discussed at the workshop.

Note that the information presented in this report is based on the experience and opinion of members of this Working Group. Note also that, due to time constraints, the results presented herein should not be considered as comprehensive.

Reference

[1] Project Opalinus Clay Safety Report, *Demonstration of disposal feasibility for spent fuel, vitrified high-level waste and long-lived intermediate-level waste (Entsorgungsnachweis)*, Nagra Technical Report NTB 02-05, 2002.

Table 1. **Use of multiple lines of evidence in assessing role of geosphere in safety case arguments**

A	B	C	D	E
Information potentially for use as multiple lines of evidence	**Isolation How is line of evidence used in Safety Case?)**	**Transport Barrier (How is line of evidence used in Safety Case?)**	**Long Term Stability and Predictability (How is line of evidence used in Safety Case?)**	**Comments**
Isotope Signatures	x	✓ (Quantitatively)	✓ (Qualitatively)	Used – effectively and efficiently
Groundwater Composition	x	✓ (Qualitatively)	✓ (Qualitatively and Quantitatively)	Used – effectively and efficiently
Natural Fluxes	✓ (Qualitatively)	✓ (Quantitatively and Qualitatively)	✓ (Qualitatively)	Under-used – under development
Temperature	x	x	✓ (Qualitatively and Quantitatively?)	Used as appropriate
Fracture Infill	✓ (Qualitatively)	✓ (Qualitatively and Quantitatively)	✓ (Qualitatively)	Under-used – reflects current level of understanding
Rock Mineralogy (Bulk)	x	✓ (Qualitatively)	✓ (Qualitatively)	Used – under development
Structural Geology	✓ (Qualitatively)	x	✓ (Qualitatively)	Used – effectively and efficiently
Geomorphology	✓ (Qualitatively)	✓ (Qualitatively and Quantitatively)	✓ (Qualitatively)	Used – under development
In-situ Experiments	x	✓ (Quantitatively and Qualitatively?)	x	Used – effectively and efficiently
Natural Analogues	✓ (Qualitatively)	✓ (Qualitatively and Quantitatively)	✓ (Qualitatively)	Under-used
Alternative Conceptual / Numerical Models	✓ (Quantitatively)	✓ (Quantitatively)	✓ (Quantitatively)	Used – effectively and efficiently

✓ Information used currently as multiple line of evidence.
x Information not currently used as multiple line of evidence or considered to be inappropriate for use as multiple line of evidence.

CONCLUSIONS OF WORKING GROUP C

PRACTICAL GUIDELINES FOR MANAGING THE INTERACTION BETWEEN DIFFERENT TEAMS IN ORDER TO BUILD A SAFETY CASE

Chair: Mark Jensen (Ontario Power Generation, Canada)
Rapporteur: Patrick Lebon (ANDRA, France)

Participants

S. VIOLETTE (Université Pierre et Marie Curie), L. YOSE (ExxonMobil), H. BESENECKER (Niedersächsisches Umweltmin.), P. BRENNECKE (BfS), H. UMEKI (NUMO), M. UCHIDA (JNC), J.C. MAYER (ENRESA), J. ANDERSSON (JA Streamflow AB), A. GAUTSCHI (Nagra), J-O. SELROOS (SKB), S. VOINIS (OECD/NEA)

The questions addressed to the Working Group C were as follows:

- How do you ensure that those responsible for acquiring data understand and support the use of their data in the Safety Case?
- How do you focus investigations early in a programme to produce information relevant to a Safety Case?
- How are different teams involved in decisions on future activities?
- How is interaction among teams managed?
- What are the means to enforce interdisciplinary communication?
- What specific steps can be taken to ensure interdisciplinary communication?
- How do you define a common basis of key issues among different groups?
- How are priorities established for collection of data that will be used in a supporting role (qualitatively)?

In providing context to answer these questions members of the Working Group shared their experience in program management through a description of organisational structures and interfaces in their respective radioactive waste management geoscience programmes. This experience also included that relevant to industrial and academic projects related to large scale multi-disciplinary reservoir or sedimentary basin characterisation, conceptualisation and numerical simulation. This summary attempts to synthesise key elements and strong points or positions that were expressed both during and after the working group sessions.

In summarizing the discussions and conclusions of the working group six practical management elements or guidelines were identified and presented during the closing round-up session of the First AMIGO Workshop on 5 June 2003. These six elements are: i) Communication; ii) Multi-Disciplinary Working Groups; iii) Geoscientific Documentation: Geosynthesis; iv) Geoscience Work Program Justification; v) International Consensus; and vi) External Geoscience Experience. These elements represent or embody practical experience and/or lessons learnt through the evolution of long-term geoscience work programmes. They also reflect in several situations the joint and shared conversation among implementing and regulatory organizations. Details and context related to these elements are described below.

i) Communication

The Working Group achieved a consensus on the importance of frequent and sustained communication and collaboration between program geoscientists, safety assessors and repository designers during iterative geosphere site conceptualisation and numerical simulation and development of the repository Safety Case. In particular, examples were provided where project teams or organisations were purposely structured to facilitate interaction and communication amongst multi-disciplinary groups responsible for geoscientific data synthesis, assessment and reporting to audiences beyond the geoscientific community. Communication was broken into three key aspects or areas: i) Informal; ii) Data Interpretation; and iii) External project communication.

*Informal*communication or dialogue on a weekly or more frequent basis is viewed as valuable in coping with communication "barriers" by creating relationships that foster the exchange of information and concepts relevant to site assessment. It is recognized that geographical distance between teams could hinder communication and in this sense has required specific organisational structure to allow for more frequent contact between specialist working groups, to enhance the flow of multi-disciplinary information, to share ideas, and to allow for improved feedback in work program co-ordination and/or collaboration. This type of informal communication is **not** intended to be onerous but to occur, ideally, through conduct of normal activities.

Another useful aspect of informal communication includes the use of periodic (e.g. 2-3 times per year) working group sessions and/or technical seminars in which researchers, specialists and management discuss/reaffirm details surrounding the applicability of site-specific results to support the Safety Case and priorities for new data to test or improve confidence in hypotheses introduced in Performance Assessment.

Data Interpretation represents another aspect of communication with a main goal of which is to create a platform to store and project multi-disciplinary geoscientific data in time and space with the intent of; i) improving traceability; ii) aiding quality assurance in data collection and synthesis; iii) improving communication between multi-disciplinary groups with respect to (among other issues) coincidence in their spatially complex site characterisation data sets during conceptual model development; and iv) allowing 3-dimensional interpretation/projection of data sets for communication with audiences with various levels of geoscientific understanding. Examples include the more widespread application of GIS technologies and application of emerging Virtual Reality Technologies, which permit 3 (and more)-dimensional data projections and ability for multi-disciplinary groups to query field data sets in real time. The application of such technology affords better utility for feedback into the work program with respect to focused activities that may strengthen geoscience aspects of the repository Safety Case.

External communication speaks to the issue of ensuring communication of geoscience program objectives, progress and findings related to site characterisation activities, geoscience data synthesis and use in predictive modelling of geosphere performance. The intent is to provide communication with stakeholders (i.e. regulatory bodies, the academic community, and the public) as the site characterisation program evolves from initiation. This is specifically helpful in conveying concepts and improving the familiarity and confidence in tools and interpretative methods unique to the assessment of sedimentary or crystalline repository settings. It is also useful in the view of obtaining feedback on the acceptance and approaches for characterisation of the geosphere and development of safety arguments.

ii) Multi-disciplinary Working Groups

A general trend toward the development of integrated multi-disciplinary groups to aid in the collection, interpretation and development of descriptive conceptual and predictive geosphere models was noted. This approach, in particular, is needed for improving the ability to put forth a reasoned case (multiple-lines of independent evidence) to constrain uncertainty associated with the prediction and understanding of long-term geosphere performance. The approach aims to:

- Improve the awareness amongst specialist groups as to the benefit of the data integration.
- Improve the awareness of specialist group role(s) in development of the site geosynthesis (i.e. descriptive conceptual site model).
- Improve opportunities for collaboration amongst multi-disciplinary geoscience groups.
- Improve ability to provide pro-active and timely feedback to on-going site investigation programmes.

Specific points made with regard to this approach from an industrial, academic and radioactive geoscience perspective were:

- The working group should be established for a period of at least two-years.
- The working group should have well-specified objectives and milestones with flexibility to change as new data and work programme discoveries require.
- The selection of working group members with professional/intellectual interest/curiosity in the work program and ability to work within a team has been found more successful.
- A group leader with a broad technical overview, coaching skills and ability to overcome difficulties is important for success.
- Working group members should ideally be located in close proximity to foster interaction and development of work relationships.

In establishing the working group and deciding on the disciplines to involve project management should be helped by a Steering Committee able to provide a broad technical overview on key issues and advice on which priorities to establish.

iii) Geoscientific documentation: Geosynthesis

The development of a Geosynthesis document to support the Safety Case has assumed a larger role in Safety Reports recently prepared or in preparation by different countries. The Geosynthesis document provides a focus for the geoscience work programme that:

- Provides improved assurance of consistency between the different geoscientific basis documents compiled/referenced within the Geosynthesis.
- Emphasizes or highlights multiple lines of geoscientific reasoning that support the arguments in the Safety Case.
- Identifies and addresses inconsistencies between supporting geoscientific documents in advance of project completion and, as such, serves as a measure of quality assurance in the preparation of the Safety Case.

Responsibility for the development of the Geosynthesis should ideally be given to a single identified group established early in the Research-Development and/or site characterisation programme.

It is noteworthy that a consensus existed that publishing data sets and geoscientific findings in the open literature, largely in order to share them with the academic community and foster their use in new research, was of benefit to the geoscience work programme.

iv) Geoscience work programme justification

An on-going and iterative process is required to justify the geoscience work program in the context of assuring that it has identified and addressed key issues affecting the Safety Case. This process should ideally involve Repository Engineering and Safety Assessment functions. The justification of the geoscience work programme allows for; i) an opportunity to improve the understanding of the role for geoscience in aiding and communicating the case for safety; and ii) ensures that the work programme is balanced within the broad sense of the overall programme goals.

As part of this justification process one approach is to allow for the development of an external steering group, a periodic program peer review or both. Several participants highlighted the particular role of the licensing authorities in the decision process for future investigations and experimental work. This role is sometimes provided for by a law, which obliges a formal technical review of program priorities.

It was further remarked that there remains a need for fundamental geoscientific research and development (i.e. less applied) that is removed from the main stream work program and need not be justified based on Safety Case requirements alone. Such work, for example, could include the development of new and innovative tools, experimental methods and/or interpretative techniques of potential benefit in understanding or predicting geosphere evolution or performance. In addition, the academic society could be more actively encouraged to participate in waste management programmes.

v) International consensus

International consensus on geoscience issues influencing the confidence and basis for geologic disposal is an important aspect of programme management. In developing a consensus, the continued development and funding of collaborative and shared geoscientific work programs, as well as, organisation of topical international forums or peer reviews for exchange of views, ideas and approaches was mentioned as being mutually beneficial. A goal of such interaction is to reach reasoned agreement on the lines of geoscientific evidence that support the Safety Case for a deep geologic repository.

vi) External geoscience experience

It was clear from the working group discussion, and emphasized by the invited workshop presentations, that external geoscience experience within the petroleum industry and academia is of significant benefit to geoscience radioactive waste management programmes. Such experience, for example, provides an unique perspective on; i) the management and organization of large multi-disciplinary reservoir site characterisation and simulation programs; ii) the application and utility of new and innovative geophysical techniques and interpretative methods (e.g. geostatistics; fracture network models; visualization methods); and iii) the development of geologic models for sedimentary basin evolution and diagenetic change relevant to long-term stability. Continued participation by geoscientific groups not associated with radioactive waste management programme was endorsed.

PART B

COMPILATION OF PAPERS

SESSION I

OPALINUS CLAY SAFETY CASE

OVERVIEW OF PROJECT *ENTSORGUNGSNACHWEIS:* AIMS AND METHODOLOGY FOR MAKING THE SAFETY CASE

Piet Zuidema
Nagra, Switzerland

1. Introduction and aims of project *Entsorgungsnachweis*

The National Cooperative for the Disposal of Radioactive Waste, Nagra, is responsible for research & development, geological investigations, design studies and safety assessment studies leading to the development of facilities for the disposal of radioactive waste in Switzerland. This paper (and the other accompanying papers) discusses Project *Entsorgungsnachweis*, a project assessing the geological and engineering feasibility and long-term safety of a deep geological repository for the direct disposal of spent UO_2 or mixed-oxide fuel (SF), vitrified high-level waste from the reprocessing of spent fuel (HLW) and long-lived intermediate-level waste (ILW) in the Opalinus Clay of the Zürcher Weinland of northern Switzerland, see Figure 1.

This paper provides the background to and describes the aims of project *Entsorgungsnachweis.* It also discusses key aspects of the methodology adopted by Nagra in developing the safety case for the proposed repository.

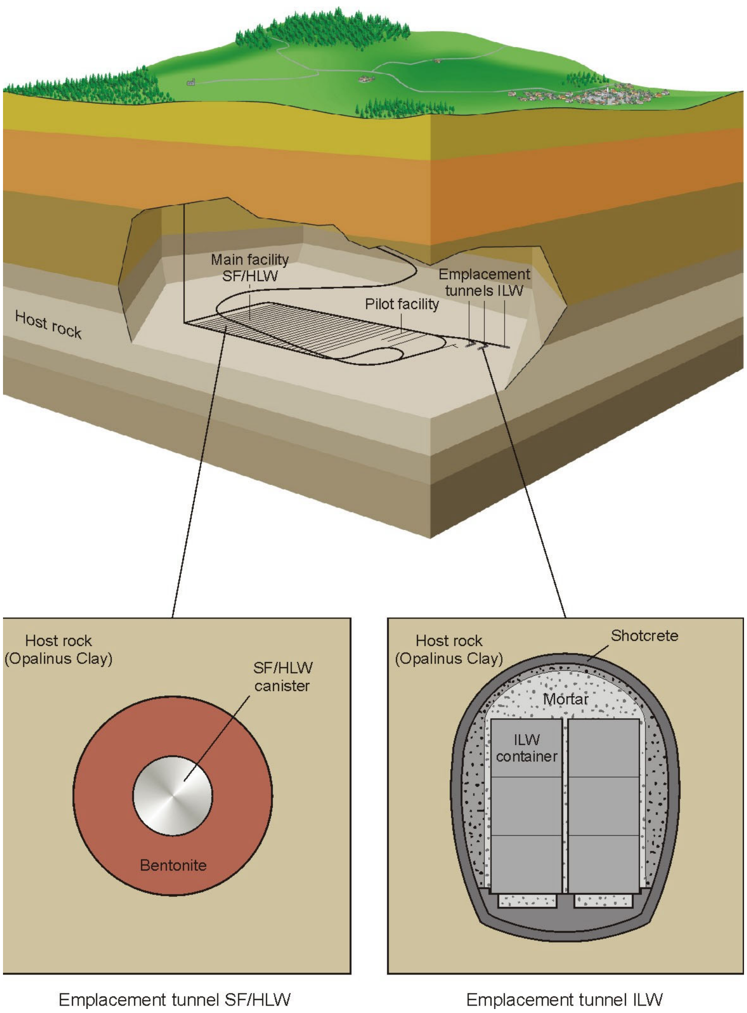
As in other countries, repository development in Switzerland is proceeding in stages. The major past and future steps in the Swiss case are illustrated in Figure 2.

The two main objectives of Project *Entsorgungsnachweis* are:

1. To demonstrate **disposal feasibility** of SF, HLW and ILW in the Opalinus Clay of the Zürcher Weinland in order to fulfil the requirements defined by the Federal Council in its judgement of Project Gewähr 1985. This includes a demonstration that
   - a **suitable geological environment** for the repository exists (siting feasibility);
   - **construction, operation and closure of a repository** is practicable in such an environment (engineering feasibility);
   - **long-term safety** from the hazards presented by the wastes is assured for such a repository (safety of disposal concept).
2. To provide a platform for discussion and a foundation for **decision making on how to proceed** with the Swiss HLW programme. This includes a presentation of the key findings and results and a discussion of the underlying scientific basis. The excellent results obtained from the geological investigations led Nagra to propose to the Swiss Government to make a formal decision to focus future work for the waste management option “Disposal of

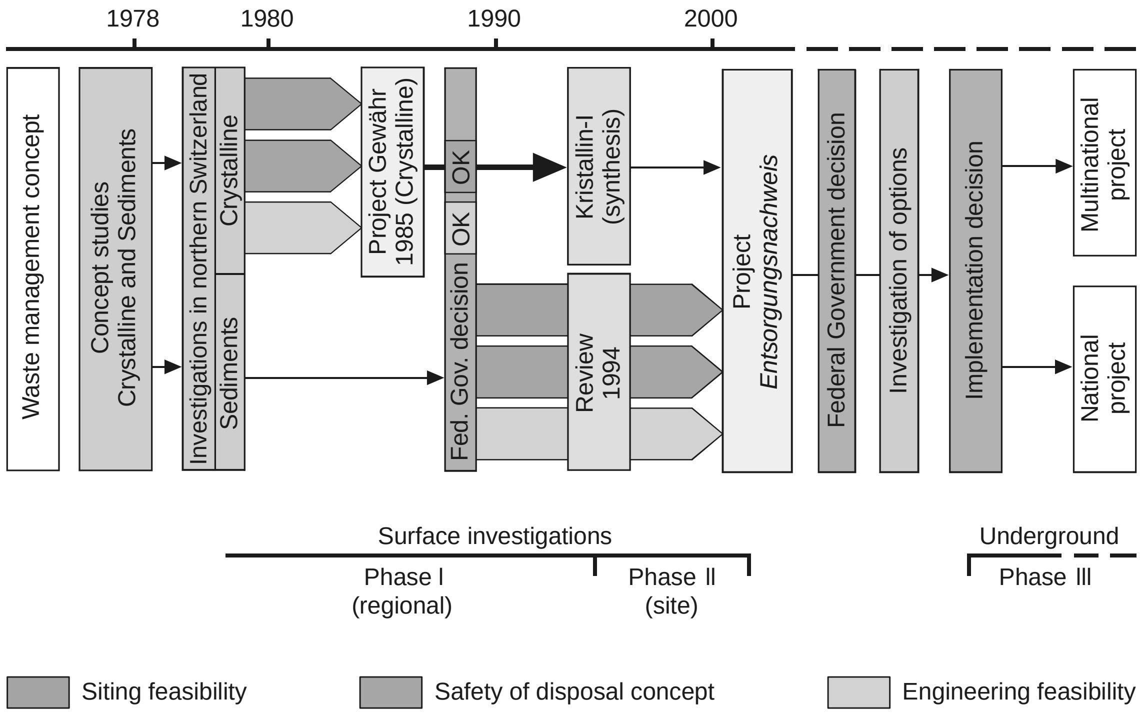
SF/HLW/ILW in Switzerland" on the Opalinus Clay of the Zürcher Weinland.[1] The choice of the Opalinus Clay as a host rock is based on its excellent barrier properties, its homogeneity and good explorability. The Zürcher Weinland was chosen because in that area the Opalinus Clay is situated at a suitable depth, with significant lateral extent and in a tectonically favourable and stable region (slightly compressive regime). Furthermore, in the Zürcher Weinland the overlying and underlying low-permeable layers (confining units) provide significant additional barriers to radionuclide migration.

Figure 1. **Possible layout for a deep geological repository for SF/HLW/ILW in Opalinus Clay**



1. Alternative siting regions exist in the Opalinus Clay and in the crystallline basement; the Lower Freshwater Molasse is considered as a reserve option. Disposal abroad is also an officially recognised option of the Swiss waste management strategy.

Figure 2. **History and future of the Swiss programme for spent fuel, vitrified HLW and long-lived ILW**



To fulfil the objectives of Project *Entsorgungsnachweis* three reports have been developed:

- a project report that addresses **siting feasibility** by providing a synthesis of geological information on Opalinus Clay and on the geology of northern Switzerland and, specifically, of the region of the Zürcher Weinland (Nagra, 2002a);
- a project report that addresses **engineering feasibility** by describing the design, construction and operation of the proposed facilities (Nagra, 2002b);
- a project report that addresses **safety of the disposal concept** by documenting the safety case for the repository for SF/HLW/ILW in the Opalinus Clay of the Zürcher Weinland (Nagra, 2002c), drawing on information from a wide range of sources, including the geological synthesis and design studies.

The three project reports, in turn, are backed up by more detailed technical reference reports.

It is important to note that licensing and implementation of a deep repository for SF/HLW/ILW in Switzerland, including the political decision to site and construct such a repository (general licence and corresponding parliamentary decision), still lies far in the future (not before 2020). The current project, therefore, need not be, and cannot be expected to be, of the depth that would be needed for the licensing applications that must precede repository implementation.

2. Aims of safety assessment and key aspects of the methodology for making the safety case

Safety assessment is used to show how the disposal system could evolve over the course of time and to test whether adequate levels of safety can be expected based on what is known about the system, and whether there are any circumstances that cannot currently be ruled out in which safety might be compromised.

Consistent with the early stage of the repository programme, the main emphasis is currently on assessing the general feasibility of the project and on discussing its robustness. Therefore, the methodology adopted for developing the safety case emphasises the evaluation of the level of confidence available for, and the adequacy of, the Opalinus Clay in the Zürcher Weinland from the point of view of long-term safety. This requires that

- all key phenomena relevant to long-term safety are identified (**completeness**);
- the current understanding of the operation of these phenomena is adequately integrated (**rigorous consideration and treatment of uncertainties**);
- the overall system performance is quantified for a broad spectrum of cases (**quantification of performance**);
- the results are described in a transparent and traceable manner (**documentation**).

Objectives and principles related to system design and to safety assessment have been developed to guide the qualitative and quantitative process of evaluating the chosen disposal system. The analysis is carried out in a systematic manner, integrating the scientific understanding available in the project (importance of team work) while avoiding inadvertent bias as far as possible. An iterative approach is adopted that allows for learning during the development of the safety case.

3. Development of the safety case

Safety assessment (defined here as tasks (i) to (iv), below) forms a key part of a wider procedure for developing the safety case for the repository and includes the following broad tasks (see Figure 3):

i) Derivation of the **system concept***:* The system concept is a description of what is known about the disposal system and its evolution, developed for the purpose of safety assessment. It includes a description of key system features, as well as events and processes that may affect its evolution, and broad conceptualisations of the possible paths that its evolution might take. It also includes a description of uncertainties.

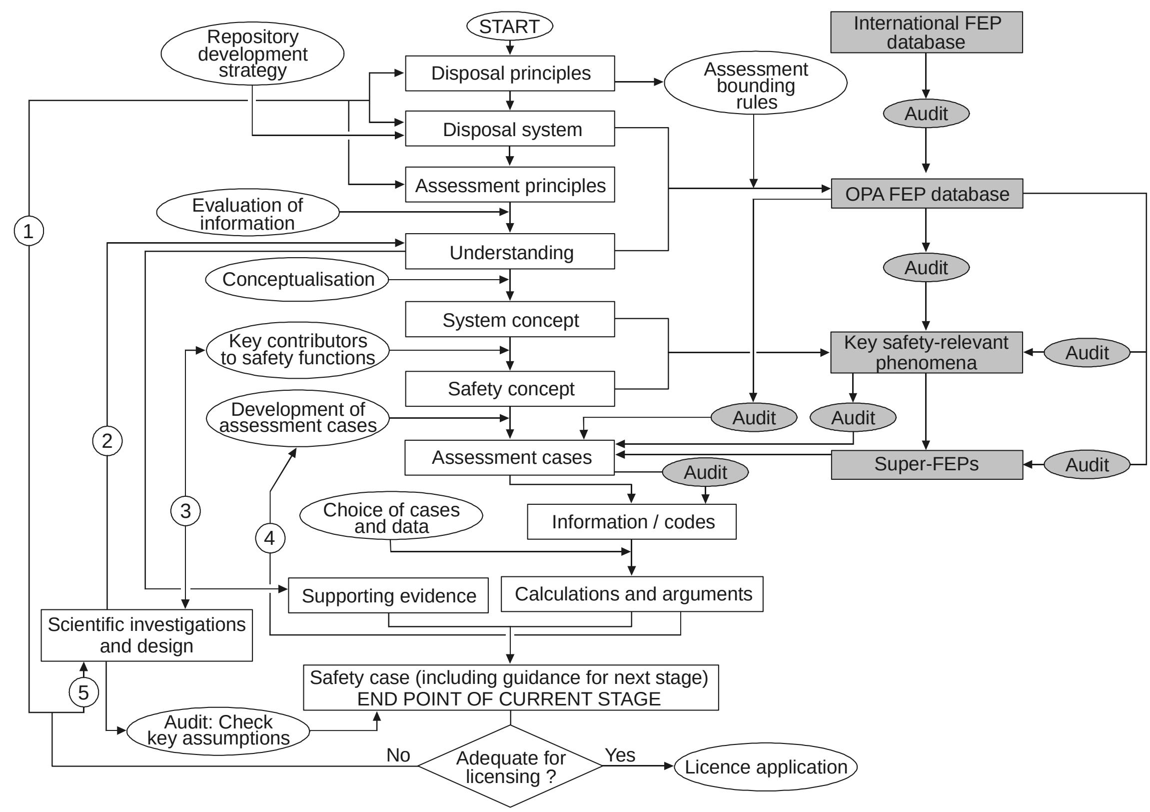
ii) Derivation of the **safety concept***:* The safety concept is the conceptual understanding of why the disposal system is believed to be safe. The safety concept is built on a limited number of effective and well-understood features that ensure that the disposal system is safe and that safety can be demonstrated, in spite of the various sources of uncertainty and the detrimental events and processes that will also affect its evolution. These effective and well-understood features are termed "pillars of safety".

iii) Illustration of the **radiological consequences** of the disposal system across the range of uncertainty by defining and analysing a **broad range of assessment cases**. This range of cases has to be representative of all realistically conceivable possibilities for the characteristics and the evolution of the system. It is developed based on the understanding of how currently existing uncertainties could affect the operation of the "pillars of safety".

iv) Compilation **of arguments and analyses for safety** (the safety case). This also includes a wide range of complementary analyses and more qualitative arguments. The types of arguments that comprise the safety case include:

- the strength of geological disposal as a waste management option;
- the safety and robustness of the chosen disposal system;
- the low likelihood and consequences of human intrusion;
- the strength of the stepwise repository implementation process;
- the good scientific understanding that is available and relevant to the chosen disposal system and its evolution;
- the adequacy of the methodology, models, codes and databases that are available to assess radiological consequences;
- the existence of multiple arguments for safety.

Figure 3. **The procedure for constructing the safety case**



The numbered arrows indicate the iterative nature of the procedure. FEP management procedures are indicated by shading.

4. Illustrating system behaviour

Different and complementary approaches are used to explore system behaviour and evaluate the consequences of different types of uncertainty. In this study, the main emphasis is on deterministic analyses to evaluate uncertainties and design/system options in terms of their impact on the radiological consequences of the disposal system, and to determine whether existing uncertainties are acceptable, or need to be addressed in the course of future stages of the programme. These deterministic calculations are complemented by probabilistic calculations that aim to enhance system understanding, ensure that no unfavourable combinations of parameters are overlooked, and test whether there are sudden or complex changes in performance as parameters are varied, which might not be detected using a purely deterministic approach.

5. The next steps

As a next step the safety authorities and their experts will examine the technical aspects of the project. The project will also be reviewed by an International Review Team under the auspices of OECD/NEA. The decision by the Federal Council on Project *Entsorgungsnachweis* and on how to proceed with the Swiss HLW programme, which will only be taken after a broad consultation with all stakeholders, is expected in 2006.

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GEOSCIENTIFIC BASIS FOR MAKING THE SAFETY CASE FOR A SF/HLW/ILW REPOSITORY IN OPALINUS CLAY IN NE SWITZERLAND (PROJECT *ENTSORGUNGSNACHWEIS*) I: OVERVIEW AND MAIN CONCLUSIONS

Andreas Gautschi, André Lambert and Piet Zuidema
Nagra, Wettingen, Switzerland

1. Introduction

This paper provides an overview of the geoscientific basis and the main conclusions concerning the safety case for Project *Entsorgungsnachweis* (Nagra, 2002a, see first paper). The key geoscientific input for the safety case is summarised in the following three papers. The data and arguments are discussed in great detail in Nagra (2002b) and in numerous reference reports cited therein.

2. Investigation programme, host rock and site evaluation procedure

A broadly based, stepwise evaluation procedure aimed at narrowing down potential siting options was conducted in close co-operation with the supervisory authorities and their experts (Figure 1, Nagra, 1988, 1991, 1994; HSK, 2001). In 1994, the Opalinus Clay – a Middle Jurassic moderately overconsolidated, marine claystone formation – was identified as the priority sedimentary host rock option and the Zürcher Weinland as the first-priority area for site-related investigations.

Detailed characterisation of the host rock and the potential siting area followed after 1994. The key elements of this research programme were a 3D seismics campaign in the Zürcher Weinland covering an area of around 50 km^2 (Figures 2 and 3), an exploratory borehole (Benken), experiments as part of the international research programme in the Mont Terri Rock Laboratory (Canton Jura) (see www.mont-terri.ch), comparative regional studies on the Opalinus Clay including deep boreholes in the near and far vicinity of the siting area, and comparisons with clay formations that are under investigation in other countries in connection with geological disposal. Thanks to the wealth of existing knowledge and the homogeneous lithology of the Opalinus Clay, parameters measured at other locations can be transferred reliably to the investigation area in the Zürcher Weinland, taking the different local rock-independent boundary conditions (e.g. different overburden of the host rock, different stress field) into account.

Figure 1. **Schematic representation of host rock and site evaluation procedure**

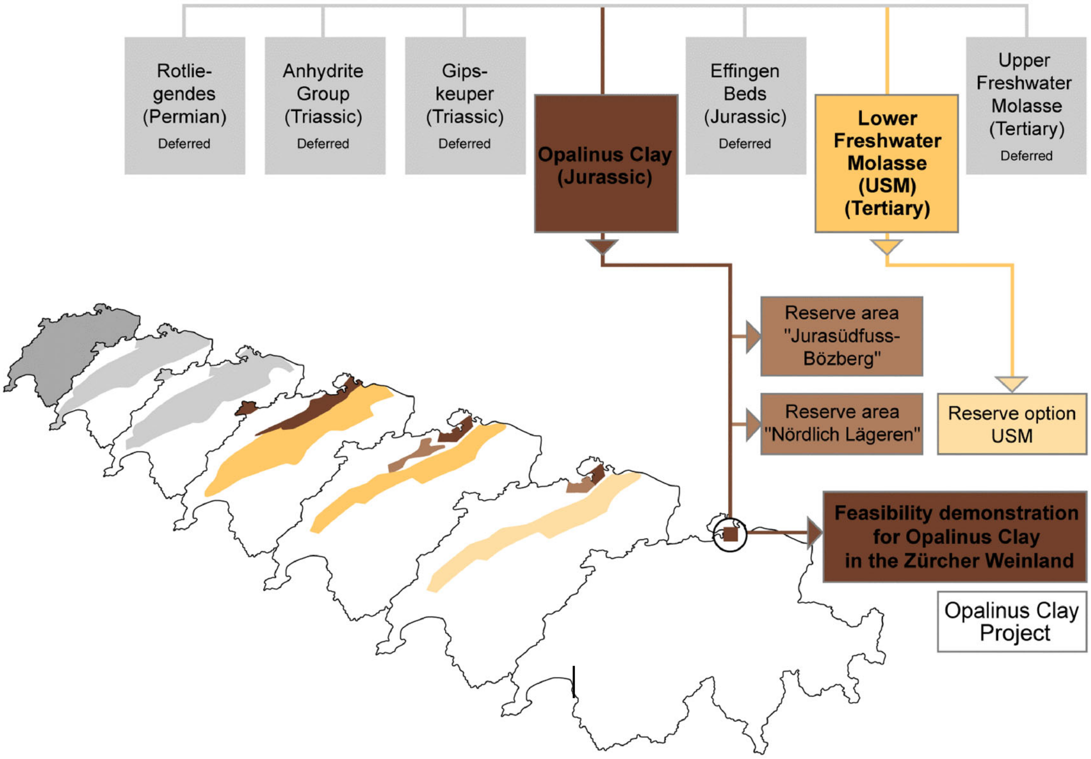
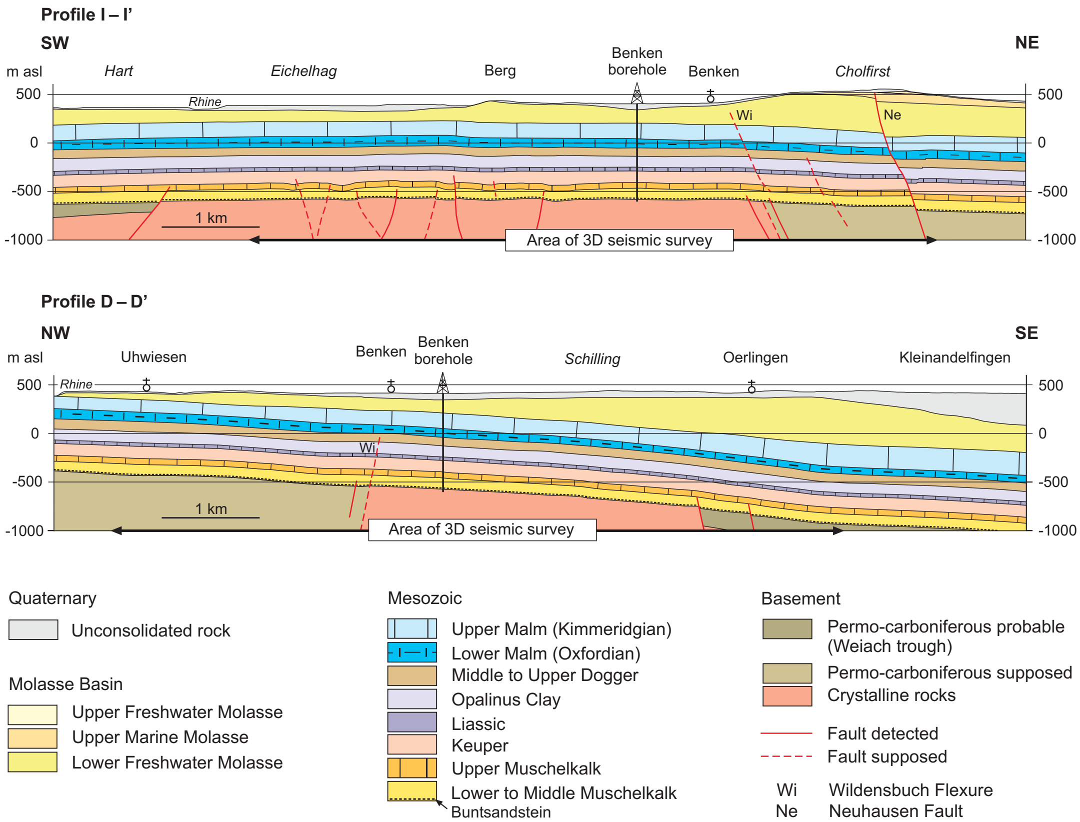


Figure 2. **Geotectonic units of northern Switzerland and adjacent areas, and location of the potental siting area (Zürcher Weinland)**

Figure 3. **Geological cross-sections (location see Figure 2) through the potential siting area**



3. Overview of results and main conclusions

Based on a synthesis of regional and local geoscientific investigations, it is shown that the selected area in the Zürcher Weinland fulfils the fundamental requirements placed on a siting area for a deep geological repository and that, in terms of the Opalinus Clay host rock option, the geological environment is advantageous. The most important properties are:

Long-term geological stability – The investigation area is located at the edge of the zone influenced by the Alps. Tectonically, it is subject to a slight compressive stress but is not significantly deformed. It also lies within one of the seismically quiet areas of Switzerland, with a small uplift and erosion rate and average heat flow.

Favourable host rock properties – The host rock in the investigation area is sufficiently thick and has a homogeneous lithology. It has a very low hydraulic conductivity, a geochemical environment that is favourable in terms of radionuclide retention and the long-term performance of the engineered barriers, and rock mechanical properties that are suitable for the construction of a deep repository. The formations above and below the Opalinus Clay (upper and lower confining units) mostly have a low hydraulic conductivity and form a supplementary geological barrier between the host rock and the regional aquifers, strengthening the barrier function of the host rock.

Sufficient extent of host rock body – Because of its almost constant thickness, lateral extent and lithological continuity, the host rock offers a large element of flexibility in locating a repository.

The lateral extent of the host rock body is significantly larger than the footprint needed for a deep repository. Because of the slight dip of the host rock unit, disposal depth can be selected and optimised according to requirements.

Avoidance of, and insensitivity to, detrimental phenomena and perturbations – With the selection of a low hydraulic conductivity host rock in a tectonically slightly compressive and seismically quiet area, as well as a disposal depth several hundred metres below the surface, conceivable perturbations (as a result of glaciation, movements along fault zones, earthquake effects) can either be avoided or kept to a minimum. The self-sealing capacity of the host rock and the stable geochemical conditions mean that perturbations caused by the repository itself (excavation disturbed zone, release of corrosion and degradation gases, chemical alterations) are either restricted to the immediate tunnel vicinity or do not have a significant impact on the long-term isolation capacity of the rock. The absence of economically viable natural resources makes a conflict of use, and thus unintentional human intrusion, unlikely in the future.

Explorability – The simple geological structure, with tectonically quiet sub-horizontal bedding, and the flat topography ensure good explorability of geometric conditions (e.g. with high resolution 3-D seismics). The homogeneity of the host rock and the very small lithological variation result in rock properties that are spatially almost constant. This allows the results from the Benken borehole to be extrapolated over the entire investigation area.

Predictability – The past geological evolution of the investigation area is well known, being based on a large number of independent quantitative and qualitative arguments. Together with the simple geological structure of the area, this means that the range of different geological evolution scenarios is very limited. The future evolution of the host rock in its geological setting can thus be predicted plausibly over the time period of one million years which is relevant for evaluating long-term safety and – with a higher degree of uncertainty – even beyond this.

To take account of existing uncertainties, for nearly all aspects considered parameter ranges or pessimistic alternative values and, in some cases, alternative conceptual models were considered in addition to reference parameters. The effect of uncertainties and the robustness of the system is evaluated as part of the safety assessment (Nagra, 2002a.). It can be assumed that uncertainties will be further reduced with future investigations – some relevant field and laboratory experiments are already underway.

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GEOSCIENTIFIC BASIS FOR MAKING THE SAFETY CASE FOR A SF/HLW/ILW REPOSITORY IN OPALINUS CLAY IN NE SWITZERLAND (PROJECT *ENTSORGUNGSNACHWEIS*) – II: THE GEOSPHERE AS A TRANSPORT BARRIER: HYDRAULIC, DIFFUSION AND SORPTION PROPERTIES

Andreas Gautschi[1], Paul Marschall[1], Benhand Schwyn[1], Paul Wersin[1], Bart Baeyens[3], Mike H. Bradbury[3], Thomas Gimmi[2,3], Martin Mazurek[2], , Benhand Schwyn[1], Luc R. Van Loon[3], Niklaus H. Waber[2]

[1] *Nagra, Switzerland;*
[2] *University of Bern, Institute of Geological Sciences, Switzerland;*
[3] *Paul Scherrer Institute, Villigen, Switzerland*

1. Introduction

Suitable hydrogeological and geochemical properties are essential for the performance of the host rock as a barrier to migrating radionuclides. In order to obtain a well-justified geoscientific database for the safety case, a broad multidisciplinary approach to assessing the transport properties of the Opalinus Clay has been pursued, taking into account and integrating data of various origin (see paper I of this series). In addition, scientific understanding has been demonstrated by using well-supported and consistent conceptual models and model calculations that are able to explain the broad range of observations. The input data for the safety case (Nagra, 2002a) – i.e. the reference datasets for a potential repository at a depth of 650 m – are supplemented case by case by pessimistic values, conservative assumptions or parameter ranges (Nagra, 2002b). The content of this paper is presented in much greater detail in Nagra, (2002b) and in supporting reports cited therein.

2. Host rock properties relevant for long-term safety

The key feature for understanding the transport processes and properties of the Opalinus Clay is its microstructure. With a porosity of around 0.12, the rock does contain a significant amount of water but, because of the extremely filigree structure of the pore space in the nanometer range, the mobility of pore water and dissolved substances is extremely restricted. Consequently, the hydraulic conductivity and the diffusion constants are very low and anisotropic due to the horizontal bedding.

2.1 Hydraulic properties and state

Hydraulic test of the host rock in the Benken borehole (*in situ* tests and lab test on core samples) showed consistently low hydraulic conductivities, suggesting representative values between 2×10^{-14} and 1×10^{-13} ms^{-1} (Figure 1, Nagra, 2001, 2002b). These values are in the range expected from comparisons with the porosity/conductivity relationship of clay formations investigated world-wide.

Hydraulic overpressures were identified in the Opalinus Clay in the Benken borehole, and can be interpreted as relics of the burial history or as a result of the compressive stress field (the largest stress component is oriented more or less north-south). Model calculations have shown that these overpressures only remain preserved over geological time periods if the effective hydraulic conductivity is smaller than that derived from hydraulic tests (Bruel, 2002, Kuhlmann *et al.,* 2002).

All the investigations carried out in boreholes and tunnels in the Opalinus Clay indicate that the hydraulic conductivity of fault zones is no different from that of the intact rock when the rock overburden is at least 200 m (Gautschi, 2001a). This is explained by the self-sealing capability of the Opalinus Clay. However, because enhanced conductivity of a fault zone at greater depth cannot be ruled out completely (although it has never been observed), a dataset for modelling radionuclide transport in a hypothetically conductive fault zone is provided as a *what if*-scenario.

The conclusion that self-sealing of discontinuities (fault zones) takes place in the Opalinus Clay is broadly supported by a range of observations and investigations. The absence of mineral veins and alterations is evidence that, in the geological past, there was no significant rock-water interaction or significant water flow through the Opalinus Clay (Gautschi, 2001b, paper IV of this series). Self-sealing processes were also observed during *in situ* experiments at the Mont Terri Rock Laboratory (Enachescu *et al.,* 2002, ongoing EU Selfrac Project, see paper III of this series). Results from rock mechanics experiments in the laboratory combined with generic understanding of clay rock rheology lead to identification of processes relevant for self-sealing: stress-redistribution, time-dependent deformation in the micro-range, disintegration of the rock, homogenisation of the pore space and swelling.

Model calculations using reasonable boundary conditions show that solute transport is diffusion-dominated. An additional argument for the very small advective component is the concentration profiles of numerous elements and isotopes in pore water, which is typical for diffusion dominated systems. Such features were observed both in the Benken borehole (Gimmi & Waber 2003) and in the Mont Terri Rock Laboratory (Pearson *et al.,* 2003). The shape of the profiles rules out any significant vertical advective flow (Figure 2).

The value of these “natural experiments” in the Zürcher Weinland and at Mont Terri lies in the fact that they are relevant for long timescales (hundreds of thousands to millions of years) and significant distances (one hundred metres and more). In the case of the Benken borehole, the diffusion profiles are apparent not only in the Opalinus Clay, but continue into the underlying and overlying formations. This also shows that diffusion is the dominant transport mechanism in a significant part of the confining units (see Chapter 3).

Figure 1. **Lithology/stratigraphy in the Benken borehole and measured hydraulic heads and hydraulic conductivities (from Nagra 2002b)**

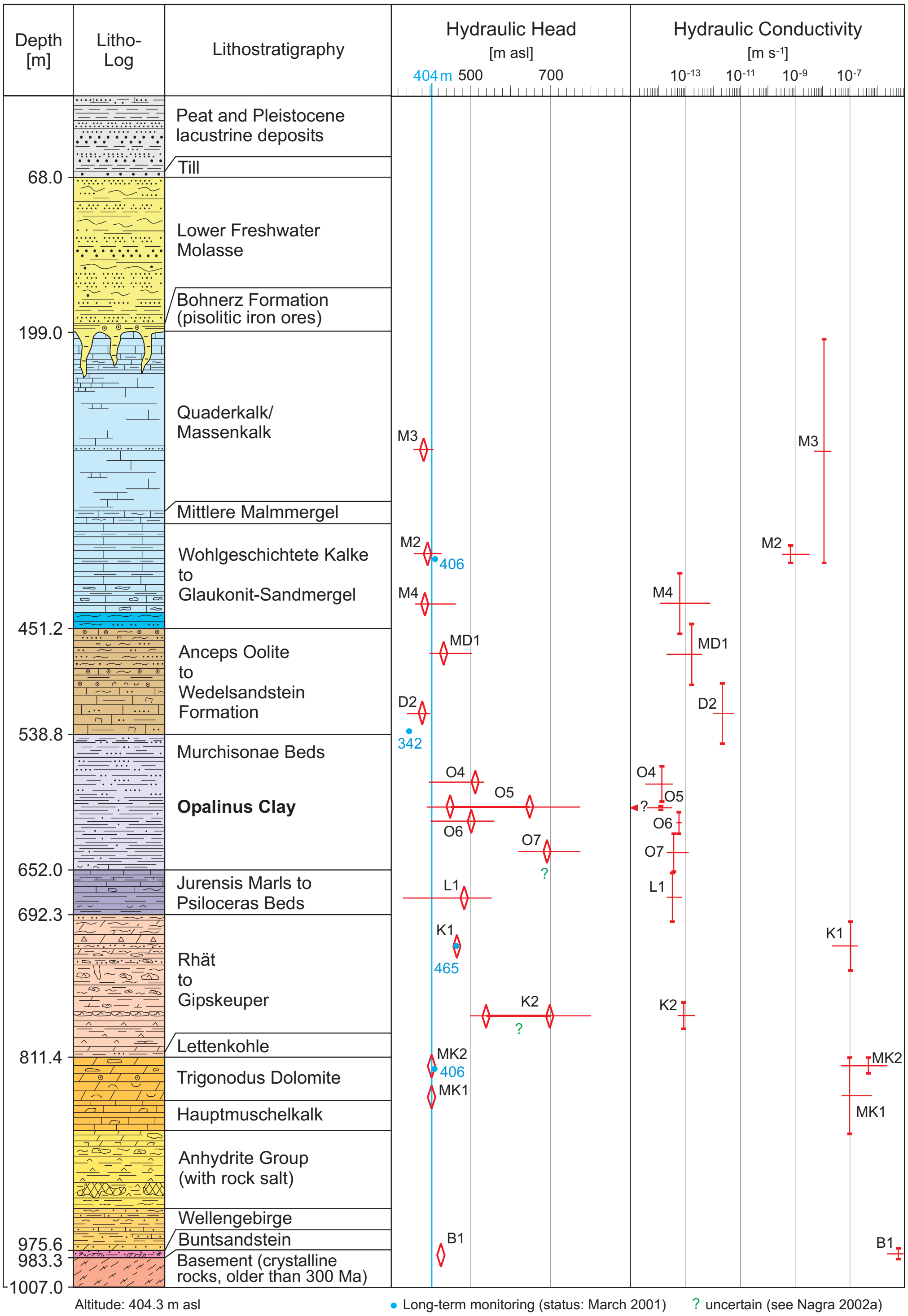
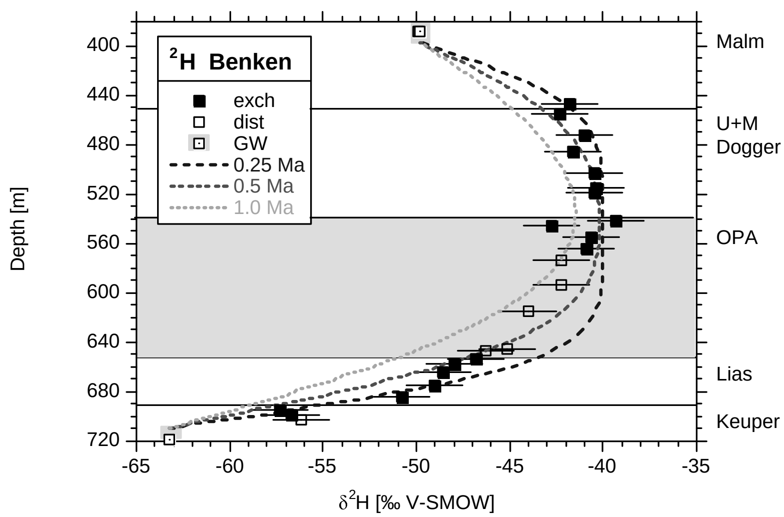


Figure 2. a) **Effect of variation of evolution time *t* on the calculated profile for δ^2H in pore water for the case of pure diffusion**

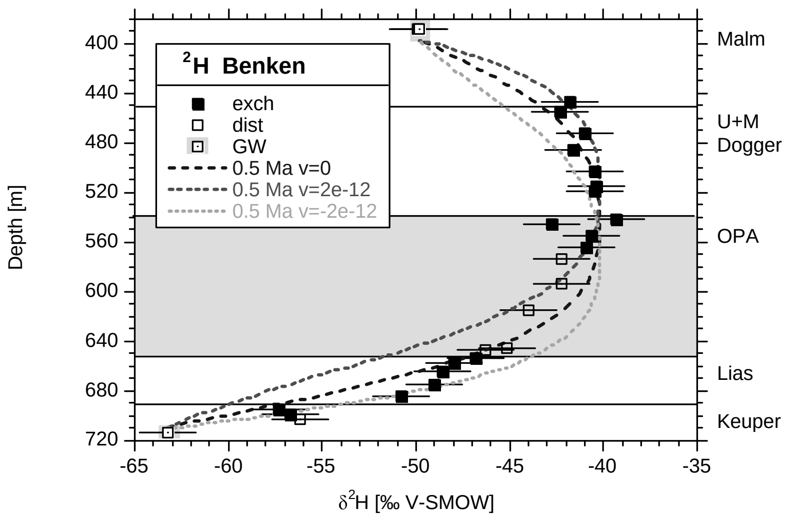
b) **Influence of a relatively small upward ($v = 2 \times 10^{-12}\ ms^{-1}$) or downward ($v = -2 \times 10^{-12}\ ms^{-1}$) advective velocity, as compared to pure diffusion, on fitted concentration profile of δ^2H, at an evolution time of 0.5 Ma**.

The curve for 0.5 Ma corresponds to the best fit. The evolution times *t* were estimated from $\xi = (D_p\, t)^{0.5}$ with the laboratory pore diffusion coefficient D_p for HTO at 40°C, which represents the *in-situ* temperature. Filled symbols: data obtained from rock samples by diffusive exchange; open symbols: corrected vacuum distillation data; GW denotes ground water samples from aquifers.

a)



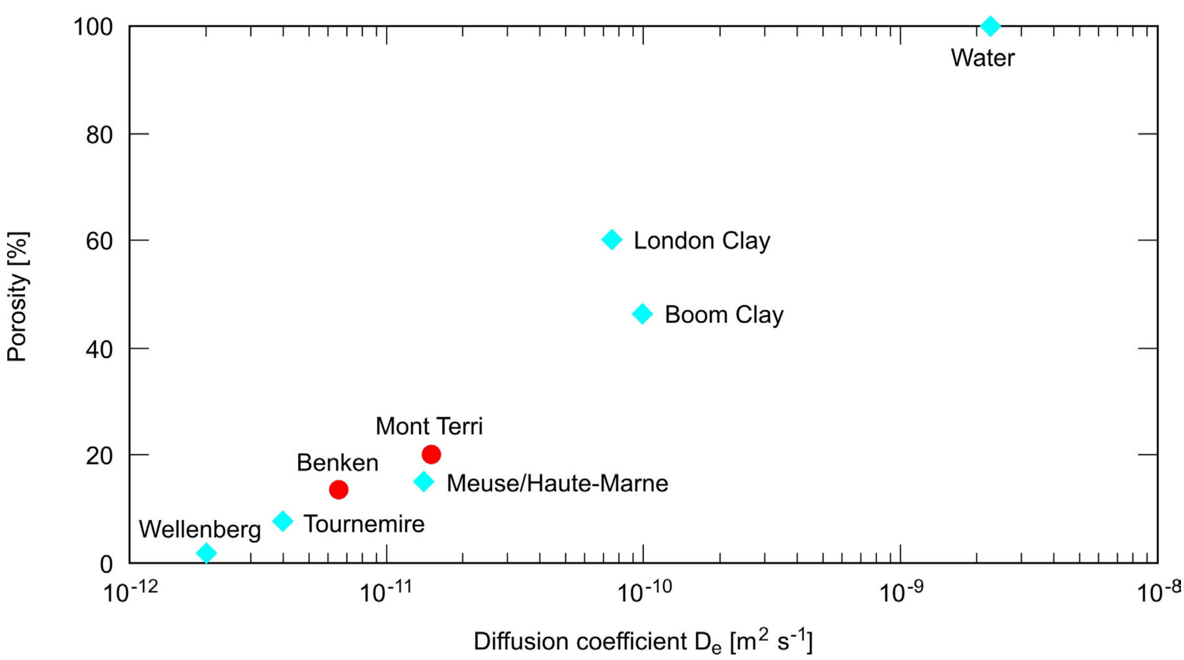
b)



2.2 Diffusion properties

The diffusion properties of Opalinus Clay have been investigated in both laboratory (Van Loon *et al.*, 2003a, 2003b, 2003c, Tevissen & Soler, 2003) and field studies. The latter include migration experiments (Palut *et al.* 2003) and analysis of the large scale distribution of solutes and isotopes carried out in the Mont Terri Rock Laboratory (Pearson *et al.* 2003). The obtained diffusion data show general agreement at different temporal and spatial scales (Nagra 2002b). The laboratory diffusion constants for Benken samples are somewhat lower than those obtained for Mont Terri samples (Van Loon *et al.*, 2003). The effective diffusion coefficients of tritiated water (HTO) for Benken samples obtained from laboratory measurements are about 6×10^{-12} $m^2 s^{-1}$ perpendicular to the bedding plane. For anions, effective diffusion constants are 10 times lower. The diffusion constants parallel to bedding are about five times higher, consistent with the strong anisotropy of the medium. The diffusion accessible porosity for HTO was found to be in the range of 0.12-0.15, whereas anions show significantly lower values of about 0.03-0.06. Very few diffusion data exist for cations. Preliminary data (Van Loon *et al.*, 2003c) suggest that effective diffusion coefficients for Na^+ are somewhat higher (a factor of 2) compared to HTO. Comparison of diffusion data for Opalinus Clay with those from other clay formations reveals a correlation between diffusion constants and porosity. Thus claystones with a similar degree of consolidation, such as the Callovo-Oxfordian of Meuse/Haute-Marne and the Toarcian of Tournemire, show similar diffusion coefficients, as shown in Figure 3.

Figure 3. **Effective diffusion coefficient and diffusion accessible porosity for HTO (perpendicular to bedding) in different argillaceous rocks (Nagra, 2002b)**



2.3 Geochemical properties

The pore water in the Opalinus Clay – which was seawater at the beginning of sedimentation – has changed its composition during burial, compaction and uplift of the Opalinus Clay over the last 180 million years; today its salinity is around one-third that of seawater. The composition of the pore water (except salinity) is determined to a large extent by chemical equilibria with the rock, particularly with clay minerals and carbonates (Pearson, 2002). The concentration of mobile components that are independent of rock composition (mainly anions) will change very slowly, and to a restricted extent (see paper by Mazurek *et al.*, this volume), because diffusion is the dominant solute transport process in the Opalinus Clay. Overall, the geochemical conditions are very stable and reducing (controlled by pyrite/sulphate couple). There is isotopic evidence that the different glaciation events had no influence on these conditions.

2.4 Sorption properties

In very low permeability formations such as Opalinus Clay, there is uncertainty concerning in situ pH/pCO_2. In order to take this uncertainty into account sorption data bases are given for a reference case (reference pore water composition, pH 7.24) and for two other pH values (6.3 and 7.8). The sorption data bases were compiled from laboratory measurements at PSI for Cs(I), Sr(II), Ni(II), Eu(III), Sn(IV), Se(IV), Th(IV) and I(-I) carried out on Opalinus Clay samples. In addition, selected distribution ratios (K_d) had to be taken from the open literature in order to complete the data bases. These values had to be modified so as to apply for Opalinus Clay reference mineralogy and pore water chemistries at the three different pH values. The resulting K_d values were then further modified using so-called lab-to-field transfer factors to produce sorption values which are appropriate to the *in situ* host rock for the selected range of pore water chemistry conditions (Bradbury & Baeyens, 2003).

3. Barrier function of the confining units over- and underlying the host rock formation

In the entire investigation area, generally low permeability argillaceous and evaporitic rocks are found between the host rock and the regional Malm and Muschelkalk aquifers (Figure 1). Particularly in a vertical (but also in a lateral) direction, these confining units form a supplementary geological barrier. Sandy, calcareous or dolomitic layers intercalated with the argillaceous formations are usually only a few metres thick and, given their lithology, represent water-conducting strata of limited interconnectedness. The effect of the confining units is that radionuclides that may not have decayed away following their transport through the host rock will only reach the biosphere after a further considerable time delay. The nuclides would first be transported either laterally along the more permeable layers in the confining units over kilometre-long transport pathways to the discharge zone (future river valley), or would move diffusively in a vertical direction through the confining units into the regional aquifers. The barrier efficiency of the confining units is estimated in the safety assessment (Nagra, 2002a) using model calculations based on reference datasets provided by geoscientists (Nagra, 2002b).

4. Summary and conclusions

The properties of the geosphere barrier that are relevant from the viewpoint of long-term safety can be summarised as follows:

- Diffusion is the dominant transport mechanism, with advection playing at most a secondary role.
- Fault zones in the Opalinus Clay do not represent preferential flow-paths, which is attributed to efficient self-sealing mechanism.
- Stable, reducing geochemical conditions are present and the host rock has favourable sorption properties.
- Clay-rich confining units over- and underlying the Opalinus Clay host rock act as a supplementary barrier to migrating radionuclides.

The main conclusions are supported by multiple lines of evidence demonstrating consistency among hydraulic properties and state of the hydraulic system, pore water geochemistry, distribution of natural tracers as well as laboratory and field diffusion experiments.

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GEOSCIENTIFIC BASIS FOR MAKING THE SAFETY CASE FOR A SF/HLW/ILW REPOSITORY IN OPALINUS CLAY IN NE SWITZERLAND (PROJECT *ENTSORGUNGSNACHWEIS*) III: REPOSITORY-INDUCED EFFECTS: EDZ, REPOSITORY GAS RELEASE, SELF-SEALING

P. Marschall, P. Blümling
Nagra, Switzerland

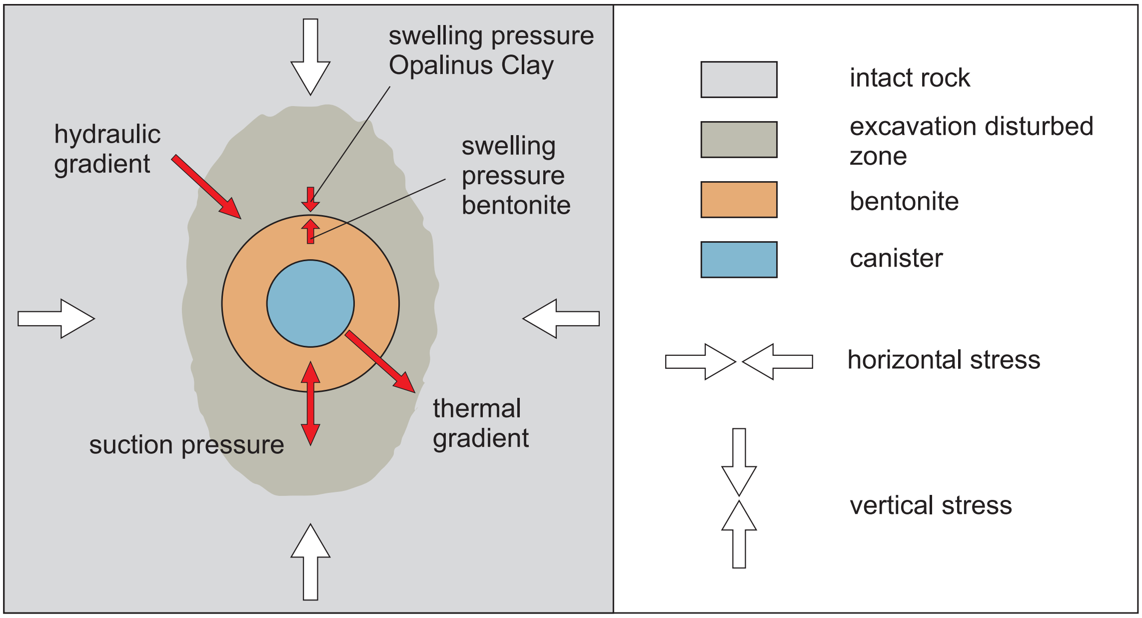
M. Mazurek
University of Bern, Switzerland

1. Introduction

Construction and operation of a repository represent a major perturbation of the natural system. After repository closure, the backfilled excavations and the near-repository host rock will undergo a transient phase, eventually approaching a new state of equilibrium in terms of hydraulic, geomechanical and geochemical conditions. Temporal and spatial evolution of the disturbed system around the disposal facilities has been the subject of intensive studies, with the emphasis on processes and perturbations which may affect long-term performance of the repository system (Nagra, 2002a, 2002c).

The disturbed system around the disposal facilities is determined by the interaction of hydromechanical processes and repository-induced perturbations (sketched in Figure 1 for an emplacement tunnel for SF/HLW). During the construction and operations phase, an excavation disturbed zone (EDZ) will form, characterised by fracturing and reduced rock strength as well as by enhanced rock permeability. After repository closure, the underground facilities will resaturate, driven by a strong hydraulic gradient and the suction pressure of both, the (bentonite) backfill material and the desaturated host rock. Long-term deformation behaviour of the host rock, together with increasing porewater pressure and swelling of the backfill, give rise to geomechanical changes in the immediate vicinity of the excavations, most probably ending in partial or complete self-sealing of the EDZ. Repository-induced perturbations such as heat and gas production, but also geochemical interactions of the backfill material with the host rock formation, will be superimposed on these processes. The evolution of the disturbed system as a whole may affect long-term repository performance. For a more comprehensive assessment of this issue the reader is referred to Nagra (2002a, 2002c).

Figure 1. **Schematic illustration of hydromechanical processes and repository-induced perturbations in the disturbed system around an SF/HLW emplacment tunnel following repository closure**



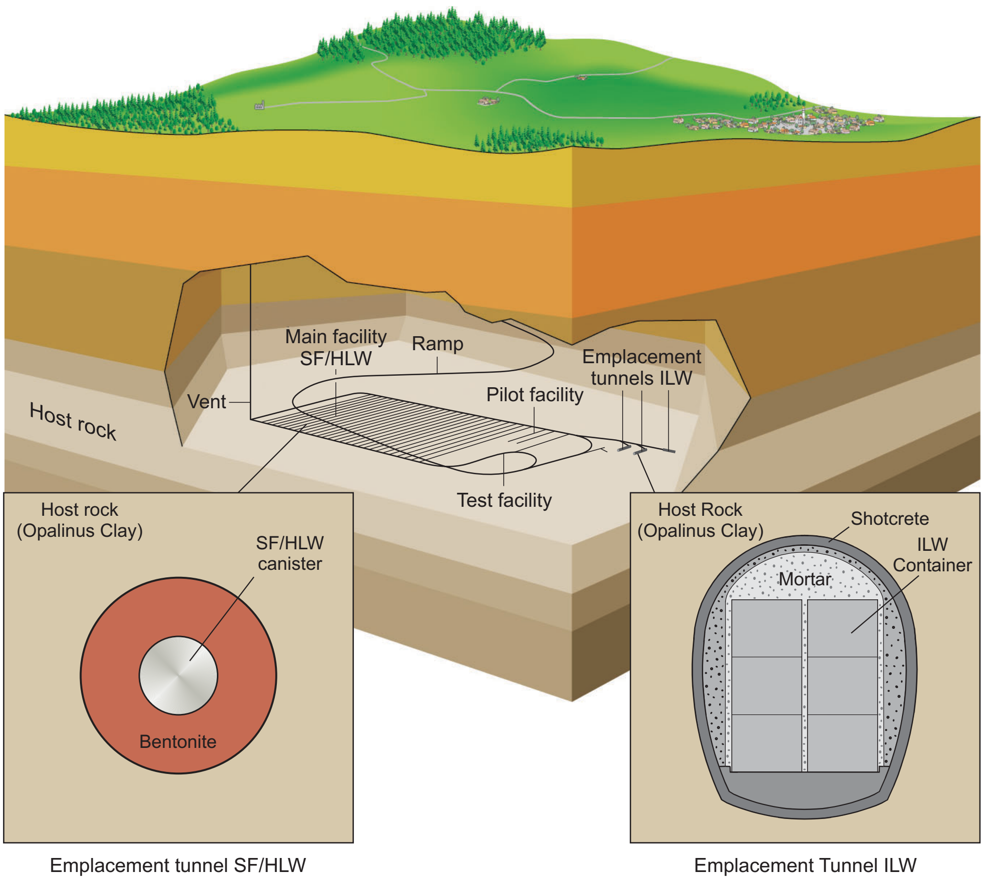
2. Repository layout and milestones of the pre-closure phase

The repository layout will significantly affect the post-closure evolution of the system and therefore requires a brief description. The main repository components are (Figure 2):

- an access ramp, construction and operation tunnels, ventilation shaft, pilot and test facilities;
- an array of SF/HLW emplacement tunnels 800 m in length, spaced 40 m apart; and
- three short emplacement tunnels for ILW.

The repository will be located at a depth of about 650 m in the centre of the host formation – the thickness of the host rock is 105-125 m. The maximum principal stress is 22-23 MPa, nearly horizontal and oriented N-S. The minimum horizontal stress and lithostatic stress are 15 and 16 MPa, respectively. The SF / HLW emplacement tunnels (diameter 2.5 m) are oriented in the direction of the maximum stress so as to maximise tunnel stability. These tunnels are expected to be self-supporting, based on experience with excavations in Opalinus Clay, although rock bolts and a light mesh are required for operational safety. For all other tunnels, including the ILW emplacement tunnels (diameter 7-9 m) and the access ramp, a concrete liner is used. The design and operation of the repository are described in detail in Nagra (2002b, 2002c).

Figure 2. **Possible layout of the deep geological repository for SF/HLW/ILW in Opalinus Clay**

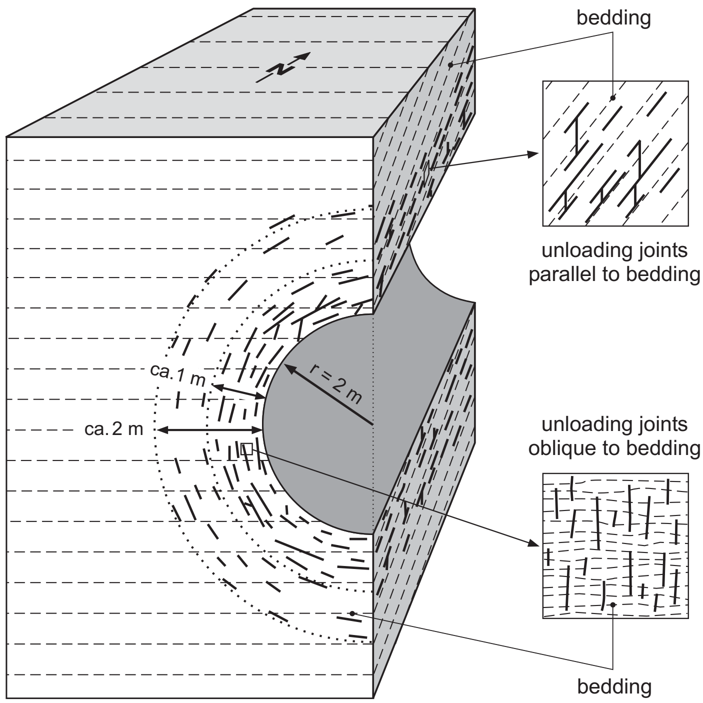


After closure of the underground facilities, the dissipation of the repository-induced perturbations is largely determined by the pre-closure history, which consists of 4 major phases. The *exploration and construction phase* (~10-12 years) includes the construction of the access ramp, pilot and test facilities, ILW emplacement tunnels, operation and access tunnel and the shaft. The *operations phase* (~15 years) consists of the excavation of the SF/HLW emplacement tunnels, waste emplacement and backfilling. The sequence of operations ensures that a given SF/HLW emplacement tunnel is open for only 1–2 years, thus avoiding significant alteration of the host rock at the tunnel periphery. The *monitoring phase* after the completion of emplacement of all wastes will last ~25-100 years. During this time, all wastes are in backfilled and sealed emplacement tunnels. The pilot facility is accessible for monitoring using the adjacent observation tunnel and monitoring boreholes. The shaft is sealed with ~40 m of highly compacted bentonite. The SF/HLW and ILW operations tunnels and the construction tunnel are backfilled with a 30/70%-bentonite/sand mixture. The *closure phase* will be completed within a few years. Final closure of the facility would involve emplacement of two ~40 m long seals of highly compacted bentonite and backfilling the ramp (Nagra, 2002c).

3. Long-term evolution of the EDZ

Low hydraulic conductivity in the order of 10^{-13}–10^{-14} m/s and favourable radionuclide retention properties ensure the excellent barrier function of the intact host rock. The EDZ surrounding the underground facilities, however, represents a potential transport path which may affect the efficiency of the overall geological barrier system. Comprehensive understanding of the temporal and spatial evolution of the EDZ is therefore an essential prerequisite for the assessment of long-term waste confinement within the engineered barriers.

Figure 3. **Conceptual structural model of the EDZ at the Mont Terri Rock Laboratory (after Bossart *et al.*, 2002)**



An empirical data base was elaborated largely as part of the Mont Terri Project (Bossart *et al.*, 2002; Martin & Lanyon, 2002). Figure 3 shows a conceptual structural model of the EDZ around an open tunnel of the Mont Terri rock laboratory. The EDZ is a composite structure consisting of two more or less concentric shells. Unloading joints parallel to the bedding are preferentially located in the roof of the tunnel, whereas oblique orientations are predominant at the side walls. For radial distances < 1 m, the typical frequency of excavation-induced features is ~5 m^{-1} (inner EDZ). A clear tendency of decreasing fracture intensity is seen at distances between 1 and 2 m (outer EDZ). Hydraulic characterisation of the inner EDZ suggests local values of hydraulic conductivity of about 1×10^{-10} m/s in the roof and in the floor of the tunnel. At the side walls, local values in the range $1\text{-}5\times10^{-7}$ m/s were determined.

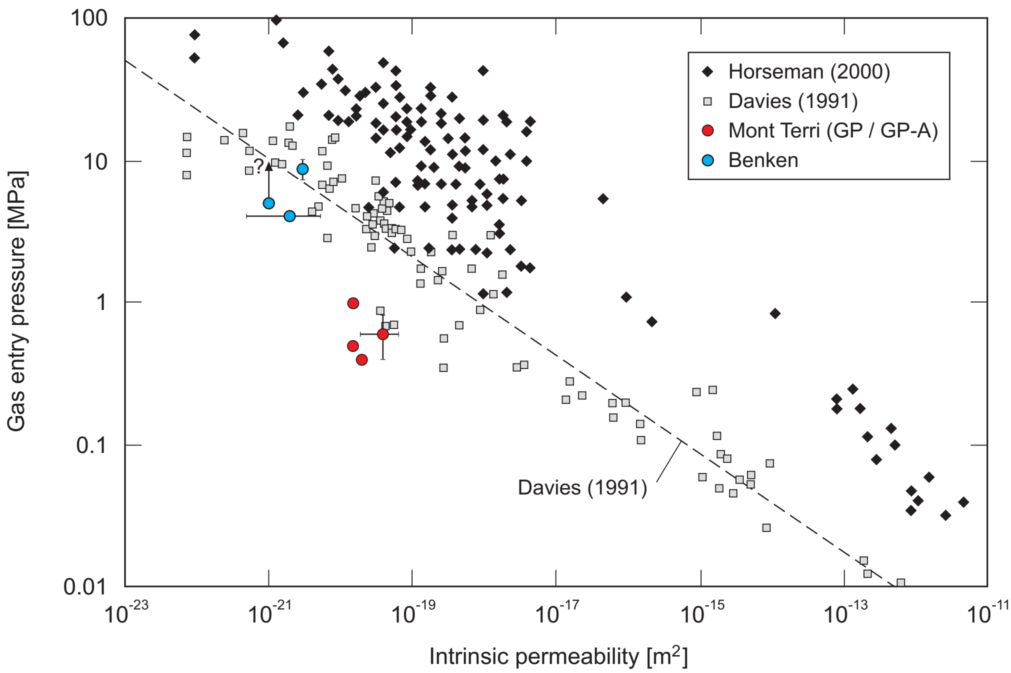
Transferability of the results from an open tunnel in the Mont Terri Rock Laboratory to the geomechanical and hydraulic in-situ conditions of a backfilled repository in the Zürcher Weinland was achieved by hydro-mechanical modelling (Nagra, 2002a). An appropriate material law was developed (elastoplastic model with creep) and implemented in a numerical EDZ model, which was calibrated with tunnel convergence measurements from Mont Terri. Eventually, the calibrated model was adapted to predict, for a repository in the Zürcher Weinland, the evolution of geomechanical conditions during operation and in the post-closure phase. The predicted thickness of the inner zone is about 0.75 m for the SF/HLW emplacement tunnels and about 1 m for the ILW tunnels. The simulated extent of the outer zone is ≤ 1.7 times the radius for the SF/HLW tunnels and ≤ 2.5 times the radius for the ILW tunnels (for the simplified assumption of a concentric EDZ). After backfilling and resaturation of the repository, swelling pressures of the backfill material and reconsolidation of the host rock will give rise to partial self-sealing of the EDZ (ongoing EU Selfrac Project). At the end of this reconsolidation phase, the expected hydraulic conductivity of the inner EDZ is in the order of 1×10^{-12} m/s and even lower for the outer zone (about 5×10^{-13} m/s).

Repository scale modelling of porewater flow indicates that the overall barrier function of the host rock is not significantly affected by the presence of the EDZ (Nagra, 2002a, 2002c). The role of the EDZ as a potential exfiltration path is quite limited as long as the intact host rock and the confining units prevent any marked vertical porewater exchange between the local / regional aquifer systems.

4. Release of repository gas

The SF/HLW and ILW will produce a significant amount of gas due to corrosion and microbiological degradation processes. Gas generation will continue for a long period after repository closure. If the gas cannot escape, gas accumulation in the emplacement tunnels may result in build-up of gas pressure, high enough to significantly affect the repository system. Expulsion of contaminated porewater into the host rock and the release of radionuclides in the gaseous phase are further gas-related processes that influence long-term safety (Nagra, 2002c, 2002d).

Figure 4. **Empirical relationship between gas entry pressure and intrinsic permeability in low permeability formations – comparison of data from the Zürcher Weinland (Benken) and Mont Terri (Nagra, 2002a) with data compiled by Davies (1991) and Horseman (2000)**



Release of gas through the geosphere may be accommodated by different transport mechanisms, including advective-diffusive transport of gas dissolved in the porewater, visco-capillary two-phase flow in the existing porespace of the rock matrix and dilatancy-controlled gas transport along induced pathways. In the context of Project *Entsorgungsnachweis*, creation of macroscopic tensile features ("gas fracs") is not considered possible, because the build-up of gas pressures in the emplacement tunnels is very slow – typically in the order of 10^3-10^4 years (Nagra, 2002a).

The gas-related properties of Opalinus Clay have been investigated through *in-situ* gas injection experiments and laboratory tests with core specimens (Nagra 2002a, Marschall *et al.* 2003). The experimental results indicate typical two-phase flow behaviour with a marked correlation between intrinsic rock permeability and gas entry pressure. The determined gas entry pressures were in the range of ~0.5-10 MPa and the corresponding intrinsic permeability values are between 10^{-19} and 10^{-21} m^2; notably, similar correlations have been compiled for many other low permeability formations (Figure 4). Microstructural analyses of the Opalinus Clay suggest that gas-water displacement preferentially takes place in the connected system of macropores of the rock matrix (equivalent pore radii > 25 nm). The host rock formation in the Zürcher Weinland has a porosity of 0.12, whereby the fraction of macropores amounts to about 20-30%. For elevated gas pressures, i.e. when gas pressure approached the magnitude of the minimum principal stress component, evidence was found for dilatancy-controlled gas flow with a marked increase in rock permeability. After pressure recovery, however, no permanent permeability enhancement was seen.

The migration of gases that have accumulated in the SF/HLW and ILW emplacement tunnels is a complex process, which is influenced by both the gas-specific transport properties of the host rock and the repository layout. Tracing the potential gas flow paths from the locii of gas generation towards the biosphere requires a decomposition of the gas path into segments: backfilled emplacement tunnels, access and operation tunnels, EDZ and sealed sections, host rock and the confining units. The significance of the different flow paths is discussed in Nagra (2002a, 2002c, 2002d).

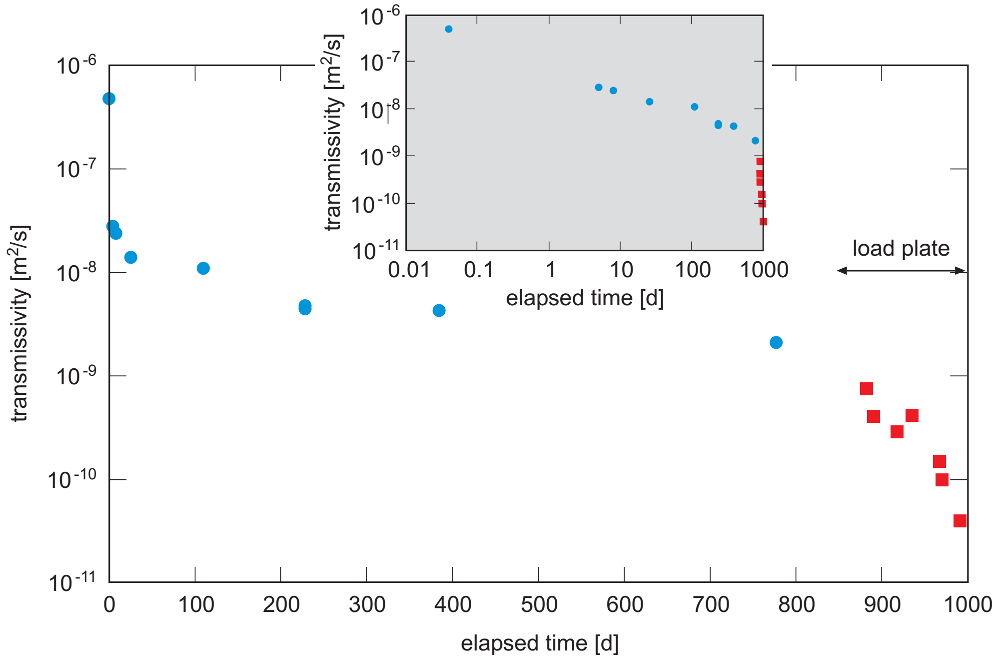
5. Self-sealing processes in Opalinus Clay

The capacity of discontinuities in the Opalinus Clay to self-seal is a primary factor favouring its selection as a host rock. Self-sealing processes are of particular importance for the long-term evolution of the excavation-induced fractures. Other repository-induced perturbations may also be entailed by a dilatancy-controlled increase in rock permeability, such as the release of repository gas.

The self-sealing capacity of the Opalinus Clay is determined by its hydromechanical and hydro-chemical characteristics (Nagra, 2002a). The drained bulk modulus of the rock is relatively low and favours closure of any fractures at low effective normal stress. Furthermore, low rock strength gives rise to reconsolidation of plastified zones around the backfilled excavations when stress conditions change in the post closure phase (increase in porewater pressure, swelling of bentonite backfill). Swelling of the host rock and other geochemical processes may also contribute to self-sealing of repository-induced features.

Empirical evidence for self-sealing processes in Opalinus Clay originates from various structural, hydrogeological and mineralogical studies in Northern Switzerland (Gautschi, 2001). As part of the Mont Terri Project, several experiments were initiated to demonstrate the self-sealing capacity of induced fractures and to investigate the time dependence of the self-sealing process. A long-term in-situ experiment, conducted in the EDZ of an open tunnel section, indicated a significant reduction of the EDZ transmissivity over a period of 800 days from 5×10^{-7} m^2/s to 2×10^{-9} m^2/s (Figure 5). During the subsequent test phase, a load plate was installed and the EDZ was subjected to radial stresses between 1 and 5 MPa to simulate bentonite swelling pressures in a backfilled emplacement tunnel. A further drop in transmissivity by two orders of magnitude to 2×10^{-11} m^2/s was observed (ongoing EU Selfrac Project; Nagra, 2002a). Another in-situ experiment was aimed at demonstrating the self-sealing capacity of an artifically created hydrofrac (Nagra, 2002a). The test results indicate a distinct enhancement of fracture transmissivity at low effective stress (< 1 MPa). After recovery of effective stress to undisturbed conditions, however, the hydrofrac was tight again.

Figure 5. **Long-term changes in EDZ transmissivity in an open tunnel section at the Mont Terri Rock Laboratory. Initially, the EDZ was saturated for a period of 800 days (blue dots) and EDZ transmissivity was monitored periodically. Afterwards, a load plate was installed (1-5 MPa) and the transmissivity measurements were repeated (ongoing EU Selfrac Project; Nagra, 2002a)**



6 Summary and conclusions

The temporal and spatial evolution of the disturbed system around the disposal facilities may affect the long-term performance of the repository system. Key processes under consideration are the evolution of the EDZ, the release of repository gas and the self-sealing capacity of the Opalinus Clay. The following conclusions are drawn:

- the EDZ around the backfilled underground excavations will reconsolidate after repository closure. Compared to the intact host rock, the expected long-term permeability enhancement is a factor of 5-10 or less. The estimated thickness of the EDZ around the emplacement tunnels is about 1.7-2.5 times the tunnel radius;
- visco-capillary two-phase flow is the prevailing transport mechanism for accommodating the release of repository gas. For elevated gas pressures, evidence was found for dilatancy-controlled gas flow with a marked increase in rock permeability. After pressure recovery, however, no permanent permeability enhancement was seen;
- the capacity of induced features in Opalinus Clay to self-seal was confirmed by in-situ experiments at the Mont Terri Rock Laboratory. Hydromechanical and geochemical self-sealing processes resulted in a transmissivity reduction of more than 4 orders of magnitude.

The main conclusions are supported by multiple lines of evidence from laboratory and field tests, from regional studies and from studies of natural systems elsewhere.

Further processes were assessed in the context of Project *Entsorgungsnachweis* (Nagra, 2002a), such as geochemical alteration of the near-repository host rock and heat generation of the SF/HLW. Their impact on long-term repository performance is assessed as being less important. Pyrite oxidation in the induced fractures of the EDZ and high pH porewaters due to the degradation of concrete are restricted to a narrow zone around the disposal facilities and may give rise to enhanced sorption capacity. The heat pulse emitted by the SF/HLW leads to a maximum temperature of 95°C at the tunnel walls and will dissipate within several hundred to thousand years.

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GEOSCIENTIFIC BASIS FOR MAKING THE SAFETY CASE FOR A SF/HLW/ILW REPOSITORY IN OPALINUS CLAY IN NE SWITZERLAND (PROJECT *ENTSORGUNGSNACHWEIS*) IV: GEOSPHERE STABILITY: LEARNING FROM THE PAST TO PREDICT FUTURE LONG-TERM EVOLUTION

Martin Mazurek[1], Andreas Gautschi[2], Thomas Gimmi[1,3], Wemer Leu[4], Paul Marschall[2], Walter H. Müller[2], Heinrich Naef[5] and Niklaus H. Waber[1]

[1]Rock-Water Interaction (RWI), Institute of Geological Sciences, University of Bern, Switzerland;
[2]Nagra, Wettingen, Switzerland;
[3]Paul Scherrer Institut, Villigen, Switzerland;
[4]Geoform AG, Minusio, Switzerland;
[5]Büro für Angewandte Geologie, St. Gallen, Switzerland

1. Introduction

A number of safety-relevant issues need to be addressed when considering long-term evolution, out of which uplift/erosion, changes in the geochemical and hydrogeological environment are particularly important and are discussed below. Among the strongest arguments in the prediction of future evolution is the extrapolation of events and processes that occurred over a long period of time in the geological past (e.g. 10 Ma) to a shorter period in the future.

The future long-term evolution of Opalinus Clay in the investigation area in the Zürcher Weinland (NE Switzerland) is considered over a time period of around 1 Ma. The geological evolution can be predicted plausibly within reasonable limits over such a time period based on a detailed analysis of geological history. Predictions extending beyond this time period are feasible but contain an increasing element of uncertainty. This paper summarises the project-related conclusions, which are presented in greater detail in Nagra (2002a).

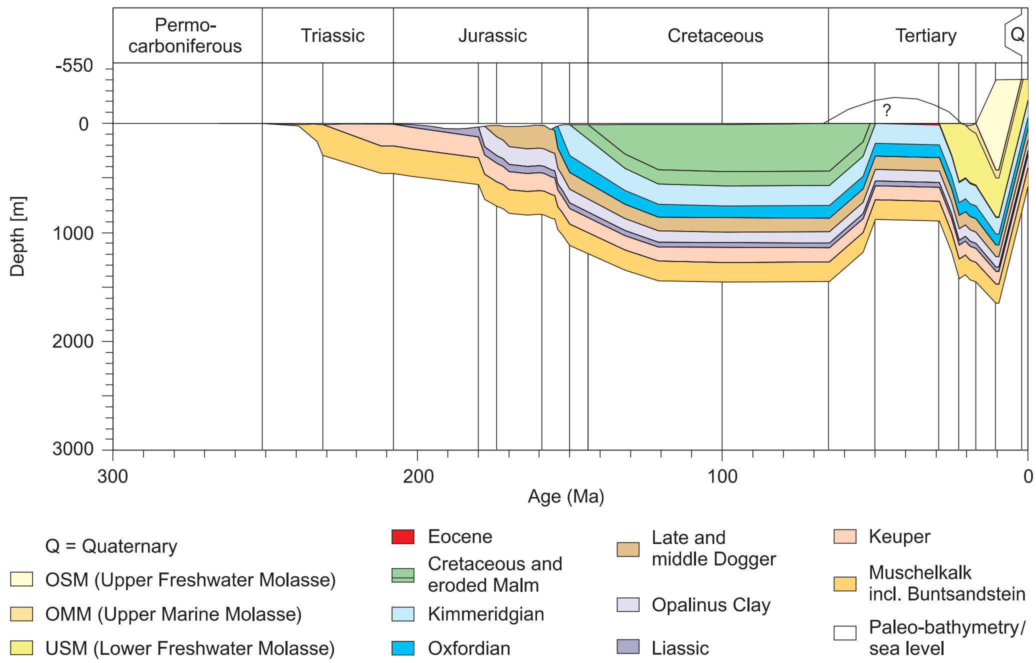
2. Uplift and erosion

The reference depth for a high-level radioactive waste repository in Opalinus Clay is 650 m below surface (Nagra 2002b). This depth may become smaller in future due to erosion, triggered either by uplift or by lowering of the erosion base level (back-erosion). Uplift and erosion in the past were quantified by four independent methods based on basin modelling, geomorphological and geodetic studies.

2.1 Basin modelling

A large number of techniques were applied to constrain the burial and temperature history of Opalinus Clay in northern Switzerland since its sedimentation 180 Ma b.p. These included stratigraphic evidence, apatite fission track analysis, organic maturity studies (biomarkers, vitrinite reflectance) and investigations of diagenetic cements and fluid inclusions therein. These methods were integrated in a basin model, and Figure 1 shows the resulting burial history of the basin in the Zürcher Weinland (Leu *et al.*, 2001). The Opalinus Clay was subjected to two successive stages of burial and uplift. It reached a maximum depth of ca. 1 650 m below surface some 10 Ma b.p., i.e. at the time of Molasse sedimentation (clastic sediments from the uprising Alps). Since that time, ca. 1 050 m of the overlying sediments were removed by uplift and erosion, which results in an average uplift rate of 0.1 mm/a over the last 10 Ma.

Figure 1. **Burial history of Opalinus Clay in the Zürcher Weinland based on basin modelling**



2.2 *Geomorphology*

Quaternary river terraces consisting of gravels occur throughout northern Switzerland. If their elevation and age are known, the rates of linear erosion since the time of deposition can be calculated by comparison with the elevation of present-day rivers. As shown in Figure 2, terraces with ages of at least 2 Ma are abundant along the whole course of the Rhine river in northern Switzerland. Some relics of gravels of the ancient Aare – Donau system with ages of ca. 5 Ma were also identified. Average erosion rates of 0.06-0.15 mm/a can be derived from these data. Assuming that linear erosion keeps pace with uplift, these values also represent uplift rates (Müller *et al.*, 2002).

Another set of data can be derived from the (realistic) assumption that the pre-glacial landscape was a peneplain and that its level can be characterised by connecting the peaks of present-day mountains and hills in the region. The difference in altitude between this level and that of present-day rivers is a measure of the extent of linear erosion over the last 2.5 Ma and thus of uplift over that period of time. The resulting values are shown in Figure 3 (based on Müller *et al.*, 2002). In the wider area of interest, the values are in a range 0.07-0.13 mm/a and thus comparable to values derived from other methods. To the south, the erosion rates reach higher values (up to 0.2 mm/a S of Zurich) but are outside the region considered for waste disposal.

Figure 2. **Elevation of Quaternary river terraces compared to the present-day course of the Rhine river**

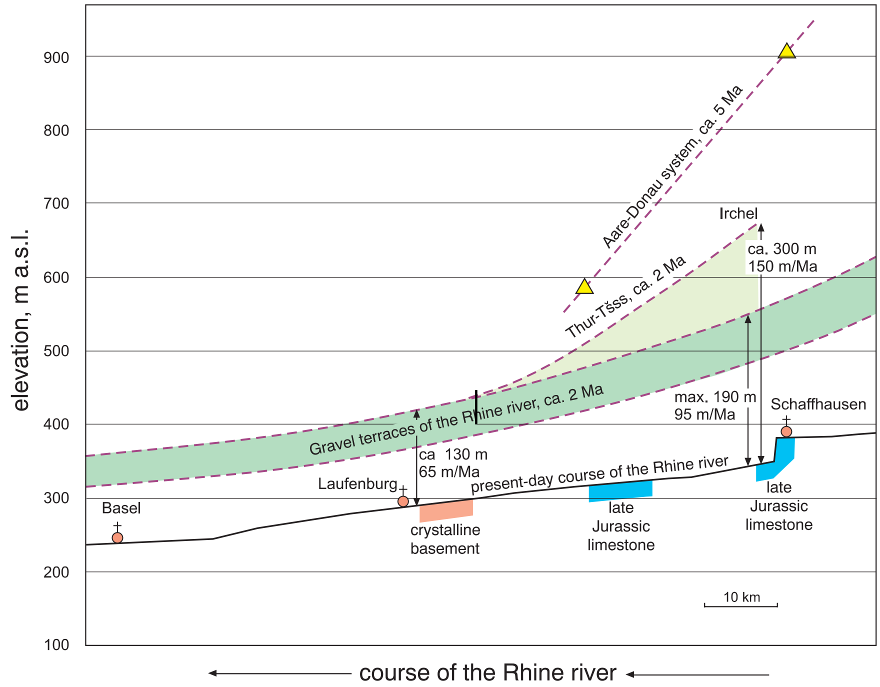
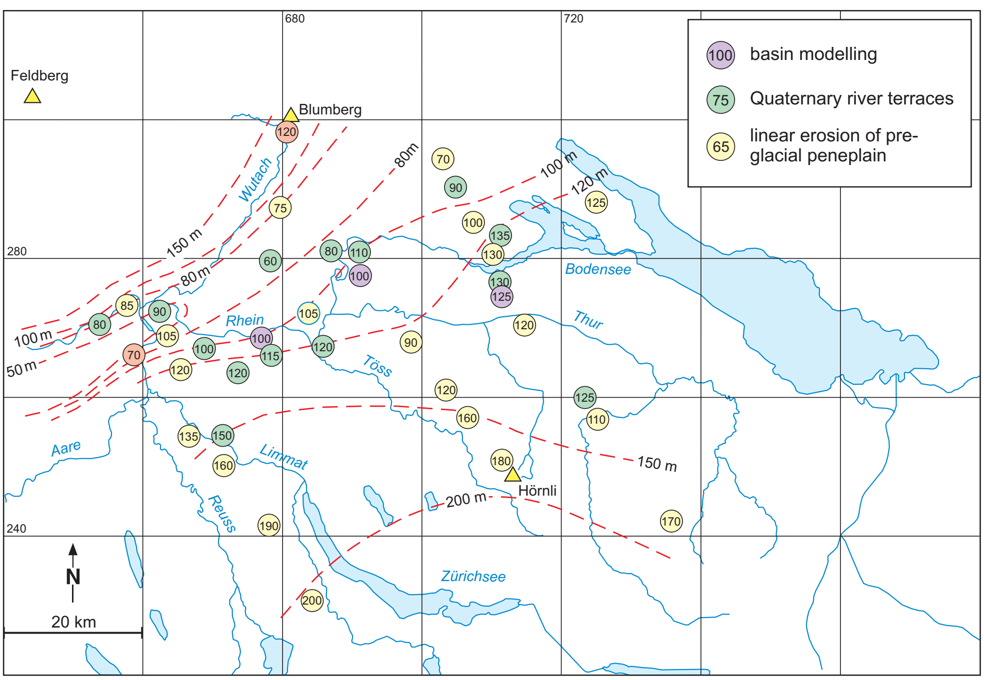


Figure 3. **Average uplift rates derived from basin models and from geomorphological studies. All data are in m/Ma**



2.3 Geodesy

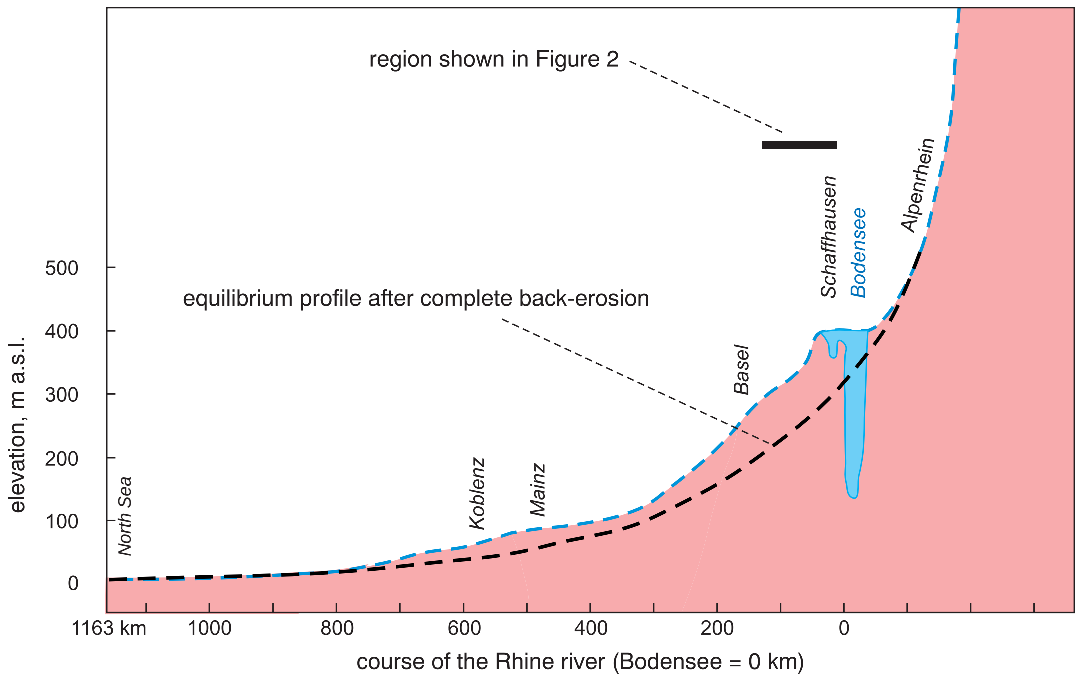
Data derived from precision levelling are available over a time period of almost 100 a. These measurements are relative to a point near Laufenburg, where the Rhine river bed consists of crystalline basement rocks (Figure 2). Accounting for the uplift rate of this reference point itself (0.65 mm/a, derived from geomorphologic studies) results in total uplift rates in the range 0.06-0.165 mm/a (Müller *et al.*, (2002).

2.4 Additional factors for erosion

Rivers have typical slope profiles from the source region to the discharge point to the sea. As shown in Figure 4, the Rhine river deviates from such an equilibrium profile. There is evidence that the existing profile remained stable over some Ma. Under the pessimistic assumption that the river profile will equilibrate completely with respect to its discharge point to the North Sea, Figure 4 shows that the complete back-erosion related to this event reaches max. 100 m (Müller *et al.*, 2002).

The Zürcher Weinland is located in the frontal part of glaciers that covered large parts of Switzerland in the cold periods of the Quaternary. The region was glaciated in some but not all cold periods, and maximum ice loads are estimated at several hundreds of meters. A general pattern can be observed that glacial advances in the past followed pre-existing valleys, partially or wholly eroding the fills from older glaciations. For future glaciations, similar patterns are expected. Glacial erosion along major valleys will keep pace with regional and local uplift and will thus be of the same order of magnitude as linear erosion. The lateral mountain ranges will remain largely intact and gully erosion will be restricted to already existing overdeepened channels. It is to be expected that the massive Late Jurassic limestones will form a protective cover in the form of a topographic elevation because of their resistance to erosion (Müller *et al.*, 2002).

Figure 4. **Profile along the course of the Rhine river compared to an "ideal" river slope profile**

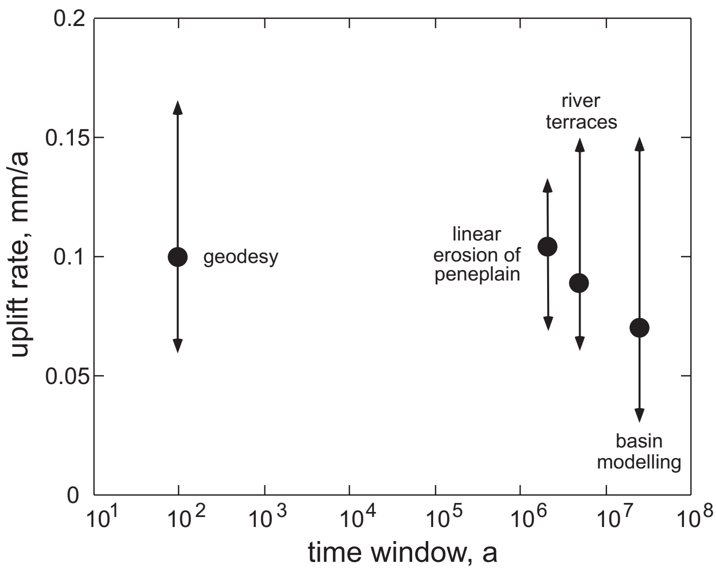


2.5 Summary

Four independent methods were used to characterise uplift and erosion of the Zürcher Weinland. The times over which these methods integrate uplift are quite different. Nevertheless, the resulting ranges are similar (Figure 5), and so multiple lines of evidence lead to consistent conclusions.

The region is located in the area of the foreland that underwent compressive stress as a result of Alpine crustal shortening. It is sensible, when evaluating long-term evolution, to assume that the movement recorded for the past will continue, at least over the time period of 1 Ma. Uplift will occur at a rate of 0.1 mm/a, and through the lowering of the base level of erosion (the Rhine river) until equilibrium is reached, an additional 100 m could be eroded away. This means that, in 1 Ma, the overburden of a repository constructed at a depth of 650 m will still be at least 450 m.

Figure 5. **Summary of results regarding uplift rates of the Zürcher Weinland**

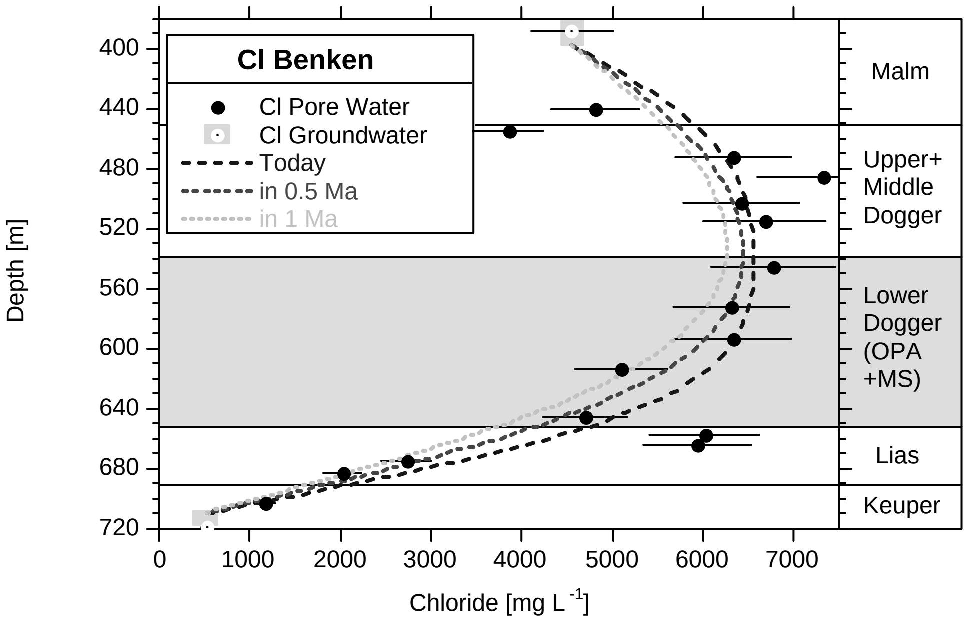


3. Geochemical environment

The geochemical composition of the pore water in the potential host rock is largely determined by equilibrium reactions with the rock minerals (clay minerals, carbonates), which have a large buffering capacity. This applies mainly to cations, neutral species and to the redox potential. Given the fact that mineralogy will not change even over millions of years, the same equilibria will control these species in future.

Mobile (or conservative) elements such as Cl and Br evolve independently of mineralogy, and their concentrations are controlled by diffusive exchange with the embedding aquifers. This process is ongoing and can be extrapolated to the next 1 Ma with confidence. For reasons of electroneutrality, the diffusive loss of Cl will be accompanied by an equivalent loss of Na. Figure 6 shows the expected changes of Cl concentrations over the next 1 Ma, assuming that diffusion will remain to be the dominant transport mechanism, and that the boundary conditions will not change substantially. The calculations for 0.5 or 1 Ma from today show that the expected changes are relatively small, less than about 20% within the potential host rock (about 10% in the centre) for the next 1 Ma (Gimmi & Waber, 2002).

Figure 6. **Calculated profiles of Cl concentration in pore water in 0.5 and 1 Ma, considering diffusion as the dominant transport process and assuming time-invariant boundary conditions**



4. Hydrogeological evolution

Hydrogeological measurements and observations in numerous boreholes and tunnels penetrating the Opalinus Clay throughout northern Switzerland indicate that a significant increase in the hydraulic conductivity of isolated fault zones in the Opalinus Clay will occur only if the overburden is less than 200 m (Gautschi 2001). A drastic increase in permeability would be restricted to the uppermost few decametres. Because the rock overburden of a repository constructed at a depth of 650 m will still be at least 450 m after 1 Ma, the permeability of the surrounding host rock will be practically unaltered. The only major change from a hydrogeological point of view will be the possible dissipation of hydraulic overpressures in the Opalinus Clay and adjacent formations. This dissipation will interfere with pore-pressure changes related to erosional unloading or glacial loading. Vertical fluxes related to these pressure changes are negligible (Kuhlmann *et al.*, 2002, Horseman, 2002).

5. Other effects

Current understanding of the regional tectonic situation is sufficient to qualify external perturbations such as magmatic activity or changes in the stress field as highly unlikely in the coming 1 Ma. The region is also characterised by a low earthquake activity. Records of fluid flow related to earthquakes in the past, such as veins or geochemical anomalies, were not identified (Mazurek, 2001). Recent differential movements are possible along the Neuhausen fault outside the region of interest, while no indications of active faulting are available from the potential siting area in the Zürcher Weinland.

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PROJECT *ENTSORGUNGSNACHWEIS:* SUMMARY OF THE SAFETY CASE

Jürg W. Schneider, Piet Zuidema, Lawrence H. Johnson,
Nagra, Switzerland
Peter Gribi
Vibro-Consult AG, Switzerland;
Gerhard Mayer
Colenco Power Engineering AG, Switzerland;
Paul A. Smith
Safety Assessment Management Ltd., UK

1. Introduction

This paper presents some key aspects of the safety case for the proposed deep geological repository for the direct disposal of spent UO_2 or mixed-oxide fuel (SF), vitrified high-level waste from the reprocessing of spent fuel (HLW) and long-lived intermediate-level waste (ILW) in the Opalinus Clay of the Zürcher Weinland in northern Switzerland (Nagra, 2002). These include arguments and analyses that:

- demonstrate safety and compliance with regulatory protection objectives; and
- indicate that the actual performance of the disposal system will, in reality, be more favourable than that evaluated in the quantitative analyses.

The process by which the arguments and analyses are developed is termed safety assessment. Safety assessment is used to show how a proposed disposal system could evolve over the course of time and to test whether adequate levels of safety are to be expected based on what is known about the system, and whether there are any circumstances that cannot currently be ruled out in which safety might be compromised. In the case of the proposed SF/HLW/ILW repository, consistent with the early stage of a repository programme, the main emphasis is currently on assessing the general feasibility of the project and on discussing its robustness. The safety assessment also provides a platform for discussion of a broad range of topics related to repository development.

2. Key features and safety functions of the disposal system

In the proposed repository, carbon steel canisters containing either SF or HLW are emplaced coaxially within a system of parallel tunnels that are constructed in the centre of the Opalinus Clay formation and aligned along the dip direction. The tunnels are backfilled with compacted bentonite. ILW is emplaced in larger-diameter tunnels, with a cementitious backfill. Access to the system of tunnels is provided, during construction and operation, by a spiral ramp. A vertical shaft for construction and ventilation is also required.

This system performs the following safety functions:

Isolation from the human environment

The safety and security of the waste, including fissile material, is ensured by placing it in a repository located deep underground, with all access routes backfilled and sealed, thus isolating it from the human environment and reducing the likelihood of any undesirable intrusion and misapplication of the materials, and also by safeguard measures defined by international organisations. In addition, the absence of any currently recognised and economically viable natural resources and the lack of conflict with future infrastructure projects that can be conceived at present reduce the likelihood of inadvertent human intrusion. Finally, appropriate siting ensures that the site is not prone to disruptive events and to processes unfavourable to long-term stability.

Long-term confinement and radioactive decay within the barrier system

Much of the radioactivity initially present in SF and HLW decays prior to breaching of the high integrity steel canisters. These are expected to remain unbreached for at least ten thousand years. In the case of ILW, containment is provided by steel drums and emplacement containers and is expected to last at least a hundred years. After the SF/HLW canisters and the ILW waste packages are breached, the stability of the waste forms in the expected environment, the slowness of groundwater flow and a range of geochemical immobilisation and retardation processes ensure that radionuclides continue to be largely confined within the engineered barrier system and the surrounding rock, so that further radioactive decay takes place.

Attenuation of releases to the environment

Although complete confinement cannot be provided over all relevant times for all radionuclides, release rates of radionuclides from the waste forms are slow, particularly from the stable SF and HLW waste forms. Furthermore, a number of processes attenuate releases during transport towards the surface environment, and limit the concentrations of radionuclides in that environment. These include radioactive decay during slow transport through the barrier provided by the host rock and the spreading of released radionuclides in time and space by diffusion, hydrodynamic dispersion and dilution.

Features of the barrier system that are key to providing the safety functions are thus:

- the *deep underground location of the repository*, in a setting that is unlikely to attract human intrusion and is not prone to disruptive geological events and to processes unfavourable to long-term stability;
- the *host rock*, which has a low hydraulic conductivity, a fine, homogeneous pore structure and a self-sealing capacity, and thus provides a strong barrier to radionuclide transport and a suitable environment for the engineered barrier system;
- a *chemical environment* that provides a range of geochemical immobilisation and retardation processes, favours the long-term stability of the engineered barriers, and is itself stable due to the phenomena mentioned above and a range of chemical buffering reactions;
- the *bentonite buffer (for SF and HLW)* as a well-defined interface between the canisters and the host rock, with similar properties as the host rock, that ensures that the effects of the presence of the emplacement tunnels and the heat-producing waste on the host rock

are minimal, and that provides a strong barrier to radionuclide transport and a suitable environment for the canisters and the waste forms;

- *SF and HLW waste forms* that are stable in the expected environment; and
- *SF and HLW canisters* that are mechanically strong and corrosion resistant in the expected environment, providing complete containment of radionuclides for an initial period.

Because of the key contributions that these features make to the safety functions, the good level of scientific understanding that is available and their expected insensitivity to perturbations, they are termed the "pillars of safety" of the barrier system.

3. Illustrating system behaviour

Different and complementary approaches can be used to explore system behaviour and evaluate the consequences of different types of uncertainty. On the one hand deterministic analyses can be conducted for a broad range of cases, while, on the other hand, probabilistic methods can be used to explore systematically the consequences of different combinations of parameters that fall within the ranges of uncertainty. In the study of the proposed SF/HLW/ILW repository, the main emphasis is on deterministic analyses for a broad range of cases that are representative of realistically conceivable possibilities for the characteristics and the evolution of the system. The objectives are to illustrate the possible radiological consequences of the repository, to evaluate uncertainties and design/system options in terms of their impact on the radiological consequences of the disposal system, and to determine whether existing uncertainties are acceptable, or need to be addressed in the course of future stages of the programme. These deterministic calculations are, however, complemented by probabilistic calculations that aim to enhance system understanding, ensure that no unfavourable combinations of parameters are overlooked, and test whether there are sudden or complex changes in performance as parameters are varied, which might not be detected using a purely deterministic approach.

The starting point for the deterministic analyses is to define and analyse a Reference Case. The Reference Case is based on a reference design/system and on the assumption that the likely/expected broad evolutionary path of the disposal system is followed (this is termed the Reference Scenario). It is also based on a number of assumptions regarding the conceptualisation for modelling purposes of key features, events and processes (FEPs) associated with the various system components (the Reference Conceptualisation), together with a reference set of parameters. The Reference Conceptualisation and reference parameter set are also generally based on the expected characteristics and evolution of the system, or currently preferred hypotheses, but some pessimistic or conservative conceptual assumptions and parameter values are also used, together with a reference, stylised conceptualisation of the biosphere. Quantitative models are used to examine the fate of radionuclides in the Reference Case, and to perform deterministic as well as probabilistic sensitivity analyses, both within and beyond the constraints of the Reference Conceptualisation and Reference Scenario. The sensitivity analyses provide understanding of the behaviour of the system with respect to perturbations and the extent to which deviations from the likely/expected characteristics and evolution of the disposal system affect overall performance and the performance of individual system components. They provide insight into the robustness of the system chosen and guide the definition of alternative assessment cases and assist in the interpretation of results. Probabilistic analyses around the Reference Case also provide an indication of compliance with regulatory criteria taking into account the combined effects of uncertainties.

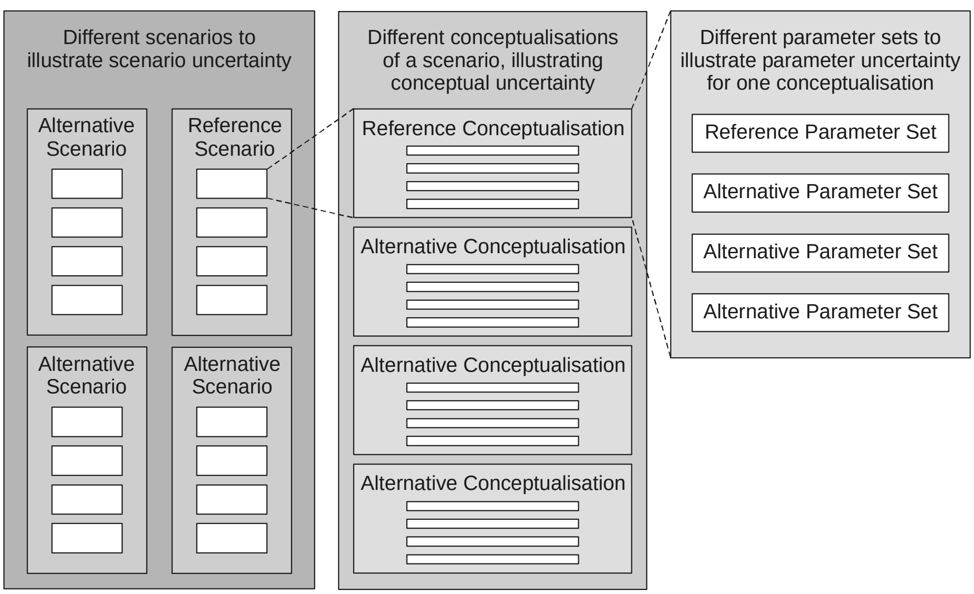
Alternative cases address other possibilities and stylised conceptualisations and are divided into a number of groups, according to the issues or uncertainties that they address. In particular, there are cases that address:

- the range of possibilities arising from particular uncertainties affecting the disposal system, where this range can be bounded with reasonable confidence on the basis of available scientific understanding;
- "what if?" possibilities, that are outside the range supported by scientific evidence, but are useful in testing the robustness of the disposal system;
- design / system options; and
- different (stylised) possibilities for future human actions and for the characteristics and evolution of the surface environment (the biosphere).

Like the Reference Case, each alternative case is defined in terms of a scenario (the broad evolutionary path that the disposal system follows), a number of conceptual assumptions for modelling key FEPs, and a set of parameters. Issues and uncertainties are assessed as to whether they (i), significantly affect the broad path of evolution of the disposal system described by the Reference Scenario, in which case they generate alternative scenarios, or whether they only affect (ii), the conceptualisation of FEPs within a given scenario, or, (iii), the assignment of parameter values within a given conceptualisation of a scenario. The result is a number of scenarios, within each of which there may be alternative conceptualisations of particular FEPs. Furthermore, for each conceptualisation, there may be a range of alternative parameter sets. This hierarchy of scenarios, conceptualisations and parameter sets is illustrated in Figure 1.

Combinations of multiple, highly unlikely possibilities are, for the most part, excluded from the assessment cases, although their consequences are screened by the use of probabilistic analyses.

Figure 1. **The hierarchy of scenarios, conceptualisations and parameter sets**



4. Compliance with regulatory Protection Objectives

In order to test whether the pillars of safety provide adequate levels of safety for all realistically conceivable possibilities for the characteristics and evolution of the system, a wide range of "assessment cases" is defined and analysed, with radiological consequence expressed in terms of the safety indicator of dose. This is a requirement of Swiss regulatory Protection Objectives, which include the statement that:

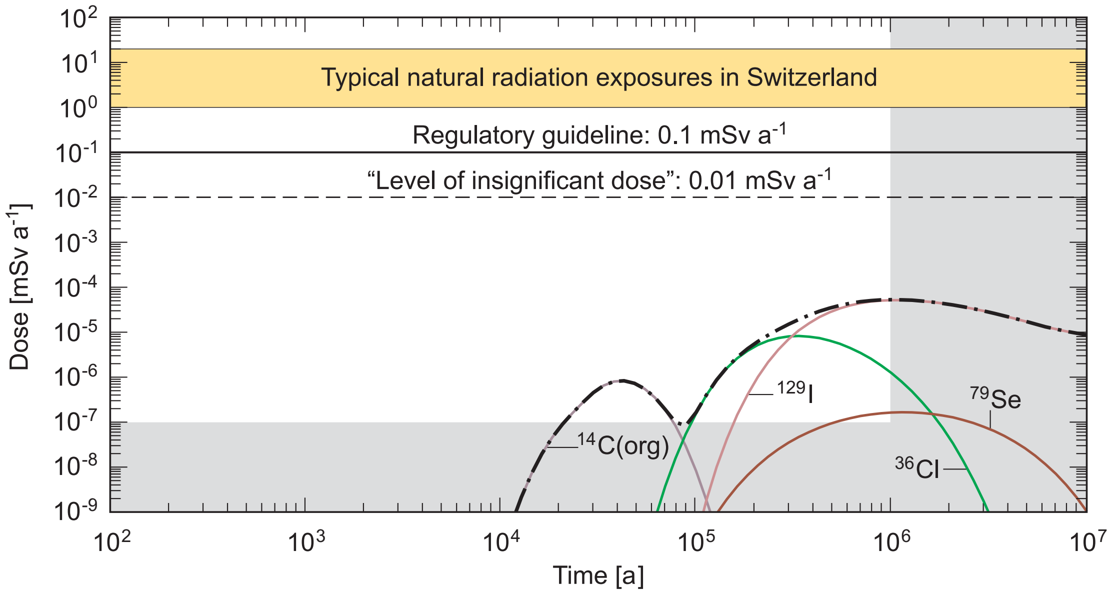
The release of radionuclides from a sealed repository subsequent upon processes and events reasonably expected to happen shall at no time give rise to individual doses which exceed 0.1 mSv per year.

The annual individual dose calculated as a function of time for the Reference Case, summed over all of the waste types, is shown in Figure 2. The maximum dose, which is predominantly due to ^{129}I from spent fuel, occurs at about one million years in the future and is more than three orders of magnitude below the maximum level set by Swiss regulations. It is also more than two orders of magnitude below the "level of insignificant dose" set at 0.01 mSv a^{-1} by the IAEA. The range of natural radiation exposures in Switzerland (1 to 20 mSv a^{-1}, where the higher end of the range is due to unusually high exposures to radon daughters) is also shown in the figure.

The maximum calculated doses and the times of these maxima for the Reference Case and all the alternative cases are shown in Figure 3. In all the cases considered, dose maxima are below the maximum level set by Swiss regulations, often by several orders of magnitude. Symbols in Figure 3 indicate to which scenario a given case belongs.

Figure 2. **Total doses for the Reference Case as a function of time (sum of all waste types)**

Shading indicates the increased uncertainty (but lower toxicity of the waste) at times beyond a million years, as well as low levels of dose that are considered radiologically irrelevant.



5. Reserve FEPs

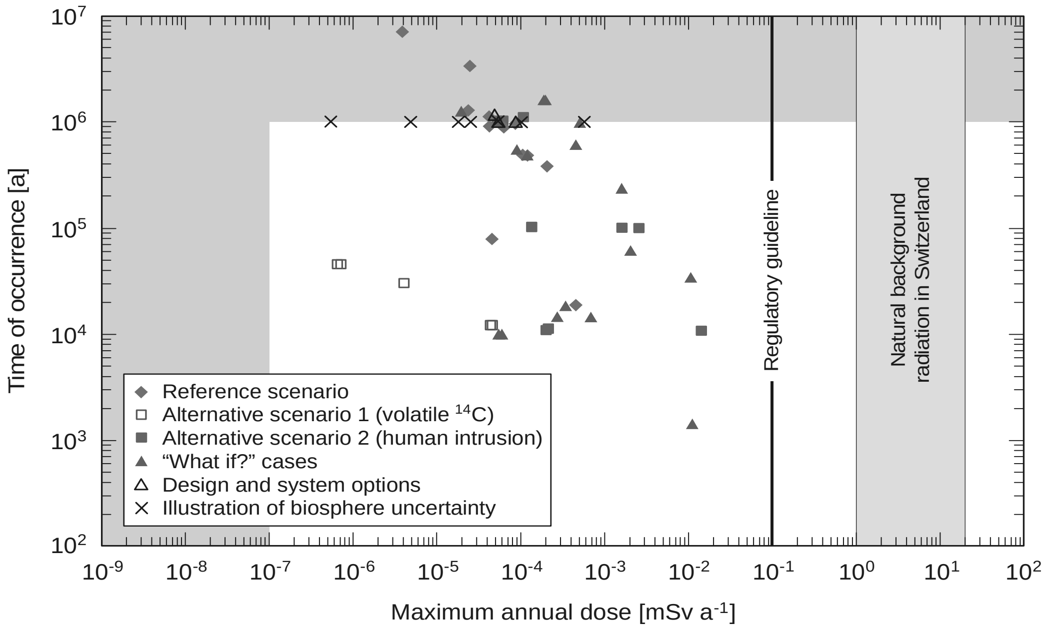
Some FEPs that are considered likely to occur and to be beneficial to safety are deliberately (and conservatively) excluded from the assessment cases, or at least from their analysis, because the level of scientific understanding is insufficient to support quantitative modelling, or because suitable models, codes or databases are unavailable. Such FEPs are termed *reserve FEPs*, since they may be mobilised at a later stage of repository planning if the level of scientific understanding is sufficiently enhanced, and the necessary models, codes and databases are developed. Reserve FEPs identified in the course of the present safety assessment include:

- the co-precipitation of radionuclides with secondary minerals derived from spent fuel, glass and canister corrosion (except for co-precipitation of radium, which is included in all cases);
- sorption of radionuclides on canister corrosion products;
- natural concentrations of isotopes in solution in bentonite porewater, which could further reduce the effective solubilities of some radionuclides;
- irreversible sorption of radionuclides in the near field and in the geosphere (surface mineralisation);
- long-term immobilisation processes (precipitation / co-precipitation) in the geosphere;
- the delayed release of radionuclides, due to the slow corrosion rate of ILW metallic materials (e.g. hulls and ends), as well as a more extended period of complete containment by ILW steel drums and emplacement containers; and
- the long resaturation time of the repository and its surroundings, which delays the commencement of corrosion and dissolution processes.

These phenomena have the potential, in the future, to provide additional quantitative contribution to the evaluated performance of the disposal system. Even in the current assessment, the presence of these reserve FEPs constitutes, in effect, an additional qualitative argument for safety, since it indicates that the actual performance of the disposal system will, in reality, be more favourable than that evaluated in the analysis of assessment cases.

Figure 3. **Scatter plot showing the maximum dose and time of occurrence of that dose for all cases analysed**

The symbols indicate to which scenario a given case belongs



6. Concluding remarks

A safety case has been made based on a careful analysis of a wide range of assessment cases that were derived in a methodical way. These analyses have not identified any outstanding issues with the potential to compromise safety. Compliance with Swiss regulatory Protection Objectives has been shown, and the existence of reserve FEPs indicates that the actual performance of the repository will be even more favourable than that indicated by the results of the analysis.

Other aspects of the safety case include arguments for:

- the strength of geological disposal as a waste management option;
- the safety and robustness of the chosen disposal system;
- the low likelihood and consequences of human intrusion;
- the strength of the stepwise repository implementation process;
- the good scientific understanding that is available and relevant to the chosen disposal system and its evolution; and
- the adequacy of the methodology, models, codes and databases that are available to assess radiological consequences.

as well as arguments for safety based on indicators of safety that are complementary to dose and risk. Although these arguments are not considered within the scope of the present paper, they are discussed in detail within the safety assessment documentation.

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THE REGULATORY REVIEW: GENERAL COMMENTS, CURRENT STATUS OF REVIEW, IDENTIFICATION OF CRITICAL ISSUES

J. Vigfusson, E. Frank
HSK, Switzerland

1. Introduction

Typically, a lot of interesting and important details add up to give a coherent and convincing picture of a safe repository. A good portion of these details must be studied and the scientific basis of the system must be clearly understood by the reviewing authority in order to be able to pass a judgement on the safety case.

HSK has already received a large part of the documentation relating to the project, including the three high level documents that summarize the synthesis of the geological information, the demonstration of repository design and construction feasibility and the safety case. After a first look at the contents of the documentation we would like to complement Nagra on the maturity and clarity of the presentation in these reports.

At this early stage, we shall not present any review judgements. The reviewer usually is dependent upon having not only the high level documents but also all the detailed reference reports in front of him in order to do his job, and HSK is still receiving very relevant documents. Thus we are still at the very beginning of our review.

Here, we offer some comments of general nature about the review process and mention a few points that seem to be uppermost in our mind at this stage.

2. The Demonstration of disposal feasibility and the criteria for its review

What we have before us is a demonstration of the feasibility of a safe disposal of spent fuel and high level waste as well as long lived intermediate level waste in Switzerland. Such a demonstration is a requirement of the nuclear legislation.

The feasibility demonstration has three parts:

- The safety demonstration that we discuss below;
- The site demonstration: Since the safety demonstration is based on the detailed properties of the host rock, it is required to show that a site with such properties can in fact be identified in Switzerland;
- The construction feasibility demonstration: The necessary construction must be shown to be technically possible.

The criteria by which HSK judges the safety demonstration are first and foremost the quantitative safety goals and qualitative requirements of the guideline R-21. There is a dose criterion of maximally 0.1 mSv/a received by a member of a critical group. This dose criterion applies to the reasonably expectable future scenarios. Complementary to that, a total risk criterion is applicable to the remaining, less expected scenarios. There is some flexibility for the implementer in which group he wants to consider the less probable scenarios.

The site demonstration is judged against a set of qualitative criteria set forth in an HSK note, HSK 23/57, issued in 1999. These criteria address such points as:

- the necessary size of the qualified host rock;
- the hydrogeological properties;
- prognostibility;
- tectonics and long term stability;
- rock mechanics;
- ressource conflicts.

How the qualitative criteria translate into numerical criteria is dependent on the needs of the other two parts of the feasibility demonstration.

3. The NEA Review Group

Besides, and to complement the HSK review, the Swiss authorities arranged for a review by an international group of experts, a group assembled and managed by the NEA. This group will provide an independent evaluation of the post-closure radiological safety assessment.

The focus of the review will be on:

- the overall strategy for demonstrating long-term safety;
- the rôle and relative weight given to the safety functions of the different barriers;
- the scientific basis for the representation of processes and barrier functions;
- the comprehensiveness of FEPs affecting the disposal system;
- the comprehensive derivation of scenarios identified for performance assessment;
- the treatment of data and model uncertainties.

The NEA Review Group will take up work end of June 2003 and is expected to complete their review in the beginning in 2004.

4. Schedule and current status of the HSK review

On certain aspects, the review of HSK has already begun. From June 2003 on, when the documentation is complete, the review work will gain in intensity and will also involve a number of experts external to HSK. The main technical review work is expected to take a year. Thus the schedule foresees that the review will be finished late in 2004.

During 2005 the feasibility demonstration and the review documents will be laid out for public comments. In 2006 the government is expected to decide whether to accept the feasibility demonstration.

The areas, where the review work has already started, include the FEPs connected with the various chemical questions that are relevant for the barrier materials or the release and transport as well as the various assumptions concerning the inventory.

5. Focus of the review

As was already indicated, the review is in a beginning stage and we can only make a few preliminary remarks now.

In this special case we are not in a licensing process, and there is not a legal requirement for a regulatory review. However, the review is undertaken in order to support the government's decision on the feasibility demonstration.

There are perhaps 3 or 4 main aspects that need to be reviewed:

- The understanding of the system and its safety functions.
- The reliability of the quantitative description of the materials and the reliability of the mathematical models and calculations done to analyse their future behaviour.
- The comprehensiveness in different parts of the analysis.

The reviewer has many options in how to do proceed. Some questions need only be superficially looked at, some in considerable detail. Sometimes it is satisfactory to consult the technical literature, but that task can also be assigned to an outside expert. If the availability of relevant data is poor, HSK may involve itself in experimental programs. HSK will usually test and complement model calculations by its own modelling, sometimes in a simplified manner, sometimes at a comparable level of detail as the original calculation.

We would like to touch quickly upon some general topics or focal areas for our review, beginning with the geology.

- The correct understanding of the site is a necessary prerequisite for modelling the hydrogeological situation and understanding the long-term behaviour of the site. The geological characterization leads to the models and delivers the parameters that are needed in order to estimate the efficiency of the geological barrier both in its role as protection of the near field barriers and as a retarding agent for the radionuclides.
- The long-term stability is intimately connected with crustal movements but also with the future climate and erosion processes.
- In the short term, the host rock is influenced by processes induced by the emplacement of the repository into the host rock. Some of these processes require mathematical models that consider a lot more variable parameters than traditionally has been necessary.

In reviewing the geological and hydrogeological evidence, the HSK geologists are assisted by external experts.

Let us take a more general vantage point and look at the safety case as a whole. On this level, we will review:

- The safety case methodology:
  - the adequacy of the overarching concepts and approaches;
  - the quality of data management procedures;
  - the comprehensiveness of the considerations and traceability of the decisions, especially concerning scenarios, models and parameters.

- How uncertainty is dealt with. An important aspect of the safety case is how the various uncertainties in models and parameters contribute to the overall uncertainty in the final result for the safety indicator dose or risk.
- How additional information or different ways of looking at the release processes can contribute to an overall demonstration of safety. How the need to reduce uncertainty is taken into account in planning future research.

The review will address the conceptual understanding of the various processes, events and features that could influence the disposal system. We need to make sure that the FEP database is comprehensive and the properties of the FEPs and their interactions well understood.

The FEPs are combined to build models of the possible current state and future evolution of the repository system, which then are analysed with respect to the possible release of radionuclides from the system. The set of such scenarios must be comprehensive and the consequences well enough understood, so that a convincing choice of a manageable number of scenarios to illustrate and bound the consequences of the numerous other reasonable possible scenarios can be made.

The choice of scenarios must be understandable to the reviewer through a clear account of the main decisions taken to arrive at the choice, also explaining their reasons.

Looking in particular at the near field, we notice many interesting problems.

- The waste has a high thermal output in the first several hundred years. As a consequence, there are strong thermal gradients and high temperature in the bentonite buffer and elevated temperature also in the adjacent host rock. The thermal conditions influence the water circulation during the saturation of the bentonite, and both influence the chemical evolution of the bentonite. It is a situation where a thermo-hydro-mechanical-chemical evolution is taking place.

Also in other aspects the bentonite buffer is an interesting object for the researcher and the reviewer:

- The bentonite buffer is likely to remain inhomogeneous for quite some time because of the slow saturation process. The inhomogeneity refers to the course structure of a bentonite granulate almost surrounding the canisters except for the fact that the canisters rest on large homogeneous compressed bentonite blocks.
- One would like to make sure that the canisters will not sink; and
- that gas, produced after contact of the canisters with water, will escape without leaving behind it preferential pathways for the radionuclides.

The release of radionuclides by dissolution of the HLW and SF matrix is the result of complex processes that take place after the corrosion has damaged the canisters.

On the estimation of release and judgement of safety:

The assessment of the transport of the radionuclides through the different barriers under various assumptions about scenarios and model parameters requires a large calculation effort. These release calculations will be punctually checked by calculations with HSK codes or those of its external experts.

The quantitative release assessment is followed by the analysis of the behaviour of the radionuclides in the biosphere resulting in an assessment of the maximal dose or risk to a member of the population. The dose or risk is compared with the formal safety criterion.

The quantitative arguments, the careful consideration of conceptual, data and model uncertainties, a consideration also of relevant qualitative information, go into the final conclusions on the long-term safety of the repository.

A judgement of the rigour of these conclusions, as drawn in the safety case, is also the final outcome of the review.

6. Summary

The review has just started, therefore only preliminary remarks can be made here. The following points stand out in our mind:

- The documentation of the safety case appears clear and comprehensive.
- The engineered barrier system is more challenging than in earlier projects. We have:
  - inhomogeneity of the bentonite buffer during an extended time period;
  - slow saturation of the bentonite during the thermal phase;
  - questions about the gas conduction in the near field.
- The thermo-hydro-mechanical behaviour of the Opalinus clay is complex.
- The fracture connectivity in the EDZ may be important for radionuclide and gas transport.

As regards the central theme of this conference we note as an example that the hydrogeochemical data have provided strong and multiple evidences of the long term isolation capacity of the Opalinus clay.

SESSION II

KEYNOTE PRESENTATIONS

Questions addressed by each of the keynote speakers

- What types of data have been integrated in your model?
- How has soft (qualitative) data been integrated into your model?
- How would you assess the value of each type of data you used?
- What data would you have liked to have had, but didn't?
- What data did you have, but found no use for?
- What is the dimensionality of your model?
- What are the time and space scales of confidence in your model?
- How have you handled temporal and spatial scaling and simplification?
- What processes were simplified in your model, and how was this accomplished?
- What were the objectives, and what are the predictive uses of your model?
- Were extreme or pessimistic cases considered, or only what you thought was realistic"?
- How have you validated or tested your model?
- What possibilities, if any, do you see for alternative models of your system?
- What is most important in making you think your model is correct or unique?
- What innovations in presentation or visualisation of your results have you made?
- How was this project managed?

INTEGRATING GEOLOGIC AND ENGINEERING DATA INTO 3-D RESERVOIR MODELS: AN EXAMPLE FROM NORMAN WELLS FIELD, NWT, CANADA

Lyndon A. Yose
ExxonMobil Upstream Research Company, USA

1. Introduction

A case study of the Norman Wells field will be presented to highlight the workflow and data integration steps associated with characterization and modeling of a complex hydrocarbon reservoir. Norman Wells is a Devonian-age carbonate bank ("reef") located in the Northwest Territories of Canada, 60 kilometers south of the Arctic Circle (Figure 1). The reservoir reaches a maximum thickness of 130 meters in the reef interior and thins toward the basin due to depositional pinchouts. Norman Wells is an oil reservoir and is currently under a 5-spot water injection scheme for enhanced oil recovery (EOR). EOR strategies require a detailed understanding of how reservoir flow units, flow barriers and flow baffles are distributed to optimize hydrocarbon sweep and recovery and to minimize water handling. Reservoir models are routinely used by industry to characterize the 3-D distribution of reservoir architecture (stratigraphic layers, depositional facies, faults) and rock properties (porosity, permeability). Reservoir models are validated by matching historical performance data (e.g., reservoir pressures, well production or injection rates). Geologic models are adjusted until they produce a history match, and model adjustments are focused on inputs that have the greatest geologic uncertainty. Flow simulation models are then used to optimize field development strategies and to forecast field performance under different development scenarios.

A key element of this workflow was integrating appropriate data at the appropriate scale to characterize reservoir architecture and properties (e.g., porosity, permeability, water saturations, etc.). An example of the different data types that were integrated for characterization of the fracture system is shown in Figure 3. These data include "static" reservoir data, such as seismic, core, and outcrops, and "dynamic" reservoir data, such as well tests and production data.

Static data provide information on geometric fracture attributes including orientation, size and density. Dynamic data provide critical information on flow behavior of fractured reservoirs, luding fracture transmissivities and flow anisotropy. Both data types are required to fully characterize the geometric and hydraulic properties of fractured reservoirs.

Figure 1. **Norman Wells location and data summary**

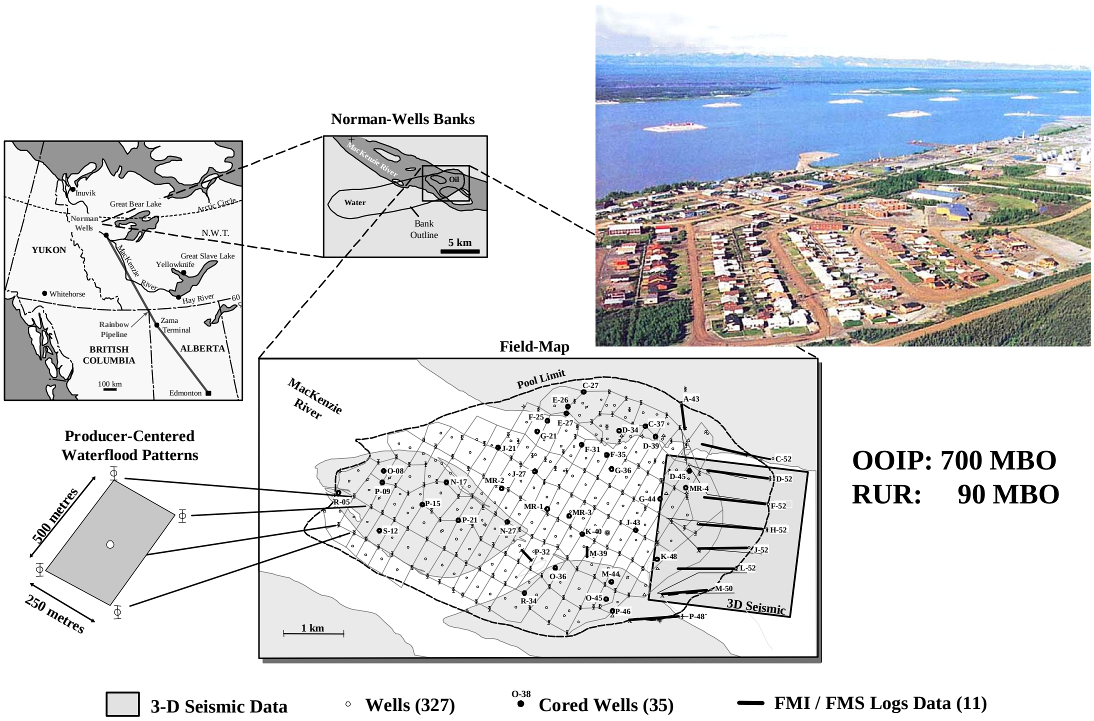


Figure 2. **3-D geologic modeling workflow**

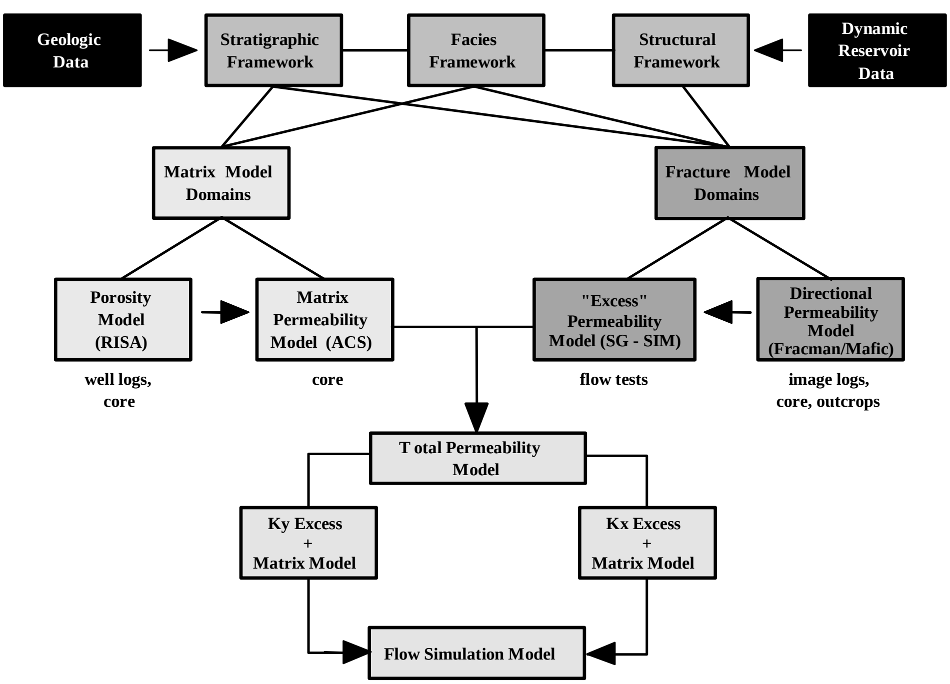


Figure 3. **Data types and scales relevant to fracture characterization**

				FRACTURE PROPERTIES				
			Fracture Presence	Geometric			Hydraulic	
				Orientation	Size	Density	Aperture	Permeability
DATA TYPES	Static	Oriented Core	X	X	X	X	X	
		Outcrop	X	X	X	X	X	
		Image Logs	X	X	X	X		
		Seismic Properties	X	X		X		
		Well Logs	X					
		Borehole Breakout		X				
	Dynamic	Transient Pressure Tests	X	X				X (effective perm.)
		Production/Injection Logs	X					X (effective perm.)
		Pulse Tests/ Interference Tests	X					X (effective perm.)
		Tracer	X	X				
		Breakthrough	X	X				

At Norman wells, reservoir architecture is influenced by matrix properties (stratigraphic and depositional controls on reservoir architecture and properties) and by fractures (high permeability conduits that cross cut depositional fabrics). Our project challenge was to develop a 3-D geocellular reservoir model for the field that integrated all available data to account for both matrix and fracture properties. The most challenging element of the project was to model fracture distributions and to assign flow properties to the fractures. As shown in Figure 1, there is a wide range of geologic, geophysical and production data available at Norman Wells. Our project was assigned one year to build the new model and to "history match" the model against historical performance data as a validation step. To address this challenge, a multi-disciplinary team was formed that included a carbonate stratigrapher, petrophysicist, two fracture experts, two geomodelers, a reservoir surveillance engineer, and a flow simulation engineer.

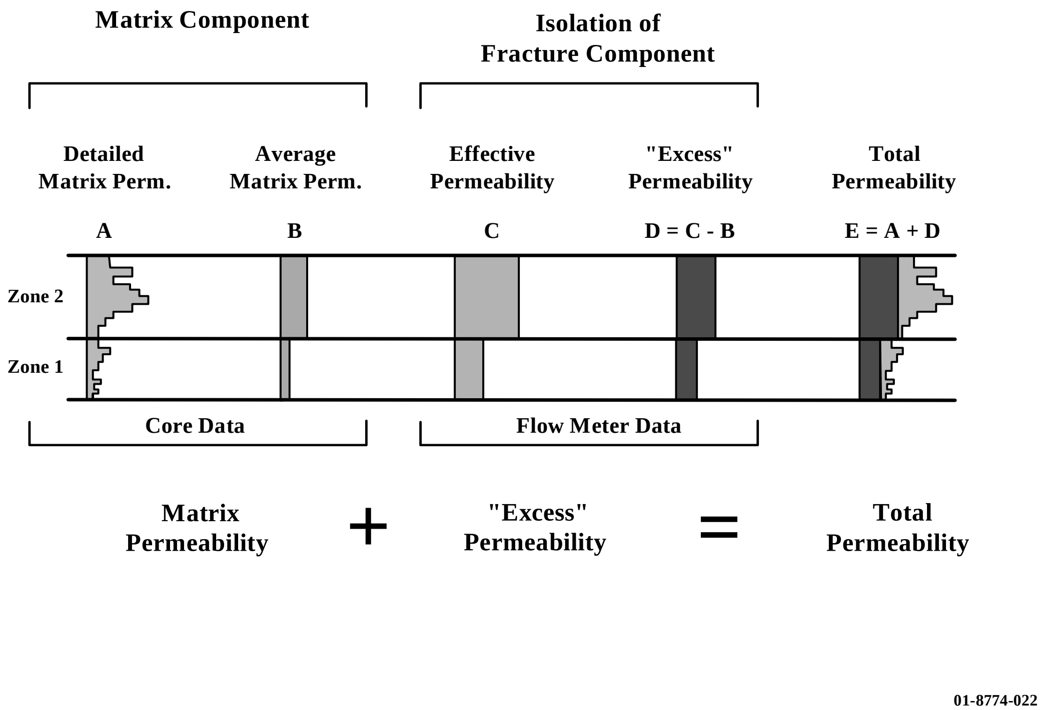
A new workflow was designed to achieve our goals as shown in Figure 2. The general work process included: 1) integration of seismic, log, core and outcrop data to define the structural, stratigraphic and depositional components of the reservoir architecture, 2) integration of core analysis and well test data to define matrix and fracture rock property distribution within the reservoir framework, 3) integration of this information into a 3-D geologic model, and 4) upscaling of the the 3-D geologic model for flow simulation.

Two fracture-modeling techniques were employed in this study:

- **Utilization of production data to quantify "excess" permeability associated with fractures:** Dynamic reservoir data (injection and production data) were used to isolate and model the distribution of "excess" permeability throughout the reservoir. Excess permeability, as defined herein, is the portion of effective permeability measured from injection and production data that exceeds permeability measured from core data. At Norman Wells, this additional permeability was found to vary in a predictable manner relative to the fracture model for the field and, thus, is interpreted as a proxy of fracture permeability. A 3-D excess-permeability model was constructed from production and injection data, and structural, stratigraphic and facies information were used to guide the distribution of excess permeability within the model. Excess permeability is interpreted to approximate the additional permeability added by fractures. Benefits of incorporating the excess permeability directly into the 3-D geologic model include 1) reduced need for adjusting permeabilities in the flow simulator, and 2) geologic information are used to guide the distribution of the excess permeability rather than history-match discrepancies in the flow simulator.

- **Directional allocation of excess permeability through discrete fracture network modeling:** Discrete fracture network modeling utilizing the *FracMan* and *Mafic* software developed by Golder Associates, Inc. was used to evaluate the geometry and connectivity of the fracture system. While the excess permeability model provides a quantitative model of the additional permeability associated with fractures, the discrete fracture network model provides quantitative estimates of the directional permeability (anisotropy) associated with the different fracture sets within the reservoir. Oriented cores, borehole image logs and nearby outcrop data were used to populate the fracture network models. The resulting models were calibrated against production data to assess directional transmissibilities of the fracture-network. A new approach was developed to utilize dynamic well test data to quantify the relative contributions of matrix and fracture permeabilities to the total permeability. This approach is highlighted in Figure 4.

Figure 4. **Integration of well test data**



2. Project Results and Key Learnings

A 3-D geologic model was developed that incorporated matrix and fracture properties into an integrated stratigraphic and structural framework. Example outputs of the 3-D model are shown in Figure 5 below. These results were achieved on schedule and were validated against historical performance data in the flow simulator.

Assembly of a multi-disciplined team was critical to the success of the modeling project, as characterization and modeling of fractured reservoirs require the integration of a wide range of data types. The involvement of reservoir and simulation engineers in the planning and implementation of the geologic-modeling project was particularly important and allowed for the integration of production and performance data early in the reservoir characterization workflow.

A critical step in the modeling process was incorporation of stratigraphic, depositional and structural information into the 3-D geologic model framework. Matrix reservoir properties vary in association with sequence stratigraphic position and depositional facies. Fracture properties vary in association with structural position and the mechanical stratigraphy. Thus, a combination of structural, stratigraphic and depositional information was required to accurately model matrix and fracture permeabilities.

The fracture-modeling approach employed in this study stresses the integration of production and geologic information and is applicable to other fractured reservoirs. It should be noted, however, that many different fracture characterization approaches could be applied, depending on the types and quantity of data available and project objectives. A critical step in any modeling project is to fully evaluate the business purpose of the model. The business purpose, in combination with the available data types and quantities, drives the modeling approach and the level of detail that is incorporated into the model.

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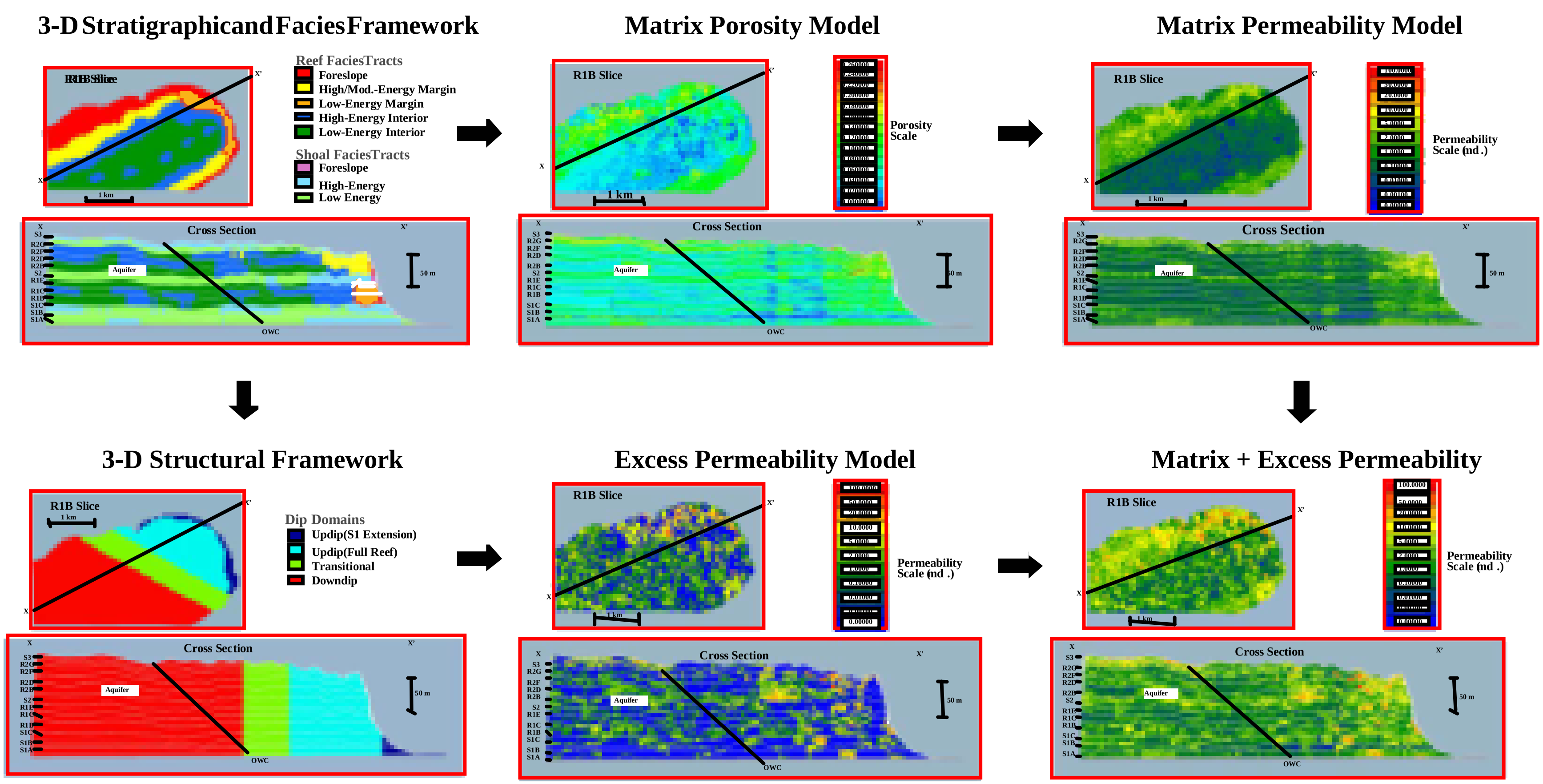
Figure 5. **3-D geologic modeling results**

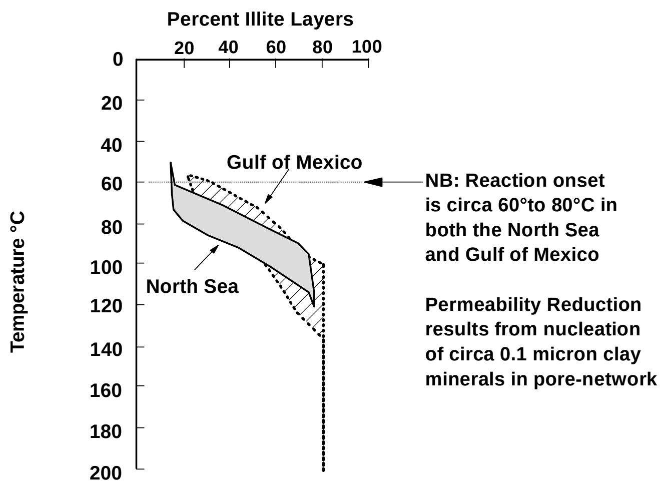


THERMO-CHEMICAL CONTROLS ON DIAGENETIC PROCESSES: IMPACT ON GEOLOGIC MODELS FOR GEOPRESSURE, FLUID MIGRATION, BIODEGRADATION, AND OPERATIONAL SAFETY

Paul H. Nadeau
Statoil, Norway

Proposed models for the effect of clay diagenesis on shale/claystone permeability based on precipitation of clay minerals in pore networks and exponential decreases in permeability (Bjørkum and Nadeau, 1998) have been confirmed by subsurface studies (Nadeau *et al.*, 2002). These results have important implication for modelling fluid flow at the basin and field scale, including: 1. overpressure development; 2. hydrocarbon migration; 3. fluid flow through oil columns, shale top seals, and possible controls on biodegradation. This communication further develops the proposed model, and evaluates the implications for petroleum systems analysis, including models for biodegradation, as well as drilling/operational safety. Conventional models for fluid flow in shales/claystones are mainly a function of porosity reduction resulting from mechanical compaction and increasing effective stress. The resulting models predict that shale permeability is mainly a function of porosity reduction with increasing depth and effective stress. Clay diagenesis models often consider that diagenetic clay minerals, typically illite, form by transformation of pre-existing smectite layers by K-fixation and layer collapse. Neoformation models for illite diagenesis, however, indicate that illitic clays precipitate within pore networks from the dissolution of mineral reactants, inlcuding smectite or kaolinite, and K-feldspar. This reaction is mainly a function of temperature, and typically begins at 60° to 80°C, and completed at circa 100°C (Figure 1).

Figure 1. **Relationship of diagenetic illite formation in shales/claystones and burial temperature in the North Sea and Gulf of Mexico. Note that reaction onset and termination occur at similar temperatures despite major differences in geologic setting and age. (modified after Srodon and Eberl, 1984)**



According to the neoformation models, exponential permeability reduction results from the precipitation of diagenetic illite at the onset of the reaction. The mechanism proceeds by the formation of illite, mainly as R>=1 I/S with particle sizes on the order of 0.1 microns, and the rapid bridging of pore throats with similar dimensions, which control shale/claystone permeability. These new models predict dramatic permeability reductions as a function of thermal history, which are mainly independent of shale porosity, particularly during the early stages of the reaction. The advent of these thermochemical/petrophysical models allow analysis methods to predict rapid permeability reduction and possible relationship to basin scale phenomena, such as overpressure development and hydrocarbon migration via hydrofracturing of low-permeability shales/claystones, mainly as a function of thermal gradient. The models predict permeability functions which are mainly independent of porosity, and for comparable hydrostatic sections, indicate reductions from micro-Darcy range to nano-Darcy range at higher porosities in higher geothermal gradient basin segments, than in lower geothermal gradient basin segments (Figure 2).

Figure 2. **Graphical representation of shale/claystone porosity/permeability ranges typical observed in nature, and the proposed effect of clay diagenesis as a function of geothermal gradient. Note that mechanical compaction processes results in relatively moderate permeability reduction as a function of porosity. Dramatic reductions due to clay diagenesis are predicted, however, at highly variable porosity values, controlled mainly as a function of temperature history. (Modified after Neuzil, 1994)**

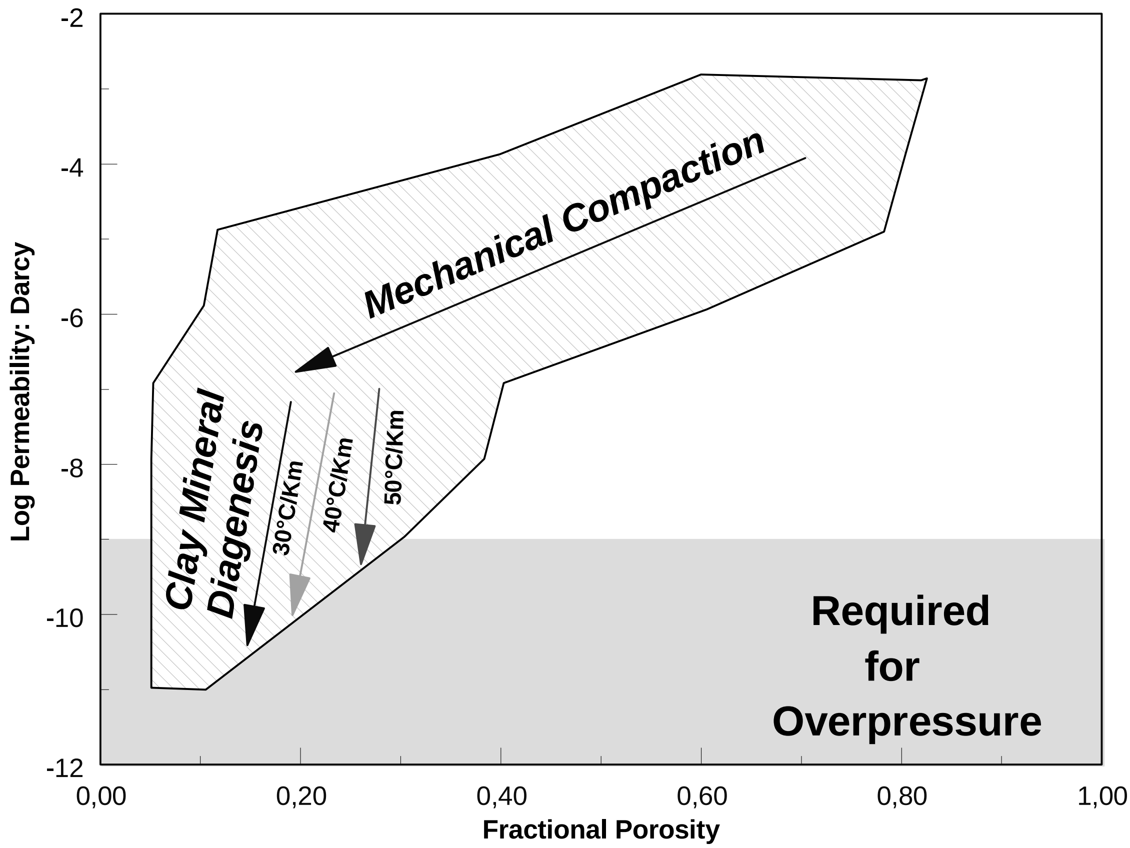
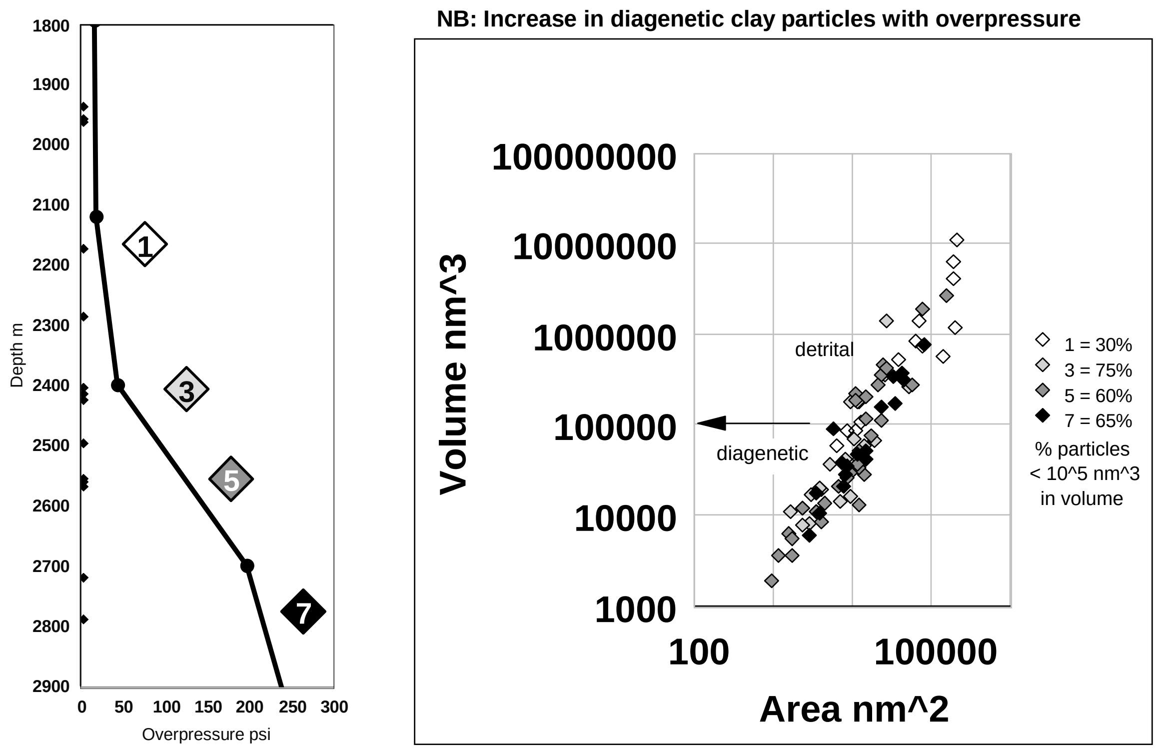


Figure 3. **Relationship of diagenetic illite formation in shales/claystones and overpressure development in the Egersund Basin. Note that the onset of overpressure corresponds with an increase of diagenetic illite particles from 30% to 75% (circa 2 160 m to 2 400 m) in the studied section (samples/measurements in diamonds, after Nadeau *et al.*, 2002)**



The proposed model and permeability reduction mechanism have been evaluated in the Egersund Basin of the Norwegian Continental Shelf. Here, the development of a circa 200 psi pressure ramp within Mesozoic shales/claystones correlates with the occurrence of *circa* 0.1 micron diagenetic illite particles, thereby supporting the inferred permeability model (Figure 3). Basin simulations of fluid pressure indicate that overpressure development supports rapid permeabilty reductions associated with the onset of diagenetic clay in the studied section.

The permeability model has important implication for petroleum systems analysis, particularly for evaluating hydrocarbon charge and pressure-ramp drilling hazards, for example within deep marine fan plays (Nadeau *et al.*, 2001). The proposed thermochemical permeability reduction mechanism also allows the development of a formation water fluid model for the biodegradation of oil accumulations, based on shale/claystone top seal permeability. This model suggests that prior to clay diagenesis, typical shales have sufficient permeability to facilitate vertical formation water flow through oil columns (eg. Rodgers *et al.*, 1999). The water flux can achieve rates of *circa* 1 liter per square meter per year, or about 1 cm/year for typical sandstone reservoirs. This flow can replace the irreducible water within a 100 m oil column every 10 000 years, and may be vital to facilitate biodegradation processes, for example by providing nutrients and/or the removal of waste products. The flux model has indeed been used to interpret the distribution of biodegraded oils within Gullfaks Field, and their inverse correlation with reservoir plagioclase feldspar contents (Ehrenberg and Jakobsen, 2001). Initial evaluation of Sr-isotopic analyses of residual formation water salts in cored

Gullfaks intervals have confirmed the proposed biodegradation model. The results from a biodegraded oil reservoir shows uniform Sr formation water compositions (little to no variation with depth), whereas a non-biodegraded reservoir shows variable Sr formation water composition (increasing 87Sr/86Sr with depth). The data are consistent with a dynamic vertical flow through the biodegraded column, and a near static or extremely low vertical flux in the non-biodegraded column.

Detailed evaluation of these models using Statoil's extensive compilation of global reservoir data has greatly increased confidence in their predictive value. Their ability to reverse and forward model geologic occurrences of overpressure and hydrocarbon migration is unsurpassed, particularly relative to conventional models based mainly on mechanical processes. The development of the thermo-chemical models, starting from Norwegian Continental Shelf data, then with further evaluation in other sedimentary basins including the Gulf of Mexico, and more recently using data from over 100 000 subsurface reservoirs, has been instrumental in building confidence using multiples lines of geologic evidence. Additional research is required, however, to further establish these and other geologic controls on key parameters such as overpressure, hydrocarbon migration, and drilling risks, in a wider variety of basin/depositional settings. This will allow more detailed integration of other basin specific geological factors, such as lateral drainage and tectonic/thermal history, to greater enhance their predictive value.

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3-D BASIN MODELLING OF THE PARIS BASIN: DIAGENETIC AND HYDROGEOLOGIC IMPLICATIONS

Sophie Violette[1], **Julio Gonçalvès**[1*], **Anne Jost**[1], **Ghislain de Marsily**[1]
and the PNRH-99.35/01.44 program team[2]

1: UMR-*Sisyphe* LGA, Paris 6, case 123, 4 Place Jussieu, 75252 Paris Cedex 05 –

2: UMR-*Sisyphe*, Paris 6 & ENSMP: Aletru V., Bruel D., Cosenza P., Goblet P., Ledoux E., Léonardi V., Madé B., Prognon F., Simon-Coinçon R., Vasseur G., Laboratoire de Paléontologie-Stratigraphie – Paris 6: Robin C.**,** LMD – Paris 6: Li L., FRE-*OrsayTerre* – Paris XI: Michelot J-L., Pagel M.**,** UPR.4661-*Géosciences* – Rennes: Dia A.**,** Bréhant E., Guillocheau F., UMR.6531-*LGMO* – Orléans: Disnar J-R.**,** UMR.7566-*G2R* – Nancy: Amir L., Martinez L.**,** UMR 5125 – Laboratoire PaléoEnvironnements et PaléobioSphère – Lyon 1: Fauquette S., Suc J-P., INERIS – Verneuil-en-Halatte: Ghoreychi M., LSCE – CEA Saclay: Ramstein G.

* Andra

Introduction

A 3-D basin model of the Paris basin is presented in order to simulate through geological times fluid, heat and solute fluxes. This study emphasizes: i) the contribution of basin models to the quantitative hydrodynamic understanding of behaviour of the basin over geological times; ii) the additional use of Atmospheric General Circulation model (AGCM) to provide palaeo-climatic boundaries for a coupled flow and mass transfer modelling, constrained by geochemical and isotopic tracers and; iii) the integration of different types of data (qualitative and quantitative) to better constrain the simulations.

Firstly, in a genetic way, basin model is used to reproduce geological, physical and chemical processes occurring in the course of the 248 My evolution of the Paris basin that ought to explain the present-day hydraulic properties at the regional scale. As basin codes try to reproduce some of these phenomena, they should be able to give a plausible idea of the regional-scale permeability distribution of the multi-layered system, of the pre-industrial hydrodynamic conditions within the aquifers and of the diagenesis timing and type of hydrodynamic processes involved.

Secondly, climate records archived in the Paris basin groundwater suggest that climate and morphological features have an impact on the hydrogeological processes, particularly during the last 5 My. An Atmospheric General Circulation model is used with a refined spatial resolution centred on the Paris basin to reproduce the climate for the present, the Last Glacial Maximum (21 ky) and the middle Pliocene (3 My). These climates will be prescribed, through forcing functions to the hydrological code with the main objective of understanding the way aquifers and aquitards react under different climate conditions, the period and the duration of these effects.

Finally, the Paris basin has been studied for a number of years by different scientific communities (geologists, palynologists, rock and water geochemists, rock mechanists, hydrogeologists, climatologists, modellers and industrial companies (Gas Storage, Petroleum and Water resources exploitation), thus a large amount of data has been collected. By integrating all these actors in a same research program (PNRH.99/35-01/44: “Paris basin modelling”) we were able to draw a more comprehensive view of the Paris basin evolution. At each step of the work, meetings and discussions were conducted to assess the validity of the data and quality of the results.

This work is still in progress, the basin model results will be first emphasized in this short paper, and while the hydro-climatologic modelling will be presented as a perspective for future work.

Building the model

Numerical code

The NEWBAS code developed by Belmouhoub (1996) reproduces processes such as sedimentation, erosion, fluid flow, heat and solute transport. It is a finite volume code taking into account evolution of the geometry along time. For the last two processes, we implemented the effect of density variations on the flow. We tested the accuracy of: i) a facies-model instead of a discrete litho-facies distribution for three layers of the system (Dogger, Lusitanian, Callovo-Oxfordian) and ii) a compaction and petrophysical law valid for carbonates (Lucia, 1995). In future work, this has to be generalised for the entire layers of the system (see below).

Fluid flow through the main faults was simplified. Most of the time, during the simulations, faults play a barrier role when a layer is geometrically disconnected from one bloc to another. But according to the geological evolution (direction of the main constraint) one of them, the Bray fault, plays a role as a drain during the last 50 My. We allowed vertical fluid flow at this time for those meshes representing the Bray fault.

In our model, we do not take into account the effect of diagenesis on porosity, and we do not integrate yet our theoretical work on the prediction of poroelastic properties of argillaceous rocks from *in situ* specific storage coefficient (Cosenza *et al.*, 2002).

The only way available to validate our model is on the present-day data set. So we have no control on what happens before and the model results are just a trend of what could have occurred according to the diagenetic data.

Geometry

According to the palaeo-geographic evolution of the Paris basin recorded in the literature (Dercourt *et al.*, 2000), the present-day limit of the basin underestimates the real extent of the flooded surface area during certain periods over its 248 My geological history. Therefore, in order to prescribe meaningful boundary conditions at the proper location, the dimension of the resulting domain is 700 000 km^2 (Figure 1). Due to the dimensionality and the variable nested squares meshing possibility of our code, the mesh is refined from the peripheral domains (20 km x 20 km^2 mesh) where the knowledge is poor, towards the centre of the basin (2.5 km x 2.5 km^2 mesh) following the main structural features where a more precise knowledge is available. The Z direction is accounted for by the time-varying thickness of the layers at each node. The precision of the study is at the regional scale, for the whole basin, except for a more accurate description at the centre of the basin where the number of data is larger. The time scale corresponds to geological events, ~1 My, but it is not precise enough for Quaternary period, for instance. This is the reason why a second model is in progress for the Quaternary, to test the hydrodynamic impact of palaeo-climatic and anthropogenic forcing effects.

Data set: input, constraints and validation

The present-day geometry and lithology is established using a stratigraphic data base of more than 1,100 petroleum well logs for the Paris basin *sensu stricto* (Guillocheau *et al.*, 2000). For the German and the English areas, qualitative data were collected from the literature (Geyer and Gwinner, 1968; Sellwood *et al.*, 1986; Baldschunh, 1996) (Figure 2).

Nineteen time surfaces inferred from a sequential stratigraphic approach were selected and, with the topographical (DEM) and basement surfaces, our model is described by 20 layers (Figure 3).

In a first approach, the lithology distribution over the simulation domain is described using a discrete litho-facies classification: the central points of 18 subdivided domains within two ternary plots which poles are shale, sand, carbonate (plot 1) or chalk (plot 2). A 19^{th} lithology is added for evaporite deposits. In this first approach, the lithology proportions from the data base are interpolated by kriging on the mesh to give the discrete litho-facies distribution. In a second approach tested for two carbonate aquifers (Dogger and Lusitanian) and one aquitard (Callovo-Oxfordian) we have developed a facies model where the interpolated proportions, obtained by kriging with the pole lithologies, are then directly assigned to the cells.

For the compaction law, we used porosity-depth functions from the literature (Sclater and Christie, 1980; Burrus, 1997).

The palaeogeographical evolution is constrained by the mean topographical and water depth gradients deduced from recent work (Guillocheau *et al.*, 2000). This work allows us to determine the timing of the main up-lifts and their amplitude.

The heat flux at the basement is considered as constant during the Paris basin geological evolution, but regionally variable due to the basement heterogeneity, as described by Lucazeau and Vasseur (1989) and Prijeac *et al.* (2000).

We need also data to constrain or validate our model. Those data concern hydrodynamic properties (porosity, hydraulic conductivity, water level, storage coefficient) and diagenetic observations (palaeo-temperature and palaeo-salinity deduced from fluid inclusions studies, Matray *et al.*, 1989, Guilhaumou, 1993, Spötl *et al.*, 1993, Demars et Pagel, 1994, present temperature profiles from petroleum monitoring, Demongodin *et al.*, 1991, Gaulier and Burrus, 1998).

Unfortunately some useful data were missing: water levels of the main aquifers before anthropogenic exploitation; hydraulic conductivity values for the aquitards; more precise data about palaeo-topography, geometry and lithology at the outcrops. We will need data about not only the geometry of the main faults of the basin but also the knowledge of their in-fillings and the timing of their evolution inferred from the tectonic constraints and the sedimentation rate from one block to another.

Results

Regional scale fluid flow has currently been invoked in fluid inclusion studies to explain diagenetic cementation stages. These studies, which provide estimates of past temperatures and salinities, also provide some constraints for the model and in return, with the model, we can propose a timing calibration for the major cementation events. Thus, the heat and salt transport reconstruction proposed in this work allows to determine the influence of hydrodynamics on diagenetic processes.

We show the importance of topography to explain high salinities in the Keuper reservoirs and the role of the Bray fault for the Dogger salinity evolution. The major uplift of the basin at the beginning of the Tertiary causes a topographically-driven flow which replaces the compaction-driven regime, thus allowing brine migration from the Eastern salt formation towards the Western Keuper reservoirs. The recharge at the outcrops affecting the aquifers leads to sufficient pressures to allow an upward motion of brines from the Keuper to the Dogger by considering enhanced permeabilities for the liassic aquitards. Although dominated by its conductive component, heat flow is also influenced by hydrodynamics with a possible convective cooling effect related to the main uplift and the recharge at the beginning of the Tertiary. This effect is likely to explain part of the highest temperatures inferred from fluid inclusions and probably coeval with the end of the Chalk deposition. From our calculations, the major diagenetic events recorded by fluid inclusions are related to the Tertiary uplift for thermal reasons (maximum burial and convective cooling) and chemical reasons (topographical event favourable to brine migration in both the Keuper and Dogger reservoirs).

Concerning the use of the basin code as a qualitative tool to estimate regional scale permeabilities, our approach presents similarities with both the genetic and the geostatistical approaches. The sedimentation and the compaction are simulated using a 3D basin model that takes as a major input a heterogeneous facies model generated by geostatistical methods. An extended stratigraphic data base is used to test the possibility of reproducing the hydrogeologic heterogeneity for only three layers (two carbonates: Dogger and Lusitanian and one argillaceous: Callovo-Oxfordian). This allows us to propose a satisfactory representation of the permeability field heterogeneity at the regional scale. This method should now be applied to the entire stratigraphic model and the permeability fields could be used in a more classical hydrogeologic model as the starting point for a fluid flow calculation to be calibrated on hydraulic head data. This approach should be compare also to other kind of methods currently used in hydrogeology (inversion, stochastic…).

The main difficulty is to validate our model. Our sensitivity study shows that from an hydrodynamic point of view, our modelled system is fixed. Because, for the last 8 My, the hydrodynamic boundary conditions prescribed on surface are unchanged and, our model has reached a steady state. This is a no-negligible simplification which sensitivity will be test through the hydro-climatologic modelling. The validation can be done on present-day data set. For the past evolution, we had to use diagenetic data. For the validation of our hydrodynamic results, the main difficulty were: i) the difference in scale between our results (more than 2.5 km in space) and the data acquired (around 100 m in x, y space, less for vertical resolution); ii) the unequal knowledge on the different layers and the heterogeneous distribution of the data. To compensate those problems, we used an upscalling method based on the work of Renard *et al.* (2000) to compare upscalled permeabilities calculated from the data set to those calculated by the simulations.

Conclusions and perspectives

The model is able to reproduce palaeo-fluids flow and their diagenetic implications based on reasonable permeability field and hydrodynamic boundary conditions. During the geological evolution of the basin, we show that no overpressure due to compaction effects existed for a time (less than 100 000 years). Other potential effects to explain the observed overpressures in some of the aquitards can be invoked, such as osmotic effects, changes in hydrodynamic and tectonic boundary conditions. For those two last effects our work is still in progress.

The present-day geometry and hydrodynamic features are now used for another modelling looking for small time scale (last 5 My) and testing the climatic and anthropogenic effects on present-day hydrodynamic.

The originality of our work lies in the way it has been performed, i.e.: the quality of the data set we used (the most complete ones), the number of scientists involved in this work (pluri-disciplinary cooperation), the time and space scales we used, the efforts of considering all the relevant processes in the evolution with time of the sediment properties.

During this programme, our goal was to provide data to our models but we did not neglect to use the Paris basin case study to develop more theoretical work on more focused aspects (Bruel et Violette, 2002; Cosenza *et al.*, 2002; Luo et Vasseur, 2002; Jost *et al.*, 2003; Gonçalvès *et al.*, submitted, cited for examples).

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Figure 1. **Maximum simulated domain extention on the Digital Elevation Model. The square nested mesh (20, 10, 5 and 2.5 km) illustrates a refinement towards the center of the Paris basin and the main structural features**

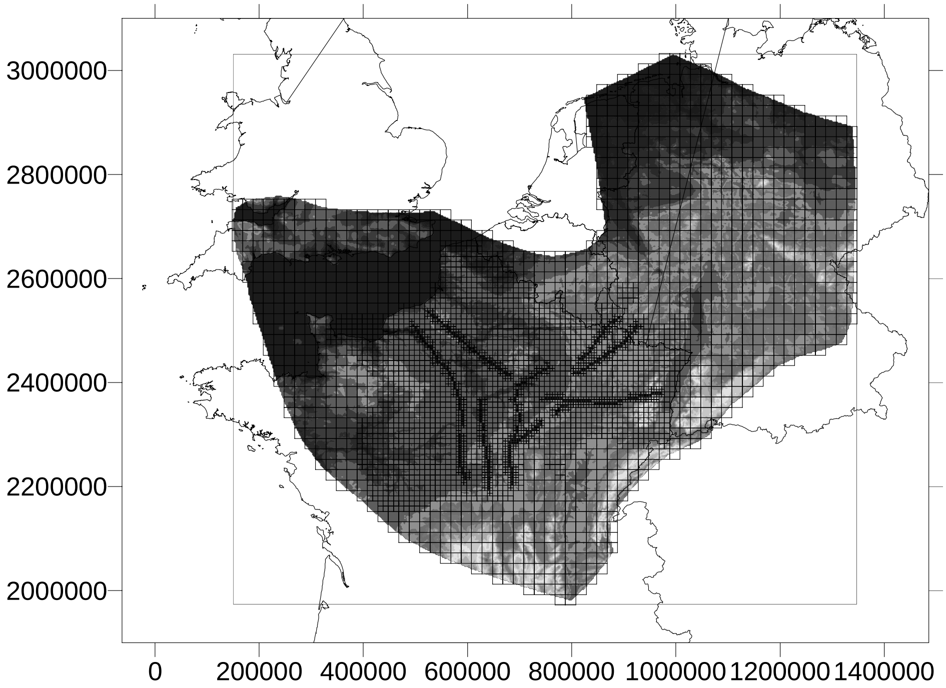


Figure 2. **Location map of the litho-stratigraphic data base**

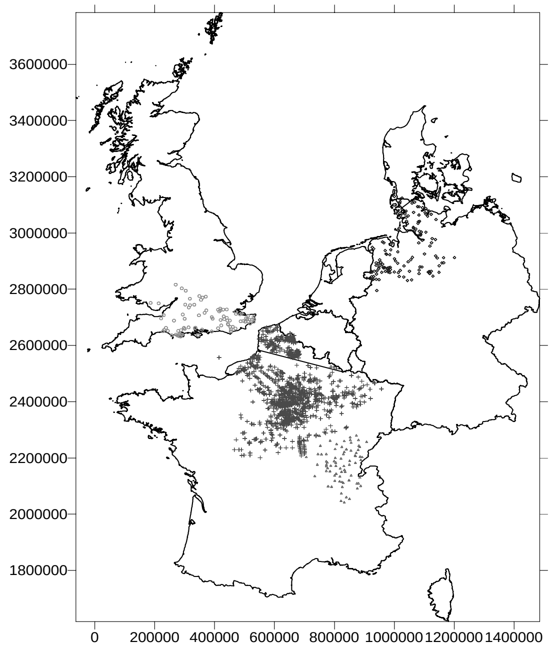
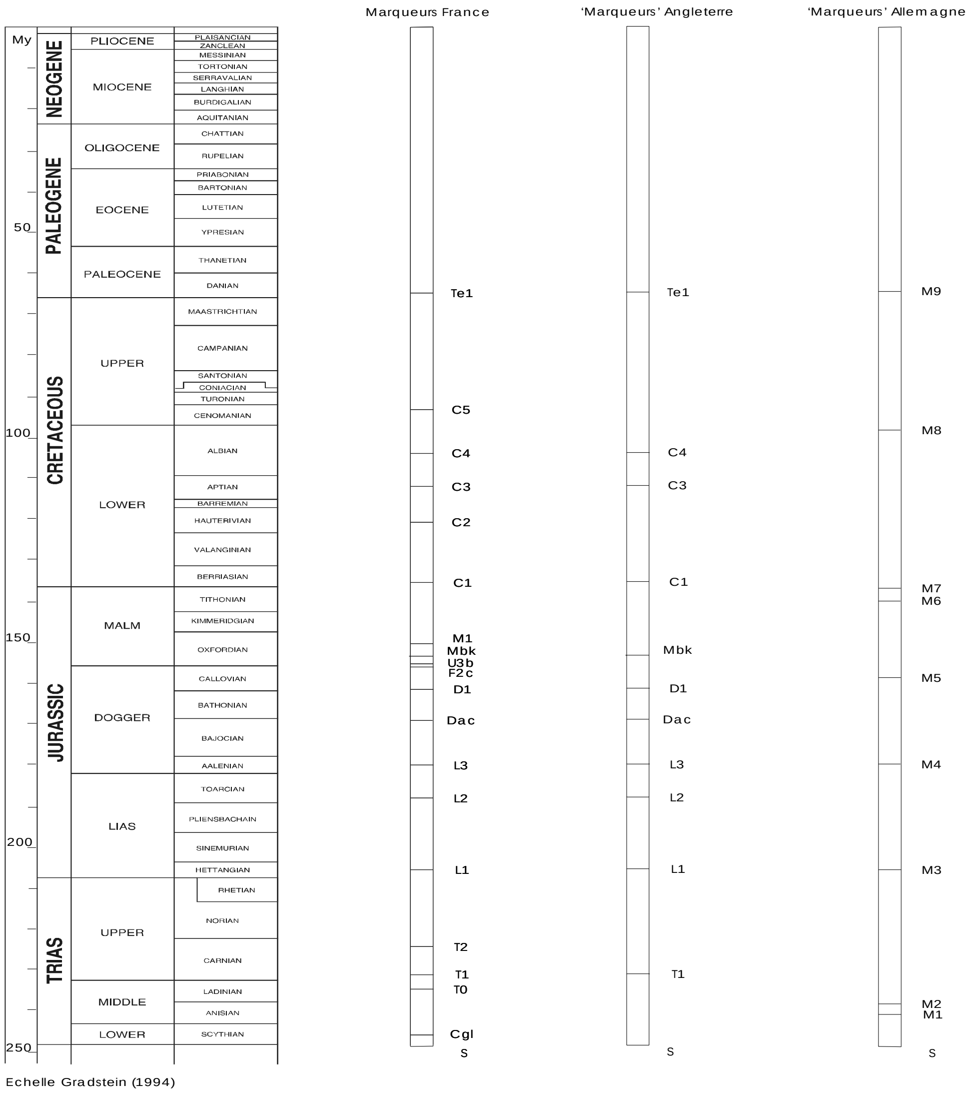


Figure 3. **Time surfaces selected for the Paris basin and their corresponding ones for the German and English domains**



SESSION III

PRESENTATIONS FROM RADIOACTIVE WASTE PROGRAMME ON INTEGRATION WITHIN THEIR SAFETY CASES

Questions addressed by each speaker from implementing agency

- What types of data or lines of evidence have been integrated in your Safety Case? (these should be listed on a single overhead)
- What are the roles of the geosphere in your Safety Case?
- How do you weigh (prioritise) evidence directly supporting dose/risk calculations versus evidence supporting other types of arguments for safety (some of which may be more qualitative) or used in conceptual model development?
- (How) Does this weighting change with time?
- How has the work of different teams been integrated?

Questions to be considered (not all can be addressed) by each speaker from a regulatory agency are:

- How do you weigh (prioritise) evidence directly supporting dose/risk calculations versus evidence supporting other types of arguments for safety (some of which may be more qualitative) or used in conceptual model development?
- (How) Does this weighting change with time?
- Which arguments do you find most and least convincing, and why?
- What value do you attach to multiple lines of evidence?
- What are important aspects of the Safety Case in addition to the results of calculation of dose and risk, including non-quantitative aspects?
- To what extent are you interested in the way in which the implementer manages integration, including the interaction between different teams?
- In what depth do you develop an independent view?

THE KONRAD SAFETY CASE: LICENSEE POINT OF VIEW

Peter W. Brennecke
Bundesamt für Strahlenschutz, Germany

1. Introduction

The protection of man and environment is the most important principle with regard to radioactive waste disposal. This fundamental principle is reflected in the licensing prerequisites for a repository. Since it is intended to dispose of radioactive waste in deep geological formations in the Federal Republic of Germany, possible releases via the water path must be investigated and assessed in particular with regard to the safety of a repository during the post-closure phase. Thus, respective investigations comprise the radiological long-term effects (radionuclide-specific radiation exposures) as well as the possible pollution of near-surface groundwater by organic and inorganic chemotoxic substances.

2. Geology and hydrogeology

The abandoned Konrad iron ore mine in the Federal State of Lower Saxony has been investigated for the emplacement of all types of solid or solidified low and intermediate level radioactive waste. These wastes are short-lived and long-lived, respectively, and have negligible heat generation. The Konrad mine is located at the southern end of a large iron ore formation. This sediment was deposited about 150 million years ago during the Upper Jurassic (Malm). The overlying Cretaceous strata mainly consist of clayish rock and completely cover the iron ore sediment by a transgression. The actual geological barrier to the near-surface groundwater is built up by the Lower Cretaceous clay layers overlying the Jurassic strata over a wide area, and is at least 170 m thick at any point above the mine. To the west, it increases to about 270 m, and to the north to nearly 400 m. The good quality of the Upper Cretaceous barrier has been proven by means of a variety of laboratory analyses of drilling cores covering petrography, geochemistry, porosity, permeability, absorption and rock strength.

The hydrogeological situation is characterised by a pronounced stockwork structure. The ground water near the surface, locally influenced by human use is mostly found in Quaternary deposits and is hydraulically connected to local water courses. Below a depth of about 100 m, the ground water contains considerable amounts of solutes. The deeper ground water levels consist of individual aquiferous strata, separated by claystone strata with minimum water-bearing properties. The system is bordered above and below by salt layers of the Middle Muschelkalk; the lateral hydraulic borders are formed by salt domes.

Based on prior experience with the low amount of already existing water in the mine openings an uncontrolled inflow of water during the operational period can be excluded. In the post-closure phase, however, the remaining voids will gradually fill up with subterranean waters. It is estimated that the original pressure conditions will not widely be restored for over 2 000 years after closure. Afterwards the natural, very slow, regional subterranean water movement should again be reestablished. Parameter studies were used to calculate the movement of subterranean waters, and to investigate various connections of layers and influences of geological fault zones. It was seen that waterpaths leading from the mine openings would reach the biosphere at various places, depending on the permeability coefficients for Lower Cretaceous.

The site investigations were comprehensive. A specially designed underground investigation programme was conducted, consisting of exploratory drifts and further drill holes as well as of a 1 000 m deep drill hole from the surface to obtain detailed information on all important geological horizons. Thus, the data base for site-specific safety assessments was established.

3. Modelling and radionuclide migration calculations

The protection goal for the period following decommissioning of a repository has been laid down by the then responsible Bundesminister des Innern in 1983. It has been expressed as follows: "Even after decommissioning, radionuclides which might get out of the closed repository and into the biosphere as a result of not completely excludable transport processes may not lead to individual doses which exceed the values of par. 45 of the Radiation Protection Ordinance" (0.3 mSv/a concept). Evidence of this protection goal being complied with must be demonstrated within a site-specific safety assessment.

Such a procedure is only reasonable for periods of time for which changes in the geological barriers and in man's environment can still be forecast with sufficient reliability.

On the basis of an evaluation of the present geological, hydrogeological and hydrological situation, it is assumed that, in the post-closure phase of the Konrad repository, formation water will contact the radioactive waste disposed of. The transition of radionuclides from the waste into the formation water, and their migration with the water from the repository area through the geosphere to the near-surface groundwater, have been treated in model calculations involving the following steps:

- Determination of the boundary conditions corresponding to the present geological and hydrogeological conditions of the Konrad site.
- Identification of a model scenario and determination of the model area.
- Calculations of ground-water movements which lead to three potential radionuclide migration paths.
- Calculations of the migration of radionuclides from the repository area along the three migration paths.

According to the main scenario for the long-term safety assessment, the contaminated waters will follow the general flow of groundwater in a northern direction. It will enter the near surface environment about 30 km from the Konrad site, where the Oxfordian formation comes near to the earth's surface. This pathway was modelled in the safety assessment and resulting individual dose rates were calculated.

At the beginning of the post-closure phase the remaining cavities in the mine openings have an volume of about $7.4 \cdot 10^5\,m^3$, and are assumed to be constant with time. Decrease of this volume due to convergence of the rock has not been taken into account. Moreover, an instantaneous refilling and hydrostatic pressure increase are assumed at the beginning of the post-closure phase. The solubility and the equilibrium distribution coefficients applied in the model calculations are derived from experimental investigations. The water flow has been calculated for two sets of coefficients of hydraulic conductivity k_f for the Lower Cretaceous barrier (variant 1: $k_f = 10^{-10}$ m/s and variant 2: $k_f = 10^{-12}$ m/s).

Geohydraulic simulation calculations, which serve to determine flow paths and travel times of the groundwater, form the basis for determining the migration of radionuclides in the repository's far field. Important parameters of these model calculations are the hydraulic characteristics (coefficients of hydraulic conductivity and effective porosities) of the individual stratigraphical units which are not locally constant due to regional and local differences in the depositional conditions of the rocks and their diagenesis. There are large ranges of variation for some of these characteristics. With the aid of a great number of two-dimensional model calculations for the groundwater movement in the model area, such values of hydraulic characteristics are selected with due regard to three-dimensional model calculations for which the sensitivity analyses furnish short travel times of the groundwater from the repository area into the biosphere.

In addition to the above-mentioned stratigraphical model, further calculations are performed. Within the so-called fault zone model, zones of higher permeability at important tectonic faults are taken into account in order to check their influence on the water movement and travel times.

Due to the long transit times of the transport medium from the repository to the biosphere, a potential radiation exposure in the biosphere results only for long-lived radionuclides and their decay products and only after hundreds of thousands of years. Effective dose equivalents of about 10^{-5} Sv/a are obtained for an emplaced activity of $7.0 \cdot 10^{11}$ Bq from ^{129}I within a period of about 300 000 years to about 360 000 years. Only after substantially longer periods, i.e. several million years, further exposures of the same order of magnitude or lower occur due to long-lived actinides and their daughter products.^{238}U and its daughter products ^{234}U, ^{226}Ra and ^{210}Pb are particulary important.

Since the potential radiation exposure will occur far beyond a time limit for which it may be assumed with sufficient reliability that the present geological and hydrogeological situation at the Konrad site underlaying the calculations are still valid, the calculated individual doses obtained are only for purposes of orientation. That is, the dose values are used to assess the isolation potential of the site. This opinion of the applicant was discussed controversially within the licensing procedure.

4. Safety-related aspects due to chemotoxic waste constituents

Waste packages to be disposed of consist of organic and inorganic non-radioactive constituents including chemotoxic substances. In order to investigate and to evaluate the possible pollution of the near-surface groundwater by these substances, very conservative model calculations were performed. The calculations considered dissolution and dilution by dispersion and diffusion during transportation through the geosphere and in the Quaternary, to yield estimates of concentrations for comparison purposes. That is, the concentrations of organic and inorganic waste package constituents were compared to concentration limitations of chemical elements and organic and/or inorganic compounds in the near-surface groundwater and/or drinking water. According to the considerations and investigations carried out, chemotoxic substances of the waste packages cannot reach the groundwater or can only reach it in such low concentrations that:

- only anthropogenicly caused, low additional pollutions of the near-surface groundwater can be expected; and
- the future danger of a damage of the groundwater quality and/or a harmful pollution of the groundwater or another detrimental modification of its characteristics need not be feared.

5. Additional evidence supporting the safety case

To augment the above conservative worst-case study, the following lines of evidence have been pointed out:

- The experimental investigations at the Konrad site suggest that convective substance transport through the deep water through the geosphere up to the area of the near-surface groundwater may not be possible. The age of the Konrad deep water is at least 10^7 years, and possibly as long as $1.5 \cdot 10^8$ years, corresponding to the age of the geological formation. These ages indicate groundwater movements in the range of less than 1 cm per 10^3 years, meaning the formation water is essentially stagnat.
- The salinity of the deep water increases with depth. Transport of the water originating from the emplacement horizons to areas with lower salt contents would, therefore, have to take place against the density gradient caused by the increase of salt concentration. Among other things, the measured density distribution indicates a diffusion-dominated vertical salt transport and, thus, stagnating deep water.
- In the case of a transport via the water path, dissolved harmful substances cannot be faster than the pure water movement. According to the model calculations
  - on groundwater movement the shortest flow times for the characteristic migration paths are in the range of 330 000 years up to 38.8 million years;
  - on the assessment of long-term safety of the Konrad repository the conservatively assumed transport of the deep water up to the near surface groundwater thus lasts at least 300 000 years.

It follows that possible pollution of the groundwater can be excluded, at least within the period of time mentioned last.

THE KONRAD SAFETY CASE: REGULATOR POINT OF VIEW

Joachim Bluth
Lower Saxony Ministry of Environment, Germany

1. Introduction

On 22 May 2002 the plan approval (i.e. licensing) decision for the KONRAD repository (located near Salzgitter in Lower Saxony, Germany) for the disposal of radioactive waste with negligible heat generation was assigned after almost 20 year duration of the licensing procedure.

According to the German regulations, the only quantitative radiological criterion for the long-term safety assessment is the limit for the individual dose, e.g. 0.3 mSv/y effective dose. An additional criterion was the limitation of chemotoxical components in groundwater given in the "regulations for drinking water" in Lower Saxony. The licensing authority required the limitations of radioactive dose and chemotoxical elements to be used as assessment criterion over the whole calculated time span until reaching the concentration maximum of the radionuclides, i.e. up to some 100 000 or even to 1 000 000 years.

2. Overall approach

In examination the Safety Case of the Konrad repository, the licensing authority (Lower Saxony Ministry of Environment) together with its experts ("Niedersächsisches Landesamt für Bodenforschung, NLfB"; "TÜV Hanover/Sachsen-Anhalt" and "Gesellschaft für Anlagen- und Reaktorsicherheit mbH, GRS") comprehended and judged the descriptions, model ideas and modelling presented by the applicant ("Bundesamt für Strahlenschutz, BfS") and developed an independent view, based on an own data acquisition, interpretation and conceptual and numerical modelling.

During the review process an independent geological and hydrogeological interpretation of the data base and alternative hydrogeological models were discussed with the applicant. Models which represent faults, weak zones, and old drillings in a more realistic way than demonstrated in the KONRAD application had been developed and evaluated. In this way the licensing authority prepared an expert opinion concerning the safety assessments and got an independent Integral Performance Assessment (IPA). Basis for the IPA – and demonstration of confidence in IPA – was the description and (qualitative) long term prediction of the future geological development within the next ca. 1 million years in the KONRAD region.

The following steps have been carried out:

- review of the documents provided by the applicant;
- working out an independent geological / hydrogeological etc. site characterisation;

- developing own data sets (aquifer geometry, hydraulic and migration parameters etc.) for the groundwater modelling;
- calculate and determine bandwidth and spatial distributions of certain parameters e.g. by expert judgement;
- review of the scenario analysis;
- scrutiny of the models;
- recalculation of the applicant's groundwater flow and groundwater transport calculations by using the applicant's codes (e.g. 3-D FD /1-D SWIFT) and additional diverse codes of the experts (e.g. 3-D FE NAMMU);
- calculations based on variations of parameters and boundary conditions;
- carry out uncertainty analyses to demonstrate the influence of different parameters on the results;
- investigation of the consequences of human intrusion by borehole drilling scenario and by a downstream iron mine scenario;
- consequence analyses concerning the influence of gas generation, microbial effects, temperature gradients, rock convergence, recriticality and chemotoxicity on long-term safety;
- using other safety indicators additional to dose limits, e.g. groundwater velocity and groundwater age;
- calculate the radiation exposures from the radionuclide concentration in the groundwater (after ca. 300 000 years) by means of a general administration regulation ("Allgemeine Verwaltungsvorschrift, AVV").

Safety assessments for the Konrad site were carried out using a freshwater model. Because the measurments are showing increasing groundwater salinity with depth, the calculated groundwater velocities must be much higher than the expected real velocities by at least one order of magnitude. Therefore the real transport is governed by diffusion. As a result the expected shortest travel times for radionuclides are much longer than the calculated ones, e.g. more than 1 million years.

3. Conclusions

Scrutinizing the applicant's licensing documents the authority / experts were finally in accordance with the applicant's assessments and safety statements. The (qualitative) long term prediction of the geological situation of the KONRAD site shows a stable and robust site and geological barrier system. The site is robust against modifications of the geological/hydrogeological situation. The overburden strata of ca. 400 m clay has strong self-healing capabilities. The robustness was proven by performing groundwater movement calculations with different conceptual models. Due to the major effectiveness of the geosphere as barrier, other technical and geotechnical barriers and the source term of the nearfield are of minor influence in the long term safety assessment.

PA-calculations done by different parties with different codes and uncertainty analyses for the groundwater situation proved the robustness of the system and therefore for the proposed waste inventory the long-term safety of the Konrad repository was demonstrated.

THE INTEGRATION OF GEOSPHERE DATA INTO A SAFETY CASE – THE EXAMPLE OF THE SAFETY FUNCTION "DIFFUSION AND RETENTION" IN THE BOOM CLAY

Ann Dierckx, Robert Gens and Philippe Lalieux
NIRAS/ONDRAF, Belgium

Norbert Maes, Lian Wang and Jan Marivoet
SCK•CEN, Belgium

1. Context

Safety Assessment and Feasibility Interim Report (SAFIR)

In Belgium, the Radioactive Waste Management Agency NIRAS/ONDRAF is considering the deep disposal of high level and long-lived radioactive waste in clay media as long-term management option.

The SAFIR report (1989) dealed with the first phase of the methodological R&D programme in a view of establishing and increasing confidence in deep disposal. The methodological programme is focused on a reference formation and site, i.e. the Boom Clay beneath the nuclear zone in Mol-Dessel (NE Belgium), without making any presumptions on the site as site for the actual implementation. In 1990, the SAFIR Evaluation Commission stated that the focus of the programme on vitrified waste an don the Boom Clay in the vicinity of the Mol-Dessel nuclear zone was justified.

However, the Commission suggested additional issues to consider in the next phase of the programme such as an alternative host formation, the Ypres Clays and the consideration of direct disposal of spent fuel. It also provided the basis for the 1990-2000 R&D programme.

SAFIR 2 [SAFIR 2, 2001] reports the results of this ten-year R&D programme in a view of obtaining a twofold governmental decision allowing (i) to continue the technical disposal programme and (ii) to open a societal dialogue with the various stakeholders on long-term waste management. SAFIR 2 is one step in the overall step-wise process for a repository in Belgium. Further development of the characterisation, assessment and implementation methodologies will be carried out focussing on the reference host formation and site and with the support of large-scale, integrated *in situ* experiments (PRACLAY).

Instead of state-of-the-art reports (like SAFIR), ONDRAF/NIRAS envisages to collect all the arguments supporting the safety and the feasibility of the proposed disposal solution in a self-supporting document. A first Safety and Feasibility Case is planned by 2012. A 2nd report would be available by 2020 and should provide all the necessary information to enter a site-specific pre-project phase.

Finally, an integration of the technical and societal dimensions of waste management issues should be achieved through a broad dialogue based among other on a strategic environmental impact assessment.

The present presentation will discuss the way that different types of geologic information have been treated in the SAFIR 2 report and will be treated in the future Safety and Feasibility Cases.

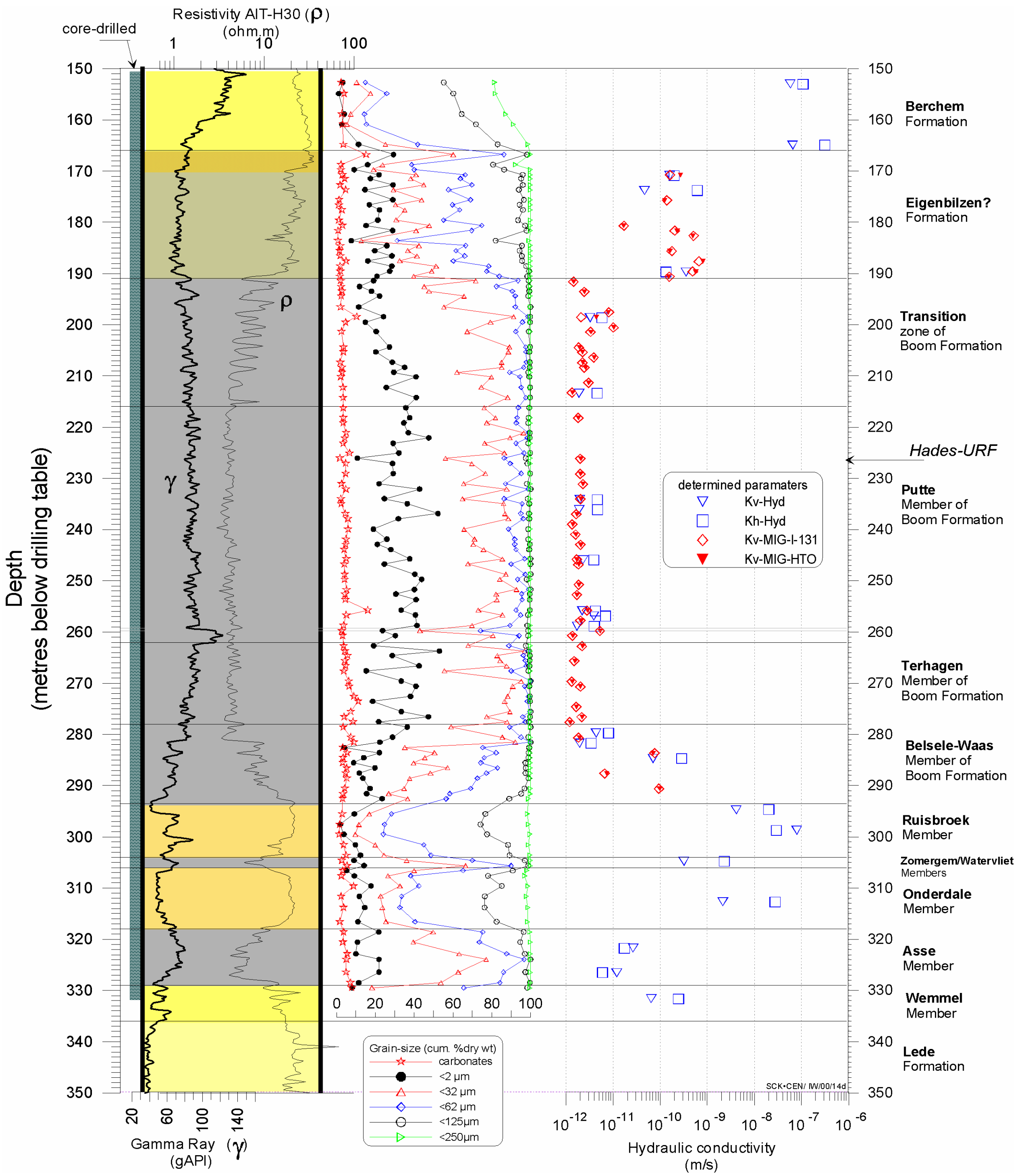
The overall geological framework has been discussed elsewhere [SAFIR 2, 2001] and only the key features of the Boom Clay conceptual site model are mentioned in Section 2 (Role of the geosphere in the overall safety of the disposal system). Also in this section, the dominant safety function attributed to the Boom Clay will be discussed. Different lines of evidence in support of the assurance of this safety function are further developed in the following section (Section 3 – Acquisition of data). The fourth section concludes with some thoughts on the integration of R&D results in performance assessments.

2. Role of the geosphere in the overall safety of the disposal system

The characterisation programme concerns the Boom Clay and the surrounding sandy aquifers. The study zone covers northeast Belgium – the Campines – and concerns five large hydrogeological units that encompass the Boom Clay to a depth of some 600 metres.

Although the lithology of the Boom Clay is heterogeneous – a banded structure is noticed – the properties related to migration are shown to be fairly homogeneous as proven by hydraulic conductivity and apparent diffusion measurements for non retarded tracers that were performed every 2 metres over the complete thickness of the formation (Figure 1).

Figure 1. **Distribution of hydraulic conductivities determined on cores from the Mol-1 borehole based on migration experiments using tritiated water (Kv-MIG-HTO) and iodine-131 (Kv-MIG-I-131), or based on conventional tests on small cylinders or plugs, cut vertically and parallel to the bedding, in permeameters (Kv-Hyd, Kh-Hyd)**



Moreover, different drillings over a large area showed a remarkable lateral continuity of the Boom Clay at regional scale.

Different performance assessments have shown that the Boom Clay is the main contributor to the safety function "diffusion and retention" which delays and limits the release of radionuclides. The repository design should therefore minimise the perturbations of the host rock, to maximise the effective thickness of the geological barrier. Long term geochemical and structural stability is assumed, no evolution was encountered for in the normal evolution scenario.

Consequently, for the past 10 years an intensive R&D programme was devoted to studying the retention mechanisms and the diffusion behaviour of radionuclides in the Boom Clay. In the future R&D programme, more attention will be given to the effects of disturbances on the main barrier and how to control/minimise them.

3. Acquisition of data relevant to radionuclide transport in Boom Clay

To assess the diffusion and retention capacities of the Boom Clay for radionuclides, different approaches have been taken. Even so, a lot of attention has been devoted to the characterisation of the geochemical environment, with the aim to understand past evolutions and predict the behaviour of the Boom Clay towards future evolutions or perturbation. Furthermore, knowledge of the geochemical environment is believed to be indispensable for the interpretation of the behaviour of radionuclides in Boom Clay experiments.

The geochemical environment

Multiple types of actions were taken to estimate the porewater composition and to test the current understanding of the mechanisms determining the composition towards possible perturbations (overview report in preparation):

- Porewater collection and subsequent analysis.
  - Piezofilters in the underground lab, squeezing technique and leaching.
- *In situ* online measurements of speciation controlling parameters.
  - pH, pCO_2, E_H
- Geochemical modelling, combined with experimental evidence:
  - Calculating the porewater composition as determined by the different constituents of the Boom Clay.
  - Modelling the E_H as controlled by pyrite dissolution and imposing this E_H in Boom Clay synthetic claywater.
  - Modelling the varying porewater composition upon oxidation of cores and verifying this by measurements.

Diffusive transport in Boom Clay

The Boom Clay beneath the Mol-Dessel nuclear zone is characterised by a very low vertical hydraulic conductivity ($K_v \approx 10^{-12}$ m.s^{-1}) and a very low downward natural hydraulic gradient (2 metres of water over 100 metres of clay thickness). Radionuclide migration is therefore controlled essentially by diffusion, with advection having only a secondary role. A preliminary study designed to assess the vertical homogeneity of the Boom Clay in terms of its migration properties has already succeeded in demonstrating uniform migration properties for non-retarded species.

Evidence for this dominance of diffusion has been given by large scale *in situ* tests, as well as by paleohydrogeological arguments, such as the study of the behaviour and migration of naturally occuring radionuclides.

The future programme evenso foresees to reinforce this argument by studying natural tracers (C-14, U/Th series, REE, ...). At the scale of the Boom Clay formation, it will be interesting to examine whether the vertical profiles of the concentrations of natural tracers can be explained as the result of diffusion of marine interstitial water towards the surrounding aquifers. The available data of natural tracers are not well understood at present and a complete profile across the Boom Clay is not available.

Retention mechanims

The retention mechanisms have been studied in very different ways:

- A large "*migration* programme" has been set up. Within this experimental programme, one always strives to determine the parameters by different methods and under different experimental conditions: i) scale variation: laboratory small scale, *in situ* large scale, ii) variation in advective component: pure diffusion test, percolation tests, as well as electro-migration tests, iii) variation in source application: pulse, upflooding, in dis- or in equilibrium with the Boom Clay.
- Laboratory supporting experiments: Sorption tests, solubility tests, reactor tests, complexation tests, … .
- Modelling: Modelling has been used both as scoping calculation and for parameter extraction from the experiments.

In the past, the interpretation of the experiments has always been in a lumped way; retardation coefficients and apparent diffusion coefficients have been derived, ignoring the complex mechanisms underlying these parameters. As the interpretation of the migration experiments with radionuclides with a complex chemistry has not been possible relying only on simple models, more and more fundamental research has been included. The challenge for the future will be and we quote the Peer Review Team [SAFIR 2: An International Peer Review, 2003] "to find a balance between building a predictive capability based on realism and mechanistic understanding and a capability to support safety through robust models and arguments".

One typical area in which such a balance should be struck is the area of organic matter. Due to high content of organic substances in Boom Clay, the influence of organic substances on the migration of radionuclides is of great concern. Up to now, the approach most followed to assess the influence is to apply conditional stability constants that are the measure of tendency to form complexes between radionuclides an organic substances. Without spectroscopic evidence for identification of the formed complexes, conventional complex-metric experiments do not provide sufficient data to establish an unambiguous model for describing the formed complexes that can be extrapolated out of the experimental conditions. In addition, difficulties in controlling the oxidation states of radionuclides often make experiments involving redox sensitive elements difficult to interpret. A recent EC programme, TRANCOM-II is looking for additional evidence to test the applicability of conditional stability constants. To that end, the effect of natural organic matter on the safety relevant parameters, i.e., apparent increase of radionuclide solubility and/or the decrease of radionuclide sorption were measured. A coherent model was pursued to represent natural organic matter and its global effect on the migration of radionuclides.

Long term stability

As it is believed that the present geochemical conditions were established already quite early after the deposition of the sediment, one concludes that the site of Mol is likely to provide the needed stability. However, in the future programme a more sound set of arguments will be furnished. One part of the arguments could come from the determination of the natural tracers. Another argument is the fact that the transition of marine to fresh water about 2 million years ago, did not result in major changes in the Boom Clay.

At present, special attention is given in this respect to the study of the organic matter, especially its origin, its mobility and its future behaviour under thermal stress.

4. Integration of R&D results in performance assessments

A procedure "Data Collection Forms (DCF)" has been established for the selection and traceability of the different parameters to be used in the performance assessment. This selection is done and arguments are given by the different experts of the R&D teams. The performance assessors check the consistency of the parameter values with the models used in the assessment. The research priorities on the other hand have always been set based on the performance assessment calculations done. In future, this approach will be further elaborated with special attention for putting explicit tacit knowledge and decisions taken. Thereto, NIRAS/ONDRAF has recently started a "Knowledge Management" system.

During the parameters assignments by R&D experts, the simplified conceptual models used in performance assessment sometimes lead to the necessity of applying different sets of parameters for a specific radionuclide. In the future program, it will be tested how far these conceptual models need to be upgraded.

In view of the upcoming Safety and Feasibility Case, a new reporting procedure is being formalised. Every report should be accompanied by an integration module, a one to a few pages summary. Assigned persons, called "integrators" will place the reported research into its broader framework and indicate its importance into the overall Safety and Feasibility Case. In this way, researchers have a broader picture, and see how their results are taken up as argument in the Safety and Feasibility Case. If necessary, they can intervene in a fast and effective way.

Another practical way which is considered to help integration within the programme is a comprehensive (and evolving) identification of the interfaces between the various scientific and technological components of the repository development (phenomenology, technology, evaluation). Each of the interfaces should also be "personified" in order to establish clear responsibilities for the transfer (back and forward) of information between the various components. Additionally, interfaces with the "external world" might be treated the same way (regulators, general stakeholders, …).

Most of the results of performance assessment calculations have been presented in terms of radiological dose for a member of the reference group. Recently [SPIN, March 2003; SAFIR 2, 2001], the fraction of nuclides that decay before they can reach the aquifer and radionuclide fluxes to the aquifer compared to the amount of natural radionuclides present in the Boom Clay have been considered as additional alternative safety and performance indicators. These indicators are sensitive to the robustness of the disposal system because they relate to a safety function that is provided by robust barriers. Their values have been compared with the quantities of naturally-occuring radionuclides in the geosphere and, more particularly, with the concentrations of radionuclides naturally occurring in the interstitial waters.

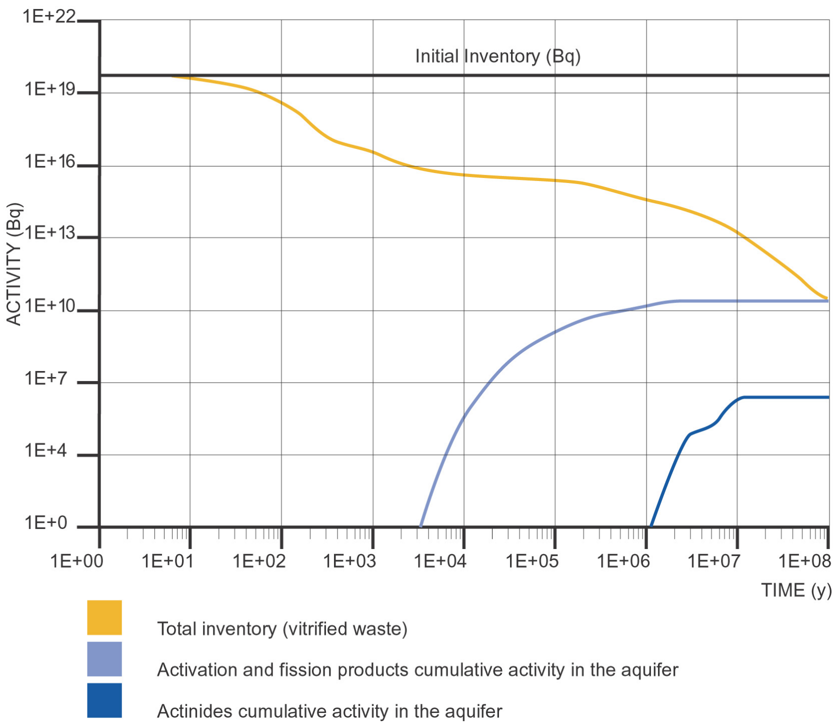
Two other variables can also give an indication of the performance of the disposal system. There are, first, the *containment factor*, i.e. the ratio of the total activity placed in the repository to the cumulative activity released by the disposal system, and, second, the *total inventory of uranium* placed in the repository, which can be compared with the alpha activity naturally present near to the facility.

In the case of vitrified waste, and except for a few very long-lived radionuclides such as ^{129}I and ^{107}Pd and some non-retarded radionuclides like ^{79}Se and ^{99}Tc, only a very small portion of the initial activity reaches the aquifer (Figure 2):

- about 2.10^{10} Bq of activation and fission products for a total initial activity of 7.10^{19} Bq;
- about 10^7 Bq of actinides for a total initial activity of around 5.10^{17} Bq (mainly ^{241}Am and ^{244}Cm).

Thus, the disposal system, with its functions of physical containment and of delaying and spreading the releases, acts as an extremely efficient containment system, with the major portion of the activity placed in the repository disappearing before it can reach the aquifer.

Figure 2. **Cumulative activity reaching the Neogene Aquifer for vitrified waste**



Acknowledgement

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SITE DESCRIPTIVE MODELLING AND USE OF THE ROCK VISUALISATION SYSTEM TOOL

Johan Andersson
JA Streamflow AB, Sweden
Raymond Munier, Martin Stigsson and Jan-Olof Selroos
Swedish Nuclear Fuel and Waste Management Co. (SKB), Sweden

The Swedish Nuclear Fuel and Waste Management Co. (SKB) has started site investigations for a deep repository for spent nuclear fuel at two different sites in Sweden. To support the site investigations, data need to be interpreted and assessed into Site Descriptive Models. The models should be multidisciplinary interpretations of geology, rock mechanics, hydrogeology, hydrogeochemistry, transport properties and ecosystems using site investigation data from deep bore holes and the surface. The modelling comprises identification of data, evaluation of primary data, three-dimensional modelling and overall confidence evaluation. In the current presentation, the methodology is exemplified for geological modelling.

1. Introduction

The Swedish Nuclear Fuel and Waste Management Co. (SKB) has started site investigations for a deep repository for spent nuclear fuel at two different sites in Sweden. The investigations should provide necessary information for a license application aimed at starting underground exploration. For this reason the site investigation data need to be interpreted and assessed into Site Descriptive Models, which in turn are used for exploring design options and for safety assessment studies. Site Descriptions are also needed for further planning of the site investigations.

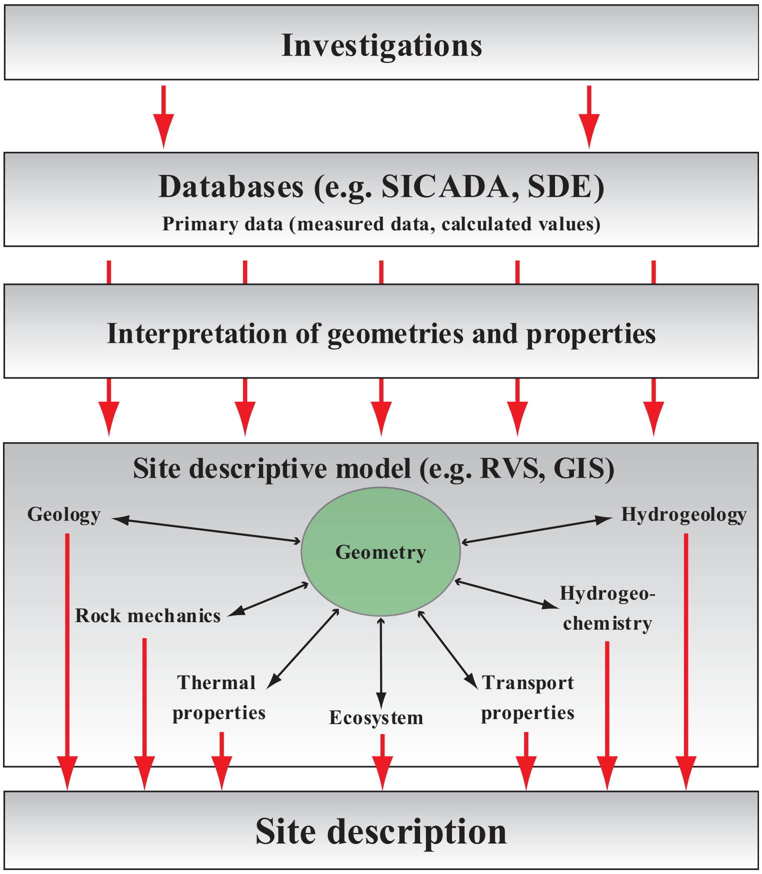
Site investigations will proceed in stages [1], where the “initial stage” includes surface characterisation and drilling and exploration of a few deep boreholes at each site. A later ‘complete stage’ includes drilling of about 10-20 deep boreholes per site. Site Descriptive Models are set up at least after each stage.

The Site Descriptive Model should be a multidisciplinary interpretation of geology, rock mechanics, hydrogeology, hydrogeochemistry, transport properties and ecosystems using site investigation data from deep bore holes and from the surface as input [2]. The modelling comprises several different components. The main components are:

- Identification of data.
- Evaluation of primary data.
- Three-dimensional modelling.
- Overall confidence evaluation.
- Documentation.

Figure 1 presents how primary data through interpretation and three-dimensional modelling result in a site description.

Figure 1. **Primary data from site investigations are assembled in a database. Data are interpreted and presented in a site descriptive model, which consists of a description of the geometry of the different units in the model and their corresponding properties. The site descriptive model is typically expressed in 3-D using the Rock Visualisation System (RVS). The "site description" consists of the site descriptive model and supporting databases**



In this paper we shortly present the components listed above, with an emphasis on geological interpretation and modelling. The geological site descriptive model provides the basic geometrical framework for all the other disciplines.

2. Identification of data

The term method-specific interpretation is used for the processing and interpretation of raw data. Method-specific interpretations within the geological discipline are generally based on the application of particular geological or geophysical techniques. This type of interpretation takes place according to standard and generally accepted procedures, and is carried out before the data is stored in SKB's databases. Method-specific interpretation is routine and is not mentioned specifically in Figure 1 (upper box, marked "Investigations"). An example of a method-specific interpretation is reflection seismic profiles which are constructed semi-automatically from the vibration data recorded during a seismic survey. Results based on method-specific interpretations are regarded as primary data sets for further modelling.

3. Evaluation of primary data

The term integrative interpretation is used for the data processing and interpretation of primary data in preparation for site-descriptive modelling. Integrative interpretation generally involves combining primary data sets from different methods to reach a synthesis of available data within a particular discipline (e.g. combining the data from geological mapping, topographic lineaments, aeromagnetics, etc. to define deformation zones). It makes use of the primary data sets stored in the databases, and the results form an important part of the input into the 3-D modelling (third box in Figure 1). The results of integrative interpretation should not be considered as primary input data, since the acquisition of new data, using perhaps a new method, will result in a revised interpretation.

Evaluation of primary data are made within each discipline first, and then compared to each other in order to check for potential inconsistencies.

4. Three dimensional modelling

The three-dimensional geological modelling results in a geometrical description complemented with corresponding properties of deformation zones and rock domains. The geometry is represented using a 3-D CAD software, RVS (Rock Visualisation System). Geological modelling is based on a geological interpretation, which in turn is based on processing and analysis of the raw data acquired during site investigations. In Figure 1, the term "geometry" represents the basic geometrical-geological model in RVS.

Other disciplines use the geometrical framework of the geological model, but will also provide feedback. While the representation is made in RVS, numerical codes etc. are sometimes used for the analysis. The hydrogeological description comprises hydraulic properties for defined geometrical units and boundary conditions for the present day conditions. The hydrogeochemical description concerns distribution of the major water types, the water type mixing proportions and lists the major type of chemical reactions occurring at the site. Even if much of the modelling can be done in parallel with other disciplines, consistency checks with hydrogeology should be made. Developing the rock mechanics description comprises the initial (i.e. prior to excavation) stresses and the distribution of deformation and strength properties of the intact rock, of fractures and fracture zones, and of the rock mass.

Common to all disciplines, the three-dimensional description should present the parameters with their spatial variability over a relevant and specified scale, with the uncertainty included in this description. Different, alternative descriptions may be required.

5. Confidence evaluation

The term interdisciplinary interpretation is used for the type of interpretation requiring interaction and consensus among the different disciplines. This is a major activity within site-descriptive modelling once the 3-D geological model has been formulated.

The different disciplines are to assess the suggested uncertainties and consider the feedback to the suggested geology, hydrogeology and hydrogeochemistry descriptions. In joint discussions overall confidence is assessed by [3]:

- checking that all relevant data are used;
- checking that different kinds of uncertainty are addressed;
- checking if suggested alternatives make sense and if there is potential for additional;

The confidence in the descriptive model is essentially a qualitative entity.

6. Documentation

The findings as well as the modelling results are to be documented in a Site Description. This description encompasses the different databases and digital models developed as well as a model report with associated sub-documentation. A model report should cover the following [3]:

- References to data sources and identification of previous model versions.
- Means of primary data evaluation including disciplinary evaluation, re-evaluation of previously evaluated data, and means of interdisciplinary comparisons.
- Means of three dimensional modelling including disciplinary evaluation with its comparisons with previous model versions, uncertainty estimates and the joint uncertainty, and confidence evaluation.
- Presentation of the Site Descriptive Model (discipline by discipline) with its uncertainties and alternatives.
- Assessment on overall confidence and discussing potentially fruitful additions to the measurement programme.

7. Conclusions

The present paper describes the site-descriptive modelling approach applied in the on-going site characterisation programme in Sweden. The approach is multidisciplinary and encompasses several components as described above. The approach, as outlined here, is believed to provide a versatile and flexible means of analysing data and presenting resulting models for further use in safety assessment and design applications. However, experiences gained in the initial phase of the site investigations may still imply changes in the site-descriptive modelling approach for later phases.

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INTEGRATION OF GEOSPHERE CONCEPTUAL MODEL IN THE SAFETY CASE: LESSONS LEARNT FROM THE "DOSSIER 2001 ARGILE" AND OPEN QUESTIONS

Patrick Landais
Andra, France

In the framework of the French act of parliament of December 1991, Andra has the responsibility of the feasibility study of the deep geological disposal of HLW. Andra has decided to present in December 2001 an initial report on the results of its research programme called "Dossier 2001 Argile". Besides the review of the work carried out by Andra, it has the status of a methodological test especially when considering the long-term safety analysis.

The RFS III-2f French rule that lays down the objectives which are to be adopted in the design and construction of a deep geological formation radioactive waste repository, indicates that the confinement system consists of three barriers: waste packaging, engineered barriers and geological barrier. It specifies that the main barrier is the geological one, particularly in the long term. On this basis geological criteria including: stability, hydrogeology (permeability, hydraulic gradients), mechanical geochemical and thermal properties as well as a minimum depth requirement, have to be considered in the technical criteria for site characterisation.

The work conducted during the exploration survey of the Meuse/Haute-Marne Site between 1994 and 1996 revealed that the Callovo-Oxfordian argillite formation met with the requirements of the fundamental safety rule.

A second stage of investigations (up to 2001) allowed to:

i. specify the favourable confinement characteristics of the geological medium (low permeability, 3-D geometry);
ii. identify the dominant phenomena governing the natural state and those involved in the potential disturbances induced by the operation of a repository;
iii. verify the geodynamic stability and define the potential outlets for radionuclides that might be released by a repository.

Geological data integrated in the safety case originate from different levels of observation: regional geology of the Paris Bassin, local and regional drill holes and associated well-logs, 2-D and 3-D seismic surveys, fieldwork (outcrops), and sample characterisation.

Effort was first concentrated on the long-term confinement properties of the potential host formation. Paleoenvironmental reconstruction helped define the sedimentation sequences and provided evidence for the local homogeneity of the Callovo-Oxfordian layer. Past geological history has been studied in detail in order to confirm the geodynamic stability as well as to reconstruct the diagenetic evolution of the sedimentary pile. Such data are used as an input for assessing the future evolution of the geological medium and to help define the transport model for radionuclides.

These types of data (for example isotopic geochemistry, stratigraphic input) are quantitative but provide only indirect information for the building of the geological conceptual model. They are used as constraints for inferring complementary information on the long-term behaviour of the Callovo-Oxfordian formation. As such, they may be considered as soft data.

These multi-scale investigations were conducted to establish a geological conceptual model on which performance calculation can be based.

The main remaining uncertainties concerning the geological medium relate to the hydrogeological patterns and more specifically:

- the potential hydraulic role of regional faults;
- the hydraulic gradients;
- the upscaling of the low permeability values of the aquifer formation measured on samples and in bore-holes.

Such uncertainties have led to consider transposed or extrapolated values for building the hydrogeological model as the density of quantitative information was not high enough. Furthermore, hypotheses concerning the role of the Triassic formation and of the regional faults have been made in order to provide a model that fit with the measured head values.

Geological data are also taken into account for defining the geographical area that can be considered geologically equivalent to that of the underground laboratory. Up to now, only the thickness and depth of the formation, the vicinity of tectonic structures, and the gross lithology of the formation have been used. Obviously, more detailed parameters (geochemical and mechanical) have to be considered and geostatistical methods have to be developed in order to more precisely define the transposition zone. For this purpose, correlations have to be established between geological data extracted from well logging and parameters obtained on samples.

Several examples dealing with specific problems associated with the integration of geological information in the safety case will be presented:

- How to integrate permeability data of aquifers that are not representative of regional (at the Paris Basin scale) average values? What type of demonstration should be built in order to reconstruct the diagenetic evolution of the aquifer formations? On what type of parameters?
- What type of geological information should be addressed for estimating the EDZ generation, extension, properties and evolution with time? Are mineralogical and geological (i.e. stratigraphic and sedimentologic) information well adapted to this task?
- What type of geological information should be used in order to assess the homogeneity of the formation at the scale of a transposition zone i.e. the geographic zone that is supposed to have similar characteristics to those of the area investigated in the underground laboratory (ca 200 km^2)?
- How do these types of questions provide additional constraints for conducting additional field investigations?

INTEGRATION OF GEOLOGIC INFORMATION IN THE WIPP SAFETY CASE

Richard L. Beauheim
Sandia National Laboratories, USA

Dennis W. Powers
Consulting Geologist, USA

Introduction

The Waste Isolation Pilot Plant (WIPP) is the U.S. Department of Energy's (DOE) deep geologic repository for transuranic (TRU) waste. The repository was constructed 655 m below ground surface in bedded halite of the Permian Salado Formation in southeastern New Mexico. Site-characterisation activities began in 1974 [1], and WIPP became a licensed, operating repository in March 1999.

The role of the geosphere in the WIPP safety case

Given that the WIPP is a geologic repository, the geosphere figures prominently in the WIPP safety case. The repository halite host rock provides the primary barrier function, effectively isolating the waste for far longer than the regulatory time frame (10 000 years) under undisturbed conditions. In the event of future human intrusion (drilling) of the repository, the overlying and underlying formations prevent the release of radionuclides across the regulatory boundary for 10 000 years through low permeability and/or high sorptive capacity. A key purpose of site investigations has been to provide the evidence needed to show that the geosphere possesses the properties described above.

Types of data collected

Over the nearly 30 years since site investigations began for the WIPP, geologic information of many types (e.g., stratigraphic, petrographic, hydrogeologic, geochemical, geophysical, isotopic) has been collected for a wide range of purposes. Geologic information has been used to develop basic conceptual models of the site, develop criteria for selection of a disposal horizon, design excavations and ground support, and provide qualitative and quantitative input to numerical models. As the WIPP project has progressed from site characterisation through repository construction and licensing to the current operational phase (with periodic relicensing), data needs and priorities have evolved. At times, particular issues have been resolved by integrating information from specific sets of sources. Integration of other types of information has been a key element in defining and defending broader conceptual and numerical models. Data are now being collected to resolve conceptual model issues raised by monitoring data, and to provide data needed for numerical representation of the revised conceptual models. These efforts involve a higher level of integration of diverse types of geologic data than has been achieved before for the WIPP.

As an example, one issue that arose during site characterisation for the WIPP that required integration of a wide range of types of data to resolve concerned pressurised brine occurrences. In a small percentage of the boreholes drilled in the Delaware Basin passing through the host formation (Salado) for the WIPP repository, pressurised, H_2S-laden brine was encountered on anticlinal structures in fractured anhydrite of the underlying Castile Formation, 250+ m below the WIPP repository horizon [2, 3]. Because this brine flowed freely at ground surface at rates as high as 37 L/s, future drilling that interconnected one of these brine reservoirs with the repository was considered as a potentially dangerous scenario. Accordingly, a multifaceted investigation was begun to learn more about the origin and properties of these Castile brine occurrences, focusing on the two that had been encountered in boreholes drilled for the WIPP.

The brine occurrence investigations entailed a variety of data types and collection techniques:

- seismic reflection surveys to define deep geologic structures [4];
- time-domain electromagnetic (TDEM) surveys to detect electrically conductive features (e.g., brine) at depth [5];
- structure contour and isopach mapping based on borehole geophysical logs;
- core studies (petrography, sedimentology, X-ray diffraction, scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy, isotopic analysis, permeability, porosity, density) [2];
- borehole geophysical logs (neutron porosity, caliper, resistivity, natural gamma, density, acoustic);
- acoustic televiewer logging of the boreholes to identify fractured zones and fracture characteristics;
- flow and buildup tests to quantify hydraulic properties (permeability, pressure, extent) of the brine reservoirs [2];
- geochemical sampling of the brine and gases for major and minor ion and trace element analyses, isotope studies, and mass spectrographic analysis to determine the composition, source, and age of the fluids [2];
- geostatistical analysis to determine presence/absence of correlations between various geologic parameters (e.g., unit thicknesses) and the occurrence of brine reservoirs;
- stress-strain calculations to estimate anhydrite response to halite movement [6];
- an unsuccessful attempt to map structures using micro-gravity techniques [7].

The geologic and geophysical data were integrated to produce a conceptual model of a rigid anhydrite beam buckling and fracturing due to differential flow of halite beneath it. Interstititial brine would then flow slowly to, and collect in, the fractures. Geologic and mechanical arguments suggest that most of the deformation occurred well after deposition, probably after the mid-Cenozoic. Multiple lines of geochemical evidence address questions of the age and origin of the Castile brine. Although different lines of evidence may support multiple hypotheses, the hypothesis most consistent with all evidence is that the Castile brines derive from seawater trapped during deposition during the Permian. Differences in brine and gas compositions from different wells, hydraulic properties from laboratory and well tests, and observations during well tests led to the conclusion that the brine reservoirs are not interconnected on a regional scale. TDEM studies suggest that a deep conductive zone (possibly indicating a brine reservoir in the Castile) underlies between 10 and 55 per cent of the area of the WIPP waste panel area. A geostatistical study of known brine reservoirs from the region around the WIPP provides an estimated probability of 0.08 of intersecting a brine reservoir under the WIPP waste panel area.

Information prioritisation

During early site characterisation, priority was given to collecting information that would confirm the expected beneficial features of the site and to assess processes (e.g., dissolution) or features (e.g., brine reservoirs) that might threaten waste isolation. Although not thought of in these terms, the information collected was needed to develop basic conceptual models of the site and to support evaluation of features, events, and processes (FEPs) that might affect the performance of the repository. As the understanding of the site evolved, priorities shifted toward better characterisation of those FEPs that seemed to have the most potential to affect the performance of the repository adversely. For example, high-permeability strata (which might be more likely to provide release pathways for radionuclides) were characterised in increasing detail, while characterisation of low-permeability strata virtually ceased. Over time, scenarios of concern became increasingly detailed, and data-collection activities were focused on providing the information needed to evaluate them.

Once the focus of the project shifted from site characterisation to preparation of the license application, priority was given to data needed for the performance assessment (PA) modelling of specific processes. To the extent that this modelling was driven by clear-cut numerical requirements given in the regulations, priorities were clear. Priorities were harder to establish for information needed to defend the models technically. By regulation, all conceptual models developed for the WIPP must undergo a technical peer review. Twenty-four conceptual models were developed after FEPs analyses for the WIPP Compliance Certification Application (CCA [8]). These 24 models and their numerical implementation in the PA were reviewed with respect to: adequacy of information; validity of assumptions; alternatives evaluated; uncertainties; adequacy of the model and its application, accuracy, results, and conclusions; and whether the model was ready for implementation in the PA process. These peer reviews require more information than is needed as input to numerical models to provide a convincing case that the model is appropriate. Prioritising the information needed for a peer review is difficult, as one can never be certain where the evidentiary threshold lies in the minds of review panel members for judging a conceptual model adequate or inadequate. In some instances, peer panels have specified the information they feel is lacking. This information is then given a high priority for collection, and the peer panel is reconvened to evaluate the new information base. A similar problem exists with defining and prioritising the information that the regulator might need to defend their decision to license the WIPP. Often, data needs and priorities can only be established through iterative discussions with the regulator.

Team integration

Over the history of the WIPP project, the work of various teams has been integrated in several ways with different degrees of formality. During the early years of site characterisation, monthly meetings were held of the Principal Investigators (PIs) and managers from the different organisations involved to summarise activities and plan future activities. Later on, separate departments were set up for surface-based investigations and underground-based investigations, a separation that sometimes resulted in less-than-optimal integration. Integration of some data types (e.g., geophysical, geochemical) has been dependent on a PI in a central role seeking it out and the availability of an appropriate expert wanting to be involved (some key experts transferred to other projects after the initial site-characterisation work had been completed).

For the WIPP license submittal application, a formal procedure was developed to ensure that PI's and PA analysts were working in an integrated fashion. Working from the information provided by PI's, PA analysts would describe the models they could use to represent various processes, and the data that would be required for each. The PIs would then approve the use of the recommended model, or suggest an alternative, and provide the data needed with qualifications on its use. Finally, both the PA analyst and the PI would sign a form summarising this information.

A hierarchy of Analysis Plans (APs; http://www.nwmp.sandia.gov/onlinedocuments/wipp-ap.htm) and Test Plans (TPs; http://www.nwmp.sandia.gov/onlinedocuments/wipp-tp.htm) is now used to ensure integration. In addition to overarching APs describing the programmes that respond to major regulatory requirements (e.g., PA, monitoring, etc.), each major component of these programmes has its own AP, which is underlain by finer scale APs. For instance, an AP describing how radionuclide transport will be calculated for re-certification describes how flow modelling performed under another AP gets integrated with K_d information developed under yet another AP. Each of those lower level APs describes the information that will be integrated in the completion of its tasks, and ultimately the APs rely on one or more TPs to provide the data to be analysed. No data-collection or analysis activity is performed outside of this umbrella of plans.

Summary

The WIPP safety case relies on integration of a diverse range of geologic information to demonstrate that the geosphere adequately contains radionuclides for the regulatory time period. Information is priortised based on its use in numerical PA models and role in supporting conceptual models. Integration is now achieved by conducting all activities under an interrelated structure of Analysis and Test Plans.

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THE ENRESA 2003 PERFORMANCE ASSESSMENT EXERCISES FOR CLAY

Julio Astudillo and Jesús Alonso
ENRESA, Spain

Clay is one of the candidate lithologies considered by ENRESA for the disposal of High-Level Radioactive Waste. Up to now, three Performance Assessment exercises have been developed by ENRESA: ENRESA 97 (Granite), ENRESA 98 (Clay) and ENRESA 2000 (granite). With the experience gained with these exercises and with the results provided by the R&D programme, a new exercise for a clay formation is presently underway. This new PA exercise will be finished at the end of 2003.

The main objectives of the PA for clay are:

- To increase the structuring and accessibility of ENRESA's knowledge, data and evaluation methodologies, adapted to the Spanish context.
- To test the numerical codes and tools developed in the R&D programme.
- Integration in the PA exercises of the research people directly involved in the R&D.
- To obtain criteria and dates to be considered in the site studies, guidance R&D programme and repository design.

The safety bases of the exercise consider the post-closure period and the effects of the operational phase on the long-term safety.

The site is a "generic site", elaborated with direct information of real Spanish clay formations. The repository reference concept and design is adapted from ENRESA 98.

Several scenarios are in consideration (normal and altered) and two approaches for consequence analysis are included (deterministic and probabilistic in scope). Sensitivity analyses will be carried out on the calculation results.

For the objectives of this workshop, the main contribution of the ongoing ENRESA 2003 is related to the use of geological data for the construction of the site conceptual model and the managing of the interaction between different teams for the evaluation.

Geological data and site conceptual model

Up to now, no candidate site has been selected by ENRESA for high-level radioactive waste disposal. During the site selection programme, a significant amount of information was obtained. Field studies, including deep boreholes, were performed for the most promising clay formations. Laboratory analyses focused on the geomechanical and geochemical properties of the clay formations, using well-preserved samples from borehole cores, have been performed for this exercise, combined with a reinterpretation of the geophysical data obtained from the boreholes and from the surface.

A new 3-D geological model is under elaboration that will be integrated with the previous hydrogeological model.

The new geochemical studies focus on the pore water chemistry in order to support the assessment of the physicochemical conditions in the repository area and of the transport phenomena in the geological barrier. Geochemical information has been used also to support the long-term stability conditions on the base of the paleogeochemical evolution of the clay formation.

Geotechnical data have been used mainly in the design of the repository and in impact assessment of the coupled thermo-hydro-mechanical evolution of the repository.

All this information and data are under reprocessing for the elaboration of a detailed geological conceptual model, considering the most relevant FEPs, and will be a key issue in the assessment. In this sense, the geological and geomorphological data obtained support the evaluation of two specific scenarios in the evaluation: effects on the hydrogeological behaviour of the detected discontinuities in the clay formation, and geomorphologic impact of climatic change (river capture in the north part of the site).

A “key reference” for this exercise is the FEPCAT catalogue elaborated by NEA. This document is one of the most relevant and useful that can be used, now and in the future, for FEPs analysis in clay sites.

Research team management

One of the main problems in all PA exercises is related to the integration of the research teams in the systematic and routine work of the exercise, from the FEP analysis to the consequence analysis and robustness of the evaluation.

In the previous ENRESA PAs, a big effort has been oriented in this sense, and the good results are now applied to the ENRESA 2003.

The structure for the ENRESA PA includes three main elements:

- ENRESA staff;
- PA engineering group;
- R&D groups.

The ENRESA staff is responsible for actively driving the different tasks of the exercise (FEPs analysis, conceptual model elaboration, scenario analysis, etc) and the coordination.

The PA engineering group is in charge of the technical secretariat of the exercise such as the performance of numerical calculations and the reporting.

R&D groups’ contributions are concerned with the analysis of the phenomena, the elaboration of conceptual models, and the scientific overview of the exercise.

The integration of all these groups has been achieved with the “Integration Thematic Groups” (GTI). The overall objective of these GTIs is communication and integration of the participants, assuring the best application to the exercise of the capabilities and knowledge acquired in the different R&D projects in which ENRESA has participated. Each GTI is co-ordinated by a member of ENRESA’s staff.

Six GTI’s have been organised for:

- Waste description and performance.
- Site description.
- Biosphere description and evolution.
- Thermo-hydro-mechanical evolution (Engineered barrier and geological barrier).
- Geochemical evolution.
- Flow and transport in the barrier system.

The functions assigned to the GTIs are:

- Detailed definition of the objectives and activities for each of them.
- Analysis of specific FEPs and data base generation
- Active participation in the process analysis and conceptual model elaboration.
- Data generation and generation of mathematical models.
- Review of the technical report produced.
- Scientific and technical support of the approach and hypothesis selected.
- Sensitivity and uncertainty analysis.
- Evaluation of results and lessons learned.

All these GTIs have elaborated detailed and coherent work programmes and time tables. Three general meetings with all the people involved in the GTI’s will be held.

The results obtained by the GTIs will let the calculation phase start after the summer while revision of most supporting reports will be carried out.

This structure assures the integration of all the information produced in the R&D programme, supports the scientific basis of the evaluation, and contributes to focusing on the main issues to be included in the future R&D actions. It also facilitates the understanding and support by all the participants (researchers, modellers, PA experts) and waste management staff.

GROUNDWATER FLOW SYSTEM STABILITY IN SHIELD SETTINGS A MULTI-DISCIPLINARY APPROACH

M.R. Jensen
Ontario Power Generation, Canada
B.W. Goodwin
Goodwin Environmental Assessment Consulting, Canada

Introduction

In November 2002, the Canadian Government brought into force the Nuclear Fuel Waste (NFW) Act. The NFW Act addresses the long-term management of used nuclear fuel in Canada through defining a process and timetable for the selection of a preferred management option. The NFW Act also required the creation of a Nuclear Waste Management Organization (NWMO), the formation of which was announced in October 2002. The NWMO is directed to undertake a study of approaches for the management of used fuel, including, but not limited to, storage at nuclear reactor sites, centralized storage either above- or below-ground and deep geologic disposal on the Canadian Shield. This study, which will involve broad public consultation, will compare the benefits, risks, and costs of each approach. The NWMO must submit its study and accompanying recommendation for a preferred approach to the federal government within 3 years of the NFW Act coming into force (November 2005). The government will then select an approach for implementation by the NWMO. The earliest decision by the government is expected in 2006.

On behalf of the nuclear fuel waste owners in Canada, Ontario Power Generation's Deep Geologic Repository Technology Program (DGRTP) conducts research and development activities associated with advancing the Deep Geologic Repository (DGR) concept. As part of the DGRTP, Geoscience work program activities are intent on advancing the understanding of groundwater flow system evolution in Shield terrain at time scales relevant to repository performance. A key issue within the program remains the geosynthesis of site-specific information, which through analysis and integration of multi-disciplinary data provides a traceable and reasoned basis to constrain predictive outcomes despite recognized site characterization uncertainties. In this respect, the synthesis of broadly diverse but corroborating geoscientific evidence can improve the traceability of geologic reasoning that bounds non-uniqueness and offers a systematic approach to communicate and convey confidence in the expected long-term performance of the geosphere (Jensen and Goodwin, 1999).

One specific topic of interest for Geoscience studies is the case for geosphere stability, particularly that associated with groundwater hydrodynamics and geochemical stability as influenced by long-term climate change. The DGRTP effort on this topic draws from elements of paleohydrogeology, hydrogeochemistry, environmental isotopes, structural geology, geostatistics and field investigations at analogue sites. In addition to conventional studies, the Geoscience program is evaluating the utility of new and revised investigative and interpretive tools.

Much of this work is in progress but important contributions have already been realized. The remainder of this discussion is concentrated on one specific issue to illustrate how different disciplines are involved to support one another. The issue concerns redox front migration as may occur during the next Laurentide (North American) glaciation with the intrusion of low-salinity, oxygenated glacial meltwater. Examination by proxy and combinations of evidence are helping to uncover Shield flow system attributes in time and space that most affect flow system stability. This process is an example of on-going efforts on flow system evolution that directly support geosphere performance assessment and that indirectly support the Safety Case for a DGR.

Groundwater flow system stability

The DGR concept envisions encapsulating used CANDU® nuclear fuel in corrosion resistant canisters and then emplacing the canisters within an engineered repository at depths of 500 to 1 000 m in crystalline plutonic rock of the Canadian Shield. A key aspect influencing repository safety relates to the stability of reducing electrochemical conditions within the repository environment. Unfavorable redox conditions could have negative influences on canister corrosion rates, used fuel dissolution rates, and contaminant solubilities and sorption coefficients (Goodwin *et. al*., 1994; SKB, 1999). Moreover, from a site characterization perspective, paleo-hydrogeologic evidence of deep penetration of oxygenated waters could imply significant future incursions that might affect the performance of the geosphere, the repository or both. Thus, the issue of redox front migration serves as one geosphere performance assessment focus, which allows hypotheses for groundwater flow domain stability to be tested and coincidence within multi-disciplinary data sets to be explored.

Geoscientific studies in three DGRTP program areas have been coordinated to develop a reasoned basis from which to illustrate an understanding of flow domain stability as it relates to redox front migration and flow system dynamics in a Shield setting. They involve: (i) development of a constrained Laurentide ice-sheet model; (ii) paleohydrogeologic evidence from the Whiteshell Research Area (WRA) near Lac du Bonnet in southeastern Manitoba; and (iii) application of 3-dimensional numerical methods to predict long-term groundwater flow system dynamics as affected by glacial and peri-glacial conditions.

Laurentide ice-sheet model.

A Design Basis Glacier Scenario (DBGS) for a hypothetical Shield repository is described by Peltier (2002). During the last half of the Pleistocene, the Canadian Shield has been subject to nine glacial events. Each cycle typically lasted for 100 kyr with ice-sheet advance to a southern maximum, approximately coincident with the Canada – United States border. The land was covered with ice for about 90 kyr, followed by rapid de-glaciation. At the time of maximum glacial extent, ice-sheet thickness approached 4 km and ice-sheet loading was sufficient to depress ground surface by 1 km.

Further description of the DBGS is provided through the development of a climate forced 3-dimensional thermo-mechanical Laurentide ice-sheet model consistent with the most recent episode of continental glaciation. The model predicts temporal and spatial ice sheet thickness, total stress, basal temperature and ice-stream formation during the presumed next Laurentide glaciation, anthropogenic changes aside. Model results at a hypothetical Shield site suggest prolonged periods of ice-cover (33 kyr) with ice sheet thickness approaching 2.4 km. Peri-glacial and glacial conditions result in land surface temperatures at or below a relative pressure melting point for time periods up to 60 kyr. Events of such frequency and magnitude would not only create transient thermal, mechanical and hydraulic boundary conditions but also alter recharge rates, recharge chemistry and groundwater residence times. Paleohydrogeologic studies and coupled numerical flow system analyses, described below, are using this information to further explore reasons for confidence in long-term groundwater flow system behaviour.

Paleohydrogeologic evidence

Related paleohydrogeologic studies have approached this issue from two lines of reasoning:

i. application of insight thermodynamic numerical modelling; and

ii. paleohydrogeologic investigations of fracture infill mineralogy at the WRA.

McMurry (2000) describes a series of stylized calculations with the thermodynamic code PHREEQC undertaken to illustrate the possible role of rock-water reactions in maintaining poised redox conditions at various depths within the WRA Lac du Bonnet batholith. A series of systematic sensitivity analyses were performed in which glacial and WRA fracture end-member waters were ‘mixed’, either as bulk mixtures or progressively along a reasoned fracture flow path, and then allowed to equilibrate with typical mineral assemblages. Consistent with the granitic Lac du Bonnet batholith mineralogy, the reactive mineral assemblage was comprised of biotite (modally ≈ 5% host granite), chlorite, calcite, kaolinite and Fe-oxyhyroxide(s). The predictive results estimate a range of groundwater fluid compositions and mineral-water interactions (precipitation/ dissolution) affecting redox front migration. Results indicated that glacial recharge and groundwater mixing alone, without reaction with Fe-bearing minerals, would not effectively lower redox potential observed today at repository depths. While recognizing the role of reaction kinetics, groundwater residence times and exposed mineral surface area on the veracity of the modeling, the results nonetheless imply that alteration of biotite and chlorite may serve as a proxy for inferring the depth of penetration by low-salinity oxygenated glacial or meteoric recharge.

This and other paleohydrogeologic evidence for the evolution and rate of change in groundwater composition within the batholith are currently being investigated in subsequent studies as described below.

Paleohydrogeologic evidence for the evolution of fracture fluid compositions and depth of penetration by Pleistocene groundwater is being further examined in a WRA study of fracture infill mineralogy. The study has focused on the characterization of rock-water interactions, fracture infill mineralogy petrogenesis, mode of occurrence and isotopic compositions, as well as, limited fracture calcite fluid inclusion data to depths of 1 000 m. McMurry and Ejeckam (2002), describe a pattern of fracture mineralization correlated with depth, fracture age and degree of fracture infilling (i.e. open vs. closed). Evidence for redox reactions was explored, in part, through petrographic and microprobe analysis of fracture exposed biotite and chlorite grains. While it is evident that the minerals have been subject to rock-water interaction throughout the batholith, oxidation was only evident in shallow fractures at depths of 10-20 m below ground surface. Further catholuminence of fracture calcites, which occur within the upper 300 m of the flow domain, reveal complex growth morphology with at least two episodes of precipitation and dissolution. Stable isotopic ($\delta^{13}C$ and $\delta^{18}O$) data suggest that the calcites are ancient and of hydrothermal origin. A few rare data on calcite fluid inclusions suggest that mineral growth occurred initially from brines (200 g/l) and then from less saline (70-100 g/l) waters. This evidence is inconsistent with non-secular U-series data for the same calcites, which suggest precipitation occurred in the latter half of the Pleistocene.

Work related to the Paleohydrogeologic study of the WRA continues on another key issue: the time period over which hydrogeochemical conditions in the shallow WRA (<300 m) flow system evolved from saline to present-day brackish cold-climate signature waters. The stable isotope data are indicative of periods beyond 10^7 years while the U-series disequilibrium is suggestive of time periods on the order 10^5 years. Regardless, paleohydrogeologic evidence when coupled with WRA hydrogeochemistry implies the possibility of a deep sluggish or stagnant flow system isolated from an active near surface regime (Gascoyne, 2000). By extension, it follows that oxygenated surface waters have not penetrated to depths below several hundred meters within the WRA setting. This hypothesis is, in part, being examined through a numerical modeling approach intent on coupling simulations of long-term climate change, Laurentide ice-sheet migration and variably dense groundwater flow in a discretely fractured type Shield setting. A 3-dimensional deterministic and stochastic modeling approach has been adopted that will explore the sensitivity and robustness of flow system predictions related to: i) complex discrete fracture network geometry and interconnectivity; ii) spatially correlated permeability fields in matrix and fracture continua; iii) boundary conditions as affected by long-term climate change (i.e. glaciation); iv) topographic vs. density gradients and v) dimensionality. A further description is provided below.

Numerical methods – regional flow system analysis

Numerical simulations are being performed at regional (1 000 km^2) and local (100 km^2) scales as part of a Third Case Study (TCS) intent on updating and illustrating aspects of post-closure safety associated with the DGR concept (Sykes, 2002). The selected regional flow domain is an anonymous 5 734 km^2 watershed site on the Canadian Shield with total relief varying 130 m. Enclosed within this regional watershed is the local scale flow domain, approximately 90 km^2 in area that was selected for the purpose of siting a hypothetical TCS repository. Within the local flow domain a complex, 3-dimensional geostatistical Discrete Fracture Network (DFN) model, honoring spatial and geometric field observation, has been embedded (Srivastava, 2002a,b). This DFN has been incorporated into a Local scale flow model using the software FRAC3DVS (HydroSphere). The modelling further incorporated a GIS framework that included digital elevation maps and a surface hydrology model.

At the regional scale, a 1.5 million grid block, 1.5 km deep spatial domain is being used to explore the sensitivity of flow to topography, variable fracture and matrix permeability distribution models, pore water salinity and glaciation. Preliminary transient analyses provide evidence of a deep seated flow system in which low topographic gradients and relatively low permeabilities (10^{-17} to 10^{-19} m^2) coupled with saline pore water create a sluggish groundwater flow system in which transport may be dominated by diffusion. Further simulations with the discrete fracture dual continuum code FRAC3DVS at the local scale are being pursued to reveal the importance of structural discontinuity geometry, permeability distributions and nature of interconnections on predictive flow estimates and consistency in interpretation with paleohydrogeologic findings.

Within the 2003 DGRTP work program, the revised Laurentide ice-sheet model will be coupled with the aforementioned groundwater flow simulations at regional and local scales. Initially, this work will focus on the influence of hydraulic and temperature related processes and mechanisms with efforts later expanded to address mass transport. The intent is that results of the modeling program will complement existing program literature by providing insight into the temporal and spatial aspects of flow system dynamics and evolution in complex Shield settings. This insight will prove useful in providing guidance to develop site characterization strategies for collection and synthesis of geoscientific data to support the repository Safety Case.

Summary

Within the Deep Geologic Repository Technology Program (DGRTP) several Geoscience activities are focused on advancing the understanding of groundwater flow system evolution and geochemical stability in a Shield setting as affected by long-term climate change. A key aspect is developing confidence in predictions of groundwater flow patterns and residence times as they relate to the safety of a Deep Geologic Repository for used nuclear fuel waste. A specific focus in this regard has been placed on constraining redox stability and groundwater flow system dynamics during the Pleistocene. Attempts are being made to achieve this through a coordinated multi-disciplinary approach intent on; i) demonstrating coincidence between independent geoscientific data; ii) improving the traceability of geoscientific data and its interpretation within a conceptual descriptive model(s); iii) improving upon methods to assess and demonstrate robustness in flow domain prediction(s) given inherent flow domain uncertainties (i.e. spatial chemical/physical property distributions; boundary conditions) in time and space; and iv) improving awareness amongst geoscientists as to the utility various geoscientific data in supporting a repository safety case.

Coordinated by the DGRTP, elements of this program include the development of a climate driven Laurentide ice-sheet model to constrain the understanding of time rate of change in boundary conditions most affecting the groundwater flow domain and its evolution. Further work has involved supporting WRA Paleohydrogeologic studies in which constrained thermodynamic analyses coupled with field studies to characterize the paragenesis of fracture infill mineralogy are providing evidence to premise understandings of possible depth of penetration by oxygenated glacial recharge. In parallel, numerical simulations have been undertaken to illustrate aspect of groundwater flow system stability and evolution in a Shield setting. Such simulations, performed using the code FRAC3DVS (HydroSphere) are focused on assessing the uncertainty and robustness of predictions for groundwater migration based on fracture network geometry and interconnectivity, flow system dimensionality, spatially variable and correlated permeability fields, topography, salinity and long-term climate change. Work in this regard is proceeding toward coupling site-specific glacial and hydrogeologic numerical models and the inclusion of geologically reasoned Discrete Fracture Network models derived from geostatistical methods that honour fracture statistics and location. This multi-disciplinary approach is yielding an improved geoscientific basis to convey a sense of understanding in Shield groundwater flow system evolution and stability as affected by climate change.

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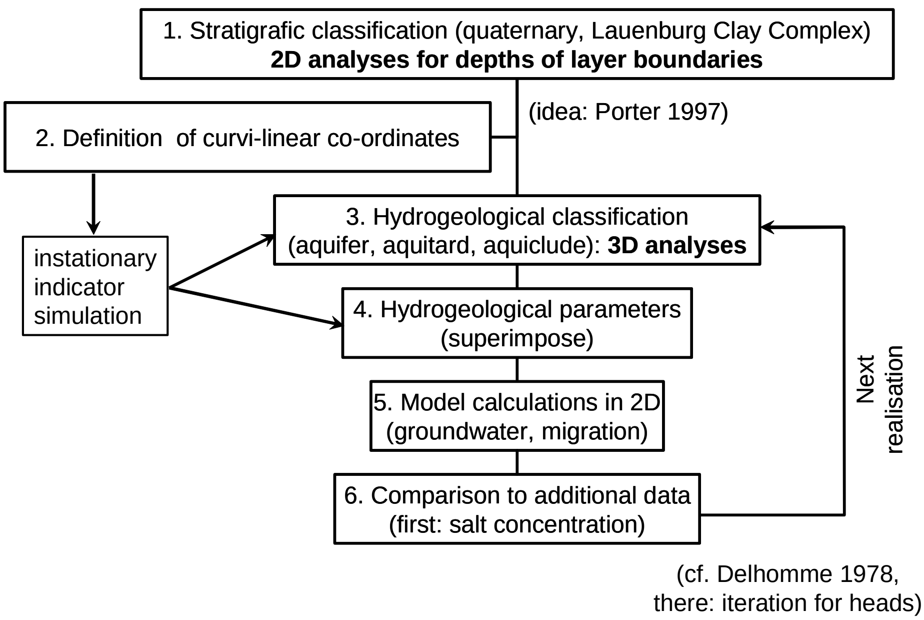
POSTER SESSION

USE OF STRATIGRAPHIC, PETROGRAPHIC, HYDROGEOLOGIC AND GEOCHEMICAL INFORMATION FOR HYDROGEOLOGIC MODELLING BASED ON GEOSTATISTICAL SIMULATION

Klaus-Jürgen Röhlig, Heidemarie Fischer and Brigitta Pöltl
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) Köln, Germany

This paper describes the stepwise utilization of geologic information from various sources for the construction of hydrogeological models of a sedimentary site by means of geostatistical simulation. It presents a practical application of aquifer characterisation by firstly simulating hydrogeological units and then the hydrogeological parameters. Due to the availability of a large amount of hydrogeological, geophysical and other data and information, the Gorleben site (Northern Germany) has been used for a case study in order to demonstrate the approach. The study, which has not yet been completed, tries to incorporate as much as possible of the available information and to characterise the remaining uncertainties. The approach consists of the following steps (Figure 1):

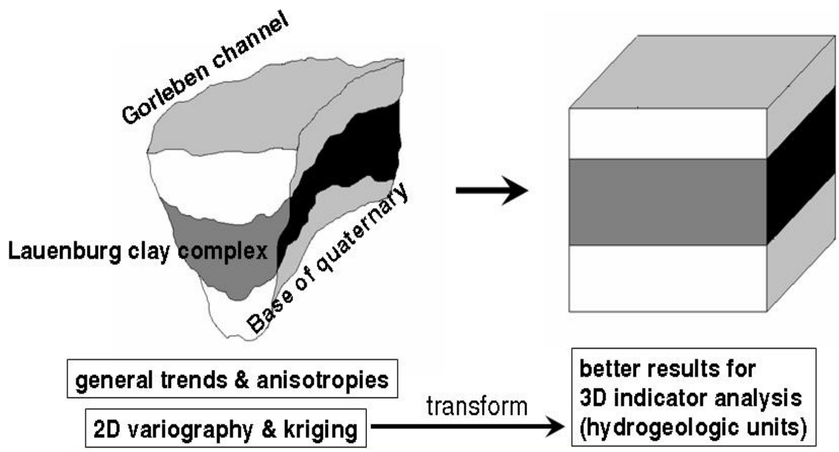
Figure 1. **Stepwise approach for the integration of information**



- In order to identify trends and anisotropies, a preliminary two-dimensional analysis of borehole data has been performed. The total thicknesses of *petrographic* and *stratigraphic* units, the portions of units in relation to the borehole lengths, and the depths of the upper and lower boundaries of units have been analysed as functions of two variables (easting and northing). The analysis included uni- and bivariate statistics, variography, and kriging.

- Developing ideas of Porter & Hartley (1997), a curvi-linear co-ordinate system has been defined as follows: The boundaries of the outcrop of the Gorleben Erosion Channel were transformed into surfaces of constant co-ordinate values for the "horizontal" co-ordinate. Kriging results for lower and the upper boundaries of stratigraphic units have been assumed to be surfaces of constant co-ordinate values for the "vertical" co-ordinate (Figure 2).

Figure 2. **Definition of curvi-linear co-ordinates**



- Using the curvi-linear system described above, variography and non-stationary conditional simulation of categorical variables characterising 3 hydrogeological units (aquifer, aquitard, aquiclude) were carried out (Figure 3, centre). The *hydrogeological classification* (Ludwig & Kösters, 2002) of borehole data served for conditioning. Compared to Cartesian co-ordinates, the curvi-linear co-ordinates allow a better fitting of variogram models and the simulation results coincide much better with the *hydrogeological site interpretation*.

- The only available data concerning *hydrogeological parameters* are bandwidths for each hydrogeological unit. Therefore, no direct variography, kriging, or conditioned simulation is possible for these data. Instead, varying assumptions have been made concerning the spatial continuity of parameters: Non-conditional simulation for parameters has been carried out and the results were superimposed on the ones for categorical variables (Figure 3, bottom).

- The obtained three-dimensional hydrogeological models were used for groundwater (freshwater) flow and contaminant migration calculations based on a vertical-plane (two-dimensional) cross section through the Gorleben channel which is regarded to be representative of the groundwater flow in this area (Figure 3, top). Probabilistic uncertainty analyses were carried out for performance measures like groundwater travel times and contaminant fluxes. In addition, a method to localise regional sensitivities for variables varying with position has been developed and tested.

- Presently, the simulation results are compared with other site-specific, namely *geochemical* information. In order to do so, it is of importance to replace the freshwater models mentioned above by density-dependent groundwater flow models because the groundwater density which depends on the salt content is an important feature for the groundwater movement. This will allow to compare the calculated salinity profiles and groundwater travel times with salinity profiles and groundwater ages measured on site (Figure 4) and thus to evaluate the results of geostatistical simulation and select the appropriate ones in an iterative process as recommended by Delhomme (1979).

In its present stage, the study has demonstrated that geostatistical analyses are promising as a first step towards an integrated assessment of the hydrogeological features of repository sites covered or surrounded by sedimentary systems. Plausible hydrogeological models consistent with the information used could be derived. The groundwater and contaminant migration calculations performed using these models can be fitted in the frame of probabilistic safety assessments and support the arguments used in a Safety Case. It has been shown how such analyses can contribute to a consistent treatment of uncertainties coming from spatial variability and lack of knowledge in safety assessments. This holds especially for sites like Gorleben where detailed data are given at a high density. However, the methods used strongly depend on the specific site under consideration. A "generic" approach or methodology will hardly be achievable.

Figure 3. **Representative cross section used for groundwater and migration calculations: Hydrogeological interpretation (top, modified from Schelkes *et al.*, 1990), conditional simulation of categorical variables (center), and conductivity distribution (bottom)**

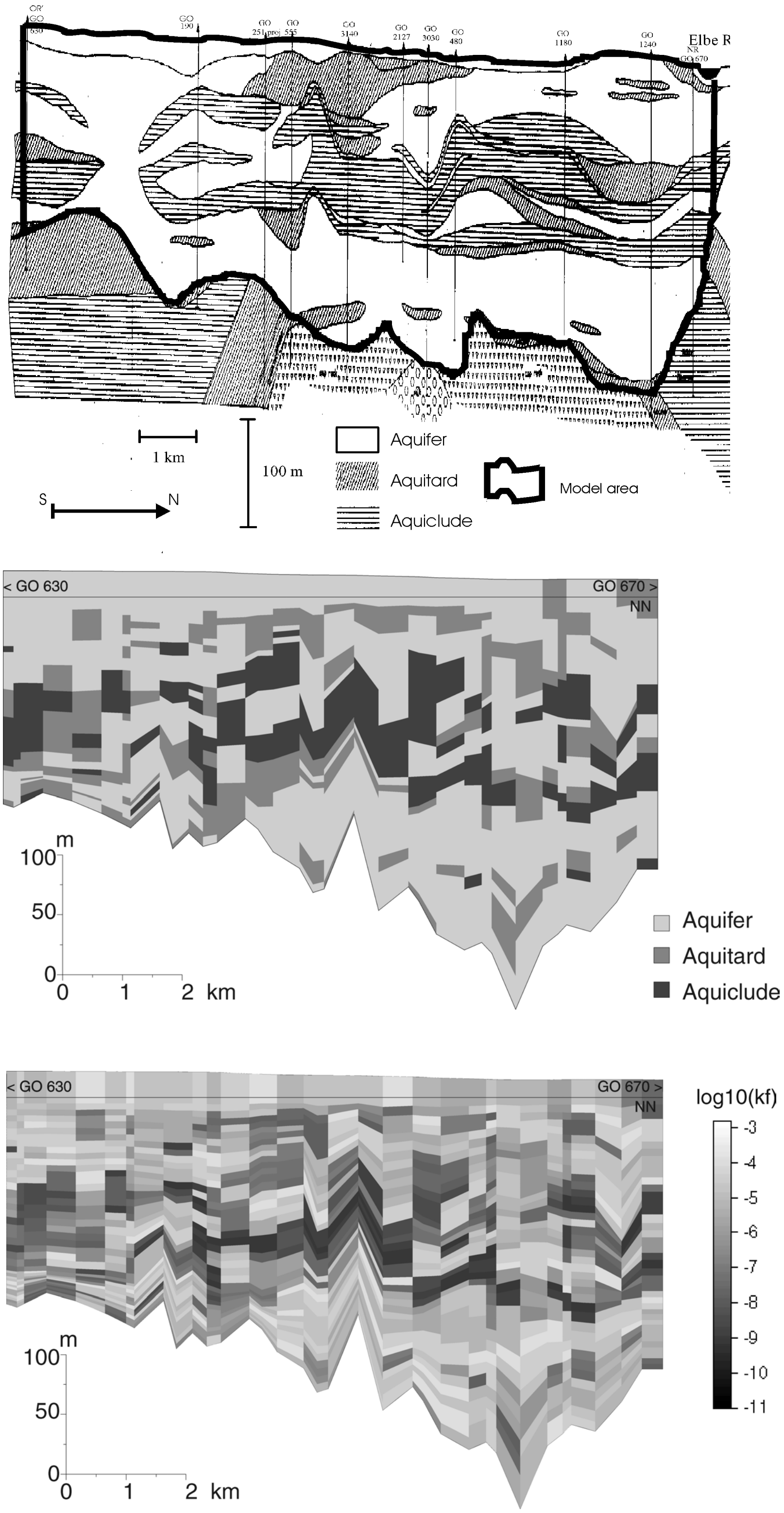
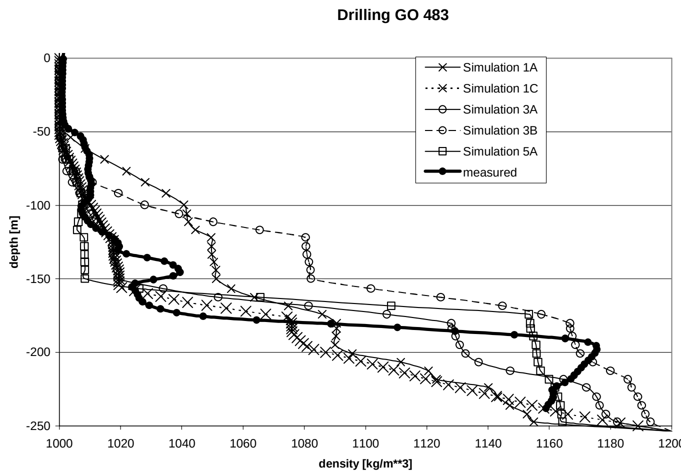


Figure 4. **Density profiles: measured values *versus* results calculated for several realisation**s



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INTEGRATION OF GEOLOGICAL INFORMATION IN A STRUCTURED APPROACH TO DEVELOPMENT OF A SAFETY CASE

Hiroyuki Umeki, Toshihiro Seo, Hiroyuki Tsuchi
Nuclear Waste Management Organization of Japan (NUMO)
Hiroyasu Takase and Richard Metcalfe
Quintessa Japan

1. Background

The Specified Radioactive Waste Final Disposal Act, promulgated in June 2000, specifies that the siting process for a high-level radioactive waste (HLW) repository in Japan shall consist of the following three stages:

- In the first stage, a literature survey is conducted on a nation-wide scale. Preliminary investigation areas (PIAs) for potential candidate sites are then nominated, based on area-specific literature surveys focusing on the long-term stability of the geological environment;
- Detailed investigation areas (DIAs) for candidate sites are then selected from PIAs following surface-based investigations (including boreholes) carried out to evaluate the key characteristics of the geological environment;
- In the final third stage, detailed site characterisation, including studies in underground experimental facilities, leads to selection of the site for repository construction.

Following discussions with relevant Government and nuclear industry organisations, the Nuclear Waste Management Organization of Japan (NUMO) has decided to proceed with repository siting based entirely on an "open solicitation procedure" (a call for volunteer host municipalities). NUMO promotes public involvement in decision making in the process of selecting sites, based on its basic policies, which consist of "adopting of a stepwise approach", "respecting voluntarism of municipalities" and "ensuring transparency". This volunteering process provides a unique challenge for ensuring transparency and traceability in development of conceptual site models which form a basis for repository concepts and associated safety cases in parallel with the step-wise siting process. A structured approach, therefore, is required to meet this target, which has been discussed partly in the light of development of Repository Concepts for given siting environments [1]. The Siting Factors for selection of PIAs has also been developed [2]. This paper illustrates a methodology for integrating geological information into the conceptual site models to be used in the structured approach.

2. Use of geological information in constructing the safety case

The safety case relies partly on the geological environment's stability and the long time scale associated with flow and transport through the geosphere. A conceptual site model integrates numerous types of information into an internally consistent understanding of these features. The model then rationalises quantitative safety analyses and develops complementary, often qualitative, arguments that support the safety case. A systematic treatment is required to integrate all the relevant geological information to form a representation of the geological environment and its evolution. Additionally it is needed to evaluate the confidence in a particular conceptual model by testing it against varied geological evidence. As a contribution to meeting these goals, one approach would be to devise a numerical model hierarchy to be applied in performance assessment and to appropriately structure the information flow to and among these models. However some information contained in the conceptual model does not contribute explicitly to numerical model development but still provides an important basis for constraining estimates of geosphere performance, thereby strengthening the safety case. Therefore, a more generic methodology is desirable, which can:

- structure multiple lines of reasoning behind a conceptual site model derived from varied multi-disciplinary information;
- evaluate confidence in a conceptual model by assessing the level of support gained by a variety of geological evidence that is often incomplete, imprecise or even contradictory;
- expedite communicating confidence and understanding about long-term geosphere performance and stability among experts in the relevant fields;
- support planning future site characterisation by propagating uncertainties in individual pieces of evidence and evaluating the relative importance of uncertainties through sensitivity analyses.

The approach illustrated here is based on Evidential Support Logic (ESL) [3], which is a generic mathematical concept based on evidence theory and consists of the following key components.

Process model

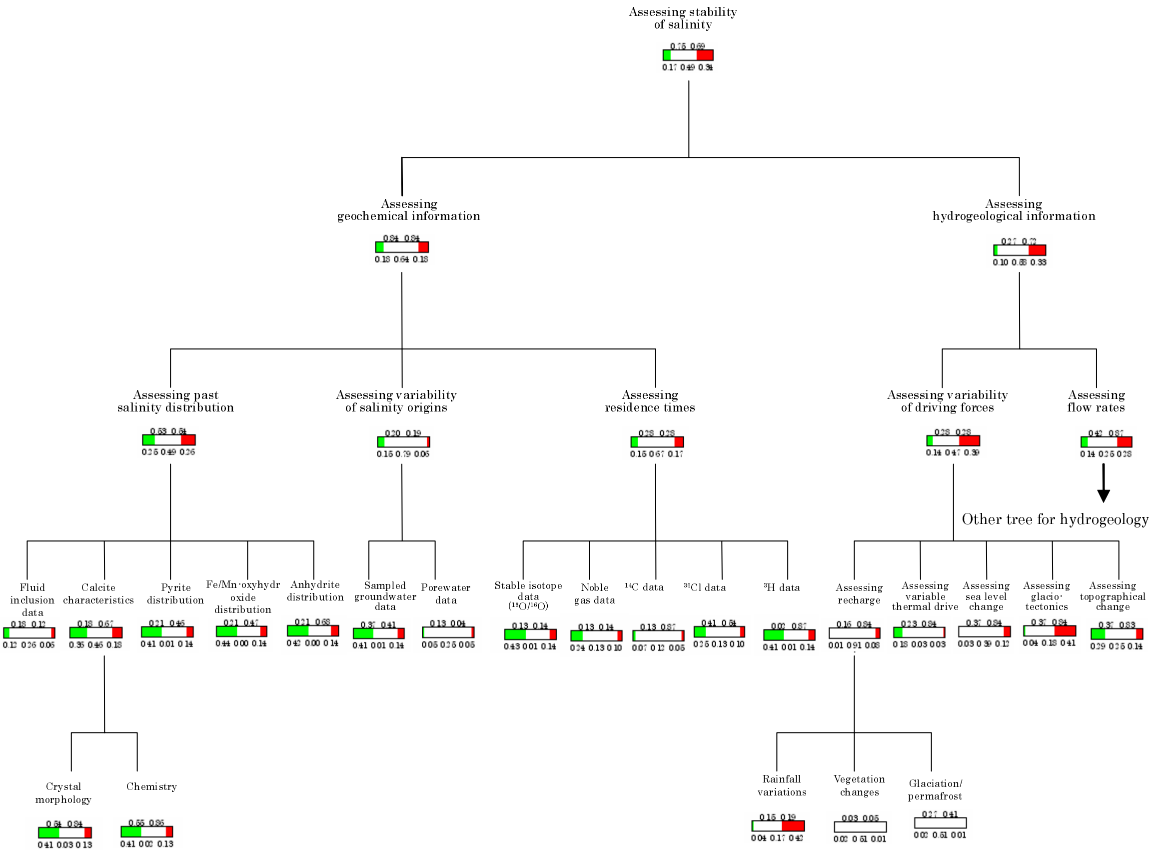
Suppose a proposition is formed by integrating and interpreting a number of information items from different sources. The first task of ESL is to unfold this proposition by constructing a process model. The "top" proposition is subdivided iteratively to form an inverted tree-like structure, with propositions at each lower level corresponding to supporting interpretations. The subdivision is continued until the original information is reached. A process model resembles an information flow sheet used in Geosynthesis [4]. However, an important difference is that a process model emphasises the logical structure's description, i.e., "how the top proposition is logically supported by the lower-level propositions and, ultimately, by the evidence at the time".

Evaluation of confidence using the Interval Probability Theory

After constructing the process model, confidence in the top proposition is evaluated. The degree of confidence in the support for each lowest-level proposition from corresponding information (i.e. evidence) is estimated and propagated through the process model using simple arithmetic (see Appendix).

Figure 1 illustrates an example process model to evaluate the degree of confidence that a variety of evidence from a hypothetical site supports stability of a saline-fresh water interface that occurs there.

Figure 1. **Example of a process model constructed to evaluate degree of confidence in stability of the current saline-fresh water interface**



2. Communication and forward planning

The process model represents a logical structure that supports a conceptual site model, or its components, based upon available geological information. The degrees of confidence that the propositions at various levels are supported by evidence illustrate how uncertainties of various (multi-disciplinary) origins are propagated through the process model. Thus, use of ESL could increase the transparency and traceability of the underlying reasoning behind a conceptual site model. In turn this increase in clarity would expedite the communication of confidence and understanding of the geological environment and its evolution. In addition to this, a "ratio plot" (Figure 2) can be used to summarise and compare confidence in a number of competing conceptual model options. The *y*-axis of the ratio plot is $\log\left[p/q\right]$ and the *x*-axis is *u*, where *p* (*q*) is the minimum degree of confidence that the model option is supported (not supported) and *u* is uncertainty associated with the evaluation. Hence a model option with stronger relative support ($\log\left[p/q\right]$) and one with greater uncertainty correspond to larger *y*- and *x*-coordinates respectively. By locating the competing model options in the ratio-plot, their characteristics can be summarised graphically and compared.

Construction of the process model and evaluation of confidence should be carried out iteratively as the siting process proceeds. To support planning of the next stage of site characterisation, it is useful to classify the importance of different types of evidence by sensitivity analyses. In the case of ESL, this can be done by calculating the reduction in the uncertainty associated with the top proposition, assuming that uncertainty in each piece of evidence vanishes in turn (Figure 3). The results of the analysis can then be used as an input to prioritise further data acquisition.

Figure 2. **Example of a "Ratio plot"**

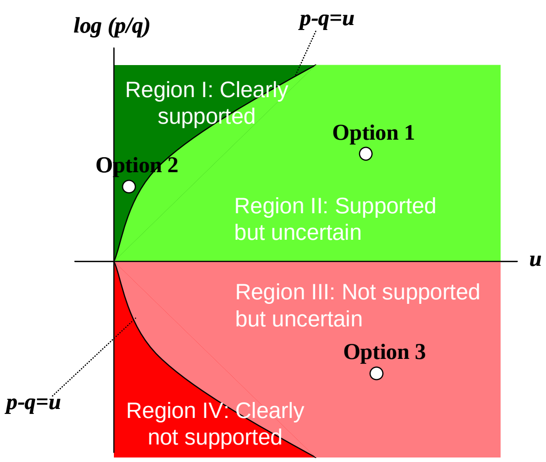
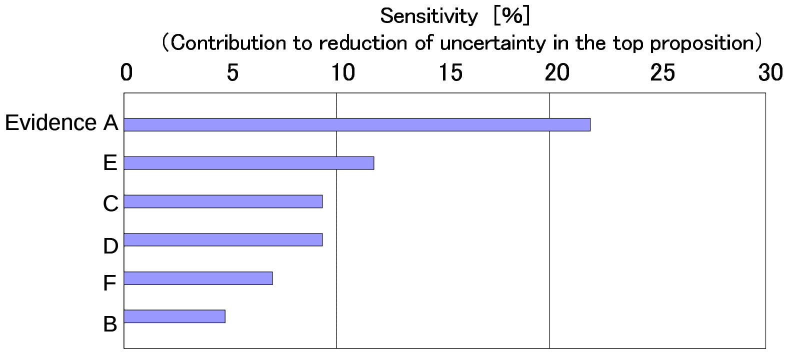


Figure 3. **Example of sensitivity analysis**



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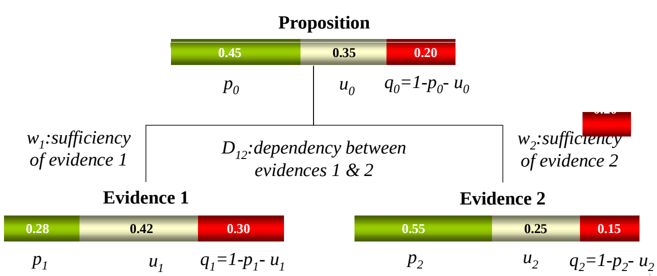
Appendix

The degree of confidence that some evidence supports a proposition can be expressed as a subjective probability. However, since evidence concerning a complex system is often incomplete and/or imprecise, it may be inappropriate to use the classical (point) probability theory. This theory cannot account for uncertainty in an actual evaluation of support, because if some evidence supports a proposition with probability *p*, the probability against the proposition is automatically *1-p*. For this reason ESL uses the Interval Probability Theory, which allows us to say "degree of confidence that evidence supports the proposition lies between *p* and *p+u*". In this case, degree of confidence that evidence does not support the proposition is between *1-p-u* and *1-p*. Hence we have (Figure A):

- minimum degree of confidence that some evidence supports the proposition is *p*;
- minimum degree of confidence that some evidence does not support the proposition is *1-p-u*;
- uncertainty is *u*.

The arithmetic to propagate degrees of confidence upward through the process model is depicted in Figure A, where "sufficiency" of an individual piece of evidence or lower level proposition can be regarded as the corresponding conditional probability. That is, "sufficiency" is the probability of the higher level proposition being true provided each piece of evidence or lower level proposition is true. A parameter called "dependency" is introduced to avoid double counting of support from any mutually dependent pieces of evidence.

Figure A. **Evaluation of confidence using Interval Probability Theory**



$$p_0 = w_1 \; p_1 + w_2 \; p_2 - \rho_{12} Min(w_1 \; p_1 \; , w_2 \; p_2)$$

$$q_0 = w_1 \; q_1 + w_2 \; q_2 - \rho_{12} Min(w_1 \; q_1 \; , w_2 \; q_2)$$

where $\rho_{12} = \frac{(1-D_{12})(w_1 \; p_1 \; w_2 \; p_2)}{Min(w_1 \; p_1 \; , w_2 \; p_2)} + D_{12}$

THE 2002 DRIGG POST-CLOSURE SAFETY CASE: IMPLEMENTATION OF A MULTIPLE FACTOR SAFETY CASE

C.B. Lean, P.D. Grimwood, L. Watts, L. Fowler, G. Thomson*, E. Kelly and D. Hodgkinson#
British Nuclear Fuels Plc, United Kingdom.
(* now at Enviros; # at Quintessa)

Introduction

British Nuclear Fuels plc (BNFL) owns and operates the Drigg disposal site, which is the UK's principal facility for the disposal of low level radioactive waste (LLW). Disposals are carried out under the terms of an authorisation granted by the UK Environment Agency (the Agency). The Agency periodically reviews the authorisation to take account of new information and any revisions to regulatory requirements. In September 2002 new Operational Environmental and Post-Closure Safety Cases (OESC and PCSC respectively) were submitted to the Agency to support the next authorisation review. The OESC [1] assesses radiological safety aspects up until closure of the site, including a post-operational management phase, whilst the PCSC [2] considers the longer-term radiological safety.

The Drigg disposal facility has been operational since 1959 (Figure 1). For the first 3 decades of operations, disposals were solely by tumble tipping wastes into excavated trenches. This was phased out in favour of vault disposal (Figure 2) and disposals to the trenches were completed in 1995. The first vault (Vault 8) commenced operations in 1988 and construction of future vaults is planned up to the estimated end of disposal operations in about 50 years time.

This paper describes the main components of the 2002 Drigg PCSC and how they relate to each other. Central to the safety case is a systematic comprehensive post-closure radiological safety assessment (PCRSA). However, the importance of the more qualitative aspects of the safety case, including a demonstration of optimisation, is also highlighted [3,4,5]. In addition, other confidence-building activities which are key to developing and presenting the safety case are discussed.

Figure 1. **Aerial photograph of the Drigg site (viewed from north-west to south-east)**

4673-004

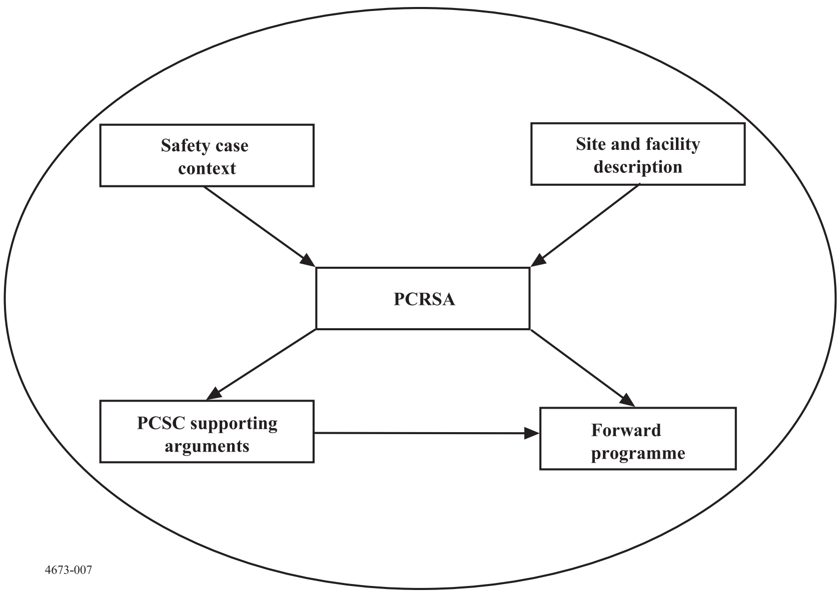
Figure 2. **Waste containers in Vault 8**

4601-024

Safety case approach

Implementation of the PCSC approach is set out in terms of a multiple factor safety case. This approach is consistent with regulatory guidance which states that a PCSC should be based on multiple and complementary lines of reasoning [3]. The PCSC is described in terms of five basic inter-related components (safety case context, site and facility description, PCRSA, supporting arguments and forward programme), all of which play an important role in making the overall safety case (Figure 3). Although the PCRSA lies at the heart of the safety case, the other components have an important role to play in making the complete safety case. For example, the site and facility description is important in that it demonstrates a comprehensive and detailed understanding of the disposal system and hence that the PCSC is based on good science and engineering.

Figure 3. T**he basic components of the 2002 Drigg PCSC**



PCRSA

The 2002 Drigg PCRSA approach has been developed to provide a logical and systematic methodology that is geared towards fulfilling regulatory expectations and that is in line with international best practice. A systematic approach, based on the IAEA ISAM approach, is important to build confidence in the use of output from the assessment to inform decision making. The main components are:

- identification of the context and other basic premises underlying the PCRSA (for example, the assessment purpose, regulatory requirements, assumptions relating to site characteristics, endpoints, timescales and spatial domain);
- identification of scenarios (broad descriptions of the evolution of the disposal system and its surroundings from the time of site closure as a result of natural, human-induced, waste-related and engineering-related events and processes) for assessment that are relevant to the evaluation of safety performance;

- description and analysis of the Process System (that is, the engineered disposal system and that part of its environment relevant to the determination of assessment endpoints), including a systematic assessment of all relevant features, events and processes (FEPs) associated with the Process System and external to it;
- implementation of the assessment models involving model runs, supporting calculations and qualitative analysis; and
- feedback of results and key factors related to safety performance to the PCSC and forward programme.

Three scenarios were adopted to provide alternative descriptions of the anticipated evolution of the Drigg Process System: the Central Projection scenario, which addresses climate and landscape change; future human actions; and natural disruptive events. Within each scenario, a number of variants were assessed, selected to address uncertainty within each scenario. Model runs were undertaken for a main simulation in which cautiously realistic conceptual models and parameter values were used. Conceptual model and parameter uncertainty were addressed through a range of deterministic sensitivity analyses. The approach to the development of these calculation cases is based on rigorous and formal methods to demonstrate systematic consideration of all relevant FEPs (both associated with, and external to, the Process System) and uncertainties.

Additional components of the PCSC

These aspects of the safety case were included to build confidence and put the PCRSA results into context to aid an informed decision-making process; that is, to use multiple and complementary lines of reasoning to build a robust safety case which is logical and transparent to informed stakeholders.

PCSC Context

The safety case context, which is the set of high level objectives, constraints and assumptions that set the overall context for the PCSC, addresses stakeholders, regulatory requirements, site context, international context, timescales, societal assumptions and financial aspects. All these aspects are considered important to enable a judgement on whether the PCSC is reasonable and acceptable.

Disposal of LLW at the Drigg site is in line with international guidance and best practice, including guidance from the IAEA that wastes suitable for disposal in near-surface disposal facilities are those containing short-lived radionuclides and low concentrations of long-lived radionuclides. Furthermore, LLW disposal at the Drigg site conforms to UK Government policy, which is to ensure that radioactive wastes are not unnecessarily created; that any wastes are "*safely and appropriately managed and treated*"; and that they are "*disposed of safely, at the appropriate times and in appropriate way*" [6]. Government also intends to safeguard existing and future generations, and the wider environment, and as such requires that wastes are managed and disposed of "*in a manner that commands public confidence and takes due account of cost*". Continued disposal at the Drigg site is in the national strategic interest and is likely to remain so for some decades.

As a near-surface LLW disposal site the Drigg site is not unique internationally and, in common with the Drigg site, there has been a tendency in recent years for to encapsulate waste in concrete and steel, thereby enhancing its isolation for the present and future. The choice of near-surface disposal allows the waste to be monitored with relative ease and leaves open the possibility to retrieve the waste, should this be required for any reason.

The Drigg site operates according to the polluter pays principle and, since 1989, disposal costs have included full allowance for all aspects of the management and closure of the site. This has had a positive influence in reducing the amounts of waste sent to the Drigg site for disposal. The costs of disposal to the Drigg site are comparable with those of similar international facilities. Financial provisions are made for all developments through to assumed site closure, based on the site development programme plus an additional contingency allowance.

All operations at the Drigg site involving radiological protection are carried out in compliance with the regulations applicable at the time. Drigg has operated safety with minimal impact on people and the environment for more than 40 years. BNFL operates a comprehensive and independently audited Environmental, Health and Safety system to ensure that this remains the case in the future.

Stakeholder involvement

Regulators are recognised as key stakeholders for the Drigg PCSC and since 1996, BNFL and the Agency have been involved in an information exchange process on the development of the technical work leading to the 2002 Drigg PCSC. This process was important to enable the regulator to build confidence that the planned safety case would be in line with regulatory requirements and that work was progressing to programme and to enable BNFL to ensure that the programme of work would meet regulatory expectations. A key part of the exchange process was the publication of the Status Report [7] to provide a detailed public statement on the intended approach for the 2002 PCSC and summarise progress to date. Both the Status Report and the Agency's review of the Status Report [8] have been placed in the public domain and formed important inputs to the 2002 PCSC.

BNFL participates in meetings with relevant stakeholders at local, national and international levels, including the Sellafield Local Liaison Committee, the UK Radioactive Waste Management Advisory Committee and the IAEA, and to respond to any queries. The Drigg authorisation review process is also open to public scrutiny and, following a review of the 2002 PCSC, the Agency plans to initiate a period of public consultation on the Drigg authorisation. It is considered that the open and transparent process being followed for the Drigg authorisation review, with opportunities for stakeholder dialogue and public consultation, will assist with regard to public acceptability.

Confidence-building

The approach to the PCSC is based on good science and engineering. Key elements of this include a systematic PCRSA, an appropriate and effective QA system and confidence building activities, such as peer review and participation in international collaborative programmes.

The disposal system including the vaults and final cap are being constructed from tried and tested materials using technologies that are widely used in civil engineering. A monitoring programme is planned for these new constructions, which is aimed at building confidence in the site's long-term performance and impact. Model and monitoring data comparisons have been undertaken [9].

Attendance of international conferences on radioactive waste disposal and safety assessment has allowed BNFL to maintain awareness of current best practice and future trends from other countries and raise awareness of the Drigg PCSC by giving oral and poster presentations. A policy of publishing Drigg-related material in open literature has also allowed feedback from experienced and knowledgeable professionals. Participation in relevant international collaborative programmes, such as the IAEA ISAM and BIOMASS programmes and the NEA IGSC programme, has also enabled raising awareness of the Drigg programme.

Multiple lines of confidence

The Drigg disposal system incorporates multiple barriers that may act in isolation or have a cumulative effect. However, because of the limited longevity of near-surface engineered barriers and the uncertainty and possible large impact of surface environmental processes (for example, climate and sea level change), the long-term safety case is founded on the low concentrations of radionuclides in LLW rather than the multi-barrier concept. Furthermore, a significant portion of the waste disposed of at the Drigg site has a relatively short half-life. The total activity is predicted to fall to approximately 6% of the activity of the disposed inventory in the trenches and Vault 8 and to approximately 12% of the activity of the disposed inventory in the future vaults within 500 years post-closure. During this time engineering measures for final site closure should remain largely intact.

Confidence in the PCSC and the PCRSA analyses is founded on an in-depth consideration of uncertainties, which is the key driver behind the systematic approach. The safety case for the Drigg site takes account of uncertainties through their systematic identification, evaluation and, where appropriate, quantification and via measures to reduce the overall uncertainty in the conclusions that can be drawn from the PCRSA.

Optimisation will be a key input into the decision making process on the Drigg authorisation. The optimisation studies within the PCSC are focussed towards assessment of the performance of the Drigg site closure engineering design and the future radiological capacity (disposals are planned to continue until approximately 2050). This approach has been used to identify risk management measures which have the potential to significantly influence risk.

Use of natural analogues

Natural evidence can be brought to bear to increase confidence that the processes included in PCRSA models and the results of modelling exercises are plausible, for example to access radionuclide mobility from near-surface uranium deposits and to compare the effect of human intrusion into such deposits with intrusion into the Drigg facility. With this aim, the BNFL geochemical modelling code (GRM) has been used successfully in simulating uranium transport and geochemical evolution of part of the Savannah River site [2].

Concentrations of uranium within the Drigg facility are comparable to those found in near-surface uranium deposits. Thus events that severely disrupt the disposal facility are likely to give rise to similar doses to those arising from the mining of such deposits. Ranges of uranium concentrations in soil and groundwater calculated in the 2002 PCRSA are generally lower than background concentrations in Cumbria and are significantly lower than environmental concentrations in the vicinity of near-surface uranium deposits. The ranges of indoor and outdoor radon concentrations calculated in the PCRSA are significantly lower than background concentrations in Cumbria.

Concluding remarks

The results of the 2002 Drigg PCSC are presented in [2] and references therein. The PCSC is currently under review by the Agency, prior to the Drigg site authorisation review which is expected in 2004.

Some of the key issues identified in the PCSC are also being taken further as part of a forward programme of technical work.

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DEVELOPMENT OF JNC GEOLOGICAL DISPOSAL TECHNICAL INFORMATION INTEGRATION SYSTEM – AN APPROACH TO INTEGRATE AND SHARE TECHNICAL INFORMATION AMONG PERFORMANCE ASSESSMENT, REPOSITORY DESIGN AND SITE INVESTIGATION

Masahiro Uchida, Hitoshi Makino, Keiichiro Wakasugi and Katsushi Shibata
Japan Nuclear Cycle Development Institute (JNC)

Introduction

This paper presents a current status of development of "JNC Geological Disposal Technical Information Integration System (JGIS)" which aims to facilitate integration and sharing of technical information among Site Investigation (SI), Repository Design (RD) and Performance Assessment (PA) teams. SI, RD and PA are inter-independent and should strongly interact to optimize each activity. SI, in particular, needs to provide basic information for all activities. However, it is not always easy to strongly interact because geological disposal requires the integration of disciplines that are highly complicated and wide-ranging. It is also difficult to understand the entire scope of activities and to correlate one's own work with the needs of other disciplines. This difficulty increases as the site investigation proceeds and more information becomes available.

JNC is developing two underground research laboratories, one in crystalline rock and the other in Tertiary sedimentary rock. RD methods and PA methods will be developed and demonstrated using these two URLs. Starting in 2001, JNC initiated the development of JGIS to activate interaction within and among each team. JGIS is an archive system of technical information in which a relational database is constructed to record, catalogue, and manage technical information in the structure of a flow chart, which systematically represents SI activities, RD activities and PA activities. JGIS facilitates the sharing of information between users and provides for up-to-date checks on the status of each activity. It also helps RD and PA to maintain traceability and consistency as well as assure quality. Thus, the system supports the integration of these three teams and facilitates the iterative SI, RD and PA processes. JNC is planning to complete the development of the initial version of the system by March 2004 and to start using it for the JNC project thereafter.

Outline of JGIS

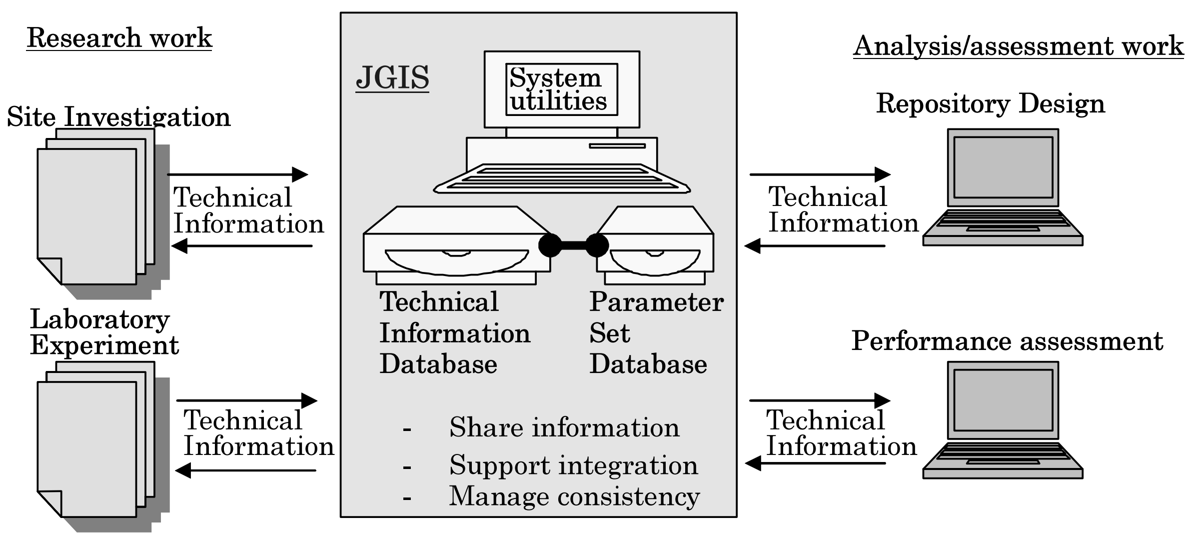
Technical information that is targeted for JGIS is:

- Data from investigations or experiments.
- Work procedures, description of implemented work (such as how data was interpreted, judgment made in work procedures, and others).
- Determined data, analyzed results of codes outside the *JGIS* system.
- Property information (date, name etc.), QA information, and others.

JGIS is a computer-aided system, which comprises the relational database and system utilities (Figure 1). The database further comprises the "*Technical information database*" and the "*Parameter set database*".

Major features are described below.

Figure 1. **Basic concept of JGIS**



Main system functions

- To manage Technical information at three hierarchical levels; the Plan level (Figure 2) as the highest level, the Task level (Figure 3), and the Work level as the lowest.
  1) Plan level: definition of objectives, strategy and the tasks/works to achieve the objectives;
  2) Task level: a group of works necessary for implementing the plan; e.g. construction of alternative hydrostructure models; and
  3) Work level: i.e., each work that comprises the task.

Figure 2. **Screen image of plan definition**

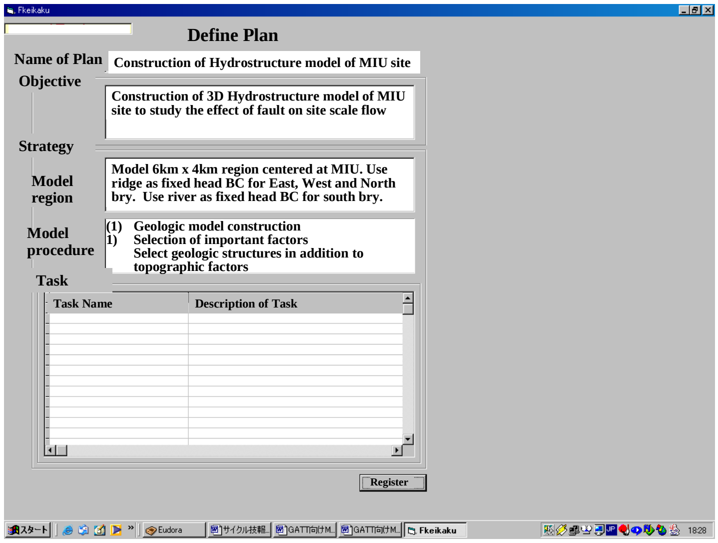
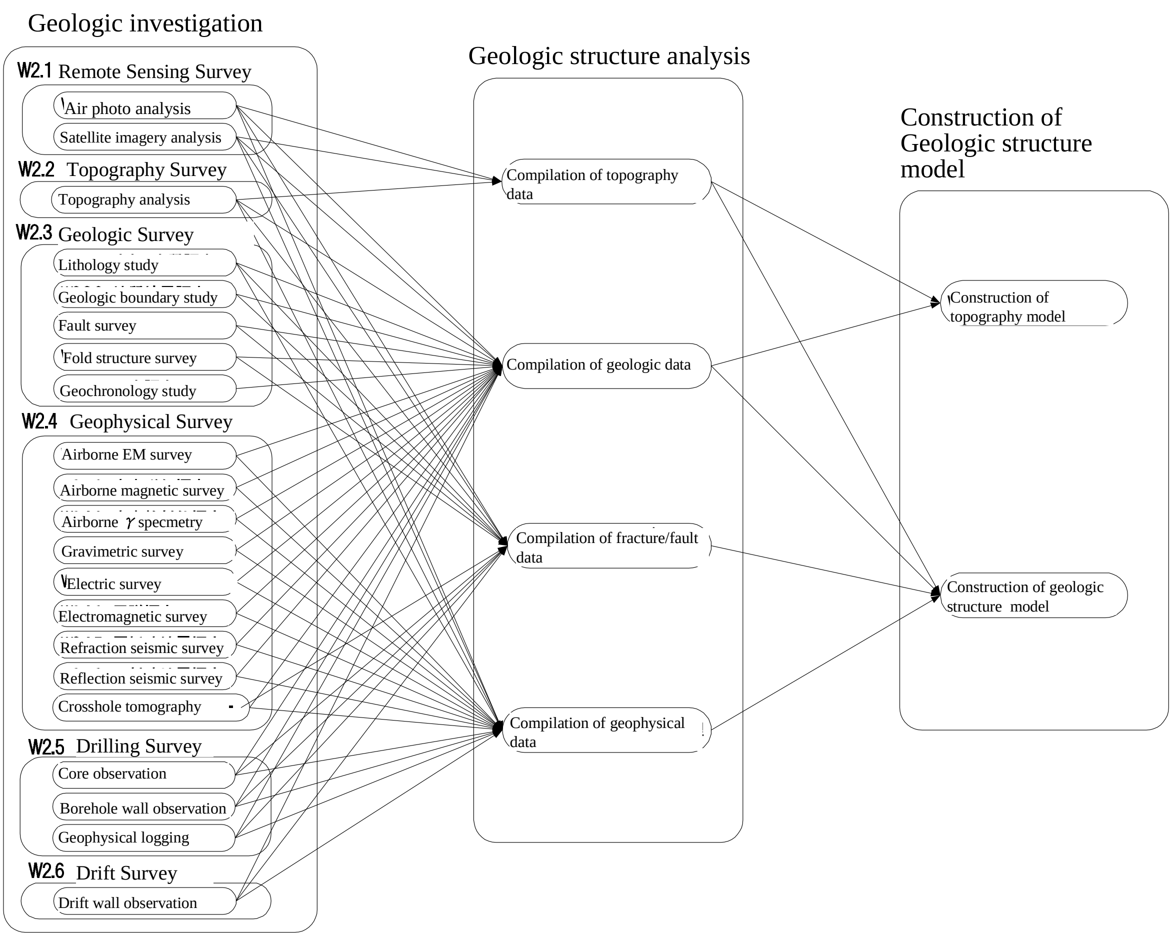
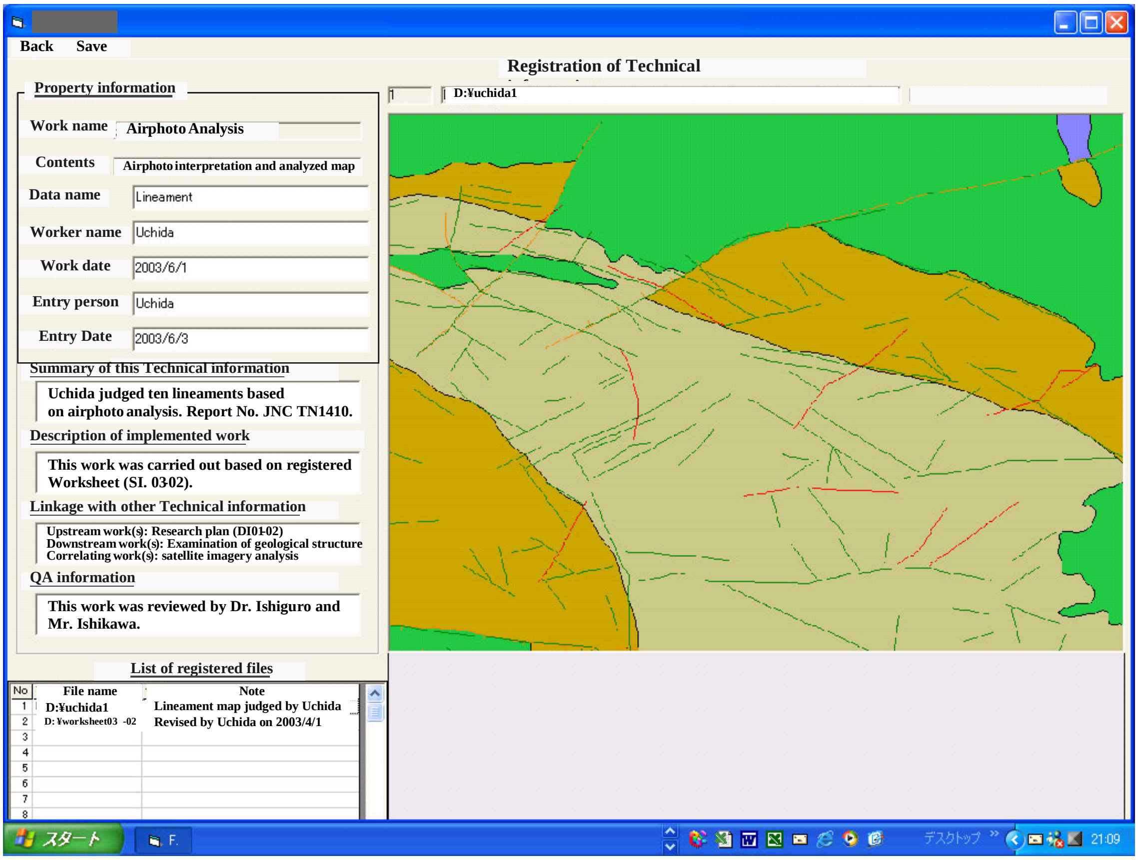


Figure 3. **Screen image of task definition**



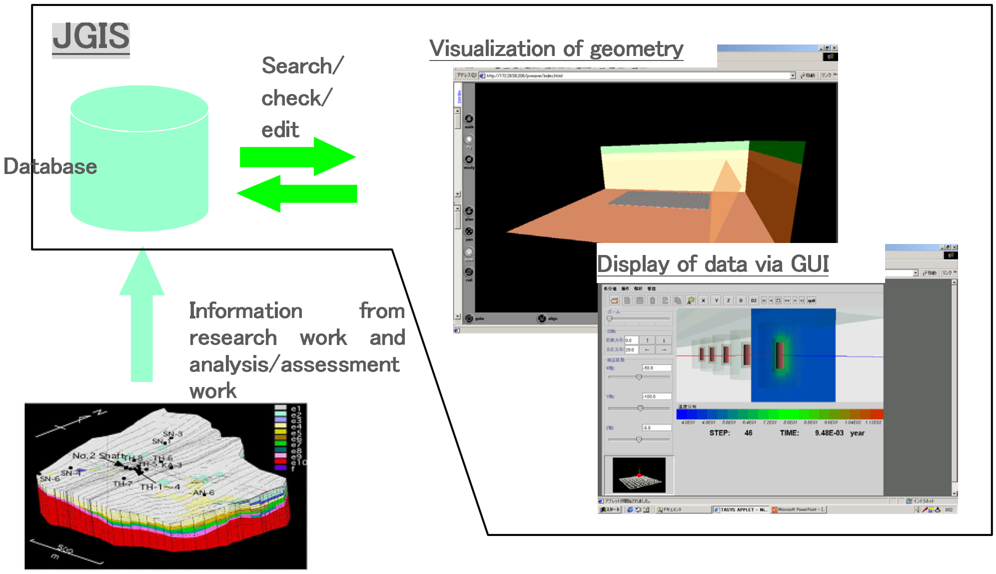
- To record the history of registration or of updates (in whole or in part) of Technical information for each work.
- To record and catalogue Technical information from research work and analysis/assessment work in the form of text, figures and tables (Figure 4).

Figure 4. **Screen image of work definition**



- To maintain traceability by recording, as linkages, how Technical information is shared or exchanged among related works (e.g. determined data, analyzed results).
- To inform selected users who are potentially affected by updated data and/or newly recorded data.
- To visualize information in order to facilitate understanding of the status of the work.
- To record and catalogue determined parameter values as a parameter set(s) to facilitate use in later assessment work.
- To prepare input data for PA calculations using the parameter set(s).
- To search/check/edit the registered Technical information and parameter set(s) by key words or other indices via a Graphical User Interface (GUI: Figure 5).
- To allow various users in different offices to access JGIS via local area network.

Figure 5. **Screen images of JGIS**



Technical information database

The *Technical information database* is the core of JGIS. It contains the Technical information on each hierarchical level of SI, RD and PA, and all the steps from data acquisition to analysis/assessment. Information for each step includes judgment, analysis/evaluation, or experiment/observation as well as input, output, constraining conditions and resources (analysis codes and others) (Figure 6). A note and remark for each step is prepared describing the general work procedure.

In the *Technical information database*, technical information is organized in two systematic flow charts; one as, "*Work flow*" and the other as "*Process and property flow*" (Figure 6). The "*Work flow*" shows the general sequence of the work, whereas the "*Process and property flow*" describes the relationship of assessment elements (such as FEP). These flow charts can be viewed in JGIS to meet the needs of the following three user categories;

a) Site investigators/laboratory researchers/modelers who need to:

- Store and utilize information obtained from SI or the laboratory.
- Collect and register the data.
- Assure the quality (traceability) of the data.

- Understand the upstream/downstream activities and information of the user's activities (e.g. It will help a site investigator to understand how the data are used in a downstream modeling activity, or a modeler to understand the status of an upstream data collection activity.).
- Understand how the data/results are used in RD and PA.

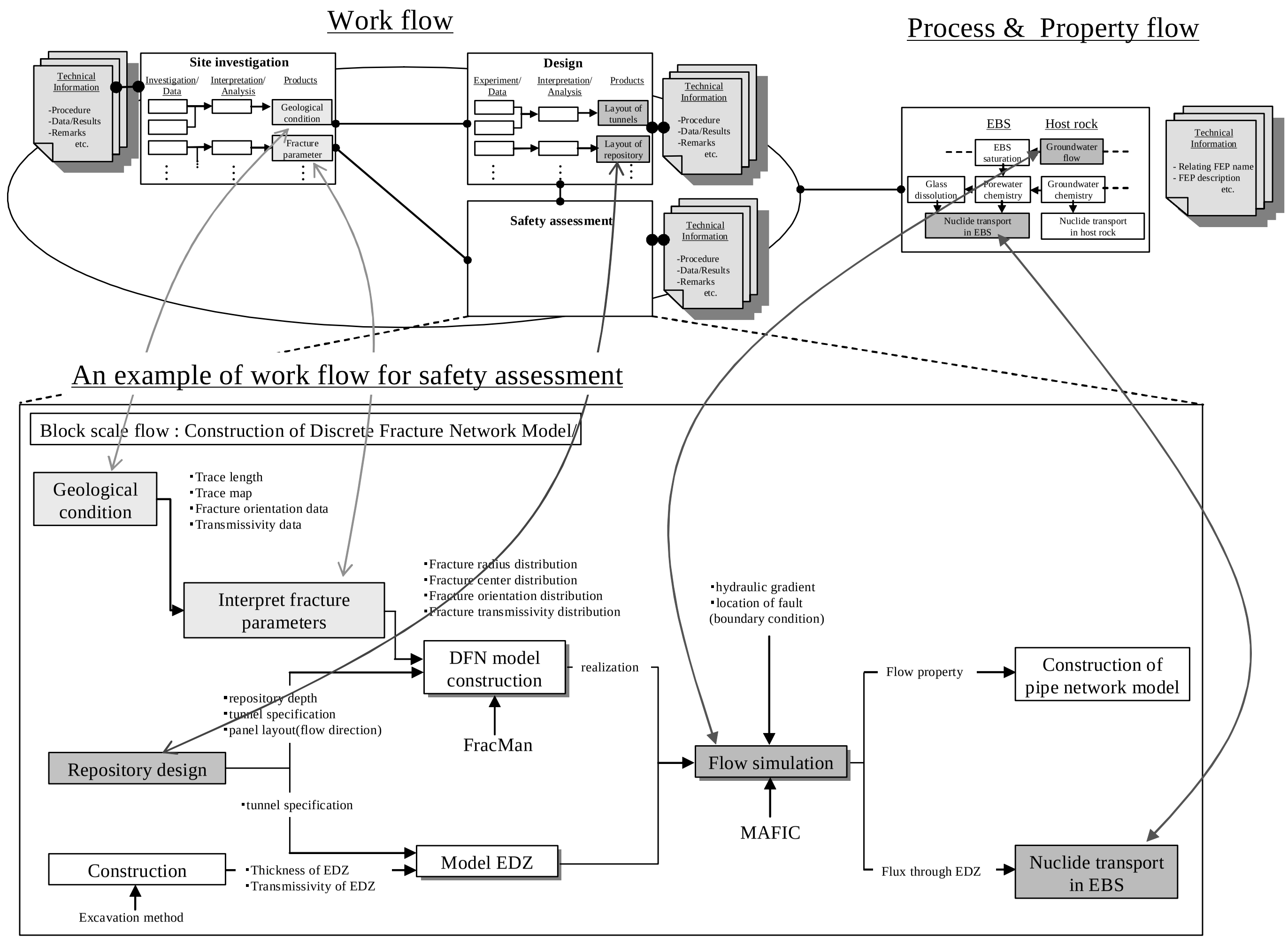
b) Performance assessors/those integrating the results who need to:

- Store and utilize the information related to RD and PA.
- Conduct PA/evaluation using data from research activities.
- Understand the upstream/downstream of the user's activities.
- Judge the consistency and the traceability of the data.

c) Project managers who need:

- To understand the status of whole projects and each activity.
- To identify the problem/issues.
- To prioritize activities.

Figure 6. **Flow structures in Technical information database (an example of flows relating to block scale flow modelling)**



To meet the need for user category “a),” the “*Work flow*” is suitable, whereas the “*Process and property flow*” is suitable for user category “b)”. Both flow charts are required for user category “c),” project managers. Both flow charts were created based on the H12 Report[1]. The “*Work flow*” for the Hydrology model was compared with the actual regional scale flow modeling of the Mizunami Underground Research Laboratory.

However, these flow charts should be regarded as a working hypothesis and are not possible to fix at this point, since one of the research objectives is the development of the flow charts. Therefore, efforts will be made to maintain flexibility of these flow charts in the system.

Parameter set database

The *Parameter set database* accommodates summarized and updated parameters from the *Technical information database* for use in RD and PA. Again, efforts will be made to maintain flexibility and future expandability of the system.

Conclusions

JNC is developing “JNC Geological Disposal Information Integration System (JGIS)” to facilitate interaction among Site Investigation, Repository Design and Performance Assessment teams via integration and sharing of Technical information. JGIS comprises the “*Technical information database*” and the “*Parameter set database*”. The main features of the “*Technical information database*” are the hierarchical levels of the work and the two flow charts; “*Work flow*” and “*Process and property flow*”. These flow charts are designed to meet the different demands and different patterns of access by each team, as well as by project managers. Flow charts are used to define general steps. One special interest is how these flow charts will be developed as the Site Investigations at the two URLs proceed and more information becomes available.

Reference

[1] Japan Nuclear Cycle Development Institute, H12 : Project to Establish the Scientific and Technical Basis for HLW Disposal in Japan, 1999, JNC TN1410 2000-001.

PART C

LIST OF PARTICIPANTS

BELGIUM

DIERCKX, Ann
NIRAS/ONDRAF
Avenue des Arts 14
1210 Bruxelles
Tel: +32 2 212 10 45
Fax: +32 2 218 51 65
Eml: a.dierckx@nirond.be

MAES, Norbert
CEN·SCK
Boeretang, 200
2400 Mol
Tel: +32 14 33 32 35
Fax: +32 14 33 35 53
Eml: nmaes@sckcen.be

MARIVOET, Jan
CEN·SCK
Boeretang, 200
2400 Mol
Tel: +32 (0) 14 333242
Fax: +32 (0) 14 323553
Eml: jmarivoe@sckcen.be

CANADA

GOODWIN, Bruce
Box 528
36 Grey Crescent
Pinawa, Manitoba, R0E 1L0
Tel: +1 204 753 83 93
Fax:
Eml: goodwinb@mts.net

JENSEN, Mark
Ontario Power Generation
700 University Ave, H16-E22
Toronto, Ontario, M5G 1X6
Tel: +1 416 592 8672
Fax: +1 416 592 7336
Eml: mark.jensen@opg.com

LEI, Shizhong
Wastes and Geosciences Division
Canadian Nuclear Safety Commission
P.O. Box 1046, Station B
280 Slater Street
Ottawa, Canada KIP 559
Tel: +1 (613) 943-1577
Fax: +1 (613) 995-5086
Eml: leis@cnsc-ccsn.gc.ca

CZECH REPUBLIC

NACHMILNER, Lumir
Head, Technical Development Department
RAWRA
Dlázdená 6
110 00 Praha 1
Tel: +420 2 214 215 19
Fax: +420 2 214 215 44
Eml: Nachmilner@rawra.cz

FINLAND

HAUTOJARVI, Aimo
POSIVA Oy
27160 Olkiluoto
Tel: +358 283723747
Fax: +358 28372 3709
Eml: aimo.hautojarvi@posiva.fi

HELLMUTH, Karl-Heinz
STUK
P.O. Box 268
00101 HELSINKI
Tel: + 358 9 75988307
Fax: + 358 9 75988670
Eml: karl-heinz.hellmuth@stuk.fi

FRANCE

BRUEL, Dominique
Centre d'Informatique Géologique
École des Mines de Paris
UMR7619 SISYPHE
35, rue St. Honoré
77300 Fontainebleau
Tel: +33 (0)1 64 69 47 54
Fax: +33 + 33 (0)1 64 69 47 03
Eml: dominique.bruel@ensmp.fr

BRUNO, Gerard (appologized)
IRSN
DES/SESID – BP 17
92262 Fontenay-aux-Roses Cedex
Tel: +33 1 46 54 77 55
Fax: +33 1 46 54 77 27
Eml: gerard.bruno@irsn.fr

DE MARSILY, Ghislain
Laboratoire de Géologie
Appliquée, B 123
Univ. Pierre et Marie Curie
4 Place Jussieu
75252 Paris Cedex 05
Tel: +33 44 27 51 26
Fax: +33 44 27 51 25
Eml: gdm@ccr.jussieu.fr

GRIFFAULT, Lise
ANDRA
1-7, rue Jean Monnet
92298 Chatenay-Malabry Cedex
Tel: +33 1 46 11 82 96
Fax: +33 1 46 11 80 63
Eml: lise.griffault@andra.fr

LANDAIS, Patrick
ANDRA
1/7, rue Jean-Monnet
92298 Chatenay-Malabry Cedex
Tel: +33 1 46 11 81 39
Fax: +33 1 46 11 84 10
Eml: Patrick.Landais@andra.fr

LEBON, Patrick
ANDRA
1-7 rue Jean Monnet
92298 Chatenay-Malabry Cedex
Tel: +33 1 46 11 80 82
Fax: +33 1 46 11 84 10
Eml: patrick.lebon@andra.fr

MOUCHE, Emmanuel
Laboratoire des Sciences du Climat
et de l'Environnement
Unité Mixte de Recherche CEA-CNRS (UMR 15)
C.E. de Saclay
91191 Gif sur Yvette Cedex
Tel: +33 1 69 08 22 54
Fax: +33 1 69 08 77 16
Eml: emmanuel.mouche@cea.fr

VIOLETTE, Sophie
Université Pierre et Marie Curie
UMF-Sisyphe, 26-0 E.5 case 123
4, Place Jussieu
75252 Paris Cedex 05
Tel: +33 (0)1 44 27 51 30
Fax: +33 (0)1 44 27 51 25
Eml: sophie.violette@ccr.jussieu.fr

GERMANY

BESENECKER, H
Niedersaechsisches Umweltminsterium
Archivstrasse, 2
30169 Hannover
Tel:+49(0)511 120 3611
Fax: +49(0)511 120 99 3611
Eml:Horst.Besenecker@mu.niedersachsen.de

BRENNECKE, Peter.
Bundesamt für Strahlenschutz
Postfach 10 01 49
38201 Salzgitter
Tel: +49(0) 1888 333 1900
Fax: +49(0) 1888 333 1605
Eml: pbrennecke@bfs.de

HERBERT, Horst-Juergen
Gesellschaft fuer Anlagen und Reaktorsicherheit (GRS) mbH
Bereich Endlagersicherheitsforschung
Theodor Heuss Strasse 4
38122 Braunschweig
Tel: +49 (531) 8012 250
Fax: +49 (531) 8012 200
Eml: her@grs.de

LARUE, Peter Jurgen
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH
Schwertnergasse 1
50667 Köln
Tel: +49 (0) 221 2068 791
Fax: +49 (0) 221 2068 939
Eml: lar@grs.de

RÖHLIG, Klaus-Juergen
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH
Schwertnergasse 1
50667 Köln
Tel: +49(0)221 2068 796
Fax: +49(0)221 2068 939
Eml: rkj@grs.de

SCHELKES, Klaus
Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)
Stilleweg 2
30655 Hannover
Tel: +49 511 643 2616
Fax: +49 511 643 3611
Eml: k.schelkes@bgr.de

WOLLRATH, Jurgen
Bundesamt für Strahlenschutz(Bfs)
Postfach 10 01 49
38201 Salzgitter
Tel: +49 (0)1888 333 1964
Fax: +49 (0)1888 333 1605
Eml: JWollrath@BfS.de

JAPAN

SEO, Toshihiro
NUMO
4-1-23 Shiba, Minato-ku
Tokyo 108 0014
Tel: +81 3 4513 1553
Fax: +81 3 4513 1599
Eml: tseo@numo.or.jp

UCHIDA, Masahiro
JNC
4-33 Muramatsu, Tokai-mura
Naka-jun, Ibaraki 319-1194
Tel: +81 29872 0928
Fax: +81 + 81 29282 9295
Eml: uchida@tockai.jnc.go.jp

UMEKI, Hiroyuki
NUMO
Mita NN Bldg., 1-23, Shiba 4-Chome, Minato-ku
Tokyo 108 0014
Tel: +81 (0)3 4513 1503
Fax: +81 (0)3 4513 1599
Eml: humeki@numo.or.jp

NORWAY

NADEAU, Paul H.
Global Exploration
STATOIL ASA
4035 Stavanger
Tel: +47 + 47 51 99 61 59
Fax: +47 + 47 51 99 00 50
Eml: pana@statoil.com

SPAIN

ASTUDILLO, Julio
ENRESA
Emilio Vargas 7
28043 Madrid
Tel: +34 91 566 8120
Fax: +34 91 566 8165
Eml: jasp@enresa.es

BRUNO, Jordi (appologized)
QuantiSci SL
Passeig de Rubi, 29-31
08197 Valldoreix (Barcelona)
Tel: +34 935 830 500
Fax: +34 935 890 091
Eml: jbruno@enviros.biz

GIL DE MINGO, Roberto
Nuclear Safety Council
C/Justo Dorado 11
28040 Madrid
Tel: +34 91 3460649
Fax: +34 91 3460588
Eml: rgm@csn.es

MAYOR, Juan Carlos
ENRESA
Emilio Vargas, 7
28043 Madrid
Tel: +34 91 5668217
Fax: +34 91 5668165
Eml: jmaz@enresa.es

SWEDEN

ANDERSSON, Johan
JA Streamflow AB
Box 181
125 24 Alvsjo
Tel: +46 (0)70 622 21 32
Fax:
Eml: johan.andersson@streamflow.se

SELROOS, Jan-Olof
SKB
Box 5864
102 40 Stockholm
Tel: +46 8 459 8425
Fax: +46 8 661 5719
Eml: jan-olof.selroos@skb.se

STIGSSON, Martin
SKB
Box 5864
102 40 Stockholm
Tel: + 46 8 459 84 54
Fax: + 46 8 459 84 65
Eml: martin.stigsson@skb.se

SWITZERLAND

BITTERLI, Peter
HSK
Swiss Federal Nuclear Safety Inspectorate
5232 Villigen-HSK
Tel: +41 56 3103992
Fax: +41 56 3103907
Eml: bitterli@hsk.psi.ch

DIAMOND, Larryn
Rock Water Interaction
Institute of Geological Sciences
University of Bern
Baltzerstrasse 1
30012 Bern
Tel: +41 + 41 31 631 87 81
Fax: +41 + 41 31 631 48 43
Eml: diamond@geo.unibe.ch

FRANK, Erik
HSK
Swiss Federal Nuclear Safety Inspectorate
5232 Villigen-HSK
Tel: +41 (56) 310 39 45
Fax: +41 (56) 310 39 07
Eml: erik.frank@hsk.psi.ch

GAUTSCHI, Andreas
NAGRA
Hardstrasse 73
5430 Wettingen
Tel: +41 (0) 56 437 12 38
Fax: +41 (0) 56 437 13 17
Eml: gautschi@nagra.ch

MARSCHALL, Paul
NAGRA
Hardstrasse, 73
5430 Wettingen
Tel: +41 (0) 56 437 13 30
Fax: +41 (0) 56 437 13 17
Eml:marschall@nagra.ch

MAZUREK, Martin
Rock/Water Interaction Group
Institute of Geological Sciences
University of Bern
Baltzerstr.1
Bern
Tel: +41 (0)31 631 87 81
Fax: +41 (0)31 631 48 43
Eml: mazurek@geo.unibe.ch

SCHNEIDER, Jürg
NAGRA
Hardstrasse 73
5430 Wettingen
Tel: +41 (56) 437 13 02
Fax: +41 (56) 437 13 17
Eml: schneider@nagra.ch

VIGFUSSON, Johannes O.
Section for Transport and Waste Management
HSK – Swiss Federal Nuclear Safety Inspectorate
5232 Villigen HSK
Tel: +41(0)56 310 3974
Fax: +41 (0)56 310 3907
Eml: johannes.vigfusson@hsk.psi.ch

WABER, Niklaus
RWI, Inst. Geological Science
University of Bern
Baltzerstrasse, 1
Bern
Tel: +41 + 41 31 631 85 20
Fax: +41 + 41 31 631 48 43
Eml: nick@geo.unibe.ch

ZUIDEMA, Piet
NAGRA
Hardstrasse 73
5430 Wettingen
Tel: +41(56)4371287
Fax: +41(56)4371317
Eml: zuidema@nagra.ch

UNITED KINGDOM

LEAN, Candida
BNFL
Rutherford House
Risley, Warrington, Cheshire,WA3 6AS
Tel: + 44 (0) 1925 836780
Fax: + 44 (0) 1925 833561
Eml: candida.lean@bnfl.com

NORRIS, Simon
UK Nirex Ltd
Curie Avenue,
Harwell, Didcot, Oxfordshire OX11 ORH
Tel: +44 (0) 1235 825310
Fax: +44 (0) 1235 820560
Eml: simon.norris@nirex.co.uk

SMITH, Paul
Safety Assessment Management Ltd
Flat 2F
20 Manor Place
Edinburgh EH3 7DS
Tel: +44 131 226 6255
Fax:
Eml: paul@sam-ltd.com

UNITED STATES OF AMERICA

BEAUHEIM, Richard L (Apologized)
Sandia National Laboratories
4100 National Parks Highway
Carlsbad, NM, 88220
Tel: +1 505 234 0006
Fax: +1 505 234 0061
Eml: rlbeauh@sandia.gov

YOSE, Lyndon
ExxonMobil
Upstream Research Company
14111 Carolcrest Circle
Houston, Texas 77079
Tel: +1 281 654 6460
Fax: +1 713 431 6166
Eml: lyndon.a.yose@exxonmobil.com

INTERNATIONAL ORGANISATION

VOINIS, Sylvie
OECD/NEA
Radiation Protection and Waste Management
Le Seine St. Germain
12, Boulevard des Iles
92130 Issy-les-Moulineaux
France
Tel: +330145241049
Fax: +33 1 45241145
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