Radioactive Waste Management

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Safety of Disposal of Spent Fuel, HLW and Long-lived ILW in Switzerland

An international peer review of the post-closure radiological safety assessment for disposal in the Opalinus Clay of the Zürcher Weinland

NEA No. 5568

NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

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FOREWORD

An international peer review has been carried out of a post-closure radiological safety assessment prepared by Nagra for geological disposal of spent fuel (SF), vitrified high-level waste (HLW) and long-lived intermediate-level waste (ILW) within the Opalinus Clay of the Zürcher Weinland in northern Switzerland. Nagra's safety assessment was undertaken as part of the *Entsorgungsnachweis* project, which is concerned with the siting, engineering and safety feasibility of geological disposal in Switzerland. The NEA organised the review after receiving a request from the Swiss Federal Office of Energy (BfE).

This report presents the consensus view of the International Review Team (IRT). The IRT was made up of nine internationally recognised specialists, including two members of the NEA Secretariat. The experts were chosen to bring complementary expertise to the review. The main objective of the review was to provide an independent evaluation, from an international standpoint, of the quality of the post-closure radiological safety assessment presented by Nagra. The main focus of the review was the Safety Report (Nagra Report NTB 02-05). The IRT has based its findings and recommendations on the information presented in the Safety Report and many supporting documents, the written responses provided by Nagra to written questions posed by the IRT, and face-to-face discussions with Nagra staff at two meetings, one of which included a tour of the Mont Terri underground research laboratory (URL).

In carrying out its review, the IRT took account of the fact that the *Entsorgungsnachweis* project is only one stage in a stepwise decision-making process, and that the decisions to site and then construct a repository still lie far in the future.

In keeping with NEA procedures for independent reviews, Nagra has only had the opportunity to check the final draft of the report for factual correctness. The IRT has made its best efforts to ensure that all information is accurate and takes responsibility for any factual inaccuracies.

ACKNOWLEDGEMENTS

All the members of the IRT would like to thank Nagra for the open and helpful way they responded to the review, the excellent organisational support, and hospitality, which facilitated the work of the IRT. The IRT also appreciated the opportunity to visit the underground facility at Mont Terri.

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SUMMARY

Introduction

An international peer review has been carried out of a post-closure radiological safety assessment prepared by the Swiss National Cooperative for the Disposal of Radioactive Waste (Nagra) for geological disposal of spent fuel (SF), vitrified high-level waste (HLW) and long-lived intermediate-level waste (ILW) within the Opalinus Clay of the Zürcher Weinland in northern Switzerland. Nagra's safety assessment was undertaken as part of the *Entsorgungsnachweis* project, which is concerned with siting, engineering and safety feasibility of geological disposal in Switzerland. The NEA organised the review after receiving a request from the Swiss Federal Office of Energy (BFE).

This review is the outcome of the work of an international review team (IRT) of nine members carried out over a period of about seven months. The main objective of the review is to provide an independent evaluation, from an international standpoint, of the quality of the post-closure radiological safety assessment presented by Nagra. The main focus of the review is the Safety Report (Nagra Report NTB 02-05). The IRT has based its findings and recommendations on information presented in the Safety Report and many supporting documents, the written responses provided by Nagra to written questions posed by the IRT and face-to-face discussions with Nagra staff at two meetings, one of which included a tour of the Mont Terri underground research laboratory (URL).

In carrying out its review, the IRT took account of the fact that the *Entsorgungsnachweis* project is only one stage in a stepwise process and that the decisions to site and then construct a repository are still far in the future.

Key observations

On the Safety Report Overall

The IRT is impressed by the overall strength and quality of the safety case prepared by Nagra for disposal of SF, HLW and long-lived ILW in the

Opalinus Clay of the Zürcher Weinland. The IRT finds that, in general, the safety case rests on a foundation of sound science that incorporates an appropriate balance of quantitative and qualitative evidence. In a number of areas the science incorporated into the safety case is at the leading edge of the state-of-the-art, e.g. geochemistry, spent fuel dissolution. The relevant phenomena and scientific reasoning incorporated into the safety case are, in general, well described in the underlying documents.

In the Safety Report, Nagra explicitly and clearly sets out the objectives and principles related to:

1. Geological disposal in general.
2. The stepwise repository implementation process.
3. Safety functions of the disposal system.
4. The means of achieving overall safety and robustness.
5. Repository siting, design and implementation.
6. Safety assessment and its documentation.

These objectives and principles reflect Nagra's commitment to implement disposal in a manner that is flexible, provides long-term safety and, at the same time, takes account of the needs and values of Swiss society.

On the Disposal Concept Proposed by Nagra

Nagra has assessed the safety of a disposal facility constructed in Opalinus Clay of the Zürcher Weinland at a depth of about 650 m below the surface. Passive safety is achieved through the use of multiple barriers designed to isolate the waste and to ensure that future radiological exposures from any radionuclides that are eventually released are below regulatory limits. The IRT notes that the use of multiple barriers is consistent with disposal concepts in other countries.

Implementation would follow a cautious, stepwise approach and, following waste emplacement, would involve an extended period of monitoring during which time retrieval of the waste would be relatively easy. As proposed by the Swiss government advisory group, EKRA, the facility would include a test facility and a pilot facility. Periodic reviews would be carried out that provide for possible reversal of decisions, including even the retrieval of emplaced wastes. The IRT finds that this approach is prudent and consistent with that followed in a number of other countries.

Waste would be placed in horizontal emplacement tunnels that would be sealed with bentonite following waste emplacement. Emplacement tunnels for

ILW would be separated from those used for the emplacement of SF and HLW to eliminate any unfavourable chemical or physical interactions. Similarly, different tunnels would be used for ILW – one for ILW wastes containing organic materials and the others for ILW wastes comprising inorganic materials. The IRT considers such separation of wastes to be a good safety practice.

Emplacement tunnels for HLW and SF would be excavated as needed, and backfilled and sealed concurrently with waste emplacement, so that a given tunnel would remain open for a maximum of two years. Once all waste had been emplaced in the main facility, the access ramp would remain open during an extended period of monitoring but the access tunnels and ventilation shaft would be sealed to ensure long-term passive safety, even in the event that closure of the access ramp did not eventually take place as foreseen. The impact of abandoning the repository without sealing the access routes has been evaluated in the safety assessment. The IRT finds that the waste emplacement strategy and the use of multiple seals to compartmentalise and isolate waste packages are feasible and prudent.

On Safety Assessment

The IRT finds that, from an overall perspective, Nagra has presented a sound and practical disposal concept based on a specific realisation of the multi-barrier concept. The safety assessment considers the relevant issues and uncertainties and demonstrates a sound understanding of overall system performance and the performance of the individual barriers. A useful combination of deterministic and probabilistic modelling is employed. The way that the system functions is clearly presented, through the analysis of its expected evolution, augmented by the use of insight models.

The FEP (Features, Events and Processes) management process has been used effectively to ensure that all relevant processes and phenomena have been considered in the safety analysis and, in doing so, Nagra has provided a convincing demonstration of the power of this tool. The IRT also notes that the introduction of the notion of so-called “reserve FEPs”, which can be mobilised in the future, is helpful and adds to confidence.

A wide range of uncertainties is considered through the analyses of well chosen assessment cases. Uncertainties are covered by varying parameter values, within their uncertainty bounds, and by modifying modelling assumptions. Although it cannot be absolutely proven that there are no remaining uncertainties that might somehow compromise safe system performance, Nagra argues convincingly that this is highly unlikely.

The IRT notes that, because of the very favourable properties of the Opalinus Clay, a wide range of uncertainties in the performance of the engineered barriers and of the waste forms can be tolerated without compromising the safety of a repository constructed in the Opalinus Clay. Nevertheless, the IRT encourages Nagra to retain the essential features of a robust system of engineered barriers and to continue to work to minimise uncertainties.

Nagra has also considered so-called "what if?" cases. These cases represent situations that are outside the range of possibilities supported by scientific evidence. The IRT notes that the "what-if?" cases presented by Nagra provide good complementary support to build confidence in the robustness of the safety case, and that regulators and members of the public are interested in such "what if?" cases. Their successful application is, to a large extent, dependent on the excellent retaining properties of the Opalinus Clay. This strengthens Nagra's safety case.

It is acknowledged by Nagra that the choice of "what if?" cases is subjective and hence somewhat arbitrary. Further, Nagra has stated that the "what if?" cases test the effects of perturbations to key properties of the "pillars of safety", but there is not a one-to-one correspondence between the "what if?" cases and the "pillars of safety." In the future, the IRT notes that it would be helpful if Nagra were to provide a clearer set of criteria for selecting such cases.

On the Opalinus Clay of the Zürcher Weinland

Safety of any multi-barrier system has to take into account the properties of the site and the design of the repository. Within this context, and given that Project *Entsorgungsnachweis* is dealing with the issue of siting feasibility, the IRT has taken particular interest in the work that Nagra has done to characterise the properties of the Opalinus Clay that are relevant to safety. The IRT recognises that the Swiss authorities will carry out a review of the geological knowledge of the site. The IRT has looked at the work done by Nagra in site characterisation from the viewpoint of the long-term safety case.

The IRT finds that Nagra has presented strong evidence, based on multiple arguments, that the Opalinus Clay of the Zürcher Weinland is a suitable host rock. It is a tight, self-sealing material that would provide strong isolation, retention, delay and dispersion of any radionuclides released from a disposal facility located in it. Natural analogue studies, laboratory and field experiments, as well as theoretical analyses, corroborate this.

The techniques and methodologies used by Nagra to characterise the geological setting and the properties of the Opalinus Clay of the Zürcher Weinland are consistent with accepted geological practice. The conclusions are supported by multiple lines of evidence as set out in the Geosynthesis Report (NTB 02-03) which is a key document supporting the safety case.

The IRT finds that the geometrical model of the Opalinus Clay of the Zürcher Weinland is well founded. From the evidence presented, the IRT finds it reasonable to treat the Opalinus Clay of the Zürcher Weinland as a homogeneous entity in the safety assessment. It is also reasonable to conclude that the safety relevant properties – determined from the Benken borehole and a large number of other investigations in Opalinus Clay, including studies of other deep boreholes and at the Mont Terri URL – can be extrapolated over a wide region.

Nagra has assessed the impact of gas released into the repository from the corrosion of iron and the decomposition of organic compounds present in some waste packages. The transport of gas out of the clay formation is one of the key issues for the disposal of waste in low permeability formations such as clay. The IRT notes that the processes governing gas migration in low permeability rocks are complex and that the mechanistic understanding of these processes is not yet fully mature. Nagra is aware of this and is contributing to developments in these areas with carefully selected and well-focused programmes, and is following developments in other radioactive waste management programmes and in relevant science, in general.

Significant improvements in understanding have been achieved by Nagra in recent years and the gas issue has been sufficiently addressed in the safety case for this stage of the project. Nagra is encouraged to continue ongoing theoretical and experimental investigations to improve the mechanistic understanding of gas transport processes.

The IRT considers that Nagra's programme on the retention properties of clay is at the leading edge and agrees that Nagra should continue this programme to increase understanding and reduce uncertainties in these properties for the Opalinus Clay and, also, for bentonite.

On the Engineered Barriers and Waste Forms for SF and HLW

The IRT notes that the engineered barrier system for geological disposal generally comprises a canister, a durable waste form and, usually, a buffer. The canisters for SF and HLW are designed to prevent radionuclide release for thousands of years. The waste form limits the rate of release of radionuclides once the canister is breached. The buffer material, with its sealing and retention properties, isolates the canisters from each other (compartmentalisation) and from the host rock. The IRT finds that:

- the disposal concept proposed by Nagra includes all these features;
- the designs of the steel canisters should provide absolute containment of radionuclides for at least 10 000 years, except possibly for a few canisters that may contain defects, e.g. welding defects;
- the copper canister represents a useful design alternative to the steel canister;
- SF and vitrified HLW are durable waste forms that will dissolve and release radionuclides very slowly (i.e. over periods of tens to hundreds of thousands of years or, in the case of SF, even longer) under the conditions expected to exist in the repository; and that
- in the Nagra design, the bentonite buffer, in addition to providing a favourable chemical environment, a strong isolation barrier and a heat transfer path, also provides a well understood mechanism (i.e. swelling force) for ensuring the self-sealing of the excavation disturbed zone surrounding the emplacement tunnels.

Spent fuel is the dominant contributor to the source term, comprising 85% of the total radioactivity in the repository. Nagra’s treatment is consistent with the approach taken internationally: i.e. two components are analysed; (a) the initial rapid release of mobile elements from the fuel matrix, and (b) the slow release of uranium and other elements as the fuel dissolves. The IRT considers that Nagra’s understanding of the behaviour of spent fuel under repository conditions is at the leading edge of the state-of-the-art.

The IRT notes that the dissolution of vitrified HLW under disposal conditions is complex and that the mechanistic understanding of these processes is not yet fully mature. On the other hand, vitrified HLW has a low inventory of the more mobile radionuclides, and very conservative analyses show that the disposal system is sufficiently robust to allow for uncertainty in the glass dissolution rate. Also, despite such uncertainties, the IRT accepts that glass is a durable waste form and that the dissolution process will take place over very long time frames (tens to hundreds of thousands of years). Thus, it is appropriate for Nagra to consider the glass matrix to be a significant barrier in the multi-barrier system.

The IRT notes that the bentonite buffer concept of Nagra differs from international practice on two particular points as follows: (i) the use of bentonite pellets, and (ii) by designing for maximum temperatures in the inner half of the bentonite buffer that are higher than 100°C. The IRT considers that the full scientific support for the swelling and sorption properties of thermally affected bentonite is still being established. The IRT notes that research by Nagra on the behaviour of the bentonite pellet buffer and the effect of high temperatures, in particular on thermal-hydraulic-mechanical (THM) processes on the scale of a disposal tunnel, is ongoing. The IRT strongly encourages Nagra to continue such research and notes that there is strong interest in the outcome of such studies, particularly the impact of high temperatures, within other waste management programmes. Also, the IRT considers that the uncertainties about thermal alteration of the bentonite buffer are covered by cases analysed in the safety assessment. The design temperature for the buffer does not need to be resolved before underground site characterisation studies are initiated.

On ILW

The ILW will be emplaced in tunnels backfilled with a cementitious mortar. Nagra has considered the effects of radiation, temperature evolution, gas production (both from iron-based and organic materials), tunnel convergence, porewater chemistry and, most importantly, the effects of the high-pH plume on the properties of the Opalinus Clay. Potentially oxidising conditions, caused by reactions of nitrate present in some of the ILW packages have also been properly addressed by applying sorption and solubility values derived for these oxidising conditions. The physical separation of the ILW tunnels from each other and from the SF/HLW tunnels are important design features that lessen the impact of any uncertainties arising from chemical effects or gas production within the ILW near field system.

Nagra adopts a simple approach to assess the ILW safety performance by assuming that the release of radionuclides does not occur until 100 years after emplacement. At that time all radionuclides are assumed to be distributed between the aqueous and solid phases. Given the complexities of the waste forms and the small inventory of radionuclides, the IRT considers this approach to be conservative, appropriate and consistent with the approaches followed in other national programmes.

On Engineering Feasibility

The IRT has not assessed the engineering feasibility of constructing a repository in the Opalinus Clay of the Zürcher Weinland but is not aware of any significant issue that would call the feasibility of doing so into question. The IRT has assumed, therefore, that construction of the repository will not significantly impact on the favourable properties of the Opalinus Clay. At the same time, the IRT notes that one of the important roles of underground research laboratories such as the Mont Terri facility, and of an underground test facility at a prospective repository site, is to undertake large-scale tests to assess and/or confirm specific engineering features of any design and so demonstrate that the essential safety properties of the repository are retained.

On the Other Confining Units

Nagra has not considered, as part of its Reference Case, the barrier to transport of radionuclides that would be provided by the confining units above and below the Opalinus Clay. Nagra has illustrated, however, the potential benefit that could result from taking into account these barriers. The IRT considers this to be a potentially useful "reserve FEP" and encourages Nagra to perform further characterisation studies on these units, should a decision be taken to focus the Swiss programme on the Opalinus Clay of the Zürcher Weinland.

Further investigation of the characteristics of the confining units would fulfil several purposes. Firstly, it would improve the understanding of transport pathways to the biosphere, especially horizontal transport through the more permeable strata. Secondly, it would allow Nagra to take account of the confining units as barriers within the reference conceptualisation. In addition, the confining layers need to be sufficiently characterised for the design and engineering work required to ensure that repository construction can proceed safely through these layers.

On the Biosphere

Nagra has followed a conventional approach in modelling the biosphere, using compartments and transfer coefficients to model the movement of contaminants in the biosphere and to calculate doses to members of the critical group. Uncertainties related to future climates and human actions are taken into account using stylised representations of the surface environment. In using such a stylised approach, it is important to note that calculated doses should be considered to be indicators of safety rather than precise measures of expected consequences.

In modelling the biosphere, quite substantial dilutions by surface water are assumed for calculating doses resulting from releases to the surface environment. The IRT finds that the dilution factors are reasonably well justified, but notes that calculated doses are inversely proportional to the dilution volume and, if the latter were substantially in error, calculated doses would be too. Nonetheless, even if the dilution volume were smaller, calculated doses would, in all likelihood, still meet the regulatory requirement, given the large difference between calculated doses and the regulatory limit.

On Documentation

The IRT considers that Nagra has done an excellent job of documenting its safety case, beginning with a clear statement of objectives and principles that have guided the safety case and its documentation. As in previous complex assessments dealing with waste repositories, the main arguments are presented in the Safety Report and supporting documents are referenced where appropriate in the text.

Each chapter in the Safety Report starts with an introduction that indicates what information will be provided and how this fits into the overall assessment. Through successive chapters, the proposed repository system is introduced, discussed and assessed. The organisation is logical, the layout is excellent, and the writing is clear and remarkably free of errors. There is a good combination of quantitative data and qualitative arguments to support the overall safety case. Overall, the Safety Report and supporting documents are of a very high quality.

The chosen organisational structure is not perfect, however. For example, the approach followed by Nagra in the Safety Report means that a given issue is likely to be discussed over several chapters. Thus, the report is somewhat fragmented and repetitious. Nonetheless, the traceability is generally good and the reviewer is able to follow the arguments from the Safety Report through to the detailed information, codes, and data in the supporting documents. In a few cases, the main document contains unsupported assertions that are not referenced back to lower level documents. The IRT considers that transparency and traceability could be improved in the future, if Nagra were to adopt a standardised approach to ensuring that statements in the Safety Report, especially those of a contentious nature, were clearly cross-referenced to detailed arguments in supporting documents.

The target audience for the Safety Report appears to be specialists and regulators, not the general public. The IRT considers that a short overview report, of say 50 to 60 pages, reviewing the whole of the *Entsorgungsnachweis* project and its documentation, including the Geosynthesis and the Facilities and Operations Reports, would be very useful to a wide readership.

The IRT notes that the Safety Report does not include in detail all the elements of an explicit "statement of confidence" as recommended by the NEA. A concise summary of why Nagra has a high degree of confidence in the safety of disposal in a repository constructed in the Opalinus Clay of the Zürcher Weinland is presented. Nagra also identifies and examines uncertainties throughout the Safety Report, but does not prioritise them in its summary. Guidance for future work is only discussed briefly. In its discussions with the IRT, Nagra indicated that it chose not to prepare a detailed work plan at this stage because it did not want to pre-empt the decision-making process or the input from various review processes underway (including this review). The IRT understands this decision but recommends that, if a decision were taken to focus the Swiss programme on disposal in the Opalinus Clay of the Zürcher Weinland, Nagra should prepare a plan that prioritises remaining uncertainties and sets out a programme of work to reduce the level of these uncertainties.

On Quality Assurance

The IRT was particularly interested in Nagra's approach to Quality Management (QM), since good quality management adds to the confidence of the safety case: conversely, evidence of poor quality assurance undermines confidence in the safety case. The IRT did not carry out an audit of Nagra's QM system, but observes that Nagra's QM programme contains many of the elements of a modern QM system. These include, e.g., strong commitment by management, use of external peer review and expert solicitation. One important aspect of QM is the assessment and management of data uncertainties since the impact of such uncertainties must be dealt with in the safety analysis. The IRT considers that certification of the Nagra QM system under ISO 9001: 2000 will represent a valuable improvement to its quality system.

On Conformity with International Practice and Guidance

The IRT considers the Nagra safety case to be at the forefront of international practice. It combines a mixture of quantitative and qualitative arguments. The multi-barrier concept and "pillars of safety" are emphasised. The geological environment is a very effective component of the system. Multiple lines of argument are used to establish a convincing case that the slow process of diffusion is the controlling transport mechanism within the Opalinus Clay. The primary containment for SF and HLW is expected to last for 10 000 years in keeping with the current emphasis on strong engineered barriers. The structure of the safety case conforms to the latest international guidance.

On Nagra's Programme

The IRT observes that Nagra:

- has a mature programme with highly competent, open-minded staff and a programme in which science, site characterisation, engineering design and safety assessment are effectively integrated;
- has strong programmes in specific areas such as geochemistry and site characterisation carried out in-house and in external institutes, such as the Paul Scherrer Institute (PSI) and the University of Bern, and within the framework of the international Mont Terri URL project;
- follows specific developments in other programmes and makes effective use of such developments in its own programme;
- follows and contributes to international developments and integrates the results within its own programme.

Concluding Statement

In summary, the IRT concludes that, for the purposes of the current assessment:

- *The overall strategy for demonstrating long-term safety is well thought out and clearly presented, and is in line with international reflections on what constitutes a safety case.*
- *The safety functions of the different barriers in the multi-barrier system have been clearly described and analysed. Given its properties, the Opalinus Clay of the Zürcher Weinland assumes a major role in contributing to safety, but other components of the multi-barrier system also contribute to, and support, the overall safety case.*
- *The methodology, models and codes that have been used in assessing performance are comparable to those used in other national programmes.*
- *The scientific basis for the representation of processes and barrier functions is state-of-the-art and fit for purpose.*
- *The features, events and processes affecting the evolution of the disposal system have been clearly documented and Nagra has carried out a detailed comparison with the NEA international FEP database to ensure that they are sufficiently comprehensive.*

- *The scenarios and assessment cases considered in the safety assessment cover a wide range of possibilities and are sufficiently comprehensive.*
- *The impact of data and model uncertainties on safety has been extensively analysed and such uncertainties have been adequately taken into account in the safety case.*
- *The relevant phenomena and scientific reasoning are well described in the documentation.*

The IRT is impressed by the overall strength and quality of the safety case prepared by Nagra for disposal of SF, HLW and long-lived ILW in the Opalinus Clay of the Zürcher Weinland. The Safety Report should provide an important plank in the platform of information to support the upcoming national debate on the future phases of the waste disposal programme in Switzerland.

1. INTRODUCTION

1.1 Background

In Switzerland, the producers of radioactive waste are legally responsible for its safe management and disposal. In 1972, to meet these obligations, the Swiss government, which is responsible for wastes arising from medicine, industry and research, and the electricity suppliers, who are responsible for wastes generated by nuclear power stations, set up the Nagra. Nagra carries out R&D and develops strategies and projects for the disposal of radioactive waste in Switzerland.

Geological isolation has been the chosen option for disposal of radioactive waste in Switzerland for many years. Both crystalline and sedimentary rocks have been considered for geological waste disposal. In the *Gewähr* project, Nagra (1985) studied the crystalline basement option for the disposal of high-level waste (HLW). In 1988, the Federal Government decided, based on the review of this study, that construction of a repository for HLW in the crystalline basement was feasible and long-term safety was achievable but the geological field data did not allow a confident conclusion concerning the availability of sufficiently large areas of suitable crystalline rock. Thus, it was concluded that siting feasibility had not been fully demonstrated (Nagra, 2002a).

Since the late 1980s, Nagra has also studied the disposal of spent fuel, vitrified HLW and long-lived intermediate-level waste (ILW) in sedimentary rock formations. Two potential formations were identified; Opalinus Clay and the Lower Freshwater Molasse.

The government advisory group EKRA (Expert Group on Disposal Concepts for Radioactive Waste) has advocated a repository system for Switzerland based on the concept of monitored geological disposal (EKRA, 2000). It is based on passive safety using a combination of engineered and geological barriers with the possibility of reversibility by retrieval. EKRA also advocates, as part of the stepwise approach to the geologic disposal of radioactive wastes, construction of a test facility and a pilot facility in addition to the main facility and, following emplacement of the wastes, a phase of monitoring prior to repository closure is foreseen. The test facility would operate before the main facility begins operation and obtain information required for construction, operation and post-closure safety assessment. The pilot facility would contain a small but representative fraction of the radioactive waste.

The new Nuclear Energy Law, "*Kernenergiegesetz*" (KEG, 2003), embodies the concepts proposed by EKRA. It specifies that radioactive waste must be disposed of in a deep geological facility, which is monitored prior to closure and from which the waste can be easily retrieved before final closure, if necessary. Under Swiss legislation, the following licences are required:

- licence for preparatory measures;
- general licence (including the siting decision);
- construction licence;
- operation licence; and
- closure licence.

The disposal concept developed by Nagra comprises two geological repositories, one for spent fuel (both UO_2 and MOX), vitrified residues from reprocessing of spent fuel (HLW) and long-lived and alpha-bearing intermediate-level waste (ILW) arising mainly from reprocessing, and a second repository for other radioactive wastes.

1.2 The *Entsorgungsnachweis* Project

The current milestone in Nagra's programme for SF, HLW and long-lived ILW is Project *Entsorgungsnachweis* (demonstration of disposal feasibility). In December 2002, Nagra submitted, to the Swiss government, the documentation of Project *Entsorgungsnachweis* for disposal of long-lived wastes in the Opalinus Clay of the Zürcher Weinland in northern Switzerland. There are two main objectives of the *Entsorgungsnachweis* project:

1. To demonstrate the disposal feasibility of SF, HLW and long-lived ILW in the Opalinus Clay of the Zürcher Weinland. Three aspects of feasibility need to be demonstrated (Nagra, 2002a):
    a. a suitable geological environment for the repository exists (siting feasibility);
    b. construction and operation of a repository is practicable in such an environment (engineering feasibility);
    c. long-term safety from the hazards presented by the wastes is assured for such a repository (safety feasibility).

2. To provide a platform for discussion and a foundation for decision making on how to proceed with the Swiss HLW programme.

The documentation for Project *Entsorgungsnachweis* comprises a series of reports which address the three elements of feasibility: the upper level documents are the Geosynthesis Report, NTB 02-03 (Nagra 2002b), the Facilities and Operations Report, NTB 02-02 (Nagra 2002c), and the Safety Report, NTB 02-05 (Nagra, 2002a). The Safety Report and this international assessment deal with the repository for long-lived wastes as described in the *Entsorgungsnachweis* Project.

1.3 The International Peer Review

In 2003, the Swiss Federal Office of Energy (BFE), requested the NEA to complement the Swiss assessment of Project *Entsorgungsnachweis* by carrying out an international peer review of Nagra's post-closure safety assessment, which is the subject of their Safety Report (Nagra, 2002a). It documents the methodology, conduct and results of the performance evaluation of the reference disposal system.

The Terms of Reference (ToR) for this study are set out in Appendix 2. The following specific items were identified for review:

1. the overall strategy for demonstrating long-term safety;
2. the role and relative weight given to the safety functions of the different barriers;
3. the methodology that is applied for the performance assessment;
4. the scientific basis for the representation of processes and barrier functions;
5. the comprehensiveness of the features, events and processes affecting the evolution of the disposal system;
6. the comprehensive derivation of scenarios and identification of assessment cases;
7. the treatment of data and model uncertainties.

The ToR also give the review team the liberty to comment upon other aspects, if found pertinent.

The NEA agreed to the Swiss request and to the ToR, and organised an international peer review of the post-closure safety assessment. The Swiss

Federal Nuclear Safety Inspectorate (HSK) was nominated as the coordinator from the side of the Swiss government.

To carry out the review, the NEA formed an international review team (IRT) comprising well-known experts familiar with the field of safety assessment, including specialists in a number of areas that are important to long-term safety. Appendix 3 provides brief résumés of the IRT members. These experts agreed to participate on the understanding that the views of the IRT do not necessarily reflect the views of the organisations with which the IRT members are affiliated.

In keeping with the ToR, the IRT conducted a technically oriented peer review based on the understanding that the final judgement on the safety feasibility is the prerogative of the Swiss authorities. The IRT was only to reflect on whether the approach developed by Nagra to assess post-closure safety is a sound one, in the context of the stepwise approach taken in Switzerland towards the development of a repository, and in line with international practices. It may be noted that, according to the ToR, a demonstration of safety feasibility "must show that in the selected host rock within the potential siting area, having the geological and hydrogeological properties as demonstrated by field investigations, and with the system of engineered barriers, the long-term safety of the repository is assured."

The IRT did not assess siting or engineering feasibility. Nevertheless, the IRT notes that siting, engineering and safety issues are interrelated and changes in one will affect the others. For this reason, any change in siting or engineering design from that indicated in the documentation for the *Entsorgungsnachweis* project would need to be assessed from a safety perspective.

In its deliberations, the IRT took account of the fact that the Safety Report is part of a stepwise process for decision making in repository development and is not intended as a submission for licensing purposes. It is acknowledged by Nagra and other interested parties that further work, as well as input from Swiss society are necessary in order to bring the project to the stage where an application for a general licence, the issuing of which would constitute a formal siting decision, would be made.

1.4 Conduct of the Review

This review was conducted as follows:

- An introductory meeting was held at Nagra headquarters from 30 June to 2 July 2003. The IRT was briefed by HSK on the aims of the review. Nagra staff gave a series of presentations on aspects of the *Entsorgungsnachweis* project and responded to questions from the IRT. On 2 July, the IRT visited the Mont Terri underground research laboratory (URL) and was shown various experiments in progress.
- During the period July – November 2003, all members of the IRT reviewed the Safety Report (Nagra, 2002a). Nagra also provided IRT members with many other technical reports. Two members reviewed the Geosynthesis Report (Nagra, 2002b), which is in German. Depending on their area of expertise, IRT members were also assigned to review additional reports. Nagra provided the IRT members with other supporting documents upon request.
- To clarify issues, two rounds of written questions were submitted to Nagra by the IRT in August and October 2003. Nagra answered these questions in writing. These written exchanges were an important component of the review.
- The IRT met privately on 23 November and at Nagra headquarters from 24-28 November. Nagra staff gave supplementary presentations at the request of the IRT and, in order to address particular technical issues, small meetings were held between IRT members and Nagra or Paul Scherrer Institute (PSI) scientists. The IRT also met in closed sessions to discuss the issues and reach a consensus. On the afternoon of 28 November, the IRT chairman, Colin Allan, gave an oral presentation of the preliminary findings of the review. All discussion sessions with Nagra were open to Swiss observers and representatives from HSK, the Federal Commission for the Safety of Nuclear Installations (KSA) and the Commission on Nuclear Waste Management (KNE) attended some or all of the sessions.
- Following the final meeting, the IRT compiled a draft report, which was submitted to Nagra for fact-checking purposes. In addition to changes suggested to ensure factual correctness, Nagra also suggested changes of an editorial nature. The latter did not affect the material content of the report. The feedback from Nagra was taken into consideration in producing this report.

The IRT was completely satisfied with the quality and timeliness of the information provided by Nagra, who responded promptly to the many questions posed by the IRT and to requests for reports and other information. The facilities provided by Nagra were excellent.

The IRT performed an in-depth review of the Safety Report and many other supporting reports. Significant conclusions and recommendations are presented in the body of the report in italicised text. Since engineering feasibility is outside the ToR, the Facilities and Operations Report (Nagra, 2002c) was not reviewed in detail. The IRT considers that its assessment fulfils its ToR as set out in Appendix 2.

1.5 Organisation of the Report

The organisation of this report is a follows:

- Chapter 2 discusses Nagra's disposal concept from an international perspective.
- Chapter 3 is an assessment of the safety case.
- Chapter 4 is a technical assessment of the multi-barrier system components and processes, with emphasis on their contribution to the safety case and the understanding demonstrated of the barrier functions and processes.
- Chapter 5 is a summary of the IRT's findings.

There are four appendices:

- Appendix 1 compares the safety case with the principles identified in a recent NEA report on confidence in the long-term safety of deep geological repositories (NEA, 1999).
- Appendix 2 sets out the terms of reference (ToR).
- Appendix 3 presents brief résumés of members of the IRT.
- Appendix 4 is a list of acronyms.

2. THE SWISS CONCEPT FOR MONITORED GEOLOGICAL DISPOSAL

2.1 The International Perspective

Internationally, the preferred method of waste management for long-lived radioactive waste is generally considered to be deep geological disposal, utilising a system of engineered and natural barriers (the multi-barrier system) to ensure long-term safety.

Although the objective of geological disposal is permanent disposition of the waste with no intention of retrieval, such disposal does not preclude the maintenance of institutional controls if society wishes, nor does it preclude the retrieval of the waste by a future society. Such a strategy "leaves open the possibility of adaptation in the light of scientific progress and social acceptability, over several decades, and does not exclude the possibility that other options could be developed at a later stage" (NEA, 1995). Nagra's disposal concept is in accordance with this strategy and with the IAEA draft safety requirements for geological disposal of radioactive waste (IAEA, 2004).

Although, in a given design, the components of such a multi-barrier system may not be fully independent and redundant over all timescales of interest, nevertheless, should one of the barriers not perform as well as expected, the other barriers will still provide a high degree of protection and limit exposures. The capability of a given design to accommodate poorer-than-expected performance of the individual barriers provides an important measure of the robustness of the design.

All modern disposal concepts utilise a combination of engineered and natural barriers, as proposed by Nagra, but their design varies according to the chemical environment and the geological strata proposed for the repository.

Internationally, several different rocks types have been investigated including crystalline rocks (for example in Finland, Sweden, Canada and Switzerland), rock salt (for example in the USA and Germany), tuff (in the USA) and argillaceous formations, including the Opalinus Clay of the Zürcher

Weinland (for example in Belgium, France, Italy, Hungary and Switzerland). The choice of rock type depends on a number of factors, such as its availability, extent, general safety-relevant properties such as permeability, and accessibility for surface-based characterisation.

The advantages of clays as potential host rocks are that they generally have a low permeability, strongly retain many radionuclides and are self-sealing. However, these properties and other mechanical characteristics vary according to the nature of the geological deposit and need to be assessed on a site-specific basis.

The chemical environment and other factors may affect the choice of engineered barriers. Thus, a different canister material may be used depending on whether the chemical environment in the host rock is oxidising or reducing.

2.2 Assessment of the Nagra Concept

Figure 1 illustrates the Nagra concept for disposal. The repository is located in Opalinus Clay of the Zürcher Weinland (typical thickness about 100 m) at a depth of about 650 m below the surface. Passive safety is achieved through the use of multiple barriers designed to isolate the waste and to ensure that future radiological exposures from any released radionuclides are below regulatory limits. The regulatory guidelines (HSK/KSA, 1993) specify a maximum annual dose rate to individuals of 0.1 mSv per year.

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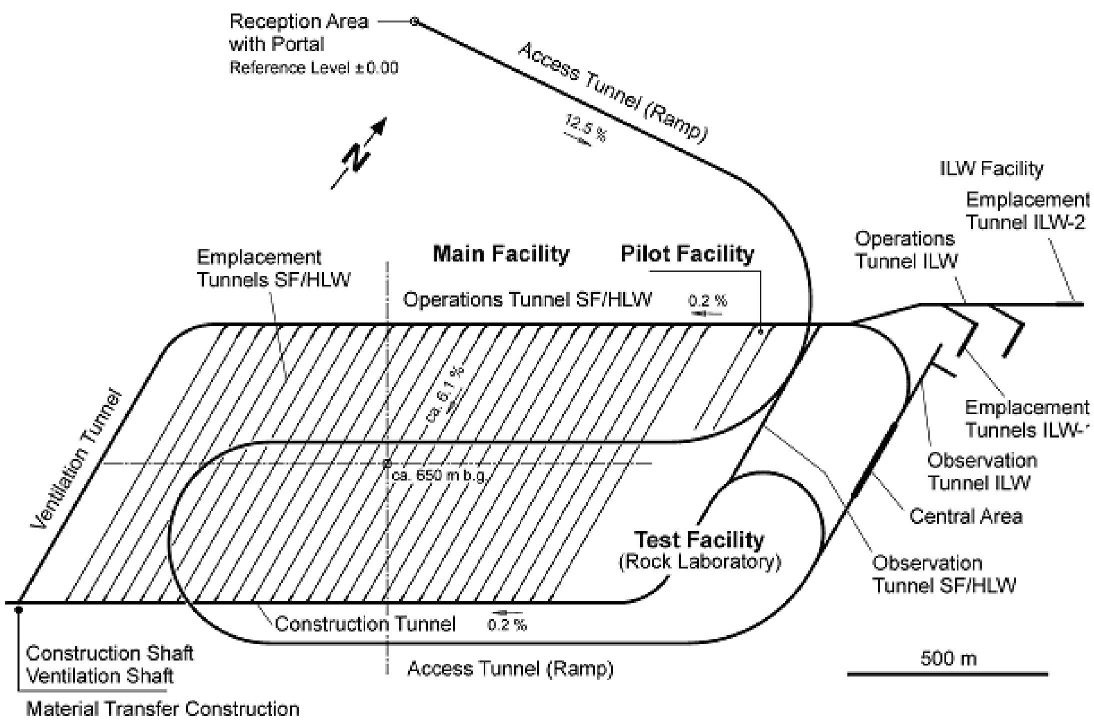
Figure 1: Plan view of the repository concept proposed by Nagra [from Nagra (2002a), Fig. 4.5-1]



The reference disposal concept corresponds to waste generated from production of 192 GWa (e) of nuclear power, equivalent to operation of the current nuclear power reactors for 60 years. This results in the generation of the following wastes (Nagra, 2002a):

- SF: 2 065 canisters containing 3 217 t initial heavy metal (UO_2 and MOX).
- Vitrified HLW: 730 canisters resulting from the reprocessing of 1 195 t SF.
- Long-lived ILW: A total number of 1 680-1 880 waste drums of different types coming from COGEMA and BNFL, representing a total volume of about 1 400 m^3 (or ~ 500 m^3 for the ILW high force compacted wastes option).

In the Nagra concept, SF and vitrified HLW would be placed in thick-walled steel canisters that should provide absolute containment of the wastes for a period of 10 000 years or more. The canisters would be placed horizontally in 2.5 m diameter, 800 m long emplacement tunnels that would be sealed with bentonite following waste emplacement. The tunnels would be spaced 40 m apart.

Emplacement tunnels for HLW and SF would be excavated as needed and backfilled and sealed concurrently with waste emplacement, so that a given tunnel would remain open for a maximum of two years. Once all waste had been emplaced in the main facility, the access ramp would remain open during an extended period of monitoring but the main facility would be sealed to ensure long-term passive safety, even in the event that closure of the access ramp did not eventually take place as foreseen. The IRT finds that this approach to waste emplacement (including the use of multiple seals to compartmentalise and isolate waste packages) is feasible and prudent.

In common with the approach followed by a number of other countries (for example France, Sweden and Finland), Nagra proposes that long-lived ILW be disposed of in tunnels excavated in the same facility. The ILW drums would be loaded inside containers and placed in larger emplacement tunnels that would be sealed with mortar. Emplacement tunnels for ILW would be separated from tunnels used for the emplacement of SF and HLW wastes to ensure that the geochemical environment in the SF and HLW tunnels would be favourable. Separate tunnels would be used for ILW: one for ILW waste containing organic and potentially complexing compounds and the others for ILW wastes comprising inorganic components. The IRT considers such separation of wastes to be good safety practice.

As proposed by the Swiss government advisory group EKRA, the facility would include a test facility and a pilot facility. Implementation would follow a cautious, stepwise approach and would involve an extended period of monitoring, following waste emplacement, during which retrieval of the waste would be relatively easy. Periodic reviews would be carried out that would provide for possible reversal of decisions, including even the retrieval of emplaced wastes. This approach is consistent with that proposed in a number of other countries and is consistent with recent international reflections (NEA, 1995; NEA, 1999; IAEA, 2004). Others (Simmons and Baumgartner 1994, SKB, 2000) have proposed constructing *in situ* test facilities similar in concept to those advocated by EKRA, and have proposed keeping the disposal facility open for an extended period of monitoring following waste emplacement [see, for example, AECL (1994) and US-DOE (2000)]. Nagra has made an important contribution with its analysis of the safety consequences of abandoning such a facility in the monitoring stage (see further discussion in Section 4.7).

The IRT finds that the disposal concept proposed by Nagra has all the desirable elements of a monitored retrievable geological repository. The multiple barriers for SF and HLW perform a number of functions appropriate to the chemical and geological environment in the proposed repository. The barriers include:

- durable waste forms (SF and HLW), surrounded by
- long-lived canisters that, except possibly for a small number of premature failures, have the potential to provide absolute containment of the wastes for a period of 10 000 years or longer, during which time the radioactivity of the wastes will decrease substantially,
- a bentonite buffer that fulfils several functions, including providing the conditions to ensure sealing of the excavation disturbed zone (EDZ) and isolation of the waste packages from the host rock and from each other, and
- the host rock, namely the Opalinus Clay of the Zürcher Weinland, which provides a geologically stable environment and which ensures that the movement of contaminants from the repository to the surface environment is constrained by the hydrological and retentive properties of the Opalinus Clay.

In the Nagra concept, the most important of these barriers, because of its properties, is the host rock. Nagra argues, convincingly in the view of the IRT, that the geologically stable environment of the Opalinus Clay of the Zürcher

Weinland is structurally simple, the clay is self-sealing, there is negligible advective water flow, the clay is chemically stable with good retention capabilities, and it has acceptable engineering properties for construction. Further, the absence of resource potential in the area reduces the likelihood of inadvertent human intrusion. The properties of the host rock are discussed in detail in Chapter 4.

The IRT notes, however, that Nagra has drilled only one deep borehole into the Opalinus Clay of the Zürcher Weinland – the Benken borehole – and that consequently additional work would be expected before going underground to confirm the characteristics of the reference disposal site and to gather information for detailed engineering design.

3. ASSESSMENT OF NAGRA'S SAFETY CASE

In this chapter, Nagra's safety case is assessed having regard for other national programmes and practice and the guidance provided by international organisations, in particular the ICRP (1991, 1997, 1998), the NEA (1997, 1999, 2001a, 2001b, 2002a, 2002b, 2004) and the IAEA (1994, 1995, 1996, 2000, 2001a, 2004).

Most of the items in the IRT's ToR (see Section 1.3 and Appendix 2) are addressed in this chapter, including the overall strategy for demonstrating long-term safety (item 1), the methodology that is applied for the performance assessment (item 3), the treatment of features, events and processes (FEPs) affecting the evolution of the disposal system (item 5), the derivation of scenarios and identification of assessment cases (item 6) and the treatment of uncertainties (item 7). (The other two items are discussed in Chapters 2 and 4.)

The high level conclusions reached in this chapter are supported by the more detailed observations presented in Chapter 4 and Appendix 1. The latter is an integral component of this report.

3.1 Overall Strategy for Demonstrating Long-term Safety

The IAEA states that the safety strategy "defines the approach to developing a disposal facility focussed on the aim of providing long term safety" (IAEA, 2004). Nagra clearly sets out its safety strategy and objectives in Section 2.6 of its Safety Report (Nagra, 2002a).

In assessing the overall strategy for demonstrating long-term safety, three related but different aspects should be distinguished, namely

1. the stepwise process for decision making, which allows for multiple reviews and the incorporation of new knowledge as time progresses;
2. the post-closure safety case, which is made iteratively and supports dialogue and decisions at important stages of the decision-making process; and

3. the safety assessment within each iteration of the safety case to assess compliance with regulatory requirements.

3.1.1 The stepwise process for decision making

The IAEA and the NEA have noted that the development of geological disposal facilities and the preparation of safety reports is a stepwise process (IAEA, 2004; NEA, 2004). There are many advantages of this approach, including the opportunity for independent technical review and public and political scrutiny at each stage of the project. Inherent to this stepwise process is the need to "maintain sufficient flexibility to cope with unexpected site features or technical difficulties and uncertainties that may be encountered, as well as to take advantage of advances in scientific understanding and engineering techniques" (NEA, 2004).

In its Safety Report, Nagra stresses the stepwise approach that has been followed to date in Switzerland, the legal and regulatory guidance provided concerning stepwise decision making and the objectives related to stepwise implementation that underpin Nagra's approach. In addition, Nagra has identified several areas where flexibility exists for changes in the disposal programme. The IRT considers that Nagra's approach is logical, thorough and in accordance with international recommendations.

The formality and technical detail required in the safety case will depend on the stage of project development and the specific national requirements (IAEA, 2004). Accordingly, the IRT has taken account of the fact that Switzerland is at an early stage of repository development and some information (such as detailed engineering of the canisters) could not reasonably be expected at this stage. Taking this into consideration, *the IRT finds that the Nagra Safety Report and the supporting technical reports are remarkably mature documents and thus valuable contributions to the current phase of the decision-making process*.

3.1.2 Post-closure safety case

Nagra defines the safety case as "the set of arguments and analyses used to justify the conclusion that a specific repository system will be safe. It includes, in particular, a presentation of evidence that all relevant regulatory safety criteria can be met. It includes also a series of documents that describe the system design and safety functions, illustrate the performance, present the evidence that supports the arguments and analyses, and that discuss the significance of any uncertainties or open questions in the context of decision-making for further repository development". This definition is derived partly from NEA (1999) and is consistent with recent international reflections (IAEA, 2004; NEA, 2004).

The IRT notes that the safety case includes the presentation of evidence that all relevant regulatory safety criteria will be met, namely the safety assessment, but is much broader. In addition to thorough and robust safety assessments, a safety case includes many other elements such as the following: the enunciation of principles and guidelines, the use of the multi-barrier concept with an adequate degree of redundancy for robustness, demonstration of scientific understanding, good engineering practice, application of good management principles including quality assurance, scientific evidence for the intrinsic quality of the site, natural analogues, high quality and transparent documentation, and the synthesis of evidence, analyses and arguments into a statement of confidence (IAEA, 2004; NEA, 1999; NEA, 2004).

In the Safety Report, Nagra explicitly and clearly sets out the objectives and principles related to:

1. Geological disposal in general.
2. The stepwise repository implementation process.
3. Safety functions of the disposal system.
4. The means of achieving overall safety and robustness.
5. Repository siting, design and implementation.
6. Safety assessment and its documentation.

These objectives and principles reflect Nagra's commitment to implementing disposal in a manner that is flexible, provides long-term safety and, at the same time, takes account of the needs and values of Swiss society.

Nagra's safety case is discussed in detail in Section 3.2 below. *In general, the IRT finds that Nagra has met all of the essential requirements of a modern safety case*. In addition to the information presented in Section 3.2, the IRT also found the criteria recently developed by the NEA (1999) to be helpful in carrying out its assessment. A detailed comparison of Nagra's safety case with these criteria is given in Appendix 1.

3.1.3 Safety assessment

The IAEA defines safety assessment as "the process of making systematic analyses of the radiological hazards associated with the disposal facility, and of the ability of the design to provide the safety functions and meet technical requirements. It will include quantification of the overall level of performance, analysis of the associated uncertainties and comparison with the relevant design requirements and safety standards. Safety assessments should also identify any significant deficiencies in scientific understanding, data or analysis such as might affect the results presented. Depending on the stage of development, safety assessments may aid in focussing research and their results can be used to determine compliance with internal or external safety goals and standards." (IAEA, 2004).

Nagra's approach to safety assessment is discussed further in Section 3.2, but it is noted here that *the IRT finds that Nagra's safety assessment is consistent with this definition*. Specifically, Nagra has performed quantitative analyses to compare calculated doses with regulatory requirements as the system evolves following closure. The major classes of uncertainty are adequately discussed and taken into account in the safety assessment, and current deficiencies in scientific understanding are identified.

3.2 Methodology for Constructing the Safety Case and Performing the Safety Assessment

Nagra's procedure for constructing the safety case and carrying out the safety assessment is illustrated in Figure 2. It includes, inter alia:

a. Adopting the multi-barrier system for disposal and developing a conceptual design having an adequate degree of redundancy and design options (assessed in Chapters 2 and 4).

b. Developing a phenomenological and scientific understanding of the behaviour of this system, its components and their evolution over time (assessed in Chapter 4).

c. Explaining clearly how the multi-barrier system is expected to perform and how its components contribute to the containment, retention, delay and dispersion of radionuclides (assessed in Section 3.2.6 below).

d. identifying features, events and processes (FEPs) that may impact on long-term safety and that need to be taken into account in the safety case, e.g. by avoiding their impact through design or by analysing their impact in the safety assessment (assessed in Section 3.2.1 below);

e. Identifying uncertainties that need to be addressed and performing sensitivity and probabilistic analyses to determine the importance of these uncertainties (assessed in Section 3.2.2 below).

f. Developing and analysing scenarios and cases that span the expected evolution of the system and any uncertainties (assessed in Section 3.2.3 below).

g. Performing quantitative modelling of the system and its components to provide quantitative "estimates" of radiation exposures for comparison with regulatory requirements as an indicator of safety (assessed in Section 3.2.4 below).

h. Employing supportive arguments and additional analyses using complementary safety indicators, based on multiple lines of evidence, including past geological evolution and natural analogues (assessed in Section 3.2.5 below and Chapter 4).

i. Summarising the main arguments and results of the safety case in a statement of confidence (assessed in Section 3.2.6).

It may be noted that steps d) to g) comprise the safety assessment, as defined in Section 3.1.2.

This procedure is adopted in most national programmes. *However, the IRT considers that what distinguishes the Nagra case is the clarity with which the safety case is constructed, the level of robustness demonstrated and the strong emphasis on supporting arguments to augment the quantitative safety analyses*.

Steps d) to h) of this procedure are discussed in detail below, followed by a discussion of steps c) and i).

3.2.1 Treatment of features, events and processes (FEPs)

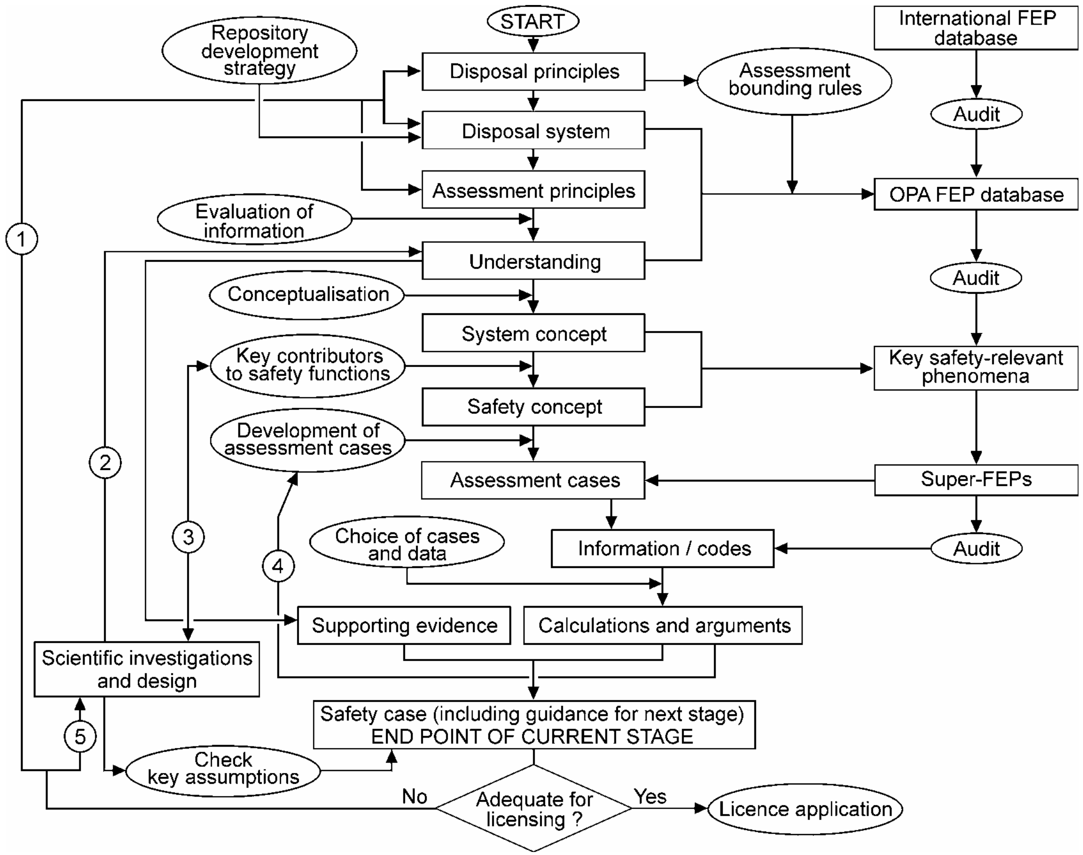
An important task in assessing the safety of radioactive waste disposal is the identification, screening and documentation of all the features, events and processes (FEPs) that may impact on long-term safety. In common with other nuclear organisations, Nagra uses FEPs as a tool to determine whether all safety-relevant factors have been considered and whether they have been adequately treated. Nagra clearly states, and the IRT agrees, that safety assessment is not a linear process but is highly iterative (see Figure 2). Thus, the identification and documentation of FEPs is done in parallel with, and iteratively with, identifying scenarios and cases, and with sensitivity and uncertainty analysis.

Nagra documents its FEP management process in a major report, NTB 02-23 (Nagra, 2002d). The IRT considers this to be a comprehensive report that enables a knowledgeable reviewer to trace the selection of FEPs and their link with safety-relevant phenomena, and determine how they have been dealt with in the safety assessment. Each FEP is well documented and the strategy for screening FEPs is clearly presented. The FEP management report also clearly shows the iterative way in which FEP management integrates into the safety assessment. This report and especially Appendices 4 and 5, assist the reader to better understand how Nagra selected each assessment case with respect to the uncertainties that need to be taken into account and to assess the completeness of the uncertainties considered.

The Nagra FEP database, which identifies 482 individual FEPs, has been compared with the NEA international FEP database (NEA, 2000) and a more recent database developed in the NEA FEPCAT project (NEA, 2003) to ensure, to the extent possible, that no FEP that should be taken into account has been overlooked. The IRT considers that the methodology developed by Nagra (2002d) is useful for ensuring that all significant FEPs have been considered in the safety assessment.

Additionally, Nagra introduces a new concept of higher-level FEPs, called “Super-FEPs”, which are linked to key safety-relevant phenomena and thus to assessment cases. These are helpful to simplify the discussion among experts about important features and processes. Nagra has also labelled as “reserve FEPs” several of the processes that are beneficial to safety but for which the understanding and, in particular, the conceptual models are not sufficiently reliable to be included in the current quantitative analyses. These might be considered in future safety assessments, if and when the scientific basis for such modelling is further developed.

Figure 2: Nagra's procedure for constructing the safety case showing the main elements and the iterative nature of the process [from Nagra (2002a), Fig. A4.1]



The IRT makes the following observations concerning FEP management for further consideration by Nagra and regulatory authorities.

1. The various tables in Nagra (2002d) set out the uncertainties, related to the Super-FEPs and the safety-relevant phenomena, which have been identified and summarise how they have been taken into account in the safety assessment. It would have been very helpful to the reader if the tables had included references to lower level reports that set out the scientific understanding of the phenomena in question and to the modelling approximations used in the safety assessment. Without such references, one is left with the impression that the tables are used simply to trace the decisions taken and not as part of the iterative process of safety assessment.

2. The assessment cases are based on an understanding of safety-relevant phenomena, including the evolution of the barriers and the associated uncertainties, which in turn draw on input from the Opalinus Clay FEP database (see Figure 2). The safety-relevant phenomena feed into the identification of the Super-FEPs that, in turn, are used as one input to the assessment cases and, perhaps more importantly, as an accounting tool.

3. The screening of FEPs is made independently from the timeframes for system evolution. Consideration should be given to linking FEPs to time frames since the level of uncertainties and their effects depend on the time frame under consideration.

Overall, the IRT finds that Nagra has used the FEP management process effectively to ensure that all relevant processes and phenomena have been included in the safety analysis and, in doing so, Nagra has provided a convincing demonstration of the power of this tool. The IRT also notes that the notion of so-called "reserve FEPs" that can be mobilised in the future was introduced in the Kristallin-I study [Nagra (1994)] and is a helpful approach that adds to overall confidence in the safety assessment.

3.2.2 Analysis of the impact of uncertainties

In their analysis, Nagra divides uncertainties into a number of classes:

- scenario uncertainty, i.e. uncertainty in how the repository will evolve;
- conceptual uncertainty, i.e. uncertainty in the assumptions or conceptual model used to represent a given scenario;

- parameter uncertainty, i.e. uncertainty in the values of parameters used in a model; and
- completeness uncertainty arising from the possibility that some important FEPs may have been overlooked.

Nagra indicates that design options are treated separately from other sources of uncertainty because they are largely under the control of the waste management programme.

Conceptual model uncertainty

Consistent with Nagra's scientific and technical understanding, various conceptualisations have been considered for the Reference Scenario and for alternative scenarios 1 and 2. These reflect different conceptual assumptions for modelling key FEPs that affect the release and transport mechanisms for radionuclides. Examples include alternative models for spent fuel dissolution (see also Section 4.3.3) and different assumptions about the performance of the bentonite buffer as a result of thermal alteration (see also Section 4.3.4).

Parameter uncertainty

The significance of parameter uncertainty is evaluated using deterministic and probabilistic methods. Simplified insight models are used as an aid to illustrate the contribution of the different barriers to system performance. Deterministic analyses are used to determine the sensitivity of calculated doses to changes in a given input parameter. For example, deterministic analyses were used to examine the impact of changes in canister breaching time, groundwater flow rate and sorption values (K_ds). Probabilistic uncertainty analysis was used to explore the consequences of combinations of parametric variations that fall within the ranges of uncertainty supported by scientific evidence. Probabilistic sensitivity analysis was used to explore the contribution of the various input parameters to the uncertainty in calculated dose rates. Other national projects, e.g., Yucca Mountain, place more emphasis on probabilistic analysis. However, deterministic analysis is simpler to understand and *the IRT concludes that the level of probabilistic analysis used by Nagra, in combination with the large number of cases analysed deterministically, provide confidence in the robustness of the system sufficient for the current phase of the project*.

The conservatism of using total correlations instead of statistical correlations among input parameters has not, however, been demonstrated. Moreover, sensitivity analyses were based on only one type of correlation coefficient and rank-transformed coefficients have not been used. *The IRT* *recommends the use of advanced tools for uncertainty and sensitivity analyses in future safety assessments.*

Expert elicitation and peer review

Expert elicitation and peer review are explicitly recognised as being an integral part of Nagra's methodology and Nagra has made wide use of experts and peer reviews throughout the project. These experts can be both internal and external to the Swiss programme. Expert judgment is used for obtaining a balanced view of current scientific understanding, including uncertainties, to ensure proper integration of scientific understanding in safety analysis, for scientific review of specific issues, and to clear data for use in safety analysis. Experts involved in meetings are instructed beforehand on the general principles applied by Nagra in the process of expert elicitation.

Irreducible uncertainty for long timescales

Stylised approaches were adopted for assessing the impact of future human actions and for modelling the biosphere (see Section 4.9). Such stylised approaches essentially serve to decouple the main parts of the analysis from those parts and situations that are affected by irreducible uncertainties. Despite obvious simplification and uncertainties, such approaches are nevertheless standard within most waste disposal projects and are accepted by regulators.

The long-term evolution of the system is discussed in Section 4.8.

Use of "what if?" cases to examine robustness to uncertainty

Nagra considers a wide range of uncertainties through the analyses of various scenarios, conceptualisations and cases. Although it cannot be absolutely proven that there are no remaining uncertainties that might somehow compromise safe system performance, Nagra argues convincingly that this is highly unlikely. The inclusion of the concept of "what if?" cases, as endorsed by the NEA (NEA, 2002b; NEA 2004) and the IAEA (IAEA, 2004), makes a significant contribution to this argument. The distinguishing feature of the "what if?" cases are that they are outside the range of possibilities supported by scientific evidence and are introduced to investigate the robustness of the disposal system.

The IRT notes that the "what if?" cases presented by Nagra provide good complementary support to build confidence in the robustness of the safety case. Their successful application is to a large extent, dependent on the excellent retention properties of the Opalinus Clay and this strengthens Nagra's safety case. The IRT notes, however, that, on the one hand, it should be possible to make a safety case based on actual uncertainty ranges without resorting to analyses outside the actual uncertainty range, whereas, on the other hand, regulators and members of the public are interested in such “what if?” cases.

It is acknowledged by Nagra that the choice of “what if?” cases is subjective and hence somewhat arbitrary. For example, Nagra has stated that the “what if?” cases test the effect of perturbations to key properties of the “pillars of safety” but there is not a one-to-one correspondence between the “what if?” cases and the “pillars of safety”. Thus, *the IRT recommends that, in the future, Nagra should provide a clearer set of criteria for selecting “what if?” cases*.

In summary, the IRT notes that, because of the very favourable properties of the Opalinus Clay, a wide range of uncertainties in the performance of the engineered barriers and of the waste form can be tolerated without compromising the safety of a repository constructed in the Opalinus Clay. Nevertheless, *the IRT recommends that Nagra continue to retain the essential features of a robust system of engineered barriers as currently proposed and continue to work to minimise uncertainties*.

3.2.3 Derivation of scenarios and identification of assessment cases

Nagra derives scenarios, conceptualisations and cases based on consideration of safety-relevant features, phenomena and evolution as discussed in Chapter 5 of the Safety Report (Nagra, 2002a). In common with other countries, Nagra has made use of expert opinion in developing the cases to be modelled and has subjected its scientific knowledge base, models, codes and safety assessment studies to external peer review, including the current review.

The starting point for analysis is the Reference Scenario, which is concerned with release of dissolved radionuclides via groundwater to the surface environment. Within this scenario, there are alternative conceptualisations and parameter variations resulting in 22 cases. The Reference Scenario considers all relevant features and is well documented. One of these cases is the Reference Case, which Nagra considers to be the expected evolution. The IRT considers that this case is soundly based and well reasoned.

In addition to the Reference Scenario, Nagra identifies alternative scenarios, some of which represent alternative pathways (release of volatile gases and human activities) while others relate to design options and biosphere uncertainty. In general, *the IRT concludes that the cases assessed by Nagra are well argued and representative of expectations and possible uncertainties*.

The IRT found the terminology used in the Safety Report when discussing scenarios, conceptualisations and cases to be somewhat confusing. The IRT acknowledges that different approaches are used worldwide (NEA, 2001b; NEA, 2002b), but encourages Nagra to continue to be involved in international discussions on this issue.

3.2.4 Modelling of the system to demonstrate compliance with regulatory dose limits

An important aspect of the safety case presented by Nagra is the demonstration that calculated doses received by hypothetical members of the general public (the critical group) who might be exposed to radionuclide releases from the repository meet regulatory requirements. For each component of the system, Nagra has developed mathematical models (described in Nagra, 2002e) to describe the processes that might lead to release and transport of radionuclides. Data for the models are obtained from laboratory studies, fieldwork or the general literature. In combination, these models are used to estimate, as a function of time, the migration of radionuclides through the multi-barrier system and into the accessible environment. A biosphere model is used to estimate dose rates to members of the critical group.

Nagra has developed models for release and near field transport of radionuclides from spent fuel (SPENT), vitrified HLW (STRENG) and cementitious waste forms (STALLION), for transport in the geosphere (PICNIC), for gas evolution and migration, and for biological uptake and dose calculations (TAME). The IRT did not examine these models in detail. However, the IRT notes that the models have been verified and that a number have been in use for some time, e.g. in the earlier Kristallin-I Project [Nagra (1994)].

The models used by Nagra, in common with models used in other countries, comprise a mixture of realistic and simplified models and approximations for components and subsystems. The latter are typically used where system complexities are such that either realistic modelling is beyond the state of the art or would be subject to significant uncertainties about the validity of the model. In all cases, Nagra argues that the simplifications employed err on the side of preserving safety. Examples of such simplifications are the assumptions that all waste containers fail at the same time rather than taking place over time, not taking credit for the containment barrier provided by the SF cladding or the HLW flask, and using stylised representations of the surface environment.

The IRT was impressed with the relative simplicity of the mathematical approach (often based on analytical equations rather than numerical methods). This approach aids in the understanding of key processes and the effects of various variables. The use of insight models is also helpful in this regard.

In assessing the safety of disposal in the Opalinus Clay of the Zürcher Weinland, Nagra has sought to show that Swiss regulatory requirements will be met, in particular the requirement that the release of radionuclides from a sealed repository arising from processes and events reasonably expected to happen shall at no time give rise to individual doses which exceed 0.1 mSv per year. While the timescales for compliance with quantitative targets vary from country to country, depending on the views of regulatory authorities, and generally range from 10 000 to 1 million years (NEA, 2002a), in Switzerland there is no cut-off.

Nagra has carried out modelling simulations over a time span of up to 100 million years but acknowledge that, for times beyond 1 million years, it becomes increasingly difficult to exclude significant changes in the geological environment. Nagra argues, using the concept of radiotoxicity index, that, after a period of ~ 1 million years, the radiological hazard from a disposal facility containing spent fuel (and HLW and long-lived ILW) is comparable to the hazard associated with (a) a high grade uranium ore deposit located within a similar volume, and (b) the naturally occurring radionuclides contained within 1 km^3 of Opalinus Clay. The IRT considers that the reasoning used by Nagra, based on radiotoxicity, to a) conclude that the timescale over which the spent fuel provides a hazard that needs special attention is of the order of about one million years, and to b) restrict the timescale of the calculations to 10 million years, is acceptable.

The IRT also notes that, because radiotoxicity does not say anything about actual exposure, such arguments should be used with care elsewhere in the assessment. The dose-dominating radionuclides in the Nagra assessment (^{129}I, ^{36}Cl, ^{14}C and ^{79}Se) are not present in uranium ores, nor do they occur naturally at the site.

In all instances, even for extreme cases, the radiation doses calculated by Nagra are orders of magnitude below the regulatory limit of 0.1 mSv per year. This is largely due to the excellent performance of the Opalinus Clay, which, because of its properties, becomes the dominant barrier in the system.

Nagra sets the lower cut-off point for dose estimation at 10^{-7} mSv a^{-1} which is much lower than the value (0.01 mSv a^{-1}) recommended by the IAEA (1996). It is stated that the risk of fatality from this exposure is 5×10^{-12} a^{-1} but it is doubtful whether this can be readily comprehended by anyone. The IRT observes that it would be more meaningful to compare dose estimates with the natural background, in which case it can be shown that a dose rate of 10^{-7} mSv is received in a few seconds of normal living.

In future assessments, the IRT suggests that less emphasis should be placed on quantitative comparison of scenarios and cases that can be shown qualitatively to result in trivial doses at long times. Instead, as the project develops from the disposal concept stage to detailed engineering design, the focus should shift to rigorous analysis of conceivable scenarios that might result in significant doses at earlier times (first 10 000 years), for example the post-closure impact of operational problems and accidents.

Overall, the IRT finds that Nagra's quantitative modelling is fit for purpose.

3.2.5 Supporting arguments, including multiple lines of evidence

Nagra makes wide use of natural analogues for confirming their understanding of the properties of the components of the multi-barrier system and as evidence that the components and system will evolve as anticipated. (see, e.g. Table 8.2-1 of Nagra, 2002a). The IRT was particularly impressed by the strength of geochemical and geophysical arguments with respect to the Opalinus Clay barrier. These arguments are based on chemical and isotopic profiles across the clay strata which demonstrate very low rates of movement of dissolved species in the past (discussed in Sections 4.1 and 4.4), the persistence of groundwater overpressures which demonstrate the low permeability of the clay, and the absence of significant fault movements and porewater anomalies. Analogue-based arguments are also used for the fuel matrix, the canisters and the bentonite buffer. The IRT notes that Nagra is engaged in international programmes to continue studying natural tracers and has a leadership role – with the support of the University of Bern – in an international programme that will be launched in 2004 under the auspices of the NEA "Clay Club". The IRT encourages Nagra to continue these programmes.

The more detailed quantitative modelling is supported by insight models that effectively illustrate the role of the Opalinus Clay in retaining sorbing radionuclides and dispersing non-sorbing radionuclides, resulting in very slow release rates to the surface environment. In addition to the quantitative assessment, Nagra uses many other arguments in support of its safety case, including complementary safety indicators such as radiotoxicity, radiotoxicity fluxes and radiotoxicity concentrations. The IRT considers the latter indicators to be of a more qualitative nature but finds that they complement the results of safety assessment and provide useful insights into the hazard of the waste as a function of time. Thus, the IRT considers that comparisons of radiotoxicity fluxes from the repository to the surface environment with those of naturally occurring radionuclides provide a useful complementary indicator that supports the argument to restrict the analyses.

The IRT concludes that the safety case utilises scientific knowledge effectively and exhibits a high level of system understanding.

3.2.6 Assessment of the main arguments in the safety case

Nagra has studied a wide number of cases to determine the robustness of the disposal design, including a number of very conservative "what if?" cases. In all cases, the safety criteria are met with a large margin of safety. In the Reference Case, diffusive transport in the Opalinus Clay ensures very low rates of release so that dose rates to individuals are well below the regulatory limits. Variations on the Reference Case that consider factors such as shorter container lifetimes and poorer performance of the engineered barriers demonstrate that, as long as diffusive transport dominates in the Opalinus Clay, the regulatory dose criterion would still be met even if the performance of the engineered barriers were much poorer than expected. Nonetheless, the engineered barriers are expected to perform as designed and remain an important part of the concept and of the safety case. The alternative cases, including the "what if?" cases, provide further evidence that, even if the performance of the Opalinus Clay is much poorer than assumed in the Reference Case, the regulatory requirements are met with a significant margin.

The results of the alternative cases can also be used, at least to some extent, more broadly to examine other situations not explicitly modelled. For example, Nagra did not explicitly model the presence of an initial defect in a steel canister as part of the Reference Scenario but they did so for a copper canister and the results of that case can be used to understand the potential impact for a steel canister.

Further, as noted in the documentation, a number of features that would further contribute to safety have not been taken into account in the modelling. Some of these are considered by Nagra to be so-called "reserve FEPs" that can be introduced in future safety assessments if needed. Thus, the conclusions set out in Chapter 9 of the Safety Report (Nagra, 2002a) are, in general, well supported and convincing. This is not to say that there are no outstanding issues that require attention but rather that there is every expectation that, with further work and study, including underground explorations and demonstrations in an underground test facility at the site, an adequate case can be developed to licence a repository for disposal in the Opalinus Clay of the Zürcher Weinland.

As discussed in Section 3.1.2, a safety case needs to present the synthesis of evidence, analyses and arguments in a statement of confidence. Nagra has presented a synthesis of evidence and arguments in Chapter 8 of the Safety Report (Nagra, 2002a). The IRT finds that this synthesis is clear, well presented and well argued and is consistent with international standards. It provides a concise summary of why Nagra has a high degree of confidence in the safety of disposal of SF, HLW and ILW in a repository constructed in the Opalinus Clay of the Zürcher Weinland.

The IRT notes that the Safety Report does not include in detail all elements of an explicit "statement of confidence" as recommended by the NEA (1999). Nagra identifies and examines uncertainties throughout the Safety Report, but does not prioritise them in its summary (Chapters 8 and 9 of the Safety Report). Guidance for future work is only discussed briefly in Chapter 8 of the Safety Report. In its discussions with the IRT, Nagra indicated that it chose not to prepare a detailed work plan at this stage because it did not want to pre-empt the decision-making process or the input from various review processes underway (including this review).

The IRT understands this decision but recommends that, if a decision is taken to focus the Swiss programme on disposal in the Opalinus Clay of the Zürcher Weinland, Nagra should revisit the safety case presented in Nagra (2002a) and use it, together with feedback from the various reviews of the *Entsorgungsnachweis* project, to prepare a prioritisation of remaining uncertainties and a future programme of work to reduce the level of these uncertainties.

The IRT finds the case presented in the Safety Report that SF, HLW and ILW could be disposed of safely and in accordance with the Swiss regulations to be sound and well thought out. It combines a mixture of quantitative and qualitative arguments. The multi-barrier concept and "pillars of safety" are emphasised. The primary containment for SF and HLW is expected to last for 10 000 years in keeping with the current emphasis on strong engineered barriers. The geological environment is a most effective component of the system and multiple lines of argument are used to establish a convincing case that the slow process of diffusion is the controlling transport mechanism within the Opalinus Clay.

3.3 Documentation of the Safety Case

The main safety document is the Safety Report, NTB 02-05 (Nagra, 2002a). It is supported by many other documents, including lower level reports, the most important of which are the Facilities and Operations Report, NTB 02-02 (Nagra, 2002c), the Geosynthesis Report, NTB 02-03 (Nagra, 2002b), the Models, Codes and Data Report, NTB 02-06, (Nagra, 2002e) and the FEP Management Report, NTB 02-23 (Nagra, 2002d). As in previous complex assessments dealing with waste repositories, the main arguments are presented in the Safety Report and supporting documents are referenced where appropriate in the text.

Each chapter in the Safety Report starts with an introduction that indicates what information will be provided and how this fits into the overall assessment. Through successive chapters, the proposed repository system is introduced, discussed and assessed. The organisation is logical, the layout is excellent, and the writing is clear and remarkably free of errors. The target audience appears to be specialists and regulators, rather than the general public. There is a good combination of quantitative data and qualitative arguments to support the overall safety case. Overall, the Safety Report and supporting documents are of a very high quality.

The chosen organisational structure is not perfect, however. For example, the approach followed by Nagra in the Safety Report means that a given issue is likely to be discussed over several chapters. Thus, the reader has to constantly cross check information across the various chapters and the report is somewhat fragmented and repetitious. Nonetheless the traceability is good and the reviewer is able to follow the arguments from the main report through to the detailed information, codes and data in the supporting documents. In some cases, however, the main document contains unsupported assertions that are not referenced back to lower level documents. In a few cases, not all the relevant information was reported even in the lower level documents.

Although it is clear that Nagra has made a significant effort to present information that is transparent and traceable, considerable effort is required of a reviewer to obtain fundamental information of interest. This, however, is not unique to the Nagra assessment but represents the reality with which reviewers must contend, namely that a considerable investment is required to understand a safety case for disposal and the underlying information that forms the basis for the case and for modelling the performance of a given system.

Overall the IRT concludes that Nagra has done an excellent job of documenting its safety case, beginning with a clear statement of objectives and principles that have guided the safety case and its documentation.

The IRT considers that transparency and traceability could be improved in the future if Nagra were to adopt a standardised approach to ensure that statements in the Safety Report, especially those of a contentious nature, were clearly cross-referenced to detailed arguments in supporting documents. A short overview report of, say 50-60 pages, reviewing the whole Entsorgungsnachweis project and its documentation, including the Geosynthesis and the Facilities and Operations Reports (Nagra, 2002b and 2002c), would be very useful to a wide readership.

3.4 Quality Assurance

Quality Assurance (QA) is an important consideration in building a safety case. Evidence of good quality assurance adds to confidence in the safety case: conversely, evidence of poor quality assurance undermines confidence in the safety case. There are two aspects of quality in project management, namely "doing things right" and "doing the right things". Both benefit from a strong quality culture.

Nagra has described their Quality Assurance Measures and Quality Management System in a general way in Appendix 8 of Nagra (2002e) and also made a special presentation on this topic to the IRT. The basic elements of this system comprise the following:

- a Company Policy that work is done by qualified people using appropriate tools;
- a Project Plan for a given project with, as required, Project Plans for sub-projects;
- a Quality Assurance Plan for a given project, setting out QA measures to be followed and, as identified in the Project Plan, QA Plans for specific sub-projects;
- a Project Documentation system to ensure that all relevant documents are catalogued and archived for any future use;
- a Data Clearance Process to ensure that data used are consistent, up-to-date and appropriate;
- audits to ensure that QM procedures are followed and to improve the QM system; and

- specific Working Procedures, Quality Assurance Guidelines and Quality Assurance Measures for specific working steps, including for the *Entsorgungsnachweis* project, for performing and checking performance assessment calculations and maintaining performance assessment codes.

The IRT has observed a number of examples of sound quality management practices followed by Nagra. These include, in addition to strong management commitment, the use of a formal project plan that sets out the project aims, boundary conditions and the responsibilities of project personnel and project groups, extensive use of peer review by both internal and external expert staff, including specific expert meetings to review scientific understanding (see also Section 3.2.2), the use of a formal change control procedure for software modifications, and the formal control of data used in safety analyses, including specific audit meetings to clear data for use in safety analyses. Another specific example of good practice was the evaluation and documentation of 3D seismic data prior to drilling the Benken borehole and the feedback of information from the Benken borehole to refine the interpretation of the 3D (and 2D) seismic data. One project group, the bias audit group, ensures that all relevant scientific understanding is taken into account in the definition of assessment cases. In seeking expert opinion on the cases to be analysed to assess the impact of uncertainties and the robustness of the proposed disposal system, either consensus was reached on the definition of the alternative case or an additional case was identified to take into account different expert opinions.

Overall, the IRT finds that there is evidence of a strong quality culture within Nagra that includes strong management commitment, the use of qualified and experienced staff, good internal communication among staff, assignments of project responsibilities and the use of a formal Quality Management System.

When the QM system was originally being developed the aim was to comply with ISO 9000, but the QM system has not yet been formally registered with ISO and has not yet been subjected to a formal external audit, although an external QA specialist has been consulted. *Nagra has, however, indicated its intention to register its QM system in compliance with ISO 9001:2000 and the IRT recommends that Nagra proceed with registration*. Doing so will involve a formal audit of Nagra's QM system. *The IRT also recommends that Nagra establishes a formal audit plan as an integral component of future project plans and of its QM system, utilising a mix of internal and external audits*.

The IRT considers information management to be a critical component of Nagra's work. The IRT understands that Nagra is aware of the importance of information management and has, to date, maintained its information satisfactorily using a project documentation approach. Geological investigations in Switzerland related to radioactive waste disposal have been ongoing since 1978. There is a general requirement to ensure that past, current and future data are organised, stored and can be easily retrieved using, e.g., a relational database or similar information system that can be updated as information technology advances. The IRT encourages Nagra to review the tools and approaches it uses for archiving, searching and retrieving information to facilitate the retention of its corporate memory, noting that, in some other organisations, project documentation has not been satisfactory in preserving all valuable information.

4. ASSESSMENT OF THE MULTI-BARRIER SYSTEM COMPONENTS AND PROCESSES

This chapter assesses how the strategy, principles and methodology used in the safety case (as discussed in Chapter 3) were applied by Nagra in analysing (a) the safety performance of the components of the multi-barrier system, and (b) the various processes responsible for the release and transport of radionuclides. The treatment of the biosphere is also discussed. In carrying out this assessment, the IRT has given particular attention to the scientific understanding of barriers and processes.

4.1 Characterisation of the Geological Environment

The safety case rests to a large extent on the very favourable properties of the geological environment of the Zürcher Weinland, and especially the Opalinus Clay stratum. Accordingly, the IRT has taken considerable interest in the geological characterisation, which is summarised in the Safety Report (Nagra, 2002a) and described in detail in the Geosynthesis Report (Nagra, 2002b).

The geological framework for the current study was derived from a systematic host rock study for the whole of Switzerland. Beginning in 1978, the geological studies involved:

- selection of tectonically inactive and simply structured areas;
- analysis of the flow regimes and groundwater chemistry;
- understanding of important groundwater recharge and discharge areas.

The study of crystalline rocks was the subject of Project Gewähr (Nagra, 1985), which was reassessed from a safety perspective in the Kristallin-I report (Nagra, 1994).

Initially, the study of sedimentary deposits concentrated on the identification and a general assessment of suitable host rocks with low permeability and sufficient thickness in northern Switzerland. Subsequently, the characteristics of the potential host rocks were determined and assessed from an engineering, hydrodynamic and safety viewpoint.

The relevant information for the performance assessment of the Opalinus Clay was derived from the investigations carried out in Nagra boreholes (1982-1988), shallow boreholes (1989-1994), Mont Terri (from 1996 on) and the Benken borehole (1998-2001). The investigations have included:

- mineralogy and porosity data from Benken, Weiach, Riniken and Schafisheim boreholes, and from Mont Terri;
- rock mechanical data from Benken and Mont Terri;
- hydraulic property data and other information from *in situ* tests at Benken, Riniken, Schafisheim, Weiach, Mont Terri, and from laboratory tests on cores from Benken and Mont Terri, from 10 tunnels in the Folded Jura and 40 shallow boreholes in horizontally bedded Opalinus Clay;
- gas transport properties from Benken *in situ* tests and cores, and from Mont Terri *in situ* tests and cores;
- porewater geochemistry data from Benken cores and Mont Terri *in situ* tests and cores;
- diffusion data from Benken cores, Mont Terri *in situ* tests and cores, and natural tracer profiles from Benken and Mont Terri.

The IRT considers that the selection of the Zürcher Weinland as the priority area for local explorations in the *Entsorgungsnachweis* project is geologically transparent since it is the largest tectonically undisturbed area with Opalinus Clay at a suitable depth. Since 1991, the investigations in the Zürcher Weinland have included;

- one deep borehole (Benken) involving an extensive testing and logging programme;
- shallow boreholes (two piezometers, various uphole measurement boreholes for 3D seismics);
- about 60 km of 2D seismics;
- about 50 km^2 of 3D seismics, interpreted using modern evaluation tools; and
- assessment of hydrogeological boundary conditions from the regional survey.

The methodology and the objectives of the geological investigations are in line with international “geo”-practice and IAEA and NEA recommendations (IAEA, 1999; IAEA, 2001b; IAEA, 2003; NEA, 2001c; NEA, 2003; ITC, 2003; Witherspoon *et al.,* 2001). The understanding of the geological conditions in the investigation area is based on the high quality of the 2D and 3D seismic campaigns as well as the cored and intensively tested Benken borehole (Nagra, 1995; Nagra, 2001a; Nagra, 2001c; Nagra, 2001d). The core material from the Benken borehole was carefully logged and selected cores were subjected to detailed stratigraphic, mineralogical and petrographic studies (Nagra, 2001b; Nagra, 2001c; Nagra, 2001d). A comprehensive geophysical programme was undertaken, including petrophysical and structural investigations and seismic measurements (Nagra, 2001c; Nagra, 2001d). Neotectonic observations extending over several years were also undertaken (Nagra, 2002f). Hydraulic investigations were carried out in the Benken borehole (Nagra, 2001c; Nagra, 2001d).

In terms of the safety of a deep repository, the most important results of the neotectonic observations can be summarised as follows (Nagra, 2002f):

- In large areas of northern Switzerland, and particularly in the Zürcher Weinland, the Opalinus Clay has remained largely undisturbed since its formation some 180 million years ago.
- Seismic analysis shows that there is only minor seismic activity in the Zürcher Weinland.
- No safety-relevant impacts (no mechanical damage to the barrier system) of earthquakes on a deep geological repository in Opalinus Clay (650 m below the surface) are expected, even in the unlikely case of a large earthquake.
- Based on data from different sources (geomorphology, burial and uplift history, geodesy), it is assumed that linear erosion keeps pace with the long-term uplift.

The IRT took particular interest in the results and interpretation of the chemical and isotopic profiles in the porewater within the Opalinus Clay and adjacent layers. Nagra has modelled the data for isotopes of hydrogen and oxygen, and argued that they demonstrate that diffusion rather than advection has been the dominant transport process in the Opalinus Clay for periods of the order of 1 million years up to the present time. The chlorine isotope data is less consistent but does not contradict this conclusion (Gimmi and Waber, 2003). The IRT was impressed by the strength of this argument because of the long timescales involved and because it complements other evidence based on permeability.

From the viewpoint of performance assessment, the IRT notes that, with respect to the Zürcher Weinland:

- The system geometry, including the depth, thickness of the host rock and the surrounding formations is, in general, sufficiently well known.
- Most safety-relevant properties of the Opalinus Clay are specific to the rock type and data from various locations show that these properties show little spatial variability. This makes an extrapolation of information from the Benken borehole to the 3D seismic area acceptable.
- Some safety functions of the Opalinus Clay, including its capacity to self-seal, depend on the rock stress and are thus related to the thickness of the overburden. The depth of the Opalinus Clay in the Zürcher Weinland, and thus the thickness of the overburden, are clearly indicated in the boreholes and in the seismic studies.
- The assessment of the properties of the host rock relevant to safety assessment and engineering feasibility are based not only on investigations in the Benken borehole, but also on a large number of other investigations in Opalinus Clay, such as deep boreholes in the near and far vicinity of the Zürcher Weinland, tunnels, the Mont Terri URL, shallow boreholes and clay pits.
- For this stage of the project, the confidence in the characterisation of Opalinus Clay is adequate for safety analysis. Although it is possible that undetected geological features (tectonic heterogeneities) might be found in more extensive investigations, they are unlikely to be a source of major uncertainty. The environmental tracers in porewater as well as the hydraulic overpressures, indicate that permeability is very low over the scales of interest, in space and time, for transport through the Opalinus Clay, which is consistent with measurements *in situ* and in the laboratory.

In summary, the IRT has reached the following conclusions with respect to the geological environment in the studied area:

- *the geometric model of the Opalinus Clay of the Zürcher Weinland is well founded,*

- *the techniques and methodologies used by Nagra to characterise the geological setting are consistent with accepted geological practice and the conclusions are supported by multiple lines of evidence,*
- *Nagra has presented substantial evidence for the homogeneity of the safety-relevant properties of the Opalinus Clay within the Zürcher Weinland and evidence that these properties can be extrapolated over a wide region,*
- *the characterisation of the underground environment involves uncertainties, including the possibility of permeability variations and faults. These uncertainties are adequately taken into account in the safety assessment,*
- *the site characterisation work is in line with current international standards, e.g. IAEA (2004).*

Within this context, the IRT considers that Nagra has good reason to focus its future efforts on the Opalinus Clay of the Zürcher Weinland. The IRT concurs with Nagra's stated intention to drill one or more additional boreholes in the Opalinus Clay of the Zürcher Weinland before going underground at this site, should a decision eventually be made to do so.

4.2 Inventory and Source Terms

Determination of the waste inventory for the repository and the associated radionuclide source terms is the starting point for the calculation of radionuclide release rates into geological strata and subsequently into the environment. Accurate information on the waste inventory is essential for safety analysis.

Nagra has developed a numerical formula for determining safety-relevant radionuclides (see Appendix 5 in Nagra, 2002e). In total, 74 radionuclides meet this criterion. The IRT has reviewed Nagra's list and finds it complete for the needs of safety assessment.

A summary of the waste types and radionuclide inventories is given in Nagra (2002a) and more detailed information is provided in McGinnes (2002). The assumptions used in determining the waste inventory (origin, nature and quantities), in line with Swiss nuclear policy, are clearly indicated although the distinction between what currently exists and future arisings (probable or certain) is not indicated.

The waste inventories are based on operation of Switzerland's five nuclear reactors for 60 years. The total rated power output from these reactors is

3.2 GW(e). The assumed energy output over 60 years is taken as 192 GWa(e), which corresponds to a 100% load factor. An alternative case of 300 GWa(e) is also considered. The assumptions used to determine the inventory are assessed by the IRT to be reasonable and conservative.

About 27% of the spent fuel will be reprocessed under existing contracts with BNFL and COGEMA, generating both vitrified HLW and various types of ILW (e.g. fuel hulls and ends, sludges), which are conditioned in cement or bitumen.

The calculation of radionuclide activities in spent fuel is a well-established process using computer codes that have been in use and continually developed for over 30 years. The most commonly used code is ORIGEN (various versions). Nagra uses this code for some calculations and another code, BOXER, developed by PSI for high burnup fuel. Nagra reports reasonable agreement between BOXER and other codes for cases where they are applicable (McGinnes, 2002). Such calculations can be expected to be accurate to within about 20%, which is more than acceptable for the purposes of safety assessment.

The IRT carried out comparisons between the specific radionuclide activities for spent fuel as calculated by Nagra and data published from other assessments (USA and France). Particular attention was given to the activities of long-lived mobile radionuclides (such as ^{129}I, ^{79}Se, ^{36}Cl and ^{14}C), which contribute most to the estimated dose. If allowance is made for different burnups, the agreement with other data sources is generally good. The IRT notes that Nagra used the latest data for the half-life of ^{79}Se (1.1×10^6 years), which was an uncertainty in earlier assessment studies. The IRT concludes that the inventories for BWR UO_2, PWR UO_2 and MOX fuel are generally consistent with those used in other programmes and adequate for the purpose of safety assessment.

The IRT found insufficient information in Nagra (2002a) or the supporting documents to allow the activities of specific radionuclides in HLW or ILW to be verified. Nagra indicates that data are based in part on calculations and additional information supplied by BNFL and COGEMA; however, no further information is provided and the methodology is unclear. Subsequent discussions with Nagra staff indicated that there is considerable uncertainty in the current estimates of ^{129}I, ^{36}Cl and ^{14}C in both HLW and ILW. This arises because of process variability and the difficulty of measuring these beta-emitting isotopes in highly active materials. Despite these uncertainties, the estimates of the HLW and ILW source term are bounded and do not impact significantly on the overall safety assessment. The IRT concludes that the inventories are adequate for the current stage.

Nevertheless, *the IRT recommends that, for future assessments, Nagra should work to obtain better estimates (through discussions with reprocessing companies or otherwise) of the activities in HLW and ILW, especially the activities of those radionuclides that contribute most to the dose estimates*. If possible, agreement should also be reached with other countries with similar waste streams (e.g. France, Japan and Belgium) so that a coordinated set of data is generated.

4.3 Barriers and Processes Within the Near Field

This section is concerned with barriers and processes in the near field, which is taken to include the waste form, the waste canister or container, and the buffer or backfill.

4.3.1 Chemical, physical and geochemical data and processes

The understanding of the performance of the near field barriers requires knowledge of the various chemical, physical and geochemical processes that control the solubility, speciation, sorption and diffusion characteristics of elements in groundwater in contact with each barrier. The IRT acknowledges the considerable amount of work required to establish and maintain the Nagra/PSI thermodynamic database (Hummel *et al.*, 2002), which takes into account the available datasets and their corresponding uncertainties. The IRT encourages Nagra to continue this activity and to closely follow new developments, and acknowledges Nagra's willingness to do so, as demonstrated by its support of NEA activities in this field.

Nagra established four geochemical databases for the near field environment for SF/HLW (Berner, 2002; Bradbury and Baeyens, 2003a) and ILW (Berner, 2003; Wieland and Van Loon, 2002). Nagra has applied an integrated approach to the treatment of solubility, retention and transport processes in the safety assessment. This integrated approach is based on the principles of chemical thermodynamics, experimentally measured data for sorption and diffusion, complemented by expert judgement where no data are available.

The IRT considers that the methodology for assessing the chemical and geochemical environment in the near field is sound and up-to-date. The initial oxidising environment is considered, as well as the evolution to a reducing environment that occurs because of the presence of iron in the canisters and containers, and reducing minerals in the bentonite and host rock.

The IRT concludes that the Swiss programme is playing a leading role internationally in the development of geochemical databases related to radioactive waste disposal and has appropriately applied these databases to its analysis of near field processes.

Chemical retention has been treated in the safety assessment calculations by means of solubility limits and sorption coefficients (K_d values) for safety relevant elements. The retardation processes are assumed to be linear, reversible, in equilibrium, and it is further assumed that solubility limits constrain radionuclide concentrations in the near field, and that the concentrations are never exceeded in the far field. These assumptions are reasonable, fit for purpose, and in accordance with international practice.

In the application of their integrated approach, a hierarchy for the available data was introduced and the uncertainties were translated into best estimate, pessimistic and optimistic values. The highest priority has been given to Nagra's own experimental work or "in-house" data, both published and unpublished. Furthermore, data from the literature and chemical analogues have been used, as appropriate. For the cases where the above data were not available, expert judgement was used. Nagra compared K_d values derived from batch and diffusion experiments for a broad range of elements. The agreement was found to be reasonable but Nagra acknowledges that differences exist between the two types of experiments, especially for the redox-sensitive tetravalent ions.

Fick's law is used to describe the diffusion process in both the near and far fields. Some radionuclides are affected by anion exclusion, which affects their diffusion coefficient and the effective porosity that can be accessed. Furthermore, colloids are assumed to be immobile in the bentonite and the Opalinus Clay and do not contribute to enhanced transport. This assumption is supported by a technical report (Voegelin and Kretzschmar, 2002) and is reasonable given the filtration properties of clays.

4.3.2 Performance of canisters and containers

The canisters and containers that surround the wastes are the first of the multi-component barriers since they must first be breached before any release of radionuclides from the waste forms can occur.

For HLW and SF

Carbon steels are selected as reference materials for the SF and HLW canisters. The steel is 150 mm thick for the SF canisters and 250 mm thick for the HLW canisters. The design lifetime set by Nagra for both types of canisters is 1 000 years but the expected lifetime is 10 000 years (Johnson and King, 2003). Copper is a more durable alternative with a lifetime in excess of 100 000 years. Nagra has indicated that the SF canister design is conceptual in nature and details have yet to be established (Nagra, 2002a). The HLW canister is the same as that proposed in Project *Gewähr* (Nagra, 1985; Nagra, 1994).

Corrosion by water is the primary process leading to SF or HLW canister failure. Johnson and King (2003) give a good description and analysis of all potential mechanisms for corrosion under disposal conditions, including generalised corrosion under oxidising conditions in the initial aerobic phase, anaerobic corrosion, pitting and crevice corrosion, stress corrosion cracking, microbial corrosion due to sulphides and the effects of radiation. Nagra also assesses the considerable body of literature on anaerobic corrosion of mild steel and concludes that corrosion rates range from 0.1 to 10 μm per year. The IRT considers that the corrosion mechanisms considered by Nagra are consistent with scientific understanding. Furthermore, the assumed rates of corrosion are reasonable (conservative but not unduly so) and consistent with values used in other programmes, in particular for the reducing conditions that are expected to develop quickly after closure of the repository.

In the Reference Case, Nagra assumes that there are no initially defective canisters and all canisters are breached after 10 000 years. The assumption of simultaneous breaching is conservative since a distribution over time could be reasonably expected. The choice of carbon steel for the canisters limits the risk of early failures but the IRT considers that this risk cannot be excluded, in particular because of possible welding defects. Consequently, the IRT would have expected that a small fraction of steel canister defects would have been part of the Reference Scenario. However, the IRT accepts that the impact of early failures is covered by other cases (pinholes in the copper canister options (cases 5.3b and 5.3c) and the "what if?" case (4.7) involving poor near-field performance where, inter alia, the lifetime of all canisters is assumed to be 100 years). The latter case illustrates the dominant role of the Opalinus Clay in limiting release to the biosphere.

Nagra takes no credit for the stainless steel flask into which the HLW glass is poured or the Zircaloy cladding that encases the spent fuel. Both these assumptions are conservative although in keeping with the assumptions made in most other programmes. The Yucca Mountain Project has, however, considered the fuel cladding to be a significant barrier (US-DOE, 2000).

In summary, the IRT concludes that the assessment of SF and HLW canisters, as part of the multi-barrier system, is reasonable and generally conservative. Although it considers that the choice of steel as the canister material is reasonable, the IRT recommends that copper be maintained as an option because of its benefits, which include a longer lifetime and less gas generation. The IRT also notes that the manufacturing defect rate for copper canisters is uncertain and concurs with Nagra's decision to follow progress on evaluation of copper in other programmes (for example, Sweden and Finland).

For ILW

A number of different container types are proposed for ILW but they generally involve a steel or fibre cement drum, which is placed inside a concrete container with a wall thickness of 20-25 cm (Nagra, 2002c). Not all the primary containers are watertight and so moisture may access the waste fairly soon after emplacement.

The corrosion of the ILW metallic containers and metallic wastes is discussed in Nagra (2003a). The metals are carbon steels, iron and stainless steels. The mechanisms of corrosion in cementitious media with temperatures up to 40°C and in the presence of chlorides are not discussed in detail, but the information used in the safety assessment is consistent with current understanding. Strongly reducing conditions are expected to develop due to iron redox buffering. The kinetics of corrosion are discussed and the values selected are reasonable (0.1 micron per year for carbon steels and 0.01 micron per year for the stainless steels).

In the reference scenario and in other cases, Nagra assumes that release of radionuclides into the cementitious backfill occurs after 100 years. Thus little credit is taken for the ILW containers. This is conservative but consistent with the approach adopted in other programmes for this type of waste.

4.3.3 Performance of waste forms

This section considers Nagra's analysis of the release of radionuclides from the three waste types (SF, vitrified HLW and ILW) once the containment has been breached and they are exposed to water.

Spent fuel (SF)

Spent fuel is the dominant contributor to the source term, comprising 85% of the total radioactivity in the repository. Intensive research has been conducted on the behaviour of spent fuel throughout the world. Nagra's treatment is consistent with the approach taken internationally i.e. two components are analysed (a) the initial rapid release of mobile elements from the fuel and (b) the slow release of uranium and other elements (assumed to be congruent) as the fuel matrix dissolves.

Volatile and mobile radionuclides produced during reactor operation will tend to migrate along cracks and grain boundaries in the fuel pellets. A fraction of these radionuclides will migrate to the gap between the fuel and the cladding. Both the radionuclides in the gap and along grain boundaries readily dissolve when the fuel is exposed to water. Nagra refers to the fraction in the gap and in readily accessible grain boundaries as the "instant release fraction" (IRF), which varies with burnup and other factors, such as the thermal history of the fuel during reactor operation. The IRF is important to the safety assessment since it determines the initial release pulse into the buffer and because the matrix dissolution rate is estimated to be very low.

Nagra reports experimental measurements on IRF for fission gases, caesium, strontium, technetium, iodine and carbon (Johnson and McGinnes, 2002). Estimates, based on chemical considerations, are made for some other elements (e.g. selenium, chlorine). The values of IRF for key elements (for the reference burnup) are iodine 4-9%, caesium 4-5%, chlorine 10-13%, carbon 10% and selenium 4-9%. Much higher values are used for higher burnups and MOX fuels. The IRT considers that these values are consistent with other studies and are slightly conservative.

Two models for SF dissolution are considered by Nagra; a radiolytic model (the Reference Case) and a solubility-limited model (which is analysed as alternative case 1.2). The discussion on the various mechanisms is in conformity with current knowledge, in particular with respect to radiolytic dissolution of the fuel. It is clearly indicated that the dissolution of the matrix is slow under reducing conditions and relatively fast under oxidising conditions.

Even if the overall repository environment is reducing, oxidising species (radicals and hydrogen peroxide) are produced by alpha radiolysis. In Nagra's radiolytic model, the fuel dissolution rate is assumed to be proportional to the alpha activity in the fuel. The model takes a Geff value of 0.01 for production of hydrogen peroxide and conservatively assumes that all the oxidants produced react with the fuel (Johnson and Smith, 2000). For this model, the fractional release rates (for the reference fuel) decrease from 2 x 10^{-6} per year after 100 years to 5 x 10^{-7} per year after 10 000 years and about 2 x10^{-8} per year after 10^{6} years.

For the Reference Case, the maximum dose from spent fuel is 4.8 x 10^{-5} mSv per year occurring after 1 million years and dominated by ^{129}I. The majority of this (about 75%) comes from the IRF rather than matrix dissolution.

Even though the radiolytic model is adopted for the Reference Case on the grounds that it is conservative, Nagra argues strongly that radiolytic oxidative dissolution does not occur at the hydrogen overpressures expected in the repository environment (Nagra, 2002a). This may be a source of confusion to the non-expert reader.

In the solubility-limited model, the uranium concentration within the breached canister is assumed to be the saturated value for reducing conditions (3 x 10^{-9} molar or 0.7 ppb) (Nagra, 2002e). The uranium then migrates by diffusion into the geosphere where it is subject to adsorption, diffusion and advection as in the Reference Case. This approach appears to be soundly based. The fuel dissolution rate calculated in this manner is more than two orders of magnitude less than the Reference Case. Release of key radionuclides for timescales up to 1 million years is therefore determined by the IRF and not matrix dissolution. The maximum dose rate for the solubility-limited conceptualisation (case 1.2) is 3.7 x 10^{-5} mSv per year, about 25% less than for the Reference Case.

Nagra also considers two "what if?" cases (4.3a and 4.3b) involving enhanced spent fuel dissolution rates. In these cases, the matrix dissolution rate is arbitrarily assumed to increase by factors of 10 and 100 above the Reference Case. Under such conditions, matrix dissolution becomes more important than the IRF and the estimated dose rates rise accordingly. For the ten-fold increase in dissolution rate, the maximum dose rate increases by a factor of about four. Finally, for a hundred-fold increase in fuel dissolution rate, the maximum dose rate (5 x 10^{-4} mSv per year) increases by a factor of about ten. The main value of the "what if?" cases is to show what would happen if the fuel dissolution were much faster, such as might occur under oxidising conditions. The hundred-fold increase in dissolution rate corresponds to complete matrix dissolution within about 50 000 years.

In summary, Nagra scientists have carried out considerable research and assessment on the dissolution of spent fuel and radiation effects. The IRT concludes that the safety analysis of spent fuel behaviour is state of the art. That is not to say that there is not more to learn and understand, especially in regard to radiolysis effects. Accordingly, there is scope for more fundamental research in this area since there is a broad range of views internationally on the effects of alpha-radiolysis on fuel dissolution.

The issue of criticality was considered in the post-closure safety assessment but an in-depth discussion was not presented. Based on the feedback at our final meeting, the IRT is satisfied that Nagra:

- is aware of the issue;
- is following the work done in this area in other programmes; and
- will, in due course, put in place appropriate processes to avoid criticality excursions in the post-closure (and operational) phase.

There is no urgency to address this issue further at this stage.

Vitrified HLW

Switzerland will receive most of the primary liquid waste from the reprocessing of its spent fuel as vitrified HLW: some material has already been received. The glasses produced by BNFL and COGEMA are similar in composition but the specific radioactivity of the COGEMA product is about 15% lower than that from BNFL. The glasses are solidified inside waste flasks; there are 730 flasks each containing about 400 kg of glass. The combined HLW contains about 15% of the total activity in the repository, but contains negligible levels of ^{36}Cl and is markedly deficient in ^{129}I and ^{14}C.

Curti (2003) gives a balanced appraisal of the state of understanding of glass leaching. In short, there are conflicting approaches to the modelling of long-term leach rates but agreement that the silica concentration in solution and diffusion of ions through the silica gel layer are important factors. The report also acknowledges that increased leach rates have been observed by other researchers in the presence of bentonite and iron corrosion products because of removal of silica from solution.

Nagra estimates the long-term leach rates of simulated (non-radioactive) BNFL and COGEMA waste glass from experiments at PSI that have been ongoing since 1990. These experiments differ in several respects (temperature, particle size, surface area to volume ratio) from the expected repository environment. Moreover, no experiments have been undertaken by PSI in the presence of bentonite or iron corrosion products. PSI used a regression fit of the release rates for times greater than 500 days to estimate the long-term leach rate. The values obtained were 1.5×10^{-3} g m^{-2} day^{-1} for BNFL glass and

2×10^{-4} g m^{-2} day^{-1} for COGEMA glass (Curti, 2003). The IRT acknowledges that the measured leach rates are within the range of values obtained in other experimental studies of this type. The large difference between the BNFL and COGEMA data is attributed by PSI to the presence of magnesium in the BNFL glass. These experiments are continuing and leach rates may be revised at a later date.

Nagra acknowledges that there are some uncertainties in current estimates of the long-term glass corrosion rate, especially related to possible sorption of silica onto bentonite (Nagra, 2002a). To take account of these uncertainties, Nagra also considers the parameter variation (case 1.1e) where the leach rate is increased by a factor of 100. There is no significant increase in the overall dose rate because of low concentration of mobile radionuclides in the HLW and the long migration time through the Opalinus Clay. The IRT accepts that the performance of the vitrified HLW stream is not critical to Nagra's overall assessment.

On the other hand, the IRT considers it unfortunate that, for a waste form of such importance internationally, the level of mechanistic knowledge and understanding of long-term performance is not yet mature. The IRT accepts that the dissolution of vitrified HLW under disposal conditions is complex, but considers that there is a need for carefully selected and well-focused co-operative programmes to reach an international consensus. Future R&D efforts need to focus not only on experimental measurements of elemental release rates from the glass matrix, but also on the growth and characteristics of the gel layer, the role of secondary siliceous mineral phases and the effects of near field materials. Nagra is aware of these issues and is working through PSI in cooperative programmes to improve fundamental understanding and predictive models.

Despite the uncertainties noted above, the IRT accepts that glass is a durable waste form and that the dissolution process will take place over very long time frames (tens to hundreds of thousands of years). Thus, it is appropriate for Nagra to consider the glass matrix to be a significant barrier in the multi-barrier system.

The IRT recommends that Nagra monitors international research programmes aimed at developing a better mechanistic understanding of, and mathematical models for, the long-term leaching of vitrified HLW under disposal conditions and maintains expertise in this area.

ILW

The ILW contains only 0.1% of the total radioactivity in the repository but proportionately higher amounts of ^{129}I (0.9%), ^{36}Cl (1.7%) and ^{14}C (8.7%) (McGinnes, 2002). It comprises a variety of physical waste types of moderate to high chemical durability, such as cement, bitumen and Zircaloy metal. The waste forms are contained inside steel containers.

Nagra adopts a simple model for ILW performance by assuming that the release of radionuclides does not occur until 100 years after emplacement (due to incomplete water saturation at earlier times). At 100 years, all radionuclides are assumed to migrate instantaneous into the surrounding cementitious backfill, i.e. no credit is taken for immobilisation of radionuclides within the waste form (Nagra, 2002a). Solubility limits are taken into consideration, however. Given the complexities of the waste forms and the small inventory of radionuclides, the IRT considers Nagra's approach both conservative and appropriate for the current phase of the project. The IRT also notes that in the future, it may be possible to define more realistic performance models for some ILW, such as Zircaloy.

4.3.4 Performance of buffers and backfills

This section considers Nagra's assessment of the bentonite buffer in the case of SF and HLW and the cementitious backfill in the case of ILW. These barriers perform a number of important functions including:

(1) providing physical confinement for the waste package at its position of emplacement;

(2) protection of the geological barriers from temperature effects due to heat generation;

(3) sealing of the emplacement tunnels and preventing tunnel convergence; and

(4) attenuation of radionuclide transport due to sorption and slow diffusion processes.

For SF and HLW

Bentonite is the preferred backfill material for SF and HLW in most international programmes because of its swelling and self-sealing properties, coupled with its excellent sorption characteristics. Since it is composed of clay minerals, bentonite is also highly compatible with the Opalinus Clay host rock.

The IRT notes that the bentonite buffer concept proposed by Nagra differs from international practices on two particular points, namely (i) use of bentonite pellets, and (ii) designing for maximum temperatures above 100°C in the inner half of the bentonite buffer.

The use of bentonite pellets rather than blocks to fill the void space around and above the waste package is an innovation that promises better sealing since pellets are better able to fill any irregular void space. However, there is currently little engineering scale data on the behaviour of such pellets. An ongoing test at Mont Terri to study thermal-hydraulic-mechanical (THM) processes should bring much information and will be of interest to other programmes. At the present time, the IRT considers that the use of bentonite pellets is promising but not yet fully proven.

The use of low moisture granules results in a low thermal conductivity and hence a higher maximum temperature in the bentonite. Nagra has calculated temperature profiles in the buffer as a function of time for SF and HLW (Johnson *et al.*, 2002). The maximum temperatures at the canister surfaces, which are reached after about 10 years, are in the range 140-160°C. The temperatures decrease slowly with time, especially for the SF, and remain above 100°C for several hundred years.

At high temperatures, bentonite is subject to mineralogical alteration and changes that affect its swelling properties and plasticity. Nagra discusses these issues in the Safety Report (Nagra, 2002a) and imposed a design condition that the temperature in the outer half of the buffer should not exceed 125°C. Under these conditions, Nagra argues, on the basis of limited scientific data, that the bentonite will fulfil its functions with no significant long-term effect of temperature on the swelling pressure, sorption properties or saturated permeability. The IRT considers that these data cannot be considered as strongly validated at this stage of the project. The IRT also notes that the uncertainties concerning the thermal degradation of the bentonite buffer are covered by cases analysed in the safety analysis and that the design temperature for the buffer temperature does not need to be resolved before underground site characterisation studies are initiated.

The model for radionuclide transport through the bentonite barrier assumes transfer by diffusion only, with linear sorption isotherms described by K_d values for each element. Reducing conditions are assumed and, where applicable, solubility limits are derived from the PSI/Nagra database (see Section 4.3.1). The effects of gas generation and any tunnel convergence on radionuclide transport are assumed to be negligible. The IRT considers these assumptions to be reasonable.

Nagra derived K_d values for the bentonite near field environment from well designed batch experiments the results of which were then extrapolated to compacted in situ conditions. This approach is highly innovative and its validity has been demonstrated by Bradbury and Baeyens (2002). Their method includes the adjustment to in situ mineralogy and porewater chemistry and the most up-to-date sorption models were used.

There are other possible interactions between the bentonite barrier and other components of the disposal system, including iron/bentonite interactions and silica cementation. The IRT notes that Nagra implicitly considers these chemical effects as negligible.

Except for radium, co-precipitation is not considered. This is conservative but leads to predictions that significant quantities of some actinides (e.g. ^{230}Th, ^{231}Pa, ^{229}Th) are released into the buffer. This is at variance with experience based on analogy with uranium ores. Co-precipitation is a "reserve FEP" and Nagra should give consideration to incorporating it into models as more data become available.

The IRT notes that the interface between the radionuclide transport models for the near field and the far field is based on simplified approaches. The outer boundary condition for the bentonite transport model is described by an "effective advective flow" approach, which is physically incorrect and somewhat arbitrary. Although accepting, based on information presented to the IRT by Nagra, that this approach is fit for purpose, the IRT also notes that the conservative nature of this approach is not self-evident. For future applications, a broader use of fully coupled models should be considered to improve the traceability and rigour of the analysis.

The effects of thermal alteration are considered in case 1.3 of the Reference Scenario. In this case, the sorption properties of the bentonite are assumed to be unaffected by degradation but the diffusion coefficient in the inner half of the bentonite is taken to be the value in free water. The calculated dose rates for this case are essentially the same as for the Reference Case. This is to be expected since the Opalinus Clay layer is much thicker than the bentonite layer and thus provides most of the radionuclide attenuation. However, this result should not be interpreted as implying that the bentonite is of little importance, since its other functions [see (1) to (3) above] are implicitly assumed to apply in all of Nagra's analyses.

In summary, the IRT concludes that the bentonite buffer, in addition to providing a favourable chemical environment, a strong isolation barrier and heat transfer mechanism, also provides a well understood mechanism for ensuring the self-sealing of the EDZ surrounding the emplacement tunnels in which the waste containers are placed. The remaining uncertainties are concerned with design issues (the use of bentonite pellets, higher temperatures and the need for tunnel support) that can be resolved before the construction licensing stage.

Having regard for the current uncertainties, *the IRT recommends that:*

- *research should continue on the behaviour of the bentonite at elevated temperatures in order to establish the maximum bentonite temperature that can be tolerated without significant detrimental effects on its performance as a barrier within the multi-barrier system.*
- *R&D and larger scale experiments should continue on the use of bentonite pellets as a backfill material with the aim of establishing the technology for use in the emplacement tunnels.*
- *possible interactions between the bentonite barrier and other components of the disposal system, including iron/bentonite interactions and silica cementation, should be investigated further*.

If current uncertainties cannot be resolved, the buffer temperature could be lowered by a number of measures such as increasing the spacing between waste packages, increasing the cooling time before waste emplacement or modifying the buffer materials to improve their heat transfer characteristics. The IRT concurs with the statement in the Safety Report that the bentonite buffer "provides a suitable environment for the canisters and the waste forms".

For ILW

The ILW will be emplaced in larger diameter tunnels and backfilled with a cementitious mortar. Nagra has considered the effects of radiation, temperature evolution, gas production (both from iron-based and organic materials), tunnel convergence, porewater chemistry and, most importantly, the effects of the high pH plume on the properties of the Opalinus Clay. Potentially oxidising conditions, caused by reactions of nitrate present in ILW-2, have also been properly addressed by applying sorption and solubility values, derived for these oxidising conditions.

In the Reference Scenario, release of all radionuclides into the cementitious mortar is assumed to occur 100 years after emplacement. Linear sorption isotherms described by K_d values for each element have been experimentally determined or taken from the literature. Solubility limits are also applied where appropriate. The effects of uncertainties are taken into account in several cases, which assess convergence-induced release, gas-induced release of groundwater and the gas release pathway. The IRT considers these analyses satisfactory for this stage of the programme.

The IRT notes that release of mobile radionuclides from the ILW is expected to be proportionately higher than from SF and HLW but that the overall ILW source term is relatively small (see Section 4.3.3); consequently, the contribution to dose is typically an order of magnitude below that of spent fuel. Emplacing the ILW in different tunnels that are physically separate from each other and from the SF/HLW tunnels are important design features that would lessen the impact of any uncertainties arising from chemical effects or gas production within the ILW near field system.

The IRT notes that several international programmes are now exploring the issue of the impact of a high pH environment due to the use of conventional cements and there is interest in alternatives that might reduce the overall alkalinity. *The IRT recommends that developments in alternative cements, aimed at reducing chemical interactions with buffers and the geosphere, be monitored*.

4.4 Performance and Characterisation of the Opalinus Clay Barrier

The Opalinus Clay of the Zürcher Weinland is the dominant barrier in the disposal concept proposed by Nagra. Some characteristics of the Opalinus Clay have been discussed in Section 4.1. This section discusses Nagra's assessment of the performance of this barrier within the overall disposal system.

Nagra has used multiple lines of reasoning in assessing the Opalinus Clay of the Zürcher Weinland, including the following:

- The hydraulic conductivity of Opalinus Clay has been measured by field tests in the Benken borehole and in various laboratory studies. The measured values range from 1^{-6} x 10^{-14} m/s from packer tests (parallel direction) and 0.6^{-3} x 10^{-14} m/s (vertical direction) from permeator tests. For the Reference Case, a hydraulic conductivity of 2 x 10^{-14} m/s was used perpendicular to the bedding.
- Measurements have confirmed that the Opalinus Clay is over-pressurised. Although there are a number of possible explanations for the overpressure, its very existence is testimony to the very low permeability of the Opalinus Clay. Modelling of the overpressure by Nagra indicates that the hydraulic conductivity must be either very low ($\leq 10^{-15}$ m/s) and/or the flow regime non-Darcian in that a threshold gradient is required for flow. The origin and persistence of

the overpressure may be worthy of further study, in order to enhance scientific understanding, but this is not critical to the safety case.

- The isotopic profiles of oxygen and hydrogen in the Opalinus Clay taken from the Benken borehole (see Section 4.1) are consistent with pure diffusion only and show significant deviations from the modelled profiles for hydraulic conductivities above 10^{-12} m/s.
- 2D and 3D seismic tests indicate relatively homogeneous structure over large distances.
- Geochemical evidence indicates that the Opalinus Clay porewater has been stable for millions of years with no identifiable perturbations from glaciation and other climate cycles.
- An analysis of mechanical properties shows that the Opalinus Clay is self-sealing and this is supported by the low transmissivities measured in faulted zones.

The IRT considers there is substantial evidence for the low permeability values used by Nagra in their modelling studies. This and other evidence cited above supports Nagra's argument that slow diffusive transport, coupled with sorption for many radionuclides, is the dominant mechanism for migration of aqueous species through the Opalinus Clay. Furthermore, the IRT finds that the geological and geophysical evidence for extensive homogeneity in permeability within the Opalinus Clay is convincing. Spatial variability exists on the small scale but, on the scale of interest for safety assessment tens of metres, such variability can be adequately accounted for by using an average value.

The *in situ* redox conditions are assessed to be reducing based on the quantities of pyrite, siderite and organic carbon in the Opalinus Clay. The remaining uncertainties on the porewater composition are related to the pH and the partial pressure of carbon dioxide. These uncertainties, however, have been adequately dealt with by means of bounding values, which have been taken into consideration in assessing radionuclide geochemistry.

A geochemical database for use in the performance assessment of Opalinus Clay has been established (Bradbury and Baeyens, 2003b). The K_d values used in the model are based largely on batch experiment data on Opalinus Clay (Lauber *et al.,* 2000; Bradbury and Baeyens, 2003b). The IRT considers that this approach is justified considering the difficulties in carrying out migration experiments on Opalinus Clay because of its very low permeability, especially for strongly sorbing elements. However, the IRT encourages Nagra to explore the possibilities of other recently developed techniques in the field of diffusion and retention studies, such as the electromigration technique (Maes *et al.,* 2002).

As for the bentonite, the K_d values used by Nagra are in reasonable agreement with those used in other programmes on argillaceous rocks, except for the trivalent and tetravalent elements. For these elements, the Nagra data are on the high side of the spectrum. However, these uncertainties have been taken care of by safety assessment cases that use pessimistic data and, from a presentation provided to the IRT, it became clear that Nagra has even tested the robustness of their system by assuming zero values for sorption.

To increase the overall confidence in the system behaviour, the IRT encourages Nagra to further validate their approach to use K_d values from batch sorption experiments in the safety assessment calculations, especially for the redox-sensitive species (Tc, U and Np), and to demonstrate the validity of using chemical analogues (for instance Th(IV) and Tc(IV)).

A one-dimensional transport model (PICNIC) with linear sorption is used to describe migration of radionuclides through the Opalinus Clay. The model used is state-of-the-art. In the absence of more specific information, a single value for effective diffusion coefficient (10^{-11} m2/s) and accessible porosity (0.12) is used for all cations, and another single value for effective diffusion coefficient (10^{-12} m2/s) and accessible porosity (0.06) for all anions in the Reference Case. The IRT considers these values to be reasonable. However, the IRT encourages Nagra to elaborate more on the detailed processes of diffusion in clay systems, to resolve outstanding issues such as the higher effective diffusivity for Na+ compared to tritium.

Nagra uses an insight model to illustrate how slow transport through the Opalinus Clay, combined with radioactive decay, attenuates the releases of individual radionuclides. This model clearly demonstrates that only long-lived, non-sorbing [^{36}Cl, ^{79}Se and ^{14}C (in organic form)] or very weakly sorbing radionuclides (^{129}I) are able to penetrate the clay barrier before they decay, while sorbing radionuclides are not.

Because of the importance of the Opalinus Clay, many of the cases analysed in the safety assessment are related to transport through the clay barrier. Cases considered include increases in the flow rate in the Opalinus Clay, a decrease in the clay thickness and transport along transmissive discontinuities. The IRT considers that the uncertainties in groundwater flow rate and possible in homogeneities in the clay are reasonably covered by the cases analysed.

In summary, the IRT finds that Nagra has presented strong evidence, based on multiple arguments, that the Opalinus Clay of the Zürcher Weinland is a suitable host rock for a waste repository. It is a tight, self-sealing material that would provide strong isolation, retention, delay and dispersion of any radionuclides released from a disposal facility located within it. Natural analogue studies, laboratory and field experiments as well as theoretical analyses corroborate this.

Overall, the IRT considers the treatment of diffusion and retention to be sufficient for the current stage of the project, especially considering the way that uncertainties have been dealt with in the safety assessment. For the future stages of the programme, however, *the IRT recommends that Nagra should:*

- *continue its efforts in the fields of geochemical retention;*
- *continue to assess its approach to using K_d values based on batch sorption experiments in safety assessment calculations;*
- *demonstrate the validity of using chemical analogues;*
- *elaborate further on the processes of diffusion in the Opalinus Clay*.

Such studies would maintain expertise while improving understanding, thereby increasing the overall confidence in the disposal concept.

4.5 Gas Generation and Transport

There are several chemical processes that generate gas within the repository. The most important of these are the anaerobic corrosion of iron, which produces hydrogen, and the decomposition of organics, which produces methane and carbon dioxide. The mechanisms for generation of gas in the repository are well understood and can be modelled in terms of processes and parameters. Some uncertainties exist in the rate of gas generation, which have been taken into account by Nagra by using pessimistic ranges of production. The main assumptions concerning gas production are partly found only in the lower level documents. The IRT considers they should also be presented in the Safety Report.

The generation of gas will result in a pressure build-up, which could affect the performance of the engineered barriers and the integrity of the host formation. It could also act as a driving force for the movement of contaminated water. The effects of gas build-up and migration are important issues in the disposal of radioactive waste in low permeability clay formations (NEA, 2001d).

The complexities of gas migration are fully appreciated by Nagra, who have carried out a detailed assessment of the issue. The migration of gas from the near field through the clay formation was described and evaluated by the use of two-phase flow models. The models take into account the relative permeabilities of the two phases and capillary pressures as a function of the saturation and the gas entry pressure. Increased permeability arising from pathway dilation at elevated gas pressures was also taken into account.

Nagra's analysis shows that the gas can migrate via the two-phase flow mechanism. If this process does not provide sufficient transport capacity for the gas generated, it can also migrate via the pathway dilation mechanism. Neither of these phenomena will cause fracturing of the clay formation and hence will not affect the long-term integrity of the clay barrier. By avoiding the development of gas fractures, which would provide long and highly permeable preferential pathways, diffusion remains the main mechanism for radionuclide migration. Hence, according to Nagra's analysis, the favourable characteristics of the clay formation as the main barrier of the disposal system are maintained.

For the release of the gas out of the clay formation, the direct pathway through the clay formation was considered. This can be considered as a conservative approach since the pore volume of the buffer could store the gas and delay the development of a pressure build-up. Based on the current results of two-phase flow calculations, the impact of gas pressure on the performance of the buffer and the other engineered barriers is also negligibly low.

Nevertheless, the IRT considers that migration of gas through the low permeability formations involves complicated processes and the knowledge and understanding of such processes is not fully mature. The IRT notes that Nagra has made significant improvements in recent years in understanding and modelling gas migration. The different processes are well discussed in the Safety Report and the gas issue has been sufficiently addressed for this stage of the project.

The IRT recommends that experimental investigations on gas transport processes should be continued. Future work should provide more experimental support for assumed capillary pressures and relative permeabilities, in particular for saturations of water between 90 and 100%. It should also provide additional experimental evidence concerning the formation of micro-fractures and any resulting increase in intrinsic permeabilities.

The IRT also recommends that modelling work on the gas transport processes should also be improved by allowing for increased permeabilities due to the formation of micro-fractures. In addition, more work is required to *validate the fundamental approaches to two-phase flow and the associated computer codes.*

If the remaining uncertainties concerning the migration of gas through the low permeability clay cannot be solved sufficiently by future research and development work, a solution is available for SF and HLW wastes involving the use of copper canisters and non-iron-based inserts. Such canisters avoid the generation of gas and will also provide a more durable containment barrier. For ILW, modified disposal strategies can be considered to ensure that gases escape via the access tunnels rather than through the clay formation.

4.6 Performance of Other Confining Geological Units

The other confining units immediately above and below the Opalinus Clay form rather heterogeneous hydrogeological units and have a discontinuous nature. These units are mainly low permeability, clay-rich sediments, which contain a complex system of partly interconnected, partly disconnected permeable sandstone and carbonate rocks. The lateral extent of these facies is mostly unknown. Their large-scale lateral hydraulic connectivity is not known, and no data are available to verify their regional-scale flow or their discharge to the surface groundwater system. Isotopic and hydrochemical evidence (Nagra, 2002a, 2002b), however, indicates that flows within these strata are small. The confining units maintain a favourable chemical environment for the Opalinus Clay and the low groundwater flow also ensures a stable thickness for the main geological barrier. Above and below the confining units are regional aquifers, comprising limestone and dolomitic rocks, which provide considerable dilution but no significant barrier to radionuclide transportation. The confining units represent further geological barriers because of their good retention properties for radionuclides and the long transport distances to the accessible environment in the case of lateral transport.

To date, Nagra's study of the other confining geological units has mainly been confined to basic system understanding. The development of that understanding has not reached a status where barrier functions in terms of dispersion and retention are well enough defined to be included in the safety case. Consequently, in the Reference Case, transport through the other confining units into the biosphere is assumed to be instantaneous. Given the excellent properties of the Opalinus Clay, this approach is conservative and reasonable.

In the conceptualisation for assessment case 1.5, Nagra has illustrated the potential benefit that could result from taking into account transport of radionuclides through the confining units. Two cases were considered: one involving vertical transport only (case 1.5a) and the other involving both vertical and horizontal transport (case 1.5b). The calculations indicated a significant reduction in peak dose and an increase in the peak time.

The IRT considers that further investigations of the characteristics of the confining units would fulfil a number of purposes. Firstly, it could improve the understanding of transport pathways to the biosphere, especially horizontal transport through the more permeable strata. Secondly, it would allow Nagra to utilise the barrier functions of the confining units within the reference conceptualisation. Also, the confining layers need to be sufficiently characterised for the design and engineering work to ensure that repository construction can proceed safely through these layers.

After leaving the confining units, the contaminated water is diluted by the aquifers above and below the confining units. The calculation of the flow rate in the Quaternary gravel aquifer (assumed to be the source of drinking water) is based on estimates of the cross-sectional area, the hydraulic conductivity and the hydraulic gradient. The basic assumptions leading to the dilution calculations are not given in the Safety Report (Nagra, 2002a). From data in lower level documents and from answers to the questions posed by the IRT, the bases for Nagra calculations were obtained. The total flow rate in the Quaternary gravel aquifer was estimated by Nagra to be 1.5×10^6 m^3/a, which was rounded to 10^6 m^3/a in Nagra (2002a). The IRT considers that the basic assumptions and data to establish the dilution effect in the subsurface aquifers should have been given and discussed in the Safety Report.

In summary, the IRT considers that the other confining units are a potentially useful "reserve FEP". Further investigations of these confining units on a local and regional scale would also improve the current understanding of transport pathways to the biosphere.

4.7 Potential Impacts of Repository Design and Development on Post-closure Safety Assessment

The safety assessment of the repository (and, in particular, the main barrier, the Opalinus Clay) is based on the assumption that the favourable primordial properties (as discussed in Sections 4.1 and 4.4) are not affected by the repository development. The IRT considers that one of the key issues in safety assessment of Nagra's disposal concept is the extent to which the engineering works involved in repository construction, operation and closure could disturb the retentive properties of the Opalinus Clay.

As noted in Section 1.3, assessment of engineering feasibility is outside the scope of this study. However, because of its relevance to post-closure safety, Nagra made a presentation to the IRT on the engineering concept, including the methods of waste emplacement, backfilling and sealing of the tunnels and access ramps, and waste retrieval (should that be necessary). The IRT notes that most of the engineering concepts (with the exception of the use of bentonite pellets, as discussed in Section 4.3.4) are similar to those proposed for other national programmes and are based on current engineering technology.

There is little discussion in the main report on the implications for long-term safety of engineering options and uncertainties with respect to the underground development in general, and the EDZ in particular. Uncertainties arise from the lack of demonstration of many of the concepts. Engineering options include the dimensions and spacing of tunnels, the method for backfilling and the thermal loadings. One safety-relevant option identified by the IRT is to increase the spacing between waste canisters to reduce temperatures in the bentonite backfill (see Section 4.3.4). A more detailed analysis of such issues would be expected at the construction licensing stage.

Further, underground experiments and detailed engineering design will almost inevitability involve some modifications to the conceptual design. Engineering design and repository safety are inexorably linked and the safety implications of any proposed engineering changes will need to be carefully reviewed. The IRT notes that Nagra's organisation structure facilitates close links between engineers and the scientists undertaking safety assessment studies.

The reference conceptualisation assumes that the geological barriers are unaffected by the excavations and other engineering works. As part of the Reference Scenario, cases are considered involving imperfect sealing of the ramp (case 1.6) and premature convergence of the emplacement tunnels (case 1.7). Abandonment of the repository is also considered (case 3.3). These variations are assessed to have little effect on releases because the seals in the emplacement tunnels are assumed to be in place and intact. There is a case for considering more pessimistic scenarios (e.g. problems arising from poor engineering implementation, abandonment of the repository with one emplacement tunnel still unsealed).

It is proposed to keep a given emplacement tunnel open for only 1-2 years in order to avoid "significant alteration" of the Opalinus Clay at the tunnel periphery (Nagra, 2002a). The IRT considers that this approach is advantageous both with respect to possible degradation of the surface of the Opalinus Clay and the safety implications in the event that the repository were abandoned or suffered some operational mishap. One effect of surface degradation could be a reduction in the effective thickness of the Opalinus Clay barrier. In this context, the IRT notes that Nagra has considered a reduction in the transport thickness to 30 m. Such a reduction results in only a small increase (less than a factor of two) in the peak dose rate.

The IRT concludes, from a safety viewpoint, that Nagra's assessment of repository design and operational issues is satisfactory for the current phase of the project. Additional information is being obtained in ongoing experiments at the Mont Terri underground facility. In addition, the proposed test facility at the actual repository site would provide site-specific information on a relevant engineering scale. As previously noted in Section 1.3, at each stage of the project, the safety implications of any design changes will need to be carefully reassessed.

4.8 Analysis of System Evolution and Timescales

Nagra discusses the evolution of the repository system in Chapter 5 of the Safety Report (Nagra, 2002a). The discussion includes an analysis of the early phase (first few hundred years) when heat production in the near field is important, the period in which resaturation of the EDZ occurs (several hundred years), the period of near field release (after 100 years for ILW and after 10 000 years for SF/HLW) and the period of migration to the environment, which takes place over hundreds of thousands to millions of years. For the most part, Nagra argues, quite reasonably in the opinion of the IRT, that the major events occur at different timescales and so the more complex interactions can be ignored. For example, heat effects are only important before the SF/HLW canisters are breached and migration of radionuclides only occurs after the EDZ has become resaturated.

The IRT finds that Nagra's analysis and discussion of system evolution is generally satisfactory for the current phase of the project. For future phases, the IRT makes the following observations and recommendations:

- Additional consideration should be given to early times (0-10 000 years), with emphasis on analysis of what could conceivably go wrong, especially in regard to engineering uncertainties and perturbations in the underground environment caused by the excavations. For example, in the current analysis, the resaturation phase is not studied in detail since the first SF/HLW canister failures (in the Reference Case) occur long after the saturation period. The IRT considers that there is a need to improve understanding at the phenomenological level of the processes involving moisture redistribution after repository closure and the effect of temperature on this process. The effect on the Opalinus Clay of moisture transfer to the bentonite buffer also needs to be carefully analysed.

- Because of the excellent retentive properties of the Opalinus Clay, the peak dose is predicted to occur at very distant times (typically about one million years in the future) when uncertainties, especially in the biosphere, are much greater than they are today. Since the public are generally sceptical of long-term predictions, it is important that Nagra makes it perfectly clear that the values for dose rate determined by models are only indicators of long-term safety and not attempts to predict dose rates in the distant future.

- The long-term evolution of the surface environment is largely controlled by future climates. Nagra has used the best available expertise in assessing the future climate in Switzerland, but needs to further stress the general uncertainty associated with all such predictions. Evidence of past climatic changes, including records of the margins of past glaciations, appears to be the strongest argument to support Nagra's analysis of the evolution of the far field environment.

- The IRT acknowledges that climate experts tend to view the impact of global warming as a short-term effect superimposed on larger climatic cycles and also understands that the impact of global warming is covered in conceptualisations of alternative climates (cases 6.2 a to d). Nevertheless, due to its high profile with the public, the IRT considers that the impact of global warming should be more thoroughly discussed in future reports.

Concerning the analysis of system evolution, *the IRT recommends that:*

- *Before finalising the design of the underground excavations, a more careful analysis should be undertaken of the resaturation phase following repository closure. This may involve coupled THMC modelling as well as large scale multi-component tests.* Further study of the post-closure impact of moisture redistribution within the open repository is also encouraged.

- *In future safety assessments, it should be emphasised, in presenting results, that predictive biosphere models are only indicators of long-term safety and not attempts to predict dose rates in the distant future.*

- *In future reports, especially those directed at the general public, the impact of global warming should be more thoroughly discussed.*

4.9 Treatment of the Biosphere

Uncertainties related to the biosphere are treated separately from those of the barrier system. Nagra has followed a conventional approach in modelling the biosphere using compartments and transfer coefficients to model the movement of contaminants in the biosphere and to calculate doses to members of the critical group. Uncertainties related to climate and future human actions are taken into account using stylised representations of the surface environment. These approaches are consistent with Swiss regulatory guidance (HSK/KSA, 1993) and, despite obvious simplification and uncertainties, are standard within most waste management projects. For example, in the proceedings of a recent workshop (NEA, 2002a), it was noted that: "There is a consensus view that a stylised approach is appropriate for dealing with the very limited predictability of the surface environment and of future human actions. The stylised situations considered in this approach can, where necessary, consider a range of conditions, including different representative climate states. The issue was considered by the workshop to be effectively 'solved', although it was stressed by several participants that the meaning of dose and risk as indicators of safety, rather then precise measures of expected consequences, needs to be stressed in the presentation of safety assessment results."

In the analysis of the biosphere, it is assumed that the contaminated deep groundwaters (released from the repository in the Opalinus Clay) are discharged into the groundwater flow of the overlying aquifers and quite substantial dilutions are assumed. The IRT considers that dilutions factors are reasonably well justified but notes that calculated doses are inversely proportional to the dilution volume. Thus, if the dilutions volumes were substantially in error calculated doses would change accordingly. Nonetheless, calculated doses would still meet the regulatory requirement, given the large difference between calculated doses and the regulatory requirement. Further, the information presented in the reference and alternative cases can be used to estimate doses that would be calculated had different assumptions been used for the introduction of contamination into the biosphere. For example, if one were to assume that water pumped from the Malm aquifer were used for crop irrigation, and not only for drinking, assuming a considerably smaller critical group, one can extrapolate the results from the Reference Case by assuming a smaller dilution factor. Even if the dilution factor were a factor of ten smaller (which for consistency would require that the critical group be a factor of ten smaller), the calculated dose would only be a factor of ten higher than for the Reference Case and so would still be well below the regulatory criteria [e.g. see Figure 7.10-1 in

Nagra (2002a)]. Similarly, if one were to assume that a more highly concentrated plume were present in the Quaternary aquifer resulting in less dilution, doses from the Reference Case can be used to estimate calculated doses for an assumed smaller dilution factor.

It may be noted that protection of the environment is an important waste management objective and needs to be considered in evaluating the performance of disposal facilities. The IAEA (2004) has noted that currently it is assumed that protection of humans against radiological hazards will also satisfy the need to protect the environment, but that the protection of the environment from ionising radiation is currently under discussion internationally. Estimation of concentrations and fluxes of contaminants and comparison to naturally occurring concentrations and fluxes may provide a useful measurement that is independent of assumptions about human habits. Another factor to be considered may be the ecological sensitivity of the environment into which contaminants may be released.

It is also noted that a full gas pathways analysis was not used in the present study, since it was assumed that gaseous releases would give rise to lower doses compared with doses resulting from gases dissolved in groundwater.

In light of the discussion above, *the IRT recommends that Nagra:*

- *maintains expertise on biosphere modelling;*
- *follows progress in ecological risk assessment (including the work of the ICRP in this area);*
- *includes a formal assessment of the gas pathway in future safety assessments*.

4.10 Interaction of the IRT and Nagra

Throughout the review, the IRT found that Nagra was open and anxious to help the IRT in its review and worked hard to deal with issues raised by the IRT.

Based on our interactions with Nagra during the review, and on our prior knowledge of Nagra's programmes, the IRT observes that Nagra:

- has a mature programme with highly competent, open-minded staff and a programme in which science, site characterisation, engineering design and safety assessment are effectively integrated;

- has strong programmes in specific areas such as geochemistry and site characterisation carried out in-house, in institutes such as PSI and the University of Bern, and within the framework of the international Mont Terri URL project;
- follows specific developments in other programmes and makes effective use of such developments in its own programme;
- follows and contributes to international developments and integrates the results within its own programme.

5. MAIN FINDINGS

In this chapter the IRT summarises its overall findings from two perspectives. The first perspective takes into account the specific aims of the Safety Report as stated by Nagra. The second perspective addresses the IRT's ToR as summarised in Section 1.3 and in Appendix 2.

5.1 Findings from the Perspective of the Aims of the Nagra Safety Report

The specific aims of the Safety Report are listed as follows [see page 12 of Nagra (2002a)]:

1. To determine the suitability of the Opalinus Clay of the Zürcher Weinland as a host rock for the repository for SF/HLW/ILW from the point of view of long-term safety.
2. To enhance the understanding of the multiple safety functions that the proposed disposal system provides.
3. To assess the robustness of the disposal system with respect to remaining uncertainties and the effects of phenomena that may adversely affect the safety functions.
4. To provide a platform for the discussion of a broad range of topics related to repository development. More specifically, the findings from the safety assessment, together with those from the regulatory authorities' review thereof, will provide guidance for future stages of repository planning and development.

The findings of the IRT that are pertinent to these aims are summarised below.

5.1.1 On the suitability of the Opalinus Clay of the Zürcher Weinland as a host rock

The IRT finds that Nagra has presented strong evidence that the Opalinus Clay of the Zürcher Weinland is a suitable host rock for a geological disposal repository. In particular:

- *i) Multiple arguments have been presented that the Opalinus Clay of the Zürcher Weinland is a tight, self-sealing material that would provide strong isolation, retention, delay and dispersion of any radionuclides released from a disposal facility located in it. Natural analogue studies, laboratory and field experiments as well as theoretical analyses corroborate this.*
- *ii) The Opalinus Clay of the Zürcher Weinland exists at sufficient depth and in sufficient thickness to host a geological repository. It is located in a seismically stable region of Switzerland and its properties are not sensitive to changes in the surface environment.*
- *iii) The geometric model of the Opalinus Clay of the Zürcher Weinland is well founded. From the evidence presented the IRT finds it reasonable to treat the Opalinus Clay of the Zürcher Weinland as a homogeneous entity in the safety assessment. It is also reasonable to conclude that the safety-relevant properties can be extrapolated over a wide region.*

5.1.2 Understanding of the multiple safety functions of the disposal system

In accordance with international practice, Nagra cites three main safety functions for a geological repository, namely:

1. Isolation from the human environment.
2. Long-term confinement and radioactive decay within the disposal system.
3. Attenuation of releases to the environment

These functions are accomplished by a system of features that are shared amongst the natural and man-made barriers, as has been discussed in Chapter 2 and more extensively in Chapter 4. The IRT finds that the depth of the repository (about 650 m) and the properties of the geological strata provide a high level of isolation from the accessible environment.

Long confinement is assured due to functions of the barriers that include:

- Thick-walled steel canisters for SF and HLW that should provide absolute containment of radionuclides for at least 10 000 years, except possibly for a very small number of canisters that may contain defects.
- Durable waste forms – spent fuel and vitrified HLW – that will dissolve and release radionuclides very slowly (i.e. over periods of tens to hundreds of thousands of years or even longer for spent fuel) under the geochemical and solute transfer conditions expected to exist in the repository.
- A bentonite buffer that, in addition to providing a favourable chemical environment, a strong transportation and isolation barrier and heat transfer path, also provides a well understood mechanism for ensuring the self-sealing of the excavation disturbed zone surrounding the emplacement tunnels in which the waste containers are placed.
- The Opalinus Clay stratum, which is geologically stable and has an extremely low permeability and high retention properties for many radionuclides.

Nagra's analysis shows that most nuclides present in the wastes would be retained within the geosphere for timescales of one million years or longer. Only long-lived, non-sorbing and weakly sorbing radionuclides such as ^{129}I, ^{79}Se, ^{14}C and ^{36}Cl would be released from the geosphere and these would be diluted by Quaternary groundwaters before reaching the accessible environment.

The IRT finds that the understanding of the performance of the components of the multi-barrier system proposed by Nagra is based on sound science and that the multi-barrier system has complementary and redundant features that should ensure that radionuclide releases to the environment would occur at very long times in the future and would be small in comparison with natural levels.

5.1.3 To assess the robustness of the disposal system with respect to remaining uncertainties

Robustness can be considered to be a measure of insensitivity to remaining uncertainties. Nagra has provided robustness through their disposal concept, which has multiple barriers with an adequate degree of redundancy.

Nagra has assessed the robustness of the concept through analysis of a wide range of cases, including "what if?" cases, which are outside the range of possibilities supported by scientific evidence. As discussed in Section 3.2, the IRT concludes that Nagra has effectively demonstrated robustness for the current phase of the project.

5.1.4 To provide a platform for the discussion of a broad range of topics related to repository development

The IRT agrees that the findings of Nagra's safety assessment provide useful guidance for deciding on the next and subsequent stages of repository planning and development in Switzerland. Despite the clarity of the documentation, the IRT considers that the very large volume of information would make it difficult for the general public to obtain an informed view. The IRT encourages Nagra, therefore, to provide a brochure of ~ 50-60 pages encompassing the *Entsorgungsnachweis* project. This document should also provide a road map to identify the various documents where the reader will be able to find additional, more detailed information.

Overall, the IRT observes that the Safety Report and associated documentation provided by Nagra clearly reflect discussions and considerations that have taken place over the past decade at the international level on the subject of what constitutes a modern safety case. It will provide a useful benchmark for other national studies.

5.2 Findings from the Perspective of Its Terms of Reference

The IRT finds that, for the purposes of the current assessment:

1. *The overall strategy for demonstrating long-term safety followed by Nagra is well thought out and clearly presented, and is in line with current international reflections on what constitutes a safety case.*
2. *The safety functions of the different barriers in the multi-barrier system have been clearly described and analysed. Given its properties, the Opalinus Clay assumes a prominent role in its contribution to safety of disposal in Opalinus Clay of the Zürcher Weinland but other components (durable waste form, long-lived canisters for SF and HLW, buffer) contribute to and support the overall safety case.*
3. *The methodology, models and codes that have been used in assessing performance are comparable to those used in other programmes and are fit for purpose.*

4. *The scientific bases for the representation of processes and barrier functions are state of the art and adequate for the purpose of safety assessment.*

5. *The features, events and processes affecting the evolution of the disposal system have been clearly documented and Nagra has carried out a detailed comparison with the NEA international FEP database to ensure that they are sufficiently comprehensive.*

6. *The scenarios and assessment cases considered in the safety assessment cover a wide range of possibilities and are sufficiently comprehensive for the current phase of the project.*

7. *The impact on safety of data and model uncertainties has been extensively analysed.*

Based on international standards and practice, the post-closure radiological assessment presented by Nagra is of high quality. It should provide an important plank in the platform of information to support the upcoming national debate on the future phases of the waste disposal programme in Switzerland.

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Appendix 1

COMPARISON OF NAGRA'S SAFETY CASE AGAINST EXAMPLES OF PRINCIPLES AND GOOD PRACTICE IDENTIFIED IN THE NEA CONFIDENCE DOCUMENT (NEA, 1999)

In the report "Confidence in the Long-term Safety of Deep Geological Repositories" (NEA, 1999), the NEA sets out, in a series of tables, examples of principles and good practices that should be taken into account in evaluating a safety case. In this Appendix, the examples taken from Tables 4 to 8 of NEA (1999) are listed in bold and then, for each example, information from Nagra (2002a) and supporting documents is summarised to provide a factual basis to evaluate how the Nagra safety case reflects the internationally-agreed NEA principles and examples. Overall, it is clear from these comparisons that the Nagra safety case is consistent with international reflections.

I. Principles, guidelines and procedures in considering the robustness of the system concept [see Table 4 in NEA (1999)]

1) Adoption of multiple safety provisions, giving rise to a robust disposal concept, in which either uncertainties are avoided or safety can be demonstrated in the presence of remaining uncertainties. This includes the multi-barrier concept, in which over-dependence on any single safety provision is avoided.

1a) The multi-barrier concept is central to Nagra's safety case and the principles related to this concept are explicitly presented in Section 2.6.2.2 of the Safety Report, Nagra (2002a), and throughout the Safety Report [see, e.g. in Nagra (2002a), Figures. 4.4-2, 4.4-3, 4.4-4; Section 5.8.2; Section 6.2 ("pillars of safety") and Figure 6.3-1]. The main components of the multi-barrier system are related to the safety functions and the latter are defined in Section 2.6.2.1 of Nagra (2002a). Models are used to describe the performance of each of the components in the multi-barrier system [see Appendix 1 in Nagra (2002e)].

1b) The types of uncertainties to be addressed are explicitly listed in Section 3.4 of Nagra (2002a) and the treatment of uncertainties is discussed in Sections 3.7.3 and 3.7.4. Moreover, the FEP management process (Nagra, 2002d) is used as a tool for identifying and managing the uncertainties [see tables in Appendices 4 and 5 of Nagra (2002d)]. Nagra discusses redundancy, insensitivity to uncertainties, e.g. isolation by SF/HLW canister in thermal phase, use of materials with experience of long-term performance (steel, bentonite), see Section 5.8.4 on p. 179 of Nagra (2002a); use of multiple bentonite seals (buffer, tunnels seals, ramp seal) to deal with EDZ uncertainties [see Figure 4.5-10, p. 109 of Nagra (2002a)]. Those uncertainties that cannot be excluded on scientific grounds are included in assessment cases resulting in coverage of a wide range of possibilities and uncertainties and are analysed in Chapter 7 of Nagra (2002a). The stepwise approach adopted in the Swiss programme is meant, amongst other things, to allow for multiple reviews and for ensuring that new understanding will be properly integrated. The EKRA concept of monitored geological disposal (EKRA, 2000), which is the basis of Nagra's design concept, is based on the stepwise decision-making process.

2) **Adoption of a flexible strategy**. **The aim is to establish and adopt a flexible strategy for design development and improvement in order to ensure efficient use of the safety potential of the host rock (e.g. "design-as-you-go").**

In Nagra's understanding, "design" refers to both the programme (e.g. evaluating siting possibilities) and the repository. Nagra has completed other safety cases for a HLW repository (Project Gewähr, Kristallin-I) and some analyses on the Opalinus Clay have also been made within the sediment programme [see Section 1.2.4 of Nagra (2002a)]. The lessons learnt from these studies, including the guidance from the authorities, have been taken into account in re-focussing the programme from crystalline basement to sediments, including Opalinus Clay.

The properties of the Opalinus Clay allow for flexibility in the design of the engineered barriers. Nagra explicitly mentions the possibilities for modifications as an objective related to the stepwise implementation [see Section 2.6.3 of Nagra (2002a)]. Alternative design options are indicated (e.g. copper canister as an alternative to steel). The inclusion of a pilot facility and an extended monitoring phase are additional strategies for fulfilling the objective of stepwise implementation.

3) Guidelines related to the characteristics of a site, e.g. a site that is structurally simple and/or simple with respect to processes and events – including geological events and possible inadvertent human intrusion.

3a) The simplicity of the site (especially in terms of uniformity in both vertical and lateral directions) and the level of confidence in extrapolation of data from Benken borehole to the high-resolution 3D seismics area and the link to the regional setting are well argued in various documents [see Nagra (2003b); Nagra (2002a), Section. 4.2; Nagra (2002b), Chapters 3 to 5; Nagra (2001a); Häring and Müller 1994].

3b) Nagra indicates that favourable host rock characteristics with respect to radionuclide migration and long-term stability are amongst the principles related to repository siting [see Section 2.6.2.3 of Nagra (2002a)]. These are discussed further and argued throughout the whole safety case and in Nagra (2002b) and as part of the "pillars of safety" as discussed in Section 6.2 of Nagra (2002a); see p. 184. The scientific background to these issues is discussed in Section. 5.2.2 of Nagra (2002a), in Nagra (2002b), and in Nagra (2002f). The absence of natural resources is discussed in Section 3.9 of Nagra (2002b). Furthermore, design measures are included to minimise effects of inadvertent human intrusion (compartmentalisation).

4) Guidelines/criteria related to waste conditioning, e.g. prohibition of liquid waste forms, use of a stable waste matrix, use of a long-lived container.

Various waste conditioning and acceptance criteria have been developed and are in place, e.g. for low- and intermediate-level wastes and long-lived intermediate-level wastes [see Zuidema *et al.* (1996), and Zuidema *et al.* (1997) referenced in Nagra (2002a)]. Indications were given to the IRT that there exist waste acceptance protocols with HLW producers as well. These are applied in a waste acceptance process [see Nagra (2002a), p. 101]. Nagra acknowledges that, in the case of SF, formal acceptance criteria are yet to be developed and that they have assumed a threshold for thermal power of the waste package for the current study. Nagra notes that the radionuclide inventory is well defined.

5) Guidelines related to the design basis, e.g. a minimum depth for the repository may be specified; a site may be sought that is larger than the minimum necessary; the possibility for retrievability and monitoring may be incorporated in the design.

Nagra presents a repository design based on compartmentalisation and the possibility for long-term monitoring and retrieval, at a depth that is suitable (about 650 m below surface) and in a suitable location (the latter based on the 3D seismic results), see Nagra (2002a), Chapter 4, and specifically Figure 4.2-5, which indicates that significant reserves in space are available. The underlying principles related to system and design are summarised in Table 2.6-1 of Nagra (2002a), p. 43.

6) Peer-review procedures for decisions regarding siting and design.

Peer-review procedures exist for decisions related to design and siting [see Appendix 4, in Nagra (2002a)]. Special expert meetings with external experts are held on key topics, see Appendix 4, p. D-5 in Nagra (2002a). The views of the external experts are recorded in the project database [see Item 4 in Appendix 8 of Nagra (2002e)], however, the final decision on the design or siting issue at hand rests with Nagra. A general description of quality assurance measures for the safety assessment is presented in Appendix 8 of Nagra (2002e), which indicates, in its item 3, that "an integral part of the QA measures is the requirement of a peer review of all Nagra Technical Reports". Expert judgement is explicitly integrated in the overall safety analysis through the FEP management process [see Appendix 4 and 5 in Nagra (2002d)] as well as Chapters 2 and 4 on audits. Expert judgement is also elicited through internal and external review and audits [p. D-5 in Nagra (2002a)]. Expert judgement is used in the data clearing process, and additional measures – such as peer review – are required when data are especially important [see Item 5 in Appendix 8 of Nagra (2002e)].

7) Quality-assurance procedures for site characterisation, waste and container fabrication, repository construction and operation.

Nagra gave the IRT an oral presentation on its internally developed Quality Management system that is built on the application of five quality management principles [Nagra (2003c)] and discussed it with the IRT. A general description of quality assurance measures for the safety assessment is presented in Appendix 8 of Nagra (2002e). For waste conditioning, specific QA guidelines are applied at the waste producer's facilities [see p. 101 of Nagra (2002a)]. A specific methodology for the assessment and management of uncertainties has been developed [see Chapter 3 of Nagra (2002a), Sections 3.7.3 p. 55 and 3.7.4 p 56ff]. Regarding site characterisation, the IRT did not review the QM documentation, but it was told that relevant QM guidelines exist and would be available upon request. In any event, QA for site characterisation appears to be done and documented in QA plans similar to those mentioned for safety assessment in Appendix 8 of Nagra (2002e). To this effect, see p. 68 of Nagra (1996). Specifically for 3D seismics, a supervision report related to quality assurance is referenced, see Laws, J. (1997) referenced in Nagra (2001a).

II. Quality of performance assessments methods and models (testing the quality of performance assessment) [see Table 5 in NEA (1999)]

II.a. Criteria to asses the quality of the approach adopted for performance assessment

1) Placing emphasis on components of the disposal concept that can confidently be expected to contribute to safety, at a particular development stage. (At any stage of development, uncertainties are likely to be more significant in some aspects of the system concept than others.)

At this stage, where the focus is on the suitability of the Opalinus Clay in the Zürcher Weinland as a host rock for a SF/HLW/ILW repository, the key emphasis is on the Opalinus Clay barrier (see Section 1.3 of Nagra (2002a) as well as the extensive geoscientific information base in the geosynthesis report, Nagra (2002b), and supporting reports Nagra (1995, 2001a, 2001c, 2001d, 2002f), and Pearson (2002). The emphasis on the Opalinus Clay is also in line with the expected excellent performance of the host rock as a barrier to the migration of radionuclides. At this stage, it is important to ensure that the EBS is compatible with the surrounding host rock but, at the same time, the contribution of the EBS to overall system performance is also investigated and some characteristics and components of the EBS are considered as “pillars of safety” (e.g. stability of the SF and HLW waste forms in the expected environment). These issues are covered in Chapters 5-8 of Nagra (2002a) and Table 5.7-1 presents, for each component, an overview of the key safety-relevant features, phenomena and evolutions.

2) The use of a small number of stylised treatments (e.g. of human intrusion and the biosphere) where there are uncertainties that are,

in practice, impossible to quantify and to reduce, thus decoupling this part of the analysis from the rest of the performance assessment.

In agreement with the international consensus on the treatment of largely irreducible and unquantifiable uncertainties, stylised approaches were adopted with regard to the treatment of future biospheres [p. 30-32 and Section 5.2.1 in Nagra (2002a)] and the treatment of future human actions [p. 32-33 and Section 5.6 in Nagra (2002a)]. Such stylised approaches essentially serve to decouple the main parts of the analysis from those parts and situations that are affected by largely unpredictable FEPs. The analysis also includes illustrative calculations of the effects of uplift on the conditions of the repository beyond several million years [Nagra (2002a), Section 5.2.2.3, p. 122].

3) Consideration of an appropriate range of envelope scenarios (each envelope representing a family of scenarios) for the evolution of the system.

The issue of having a sufficiently broad range of scenarios/assessment cases is addressed by choosing an appropriate methodology for developing the safety case (Nagra (2002a), Chapter 3; specifically Sections 3.4, 3.7.4 and 3.7.5) and a classification of each type of scenario is well explained within this chapter. A summary is given in Nagra (2002a), Section 8.2.7, p. 328. A key component of this methodology is the FEP management process, see Nagra (2002d) and there specifically Section 2.2. The aim was to derive and trace a sufficiently broad spectrum of cases that is "representative of all realistically conceivable possibilities for the characteristics and the evolution of the system" [see e.g. Section 3.6.4 of Nagra (2002a), p. 49].

4) Consideration of alternative conceptual models.

Alternative conceptual models were developed for important areas where such uncertainties exist at a conceptual level, e.g. the two SF dissolution models [see also Nagra (2002a), Table 6.8-2, column 2 for other alternative conceptualisations]. This is in line with the methodology discussed in Chapter 3 of Nagra (2002a), see Section 3.4, p. 47. Appendix 9 of Nagra (2002d) presents an overview of the Super-FEPs that are considered in the analysis with the corresponding alternative models and codes.

5) Consideration of parameter uncertainty. The importance, in terms of safety, of uncertainties in the parameterisation of assessment models

should be evaluated (e.g. through sensitivity and uncertainty analysis, carried out either deterministically or through stochastic sampling).

The significance of parameter uncertainty (parameter sensitivity analysed with both deterministic and probabilistic analyses) is evaluated in Chapter 6 of Nagra (2002a) and also in several assessment cases as described in Chapter 7 of Nagra (2002a). Deterministic analyses are described in Nagra (2002a), e.g. canister breaching time (p. 216), groundwater flow rate (p. 218 - 221), K_ds (Figure 6.7-9, p. 223). Probabilistic analyses are described also (Section 6.7.4, p. 226ff).

In addition, the effect of parameter uncertainty on the maximum dose rate (summed for all radionuclides) is summarised in Nagra (2002a) on p. 316-318. The effect of parameter uncertainty is also explored through probabilistic calculations for the Reference Case (p. 267-268), the high flow rate "what if?" case (p. 295), the transmissive discontinuity "what if?" case (p. 299), and the redox front penetration "what if?" case (p. 301).

Uncertainties in parameters and in understanding are discussed in Chapters 4 and 5 of Nagra (2002a).

With regard to uncertainties in the geo-database parameters: reference and alternative pessimistic parameter values of the geo-database are compiled in Chapter 9 of Nagra (2002b), including reasoning and justification for their choice. The uncertainties related to the Opalinus Clay are considered in this report, which discusses the data (reference, pessimistic etc) that need to be taken forward into the safety analysis, as described above.

II.b Level of understanding of the safety-relevant features, events and processes (FEPs)

1. Understanding and completeness of FEPs that describe the system concept.

The FEP management process [see Nagra (2002d)] has been used effectively (through audits against the international NEA FEP and the FEPCAT databases) for ensuring that all relevant processes and phenomena have been included in the current safety analysis.

The current understanding of the system and its evolution is summarised in Nagra (2002a), Chapters 4 and 5; the "statement of confidence" regarding this is given in Nagra 2002a, Chapter 8; specifically Section 8.2.6 and Table 8.2-1. Using the methodology described in Chapter 3 of Nagra (2002a) and, in more detail, in Nagra (2002d) this information is broken down into Super-FEPs and the completeness of these Super-FEPs is ensured through a detailed audit process including comparison with international FEP databases. This also provides confidence in completeness of the evaluation of scientific understanding.

Some FEPs (namely "reserve FEPs") are considered to be potentially beneficial to safety but, at the current stage, they are not included in the quantitative analyses because of lack of suitable data, understanding or codes [e.g. other confining units, co-precipitation, see Section 8.2.8.3 of Nagra (2002a)], but could be mobilised at a later stage in the project.

II.c Availability of the conceptual and mathematical models and computational tools

1) Formulation, where possible, of conceptual models of relevant processes, the applicability of which is supported by a wide range of independent evidence.

The conceptual model of the Opalinus Clay of the Zürcher Weinland, supported by multiple lines of evidence, is presented in Nagra (2002b).

Conceptual models are based on current scientific understanding, which is summarised in Chapters 4 and 5 of Nagra (2002a) and in the lower level supporting reports. The management of the scientific information (and integration into safety assessment) is handled within the framework of the FEP management process (Nagra 2002d, 2002e). If credible alternative conceptual models are identified, these alternatives are considered. In the case of geosphere transport (one of the most important processes), a very strong piece of evidence is provided through the observed diffusion profiles of natural tracers and the non-observation of flow into tunnels in case of fracturing for overburdens > 200 m. Complementary evidence also exists for the EBS (e.g. natural analogues for glass and fuel dissolution, corrosion of iron for canister, bentonite stability). When no code is suitable or considered relevant to treat favourable FEPs, these FEPs are considered as reserve FEPs [see Nagra (2002d)].

2) Use of "reasonably" conservative assumptions in performance assessment, where there is uncertainty (and where it is possible to show that the assumptions are, indeed, conservative).

The understanding of the important phenomena is documented in Chapters 4 and 5 of Nagra (2002a). In the performance assessment calculations, the evaluation of information is used to select adequate parameters: in the case of uncertainty, the calculations include pessimistic or conservative assumptions [see list of calculations in Table 6.8-2 of Nagra (2002a)]. One conservative assumption is to deliberately omit some FEPs that are favourable to safety [see Table 6.8-3 in Nagra (2002a)].

3) Development of appropriate assessment models and parameterisation.

A systematic and defined method has been adopted for conducting the analyses [p. 41 in Nagra (2002a)]. This includes a systematic approach to information collection, treatment and abstraction, treatment of uncertainties, development and validation of models and databases. The conceptual models and data sets are described in full detail in Chapters 3-8 in Nagra (2002e). In all areas of importance, specific checks have been made to ensure that the simplified models do represent the more detailed models sufficiently well [e.g. comparison of resistor network model with 3D hydro model, see Nagra (2002e), p. 58/p.134; for a comparison of the 2D transport model with 1D transport model, see Nagra (2002e), Appendix 7].

Additionally, the adequacy of the models is tested by comparison with independent evidence or other observations (e.g. diffusion profiles for geosphere transport, several analogues for the EBS, etc.).

4) Use of codes that solve the equations for the mathematical representation of the conceptual models, that are verified (e.g. through comparison with analytical solutions and independent codes).

Each computer code used in the performance assessment was verified before application by comparison with other codes and analytical calculations. The verification measures taken are documented for each code separately in Appendix 1 of Nagra (2002e), (for example, see p. A-28ff for SPENT, p. A-39ff for STRENG, p. A-46ff for STALLION, etc.).

Cross-checking with the Super-FEPs is presented in Appendix 9 of Nagra (2002d).

III. Reliability of the application of methods, models and data in performance assessment [see Tables 6 and 7 in NEA (1999)]

1) Quality assurance procedures for the analyses that have been performed, including peer-review procedures.

There is use of a bias audit group as an integral part of the safety case development, see Appendix 4 of Nagra (2002a). Principles that apply to use of expert judgement have been developed, see Appendix 4, p. D-5 of Nagra (2002a). Records of expert meetings are logged in project documentation [see Item 4 in Appendix 8 of Nagra (2002e); see also Nagra (2003c)]. Peer reviews are an integral part of QA. A data clearance process exists. These aspects are mentioned in Items 3 and 5 of Appendix 8 of Nagra (2002e); see also Nagra (2003d).

2) Use of independent evidence (e.g. natural analogues).

Natural tracer profiles constrain vertical advective fluxes [fluxes $< 3 \times 10^{-13}$ m/s, see Gimmi and Waber (2003)]. Absence of macroscopic evidence for water flow along faults in strongly faulted Opalinus Clay in tunnels indicates that faults do not act as preferential pathways if the overburden is > 200 m [Nagra (2002b), Section 5.8]; observed over-pressures in Opalinus Clay at Benken are evidence of extremely low permeability (lower than those measured in hydraulic tests at Benken) and/or non-Darcy behaviour [Nagra (2002b), Section 6.3].

Also, natural analogues are applied for components of the EBS. For instance, cast iron and mild steels have been use for over 1 000 years, and show evidence for the corrosion rate of these materials over a time frame comparable to the expected lifetime [see Section 5.7 of Nagra (2002a) and Johnson and King (2003)].

3) Demonstrate a broad understanding of the results (e.g. through the use of simplified models of key processes).

This includes comparison with independent evidence as well as the use of different models, some of them simplified. Thus, testing of diffusion-dominated transport on natural tracer profiles and testing various assumptions regarding transport properties of the Opalinus Clay by simplified insight models indicate that transport in the Opalinus Clay is expected to be diffusion-dominated [see Chapters 4.2.5 and 6.7 in Nagra (2002a)]. Mass balance calculations assuming full degradation of concrete and the low proportion of Opalinus Clay reacting with cement porewater confirm that the alteration zone is limited to a few metres around the tunnel [see Section 5.4.4 on p. 153 in Nagra (2002a)].

In general, the use of insight models contributes to system understanding [see, e.g. p. 203ff of Nagra (2002a) for an application to radionuclide release calculations].

4) **Adoption of a stepwise approach to repository development.**

The Swiss programme adopts a stepwise approach (this is also reflected in law, which requires stepwise licensing) see Nagra (2002a), Section 1.2.5, Figure 1.2-3. The objectives of stepwise implementation are also discussed in Sections 2.4.5 and 2.6.3 of Nagra (2002a). Nagra explicitly indicates that the present safety assessment is a platform for discussion and guidance for future stages [see Section 9.5 of Nagra (2002a)].

5) **Establishment of a "safety culture", i.e. "a consistent and pervading approach to safety", governing actions associated with repository development.**

In Appendix 4 of Nagra (2002a), Nagra defines the roles and responsibilities of the groups that contribute to the safety case. Nagra also has in place a QM system [see Appendix 8 of Nagra (2002e)]. In the presentations to the IRT, Nagra discussed and emphasised the role of experts in providing a balanced and unbiased view on scientific issues and the importance of a proper and unbiased integration of scientific understanding into the safety case. Chapter 2 of Nagra (2002a) explicitly presents the principles and objectives related to the safety assessment. Nagra also displayed an open attitude in discussions with the IRT. All of the above are examples that indicate the presence of a safety culture in the organisation.

IV. Methods to identify and reduce uncertainties in the three classes of uncertainty within the assessment capability [see Table 8 of NEA (1999)]

1) Focus of R&D efforts to better characterise or reduce uncertainty in phenomena that are important to safety.

A number of areas for continuing programme emphasis (and future programmes) are discussed on p. 340 of Nagra (2002a). Nagra recommends that future work should focus on phenomena directly linked to the "pillars of safety". As discussed at the NEA-IRT meeting, detailed plans for the future will only be developed when the input from the technical review and political/societal discussions are available.

2) Expert elicitation and peer review. (Such methods can, for example, independently provide confidence that there are no undetected geological features or that the intrusion of oxidising water as a result of climatic events will not occur.)

Expert elicitation and peer reviews were used throughout the project. This is discussed in Nagra (2002a), Appendix 4 and in Nagra (2002d) [e.g. audits, Section 4 and 5]. QA measures applied are outlined in Nagra (2002e), Appendix 8. In the presentations to the IRT, Nagra explained and emphasised the role of expert elicitation and peer review. The results of expert elicitation are reflected in the databases and codes used in safety assessment.

Model uncertainty has been assessed by expert elicitation. Experts involved in reviewing models were instructed beforehand on the general principles applied by Nagra in the process of expert elicitation [see Appendix 4, p. D-5 in Nagra (2002a)]. Protocols of the expert meetings can be found in the project documentation. The expert elicitation process (e.g. standard questions) was also discussed in the NEA review meeting. External experts are used for two main purposes: to review Nagra's work and to develop/confirm scientific understanding for integration into the safety analysis, e.g. in the FEP screening.

Data uncertainty for all input data sets (e.g. geological data, geochemical data, inventories, etc.) has been assessed by expert elicitation.

3) Integration of general scientific and technical experience and literature (theoretical and experimental experience from inside and outside the radioactive waste field). (General scientific and technical

experience can be used, for example, to identify uncertainties regarding secondary processes affecting radionuclide migration.)

The general literature on clay rocks in terms of geochemistry, porosity and hydraulic conductivity has been very broadly used in support of understanding and model development, e.g. see p. 81 of Nagra (2002a) and Chapter 5 in Nagra (2002b). Also, see many references in the internal report on gas transport in clay host rocks (Nagra, 2003a). Studies performed outside Nagra played an important role in assessments of canister corrosion [Johnson and King (2003)], in solubility studies (incorporated in the Nagra/PSI thermodynamic database incorporating the NEA database) and in sorption/diffusion models [p. 147ff, Nagra (2002a)]. The information and data provide a basis for constraining model uncertainty. The information in the Geosynthesis Report that presents key conclusions supported by multiple lines of evidence (Nagra 2002b) is a key input to the safety analysis.

Generally, published literature from academia, the hydrocarbon exploration industry and applied engineering geoscience was considered where appropriate [extensive reference list in Nagra (2002b)]. Specifically, broad experience in 36D seismic and borehole geophysical logging developed by the hydrocarbon exploration industry (field activity, processing, evaluation tools) is fully taken into account [see Nagra (2001a, 2001c, 2001d)]. Experience of experts in hydrocarbon exploration (gas fracture tests, long-term performance of argillaceous cap rocks) was also used [see minutes of expert advisor meetings, numerous references in Sections 5.9 and 7.7 of Nagra (2002b)]. Experts from academia and experts with broad geotechnical experience in the construction of underground facilities participated in audits and reviews (various documents in project documentation). This is also true for the area of geochemistry (see e.g. references in PSI reports [Hummel and Berner (2002), Hummel *et al.* (2002)]. Canister options [see Johnson and King (2003)] have been also evaluated based on extensive references and, in particular, on the technical experience of other researchers (e.g. copper studies in Sweden and Finland).

4) Adoption of a structured approach to system description. (By using, for example, "Interaction Matrices", processes and interactions between different elements of the system can be systematically sought in striving for completeness).

A "structured system description" is given in Nagra (2002a), Chapters 4 and 5. Systematics for transferring uncertainties into FEPs and Super-

FEPs is given in Nagra (2002d); specifically Tables 4.2-1 and A5.4.1. Note, however, Nagra's dual-track approach for development of a system description with key safety-relevant phenomena (Nagra (2002a), Chapters 4 and 5, especially Table 5.7-1 and Figure 5.7-1) and, on the other hand, the description of the system in terms of Super-FEPs, see Table 6.8-1 in Nagra (2002a) and Nagra (2002d). The FEP management process [see Nagra (2002d)] is used as a "bookkeeping tool" to ensure completeness, proper treatment of FEPs and FEP interactions. Interactions between FEPs are presented [see Appendix A5.4 of Nagra (2002d) with the corresponding voluminous Table A5.4.1 where interactions are systematically checked for relevance and inclusion into assessment cases].

5) Identification of the range of conceptual models that is consistent with available information, and comparison of results of different conceptual models to evaluate the consequences of uncertainty.

Various alternative conceptual models are summarised in Table 6.8-2 on p. 250 of Nagra (2002a), supported by Nagra (2002e). These have arisen from identifying the possible different behaviours of the system that lead to different pathways or mechanisms for radionuclide release.

6) Use of natural analogues.

Natural analogues are widely used to support understanding and model development and to constrain uncertainties in many important areas, see e.g. for Opalinus Clay [p. 167, Nagra (2002a)], limited penetration depth of high-pH plume in low permeability rocks [Nagra (2002b), p. 485-486), steel corrosion (Figure 5, p. 25, Johnson and King (2003); p. 168, Nagra (2002a)), SF dissolution [p. 15, Johnson and Smith (2000); p. 168, Nagra 2002a), solubilities of radionuclides (p. 169, Nagra (2002a)) and bentonite performance [p. 167, Nagra (2002a)]. Table 8.2-1 in Nagra (2002a) summarises all the evidence, including evidence from natural analogues.

7) Examination of past behaviour of similar rock formations

The examination of past behaviour of similar formations and Opalinus Clay in other areas is taken into account in basin modelling (burial and temperature history; Nagra (2002a), Figure 4.2-3; Nagra (2002b), Section 3.3; Nagra (2002f) and Leu *et al.* (2001)) and also for comparing critical parameters amongst argillaceous rocks of different maturity [see p. 81 and, in particular, Figure 4.2-11 in Nagra (2002a)].

8) Large-scale field and rock laboratory studies

A large-scale "mine-by" test was carried out at Mont Terri in order to test hydromechanical models predicting the short-term evolution of underground structures [Martin and Lanyon (2002)]. Cross-hole experiments at Mont Terri constrain conceptual and parameter uncertainties with respect to gas transport and gas fracture self-sealing [Marschall *et al.* (2003), Enachescu *et al.* (2002)]. For RN migration, both the migration experiments at Mont Terri and the measurements related to the natural tracer profiles (Benken, Mont Terri) are relevant [see Nagra (2002b), Section 5.10].

9) International co-operation

Nagra has been involved for many years in international co-operation and the safety case reflects such involvement. Nagra's involvements include GAMBIT [incorporated in Nagra's internal report on gas transport, Nagra (2003a)]; the Clay Club; bilateral exchange with ANDRA [e.g. diffusion data p. 81 of Nagra (2002a)]; EU GLASTAB (Nagra and PSI involvement and contribution of glass dissolution data); EU SFS (Spent fuel stability – Nagra contributes to IRF model development and draws on matrix dissolution experiments by other members). There has been broad involvement of scientists from outside the waste management community in hydrogeology aspects (including gas migration) and long-term geological evolution. Nagra's involvement in the development of the FEPCAT database is acknowledged and this database has been used throughout the FEP management process and the cross-checking process.

International co-operation has provided essential elements that have contributed to model development and evaluating model and data uncertainty. Evaluation of international data and parameters obtained within other programmes is used in geochemistry [Nagra (2002a)], geological properties [geosynthesis, permeability, diffusion, see Nagra (2002b)] and EBS [e.g. fuel dissolution, glass dissolution *etc.*, see Chapter 5 of Nagra (2002a)]. Concerning specific topics see: for gas release through bentonite: p. 131; for near field geochemistry: p. 134; for bentonite stability: p. 138; for fuel dissolution, p. 142; for radionuclide retardation: p. 145ff, *etc.* [in Nagra (2002a)].

10) Identification of critical, safety-relevant parameters (through sensitivity and uncertainty analysis) and reduction of uncertainties in these parameters through site characterisation and experimental programmes.

Safety-relevant parameters are identified by sensitivity analysis in Chapter 6 of Nagra (2002a) and the supporting document Nagra (2002e). The significance of uncertainties is summarised in Table 6.8-1 of Nagra (2002a). Guidance for future planning and experimental research is discussed on p. 340 of Nagra (2002a), but will be expanded in a more detailed plan once the input from the technical review and the results of the societal/political discussions are available.

11) Development of mechanistic models for extrapolation of laboratory measurements to *in situ* conditions.

Mechanistic models have been derived for interpretation and extrapolation of laboratory data and field experiments for many areas in which parameter uncertainty is evaluated. This includes: fuel dissolution

[IRF as a function of burn-up – p. 17-19, Johnson and McGinnes (2002)]; fuel dissolution rate as a function of burn-up (p. 28, Johnson and Smith (2000); steel corrosion rate [p. 26, Johnson and King (2003)]; glass dissolution [p. 143-144 in Nagra (2002a) and Curti (2003)]; diffusion and sorption models [p. 144ff in Nagra (2002a); for details see Bradbury and Baeyens (2002)].

Appendix 2

EXCERPT FROM THE TERMS OF REFERENCE ON SCOPE AND OBJECTIVES OF THE PEER REVIEW

The long-term safety of geological disposal of spent fuel, high level and long-lived waste is widely discussed at the international level. Peer reviews of national projects by international expert teams have proven to be very valuable. For these reasons, the relevant Swiss authorities would like to complement their assessment of Nagra's work with an international peer review. Switzerland, through its Swiss Federal Office of Energy (BFE), has thus made a request to NEA to carry out such a peer review during 2003. NEA agreed to follow the Swiss request and to organise an international peer review.

Scope

The peer review should address the post-closure radiological safety assessment, which is the subject of Nagra's "Safety Report" NTB 02-05. This Safety Report documents the methodology, conduct and results of the performance evaluation of the reference disposal system.

To the extent that information in the Geosynthesis (NTB 02-03) and Facilities and Operations (NTB 02-02) Reports is regarded as a foundation for some aspects of the safety case, as presented in NTB 02-05, it may be also necessary to review portions of these reports.

As far as necessary, the scope of the review will also extend to examining various other documents supporting the Safety Report that deal with safety-relevant aspects of the engineered and natural barrier system

Objectives

The main objective of the peer review is to provide an independent evaluation, from an international standpoint, of the quality of the post-closure radiological safety assessment presented by Nagra. This assessment will be based on international standards and practice in this area.

It is expected that the review should constitute a technically oriented appraisal and should include a critical analysis of the following aspects:

- the overall strategy for demonstrating long-term safety;
- the role and relative weight given to the safety functions of the different barriers;
- the methodology that is applied for the performance assessment;
- the scientific basis for the representation of processes and barrier functions;
- the comprehensiveness of the features, events and processes affecting the evolution of the disposal system;
- the comprehensive derivation of scenarios and identification of assessment cases;
- the treatment of data and model uncertainties.

Further aspects that the international review team find pertinent may be included in the review.

Recommendations are expected for specific improvements that would help the safety demonstration for geological disposal.

The review is expected to provide a broad perspective for consideration by the competent Swiss authorities in their own appraisal of the safety case.

Appendix 3

MEMBERS OF THE INTERNATIONAL REVIEW TEAM

Colin J. Allan (President, Allan Enterprises, Canada) – IRT Chairman

Colin Allan obtained a B.Sc. (Honours) in mathematics and physics and a Ph.D. in nuclear physics both from the University of Manitoba. He joined AECL in 1972 where he worked for over thirty years before retiring in November 2002. In his career with AECL, he worked in a number of technical areas including heavy water plant safety, in-core reactor instrumentation, industrial applications of radiation and tomography, industrial accelerators, reactor development, heavy water production and processing, and radioactive waste management and decommissioning. He was General Manager of Decommissioning and Waste Management, AECL, when he retired. In this position his responsibilities included: AECL's work in Geological Disposal of Nuclear Fuel Waste; the Low Level Radioactive Waste Management Office that is responsible for cleaning up historical waste sites that are the responsibility of the Federal Government of Canada; decommissioning and management of AECL's nuclear legacy liabilities; radioactive waste management improvement projects; and engineering and project services at the Chalk River Laboratories. From 1991 to 1997 he was the senior manager responsible for the Canadian Nuclear Fuel Waste Management Programme, which developed the concept for disposal of Canada's nuclear fuel waste in plutonic rock of the Canadian Shield, and led the programme through a comprehensive environmental review. The review included an intensive scientific assessment of the safety of the concept and concluded that: "from a technical perspective safety of the AECL concept has been on balance adequately demonstrated for a conceptual stage of development".

Colin Allan has served on a number of national and international committees, including the Bureau of the OECD/NEA Radioactive Waste Management Committee; the Radioactive Waste Safety Standards Advisory Committee (WASSAC), the International Safety Advisory Group (INSAG), the

International Waste Management Advisory Committee (INWAC), the International Radioactive Waste Technical Committee (WATEC) and the Working Group on Principles and Criteria for Radioactive Waste Disposal of the IAEA; the Board on Radioactive Waste Management of the U.S. National Academy of Sciences; the Economic Innovation Technology Council of Manitoba and its Standing Committee on Science and Technology; the *Conseil d'administration* of le *Centre canadien de fusion magnétique*; and Chairman of the Steering Committee of the Canadian Fusion Fuels Technology Programme. Most recently, Dr. Allan joined the IAEA International Project on Innovative Reactors and Fuel Cycles (INPRO) to edit the final report on the first phase of this project.

Johan Andersson (JA Streamflow, Sweden)

Johan Andersson has a M.Sc. in Engineering Physics, a Ph.D. in Water Resources Engineering and a D.Phil. in Hydraulics. He has been a part-time professor in Engineering Geology at Chalmers Institute of Technology since 1999. After four years of post-doctoral research on modelling flow and transport in porous media and crystalline rock, he spent six years at the Swedish Nuclear Power Inspectorate managing, among other things, the Inspectorate's integrated performance assessment projects and had a leading role in reviewing industry's research programmes. He was project manager of the SKI Performance Assessment projects SKI Project-90 and SKI SITE-94. Since 1995 he has been a consultant. As such, he was deeply involved in the SKB SR 97 performance assessment where he compiled all input data for consequence analysis, acted as a geosphere expert and provided internal peer review. He also helped SKB planning their now ongoing site characterisation programme. When at SKI he was a member of the core group of the Performance Assessment Advisory Group (PAAG) of the OECD/NEA and later, as a consultant to OECD/NEA has participated in the IPAG activities.

Johan Andersson is now President of JA Streamflow AB, Sweden. He provides general advice on projects related to development and safety assessment of radioactive waste repositories and other installations with environmental implications. Johan Andersson is presently involved in the SKB site evaluation activities of their ongoing site investigation and in the connected Safety Assessment and Repository Engineering planning. He was involved in the update of the safety assessment of the repository for operational waste (SFR). He has edited the Posiva ONKALO Underground Characterisation and Research Plan and is now leading the integrated modelling task force connected to the ONKALO work. He is a member of the International Technical Advisory Committee (ITAC) to NUMO, the HLW nuclear waste management organisation in Japan. He also provides services to the OECD/NEA, the Swedish Nuclear Power Inspectorate, *Bundesamt für Strahlenschutz* in Germany and the Railway Authority in Sweden.

Ann Dierckx (ONDRAF/NIRAS, Belgium)

Ann Dierckx graduated as an Engineer in Chemistry and Agricultural Industries at the *Katholieke Universiteit Leuven*, Belgium, where she also gained her Ph.D. in Agricultural Sciences. Her doctoral research was in the field of radioactive waste management and within the European Commission's Project Mirage (Migration of Radionuclides in the Geosphere).

She joined the Belgian Nuclear Research Center in Mol in 1995, first as scientific collaborator studying the influence of organic matter on radionuclide mobility and later as a task leader for R&D related to the behaviour of radionuclides in argillaceous environments. She was responsible for the overall scientific coordination of the EC sponsored TRANCOM-Clay project on the role of organic matter in radionuclide transport.

In 2000, she joined the Belgian agency for radioactive waste and enriched fissile materials (ONDRAF/NIRAS). Her major responsibilities in the high-level waste disposal programme are geochemical issues, retention processes and migration studies in the Boom Clay as well as geochemical aspects of the near field. She also ensures the scientific coordination of the low-level waste working programme and coordinates further ONDRAF/NIRAS activities in a remediation programme of radium-contaminated sites. She participates in several international activities of the European Union, the IAEA and the NEA and is on the Management Board of the TDB III and Sorption II project.

Des Levins (Waste Management Consultant, Australia)

Des Levins has B.E. and PhD degrees in chemical engineering from the University of Sydney. From 1969-1999, he was employed by the Australian Nuclear Science and Technology Organisation (ANSTO) and its predecessor, the Australian Atomic Energy Commission (AAEC). He has over 25 years' experience in radioactive waste management and the environmental aspects of the nuclear fuel cycle. He has carried out extensive research on the chemical durability of high level waste forms and the environmental impact of uranium mining and milling.

From 1972-75, he was a guest scientist at Oak Ridge National Laboratory, Tennessee, where he carried out research related to the production of transuranic elements and the treatment of radioactive wastes.

At ANSTO he held various positions, including Head of the Chemical and Waste Engineering Section, Leader of Waste Operations and Technology Development, and Manager of ANSTO's Waste Management Action Plan.

He has served on a number of committees of the IAEA and the NEA. He was Australia's chief scientific investigator on the IAEA Co-ordinated Research Programme on the "Performance of Solidified High-Level Waste Forms and Engineering Barriers under Repository Conditions".

From 1996-1998, he was a member of the international study, organised by the IAEA, on the radiological situation at the atolls of Mururoa and Fangataufa in French Polynesia. Dr. Levins was responsible for coordinating the scientific assessment of the long-term releases of radionuclides from the underground cavities where nuclear tests had been conducted.

In 2001, he was a member of an NEA/IAEA team that carried out an international peer review for the USDOE on the total system performance of the proposed high level waste repository at Yucca Mountain, Nevada.

In 2002, Dr. Levins prepared a report for the IAEA on the status of radioactive waste management and disposal practice in East Asia and the Pacific.

Zoltan Nagy (PURAM, Hungary)

Zoltan Nagy graduated from Eötvös Lorand University of Budapest with Dipl. Ing. in Geophysics in 1972 and a Dipl. Ing. in Geology in 1979.

He initially worked as a geophysicist and later as a geologist in uranium ore exploration in Hungary. His work was concerned with exploration of uranium ore deposits in deep and shallow sedimentary geological formations.

Since 1993 he has participated in the project dealing with the final solution for the safe disposal of the Hungarian high-level and long-lived radioactive waste. This programme has focused on *in situ* investigations, which were carried out by the Canadian AECL and the Mecsek Ore Mining Company in a URL at a depth of 1 100 m in the area of the Boda Claystone Formation.

The purpose of the project was to carry out a detailed investigation of the formation.

Since the closure of the URL, he has participated in the dismantling and site recultivation of closed Hungarian uranium mines, mill and tailing ponds.

At present, Zoltan Nagy is the leading geologist of the Public Agency for Radioactive Waste Management (PURAM) in Hungary. He is responsible for the management of research for the safe geological disposal of:

- low- and intermediate-level radioactive waste in granitoid rocks, and
- high-level or long-lived radioactive waste and spent nuclear fuel in the Boda Claystone Formation.

Zoltan Nagy also has wide experience in geomathematics, control of data quality and the planning and development of the relational databases for research information systems.

Claudio Pescatore (OECD/NEA)

Claudio Pescatore holds a Ph.D. in nuclear engineering from the University of Illinois, Urbana-Champaign (USA). He has over 25 years' experience in the field of nuclear waste management and research covering low-level waste, high-level waste, and spent fuel storage and disposal.

Claudio Pescatore joined the Brookhaven National Laboratory in 1982 and was involved in the study of high-level waste and spent fuel disposal concepts in basalt, salt, and tuff formations. His work covered reliability and modelling studies of waste package materials during storage and disposal, analyses of gaseous and aqueous pathways for radionuclide migration, and peer reviews of environmental impact assessment studies and site characterisation plans. At Brookhaven, he was group leader for Radioactive Waste Performance Assessment. Until 1995, he was also adjunct Professor of Marine Environmental Sciences at the University of New York, Stony Brook.

Claudio Pescatore joined the OECD/NEA in 1992 in the Division of Radioactive Waste Management and Radiation Protection, where he is the Deputy Head for Radioactive Waste Management. He has been at the centre of several recent international initiatives such as the IPAG studies, the setting up of the NEA working party on the safety case for disposal (IGSC), the Forum on Stakeholder Confidence (FSC), and the working party on decommissioning (WPDD). He is the co-author of several NEA reports on the status of and issues in radioactive waste management worldwide in particular he is a co-author of the NEA Confidence Document, which has been instrumental in defining the modern concept of a “safety case”. He serves as the technical secretariat of several NEA committees that operate at both a strategic and technical level: the Radioactive Waste Management Committee (RWMC), the RWMC Regulators’ Forum, the WPDD and the FSC.

Claudio Pescatore has organised, and participated in, numerous international peer reviews of national safety studies on behalf of the NEA. These include: SKI’s Project-90 (Sweden), AECL’s Environmental Impact Statement of the Disposal of Canada’s Nuclear Fuel Waste, the 1996 Performance Assessment of the US Waste Isolation Pilot Plant (WIPP), SKI’s SITE-94 project (Sweden), the Nirex methodology for scenario and conceptual model development (UK), JNC’s H-12 Project to establish the technical basis for HLW disposal in Japan, the SR 97 study by SKB (the Swedish spent fuel and waste management company), the SAFIR 2 report produced by the Belgian Agency for Radioactive Waste and Fissile Materials (ONDRAF/NIRAS) and the *Dossier 2001 Argile* produced by French national agency for the management of radioactive waste (Andra).

Frédéric Plas (Andra, France)

Frédéric Plas graduated as a Civil Engineer from the School of Applied and Engineering Geology of the National Polytechnic Institut of Nancy. He also has a master’s degree in hydraulics and mechanics.

He started his career in 1985 at the *Commissariat à l’Énergie Atomique* (CEA) in the research laboratory of Thermal, Hydraulic, Mechanical and Chemical Behaviour of Clays and Engineered Materials within the framework of feasibility studies on deep geological radioactive waste disposal. Within this sphere of work, he has been involved in various European research projects either as participant or coordinator.

Frédéric Plas joined the French national radioactive waste management agency (Andra) in the early 1990s in order to work on the design and the phenomenological behaviour of engineered barriers. From 1996 to 2001, he was the Head of the Materials Department (which included responsibility for the waste packages) and contributed to the Andra *Dossier 2001 Argile* on the feasibility of High Level Waste, Spent Fuel and Intermediate Level Waste disposal in a deep Argillaceous formation. Since 1999, he has trained students at the National School of Chemical Engineers (University of Paris) in engineered materials and their utilisation in radioactive waste management.

For two years, he has been responsible within the Performance Assessment Department for the conceptualisation of safety scenarios, and particularly for the development of phenomenological and mathematical models which support safety assessment of waste repositories.

Since 2000, Frédéric Plas has been involved in various activities of the Integration Group for the Safety Case (IGSC) of the Nuclear Energy Agency (NEA). In particular, he is member of the Steering Group of the IGSC-EBS (Engineered Barrier Systems) Project.

Richard Storck (GRS, Germany)

Richard Storck graduated from the Technical University of Berlin with a Dipl. Ing. in Nuclear Engineering. He went on to obtain a Ph.D. (Dr. Ing.) at the same university in 1980 for a thesis on methodologies for probabilistic risk assessment of technical facilities. As a scientific employee of the Technical University of Berlin, he then worked for four years on the first German project for the long-term safety of deep underground disposal systems for radioactive waste in salt formations (PSE).

He continued his work as a Group and Project Manager at the GSF research centre in Braunschweig. He was involved in the performance assessments of the European Community for high-level waste (PAGIS), low-level waste (PACOMA) and spent fuel (SPA). For the German disposal project, he managed the safety assessment for the application of the abandoned iron ore mine at the Konrad site for disposal of non-heat-producing radioactive waste and for the development and demonstration of methodologies for the safety assessment of the planned repository at the Gorleben site for all types of waste.

In 1995, the research activities of the GSF concerning radioactive waste disposal were transferred to the GRS. He was appointed Head of the Performance Assessment Department. The department is responsible for the development and application of performance assessment tools regarding radioactive and chemical waste disposal. Over the last years, the work of the department has focused on the development of the safety case for the backfilling and sealing of the Morsleben repository for low-level waste. He has been a member of the OECD/NEA Performance Assessment Advisory Group since 1988 and the succeeding Integration Group for the Safety Case.

Sylvie Voinis (OECD/NEA)

Sylvie Voinis graduated as a chemical engineer from ENSCT (*École Nationale Supérieure de Chimie de Toulouse*). After working in R&D on polymer at Philips for a few years, she then joined Andra's (French waste management agency) Safety Division. She has over 15 years' experience in the field of nuclear waste management and research covering low-level waste, high-level waste and spent fuel disposal.

She started in Andra by working on the source term and near-field environment and was then involved in a variety of activities associated with radioactive waste management, especially those concerned with safety aspects. During her time at Andra, she participated in the development of methodologies for safety and for other projects, which covered aspects such as functional analysis and qualitative analysis. She became head of the "safety methodology" team that was in charge both of near-surface and deep geological disposal. She has also chaired the IAEA ISAM project.

Sylvie Voinis joined the NEA in 2000 where, as scientific secretary, she is in charge of the coordination of the activities carried out by the IGSC (Integration Group for the Safety Case) and the Clay Club. She has participated in the elaboration and publication of several NEA technical reports on the status of and issues in radioactive waste management. On behalf of the NEA, she participated in the international peer review of the SAFIR 2 report produced by the Belgian Agency for Radioactive Waste and Fissile Materials (ONDRAF/NIRAS). She is also a member of the French permanent group on nuclear facilities other than power plant and waste disposal facilities.

Appendix 4

ACRONYMS

AECL	Atomic Energy of Canada Ltd
Andra	*Agence nationale pour la gestion des déchets radioactifs* (French National Agency for Radioactive Waste Management)
BFE	*Bundesamt für Energie* (Swiss Federal Office of Energy)
BNFL	British Nuclear Fuels Ltd
BWR	Boiling Water Reactor
COGEMA	*Compagnie générale des matières nucléaires* (French company specialised in nuclear fuel cycle)
EBS	Engineered Barrier System
EDZ	Excavation Disturbed Zone
EKRA	*Expertengruppe Entsorgungskonzepte für radioaktive Abfälle* (Expert Group on Disposal Concepts for Radioactive Waste)
FEP	Features, Events and Processes
FEPCAT	Features, Events and Processes Evaluation Catalogue for Argillaceous Media
HLW	High-level Waste
HSK	*Hauptabteilung für die Sicherheit der Kernanlagen* (Swiss Federal Nuclear Safety Inspectorate)
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
IGSC	Integration Group for the Safety Case (An NEA expert group)

ILW	Intermediate-level Waste
IRF	Instant Release Fraction
IRT	International Review Team
ISAM	Implementation of Safety Assessment Methodologies
ISO	International Standards Organisation
KNE	*Kommission für Nukleare Entsorgung* (Swiss Federal Commission on Nuclear Waste Management)
KSA	*Eidgenössische Kommission für die Sicherheit von Kernanlagen* (Swiss Federal Commission for the Safety of Nuclear Installations)
MOX	Mixed Oxide (fuel)
Nagra	*Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle* (Swiss National Cooperative for the Disposal of Radioactive Waste)
NEA	Nuclear Energy Agency (of the OECD)
OPA	Opalinus Clay
PSI	Paul Scherrer Institute, Switzerland
PWR	Pressurised Water Reactor
QM	Quality Management
SF	Spent Fuel
SKI	*Statens kärnkraftinspektion* (Swedish Nuclear Power Inspectorate)
THM	Thermal-hydraulic-mechanical
ToR	Terms of Reference
UO_2	Uranium Oxide (fuel)
URL	Underground Research Laboratory

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