Disposal of Radioactive Waste

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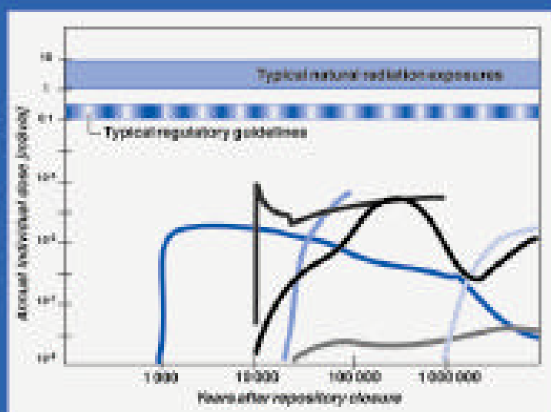
Lessons Learnt from Ten Performance Assessment Studies



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DISPOSAL OF RADIOACTIVE WASTE

Working group on Integrated Performance Assessments

of Deep Repositories

LESSONS LEARNT FROM TEN PERFORMANCE ASSESSMENT STUDIES

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- developing exchanges of scientific and technical information particularly through participation in common services;
- setting up international research and development programmes and joint undertakings.

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FOREWORD

The management of radioactive wastes and, in particular, the safety assessment of radioactive waste disposal systems are areas of high priority in the programme of the OECD Nuclear Energy Agency (NEA). The NEA's Radioactive Waste Management Committee (RWMC) and its Performance Assessment Advisory Group (PAAG) and Co-ordinating Group on Site Evaluation and Design of Experiments (SEDE) are committed to promoting information exchange and co-operation among OECD member countries on subjects related to radioactive waste management strategy, safety assessment of disposal systems, and characterisation of potential disposal sites.

Through international exchanges co-ordinated by the NEA, a general consensus has been reached that:

- the responsibilities of this generation to future generations are better discharged by a strategy of final disposal, and disposal of radioactive wastes in geologic repositories is currently the most favoured option;
- appropriate use of safety assessment methods, coupled with sufficient information from the proposed disposal sites, can provide the technical basis to decide whether specific disposal systems would offer to society a satisfactory level of safety for both current and future generations.

As progress is made in methods of site evaluation and safety/performance assessment, continued co-operation is important to examine and evaluate these developments in international fora. This on-going international exchange provides interested organisations with a basis for re-assessing their national programmes and facilitates peer review.

In 1994, a Working Group was set up under the PAAG on Integrated Performance Assessments of Deep Repositories (IPAG). The aim of the group is to provide a forum for informed discussion on performance assessment (PA), and to examine the overall status of PA and specific issues identified by the group and the PAAG. The work will be carried out in several phases where the membership and tasks of the group are expected to change between phases. This document presents the report of a first phase of work completed in December 1996 and is expected to be of most interest to practitioners of repository PA and those with an interest in technical review of PA studies. A further phase of work is being planned emphasising the experience of peer review, and especially regulatory review, of PA studies.

This report is published under the responsibility of the Secretary General of the OECD. It does not in any way commit the countries of the OECD.

ACKNOWLEDGEMENTS

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CONTENTS

EXECUTIVE SUMMARY

The IPAG Phase I

In 1991, the RWMC and PAAG participated in the development of the NEA/IAEA/CEC "Collective Opinion" document on current prospects in the evaluation of the long-term safety of deep geologic repositories for long-lived radioactive wastes [1]. This was based on experience of safety assessment studies up to that time, as summarised in the NEA "Review of Safety Assessment Methods" [2] and as presented at the NEA/IAEA/CEC International Symposium on the Safety Assessment of Radioactive Waste Repositories held in Paris in 1989 [3]. Since this time, several major repository safety and/or performance assessment (PA) studies have been carried out. In particular, progress has been made in several countries towards assessments based on more detailed site information, where results may be used within the national waste management programmes and regulatory review process.

In 1994, the Working Group on Integrated Performance Assessments of Deep Repositories (IPAG) was set up by the NEA Performance Assessment Advisory Group (PAAG). The overall aim of the group is to provide a forum for informed discussion on performance assessment (PA), and to examine the overall status of PA and specific issues identified by the group and by the PAAG. The work will be carried out in several phases where the membership and tasks of the group are expected to change between phases.

In Phase I, the goal of the IPAG was to examine recently completed PA studies as a practical body of evidence that would indicate the current status of PA and could shed light on what can and should be done in future studies. Ten organisations participated in this phase, where each submitted their most recent integrated PA study for examination and as a basis for discussion within the group. These organisations (see Table 2 of the main report) represent organisations responsible for implementing waste management facilities and related R&D, as well as regulatory agencies.

Phase-1 of the IPAG study was carried out mainly between June 1995 and April 1996 and focused on the production, refinement and answering of a questionnaire on the submitted PAs, and examination and discussion of the answers. The information base which the IPAG compiled is presented in Appendices to the main report. These offer, in a consistent format, a condensed record of the scope, methodology and documentation approach of ten safety assessments of deep geological repositories.

The submitted PAs differ in many respects. In particular, they represent assessments of different waste forms and of different geologic media and were:

- carried out for different purposes, e.g. in the context of different siting and licensing processes, by proponents and by regulators, and at different stages of repository development programmes;
- undertaken with different levels of ambition and resources;
- completed at different times within a period (1991-1996) during which methods of site evaluation and PA have been developing; and
- documented at different levels of detail.

The mix of different organisations, disposal concepts, stages of implementation etc., offered a valuable opportunity for exchange of information and discussion amongst the participants, and the information compiled during the study is a useful source of reference and introduction to the studies. On this basis, the IPAG has formulated a set of observations and recommendations summarised below.

Because of the heterogeneity of the source material it was not intended that comparisons should be made between the studies. Likewise, the reader is advised not to undertake comparisons between studies, nor to try to draw wide-ranging and definitive conclusions from the information compiled.

Observations and recommendations

The IPAG summarises its findings in twelve observations and recommendations. These are addressed mainly to PA groups and reviewers of PA, but include some specific recommendations to the PAAG and SEDE. The observations and recommendations are presented in abbreviated form below and, in full, in Section 2 of the main report.

1. Progress since the Collective Opinion of 1991

On the basis of its examination of ten recent PA studies, the IPAG concludes that:

– dealing with data sets from actual sites, as has been increasingly practised since 1991, presents some challenges and requires more resources than expended in earlier PAs, but
– no new insurmountable problems have been encountered in the application of PA, and thus the NEA/IAEA/CEC "Collective Opinion" of 1991 remains valid.

The IPAG identified several areas in which there have been significant advances in method and application. There are, however, still prospects for specific improvements (for example in developing traceability and transparency, interaction between site characterisation and PA, and treatment of spatial and temporal variability and uncertainty) and for the development of a more profound general understanding.

2. Sharing of PAs

Members of IPAG found the opportunity to meet and discuss recently completed integrated PAs both interesting and helpful, and recommend that PAAG should continue to give high priority to presentation and discussion of PAs in its meetings. PA groups should be encouraged to give presentations of recently completed studies, where the presentations should include discussion of the method and rationale for its choice, "high-lights" and "low-lights" of the application, and key lessons learnt.

The questionnaire and information compiled by IPAG is a useful source of reference that could provide a model for a PA database to be maintained by the NEA Secretariat. This, however, has resource implications for PA groups and the NEA which require consideration.

3. *Traceability and transparency of PA*

Traceability in PA refers to an unambiguous and complete record of the decisions and assumptions made, and of the models and data used in arriving at a given set of results. This is an important element of quality assurance and, in principle, complete traceability can be achieved, even though at high cost in terms of time and resources.

Transparency refers to the PA being clearly reported, so that the audience can gain a good understanding of what has been done, what the results are, and why the results are as they are. This is a more subtle, and audience-dependent, requirement. The IPAG has set out nine points of guidance on promoting transparency to technical audiences and reviewers.

4. *Scope of assessment*

All assessments have limitations in scope, for example, related to the intended use of the PA, regulatory requirements, and also the available resources. Limitations in technical scope, e.g. a partial selection of scenarios, may lead to a bias in the results of the analysis. It is important, therefore, that PA groups should document decisions on the scope of their PA, recognise the potential impact of the limitations on the analysis, and place appropriate caveats on the results and conclusions.

5. *Content of safety assessment report*

The content of a safety assessment report will be influenced by external factors related to its specific purpose in the disposal programme, and practical constraints, e.g. related to methods adopted, resources and time allowed for documentation. Therefore, a universal plan of contents cannot be recommended. Examination of the PAs submitted to IPAG suggests, however, that there are common elements in most PA reports. Taking account of the need to promote transparency in PA documents, IPAG recommends a set of eighteen elements (or topics) that should be addressed in a safety assessment report.

6. *Roles of the geosphere, interaction between site characterisation and PA*

The geosphere is a key component in any deep geological disposal system as it both protects and preserves the wastes and engineered barrier system, and may also retard and disperse contaminant releases. Thus, a key issue for PA is the extent to which site characterisation can provide data that can give confidence (or support analyses to demonstrate) that the required functions of the geosphere will be realised. The IPAG has identified critical phenomena and uncertainties associated with geosphere functions and discussed the potential for resolving these uncertainties from site measurements for the host rock types considered in the ten PAs submitted, i.e. crystalline rock, unsaturated tuff and salt formations.

General issues identified are:

- the potential uncertainties/errors introduced by the use of idealised models of rock heterogeneity, e.g., stream-tube models;

- the long-term stability and predictability of the disposal system - PA should emphasise the particular requirements on the geosphere and engineered components within the safety design, and the scientific basis for the assumptions made;
- the co-ordination and feedback between site characterisation, system design and PA activities - the IPAG recommends that the PAAG and SEDE stimulate activities concerning the interaction between PA, site characterisation and design, and the use of PA as a tool to guide field and laboratory investigation programmes.

7. Treatment of spatial and temporal variability and uncertainty

Spatial and temporal variability refers to an entity that varies in space and/or time, but at a given space-time point is well defined. Uncertainty, on the other hand, refers to a lack of knowledge or precise characterisation, e.g. either a lack of knowledge concerning future events or the inability to define precisely an entity in space and time. Most PAs classify uncertainties into scenario (completeness) uncertainty, conceptual model uncertainty and parameter uncertainty, although the boundary between these classes in any given PA may be largely an operational one.

Deterministic and probabilistic calculational approaches have been used to investigate and illustrate the effects of uncertainties in PA results. Both approaches have advantages and disadvantages and the most appropriate approach to take in a particular case will depend on national regulatory guidance, the level of data available and presentational requirements. Not all uncertainties can be quantified; examples include scenario completeness and the existence of alternative conceptual models. Such non-quantifiable uncertainties should, nevertheless, be addressed in PA.

8. Stylised presentations

Stylised presentations may be used in PA to illustrate the impact of phenomena for which there is a general lack of experimental evidence, e.g. future human actions and future conditions of the biosphere. In such cases, the scenarios, models and/or parameter values must be predominantly subjectively chosen. The acceptability of stylised presentations cannot be decided by the PA community alone. For regulatory compliance, the regulator will decide the acceptability of stylised presentations. More generally, the views of wider technical audiences, and also of the public, may be valuable.

IPAG recommends that PAAG should explore whether there is interest in international co-operation to develop stylised presentations for use in PA in respect of specific processes or aspects of the disposal system performance.

9. Formal procedures for handling FEPs

Substantial progress has been made in the last few years in developing formal procedures to identify and document relevant features, events and processes (FEPs), e.g. the use of interaction matrices, influence diagrams and database software. These methods assist PA by improving the comprehensiveness of considerations, providing a formalism to discuss the long list of potentially relevant issues and providing documentation of assumptions and decisions made that lead to the choice of scenarios, models and calculation cases.

Recent developments in the area of FEP analysis and scenario formulation may make this an opportune time to revisit this topic. Specific recommendation are expected from the NEA FEP Database Working Group.

10. Natural analogues

There are few examples of the direct use of data from natural analogue projects in the PAs submitted to IPAG. Rather, natural analogues are seen as a component of the confidence-building process. They support the understanding of key processes and also provide evidence that no other processes or phenomena that have had a significant long-term effect have been overlooked.

11. Nuclides contributing most to dose rates

The IPAG was asked to identify, in descending order of importance, those radionuclides that contribute most to dose in a “reference case”. This has been done for the ten PAs submitted. These results must be treated with caution as they emphasise releases, whereas the retention of safety-relevant radionuclides is even more important in developing a safety case. Moreover, the “reference case” considered in each assessment is different in many respects, and comparisons cannot be made between the studies. Only programmes having similar concepts could perform such comparisons.

12. Vocabulary

Several differences in terminology were noted during the examination of the PAs and related discussion, e.g. the use of the words ‘scenario’ and ‘model’. IPAG does not propose that a common vocabulary should be established, but recommends that terms that have a special meaning within a project should be defined and used consistently in PA documents. A hierarchy of definitions is suggested for the terms ‘performance analysis’, ‘performance assessment’, ‘safety analysis’, ‘safety assessment’ and ‘safety case’. This hierarchy is consistent with the IAEA waste management glossary definitions and may be helpful to describe the scope of an analysis or assessment.

Conclusions

IPAG has carried out a thorough examination of the practice of PA in several countries in the period 1991 to 1996. The primary value of the study has been to the participants, who have gained a greater understanding of PAs carried out in other countries and also have been given a fresh perspective on their own PAs. The experience, starting with the formulation of the questionnaires and ending with the drafting of this report, has been interesting and worthwhile to all the participants. In addition, the work has led to the formulation of pertinent observations and suggestions to PA groups and reviewers of PA, and practical recommendations to the PAAG and SEDE. Finally, the information compiled by the IPAG is a useful source of summary information related to the ten submitted PAs, and may provide a model for collating information on future PA studies.

As a result of further discussion at PAAG, and in other fora, a new phase of IPAG work is being planned. The new phase will emphasise the experience of peer review, and especially regulatory review, of performance assessment studies.

References

1. Disposal of Radioactive Waste: Can Long-term Safety be Evaluated? An International Collective Opinion. OECD Nuclear Energy Agency, Paris, 1991.
2. Disposal of Radioactive Waste: Review of Safety Assessment Methods. OECD Nuclear Energy Agency, Paris, 1991.
3. Safety Assessment of Radioactive Waste Repositories. Proceedings of an International Symposium organised by the NEA, IAEA, CEC in Paris 1989. OECD Nuclear Energy Agency, Paris, 1990.

1. INTRODUCTION

1.1 BACKGROUND

NEA's Radioactive Waste Management Committee (RWMC) and its Performance Assessment Advisory Group (PAAG) and Co-ordinating Group on Site Evaluation and Design of Experiments (SEDE) have long been committed to foster co-operation leading to improved understanding and, eventually, to the successful implementation, of facilities for the deep geologic disposal of long-lived radioactive waste. To that effect, a safety assessment report is the means to convey to the various parties that participate in the licensing process the information necessary to judge whether the repository, as located, designed, and implemented, provides reasonable assurance that the safety goals are met.

In 1991, RWMC and PAAG participated in the development of the Collective Opinion by NEA, IAEA, and CEC addressing the question "Can Long-Term Safety Be Evaluated ?" (NEA/IAEA/CEC 1991). The Collective Opinion confirmed that safety assessment methods are available to evaluate adequately the potential long-term impacts of waste disposal systems. However, it also concluded that sufficient information about proposed disposal sites was needed, and that assessment methods would be developed further as a result of ongoing work.

Several performance assessment/safety assessment (PA/SA) studies have become available since 1991. In a situation where PA studies are being used to defend present repository concepts on investigated potential sites, and are soon to be used in applications for the siting of deep repositories, it has been found to be of immediate interest to many NEA member organisations to increase the level of understanding of the existing assessments. They can be viewed, and analysed, as an information base on what can or could be done in PA. It may be observed that the commonalities define the state-of-the-art, while the differences may reflect different reference conditions or highlight areas for further reflection.

Thus, following an initial proposal by SKI, the Swedish Nuclear Power Inspectorate, and a subsequent request by RWMC, PAAG set up first an ad-hoc Working Group, and then a full Working Group on Integrated Performance Assessments of Deep Repositories (IPAG). The Terms of Reference approved by PAAG in October 1995, specify the following goals for IPAG:

- to analyse existing PA studies and learn about what others have produced
- to shed light on what can and should be done in future PA studies
- to produce a report to be used as the basis of an NEA document on safety assessments of deep repositories
- to report the study results to PAAG and to the Site Evaluation and Design of Experiments (SEDE) group

The present document fulfilled this final goal.

The development of the IPAG initiative, along with the relevant documentation, is detailed in Table 1. Central to the progress of the initiative was the formulation of a questionnaire on the contents of available PA studies.

Table 1. Development of the IPAG initiative.

Action / meeting	**Content / outcome**	**NEA Document(s)**
SKI proposal to RWMC for PAAG activities to increase understanding of existing PA methods	"... these studies could serve as a body of evidence to explore and draw lessons from, and for suggesting practice-oriented future work priorities within PAAG"	NEA/RWM/DOC(92)7/ REV2/ADD
25th meeting of RWMC (February 1993)	RWMC directs PAAG to implement SKI's proposal. Methodological aspects for conducting a PA seen as very important.	NEA/SEN/RWM(93)1
9th meeting of PAAG (September 1993)	Ad-hoc group is to be convened under the chairmanship of Mr. J. Andersson to elaborate further on SKI's proposal and suggest actual working plan.	NEA/SEN/RWM(93)3
Ad-hoc working group on integrated assessments (meeting in February 1994)	The ad-hoc group presents preliminary observations of items that would benefit from joint discussions, and suggests potential WG tasks, modes of operation, participation, and schedule. A questionnaire is provided to facilitate the collection of information.	NEA/PAAG/DOC(94)5
10th meeting of PAAG (October 1994)	Strong interest in qualitative intercomparisons of PA studies. Working group is to be formed, under the chairmanship of Mr. J. Andersson, after reception and analysis of answers to questionnaire.	NEA/SEN/RWM(94)6
1st meeting of IPAG (June 1995)	Ten organisations responded to the questionnaire. A first compilation is made available and discussed. Agreement is reached to proceed with a revised questionnaire and to draft a mandate for IPAG.	NEA/IPAG/DOC(95)1
Informal IPAG meeting (October 1995)	New questionnaire is approved. A set of "extra questions" is formulated. Mandate is finalised. Group members will also communicate three main observations and recommendations for the final report of the group. New Chairman: Mr. T. Vieno	NEA/IPAG/DOC(95)2
11th meeting of PAAG (October 1995)	PAAG approves IPAG mandate. First phase of work programme is to end in Autumn 1996 with a written report.	NEA/IPAG/DOC(95)3/REV NEA/SEN/RWM(96)1
2nd meeting of IPAG (April 1996)	Discussions on 1. the tabulation and compilation of answers to questionnaires, 2. observations and recommendations, 3. IPAG contribution to a joint PAAG/SEDE topical session in October 1996, and 4. future work.	NEA/IPAG/DOC(96)1
12th meeting of PAAG (October 1996)	Preliminary version of the final IPAG report and IPAG contribution to PAAG/SEDE topical session on the role of the geosphere in performance assessment.	NEA/SEN/RWM(96)4

Core Group of PAAG (February 1997) and 29th session of RWMC (March 1997)	Approval of the publication of the final report. Launching of a new IPAG phase emphasing the experience of regulatory review of integrated performance assessment studies.	NEA/SEN/RWM(97)4

1.2 MODES OF OPERATION

Ten organisations, identified in Table 2, participated in the IPAG exercise. They represent safety authorities as well as organisations responsible for R&D and implementing of waste management facilities. All organisations submitted their most recent integrated PA study for analysis and discussions, and provided answers to the questions formulated by the group. Table 3 offers a summary of the disposal concepts that were addressed.

The mix of several types of waste management programmes, disposal concepts and PA studies has offered a unique opportunity for the exchange of information and discussion. As there are substantial differences in the disposal concepts and also in the objectives and scopes of the PAs, IPAG was not requested to perform detailed, quantitative intercomparisons of the submitted PAs. However, some of the participating organisations having similar disposal concepts (repositories in crystalline rocks) have recently compiled such intercomparisons of PAs (Neall et al. 1994, SAM 1996).

Table 2. Participating organisations and their integrated PA studies

Organisation	**Integrated PA study submitted to IPAG**
AECL, Canada	The disposal of Canada's nuclear fuel waste: Postclosure assessment of a reference system (Goodwin et al. 1994)
GRS, Germany	Analysis of the long-term safety of disposal concepts with heat producing radioactive wastes (Buhmann et al. 1991) (*in German)*
NAGRA, Switzerland	Kristallin-I Safety Assessment Report (Nagra 1994)
PNC, Japan	Research and development on geological disposal of high-level radioactive waste, First progress report (PNC 1992)
SKB, Sweden	SKB-91, Final disposal of spent nuclear fuel. Importance of the bedrock for safety (SKB 1992)
SKI, Sweden	SKI SITE-94 Deep Repository Performance Assessment Project (SKI 1996)
POSIVA, Finland	TVO-92 safety analysis of spent fuel disposal (Vieno et al. 1992)
US DOE/WIPP	Draft 40 CFR 191 Compliance Certification Application (DCCA) for the Waste Isolation Plant (SNL 1995)
US NRC	NRC Iterative Performance Assessment Phase 2: Development of capabilities for review of a performance assessment for a high-level waste repository (NRC 1995)

US DOE/YMP	Total-System Performance Assessment - 1995: An evaluation of the potential Yucca Mountain repository (Andrews et al. 1995)

Table 3. Some relevant characteristics of the disposal concepts in assessments examined by IPAG

Study	Waste	Host Rock	Canister	Repository	Site
GRS's GSF-91	Vitrified HLW. Spent fuel (LWR, THTR), 35000 tU. Reprocessing sludge, Cement, Reactor waste.	Rock salt	Drums, HLW steel containers, Pollux casksfor HLW and spent fuel	870 m deep. Drift emplacement for Pollux casks. Borehole emplacement for drums and canisters. No buffer. Salt backfill.	Gorleben
AECL's EIS	162 000 tU of spent CANDU fuel	Low permeability granitic rock	Thin-walled titanium container	500 - 1000 m deep. Individual vertical emplacement holes. Clay/sand buffer. Clay/rock backfill.	Based on Whiteshell Research Area URL
NAGRA's Kristallin-I	Vitrified HLW from reprocessing of 3 000 tU of spent LWR fuel	Crystalline basement of Northern Switzerland covered by sediments	Carbon steel thick overpack	1000 m deep. Horizontal, in-tunnel emplacement. Thick bentonite buffer.	Two potentially suitable siting areas in Northern Switzerland
PNC's H3	Vitrified HLW from reprocessing of 55 000 tU of spent LWR fuel	Wide range of crystalline and sedimentary rocks are considered	Carbon steel thick overpack	Deep rock. Horizontal, in-tunnel emplacement. Thick bentonite buffer.	Not specified
SKB's SKB-91	7000 tU of spent LWR fuel	Crystalline rock	Lead filled copper canister	500 m deep. Individual vertical emplacement holes. Bentonite buffer.	Based on Finnsjön study area
SKI's SITE-94	800 tU of spent LWR fuel	Crystalline rock	Copper with inner steel canister	500 m deep. Individual vertical emplacement holes. Bentonite buffer.	Based on Äspö HRL (hypothetical repository)
POSIVA's TVO-92	1840 tU of spent BWR fuel	Crystalline rock	Copper with inner steel canister	500 m deep. Individual vertical emplacement holes. Bentonite buffer.	Five investigation sites
WIPP's DCCA	TRU 175 000 m^3	Rock salt	Drums; Steel containers	In gallery at 657 m.	WIPP Site
YMP's TSPA-95	70 000 tU of spent LWR fuel	Unsaturated fractured tuff	Several within multi-layer container	300 m deep. Several emplacement and buffer options.	Yucca Mountain
NRC's IPA-2	70 000 tU of spent LWR fuel	Unsaturated fractured tuff	Overpack container	300 m depth. Vertical emplacement. No buffer or backfill.	Yucca Mountain

The IPAG group met officially twice, in June 1995 and April 1996. An informal meeting was arranged on the occasion of the PAAG meeting in October 1995. Additional contacts among the group members have taken place throughout the process on various occasions and by means of regular communication channels.

The June and October 1995 meetings were devoted, for the most part, to:

- updating the questionnaire on the contents of the submitted PAs that had been developed, distributed, and analysed by the ad-hoc working group preceding IPAG
- formulating a set of "extra questions" reflecting some specific aspects and judgemental choices
- drafting specific terms of reference for the future work of the group.

The formulation of the "new questionnaire" and the "extra questions" (Appendix II of the present report) offered excellent ground for discussion and was good experience for the IPAG members. These questionnaires were distributed to the participating organisations, and their answers have constituted the background material for much of the later work of IPAG.

All individual answers were made available to the group members, who were asked to comment upon them by providing their observations and recommendations.

The answers to the questionnaires, along with the observations and recommendations provided by the IPAG members, were used to prepare, with the help of two consultants, a self-standing document (Appendix I of the present report) referred to as "the compilation" hereafter.

Another activity was the preparation of observations and recommendations. On the basis of the IPAG experiences, each member was asked to formulate at least three observations or recommendations directed either generally to PA groups and reviewers of PAs or specifically to PAAG and SEDE on potential actions within NEA. On the basis of the input from the group members, the chairman and the secretariat with the help of the consultants compiled an initial set of fourteen observations and recommendations which were distributed for review to the group before its last meeting in April 1996.

The April 1996 meeting was then devoted to:

- discussion of the compilation and the tabulation of the questionnaire answers,
- drafting of a final set of observations and recommendations
- preparation of IPAG's contribution to the joint PAAG/SEDE Topical Session on the interaction between PA and site characterisation
- assessing the experience gained by the group as well as future work needs, and
- agreeing the structure of the present report.

1.3 END-PRODUCTS AND ORGANISATION OF THE REPORT

This document represents the accomplishments of the first phase of IPAG which, according to the group's Terms of Reference, was concluded shortly after the 12th meeting of PAAG in October 1996.

IPAG's end-products for this first phase of work constitute of the following:

- Appendix I of this document comprising of the compilation and analysis of the answers to the IPAG questionnaires which are reproduced in Appendix II.
- Observations and recommendations for PA groups and reviewers of PAs, and specific recommendations to PAAG and SEDE on potential actions within NEA are presented in Chapter 2.
- IPAG's recommendations on the continuation of work on integrated PAs within NEA are summarised in Chapter 3.

The above materials have also formed the basis of a joint PAAG/SEDE topical session on the role of the geosphere in integrated performance assessments.

2. OBSERVATIONS AND RECOMMENDATIONS

On the basis of the answers to the IPAG questionnaires and discussions within the group, IPAG summarises its findings in twelve observations and recommendations (the numbering refers to the Sections of the report):

2.1 Progress since the Collective Opinion of 1991
2.2 Sharing of PAs
2.3 Traceability and transparency in PA
2.4 Scope of assessment
2.5 Content of safety assessment report
2.6 Roles of geosphere, interaction between site characterisation and PA
2.7 Treatment of spatial and temporal variability and uncertainty
2.8 Stylised presentations
2.9 Formal procedures for handling FEPs
2.10 Natural analogues
2.11 Nuclides contributing most to dose rates
2.12 Vocabulary

Most of the observations and recommendations are directed to PA groups and reviewers of PAs. Specific recommendations are also made to PAAG and SEDE on potential future actions within NEA. The latter are also summarised in Chapter 3 along with additional recommendations on possible future actions and the continuation of IPAG's work.

2.1 PROGRESS SINCE THE COLLECTIVE OPINION OF 1991

Background

It was concluded in the NEA/IAEA/CEC Collective Opinion (NEA, IAEA, CEC 1991) that

- safety assessment methods are available today to evaluate the potential long-term radiological impacts of a carefully designed radioactive waste disposal system on humans and the environment, and
- appropriate use of safety assessment methods, coupled with sufficient information from proposed disposal sites, can provide the technical basis to decide whether specific disposal systems would offer to society a satisfactory level of safety for both current and future generations.

This was supported by a Review of Safety Assessment Methods (NEA 1991) based on experience prior to 1991.

Observations based on the IPAG exercise

Since 1991, developments have been made in PA methods and experience has been gained in their application. A large fraction of this experience is included in the assessment projects which have been represented in the IPAG exercise, and the exercise has given the opportunity for participants to both reexamine their own experiences through filling in the questionnaires and to discuss key features of method and experience with each other. On this basis, the group concludes that:

- dealing with data sets from actual sites, as has been increasingly practiced in PA since 1991, presents some challenges and requires more resources than expended in earlier PAs, but
- no new insurmountable problems have been encountered in the application of PA, and thus the findings of the NEA/IAEA/CEC Collective Opinion document remain valid.

In addition, whereas developments have been made in a number of specific areas (see below), the NEA document "Review of Safety Assessment Methods" should, in principle, continue to provide an acceptable, general statement of safety assessment methods.

Areas in which there have been more significant advances in method and application include:

- comprehensive identification of relevant features, events and processes (FEPs), and tracking of decisions on treatment and/or incorporation of FEPs into assessment models (these are discussed in more detail in Section 2.9)
- dealing with large site data sets and more formal methods of reduction of data for use in assessment models
- more sophisticated use of geochemical codes and data to simulate pore water composition and evolution and to arrive at element speciation and solubility equilibria
- use of three-dimensional models of groundwater flow including density and transient effects, and use of spatially-variable models of hydrogeological media, based on site data
- greater understanding of transport of contaminants through fractured rock and unsaturated rocks (discussed in Section 2.6)
- better-based models of particular processes, e.g. volcanism and its effects, treatment of colloids, gas-mediated releases
- more sophisticated use of probabilistic codes including representation of time-dependent processes and events
- application of more rigorous quality assurance procedures for assessment decisions, control of input/output data sets, and code development.
- the incorporation of qualitative understanding in the argumentations of safety.

However, in some of the above mentioned areas, there are still prospects of more profound understanding and more mature PA practices. Today's frontiers of R&D are explored, for example, in Sections 2.3 “Traceability and transparency in PA”, Section 2.6 “Roles of geosphere, interaction between site characterisation and PA”, and Section 2.7 “Treatment of spatial and temporal variability and uncertainty”.

In general, the use of PA for licensing of waste management facilities calls for a closer interaction between PA site characterisation, engineering, and supporting R&D. Ancilliary areas in which there is still experience to be gained, in most countries, are i) the management of the technical exchange between proponent and regulator, bearing in mind their respective, distinct roles, and ii) presenting information related to that exchange at an appropriate level of detail for the public.

2.2 SHARING OF PAs

Members of IPAG have found the opportunity to meet and discuss recently completed, integrated PAs both interesting and helpful. We would encourage all PA groups, especially those who have not taken part in IPAG, to communicate and share their experience with other PA groups. We consider that exchange of information and experience on PAs should continue to take place at the PAAG level. We recommend that PAAG should give a high priority to presentation and discussion of PAs, for example, by having a session in each meeting for presentations of recently completed PAs. (This recommendation has already been implemented by PAAG.)

Recommendation: Presentations of PAs to PAAG

There are different levels of detail for presentations of PAs to PAAG. A discussion is necessary within PAAG to determine which form of presentation will achieve most support and active participation from PAAG members and PA groups, bearing in mind that different Member countries may have different interest in such presentations depending on the stage at which their particular programmes are.

We suggest that the following topics should be covered when presenting a PA to PAAG:

- the PA method and rationale for the chosen method, e.g. regulatory influence, level of site data, safety assessment philosophy, practical constraints
- "high-lights", i.e. special or new techniques and capabilities employed or aspects of the PA of which the PA group is particularly proud
- "low-lights", i.e. particular difficulties or issues where the PA group is not satisfied with their current treatment
- key lessons learnt, i.e. how will the experience change or direct future PA efforts by the group ? This could include management, organisational, resource and documentation issues as well as technical modelling and calculational issues.

We encourage all PA groups to give a presentation of their PA in PAAG, and to deliver PA reports to all members of PAAG. We recommend also that a list of PAs that have been presented to PAAG, and a list of PA reports delivered to PAAG members, should be maintained and included as an appendix in the minutes of the PAAG meetings.

Recommendation to PAAG: Development of the questionnaire and a PA database

Much information, related to the actual contents of the submitted PAs, is presented in the answers to the IPAG questionnaires. This information is a useful source of reference and could form the basis for a catalogue or database of PA information. Such a catalogue, if maintained and periodically updated to include new assessments, could document the progress made over the years in performing PAs.

To produce and maintain such a catalogue has resource implications and the potential uses of the catalogue need to be considered. A minimum function of the catalogue would be to flag the existence of a documented project and outline of its scope so that other programmes could decide whether they wish to examine a particular PA in detail. This function could be achieved through a catalogue including the title, contents list and (executive) summary of the report. In addition, a compilation of factual information might be considered covering, for example, the waste type and amount, the engineered design, the host rock type, the purpose of the assessment, the period over which the work was carried out, the connection to past and (planned) future national PAs.

A second level of detail would be to adapt the existing IPAG questionnaire to be more generally applicable and ask that this information also be provided. The IPAG group is of the opinion that the current questionnaires and answers have served their purpose of analysing the scope and assisting comparison between the PAs submitted to IPAG. If completion of a questionnaire at a similar level of detail were to be a requirement for future PAs, then the existing questionnaire needs to be reviewed so that it can remain valid over a substantial (e.g. 10 year) period. This course would require some resources both to produce an acceptable questionnaire and for future PA studies to answer the questionnaire.

2.3 TRACEABILITY AND TRANSPARENCY IN PA

Observations and definitions

It is obvious that PA groups should strive for traceability and transparency in their PA but to progress further we need to define these terms and consider how the desired qualities can be achieved.

By **traceability** we understand an unambiguous and complete record of the decisions and assumptions made, and of the models and data used in arriving at a given set of results. To be complete, this should include information on when and by whom various decisions and assumptions were made, on what basis, how these decisions and assumptions were implemented, what version of codes and data sets were used etc. This is an important element of quality assurance and, in principle, complete traceability can be achieved, even though at high cost in terms of time and resources. A test of traceability is that an independent PA group should be able to reproduce the analysis or selected parts thereof.

A formal set of QA procedures to promote traceability, and evidence that these procedures have been consistently applied will be a vital aspect of a PA that is at the stage of license application. At stages of preliminary assessment, a less rigorous approach may be acceptable, and may allow a more flexible or rapid approach to preliminary modelling. Nevertheless, care must be taken that key decisions are recorded and supported. It seems unlikely that all the information necessary to achieve complete traceability (i.e. to the degree necessary for repeatability) will be found in the top level PA report. It should, however, be found in supporting technical reports and catalogues that should be available for inspection by a technical reviewer or QA auditor.

By **transparency** we understand the PA report to be written in such a way that its readers can gain a clear picture, to their satisfaction, of what has been done, what the results are, and why the results are as they are. This is a more subtle requirement than that of traceability. We observe, as well, that transparency is audience-dependent, i.e. a document that is transparent to a regulator or practitioner of PA may not be transparent to a member of the public and vice versa.

PA documents are typically written as narrative descriptions of the analysis and assessment process from the point of view of the group performing the PA. PA documents must address, as well, the needs of a technical or regulatory reviewer, who will want to have an overview of the work done and its outcomes, but who will also wish to use the document to focus in on very specific issues or aspects of the system. The document should be structured, or provide guidance, to facilitate in-depth reviews so that the technical reviewer does not have to search an entire document to compile information for a specific issue of interest. Such a structuring is part of the task of designing a PA to be transparent and complete.

Guidance on methods of promoting transparency

We concentrate here on how transparency to technical audiences can be encouraged and especially on transparency that a regulator might expect. We propose the following guidance on promoting transparency in PA.

- ***Present the method*** - if a logical method is clearly set out and consistently followed then the descriptions of how particular aspects of the system were analysed, i.e. how the methods were applied for specific subsystems, can be simpler.
- ***Present the assumptions made and their basis*** - within an assessment there is usually a hierarchy of assumptions starting from assumptions defining the scope of assessment (see Section 2.4) down to assumptions concerning specific processes and the validity of given data.
- ***Present the modelling accurately*** - The broad scientific basis of the PA needs to be emphasised. However, the reviewer needs also an accurate description of exactly what conceptual features and processes are represented in the models, and by what algorithms.
- ***Present the data used and their sources*** - discuss the quality and uncertainties associated with data, where applicable, and be clear about what data have been used in a peripheral sense, e.g. to guide modelling assumptions or lend confidence to analytical results, and what data are used directly in the analysis.
- ***Present intermediate results*** - intermediate results appropriate to the disposal system, e.g. of thermal analyses, groundwater flow and transport, and contaminant release from individual subsystems, will help the reader to build up an understanding of the behaviour of the disposal system. Amongst the intermediate results there should be a presentation of nuclides with high potential risks (e.g. Pu) and not only those contributing to the final dose (e.g. I-129). Results of this kind build confidence that the repository fulfills its intended function.
- ***Present deterministic analyses*** - if the PA study is based on probabilistic simulation, also present deterministic calculations that are typical of behaviour, e.g. median value calculations, and represent extremes of behaviour, e.g. simulations contributing most to risk. Presenting the complete input data and results of deterministic runs helps reviewers to understand the behaviour of the modelled system.
- ***Analyse the results to identify key assumptions, models, data and uncertainties*** - identify and trace back the origin of key assumptions, data etc. and thus assess the confidence in the results by reference to confidence in their basis.
- ***Explain the results*** - in terms of the physical features and processes that are represented in the models and give rise to the results. Confirm the overall logic and consistency of the physical arguments and, if possible, present other evidence or lines of argument that give clarity or support to key physical arguments, e.g. scoping and bounding calculations, natural analogues, etc.
- ***Identify points of weakness*** - at least in preliminary assessments, identify any key assumptions, models or data that are weak and indicate the need for further work.

2.4 SCOPE OF ASSESSMENT

Observations

All assessments have limits in scope. Reasons for limiting the scope may be due to the intended use of the PA, the scope of previous or planned PAs, regulatory requirements, and also the available resources. Examples of measures to deliberately limit scope include the use of FEP screening rules, giving deliberate attention to certain regions of the system (e.g. performance of engineered barrier options, influence of geological uncertainties), giving more attention to certain process subsystems (e.g. processes affecting canister integrity, groundwater-mediated radionuclide migration), and limiting the time scale of analysis (e.g. by reference to regulatory advice or site specific physical factors). Such limits in scope should not be confused with the extent of model boundaries, which are generally determined based on the specific phenomena being modelled.

Limits in scope may affect scenario (or completeness) uncertainty (see Section 2.7) and may also lead to bias in the results of the analysis. For example, a narrow scope may imply that potentially important FEPs will not be identified, or a decision to exclude potentially beneficial FEPs may result in an over-conservative assessment.

Recommendation to PA groups

We recommend that PA groups should document decisions on the limits of scope in their assessments and explain the reasons for them. The impact of limits of scope on the results of the assessment should be recognised, and appropriate caveats should be placed on the results obtained and on the conclusions drawn.

2.5 CONTENT OF SAFETY ASSESSMENT REPORT

Safety assessment is a combination of qualitative and quantitative elements. Here a possible skeleton for a safety assessment report is discussed.

The content of a safety assessment report cannot be viewed in isolation. To a large extent it is influenced by external factors, as illustrated in Figure 1. In general, these factors will be different for each safety assessment report, therefore a complete, universally valid table of contents cannot be defined. Nevertheless, examination of the contents and "walk-throughs" of safety assessment reports submitted to IPAG (e.g. see Table 4-1 in Appendix I) suggests that there are a number of elements in common.

A possible skeleton for a safety assessment report is presented below that includes the common elements found in reports submitted to IPAG. The headings indicate topics that should be discussed rather than chapter headings. For some topics, e.g. "description of models", several chapters may be required to cover the different subsystems represented. Account is taken of the measures to promote transparency in PA documents discussed in Section 2.3.

Recommended elements of a safety assessment report

- **Programme context** - the historical perspective (stage of waste management programme), regulatory context (stage of license application or preparation) and relation to previous or future assessments should be described. The waste disposal concept itself should be briefly outlined, e.g. waste type and amount, host rock type, planned date for operation, and whether alternatives are under consideration.

- **Regulatory criteria** - the national regulatory criteria or other relevant environmental guidance or criteria that the repository/assessment must satisfy or follow should be outlined. These criteria may be both quantitative and qualitative, and concern overall impact or specific aspects of performance. Regulatory criteria may also limit the scope of assessment.

- **Objectives and scope of the assessment** - objectives of the safety assessment will be related to the programme context. Scope of assessment is discussed in Section 2.4.

- **Description of the system at the conceptual level** - the overall concept of how the disposal system can be expected to provide the required level of safety should be outlined, e.g. by reference to the multi-barrier concept and safety functions of individual system components.

- **Statement of the constraints** - the particular features of the assessment constraints should be stated, for example, the long time scales for analysis, requirement for reasonable assurance, lack of direct evidence for long-term behaviour, limited geological and other data, need for abstraction, the presence of variability and uncertainty.

- **Approach to safety assessment** - the approach to safety assessment should be outlined, for example, in a discussion of uncertainties and their treatment, how models are used, levels of detail in data and models, balance of realism and conservatism, role of experts, traceability and quality assurance.

- **Detailed description of the disposal system** - the waste forms, engineered barriers and site characteristics should be described together with comments on uncertainties.

- **Interpretation and elicitation of databases** - the sources of data for actual use in the analysis should be outlined including methods by which site or other data have been interpreted and use of experts to elicit data.
- **Scenario development (or analysis)** - is the term usually applied to the process of identifying the relevant features, events and processes, and deciding which should be represented in the analysis and how that analysis may be conveniently broken down to match the available models. The methods of identifying, screening and organising FEPs into scenarios and models should be described and the process as applied in the particular assessment documented. The consequences of FEP omissions and simplifications for " matching to available models" should be described (e.g. conservative/irrelevant/open questions,...).

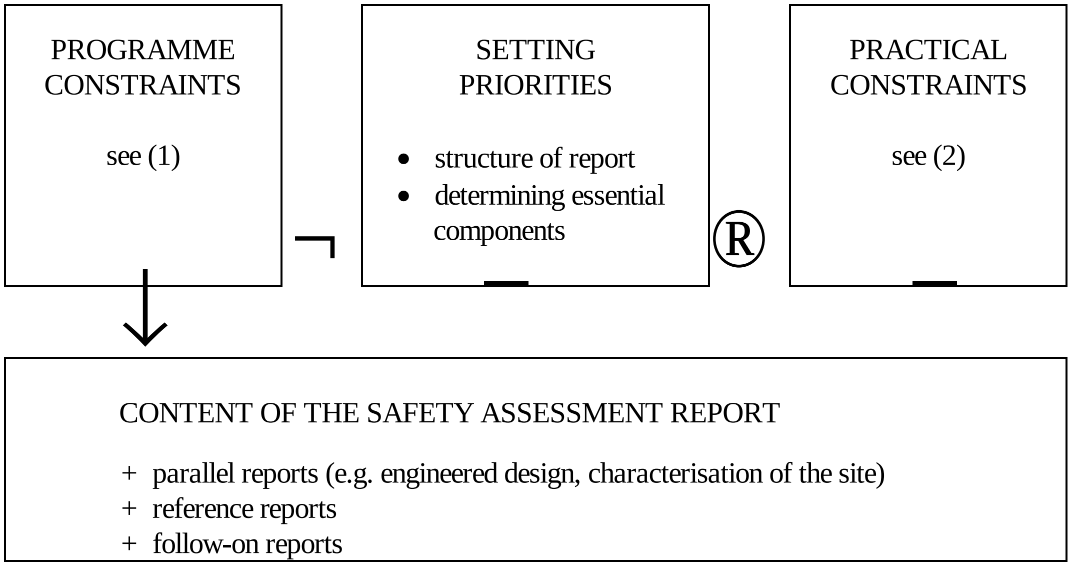
- **Description of models** - the conceptual basis and mathematical expression of models should be described (possibly only in supporting reports). Models at different spatial and temporal scales and of both parts of the disposal system and the whole system may be used. In general, detailed models of specific subsystems or temporal/spatial domains are used to provide data or guidance for simpler models simulating the release and transport of contaminants. Where alternative plausible model assumptions exist, this should be acknowledged (model uncertainty).

- **Results and interpretation** - results and interpretation should be presented for individual subsystems and the total system; auxiliary analyses may be required to represent processes not included in the main assessment model chains. Results of sensitivity and uncertainty analyses should be presented, including sensitivity to alternative evolution scenarios and model assumptions, and complementary types of calculations.

- **Confidence in key arguments** - the key processes, models, data and assumptions identified by sensitivity and uncertainty analyses should be revisited and their basis examined. Supporting evidence may be presented that lends confidence to the validity of key arguments or results.

- **Compliance with regulatory criteria** - the overall compliance with regulatory (or other relevant) criteria should be assessed. This should include both comparison to quantitative limits and checking of compliance with qualitative requirements.

- **Conclusions** - overall conclusions should be drawn, which in the case of preliminary assessments will include indication of the areas in which further data gathering, model development or research is required. The extent to which defined assessment goals have been reached may be usefully discussed.



(1) Programme constraints (on waste management programme as a whole)	**(2) Practical constraints** (on safety assessment study and documentation)
• Reasons for the study (e.g. license application, etc.) • Objectives of the study • System to be analysed (waste type, inventory, host rock type, etc.) • Target audience (implementors, regulators, other) • Legal requirements (protection objectives, etc.) • General background to the project (political situation, project historical perspective, etc.) • Safety assessment approach (treatment of uncertainty determines structure of calculations)	• Readability of the report - limited length - give only key messages - limited technical details and specialist vocabulary - reference to supporting reports • Availability of data • Availability of safety assessment tools • Availability of project staff • Schedule issues: - deadlines are usually set externally - safety assessment depends on other project components (e.g. delivery of geological data set) - an early draft document or detailed document plan can give early warning of technical gaps to be filled - structure reports such that late results or recent data can be incorporated

Figure 1. Factors that influence the content of a safety assessment report.

2.6 ROLES OF GEOSPHERE, INTERACTION BETWEEN SITE CHARACTERISATION AND PA

Roles of geosphere

The geosphere is a key component of any deep geologic disposal system as it

- protects the waste against surface processes, including human actions
- provides stable mechanical, chemical and hydrological conditions for the engineered system
- limits the amount of groundwater that may come in contact with the waste packages within the engineered system
- retards and disperses potential releases from the waste containers.

PA should take into account potentially detrimental geosphere FEPs such as volcanism, faulting, earthquakes, unfavourable geochemical conditions and effects of climatic changes. Inadvertent human intrusion is also typically addressed, e.g. based on evaluation of the resource potential of the geological environment.

Another key component of a repository is the engineered system. The waste form, waste packages, packing materials, underground openings, backfills and seals are typical components of an engineered system. An important purpose of the waste packages and other engineered barriers is to contain the waste at least during the first centuries when fission product content and heat output are high. In many disposal concepts, the engineered system is designed to contain most of the radioactivity for even much longer periods.

In order for the geosphere to fulfil its roles (listed above), the physical and chemical environment it provides must be compatible with the materials and properties of the engineered system's major barrier components. The responsibility of assuring this compatibility is shared between site characterisation, engineering, and performance assessment. A key issue for PA is the extent to which site characterisation can provide site-specific data to provide confidence that the required functions of the geosphere will be realised.

Critical phenomena and uncertainties associated with geosphere functions, and potential for resolving these uncertainties for the specific host-rocks examined

Crystalline rocks

For crystalline rock PAs the geosphere has an important role in providing favourable (reducing) chemical and hydrological conditions at repository depth. Critical uncertainties related to this function may be associated with major future climatic changes. At northern latitudes and in mountain regions, future glaciations which may cause mechanical loading, drawdown of oxygenated waters and high groundwater fluxes in the bedrock are of a special concern. The main uncertainties associated with the mechanical stability of the rock are related to postglacial rock movements and creation of new fractures as a result of the heat load from the waste and the swelling pressure of the bentonite. These potential effects, however, may be greatly mitigated by the presence of a thick sedimentary cover in some cases where one is available (e.g., Kristallin-I). Some PAs explicitly evaluate the ensuing uncertainties but, in many cases, they were discarded by qualitative reasoning in the FEP screening process.

Where advection through water-conducting features is the dominant transport process (which is true of most of the crystalline rocks considered in PAs), it is recognised that migration of reactive radionuclides is governed by the ratio between Darcy velocity and flow-wetted surface area of water-conducting features, together with retardation by diffusion and sorption processes within and around these fractures. At the same time, it must be noted that it is difficult to obtain site specific data on the flow-wetted surface area. Some PAs address this uncertainty by evaluating alternative idealised geometrical representations of water-conducting features.

The most critical uncertainties associated with predictions of radionuclide migration in crystalline rocks concern the detailed geometrical, hydrological and mineralogical properties along the radionuclide migration paths (fractures and flow channels), including the heterogeneity of these properties. Specifically, PAs for crystalline rocks suggest that there are a few parameters that govern the capacity for retention of radionuclides in the geosphere, including:

- Darcy velocity
- flow-wetted surface area
- retardation by fracture infills (when the matrix is tight!)
- data related to retardation in the rock matrix (K_d-values, accessible matrix depth, matrix diffusivity and porosity)
- correlation among the above parameters in the fractures and flow channels.

The PAs submitted to IPAG do not provide guidance to site characterisation on how to resolve these uncertainties. In the answers to the questionnaires, some suggested that it is not meaningful to attempt to characterise in detail the small-scale phenomena and variability related to the flow wetted surface area along the potential transport paths from the planned repository to the biosphere. Useful general information may be obtained from rock laboratories and field tests performed at several sites in similar rocks. Others suggested that the uncertainties can be reduced by means of hydraulic measurements and tracer experiments at the planned site of the repository.

Tuff

Unsaturated tuff host rock may provide chemical and mechanical stability for the engineered system. Considering uncertainty in the chemical environment is important when estimating the source term, which depends on the availability of water as well as the chemistry of that water to determine the rate of container corrosion, waste form dissolution and release to the geosphere. Determining mechanical stability involves estimating the likelihood and character of rock falls, especially in response to repository cooling and potential seismic events. Mechanical stability is not likely to be a critical system performance issue if the engineered system design can provide for survival of waste packages in the event of a rock fall.

Key uncertainties identified for radionuclide transport in fractured tuff include:

- flux in the unsaturated zone and in the saturated zone at present, and in response to climate change and potential disruptive events
- potential localised flux contacting waste packages (effect of discrete paths such as fractures)
- dispersion, matrix diffusion and sorption along radionuclide contaminant transport paths
- mixing and dilution in the saturated zone
- geochemical conditions impacting the source term (rate at which radionuclides enter the geosphere, and the chemistry of the carrier plume).

Salt formations

For disposal in salt formations, the geosphere comprises the salt deposit (dome or bedded salt) in which the repository is located, as well as underlying and overlying sedimentary formations. The most important uncertainties associated with salt formations are associated with:

- the potential presence of brine pockets
- the permeability of interbeds (e.g. anhydrite and clay layers) and other heterogeneities
- the convergence rates of salt rock (for brine intrusion scenarios).

Key uncertainties for media below and above the salt formations are similar to those for crystalline rocks noted above, as far as they are applicable to sedimentary formations.

The potential presence of brine pockets is a particularly difficult uncertainty to resolve. In recent performance assessments, this uncertainty has been taken into account through conservative assumptions. As for the uncertainty in the convergence of the rock salt over long time periods, compacted backfill, if utilised, hinders this convergence process. Such uncertainty might be resolved by laboratory and in situ experiments.

A common issue in some geologic media, including the far-field of repositories in salt and crystalline formations, is the modelling of density effects on groundwater flow. The higher density at greater depth is likely to reduce the groundwater flux significantly and to improve the barrier function of the geosphere. For PA modelling, there are two options to deal with this phenomenon (i) models taking it explicitly into account can be developed and validated or (ii) it shall be demonstrated that not taking it into account really gives conservative results.

Modelling of transport in the geosphere

In most PAs submitted to IPAG, the modelling of radionuclide transport through the geosphere is based on the concept of one-dimensional streamtubes with averaged, constant conditions along the streamtube. In most PAs, modelling of sorption is based on the linear sorption equilibrium, K_d, concept. Phenomena at the interface of the (deep) reducing and (shallow) oxidising conditions, or at the geosphere-biosphere interface are usually not explicitly accounted for in PA calculations. The potential errors and uncertainties associated with the use of these simplified transport models were not evaluated in any of the PA documents.

Recommendation to PAAG: Workshop on radionuclide transport codes used in PA

IPAG recommends that PAAG organises a Workshop to discuss radionuclide transport codes used in PA. In particular, efforts should be made to evaluate the potential uncertainties/errors introduced by the use of idealised models of rock heterogeneity (e.g. streamtube models) for PA calculations, and to learn about recent developments of more sophisticated PA codes (integrated modelling of groundwater flow and radionuclide transport; codes which take into account both the large-scale and micro-scale heterogeneities affecting groundwater flow and radionuclide transport). PAAG could coordinate the organisation of this workshop with the programme of GEOTRAP.

Recommendation to PA groups

PA documents should emphasise and discuss the scientific basis of the long-term stability and predictability of the disposal system, and explain the basis for selecting geosphere functions to be taken into account and to be discarded in PA calculations. This will help to clarify the different functions of a particular barrier in the disposal system analysed and why different PAs give different weights to various components of the multi-barrier system.

Recommendation to programme managers

PA experts play an important role in providing feedback to site characterisation and supporting research. Based on the results of recent PAs, it should be possible to provide more precise information on how site characterisation should be improved and what should be measured to meet the demands of PA. Conversely, site characterisation experts should provide feedback to the PA groups regarding the feasibility to reduce or quantify the critical uncertainties identified in the PA consequence calculations.

Site characterisation as well as engineered barriers design and PA should be clearly co-ordinated within national programmes. The final safety assessment must be a product that properly reflects the data gathering, data interpretation, and first level of modelling that may be done under the auspices of the site characterisation programme as well as reflecting the PA perspective. An example of a site characterisation perspective is comparing model results with observations, and judging whether at the process level, there may be alternative conceptual models that should be considered. A PA perspective would be whether total system or subsystem results and sensitivities are traceable and reflect what are considered to be the key conceptual models and processes. A similarly structured cooperative effort may be needed to assure coordination between engineered system design and PA.

Recommendation to PAAG and SEDE: Integration of site characterisation and PA

Development of site characterisation methods and PA methodology are typically performed as an iterative process over several years. However, it is often not obvious how the results of PAs have been or will be used to guide the development of site characterisation programmes and how site characterisation results are used to re-evaluate PA modelling. IPAG therefore recommends that PAAG and SEDE stimulate activities concerning the interaction between PA and site characterisation and the use of PA as a tool for the development of field and laboratory investigation programmes. The objective would be to exchange experience on how different national programmes have approached the integration of site characterisation (SC) and PA, and to discuss the successes as well as difficulties encountered. IPAG recognises that the joint PAAG/SEDE Topical Session in October 1996 is a good first step, and recommends that PAAG and SEDE consider the establishment of a Workshop or Working Group in order to take the discussions further. The effort dealing with the SC/PA interaction at the organisational level and development of site-specific databases for PAs would be complementary to GEOTRAP which focuses on radionuclide transport predictions in actual geologic media.

2.7 TREATMENT OF SPATIAL AND TEMPORAL VARIABILITY AND UNCERTAINTY

Distinction between variability and uncertainty

There is an important distinction between (spatial and temporal) variability and uncertainty. Spatial and temporal variability refers to an entity that varies in time and/or in space, but at a given space-time point is well defined. Uncertainty, on the other hand, refers to ignorance and may result from the inability to precisely determine the entity and its variability in space and time.

Classification of uncertainty

Most PAs classify uncertainties into scenario uncertainty, conceptual model uncertainty and parameter uncertainty.

- A scenario represents a set of FEPs and interactions. Scenario uncertainty results from difficulties in identifying a complete set of scenarios, a complete set of FEPs for each scenario, and correctly identifying which interactions between significant FEPs should be included in PA models.
- Conceptual model uncertainty refers to uncertainty about the model used to represent a given set of FEPs and interactions, or choice of models. Simplifications introduced, e.g. applying one- or two-dimensional models to represent a three-dimensional system, are part of the conceptual model uncertainty, as is the uncertainty introduced by selecting a scale of spatial and temporal representation.
- Parameter uncertainty refers to uncertainty in the parameter values to be used in a model.

It is recognised that there is overlap between these classes of uncertainty and allocation to a particular class may involve a qualitative or abitrary decision.

Quantification of uncertainty

Not all uncertainties can be quantified mathematically or statistically. Ready examples of non-quantifiable uncertainty refer to scenario completeness and conceptual model uncertainty: It is not possible (i) to demonstrate that all relevant FEPs, the interactions among them, and proper conceptual models have been identified, and (ii) to calculate the uncertainty deriving from potentially missing information.

Some PA studies do attempt to obtain quantitative estimates for those uncertainties through use of expert judgement. However, other PAs doubt whether such quantifications are meaningful.

Studies supporting the view that most uncertainties can be meaningfully quantified argue that all uncertainties can be treated eventually as parameter uncertainty, provided proper attention is given to the expert elicitation process. Studies unwilling to quantify all uncertainties, instead claim that such uncertainties may be handled by qualitative methods. They refer to several methods including the logic of argumentation, reasonable projections into the future in a qualitative sense, techniques for FEPs identification, and the use of peer review.

Deterministic and probabilistic approaches

There are essentially two broad methods employed for quantitative uncertainty analysis in PA: deterministic and probabilistic approaches. Probabilistic analyses use deterministic models to calculate outcomes for given (sampled) inputs, and are in this respect no different from the deterministic ones. However, unlike deterministic analyses, probabilistic analyses assign probability estimates, or probability density functions, to individual parameter values, which allows for sampling of inputs and generation of a distribution of consequences. This sampling implies that many calculations are necessary to achieve satisfactory output statistics.

In some countries, the probabilistic approach for PA is suggested by regulation. In other countries the regulators are of the opinion that deterministic analyses should form the basis of PA and recommend that probabilistic methods be used as a complementary tool to analyse the impacts of parameter uncertainty. A few programmes implement a combination of both methods.

Deterministic PAs usually present a reference case intended to be either a realistic or a moderately conservative interpretation of the system performance. The behaviour of the disposal system under various conditions and the effects of other uncertainties are evaluated by analysing a suite of variants where alternative parameter combinations or conceptual models are used. The variants may be motivated by uncertainties belonging to any of the three different classes of uncertainty discussed above. The likelihood of different variants is usually evaluated only in qualitative terms.

Benefits of the deterministic approach include (i) transparent treatment of different types of uncertainties and clear presentation of expert judgements involved, (ii) results of individual variants are easy to understand and communicate, and (iii) it may be possible to evaluate consequences with relatively complex models. Disadvantages include the difficulty of explaining the logic of the selection of variants, difficulty in demonstrating that adequate coverage has been given to combinations of uncertainty, and the difficulty to produce a total risk estimate, if one is required.

Advantages of the probabilistic approach are (i) the explicit representation of parameter uncertainty and (ii) derivation of a risk estimate for the whole system (conditional on the accuracy of simulation models and data). Probabilistic models can, of course, be used in the deterministic mode by giving a fixed value for each parameter. Likewise, probabilistic models based on alternative conceptualisations may be used. In this case, an overall risk estimate is obtained only if the likelihoods of the alternatives can be estimated.

Disadvantages of the probabilistic approach include (i) the need to obtain appropriate density functions for each parameter, (ii) the need to either ensure sampling of independent parameters or develop quantitative descriptions of correlations between non-independent sampled parameters, so that non-physical combinations are avoided, (iii) the difficulty in demonstrating appropriate representation of low-probability/high-consequence "tails", and (iv) the difficulty in communicating probabilistic assumptions and results. The communication of probabilistic results may be enhanced by presenting the input data and results of a number of individual runs in the PA report. The need to estimate input parameter probability distributions, and indeed correlations, is apparently an additional burden with respect to performing deterministic analyses. In a qualitative sense, however, this is a problem shared with the deterministic analyses where a single value must be selected for each parameter and justified, and a consistent set of single parameter values is to be finally adopted accounting for interactions and correlations.

Recommendations to PA groups

- It is not advisable to discuss uncertainties in isolation. Pertinent consideration of uncertainties should rather be an integral element in all parts of the PA.
- The difference between spatial and temporal variability, and uncertainty should be emphasised. The terms should be clearly defined in the context in which they are used in each PA report.
- The distinction between scenario uncertainty, conceptual model uncertainty and parameter uncertainty should be emphasised.
- No single approach of treating quantifiable uncertainties and variability can be recommended for use in PA. Either a deterministic or a probabilistic approach, or parallel use of both, may be appropriate in different circumstances.
- PAs should address the issues of non-quantifiable uncertainties and completeness in the context of the safety arguments and relevant characteristics of the specific disposal system.

Recommendation to PAAG

PAAG should further explore the methods for treatment of uncertainty and spatial and temporal variability in PA. In particular, there seems to be a need for an in-depth exchange of information on two issues:

- The relative merits of the different approaches (deterministic and probabilistic) for the treatment of quantifiable uncertainties, the most effective use of these methods and the communication of results produced.
- Procedures to address non-quantifiable uncertainties and completeness.

2.8 STYLISED PRESENTATIONS

A stylised presentation refers to a situation where a part of the disposal system is treated in PA in a standardised or simplified way. The need for stylised presentations occurs if there is a general lack of experimental evidence such that decisions on treatment and parameter values to put into PA is highly judgmental. Such presentations could be made on a high level, such as prescriptions to consider present-day technology when assessing future human actions, but could also be quantitative such as radionuclide release-to-dose relations. The acceptability of stylised presentations cannot be decided by the PA community alone, although the PA community may contribute with suggestions on how to treat such situations. If results for comparison with regulatory criteria are being calculated then the regulator will judge whether a stylisation is acceptable or not. In addition, account could be taken of public views.

Situations in which stylised presentations may be acceptable include, for example:

- reference biospheres
- human action scenarios
- approaches to handling climatic evolution (e.g. glaciations)
- reference critical groups

IPAG notes that a report on the subject of reference biospheres for safety assessment of geological disposal is expected from the BIOMASS project.

Recommendation to PAAG and PA groups

PAAG should explore whether there is an interest in international cooperation to produce stylised presentations for use in PAs. If there is enough interest, goal-directed work can be launched first in one area. Depending on the breadth of the interest, the project can be carried out in an NEA framework or as a multilateral cooperation of the interested parties. Those (and only those) PA groups who think that a particular stylised presentation can be used in PA need participate in its development.

2.9 FORMAL PROCEDURES FOR HANDLING FEPs

Motivated by the need to demonstrate a comprehensive consideration of features, events and processes (FEPs) and to justify the choice of calculation cases, substantial development has taken place, in the last five years, in the area of FEP analysis and scenario development. Several organisations have developed and/or used formal procedures to identify FEPs and interactions between FEPs, and to develop scenarios and conceptual models. These procedures include:

- formal screening criteria
- matrix diagrams, e.g. Rock Engineering Systems (RES)
- influence diagrams, e.g. Process Influence Diagram (PID)

However, in the actual assessments submitted to IPAG, the treatment and modelling of FEPs is usually confined to modelling tools and knowledge of data that had been assembled from previous (less formal) assessments.

Suggested benefits of the more formal approaches are that they provide a means:

- to strive for completeness through their connection to existing FEP databases and accessibility for systematic expert review and subsequent updating
- to handle the long list of issues that do not need to be considered in the quantitative analysis
- to provide open and transparent documentation of assumptions and decisions made.

The question to be considered by individual PA groups is whether the resources required to implement the formal approaches match the benefits gained at a particular stage of PA development for a given disposal proposal and in the national regulatory context.

IPAG notes that recent developments in the area of FEP analysis and scenario formulation may make this an opportune time to revisit the NEA Scenario Working Group Report (NEA 1992), but also notes that more specific recommendations on this topic are expected from the FEP Database Working Group under PAAG.

2.10 NATURAL ANALOGUES

There are few examples of direct use of data from natural analogue projects in the PAs submitted to IPAG. Natural analogues are rather seen as a component of the confidence building process as they 1. support the understanding of key processes regarding engineered barrier materials and radionuclide transport in the engineered barriers and geosphere, and 2. provide evidence that no unexpected processes or phenomena have been present or active. They have been used to justify the conservatism of fuel and waste degradation models, to provide support for the long-term stability of buffer and container materials, and for the study of migration processes, matrix diffusion, and redox front formation.

2.11 NUCLIDES CONTRIBUTING MOST TO DOSE RATES

The question has been posed to the IPAG group members on which nuclides (in descending order) contribute most to the dose rate in a "reference case". The answers are summarised in Table 4.

The list of nuclides in the table does not necessarily represent the most interesting and important nuclides from a safety perspective, for the repository barriers are designed to contain the most harmful radionuclides (e.g. plutonium isotopes and shorter-lived nuclides with high activity inventories). That these do not appear in the table is a measure of the success of the disposal system for the assumed conditions and parameter values, but research might still be required to ensure that such conditions and parameter values are valid. Therefore, Table 4 should be used with caution. In addition, the reference cases differ between assessments, (the concept of a “reference case" is not used in all of the assessments), and the time cut-offs and treatment of nuclide chains also differ. Thus, the list of nuclides is not really comparable between assessments.

I-129 (which has a rapid release component from the gap and gain boundaries inventories in spent fuel, almost no sorption, and a long half-life) dominates the dose rate in PAs considering spent fuel disposal in saturated conditions. It is present in only very small quantities, and is therefore not important, in the cases of vitrified high-level waste. However, it must be noted that there is sometimes a lack of similarity in answers even when there are apparent similarities in waste and assessment approaches. These differences may be due to differences in the input parameter values used in the consequence analyses or to differences in detailed model assumptions. We encourage the programmes having similar disposal concepts to continue the efforts (see, e.g., Neall *et al.* 1994, SAM 1996) to clarify the reasons for these differences.

Table 4. Radionuclides contributing most to dose rate in a "reference case" (see clarifying text in section 2.11)

Study	**Waste type**	**Nuclides contributing most to dose rate in the "reference case"**
EIS	SF	I-129, C-14, Cl-36, Tc-99
Kristallin-I	HLW	Cs-135, 4N+3 chain (Pa-231, Ac-227), Se-79
H3	HLW	Pd-107, Pa-231, U-236, Ra-223, Np-237, Th-229
SKB-91	SF	I-129, Pa-231, Cs-135, Ra-226
SITE-94	SF	I-129, Ra-226, C-14, Cl-36, Cs-135
TVO-92	SF	I-129, Pa-231, Nb-94, C-14, Pu-242, Ra-226, Se-79
GSF-91	SF, HLW, MLW	I-129, Cs-135, Np-237, Se-79, Tc-99, Ra-226
DCCA	TRU	zero doses over the regulatory time frame of 10 000 years
IPA-2	SF	C-14, Am-243, Tc-99, Pu-239, Pu-240
TSPA-95	SF, HLW	Np-237, Tc-99, I-129, C-14, Th-229, U-233, Cl-36

* SF = spent fuel; HLW = high-level (vitrified) waste from reprocessing of spent fuel; MLW = medium level wastes; TRU = transuranic wastes.

2.12 VOCABULARY

Observation

The IPAG compilation of answers identifies differences in the use of the words scenario, safety assessment and performance assessment. For example, "scenario" is used in different projects to refer to: the evolution of the modelled system, a set of conditions outside the system that leads to evolution of the system, and a set of conditions both inside and outside the system that leads to evolution. During the discussions in IPAG it was observed that there are other words, such as model and conceptual model, which also have different meanings in different assessment projects.

Recommendation

IPAG does not propose that a common vocabulary should be established, but recommends that whenever terms are used that have a special meaning within a project, then they should be defined. In current usage, the terms performance analysis and assessment, and safety analysis and assessment, may be used interchangeably although there may be significant differences in the actual scope of the projects. The most important requirement is that, within a given programme, terms should be defined and used consistently.

There may also some merit in having a set of terms that have an accepted meaning internationally, although a significant difficulty is that terms defined in English (or any other language in which a vocabulary is defined) may not have an exact or unique translation in other languages. The hierarchy of descriptions presented in Table 5 are consistent with the IAEA glossary (IAEA 1993), and may be helpful to describe the scope of an analysis or assessment. In the proposed hierarchy, all "PAs" considered in the IPAG exercise would belong either to the class D. Safety Assessment or to the class E. Safety Case.

Table 5. A suggested hierarchy of descriptions of the terms “performance analysis”, “performance assessment”, “safety analysis”, “safety assessment”, and “safety case”

A. Performance Analysis Quantitative analysis of at least some subset of processes relevant to the behaviour of the disposal system and calculation of (at least) intermediate parameters of interest, e.g. thermal evolution, container life time, contaminant release from some subpart of the disposal system.	**B. Safety Analysis** Quantitative analysis of a set of processes that have been identified as most relevant to the overall performance of the disposal system and calculation of a measure of overall performance relevant within the given national regulatory regime, e.g. individual dose to members of critical group, integrated total release of contaminants.
C. Performance Assessment Includes A. In addition, comparison of intermediate parameters to appropriate criteria set by regulation or design targets, e.g. maximum allowable temperatures, minimum groundwater travel time, contaminant release from a subsystem.	**D. Safety Assessment** Includes B. In addition, testing of arguments that a sufficient subset of processes have been analysed, appropriate models and data used, plus comparison of calculated measures of overall performance to regulatory limits and targets.
E. Safety Case Includes C and D. In addition, a full trace of arguments and evidence that a sufficient set of processes have been analysed and appropriate models and data used; relevant overall measures of performance and safety are within acceptable ranges allowing for uncertainties. More qualitative, parallel lines of evidence and reasoning may be also used to support results of the quantitative modelling and to indicate the overall safety of the system, e.g. that the disposal system does not rely overly on one component, and	

the analysis does not overly rely on particular data or methods.

3. FINAL CONSIDERATIONS

3.1 THE IPAG EXPERIENCE

Overall, IPAG is satisfied that the group's efforts provided a good attempt at illustrating the role of integrated PAs in a concrete way, which resulted in practical observations and recommendations (Chapter 2).

The whole experience, starting with the formulation of the questionnaires and ending with the drafting of the present report, has been worthwhile in many ways:

- Exchange of information occurred across several boundaries (crystalline-tuff-salt host rocks; implementers-regulators-researchers; large-small programmes; deterministic-probabilistic PA approaches).
- The compilation of the answers to the questionnaires offers a convenient and easy comparison of the various participating studies. The latter constitutes most recent available integrated PAs, which provides a good status report. The compilation will also provide good material for use in future presentations to regulators, the public, and other waste management organisations.
- Retrieving the required information from the actual PA reports and rearranging it in a prescribed format provided important feedback on the transparency of the existing PA studies and generated input on future improvements in information retrieval (see Section 2.3).
- IPAG offered the inspiration to borrow some useful techniques from other studies, e.g., for communicating and presenting the results of integrated PAs.

The PAs examined and the outcomes of IPAG will remain a reservoir of useful information. However, new PA studies incorporating the latest results of R&D and also some new ideas for PA practices are already under way in several organisations.

3.2 ISSUES REQUIRING FURTHER EXAMINATION

The observations and recommendations provided in Chapter 2 form a concrete contribution by IPAG towards improving the understanding and efficacy of PA studies. Some of those recommendations suggest practical initiatives by PAAG and SEDE, and are summarised below in Section 3.3.

There were, however, some issues that IPAG could not fully explore because of lack of time and limited manpower. These are described below.

How mature are integrated PAs today ?

This judgement has been requested by some NEA bodies and IPAG participants. IPAG recognises the importance of this issue to the decision makers, however, even if no irreconcilable discrepancies among PAs were noticed, a full judgement of the submitted studies vis-à-vis their use for licensing or establishing safety could not be reached. There are several reasons for this:

- the eight waste management programmes and the two research projects of regulators considered by IPAG are at different stages
- the ten PAs have been performed with different objectives
- the efforts used to produce the PAs vary over a wide range
- the contents and results of the PAs have been reported in different ways
- the answers provided to the questionnaires were of varying detail
- a judgement of maturity varies with the different decisions that are to be taken based on the specific PAs.

IPAG also recognises that a judgement of maturity belongs, perhaps, to a group with a wider membership than only those organisations who have performed PA studies.

On a related topic, IPAG cannot affirm, categorically, that the "Review of Safety Assessment Methods" document (NEA 1991) is up-to-date in its entirety. The group did not discuss it vis-à-vis the information provided in the answers to the questionnaires. Although the group thinks that the 1991 document should continue to provide an acceptable general statement of safety assessment methods, it is fair to say that

- better comprehension exists today than in 1991 concerning such issues as conceptual model uncertainty, and more concrete experience in the identification of FEPs and the development of scenarios; and
- it is likely, as well, that the number of different approaches implemented in the present PAs, and the current trend towards increasing the weight of qualitative (soft) evidence and the line of argumentation is not adequately reflected in the 1991 publication.

PAAG could check further on the need and potential for an updated NEA document on safety assessment methods.

The role of confidence-building/validation in assembling a PA study

This issue was not discussed in-depth within IPAG, although it was recognised to be very important.

IPAG is aware of the existence of an NEA working group on validation/confidence building and that this working group has shown interest in having IPAG providing specific contributions on approaches and methods to building confidence in PA studies. Based on the documentation and experience accumulated so far, IPAG could, possibly with a revised membership, identify the confidence building/validation aspects of presenting/defending specific sections of the analyses.

In a similar vein, a new, revised IPAG might consider how to develop a catalogue of existing conceptual (mathematical) models for key processes, which could provide a scientific basis for treating model uncertainties and the simplification of models for the purpose of conducting an integrated PA study.

3.3 RECOMMENDATIONS FOR FUTURE WORK

Based on the material in Section 3.2 and other relevant Sections in Chapter 2, IPAG's recommendations for further work under the aegis of PAAG and SEDE can be divided in two categories:

1) start-up of a new IPAG phase with a revised group membership, and
2) specific ad-hoc initiatives.

A new IPAG phase

A new IPAG phase, at the end of the present one, is foreseen in IPAG's mandate. The PA community could benefit from a new IPAG phase having at least some of the following items on its mandate:

a) to help to provide a judgement of the maturity of existing integrated PAs
b) to identify areas (methodological and specific) where progress is as yet sufficient/insufficient
c) to review the 1991 NEA "Review of Safety Assessment Methods" vis-à-vis the current state-of-the-art in safety assessment and suggest improvements, if any
d) to identify the important blocks of a safety assessment and, on specified topics, the confidence building measures that have been implemented in order to defend the assessment
e) to develop a new questionnaire with a view for PAAG to maintain an archive of existing PA studies over the years to come (see Section 2.2). Further, an archive in electronic form would be a good tool for contact with the public and to show transparency.

Ad-hoc initiatives

Consider organising a workshop or starting a working group on one or several of the following:

a) integration of site characterisation and PA (see Section 2.6)
b) radionuclide transport codes used in PAs (see Section 2.6).
c) treatment of variability and uncertainty (see Section 2.7)
d) stylised presentations (see Section 2.8)
e) methods for handling of FEPs (see Section 2.9).

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APPENDIX I

COMPILATION

OF THE ANSWERS TO

THE QUESTIONNAIRES

Contents

1. Introduction

This report is a compilation of the answers to questions formulated in two documents, hereafter referred to as "the questionnaire" and "the extra questions", respectively, that reflect information as to the actual contents of recently completed integrated performance assessment (PA) studies of deep repositories of radioactive waste in OECD countries. Both documents were prepared and distributed by the NEA Working Group on Integrated Performance Assessments of Deep Repositories (IPAG). The "questionnaire" [NEA\IPAG\DOC(95)2] was built upon an earlier version of the same [NEA\PAAG\DOC(94)5]. The "extra questions" were compiled from a list of questions of more general character discussed at the October 1995 meeting of the IPAG. The "questionnaire" and "extra questions" are presented in Appendix II.

Ten organisations from seven NEA members countries have responded to the questionnaire, its earlier version, and to the extra questions. The sets of answers range in length from 10 to 50 pages per PA study, and comprise about 300 pages overall. In most cases, all asked questions were answered, although, in a few cases, the answers were incomplete.

This compilation is meant to be one of the end-products of IPAG, and has served as a means to stimulate and articulate the discussion of integrated PA studies within the group. The focus is on commonalities and differences between the ten PA studies in an attempt to highlight areas for further reflection and potential improvement.

In the main, the compilation follows the outline of the questionnaires. At times, however, some questions have been brought together, or the order between questions has been changed.

Each section starts with a particular question and the observations of commonalities and differences in the answers to that question. In order to provide a better basis to the observations made, the latter are followed, in some cases, by a synopsis of the actual answers printed in a smaller font.

When analysing the answers and providing the observations, some practical limitations were observed and need to be born in mind.

- The PA studies differ in many respects, as will become clearer later. Furthermore, the level of detail and the style of the answers to the questionnaire vary greatly from one study to another.

- The information elicitation process was partially iterative. In preparing the answers to the first and then to the second version of the questionnaire, it became possible to reflect on the answers given earlier by the other experts before delivering new ones. While this has normally improved the quality of the answers, there may also be a risk of "iterative consensus".

- The original idea was that the answers should be a direct reflection of only the actual contents of the submitted PA studies. However, especially for the extra questions, they also reflect, to some extent, the current opinions of the experts answering the questionnaire.

Where there was a strong variability in the level of detail of the answers, it was decided not to draw too many conclusions. This applies, in particular, to the questions concerning "Treatment/ addressing of some specific features/issues" (section 7 in the questionnaire and chapter 8 in the present compilation). The answers to questions not directly reflecting the contents of the submitted PA studies, particularly the extra questions, were judged to be interesting and are therefore included in this compilation. For simplicity, these answers are also referred to by the acronym of the PA study.

Finally, it must be recognised that the present compilation cannot account for the full breadth of the answers given, and the more interested reader should consult the original answers or PA studies.

2. Title, reason, and objectives of the studies

2.1 Titles

The titles of the different assessments appear in Table 2-1. Full references are given at the end of this report. Some titles include the word safety, other contain the word performance. These differences are probably due much more to differences in vocabulary (see section 5.1) than intended differences in scope or objectives. The DCCA contains the word "compliance", for the obvious reason that it is a (draft) license application. The title of Kristallin-I is "Safety Assessment Report", since the Kristallin-I project also included a geological synthesis and planning study for future site investigations in the crystalline basement of Northern Switzerland (Thury et al., 1994). The title of SKB-91 indicates that it is focused on geosphere migration and the titles of the NRC, PNC and SKI reports indicate their focus is on research and development.

Table 2.1 Titles of the participating assessments and acronym used later in the report

Acronym used in this document	**Title**
AECL	The disposal of Canada's nuclear fuel waste: Postclosure assessment of a reference system, AECL, (Goodwin et al., 1994)
GSF-91	Analysis of the long term safety of disposal concepts with heat producing radioactive wastes, GSF, (*title translated from German)* (Buhman et al., 1991)
Kristallin-I	Kristallin-I safety assessment report (Nagra, 1994a)
H3	Research and development on geological disposal of high-level radioactive waste, First progress report, (PNC, 1992)
SKB-91	SKB-91 Final disposal of spent nuclear fuel. Importance of the bedrock for safety (SKB, 1992)
SITE-94	SKI SITE-94 deep repository performance assessment research project (SKI, 1996)
TVO-92	TVO-92 safety analysis of spent fuel disposal (Vieno et al., 1992)
DCCA	Draft 40 CFR 191 compliance certification application DCCA for the Waste Isolation Plant (SNL, 1995)
IPA-2	NRC iterative performance assessment phase 2: Development of capabilities for review of a performance assessment for a high-level waste repository (NRC, 1995)
TSPA	Total-system performance assessment - 1995: An evaluation of the potential Yucca Mountain Repository (USDOE, 1995)

2.2 Reasons for the study and project objectives

There are some differences in the reasons for why the studies have been performed. In summary the following main reasons have been reported:

- to support decisions by regulatory agencies (or other bodies) on the future development of the nuclear waste programme (TVO-92 and AECL)

- to allow technical discussions with the regulatory body before the submission of a final license application (DCCA)

- to support selection of sites or geologic media (TVO-92, Kristallin-I, DCCA, TSPA)

- to focus/summarize R&D status and provide support for continued research and development programme (H3, Kristallin-I, TVO-92)

- to study different disposal options (GSF-91)

- to provide a step in the ongoing process of evaluating the methodology for safety assessments (SKB-91, Kristallin-I)

- to develop regulatory review capacity (IPA-2, SITE-94)

There is a quite close correlation between the stated reasons for the studies and their objectives. The types of objectives listed that may be roughly derived from the reasons of the studies are:

- to develop, evaluate or demonstrate safety assessment tools (AECL, IPA-2, Kristallin-I, SITE-94)

- to establish desirable ranges for parameters as input to the identification of sites for additional field work based on a detailed examination of the performance of the geologic barriers (Kristallin-I)

- to explore how to evaluate site-specific data in the context of a performance assessment (SITE-94)

- to understand the relative roles of the engineered and geologic barriers (Kristallin-I)

- to evaluate different performance measures (IPA-2 and TSPA)

- to make a detailed evaluation of a given disposal design or site at the current state of knowledge and assessment capability, as a basis for directing further research, capability development or site investigation (applies to all).

Studies which may be used as supporting arguments for future developments of a nuclear waste programme aim to actually make a safety case (i.e. show that plans lead to safe solutions). This is in contrast to the studies of more limited scope (SKB-91 and GSF-91) and the regulatory studies (IPA-2 and SITE-94), which concentrate on the development of a PA practice. Furthermore, some studies involve methodology development. This may, or may not, have had an impact on the coverage of all issues and it may also have had implications for presentation.

No study, apart from GSF-91 directly uses the performance assessment as one of the inputs to select design options, and only the AECL uses PA in order to optimise repository layout or derive design constraints. In general, design selection is not an issue for the actual studies although other assessments have been used or are planned for this purpose. The design or different designs studied have already been suggested by other studies. The regulatory organisations note that design is not their duty. In many organisations, PA personnel also participate in the design work. Both TVO-92 and H3 point out this link between PA personnel and design.

Compilation of answers

The overall reason for the GSF-91-study is that the German Government authorities required comparison of different disposal techniques. The GSF-91 long term safety analysis is part of an integrated performance assessment on different disposal concepts called “system analysis dual-purpose repository” conducted for the German ministry of research and technology (BMTF). The GSF-91 report is one of 10 appendices. The GSF-91 study is also seen as an application of long term assessment tools. The stated objectives of the GSF-91 study are to compare different disposal techniques, to evaluate the influence of uncertainty of input parameters and to guide research.

The PNC H3 study is designed to document the current status of R&D by PNC, in accordance with the overall programme set forth by the Atomic Energy Commission of Japan. The stated objectives of the H3 are to confirm scientific and technical feasibility of the geological disposal concept in Japan, and to evaluate whether a multi-barrier system will maintain the desired performance over a long period of time, taking account of a wide range of geological environments in Japan.

The Canadian concept for the disposal of nuclear fuel waste is now being reviewed under the Canadian federal Environmental Assessment and Review Process. The AECL report was produced as input to this process. The objective of the AECL report is to develop and document a method for risk assessment methodology and through this demonstrate the feasibility and safety of the general concept of geological disposal in the Canadian Shield, prior to site selection. The study is conducted on a (hypothetical) reference disposal system.

Nagra’s Kristallin-I study marks the completion of regional geological investigations of the crystalline basement of Northern Switzerland taking account of the R&D in the Swiss programme. It also marks the transition from regional to local studies. It was not conducted in response to a legal requirement, but will be reviewed to judge the appropriateness of further work on this potential host rock. The stated objectives of Kristallin I are to re-evaluate and quantify the level of safety that can be reasonably expected for a repository located in the crystalline basement of Northern Switzerland, to improve the understanding of the roles of the engineered and geologic barriers, to establish desirable ranges for parameters as input to the identification of sites for additional field work based on a detailed examination of the geologic barriers, and to develop and test a more complete safety assessment methodology and tool kit.

SKB-91 was seen as a step in the ongoing process of evaluating the methodology for safety assessments. There was no regulatory requirement to produce SKB-91. It was however, reviewed within the framework of the authority review of the SKB RD&D programme. The stated objective of SKB-91 is to evaluate how the rock barrier performs under the assumptions that radionuclides are released from the engineered barriers.

According to general targets and schedules in Finland's nuclear waste programme, TVO was obliged to carry out preliminary site investigations on several sites and by the end of 1992 to propose suitable areas for more detailed investigations, and to present updated technical plans and safety analysis of spent fuel disposal. The stated objectives of the TVO-92 safety analysis are to evaluate whether candidate sites were suitable, to assess whether concepts (new copper/steel canister) and sites fulfil safety requirements, and to utilize and summarize results of relevant studies carried out in Finland and abroad since the previous assessment in 1985.

The main reason for SKI to conduct SITE-94 was to develop and maintain an independent performance assessment capability in order to be able to act as licensing authority. In addition, SKI saw the need to prepare for a review of license applications based on surface and borehole investigation data. The stated objectives of SITE-94 are to determine how site specific data should be assimilated into the performance assessment process and to evaluate how uncertainties inherent in site characterization will influence PA results, to develop a practical and defensible methodology for defining and constructing scenarios, to develop approaches for treatment of uncertainties and to analyse mechanisms influencing canister integrity.

The US DOE is preparing an application to demonstrate compliance with the requirements in 40 CFR 191 for the WIPP. US EPA must evaluate compliance within one year of receiving a complete application. In order to allow technical discussions with EPA before the one year compliance determination begins DOE are producing a draft application in two parts. DCCA is the first of these two drafts. The DCCA focuses on background repository information, the PA methodology, the most likely scenarios, the characteristics of the wastes, the quality assurance programme and DOE's approach to demonstrate compliance. The draft does not provide detailed information on experimental work, engineering alternatives and additional research needed to support a full scale prediction, level of quality of software and input data, detailed designs for long term monitoring, markers and active institutional controls or performance based waste acceptance criteria (among a few other things).

The NRC IPA-2 was conducted in the framework of the overall objective of NRC's performance assessment programme to maintain and enhance the staff capabilities necessary to support the geologic repository programme activities. The stated objectives of the IPA-2 are to evaluate the ongoing DOE site characterization programme, to evaluate ways to implement the 10 CFR 60 performance objectives, to provide input to the evolution of the EPA 40 CFR 191 standard, to provide input to regulatory guidance especially the Draft Licence Application Review Plan (LARP), and to assist in the definition of the Office of Nuclear Material Safety and Safeguards technical assistance and research programmes in the area of HLW.

The intention of the US DOE (Yucca Mountain Project) TSPA-95 is to provide a quantitative evaluation of the suitability of the Yucca Mountain site, to focus the investigation programme, identify investigation areas where results would improve performance or reduce uncertainties and in general update TSPA-93 for the normal and undisturbed case. The general objectives of a TSPA are to incorporate reasonably conservative assumptions to relevant processes and representations, to evaluate a range of conceptual models, to focus on the most robust parts of the disposal system, and to evaluate long term safety using a range of possible measures (cumulative release, peak concentration or dose, or other measures). Specific objectives for TSPA-95 are to update model assumptions, to incorporate recent design information and to evaluate the correlation between different long term safety measures.

2.3 The intended audience and report language

In general, all the studies are directed to audiences with a similar background to the authors themselves. Apart from AECL, which is part of an Environmental Impact Statement, the reports are not primarily intended for wide audiences. Most studies do list the interested technical community as a desired audience. However, only AECL and TSPA-95 remark that specific actions were taken (editing for jargon and acronyms) to make the report more readable for these groups. The conclusions of Kristallin-I are also published in a separate, less-technical report aimed at a more general readership (including the local population) (Nagra, 1994b)

Several countries require that the reports are issued in the national language, but there is a strong tendency to also publish in English even where this is not the national language. This is related to the international character of the intended readership, and also a desire for international recognition and review.

Compilation of answers

The GSF-91 and DCCA list the most limited intended audiences. The GSF-91 intended audience is in practice limited to research facilities and involved authorities. The DCCA is intended for the staff at the US EPA. The other studies have almost identical intended audiences, such as the regulatory bodies, the nuclear waste management community, the scientific community in general and interested members of the general public. However, the AECL was produced in support of an Environmental Impact Statement, which is input to a federal environmental review, which will include public hearings. Some studies explicitly note their own management as receivers (TSPA-95 and SITE-94). This is probably true for more studies.

All studies conducted in English speaking countries (AECL, IPA-2, DCCA and TSPA-95), are, of course, written in English and are not translated into other languages. Most other studies were first issued in the national language, GSF-91 (German), H3 (Japanese), SKB-91 (Swedish) and TVO-92 (Finnish). These reports were followed by a translation into English, apart from GSF-91 where there is only a CEC report in English which provides the main results. Two PAs from non-English speaking countries were issued directly in English: Kristallin-I (summarised in German) (Switzerland) and SITE-94 (Sweden).

3 Regulatory framework

The regulatory framework and the criteria for radioactive waste disposal differ from country to country. Differences and commonalties are only commented upon in this document if they have implications on the relevant PA studies.

3.1 Observations

The studies take regulatory criteria into account when they are available and defined. In countries with unspecified criteria the studies strive to apply criteria that may be adopted in the future (e.g. GSF-91, H3, SKB-91, TVO-92, SITE-94, IPA-2, TSPA-95). Both IPA-2 and TSPA-95 evaluate different suggested criteria as well as the correlation between these criteria. All studies, apart from DCCA, calculate individual doses and all studies, apart from DCCA, address times longer than 10 000 years.

For the WIPP site, the information required by the regulatory criteria are defined and the DCCA intends to deliver the information as specified in the criteria. The other studies are at a much earlier stage of the licensing process, which allows a more free interpretation of criteria or can refer to future work if some criteria are not addressed.

The Swiss and the suggested Nordic regulatory criteria contain risk measures as secondary criteria that can be applied in the case of low probability scenarios giving rise to high doses. However, the relevant PA studies (Kristallin-I, SKB-91, TVO-92 and SITE-94) are essentially deterministic, effectively assigning unit probability to each scenario evaluated. In contrast, the quantitative probabilistic criteria in the USA and Canada have led to direct efforts in quantifying probabilities for a large class of scenarios, especially in DCCA and AECL. There are, however, differences in how these probability estimates were combined into a joint risk estimate.

Regulations with subsystem criteria only apply to the civilian nuclear waste programme (Yucca Mountain) in the U.S. However, neither IPA-2 nor TSPA restrict the analysis to subsystems; instead they attempt to analyse the total system.

3.2 Compilation of regulatory requirements

AECL

The AECL assessment is specifically organised to yield the safety parameters required by AECB (the Atomic Energy Control Board). The regulatory objectives and guidelines applicable to long term safety of disposal of all types of radioactive waste are set out in the AECB document R-104. The main requirements are as follows:

- predicted risk to individuals shall not exceed 10^{-6} per year, without advantage of long term control

- if this cannot be met, an optimisation shall be done to determine a preferred option, the risk should then not exceed that currently accepted from operations involving the same wastes

- compliance with the risk requirement need not exceed 10 000 years; thereafter reasoned arguments are required, that the release will not suddenly increase

In addition it is noted that probabilities should be assigned to scenarios and that the risk from a scenario may be calculated from the arithmetic mean of a probabilistic dose distribution. The risk requirement applies to a group located at the time and place where the risks are greatest.

In the AECL PA most attention is given to a set of scenarios representing the groundwater pathway and these scenarios are included in a single probabilistic model. Other, less likely scenarios, e.g. human intrusion and open borehole scenarios, are considered separately, taking account of estimated probabilities of occurrence.

GSF-91
In principle, GSF-91 is free from regulatory requirements. However, it takes into account the German dose rate limit from the radiation protection act and applied procedures (e.g. calculation of dose conversion factors).

H3
As yet there is no specific regulatory framework for the disposal of nuclear fuel waste in Japan. The main focus is on performance of the engineered barriers, but individual dose is calculated for a hypothetical drinking water pathway considering radionuclide fluxes at 10 m, 100 m and 1000 m from the repository tunnels.

Kristallin-I
Kristallin-I takes account of requirements and guidance specified in the Swiss regulatory document R-21 (HSK and KSA, 1993). These requirements and guidance concern protection objectives (health and safety criteria), validation of models, time scale for calculations (not specified quantitatively), scenarios (analysis is not required of intentional human intrusion or scenarios with dramatically-worse direct effect than any long term radiological consequence, e.g. meteorite strike), treatment of the biosphere (dose calculations provide indicators for evaluating the impact of potential releases; use of reference biospheres), design specifications (aim at complete containment for the first 1000 years), non-human organisms (protection assumed if human individuals are protected). The protection criteria in R-21 are limits on individual dose rate (0.1 mSv/yr) resulting from processes and events reasonably expected to happen with no time limit, individual risk from unlikely events must not exceed 10^{-6}/yr and, after closure, no further measurements shall be necessary to ensure safety. In Kristallin-I compliance with regulatory criteria is illustrated by dose calculations which show dose rates below 0.1 mSv/yr even when uncertainty in data and models is taken into account. There is no attempt to calculate risk in Kristallin-I, although risks may be estimated in later stages of the programme.

The Nordic studies: TVO-92, SKB-91, SITE-94
TVO-92 applies the protection criteria suggested by the Nordic safety authorities by calculating the performance measures suggested in these criteria. In short these measures are individual dose (0.1 mSv/yr) for the expected evolution and for unlikely events a risk corresponding to 0.1 mSv/yr. For long time periods the inflow of the disposed radionuclides to the biosphere should be low in comparison with the inflow of natural radionuclides.

SKB-91 does not specifically consider the regulatory framework, but makes reference to the criteria suggested by the Nordic safety authorities.

SITE-94 is a research project and is not intended to show compliance with criteria. The basic repository safety requirements appear directly in the legislation, but are quite general. SKI and other authorities have as yet not issued more detailed regulations, but these will likely be based on the protection criteria suggested by the Nordic safety authorities. However, the overall structure of SITE-94 reflects some general safety principles: the repository should provide containment, safety should be evaluated over long time periods - more than 100 000 years, there should be small releases to the biosphere with individual dose rates less than 0.1 mSv/year, and the safety should not depend on supervision or maintenance of the repository.

USA: DCCA - WIPP, IPA-2 and TSPA-95

For WIPP the US EPA have specified performance measures in 40 CFR (Code of Federal Regulation) 191, 40 CFR 194 and 40 CFR 268. These regulations specify likelihood limits for the cumulative release of radionuclides over 10 000 years expressed as a cumulative complementary distribution function (CCDF). The cumulative release is calculated with a nuclide-specific weighting function included in the regulation. *Proof* of performance is not expected in the ordinary sense of the word, rather there must be a reasonable expectation that limits will be met.

For Yucca Mountain US Congress has set aside the regulations 40 CFR 191 issued by EPA. The 10 CFR 60, which specifies container performance and groundwater travel time issued by NRC, is thus also effectively set aside since it implements whatever the EPA regulation will be. The National Academy of Science has suggested that 10 CFR 191 be replaced with a health based (dose or risk) standard. When the new standard is adopted NRC will change 10 CFR 60 so that it conforms with the new requirements. Proposed new versions of these rules are expected in mid-1996.

In IPA-2 different performance measures are calculated based on the NRC regulation 10 CFR 60, the EPA regulation 40 CFR 191, and the suggested dose measures.

TSPA-95 calculates different measures (waste package life time, the peak EBS release rate, the cumulative release at the edge of the accessible environment and the peak dose to the maximally exposed individual located at the accessible environment) as suggested by the different criteria. TSPA-95 also evaluates the correlation between measures.

4 List of contents

Contents lists are available for all of the assessments. "Walk-throughs" - which provide comments and identify key points covered in each chapter or section - were also prepared input to IPAG.

In this chapter an overview of the assessment report contents and coverage will be made in two parts:

- a comparison of the assessment report contents against a suggested list of expected basic contents;

- summary comments on the nature and structure of each report and its relation to objectives, project status (including site data availability) and methodology of the assessment.

4.1 Suggestion of a common list of elements

An important aspect of the IPAG comparison is that guidance may emerge on what are the essential and desirable elements of a performance assessment document, where an element indicates a topic to be addressed rather than a chapter heading. Such a discussion was initiated at the first ad-hoc IPAG meeting in Wettingen, February 1994. The specific content of a PA/SA report depends on many factors. Nevertheless, examination of the lists of contents and the "walk-throughs" of the reports submitted to IPAG suggests that these have a number of such "elements" in common, The following, preliminary, list of elements may be identified:

- Statement of assessment objectives.

- Statement of document structure and content.

- Statement of imposed boundaries/scope of analysis, including regulatory guidance, relation to previous or future analyses etc.

- Statement of assessment methodology, especially the treatment of uncertainties.

- Description of the disposal system (wastes, engineered barriers and repository design, natural site characteristics).

- Parameter database (or reference to factual database), site specific and non-site specific data.

- Identification of relevant processes (may include statement on relevance, scope of models and spatial/temporal domains for evaluation).

- Evaluation of processes occuring within various subsystems and development of conceptual models and/or scenarios that will be basis for quantitative consequence evaluation.

- Description of mathematical models or system for quantitative consequence analysis.

- Presentation of results for:
  - key subsystems (e.g. hydrogeology, EBS evolution, near-field release, environmental change)
  - overall impacts (e.g. dose, risk or integrated release) for comparison to regulatory or other targets.

- Analysis of sensitivity and uncertainty

- Conclusions - primarily with regard to safety of analysed system/site, but also regarding implications for future data acquisition, outstanding issues, uncertainties and caveats.

Table 4-1 identifies where these topics are covered within the chapters and sections of the assessment reports.

4.2 Summary contents of each report

The AECL postclosure assessment of a reference disposal system (Goodwin et al., 1994 - referred to as AECL in this report) is one of a set of nine reports which support the Environmental Impact Statement of the concept for disposal of Canada's nuclear fuel waste, where three of the set are more detailed reports concerning the vault, geosphere and biosphere models (Johnson et al., 1994, Davison et al., 1994, Davis et al., 1993) used in the postclosure assessment. Thus although Goodwin et al., (1994) is a comprehensive report of the postclosure analysis work, details of the models and their basis are contained in the supporting vault, geosphere and biosphere model reports.

The GSF analysis of long term safety for repository concepts for heat generating wastes (Buhman et al., 1991, referred to as GSF-91 in this report) is part of an integrated performance assessment of different concepts and is one of ten technical appendicies which support a summary report (KWA 1989). It is notable that statements of objectives, scope of analysis and methods are not found in Buhman et al. (1991) and it is presumed that they may be found in the overlying reports. Buhman et al., cover the identification of choice of processes for inclusion in models, physical and mathematical description of the models quite adequately within a single chapter (Chapter 5). Analysis of sensitivity is combined with analysis of central results in chapters covering results from deterministic calculations (Chapter 6) and results from probabilistic calculations (Chapter 7).

Table 4.1: List of elements that might generally be expected in an assessment document and confirmation tha assessment reports considered by IPAG. (Numbers refer to chapter and section numbers in the ass

Document contents	AECL	GSF-91	Kristallin-I	H3	SKB-91	SITE-94	TVO-92
Statement of assessment objectives	1.2	Overlying report	1.4	1.6 (partly)	1.2	1.2	discussed in 1.
Statement of document structure	not found	not found	1.5	1.6 (briefly)	2.1	1.3	outlined in 1.
Statement of imposed boundaries and scope of analysis	1.1, 1.3, 1.4	not found	partly in 2.3 App. 1	1.1 (partly)	2.4	2.1	5.2
Statement of assessment method and treatment of uncertainties	2.	not found	2.4 to 2.7	outlined in 4.1	outlined in 2.2 and 2.3	2.2, 2.3, 2.4	6.
Description of disposal system - wastes EBS, site	3.	2, 3, 4.1	3.	2., 3.	3., 4., 5.	3., 4., 5.	2., 3., 4.
Factual database and sources	in sup. vols.	partly in apps.	summary in 3.7	dispersed in 4.	dispersed in 3. to 8.	6. but also dispersed	dispersed in 2.-4., 7.-13.
Identification of relevant factors or FEPs	4.	5.	4.	not formally discussed	ref. to prev. rep.	7., 8., 9.	not formally discussed
Evaluation of processes within subsystems and model scenario development	partly in 4. mainly in sup. vols.	5.	4. and 5.	4.2, 4.3, 4.4., 4.5	3. to 6.	7., 8., 9., 11., 12., 13.	7. to 11. but also 12., 13.
Description of mathematical models or analysis system	overview only in 5.	5.	5.	integrated in 4.2 to 4.5	outlined in 7. and 8.	14., 15., 16.	within 12.
Presentation of results for a) key subsystems b) overall impact	in sup. vols. 6.	 6 6.1, 7.2	 5. 6.	 4.2 to 4.5 4.5.6.3	 7. and 8. 9.	 11. to 15 17.	 7. to 11. 12.
Analysis of sensitivity and uncertainty	App. D&E	6.2, 6.3, 7.3-5	within 5. and 6.	within 4.2 to 4.5	within 8. and 9.	throughout 14 to 17	13.
Conclusions	8.	8.	7.	within 5.	10.	18. and 19.	14. and 15.

The Nagra Kristallin-I safety assessment report (Nagra, 1994a) contributes to the Kristallin-I project (Nagra 1994b), which also includes a synthesis of geologic data and understanding of the crystalline basement of Northern Switzerland and a planning study for more detailed site investigations (Thury et al., 1994). The assessment report includes all topics identified in section 4.1 although the results from individual submodels are combined with physical and mathematical descriptions of the models in Chapter 5. Detailed modelling is covered in supporting reports, e.g. hydrogeologic modelling is included in Thury et al., (1994). Discussion of sensitivity to submodels to parameter variations is included in Chapter 5. Results of complete model-chain calculations, including parameter variations, alternative models and alternative scenarios are presented in Chapter 6.

The PNC safety assessment is included as a single chapter, Chapter 4, within a volume (PNC, 1992 referred to as H3 in this report), which presents a comprehensive summary report on research and development on geological disposal of high-level radioactive waste in Japan. Other chapters cover a survey of geological conditions (Chapter 2), and on the engineered barriers (Chapter 3). Since the assessment is mainly a demonstration of model capability, objectives of the assessment are not discussed, nor bounds of the analysis (regulatory criteria are not yet in place in Japan). The assessment considers only the groundwater mediated release pathway and there is therefore no comprehensive identification of relevant factors or FEPs. The models, data and results are adequately described in sections 4.2 to 4.5. A simple indication of overall performance, considering a drinking water pathway is presented in section 4.5.6.3.

The SKB-91 assessment (SKB, 1992) provides a free-standing description of an analysis which focuses on the importance of the geological barrier to long-term safety. All topics identified in section 4.1 can be identified in the report, except that the description of the input data is not complete in all areas (although it occurs in supporting reports) and the report does not include an identification of relevant factors or FEPs, but makes reference to such identification previously developed in a joint SKI/SKB project (Andersson ed., 1989). Deterministic models of the release from a canister and of the biosphere are used, but a probabilistic hydrogeologic model is used to provide input to the geosphere transport model, with an attempt to capture the detailed flow variability. Most attention is given to sensitivity of groundwater flow and radionuclide transport, to various boundary conditions and alternative assumptions of rock properties (Chapter 9).

The TVO-92 safety analysis (Vieno et al., 1992) is a stand alone report but supported by 8 more detailed reports. The report summarizes information on the fuel wastes, engineered barriers and safety related data from investigations at five sites in Finland. All topics identified in section 4.1 can be found in the report, although there is no designated chapter for dealing with identification of relevant factors or FEPs. However, coverage of scenarios is discussed at the end of the report (section 13.3) . The report pays special attention to the performance of the copper/steel canister (Chapters 9 and 10), which at the time of the project was a novel design variant of the long-life copper canister considered in Sweden and Finland for more than 10 years. A single canister failure by undefined processes is postulated in order to provide a source term for evaluation of the near field and the geosphere barrier (Chapter 12). Significant effort is spent on describing the basic models for release and transport (Chapter 12). A wide range of, generally pessimistic, alternative cases are investigated (Chapter 13).

The SKI SITE-94 project (SKI, in prep.) is a research project with the overriding objective of developing an independent assessment capability, thus while it is quite detailed in some selected areas it is not expected to present a safety case. Examination of the contents and walkthrough still indicate that all topics identified in section 4.1 can be found. There is specific emphasis on statement of assessment method, system description as well as on identification and evaluation of relevant factors in the geosphere and in the copper/steel canister.

The SNL performance assessment, produced on behalf of USDOE, is the first part of a draft Compliance Certification Application (DCCA) for the Waste Isolation Pilot Plant (WIPP) against title 40, part 191 of the Code of Federal Regulation for the permanent disposal of transuranic waste; a second part providing more details relative to human intrusion scenarios is in production. These drafts will allow DOE and EPA to begin technical discussions before a one-year compliance determination period begins. The information submitted to IPAG describes a report that builds on supporting engineering, research and performance assessment studies and covers only the "undisturbed" repository performance.

Similarly to the SKI SITE-94 report, the NRC Iterative Performance Assessment Phase 2 (IPA-2) describes work carried out by (and on behalf of) a regulator with the primary aim of developing capabilities for independent review of performance assessments to be prepared by a developer. The report does not appear to include detailed description of the wastes or EBS, presumably covered by the appendicies, but otherwise contains the suggested elements. The main body of the report is structured according to sub-models considered in the analysis: scenario analysis, flow and transport, disruptive consequences, and dose and release assessments, with details of the models covered in the same chapters.

The USDOE Total System Performance Assesment - 1995 (Andrews et al., 1995, referred to as TSPA-95 in this report) is the third in a series of TSPA for the Yucca Mountain site for USDOE, taking into account new site and engineering data. There appears to be a discussion on the regulatory requirements or other boundary conditions on the assessment and an identification of relevant factors in Chapter 1.4; it is also assumed that these are covered in supporting documents, which are referenced. Furthermore, the regulatory situation is presently unclear. However, detailed descriptions of the model elements and discussion of relevant processes are given in Chapters 4 to 7.

5. Terminology

5.1 Performance assessment, safety assessment, etc.

The term Total System Performance Assessment is only used within the US HLW Programme. It is evidently needed to be distinguished from assessments of sub-systems performance. No-one seems to use the word Integrated Performance Assessment (IPA-2 in the NRC study stands for “Iterative Performance Assessment”). There are differences in the use of the words “Safety Assessment” and “Performance Assessment”, both with regard to what is the difference between a PA and SA and to what should be included in these activities.

According to the IAEA (1993) definition, a Safety Assessment concerns the whole system whereas a Performance Assessment may concern a sub-system. However, most studies are either called Performance Assessment or Safety Assessment and do not define the other word and it is quite unclear if the distinction between the words is well recognized in the Waste Management community. (Partly this may be due to language differences. In Sweden “assessments” are usually called “säkerhetsanalys”, in Switzerland “Sicherheitsanalyse” and in Finland “turvallisuusanalyysi”, all these words literally translate into Safety Analysis).

There are differences in the suggested scope of a Performance or Safety Assessment:

- the IAEA (1993) definition stresses quantitative predictions

- many wish to explicitly include in the definition also the activities made to support predictions and the development of understanding (Kristallin-I, SITE-94, IPA-2, TSPA-95)

- the assessment should be organized such that it supports decisions (SITE-94).

Compilation of answers

Only IPA-2 and TSPA-95 discuss and define the term Total Systems Performance Assessment. According to them a Total Systems Performance Assessment concerns the evaluation of the ability of the overall system to meet the objectives specified in the applicable regulatory standards (TSPA-95), or a Performance Assessment that concerns the overall safety of a geologic repository (IPA-2).

No study actually use or define the term Integrated Performance Assessment (IPA), although TSPA-95 (and SKB-91) suggest that it is the same as TSPA.

AECL defines Performance Assessment as critical appraisal or evaluation (of a whole waste disposal system) in terms of one or more performance standards. They note that this would be equivalent to Safety Assessment if the system under consideration was the entire disposal system and the performance measure was radiological impact or some other global measure of impact. This definition is quite close to the IAEA (1993) one.

GSF-91 do not define Performance Assessment but considers "whole system analysis for a dual purpose repository" as a performance assessment. The safety assessment is a part of this system analysis and emphasizes the long term radiological (safety) aspects within the performance of the repository system.

H3 accepts the IAEA (1993) glossary definition of Performance Assessment ("An analysis to predict performance of a system or sub-system followed by comparison of the results with criteria").

In accordance with NEA (1991), Kristallin-I defines Safety Assessment as a broad activity aimed at developing a sufficient understanding of the physical and chemical behaviour of the disposal system, quantifying understanding in order to allow estimates of future system performance, evaluating uncertainties in the estimates, convincing all relevant groups of the adequacy of the analyses. (The terms Integrated SA, TSPA or PA are not used in Kristallin-I.)

TVO-92 basically accepts the definitions of the IAEA (1993) glossary. There Safety Assessments concerns the whole system, and it is based on Performance Assessments of the various subsystems. However, TVO-92 was a safety *analysis* and it is suggested that *assessment* is what authorities should do.

According to SKB-91 Performance Assessment is the evaluation of time dependent changes in the repository, whereas a Safety Assessment expresses the result in terms of dose or risk to man.

According to SITE-94 Performance Assessment should provide a basis for decisions on issues related to repository safety. In Performance Assessment the repository and its surrounding environment is described as an integrated system with the object of exploring under what circumstances radionuclides disposed in the repository may be released and transported to the environment and to man. Treatment of uncertainty, models for description of complex systems, and quantification of performance in terms of different measures therefore have prominent positions in Peformance Assessments.

DCCA does not answer directly but refers to 40 CFR 191 (i.e. an assessment that provides the information mentioned in the definition).

According to IPA-2 Performance Assessment is a systematic and quantitative method for analysing and evaluating safety of constituent parts of a geologic repository through the use of predictive models, but also involves activities to obtain an essential understanding of key processes, their interactions and implications for safety, as well as documentation and auxiliary analyses.

According to TSPA-95 Peformance Assessment involves quantitative predictions based on understanding the processes and parameters potentially affecting the long term behaviour of the disposal system, used to assess the ability of the site and associated engineered designs to meet the performance objectives.

The term Safety Assessment is not used in H3, SITE-94, TSPA-95, IPA-2. In the U.S., the 10 CFR60 regulation defines a Safety Analysis Report as part of the formal license application. This is a primary reason for the Yucca Mountain Project avoiding the use of "safety assessment", since it would have the same abbreviation as Safety Analysis it could suggest a product meant to be part of a formal license application.

5.2 Scenario

GSF-91 and H3 define scenarios with words, such as “possible situations” or “future conditions that may have to be considered” for consequence analysis. Some point out that scenarios are assumed (e.g. for the purpose of confidently overestimating consequences) and are not predictions of actual future conditions (AECL, Kristallin-I, TVO-92, SITE-94). Most studies specify further that scenarios are combinations of Features, Events and Processes (or factors) that may affect the repository performance (AECL, Kristallin-I, SKB-91, DCCA, TVO-92, SITE-94, IPA-2 and TSPA-95). In SITE-94 such combinations are initiated by FEPs outside the analyzed system. The TVO-92 practice of calling cases of consequence analyses “scenarios” may be contrasted with the definitions in other assessments that scenarios are formed in order to formulate cases for consequence analysis.

Compilation of answers

In GSF-91 scenario is defined as a possible future development of the disposal system.

According to AECL a scenario in the postclosure assessment is a set of factors (features, events and processes) that could affect the ability of the disposal system to immobilise and isolate nuclear fuel waste. AECL distinguishes between “SYVAC scenarios” describing scenarios that can be represented by the SYVAC model of groundwater-mediated release, alternative scenarios that are less probable but potentially significant and worst case scenarios representing the most severe situation conceivable on the basis of pessimistic assumptions.

Scenario is not defined in H3, but the term is used as the broad range of possible futures to be considered in the subsequent modelling and consequence analysis.

The Kristallin-I definition is based on that of SKI, HSK, SSI: “a hypothetical, but physically possible sequence of processes and events that influence the release and transport of radionuclides from the repository to the biosphere and the exposure to humans”(SKI/HSK/SSI, 1990). However, in the Kristallin-I definition, scenarios do not need to be either realistic or encompass the expected future evolution of the system. Rather, taken together, they provide the basis for calculations that are confidently exepected to over-estimate radiological consequences. Kristallin-I also makes the point that scenario development is the means by which the importance of processes and events are discussed and, where necessary, scenarios are defined and calculations performed to quantify the impact of omission or inclusion of particular processes and events.

SKB-91 defines scenarios as repository development with time given a set of identified internal processes affecting the repository system, a set of initial conditions and external events.

The SITE-94 definition is that a scenario is a hypothetical sequence of processes and events, and is one of a set devised for the purpose of illustrating the range of future behaviours and states of the repository system. Scenarios are considered to be initiated by FEPs outside the analyzed system (EFEPs).

TVO-92 accepts the IAEA definition according to which a “scenario is an assumed set of conditions or events”. In practice, the view is that a scenario is close to a “case of consequence analysis” i.e. the scenario comprises the assumptions, conceptual models and data in a particular case of consequence analysis.

40 CFR Part 191 does not use the term scenario but refers to "Processes and Events". In DCCA combinations of FEPs that remain following a screening processes described in the report are used to form scenarios.

In IPA-2 a scenario is defined as any postulated future sequence of events and processes external to the repository system which is sufficiently credible to warrant consideration of its projected effect on repository performance.

In TSPA-95 scenarios are externally initiated natural events and processes that may disrupt the repository if they occur. Climate change is part of the expected case, and is not classed as part of these potentially disruptive event scenarios.

6 Disposal concept

6.1 Type of waste, repository design, host rock, etc.

Information on waste forms, canister design, repository design, host rock, site and biosphere is given in Table 6-1. For detail the reader is referred to the answers to the questionnaire or to the original assessment documents.

The engineering feasibility, as applied to all barriers, is generally assumed, by reference to previous studies, and it is usually not discussed in the assessment report. The AECL PA considers a specific engineering design which is considered feasible, but a wide range of design variants have been studied in supporting work, and would be considered within the scope of the general disposal concept. Even though TSPA-95 does not explicitly address engineering feasibility, there is a discussion of the infeasibility, from an engineering perspective of the emplacement of a capillary backfill.

No study evaluates anything other than the main waste type. However, GSF-91 considers MOX fuel as part of the inventory in the calculations for the reprocessing waste. Nagra notes that, if a HLW repository were to be constructed in Switzerland, spent UO_2 and MOX fuel, and long-lived ILW would need to be considered as well. Effects of higher burnups are discussed in TVO-92, whereas MOX fuel is not relevant for Finland. TSPA-95 notes that other waste types, related to defense activities may need to be emplaced, but they were not evaluated. Evidently organisations that face different waste types also plan to evaluate them, but so far the analyses concentrate on the main waste type.

6.2 Type of field data

Only AECL and DCCA have access to data from underground excavation at the site under evaluation. The other studies are based on data from surface geology and geophysics, and data from deep boreholes, but this is supplemented by data from underground measurements at other sites.

Compilation of answers

The geosphere data used in H3 originate from open literature, boreholes and existing galleries. It is used in order to take a wide range of Japan's geological environment into account.

The AECL PA is based on detailed characterisation of the Whiteshell Research Area, which is also the site of the AECL Underground Research Laboratory (URL), where a ten year programme of site investigation and development of methods has been carried out.

The other crystalline site studies (TVO-92, Kristallin-I, SKB-91 and SITE-94) had access to fairly similar types of field data, with surface information complemented by information from deep boreholes at the actually studied (hypothetical) repository site, as well as regional data. The quality and density of information may, however, differ between the studies. The Kristallin-I data is based on a regional survey including 9 deep boreholes, geophysics (seismic and gravity surveys), and surface geology (mapping, outcrops in the Black Forest in Germany). SKB-91 is based on site specific data including deep drillings from the Finnsjön study area. SITE-94 uses pre-investigation data from the Äspö HRL which consist of various types of maps and other surface information, local ground geophysical measurements, core logs, borehole geophysical logs, hydraulic test data in boreholes, a long term pumping test, groundwater chemistry samples, rock stress measurements. TVO-92 uses field data from site investigations including deep drillings carried out at five sites.

Table 6.1: Type of waste, waste form, canister design, repository design, host rock, site and biosphere in the assessments considered by IPAG.

Study	**Waste**	**Canister**	**Repository**	**Host Rock**	**Site**	**Biosphere**
GSF-91	Vitrified HLW. Spent fuel (LWR, THTR). Reprocessing sludge, Cement, Reactor waste.	HLW steel containers. Pollux casks for HLW and spent fuel. Drums.	870 m deep Drift emplacement for Pollux casks. Borehole emplacement for drums and canisters. No buffer Salt backfill	Rock salt	Gorleben	A well scenario Self sustained community
AECL	Spent CANDU Fuel	Thin-walled titanium containter	500-1000 m deep Vertical emplacement. Clay/Sand buffer. Clay/Rock Backfill.	Low permeablity granitic rock	Based on examples from Whiteshell Research Area URL	General features of Canadian shield and the URL discharge zone
Kristallin-I	Vitrified HLW from LWR fuel reprocessing	Carbon-steel, thick overpack	1000 m deep Horizontal tunnel emplacement. Thick bentonite buffer.	Crystalline basement N. Switzerland covered by sediments	Two potentially suitable siting areas	Representative of expected discharge zone - River Rhine valley and alternatives
H3	Vitrified HLW from LWR fuel reprocessing	Carbon-steel, thick overpack	Deep rock Horizontal tunnel emplacement. Thick bentonite buffer.	Wide range of crystalline and sedimentary rocks are considered	Not specified	Only drinking water
SKB-91	Spent LWR fuel	Lead filled copper canister	500 m deep Individual vertical emplacement holes. Bentonite buffer	Crystalline rock	Finnsjön study area	Stylized farm well and a lake
SITE-94	Spent LWR fuel	Copper with inner steel canister	500 m deep Individual vertical emplacement holes Bentonite buffer	Crystalline rock	Data from Äspö HRL (hypotetical repository)	A well A farm based on present day.
TVO-92	Spent BWR fuel	Copper with inner steel canister	500 m deep Individual vertical emplacement holes Bentonite buffer	Crystalline rock	Five investigation sites	Stylized farm, well and a lake
DCCA	TRU waste	Drums. Steel containers.	In gallery at 657 m	Rock salt	WIPP Site	Not used
TSPA-95	Spent LWR fuel and vitrified HLW	Several within multi layer container	Several emplacement and buffer options	Densely welded tuff above water table	Yucca Mountain	Drinking water
IPA-2	Spent LWR fuel	Overpack container	300 m depth Vertical empl. No buffer or backfill	Densely welded tuff above water table	Yucca Mountain	A farm. Eating beef. Airborne releases.

In GSF-91 the data for the far-field are obtained from a former study and include information from borehole measurements and laboratory analyses on material from borehole exploration. The DCCA data are obtained from approximately 25 years of work and a completed mine.

6.3 Whether site evaluation is part of the assessment

Most studies, except GSF-91, consider site evaluation to be a part of the performance assessment, but judging from the answers “site evaluation” does not have a well defined meaning. Furthermore, Kristallin-I is an evaluation of the suitability of a region, rather than a specific site. All assessments feed site specific data into the consequence calculations in order to evaluate the safety of the potential repository site (or region). It is not clear whether the activity of interpretation of site measurements (injection tests, tracer tests, etc.) to provide parameters for consequence calculations is considered part of PA/SA. Furthermore, there are other potential interpretations of the term site evaluation including regional reconnaissance, field measurements and primary interpretation of data.

7. Assessment System Boundaries

Any performance assessment needs to limit the scope of the analysis in order to focus on phenomena of most importance. The scope can be restricted by analysing a limited spatial region and a limited time scale as well as through the selection of the Features, Events and Processes analysed. The actual choices vary somewhat between assessments, as does the extent to which this limit in scope is addressed explicitly and thereby motivated.

7.1 Limiting the scope of the analysis

7.1.1 Specific attention to certain barriers

Some studies deliberately put most of their attention on certain barriers, whereas the surrounding barriers are modelled only to provide appropriate boundary conditions for the barrier(s) considered. All these studies appear to have a limited objective in the sense that they are tools in programme development rather than studies aiming at showing safety of the disposal system (see chapter 2).

Compilation of answers

In GSF-91 the near-field is modelled in more detailed than the geosphere and the biosphere (the same geosphere and biosphere was used for all disposal concepts assessed) as the reason was to compare different designs. In H3 the assessment focuses on the EBS with a small region of surrounding host rock, implicitly assumed as the primary system as there is a need to consider a wide range of geological environments and it would be beneficial if analysis showed insensitivity to the geological environment. Most of the attention in SKB-91 is on the geosphere and a reasonably realistic source term is used in order to allow studies of optimization of the repository layout, which would have been skewed with a far too conservative source term. In the detailed analysis work of SITE-94 the main focus is on the geosphere and on processes affecting canister integrity, motivated by development needs and it was recognized that this may not cover all issues identified in the scenario analysis and that there will be a need to update actual calculations in a "real" PA. Also in TSPA-95 there are different examples of focusing attention to different phenomena in different barriers, and there is no scenario analysis, because it was felt that TSPAs from 1991 and 1993 adequately addressed disruptive scenarios and no significant new information was available for 1995. In Kristallin-I a "Robust Scenario" is defined in which no account is taken of retardation in the geologic barrier. This is due to the fact that most uncertainties are currently regarded as being associated with this barrier. This bias may be redressed, to some extent, as more information becomes available.

7.1.2 Regulatory requirements

Most regulations give some guidance on the scope of the analysis. AECL and Kristallin-I includes the biosphere inside the system boundaries as this is required by regulations. In TVO-92 there is less much attention to the behaviour of radionuclides in the biosphere or at the geosphere/biosphere interface, partly because this interface is the assessment boundary for long term consideration according to the suggested Nordic criteria. In DCCA, IPA-2 and TSPA-95 the boundary of the accessible environment is given by regulations, although it is unclear if new regulations for HLW will redefine the boundaries. For TSPA-95 drift and repository boundaries were determined in design documents.

7.1.3 Screening of FEPs

A complementary way of limiting the scope of an assessment is by screening the Features, Events and Processes to be considered. This is done in all assessments, but only some document the screening process itself, whereas most document its final results in terms of selected FEPs.

Compilation of answers

The AECL PA is supported by a specific scenario analysis project. In the assessment approach, a priori, equal attention is given to the different model domains, but results of the analysis may focus attention on those parts of the system requiring further definition or improved modelling and data.

In Kristallin-I, a FEP list was developed that gave equal attention to each of the main safety relevant elements of the disposal system:waste form, container, buffer and host rock, plus the main external climatic, geological and human influences. These were examined and the majority of the safety relevant FEPs have been included in the reference and alternative models of the Reference Scenario. Other FEPs are classified as "reserve FEPs", i.e. not included but with potentially positive effect on safety if they were included and "open questions", i.e. not included and potentially detrimental to safety, but with low probability or could be avoided by attention to quality control or design. The majority of relevant FEPs related to climatic or external geologic influences are included in alternative scenarios.

In SITE-94 the system comprises the FEPs in the EBS and the geosphere that directly or indirectly affect radionuclide mobilisation and transport. These FEPs were organized in a Process Influence Diagram showing influences (with difference importance levels) between these FEPs. Low importance FEPs were not considered for further analysis. The surface environment was scoped out, apart from FEPs directly influencing the system. No (or little) consideration was given to influences between the external FEPs. The selection has been influenced on a judgement on where the repository performance will be relatively insensitive to location of the boundary or the FEP screening criteria.

In DCCA a detailed exhaustive FEP screening process is used such that all processes were considered. However, application of screening criteria, based on regulation, probability or consequence, significantly reduced the number of FEPs that were passed on for quantitative analysis.

In IPA-2 the scenarios are identified and screened as part of the system description.

7.2 Where to place the primary system boundaries

Most answers regarding the system boundary concern the physical extent of boundaries in computer models for hydrogeology, rock mechanics and transport. Many also make the observation that the proper extension of such model boundaries is model dependent and cannot be addressed generally. However, all studies qualitatively describe how they limit the scope of the assessment. The following observations are made:

- The most common way of describing the scope (or focus) of the assessment is to use words like "near-field", "far-field" and "biosphere". Many seem to agree that most attention should be given to near-field and far-field, although some studies need to embark on relatively extensive biosphere modelling due to regulatory requirements. Some remark, however, that, a priori, equal attention is given to all parts, but evaluation reveals areas where more attention is needed or would be fruitful. Studies not directly aiming to show safety sometimes limit the scope even further and concentrate on certain aspects of the near-field and the far-field.

- Some couple (directly or indirectly) system boundaries to the selection of FEPs. This could involve both physical extension (only FEPs inside the geosphere) as well as other screening arguments (no impact, low probability).

- Limiting the system boundaries implies bias. Kristallin-I suggests that excluding potentially positive but less well supported FEPs makes the geosphere model less favourable than it may be in reality. SKB-91 notes that a realistic near-field is needed in order to properly judge far-field properties.

- Few studies, apart from SITE-94, discuss the words "system boundaries". A discussion of system boundaries may highlight the potential problem of biasing the analysis.

8. Treatment/addressing of some specific features/issues

8.1 Introduction

The following chapter addresses whether and how the studied assessments treat some Features, Events and Processes (i.e. FEPs). The selection of FEPs considered here is somewhat arbitrary, and should not be regarded as a recommendation of FEPs that should be considered nor that these FEPs are the only ones to consider. All assessments handled many more FEPs than those discussed below.

8.2 General assumptions for the setup of main calculation case

The "reference case" assumptions are largely disposal-concept dependent, but seem to be rather similar in assessments considering similar concepts. There are, however, differences in input data used that may not be explained by differences in overall assumptions.

The "crystalline" spent fuel assessments

TVO-92, SKB-91 and SITE-94 assume that only few canisters fail in the reference case. SKB-91 assumes an initial small hole in the canister which significantly restricts release. Both TVO-92 and SITE-94 assume complete failures, at 10 000 and 1000 years respectively. These differences in assumptions probably reflect differences in design (SKB-91 concerned a lead-filled copper canister), but also different attitudes to the stability of the canister. In AECL, the failure time of canisters is calculated taking temperature-dependent corrosion processes into account.

All studies assume that the buffer will work as intended, although several studies (e.g. AECL) make extensive discussions and reference to experimental data and natural analogues to confirm this.

Models for spent fuel degradation, radionuclide release and transport through the near-field are very similar although slightly different simplifications are made (AECL can rule out radiolytic oxidation of the fuel on account of the lower activity of the fuel type, TVO-92 assumes release from the buffer to the excavation damaged zone, SKB-91 uses steady state mass flow rates and thus neglects the transient phase in the engineered barriers).

AECL uses an equivalent porous medium model of geological units, and takes into account of a number of pathways to the biosphere by means of a network model. The other assessments model geosphere migration in one-dimensional streamtubes with advection and matrix diffusion. TVO-92 neglects dispersion since a conservatively chosen "fast" pathway is analysed, and SITE-94 shows that this is allowed for most nuclides. TVO-92 maintains that values used for groundwater flow rate and "flow wetted surface" result from pessimistic assumptions regarding the properties of the excavation damaged zone and placement of repository allowing for a U-tube flow. However, both SKB-91 and SITE-94, which do not make these assumptions, but employ stochastic methods for describing groundwater flow variability, use transport parameters of the same order of magnitude as TVO-92.

The dominating biosphere pathway is a well and differences in dose conversion factors are due to mainly different assumptions on dilution and well water use.

For the reference case assumption, the resulting dose rate is dominated by I-129, which is not solubility limited, is released directly and sorbs weakly or not at all. Short-lived and all strongly sorbing nuclides are largely retained and decay in the near-field.

Vitrified HLW in hard rock and sediments

There are great similarities in reference case assumptions for H3 and Kristallin-I. The steel canisters are designed to remain unbreached for at least 1000 years after emplacement. It is shown that this can be achieved even taking account of pessimistically high rates of corrosion and the maximum pressures that could develop in the buffer. The canisters are expected to remain unbreached for a much longer time than 1000 years, but in the assessment, all the canisters are assumed to fail at 1000 years. From the failed canisters the nuclides are released congruently with the waste glass corrosion and are further restricted by elemental solubility limits.

Migration through the buffer is governed by diffusion and sorption and geosphere transport is modelled by one-dimensional advection-dispersion with matrix diffusion and sorption. In Kristallin-I, alternative models examine the consequences of assumptions on the internal structure of water conducting features, which are expected to be the path for contaminant transport through the geosphere. These models are based on observations of features identified as flowing zones in deep Nagra boreholes and regional hydrogeological models on a series of spatial scales. H3 considers contaminant transport in idealised parallel-plate planar fractures representing a fractured rock, and also in an equivalent porous medium representing a sediment.

In Kristallin-I, detailed biosphere modelling is carried out and a range of alternative scenarios are evaluated. In H3, geosphere fluxes at 10 m, 100 m and 1000 m are diluted in water volumes typical of those extracted from wells and at rivers heads in Japan, and doses are calculated for humans drinking this water.

Salt repositories

In GSF-91 the reference scenario is a combination of brine intrusion via main anhydrite from brine pockets in the surrounding salt rock. In the far-field radionuclides migrate through an advection-dispersion-sorption model in one-dimensional streamtubes estimated from three-dimensional groundwater flow modelling.

Spent fuel at Yucca Mountain

In IPA-2 the base case assumes canister failure both due to defects and through corrosion (calculated), release through groundwater and air. A special case in TSPA-95 (83 MTU/acre, backfill and high infiltration) is formed to evaluate the containment capabilities of the subsystems.

8.3 Partitioning, chemicals and criticality

8.3.1 Modelling of radionuclide partitioning in various barriers

The release models from the waste form are waste-form dependent. Vitrified HLW studies (e.g. H3 or Kristallin-I) apply congruent dissolution of the glass. The (saturated) spent fuel studies (SKB-91, TVO-92, SITE-94) apply a model based on oxidative degradation of the spent fuel due to alpha radiolysis combined with a fraction of certain nuclides that are assumed to be directly available for release. AECL can rule out radiolytic oxidation of fuel on account of the lower activity of the CANDU fuel.

Most assessments apply solubility limits at the waste form, unless the radioelement has a high solubility (the latter in particular applies to IPA-2, TSPA-95). There are some differences in how far out in the barriers solubility limits are applied and if precipitation due to in-growth is considered or not. Precipitation in the buffer is, for example, neglected in Kristallin-I and TVO-92, but is included in AECL, H3 and SITE-94. These differences are apparently due to differences in judgement and computational capabilities.

All studies apply linear sorption (K_d values) for migration through the various barriers. At Yucca Mountain, it is applied only for migration through the rock mass with values assigned to specific units of the bedded tuffs (IPA-2, TSPA-95). Kristallin-I uses a single K_d value for all rock types as differences in K_d values for different mineralogies were found to be small. AECL uses a formula that takes account of mineral type and salinity along the flow path.

There are only limited efforts in applying non-linear isotherms. Kristallin-I considers non-linear sorption of Cs in the geosphere. SITE-94 evaluates a surface complexation model for Np in the far-field, but concludes that it does not provide any new insight.

8.3.2 Non-radiological impact

Chemically toxic elements

Evaluation of chemically toxic elements are included in AECL and DCCA, both being developed for licensing directed efforts. In AECL, concentrations of a range of chemically toxic elements released to the biosphere are compared to naturally occuring levels. DCCA considers both heavy metals and organics as it is a (draft) license application which also applies to non-radiological hazards. Some studies remark that chemical toxicity does need to be addressed in the final license applications and EIS.

Effects from extraneous chemicals e.g. concretes and shotcretes, and from non-HLW

The effect of extraneous chemicals and non-HLW have not been analysed in great detail in the studies. GSF-91 evaluates the effect of corrosion products and other materials on pH, but there is no detailed modelling of the chemical environment. In H3 the effect of concrete is considered negligible because of the small amounts. The cementitious pore water and organic contaminants from the TRU silos are mentioned in the Kristallin-I scenario development, but it assumed that they can be sited to avoid any effect. SKB-91 assumes no effect from concrete and does not take the non-HLW into account as it will be disposed in such a way that it will not interact with the HLW. SITE-94 recognises the issue, for example in the PID, but does not analyse it further. It is discussed in TVO-92 and covered by conservative retardation data (low K_d values). It is considered in DCCA through the use of side calculations with EQ3/6 and other chemical codes. It is not considered in IPA-2 or TSPA-95, but there are plans to consider it in future assessments.

8.3.3 Criticality

Criticality is either not analysed, or ruled out as being unlikely.

DCCA address criticality directly. In AECL criticality is ruled out during the scenario analysis on the basis of the detailed analysis presented in earlier supporting work, which shows that the necessary conditions of selective segregation and accumulation of fissile isotopes are extremely unlikely, and no mechanism by which they might occur could be identified in the AECL vault conditions. H3 and Kristiallin-I (and partly GSF-91) do not mention criticality, which can be justified on the basis of the relatively low amounts of fissile isotopes in the high-level wastes, compared to those in spent fuel. SKB-91 does not mention it. TVO-92 refers to earlier studies and SITE-94 discusses it but there are no quantitative analyses. IPA-2 does not address it. TSPA does not address criticality, but notes that it will have to be addressed once waste package design is more mature.

8.4 Migration in the geosphere and related site features

All studies quantitatively assess the groundwater migration pathway. Other pathways, such as migration through tunnels and shafts due to improper functioning of seals, are considered but either discarded based on qualitative reasoning or on a simple quantification (Kristallin-I). Some studies mention the gaseous transport pathway (Kristallin-I, TVO-92, and IPA-2).

8.4.1 Spatial heterogeneity

Most studies, apart from GSF-91 and H3, specifically acknowledge geosphere spatial heterogeneity in the transport modelling. There are, however, some differences in approaches to this problem, which may also be medium specific.

Studies explicitly considering spatial variability in the geosphere usually do so by implementing relatively complex groundwater flow models. These may be deterministic or stochastic and may represent the rock either as a network of discrete fractures or as a spatially varying continuum. Solute transport, however, is almost exclusively represented by one-dimensional models, whereby the distribution of Darcy velocity is represented by a large dispersivity (TSPA), by potentially conservative assumptions (TVO-92, Kristallin-I), or by a range (distribution) of different one-dimensional streamtubes (SKB-91, SITE-94). AECL considers a number of routes though different geological units through a network model.

Compilation of answers

Non-crystalline studies
In TSPA-95 large scale features are part of saturated flow domain. Small scale features are handled by 1D longitudinal dispersion. DCCA considers spatial variability in the Culebra aquifer above the salt dome. This is modelled as two-dimensional heterogeneous plane.

Crystalline Studies

All crystalline studies acknowledge specific features (fracture zones and fractures) in different scales. Below some scale, that may depend on the properties of the rock and the exploration methods used, the actual position and properties of these features is uncertain. TVO-92 includes deterministic features down to relatively detailed scale, and treats the uncertainty with the conservative assumption of placing the completely failed canister in the "worst possible location". The other studies (AECL, Kristallin-I, SKB-91 and SITE-94) adopt stochastic approaches below some scale.

AECL considers a number of routes from the vault to the biosphere by means of a network model in which separate units are recognised - lower rock zone, middle rock zone, upper rock zone, major fractures and overburden. In addition, the transport properties of the network segments are sampled from parameter distributions taking into account of expected correlations.

In Kristallin-I, a 3-D conceptual model is developed that incorporates heterogeneity in three scales (1 km, 100 m, 10 m to 1 cm). This model is used for groundwater-flow modelling. For geosphere transport modelling the heterogeneity is further simplified into a one-dimensional representation, where the three-dimensional model of the geosphere is used to derive parameter values as input.

SKB-91 acknowledges specific features in regional scale and takes care of repository scale variability by a stochastic continuum description. This model produces a set of streamtubes as function of release point. A one-dimensional transport model is fitted to each streamtube.

In SITE-94 a detailed structure model is developed, based on geological, geophysical, hydrological and geochemical data. Alternative conceptual models and variants are developed to provide a stochastic description of rock mass heterogeneity (stochastic continuum, discrete fracture network). These models produce streamtubes and a one-dimensional transport model is fitted to each streamtube. The rock mechanical analysis acknowledges discrete fractures, but no variability of properties. Speciation calculations are done with varying mineralogy. Different groundwaters and mixing between those are identified.

8.4.2 Treatment of transients and the normal geodynamics of the site

In general, the view appears to be that transient phenomena such as resaturation, changing flow direction or climate evolution are of minor significance or can be treated as perturbations on the model systems, e.g. through extended parameter ranges or alternative scenarios represented with the same model chain. Few transient analyses are performed, instead they are replaced by qualitative reasoning and by conservative assumptions. However, in many assessments this relates to the period over which the models are expected to be realistic. In some assessments, climate-induced changes at times beyond about 10 000 years may significantly disturbe the hydrogeology, whereas in others the deep systems may be relatively unaffected by such changes.

Resaturation

With few exceptions, regarding phenomena close to the waste package, the studies do not quantitatively evaluate the resaturation period. Although this has been treated in supporting studies to several of the assessments.

There are some media specific differences. For salt repositories resaturation is less of an issue, although DCCA calculates the brine inflow. TSPA notes that Yucca Mountain is unsaturated to begin with, although IPA-2 assumes no water in contact with the waste package before the time at which temperature drops below boiling. For crystalline repositories the amount of entrapped air is considered in the corrosion estimates (see e.g. H3, TVO-92 or Kristallin-I), but release calculations start out with saturated conditions. This is because the expected life time of the waste containers, which exceeds the estimated time for resaturation.

Geodynamics

To some extent most studies take the geodynamics of the site into account, although detailed analyses are often deemed to be unnecessary by qualitative reasoning.

GSF-91 assumes a stable region, considering creeping of rock salt being a normal process. H3 assumes that the geodymamics do not affect the small near-field region. Kristallin-I considers potential changes in regional hydrology and in the location and nature of the biosphere discharge zone due to uplift, displacement of river network and resulting erosion. The overlying sediments make the groundwater flow in the crystalline basement relatively insensitive to climate induced hydrogeologic changes. In addition, the conservative assumption of immediate transport in the upper zone of the basement rocks and the overlying sediments makes the assessment model relatively insensitive to the hydrogeological effects of climate change. SKB-91 discards tectonics based on qualitative reasoning. SITE-94 considers a climate evolution scenario with sea-level changes, permafrost, and ice-load. TVO-92 discusses and analyses the effects of glaciations and discussed earthquakes. DCCA varies the rainfall. Through the scenario analysis IPA-2 considers impact of volcanism and seismicity caused failure of waste packages. TSPA considers climatic change over 1 000 000 years.

8.4.3 The excavation damaged zone

The significance of an excavation damaged zone appears to be medium specific. The real attention to this phenomenon is in crystalline rock, which can also be seen from the studies that address this (H3, Kristallin-I, SKB-91, SITE-94, TVO-92). All these studies seem to treat the EDZ by increasing, conservatively, the local permeability around tunnels and shafts. There appears to be little or no analysis of the formation of the EDZ and of its long term properties in the main summary reports (although it has been the subject of several supporting reports issued by e.g. SKB or AECL).

8.4.4 The most critical uncertainties associated with predictions of radionuclide migration in the geosphere and whether these uncertainties can be resolved by more site specific data

All assessments, except for AECL, consider the (small scale) groundwater flow to be one of the most critical uncertainties associated with predictions of radionuclide migration in the geosphere. In addition GSF-91 notes the uncertainty in K_d values but also notes that the salt is the most important barrier. The crystalline studies also put “flow wetted surface” and matrix diffusion properties on this list. Additional noted uncertainties are irreversible sorption on colloids (Kristallin-I) and migration path length (H3). Large scale features are important (SKB-91), but assumed to be characterized by a detailed site investigation.

There are varying degrees of optimism concerning the possibility of reducing the noted uncertainties in local flow, “flow wetted surface”, and matrix diffusion properties. The TVO-92 answer suggests that it is not meaningful with site specific efforts to characterize these small scale phenomena, but that it still would be useful to increase general knowledge from rock laboratories and related efforts. In contrast the Kristallin-I and the H3 answers suggest that additional site-specific data would reduce these uncertainties. The SKB-91 answer suggests that the uncertainties in flow wetted surface may always be a problem. The SITE-94 answer suggest that these uncertainties could possibly be reduced by multiple tracer (sorbing and non-sorbing) experiments conducted over different scales combined with a detailed characterization of transmissive features.

For Yucca Mountain the future deep percolation in the unsaturated zone (IPA-2, TSPA) and in the saturated zone (IPA-2) are the most important uncertainties. More knowledge will be obtained from site evaluation (TSPA). The IPA-2 answer suggests that these issues may be resolved by site specific meteorological and topographic data, and by data on site specific hydrogeologic properties.

8.5 Biosphere related issues

8.5.1 Definition of the critical group

Partly, regulations determine the the way the critical group is defined. No study views the biosphere to be a safety barrier. In several assessments biosphere modelling is viewed as a procedure for the conversion of releases to a common scale accepted as an appropriate measure of radiological hazard.

Neither DCCA nor H3 define the critical group.

AECL treats a critical group based on a single household/farmstead where the number of persons in the group is a sampled parameter. The group makes extensive and varied use of the potentially contaminated environment, including extracting water from a well placed in a major fracture zone expected to be a primary route for release of contaminants.

GSF-91 assumes a small, self-sustained local community and judges this assumption to be moderately conservative and in agreement with regulations. The hypothetical critical group in the Kristallin-I reference biosphere model is a self-sustained agricultural community on a section of the River Rhine valley, estimated to be the smallest area into which contaminants emerging from a repository in the crystalline basement of Northern Switzerland could be diluted. SKB-91 assumes a self-sustained farm using a well in a fracture zone connecting the repository area and judged this to be conservative, but reasonably realistic. TVO-92 assumes a self-sustained farm using water from a well and a lake where nuclides end up. SITE-94 does not include a full biosphere analysis, releases are converted into doses by utilising well dose factors, but there are also limited analyses of people eating fish, a self-sustained farm and even doses to fish.

The Yucca Mountain studies are only partly dose oriented as regulations there are being redefined. For dose calculations IPA-2 employes the notion of “exposed groups” being three people living on self-sustained farm down gradient Yucca Mountain, a greater population eating meat from this farm and 22 000 people within 100 km subject to potential airborne exposure. TSPA evaluates dose to an individual at the accessible environment boundary drinking 2 litres of groundwater daily. This is simpler than the IPA-2 exposed groups - but possibly not less conservative as most doses are dominated by the drinking water pathway.

8.5.2 Treatment of human intrusion

Only few of the assessments make quantitative assessments of human intrusion (AECL, DCCA and IPA-2). It is discussed in some of the other studies (Kristallin-I, H3, TVO-92 and SITE-94), but the remark is also made that human intrusion has been discussed in previous assessments.

DCCA analyses human intrusion. IPA-2 analyses drilling directly through the waste packages. There are no dose estimates, but the quantities brought to surface are factored into the cumulative release.

AECL undertakes a detailed analysis of inadvertant human intrusion into the repository by deep drilling. Doses and risks are calculated for: a member of the drilling crew exposed to undispersed wastes; a laboratory core examination worker; a construction worker exposed to previously extracted and dispersed wastes on the site; and a resident exposed to previously extracted and dispersed wastes on the site.

GSF-91 does not consider human intrusion at all. H3 does not consider it in detail. It is not within the scope of SKB-91. It is not considered but discussed in SITE-94. TSPA-95 does not address it, but it was addressed in TSPA-91. For Kristallin-I deliberate human intrusion is ruled out in the regulation. The deep repository is believed to not attract inadvertent intrusion, although low energy geothermal energy extraction is considered as a potential use of the crystalline basement and if developed in the same rock block as the HLW repository could have implications for the long term stability of the repository. There is no quantitative analysis at the present stage since the primary aim is to help guide further geological investigation.

In discussing human intrussion in TVO-92 the following points are made: the assessment is based on a selection of sites with low ore and mineral potential; care will be taken to store information; advertent intrusion is the responsibility of the intruder; the risk of accidental intrusion is small since repository is likely to be discovered in the geophysical investigations that should precede any drilling or excavation activity. It is also noted that it is not meaningful to quantify risk of drilling (e.g. a large percentage of deep drillings in Finland so far have been made just for investigations of repository sites). The criteria suggested by the Nordic safety authorities suggest that non-advertant intrusion, for which quantitative assessments are in practice impossible can be interpreted as a “residual risk”. The risk is also independent of the disposal site - if in a common rock type.

8.6 Simplification and handling hypothetical features

8.6.1 Idealizations of the geosphere and EBS

Modelling of the Engineered Barrier System (EBS) and modelling of the geosphere imply numerous simplifications. In the transport modelling, the EBS, geosphere and biosphere are simplified in several ways, generally in the conservative direction.

DCCA implements the FEPs kept through the screening process. In TSPA-95 there is an "abstraction" process (described in the report), which results in simplified geosphere and EBS representations based on process-level modelling and more detailed natural system and engineered system design information. A typical example of a simplification made in most studies is that geosphere migration is modelled in 1D streamtubes, with average properties along a streamtube, even if groundwater flow may be modelled in 3 dimensions.

Some simplifications are made in order that calculations do not place prohibitive requirements, e.g. on computer time and storage, whereas others are made in the conservative direction in order to handle a lack of knowledge concerning detailed processes and phenomena. Both motivations lie behind the use of 1-D, constant properties, geosphere transport codes. However, as can be noted from section 8.6.4, few studies are of the opinion that uncertainty would be reduced by application of more complex codes.

8.6.2 Consequences from not observed potentially negative features?

Most studies analyse consequences from non-observed features. For example GSF-91 analyses a temperature-induced crack of the main anhydrite and undetected brine volumes. SKB-91 analyses an extra subhorizontal zone below the repository. TVO-92 assumes a U-tube flow by placing the repository between two fracture zones and by assuming high permeability of the repository. DCCA analyses all FEPs left from the screening process. IPA-2 assumes fast flow down fractures to the water table, no retardation in fractures, no protection afforded by the failed waste package, and no matrix diffusion. All these, and other examples, are motivated by a more or less well-founded uncertainty whether the feature would actually exist and if it would actually be detrimental to safety. In Kristallin-I a methodology is outlined to define a robust case with reduced impact from these uncertainties.

8.6.3 Identified phenomena discounted for further analyses

Assessments usually discuss a large number of phenomena, but only a few are retained for quantitative analysis. For example, most studies discard meteorites based on earlier assessment of impact probabilities. Kristallin-I identifies a number of potentially detrimental processes and events, such as improper emplacement of the buffer, hydrogen gas production from anaerobic corrosion and canister sinking. These are evaluated by qualitative arguments or scoping calculations and it is considered that the potentially detrimental effects can be avoided by design or appropriate quality control measures. In general, FEPs screening methodologies applied in many studies can be seen as a means to structure such qualitative or semi-qualitative analyses.

8.6.4 Why try to simplify calculations?

There are several reasons for simplifying models and calculations.

One reason is simply to save computer time and other resources. This may be trivial but it is worth remembering that it is physically impossible to analyse all combinations or to evaluate every conceivable FEP or alternative model. That would require infinite resources. Therefore, judgements and limitations of scope are necessary.

Another reason for simplification is to overcome uncertainties arising from incomplete description of features, incomplete understanding of processes, incomplete data or inadequacy of currently available codes in order to make a safety case. It is suggested that a safety case can be built on simplified calculations as long as there is a rigorous methodology for identification of FEPs, due consideration has been given to all these FEPs, and it can be shown that if a FEP is omitted or simplified the net result would be to overestimate consequences.

Simplifications may also be a means to clarify understanding and to focus on the more important issues. On the other hand it has been suggested that more detailed and possibly realistic calculations may be needed for a detailed design study and to show understanding of various phenomena.

It has also been suggested that simplifications are a means to reach acceptance with the public. Such simplifications might help to make a more easily understood safety case. Some have the view that the public wants a simple answer to the question of whether the repository is safe, while technologists may prefer more detailed, scientific models. On the other hand it is suggested that both the technologists and the public are skeptical of complex computer codes. It is observed that proponents of discarded modelling concepts may be offended. One answer even suggests that the hard core resistance to simplifications may come from scientists or consultants who think they can make a living by "keeping the problem alive". At any rate some answers suggest that, in order to gain acceptance from the public and scientific community, the rationale for simplifications must be explained, the simplifications documented, and the resulting bias discussed.

8.7 Assessment issues

8.7.1 Quality assurance and consistency of data and assumptions

Most studies apply Quality Assurance (QA) procedures, such as benchmark tests, comparison with analytical solutions and documentation for the computer codes. Some studies also apply or try to apply QA procedures for the whole assessment and there seems to be room for more development in that area. Usually these latter actions concern means to ensure consistency of data and assumptions across various analyses. Formal QA-plans are generally not used, but QA is discussed in some of the studies.

Compilation of answers

For the GSF-91 one of the companies in the overall project attempted to assure consistency by a compilation of data and through several project meetings. In H3 a flow sheet was used to assure the quality of the whole analysis, with defined input and output operations, but this is not mentioned in the report. For TVO-92 TVO's and VTT's normal QA procedures are applied. The assumptions and data were discussed among the assessment team of four and the experts delivering data, whereas final decisions were made by the project manager. In Kristallin-I a formal data file handling system was used to ensure control and traceability of data used in assessment calculations. SITE-94 notes that the methodology used for handling FEPs and to generate calculation cases could also be used for QA, and to establish contracts between suppliers and users of information, but this aspect of the methodology was not fully applied. IPA-2 applied a Total System Code, but the high complexity of the system code, contributed to general lack of transparency in the analysis. In TSPA there were systematic and irregular checks of data and assumptions by modelling teams and in between modelling teams.

8.7.2 Expert judgement

All studies use expert judgement in particular for selection of FEPs and conceptual models, to make simplifications, as well as for final selection of data and calculation cases. External review is also mentioned as a use of expert judgement. The use of expert judgement is both explicitly acknowledged and implicitly understood to take place. No study directly applied formal procedures for expert elicitation.

8.7.3 Use of natural analogues and international projects

Input from different international projects is certainly being used in most of the studies. Bilateral cooperation may provide various sources of inputs. The information in some international databases such as thermodynamic data and FEPs lists are directly used. International intercomparison projects, such as Stripa, Hydrocoin, Chemval or Intraval are more used for building confidence in code verification, approaches, models, assumptions and data used.

There are few examples of the direct use of natural analogue projects. They were rather seen as a component of the confidence building process as they support the understanding of key processes, regarding EBS materials and radionuclide transport in the EBS and geosphere, although, in general, only in a qualitative manner.

9. Treatment of uncertainty

9.1 Classification

9.1.1 Scenario uncertainty

There seems to be a tendency to couple scenario uncertainty with uncertainty in comprehensiveness of the list of FEPs and interactions between FEPs.

Compilation of answers

Kristallin-I defines scenario uncertainty as the uncertainty in future evolution, i.e. uncertainty in the FEPs that should be accounted for within the quantitative analysis. H3 defines it as the identification of FEPs and their relationship. DCCA has a similar definition. In SITE-94, scenario uncertainty is restricted to the FEPs outside the system, whereas uncertainty in FEPs and interactions inside the system is given the term *system uncertainty*. The SITE-94 distinctions rest on the idea of a predefined system boundary in terms of FEPs in different barriers. AECL refers to "factors", which are equivalent to "FEPs" identified and manipulated in other assessments.

9.1.2 Conceptual model uncertainty (CMU)

There seems to be convergence on the idea that CMU concerns uncertainty in the representation of a FEP and/or FEP interactions. However, the concept of a FEP is not well defined. A general FEP can usually be split up into small-scale FEPs and interactions; on the other hand many detailed FEPs may be merged into a super-FEP. Consequently, there is a judgmental aspect on the difference between scenario and conceptual model uncertainty - it refers to scale in terms of FEPs.

Compilation of answers

Kristallin-I defines conceptual model uncertainty as the uncertainty in the representation of what constitutes an appropriate model or models of the relevant FEPs. H3 defines it as the uncertainty in the representation of each FEP, both with regard to the mathematical model, the algorithm, and concept. SITE-94, and probably DCCA have similar definitions to Kristallin-I. However, H3 finds it difficult to separate scenario uncertainty and CMU as uncertainty in interactions of FEPs could be a source of scenario uncertainty. For cases where it is felt that alternative conceptual models are supported by the available information, in the opinion of the TSPA analysts, these alternatives are either discussed or analytically evaluated.

9.1.3 Parameter uncertainty

Kristallin-I defines parameter uncertainty as the uncertainty in the data and parameter values to be used in the models. H3, SITE-94 and (probably) DCCA use similar definitions. SITE-94 points out that variability is different from parameter uncertainty.

9.2 Scenario analysis: handling of FEPs

9.2.1 Informal use of FEPs lists in scenario construction

Most of the studies have not applied a formal procedure for coupling FEPs into scenarios and subsequent calculation case development.

Compilation of answers

Scenario analyses are outside the scope of TSPA-95 and SKB-91, but the answers do suggest that such analyses should be done. In GSF-91 there is no systematic approach to select the FEPs that actually have been applied; the scenario selected was based on expert judgement.

H3 identifies direct exposure FEPs such as uplift/erosion or volcanic activity. Qualitative assessment suggests that these FEPs could be disregarded through proper site selection. Evaluations of FEPs that indirectly could lead to radionuclide release through other processes confirm groundwater to be the only possible alternative. Subsequent quantitative analyses concentrated on groundwater release.

TVO-92 uses a top-down approach for constructing scenarios and calculation cases. There is no formal use of FEPs or FEPs lists in the generation of these cases. However, in concluding the report, the significance of FEPs identified in other studies and not quantitatively assessed in TVO-92, are discussed.

9.2.2 Formal procedures for handling FEPs and scenario development

AECL, Kristallin-I, SITE-94, DCCA, and IPA-2 apply formal procedures to couple FEP lists with actual calculations. These procedures are used to identify which FEPs and interactions between FEPs that should be considered in the quantitative assessment.

Based on the answers to the questionnaire it is hard to tell if the formal approaches produce different calculation cases than what would have resulted otherwise. They do, however, lead to a more complete discussion of potentially relevant FEPs and arguments by which some FEPs are omitted from quantitative analysis. In the assessments, the representation of FEPs is usually confined to modelling tools, and knowledge of data that have been assembled from previous (less formal) assessments. Nevertheless, there may be advantages with the formal procedures (I) as they represent a means to strive for completeness, (ii) as they are a means for handling the long list of issues that do not need consideration in the quantitative analysis, and (iii) as they provide a means for open documentation of assumptions of the current assessment calculations and future development needs (if any).

Compilation of answers

In the AECL PA a systematic search is made for all factors that could affect the future performance of the reference disposal system, e.g. container corrosion, diffusion of contaminants in groundwater, movements of groundwater and contaminants in the geosphere, changes in climate and aspects of human intrusion. The factors are assembled into *scenarios*, or combination of factors, for detailed assessment. Three types of scenarios requiring quantitative evaluation are identified; the range of most likely and expected scenarios (containing most of the identified factors) are called the "SYVAC scenarios" (the name of the simulation software), "unlikely and unexpected scenarios" (containing additional factors) are not folded into the main body of SYVAC scenarios because of the large uncertainty associated with their occurrence, and finally "disruptive events" are events that could seriously impair the integrity of a disposal system such that a situation outside the scope of the SYVAC system models arises.

In Kristallin-I, a large number of FEPs are identified, a large fraction of which are considered in the various scenarios and alternative models represented in consequence analysis. Two groups of screening arguments are used, both to screen out FEPs from the list and also explain the reasons why certain classes of FEPs are not included in the list. The screening arguments are based on (i) site and disposal concept and (ii) assessment basis. The FEPs remaining after screening are examined and the majority are included in reference and alternative models of the reference scenario. Other FEPs are identified as "reserve FEPs", i.e. not included in current models but if included would have a positive effect on safety, and as "open questions", i.e. not included in current models and could be detrimental to safety, but either of very low probability or could be avoided by attention to design and quality control. The majority of FEPs related to climatic and geologic influences are included in alternative scenarios, although the effects are mainly within the conservatively defined scope of the reference scenario, except for the biosphere where a range of alternative scenarios are considered.

SITE-94 includes construction of a Process Influence Diagram (PID) showing influences between FEPs in the EBS and in the geosphere of any significance to radionuclide release and transport (the system). The PID as well as FEPs outside the PID are "audited" against international FEPs lists with screening criteria such as concept and site. The PID has been reviewed and importance levels are assigned to influences through expert judgement. A set of FEPs outside the PID were compiled, through the Sandia methodology, to form the scenario generating external FEPs (EFEPs). Of these SITE-94 only pursue the climate evolution EFEPs. These are applied to the PID and result in an update in importance levels. The highest importance level FEPs in the PID are mapped onto the actual modelling tools described in a flow chart called the Assessment Model Flow Chart (AMF). This mapping results in an updated AMF, such that it would encompass the FEPs for the selected scenario, but it also shows which FEPs and interactions that are not well represented by present modelling tools. Calculation cases are developed and uncertainty is propagated through the AMF information flow structure. The PID and the AMF are both documented in a relational database with a graphical interphase.

DCCA first identifies and classifies all potentially important FEPs. Some FEPs are then eliminated according to defined screening criteria. Scenarios are formed by combining FEPs to specify scenarios for consequence analysis. Conceptual models, that capture the FEPs in the different scenarios are developed for each scenario based on the observation of the system being modelled.

IPA-2 employs a modification of the Sandia methodology to identify, classify, screen and combine Events and Processes into scenario classes and then to screen the scenario classes. Within the scenario classes parameter variations are used to generate a large number of input vectors for the analytical models.

9.3 Propagation of uncertainty

There are essentially two broad methods employed for propagating uncertainties in the assessments, deterministic and probabilistic approaches. It should be recognized, however, that both methods rely on the possibility to quantify aspects of uncertainties and that there are different attitudes within the different methods regarding the possibility to parameterise conceptual model uncertainty. The main difference between deterministic and probabilistic methods is that the latter explicitly tries to quantify probabilities and to combine these into risk estimates.

9.3.1 Conservative assumptions

All studies, including those employing probabilistic methods, make some conservative assumptions. These are usually identified and motivated. The main reason for making such assumptions is to avoid a more complex analysis and it is thus non-trivial to quantify the impact of the assumptions. However, it may not be necessary to quantify conservatism, if one can show, on logical grounds, that the proposed argumentation is conservative with respect to some identified consequences. For quantified, especially parameter, uncertainties, sensitivity analyses may be performed to evaluate the degree of importance relative to system performance and the degree of conservatism can be quantified.

9.3.2 Quantification of conceptual model uncertainty into parameter ranges and distributions

In order to propagate scenario uncertainty or conceptual model uncertainty in a quantitative calculation, aspects of these uncertainties need to be quantified. It is recognized among most questionnaire answers that there are many examples where the effect of scenario or conceptual model uncertainty can be quantified with a parameter uncertainty using the “standard model chain”. However, some point out that there are scenarios and conceptual models that would require new models and model couplings, which could not be represented by a distribution of parameters in the “standard model chain”. Furthermore, the issue of completeness, whether all relevant alternative conceptual models have been identified, cannot be quantified.

Even if conceptual model uncertainty may be described as a parameter range, some answers point out that it is still essential to distinguish between uncertainties of different origin. First, this would assist in making a structured presentation of uncertainties, and second a parameter range representing a specific conceptual model uncertainty may only be valid under certain conditions and other ranges would be needed if these conditions were to change.

9.3.3 Deterministic approaches

To varying degrees, deterministic approaches rely on the possibility to make bounding analyses. Usually, the deterministic approaches evaluate a number of variants (i.e. different input parameter combinations) either to support the conservatism of the “reference assumptions” or to illustrate the impact of conditions deviating from the reference conditions. Such variants are sometimes traced back to scenario and conceptual model uncertainty, but in some assessments they are more presented as “what if” assumptions. Some assessments may implicitly assume that the variants represent less plausible situations, in others there are no assumptions about the likelihood of any variant but qualitative arguments are made that the likelihood of detrimental cases is low.

Compilation of answers

H3 is a bounding analysis and does not make any distinction between classes of uncertainties.

The assessment calculations in Kristallin-I are a set of calculation cases. These calculation cases are centered around a “Reference Case”, which is a model representation of a “Reference Scenario”, employing “Reference Model Assumptions” and “Reference Data”. The reference scenario includes the key phenomena expected to determine repository performance, the reference models and data are selected such that they lead to the highest consequence, but the selection is limited to plausible model assumptions within the reference scenario and to the realistically supported available information. Within the reference scenario a range of cases are evaluated considering alternative models of key FEPs and parameter variations. Alternative scenarios are also considered. The strategy is to span a wide range of hypothetical states, showing that these states comply with regulatory criteria. There is also a “Robust Scenario” in which the most pessimistic view is taken of current uncertainties in the geosphere, and which thus quantifies the minimum level of safety that can be relied upon given the current state of knowledge.

SITE-94 uses a methodology apparently very similar to the Kristallin-I approach. The input to the consequence calculations is given as a suite of *variants* . A single variant is simply a set of parameter input values for the consequence codes. A suite of variants are formulated for each scenario (i.e. external condition) analysed. Most of the variants are formed to explore a Reference Case (i.e. a Reference Scenario to use the Nagra methodology) and these reference case variants are centred around a “zero-variant” (“Reference Case” in the Nagra terminology), which represents best estimates or slightly conservative parameters and conceptual models. Parameter variants are formed by manual sampling from the parameter ranges for the zero-variant conceptual models and conceptual model variants are formed by changing conceptual models. The sampling tries to identify high consequence combinations. Apart for the Reference Case there are also variants formed for a Central Climate evolution scenario which implies a suite of different external impacts on the system (such as sea-level change, permafrost and glaciation). The impact of the changed boundary conditions are traced through the rock-mechanical, hydrogeological and geochemical models, which are part of the system models, in order to provide new conditions for radionuclide release and transport calculations. Other external conditions are only discussed qualitatively.

In TVO-92 there is no formal separation of the impact of uncertainties originating from external conditions, conceptual model uncertainty or parameter uncertainty. TVO-92 presents a Base Case, which is stated to represent the expected performance, supported by a qualitative canister analysis, which implies no canister failure and consequently no releases. A reference case, presented as a “what if case”, explores the consequences of a single complete canister failure after 10 000 years. Most radionuclide release and transport parameters are supposed to be conservative in this reference case. In addition, TVO-92 performs a set of sensitivity and uncertainty analysis, which usually are conducted as radionuclide release and transport calculations under various assumptions of the model parameter values. These cases are also presented as “what if”. The impact of different external conditions are discussed qualitatively. Variability between sites was contained in the uncertainty and subsequent conservative assumptions made.

SKB-91 treats uncertainty in the geological structural model by variation cases. Spatial variability in rock hydraulic properties, in repository scale, is treated with stochastic continuum simulations, whereas other parameter (conceptual) uncertainty in the geosphere is treated by variation cases. Conceptual model uncertainty is partly covered by model variation. The distributions of input data, i.e. the number of failed canisters and the spatial distribution of geosphere properties, are numerically propagated by the PSA technique, with no formal separation between spatial variability and uncertainty.

9.3.4 Probabilistic approaches

Probabilistic assessment build on deterministic analyses of single effects and conditions, and are, in this respect, not different from the deterministic analyses. The difference is that probability estimates are made for each condition, which allows for sampling of the consequences of the different variants into total or conditioned risk estimates. Usually this sampling implies that many more calculation cases are generated, in order to produce statistically valid results. It is also necessary to pay attention to the correlation between different cases. Usually this is treated by generating (presumed) statistically independent cases or by sampling a more basic parameters. However, there are also examples of efforts to quantify the correlations between the large number of parameters and events in the system (see e.g. DCCA).

Compilation of answers

GSF-91 describes all uncertainty as parameter uncertainty, given by mean values and distribution functions. The uncertainties are propagated through Monte Carlo methods.

The AECL assessment employs a probabilistic approach. Probabilities are taken into account in two main ways. First, the estimates of effects that would arise in a particular scenario are weighted by the probability that the scenario would occur. Second, the values of many of the parameters in the system model are selected from probability distributions. The results from the system model is a distribution of estimates of effects that reflects the variability in parameter value (i.e. AECL do not really separate uncertainty from variability). The distribution allows the expected value of the estimated effect and its variability to be calculated for comparison with the AECB criterion.

For the scenarios selected through the FEPs screening methodology, described in a previous section, DCCA developed mathematical models representing the processes at the site. Numerical models, being approximations of mathematical models, are implemented into a computational model. Data, being descriptors of the physical system, are normally obtained by experiment and observation. Parameter and parameter distributions are derived from data sometimes using expert judgement. These uncertainties are all propagated and combined into a single risk estimate by calculating the sum of consequences and probabilities for a large set of unconditioned events through a Monte-Carlo technique. The technique involves i) selection of variables ii) generation of samples iii) propagation of samples through the analysis iv) uncertainty and v) sensitivity analysis.

IPA-2 adopts a probabilistic approach where quantifiable uncertainties are addressed through random sampling of parameter values (e.g. Latin Hypercube Sampling) from a known range of distributions using the Monte Carlo approach into a single combined assessment model. The consequences from disruptive events are treated by adjusting submodel parameters, introducing LHS variables, or through additional dependent or independent calculations. Scenario uncertainty as treated in the form of the prediction of future system states for a period of 10,000 years. Such calculations necessitate the identification of appropriate future conditions to consider and estimates of their probabilities of occurrence. Scenarios such as volcanism, identified through the screening process described in a previous section, are considered to be external conditions imposed on the repository system. The repository system then responds to these external conditions and these responses are modelled in the consequence analyses. With this approach conditions and events inside the system (e.g. waste package failures) are model consequences and will only be combined with those external event that would lead to the internal event.

In TSPA-95, results of detailed (deterministic) modelling are abstracted into parameter ranges for the PSA models and then propagated through the PSA technique. Several designs and several scenarios for natural system behaviour are considered (and treated separately). Various statistical evaluations of specific uncertainties are shown, in part illustrating that different approaches have strengths and weaknesses.

9.3.5 Motivation for using deterministic or probabilistic approaches

Usually, the studies applying deterministic approaches state reasons to favour them over probabilistic approaches and vice versa. The reasons suggested in support for deterministic approaches are:

- they are judged to be easier to understand and verify, which may provide a transparent illustrations of system performance and the origin of different uncertainties;

- that the available data are insufficient to provide statistically justified ranges or distributions for certain safety-relevant parameters;

- the possibility to analyse consequences or repository evolution with complex models;

- the fact that expert judgments on the likelihood of alternative models or scenarios have to be presented explicitly.

Some questionnaire answers suggest that the reason for pursuing a probabilistic approach is that it is required by regulations. However, SKB-91 and GSF-91, which both had some PSA elements, were conducted in countries without specific regulatory requirement for probabilistic analyses and it is clear that there are more potential advantages of a probabilistic approach. The principle advantage of PSA is that it provides an overall risk estimate for the whole system that includes the effect of all processes and uncertainties incorporated in the model, and a wide variety of presentations of results can be made to illustrate the distribution of possible outcomes and uncertainty. Additional potential advantages include:

- the logic provided for the selection of calculation cases;

- the fact that the effect of all uncertainties within the model are evaluated together thus, during sensitivity analysis, those uncertainties that dominate the overall uncertainty in estimates of performance can be properly identified and ranked in importance,

- the possibility, by sampling, to explore a range of conditions and thereby "discover" conditions (regions of parameter space) that are important to performance or risk, but may not have been identified by a priori reasoning.

The difficulty of communicating probabilistic results is generally recognised. In addition, a disadvantage of probabilistic approaches, suggested by studies adopting deterministic approaches, is the difficulty in assigning probability density functions and correlations, as there are no data to support statistical distributions for much of the scenario and conceptual model uncertainty. It is suggested that these uncertainties may dominate over the ones that can be quantified based on experimental data. This may result in significantly skewed results as well as a risk of sampling unrealistic parameter combinations, which need to be rejected in retrospect. However, it should be recognised that in a qualitative sense this problem is shared with the deterministic approaches, which often use words such as “far-fetched”, “unlikely”, “pessimistic” etc. to describe deterministic cases.

9.4 Completeness, non-quantifiable uncertainties, common mode failure and unavoidable uncertainties

9.4.1 Completeness

Generally, it is realised that completeness cannot be proved. It is addressed through careful documentation and through auditing against international FEPs lists. The application of formal procedures for treating FEPs are cited by those who used them.

Compilation of answers

In GSF-91 best estimate values are used for parameters and ranges, and it is understood that it is not possible to address the completeness problem. Kristallin-I employes an elicitation procedure, where FEP lists produced over the years by project staff were complemented by international experience, such as participation in the NEA/ PAAG. In addition, the preliminary FEP list was audited against an “international FEP list” compiled from projects in other countries. SITE-94 states that completeness cannot be proven, and addresses it through open and traceable documentation to facilitate updating and review, and by auditing against international FEPs lists. TVO-92 performs a check of various FEP lists in other assessments. DCCA addresses the completeness problem through FEPs screening, conceptual model screening and data distributions. TSPA-95 does not consider external events, but there is careful attention to documentation and identification of sources of support to allow for review.

9.4.2 Non-quantifiable uncertainties

Philosophically, it is not possible to know whether all relevant FEPs, interactions or conceptual models have been identified, and therefore it is not possible to quantify the impact of their omission. In addition, there often is a lack of experimental data to directly infer quantitative estimates of scenario or conceptual model uncertainty. Assessments quantifying such uncertainties instead use expert judgement. The answers to the IPAG questionnaire show that many assessments, both deterministic and probabilistic ones, doubt whether such uncertainties could be quantified or if it is meaningful to do so, whereas other maintain that quantification is both possible and meaningful.

Studies supporting the view that most uncertainties could be quantified argue that all uncertainties can be folded into parameter uncertainty, provided proper attention is given to the expert elicitation process. The contrary view is that, in the case of uncertainty associated with the selection and representation of relevant processes, there is little point or none at all employing simplistic probabilistic estimates of such uncertainties, in particular when it comes to estimation of joint probabilities and correlations. Studies unwilling to quantify all uncertainties instead claim that such uncertainties may be handled by qualitative methods. They refer to several methods including conservative assumption, reasonable projection into the future in a qualitative sense, techniques for FEP identification and the use of peer review.

9.4.3 Common failure model analysis

No study seems to have applied a formal Common Failure Model analysis. Kristallin-I notes, however, that individual calculations assume several detrimental and unlikely phenomena to occur simultaneously. SITE-94 notes that the development of the PID was thought to be a means of handling Common Mode Failure, by exploring for possible high consequence interactions. TVO-92 analyse several common failure scenarios.

9.4.4 Unavoidable uncertainties

In general, the assessments do not discuss the term “unavoidable uncertainties”. Some have the view that there are many such uncertainties, whereas others claim that except for non-quantifiable uncertainties most uncertainties can, if necessary be reduced, though not entirely eradicated by further R&D work. There are, however, practical limitations to such R&D work and some suggest that residual uncertainty in host rock heterogeneity may be regarded as practically unavoidable.

9.5 Documentation of uncertainty

Most studies document uncertainties in the report. In addition to this, SITE-94 fed the description of FEPs and influences into a relational database containing, for each FEP and influence, explanations for the FEP/influence, references to previous work, records of the decisions of importance, and records of how the FEP/link was actually treated in the assessment. The other studies with formal scenario analysis procedures may have similar databases, although not recorded in the questionnaire answers.

10. The safety case

10.1 What is meant by "safety case" and its reflection in the report outline

There appears to be a broad consensus that the safety case includes the line of arguments and a demonstration that all potential detrimental issues have been dealt with. It is clear that assessment of confidence level, completeness and traceability is part of the safety case. In addition, the general view is that exploration of conditions when the system fails and exploration of points of weakness contributes to the safety case, but there is a danger in presenting non-physical "what if" cases. There are different views on whether the safety case is the entire assessment report or just a part of the conclusions. The safety case is usually defined as the line of argument, and is thereby directly part of the report outline. An alternative opinion is that the safety case is the output, rather than the input to the analysis and is thus presented in the conclusions of the safety assessment report.

Compilation of answers

There is some similarity among the answers on what is meant by "the Safety Case". GSF takes the view that the Safety Case is the entire description in the report, but also remarks that there is no German word for "Safety Case". According to H3 the safety case is the written statement with the reliable "evidences" to show long term safety. The safety case is elaborated to build confidence. According to Kristallin-I the safety case includes a scenario analysis leading to a comprehensive set of consequence calculations spanning identified uncertainties, as well as measures aimed at building confidence in methods, tools and data and the report was structured to address these components. To SKB-91 it is the final summary of why the repository system is regarded as acceptable. Such a safety case would be the "executive summary" of the safety report in the final acceptance license for the repository. The SITE-94 answer is that the analysis results must, of course, be argued in a discussion of the confidence of the employed methods. It is also necessary to follow a logic outline in the report and, thereby address all issues which have been identified by international consensus. For TVO-92 the safety case involves the broad line of argumentation and the way you argue the conclusions and recommendations at the end of the report. DCCA does not use the word safety case, but the goal is to build as much confidence in the calculations and system as possible.

10.2 "Reasoned arguments" for long times?

Specific regulatory requirements on reasoned arguments for times longer than 10 000 years only apply to the Canadian situation. All assessments use reasoned arguments for evaluation of the implications of calculations made over different time frames.

Compilation of answers

H3 uses reasoned arguments for phenomena related to long term changes of the geological environment. In Kristallin-I as time progresses results should increasingly be viewed as illustrations, indeed shading is incorporated into figures showing dose against time results to indicate the increasingly indicative nature of the models and results at long times. The SKB-91 answer is that this complex problem has not been addressed and that there is not always room for realistic quantitative analysis. For SITE-94 the present SKI staff position is that calculations up to one million years are meaningful, but new regulations, which will discuss this matter, are expected in the near future. In DCCA examples of "reasoned arguments" are the

FEPs screening arguments, but the view is that both qualitative and quantitative analyses could be made when there is support for them. In TSPA-95 quantitative results are presented (and discussed) for 10 000 years up to 1 000 000 years as part of an effort to cover the range that may be reflected in new regulations. No arguments were made for or against long times, but correlations of different performance measures and times could be interpreted to suggest that regulating for shorter times may be an adequate approach.

11. Identification of key factors and their justification

The key factors that contribute to safety and the factors that are potentially detrimental to safety are to a large extent media specific. However, all assessments note that the biosphere is not a safety barrier. Biosphere analyses are needed in order to assess the implications of the assessed function of the repository, but also analyses of the biosphere (in common with other model domains) are necessary to identify key phenomena and pathways for which additional research and/or data gathering may be required to provide a more accurate representation. Few assessments conclude that the exact canister life time distribution is essential, and instead conservative assumption could by imposed. Also for the the long-life canister concepts (Sweden and Finland) the exact failure time is not important, but credit is usually taken from the possibility that not all canisters fail simultaneously.

11.1 Saturated hard rock studies

11.1.1 Key positive features

The key positive factors suggested from the hard rock assessments (AECL, H3, Kristallin-I, SKB-91, TVO-92 and SITE-94) are listed in Table 11-1. Despite differences in waste form (spent fuel or vitrified HLW) and canister (iron, titanium, copper or copper/steel) most answers are similar with the following possible exceptions.

- The long life container concepts take credit from the possibility that not all canisters fail simultaneously.
- If iron is present, credit is taken for its redox buffering properties.
- Only AECL assumes that the rock surrounding the repository is sufficiently sparsely fractured that this rock can be represented as an equivalent porous medium in contaminant transport calculations.

11.1.2 Possibly detrimental factors

The key potentially detrimental factors noted by saturated hard rock assessments are listed in Table 11-2. There is a fair amount of overlap between the listed issues. It may be noted that only SITE-94, TVO-92 and H3 raise any concern of EBS features (canister integrity and bentonite properties). All agree on a potential concern over future external events.

Table 11.1: Key positive factors suggested from the hard rock assessments (H3, Kristallin-I, SKB-91, TVO-92 and SITE-94)

Key Feature	**Motive and study**
Physical containment by steel overpack during high radioactivity and heat generation period	Short-lived nuclides decay (H3, but true for all)
Long-lived copper container	Non simultaneous release. Exact life time of minor importance. (SKB-91, TVO-92, SITE-94)
Pb filling of Cu-canister	1000 year delay due to Pb filling eliminates short-lived nuclides even in the event of canister failure (SKB-91)
Limited size of canister defect	Reduces leakage from canister (SKB-91)
Redox buffering capacity of iron in container	Ensures low solubility of many radionuclides (H3, Kristallin-I, TVO-92, Site-94)
Mechanical, hydrological and chemical buffering capacity of the massive bentonite	Hydrostatic stress, no advective water flux, favourable chemistry, colloid filter, medium-lived radionuclides decay out in the buffer. (All)
Radionuclide solubility limits	Apply near the waste and limit releases. (All)
Geological conditions affecting: physical stability, low water flux and favourable chemistry	Assure EBS performance. (All)
Host rock retardation properties	Matrix diffusion and sorption have the potential for significant retardation also of very long-lived nuclides. (All; but not necessarily a Key Feature)
Availability of large volumes of low permeability rock with major fault zone(s) sufficiently far from repository	(AECL)
Overall characteristics of host rock which are unlikely to attract geological exploration	Indicates ow likelyhood of inadvertent human intrusion (AECL, Kristallin-I, SITE-94)
Thick sedimentary overburden	Isolates, or buffers, the hydrogeological regime at depth from near-surface phenomena, e.g. climate effects (Kristallin-I).

Table 11.2: Key potentially detrimental factors noted by saturated hard rock assessments

Key potentially negative feature	**Means of handling**
Difficulty to prove long term stability of canisters due to manufacturing flaws, localized corrosion, etc.	Raised issue (SITE-94)
Initial hole in copper container leading to corrosion of the steel canister	Analysed and will not ruin safety (TVO-92)
Bentonite longevity (changes of physical properties are the main concern)	Detailed modelling and natural analogues supports long term stability (Kristallin-I)
Bentonite rheology	Assessed by ancillary calculations (H3, Kristallin-I) Extrusion limited by narrow fracture apertures (H3)
Gas generation and transport	Qualitative assessment (H3, TVO-92, Kristallin-I)
Complex small-scale structure of water conducting features and difficulty to characterize heterogeneous rock	Highly conservative assumptions (Kristallin-I). Uncertainty in efficiency of important retarding mechanisms (SITE-94). Possibility of extreme channeling in far-field (TVO-92, Kristallin-I)
Oxidizing conditions in near-field and far-field	Repository depth (TVO-92, SKB-91)
Colloid-facilitated transport in the geosphere	To be considered (H3). Problem only if combined with irreversible sorption on highly mobile colloids (Kristallin-I)
Geodynamic processes such as uplift/erosion, seismic activity, faulting, volcanisms and human intrusion	Could be avoided through appropriate siting. (H3).
Large post-glacial displacements	Partially analysed (TVO-92, SKB-91, SITE-94)
Unfavourable chemistry during glaciations	Partially analysed (SITE-94, TVO-92)
Shaft-seal failure or unsealed boreholes near waste	Assumed good QA in repository construction (AECL, H3)
Unintentional human intrusion	Avoided by depth, siting and preservation of information (SKB-91)

11.2 Rock salt studies

There is no answer from DCCA. For GSF-91 the suggested positive factors are listed in Table 11-3 and the potentially detrimental ones are listed in Table 11-4.

Table 11.3: Positive factors suggested in GSF-91

Key positive feature	Motive
Creeping of rock salt	Will close voids
Radionuclide solubility limits	Limits release also of important longer-lived nuclides
Sorption of short-lived nuclides in overburden	Nuclides will decay before they reach biosphere

Table 11.4: Potentially detrimental factors suggested in GSF-91

Key potentially detrimental factors	Means of handling
High groundwater flow rate.	
Failure of seals	Proper functions must be demonstrated
Large volumes of brine close to emplacement sites	Demands on site evaluation

11.3 Yucca Mountain

The IPA-2 answers do not distinguish between positive and negative factors. TSPA-95 addresses two groups of issues. The first is an exploration of the potential (sensitivity) for consequence increase in non-conservative assumptions. Table 11-5 lists the factors thought to be potentially significant by the two studies. There are some differences between IPA-2 and TSPA-95 issues, which concern Np-237, and may be because TSPA-95 is more dose oriented than IPA-2. IPA-2 also evaluates external FEPs. Both studies agree on the importance of the percolation fluxes.

TSPA-95 notes that the groundwater travel time is not too important as the key concern is Np-237. TSPA-95 also notes that the relative importance of an issue may depend on time frame, but usually not the absolute importance.TSPA-95 also evaluates the potential for reduction in conservative estimates and concludes that virtually every element of the total system is a candidate for discussion. Specific examples concern percolation fluxes, canister life time, dilution and mixing, and Np solubility.

Table 11.5: Potentially significant factors suggested by IPA-2 and TSPA-95

Potentially significant factors	**Motive and study**
The unsaturated zone percolation flux	Strongly affects predicted releases. (IPA-2, TSPA-95)
The dissolution rate of the spent fuel	IPA-2, TSPA-95 especially important for shorter times
Different pathways in the fractured unsaturated matrix	IPA-2, TSPA-95 (matrix vs fracture flow)
The repository heat load	IPA-2, TSPA-95 (sensitivity studies)
Uncertainty in present model for magmatism	IPA-2
Near-field hydrothermal processes	Affecting canister life time (IPA-2, TSPA-95)
Fracture geochemistry	IPA-2
Abstraction from multi-dimensional non-isothermal two-phase models	IPA-2, TSPA-95 for drift scale to define waste package environment
The dose conversion factor	TSPA-95, sensitivity to selection for peak dose
Solubility of Np-237 at present percolation flux - for other fluxes other nuclides may dominate	TSPA-95
Saturated zone mixing and flux	TSPA-95, sensitivity of peak dose
Colloidal transport of the radionuclides	Has not been considered, (TSPA-95)

12. Conclusions

Several observations can be made that may form a starting point for further discussions.

12.1 What should be included in a safety case and in the report

Judging both from the answers to the direct question on what constitutes a safety case and the outlines of the different reports, it appears that consensus may be reached on what needs to be presented in order to make a safety case. In general, the safety case includes the line of arguments and a demonstration that all potential detrimental issues have been dealt with. It is also clear that assessment of confidence level, completeness and traceability is part of the safety case. Inspecting the outlines of the different reports, there may still be room for discussion if certain topics belong to a safety case and it may also be worthwhile to discuss the level of detail that is appropriate in a main safety assessment report.

Some specific points to consider are:

- The specific content of a PA/SA report depends on many factors. Nevertheless, examination of the lists of contents and the “walk-throughs” of the reports submitted to IPAG suggests that there are a number of elements in common. It appears worthwhile to further develop a list of recommened elements in a safety assessment report, while making understood that these elements indicate topics that should be discussed rather than chapter headings.

- It would be worthwhile to bring some order to the use of the words Performance Assessment and Safety Assessment, as discussed in the compilation.

- No study views the biosphere to be a safety barrier. In several assessments, biosphere modelling is viewed as a procedure for the conversion of releases to a common scale accepted as an appropriate measure of radiological hazard. It would be worthwhile to reflect upon whether conclusions (not only numerical results) of PA/SA are sensitive to definitions of critical groups or other details of the biosphere modelling.

- Some studies do not have the primary objective of showing safety, but could be early feasibility studies, preliminary explorations of different designs or mainly be methodology development. While these studies are performed under the framework of a safety assessment it would be useful if this limited scope was made explicit - it can certainly explain many differences in ambition levels (such as waste forms covered, scenarios analysed, depth of analyses etc.).

- It is always necessary to limit the scope of an assessment, but there is no agreed way of describing how the scope was limited or how to motivate it. How should this limiting of scope be described: by reference to regulatory requirements, in terms of “near-field”, “far-field”, ”biosphere”; by defining a system boundary; by the geometrical extent of boundaries in computer models; by FEP screening rules, or not at all? Is it necessary to account for biases resulting from omitting certain parts from the analysis?

- Exploration of conditions when system fails and exploration of points of weakness within a safety case. However, there is always danger of misunderstanding in presenting non-physical “what if” cases.

- All studies utilise results of site specific observatons in the assessment calculations in order to evaluate the safety of the potential repository site, but the process of abstraction/conversion of site measurements (injection tests, tracer tests, etc.) into parameters for PA/SA is not always included. Should it be?

- To what extent should simplifications be made and documented? For what purpose? Evidently simplifications are needed to adapt to resources and to overcome uncertainties in incomplete description of features, incomplete understanding of processes, and inadequacy of currently available information. However, it has also been suggested that simplifications are a means to reach acceptance by the public, while technologists, and particularly scientists, may oppose simplification on grounds of scientific accuracy possibly combined with a wish to make a living by “keeping the problem alive”. Are these valid observations?

12.2 Need for more R&D on barrier performance

In general, it would be worthwhile to inspect and complement the various tables (Chapter 11) that list key positive and key potentially-detrimental issues, when discussing the need for further R&D on barrier performance.

There are many areas were there is a widespread consensus that there is not much need for more development, but there are also more problematic areas that warrant further efforts. The following examples try to illustrate the situation:

- All PA studies with reducing groundwater chemistry apply 1. conservative estimates of solubility limits (based on thermodynamic equilibrium data) for estimating near-field release, and 2. linear sorption models (conservatively selected K_d-values) for radionuclide migration. No study raised strong concern over these models, which indicates that, in spite of the great uncertainties in the model assumptions, defendable conservative assumptions can be still made that result in an acceptable safety case.

- Currently, most studies are pessimistic regarding the possibility to show significant retention in the geosphere. Uncertainties are noted in groundwater flow, porous structure (“flow-wetted surface”) and matrix-diffusion properties. The latter are particularly important in crystalline rocks. There are varying degrees of optimism and recommendations concerning the possibility to actually reduce the noted uncertainties. Some suggest that it is not meaningful with site specific efforts to characterize these small scale phenomena, but that it still would be useful to increase general knowledge from rock laboratories and related efforts, others suggest that additional site-specific data would reduce these uncertainties.

12.3 Scenarios and formal procedures for handling FEPs

There seems to be some convergence towards coupling scenario uncertainty with uncertainty in FEPs and interactions between FEPs, although there are differences with respect to whether a scenario is the evolution of the modelled system, a set of conditions outside the system that leads to evolution of the system, or a set of conditions both inside and outside the system that leads to evolution. It could be worthwhile to strive for a common definition of the word scenario.

The coupling between scenarios and FEPs has made many organisations develop formal procedures for handling FEPs and interactions between FEPs. Based on the answers to the questionnaire it is difficult to tell whether this formal approach produced really different calculational cases than would have resulted otherwise. The different screening procedures identify which FEPs need to be considered. In the actual assessments, however, the representation of FEPs is usually confined to modelling tools, and knowledge of data that have been assembled from previous (less formal) assessments. Nevertheless there may be advantages with the formal procedures as (i) they represent a means to strive for completeness, (ii) they are a means for handling the long suite of issues that would not need consideration in the quantitative analysis, and (iii) they provide a means for open documentation of assumptions and future development needs (if any).

12.4 Propagation of uncertainty: deterministic and probabilistic approaches

There are essentially two broad methods employed for quantitative handling of uncertainties in the assessments: deterministic and probabilistic approaches. It should be recognized that both methods rely on the possibility to quantify aspects of uncertainties but that there are different attitudes within the different methods regarding the possibility to parameterize conceptual model uncertainty. The main difference between deterministic and probabilistic methods is that the latter explicitly tries to quantify probabilities and to combine these into risk estimates, whereas deterministic methods do not take this quantitative step. It should be worthwhile to further discuss differences and commonalities between these approaches as well as arguments for using one or the other method. Specifically the following may be noted:

- To varying degrees, deterministic approaches rely on the possibility to make bounding analyses. Usually, the deterministic approaches evaluate a number of variants (i.e. different input parameter combinations) either to support the conservatism of the “reference assumptions” or to illustrate the impact of conditions deviating from the reference conditions. Such variants are sometimes traced back to scenario and conceptual model uncertainty but, in some assessments they are more presented as “what if” assumptions. Some assessments, may implicitly assume that the variants represent less plausible situations, while in others there are no a-priori assumptions about the likelihood of any variant but an effort is made, in qualitative terms, to show that the likelihood of detrimental cases is low.

- Probabilistic assessments build on deterministic analyses of single effects and conditions, and are, in this respect, no different from the deterministic analyses. The difference is, rather, that probability estimates are made for each condition, which allows for sampling of the consequences of the different variants into total or conditioned risk estimates. Usually this sampling implies that many more calculation cases are generated, in order to produce statistically valid results. It is also necessary to pay attention to the correlation between different cases. Usually this is treated by generating (presumed) statistically independent cases or by sampling a more basic parameters. However, there are also examples of extensive efforts in actually quantifying correlation matrices between the great number of basic parameters and events in the system.

- Both methods share the problem of how to quantify scenario and conceptual model uncertainty. In many cases, aspects of these uncerta inties can be represented with the standard chain of “consequence models”, but there are scenarios and conceptual models that would require new models and model couplings, which could not be represented by a distribution of parameters in the “standard model chain”. Even if conceptual model uncertainty may be described as a parameter range, some answers point out that it is still essential to distinguish between uncertainties of different origin. First, this would assist in making a structured presentation of uncertainties, and second a parameter range representing a specific conceptual model uncertainty may only be valid under certain conditions and other ranges would be needed if these conditions were to change.

- Generally the studies applying deterministic approaches favoured them over the probabilistic approaches. The reasons given in support of this preference are that (a) they are judged to be easier to understand and verify, (b) the difficulty in assigning probability density functions, (c) the risk to sample unrealistic combinations, and (d) the fact that the largest uncertainty may lie in the selection and representation of processes (which it may not be appropriate to represent as probability density functions, as discussed above).

- The principal advantage of PSA is that it provides an overall risk estimate for the whole system and represents, explicitly, at least some types of uncertainty. Risk estimates are required by regulation in some countries. The problems of estimating probabilities, and correlations, appears to be a major difficulty with PSA techniques. However, it should be recognised that, in a qualitative sense, this problem is shared also by the deterministic analyses which often employ words such as “far-fetched”, “unlikely”, “pessimistic” etc. Thus, the main difference of the deterministic approach to the PSA one seems to be the reluctance of the former to quantify probabilities and combine different cases or events into a joint risk estimate.

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APPENDIX II

QUESTIONNAIRES

Contents

IPAG QUESTIONNAIRE

1. Title, reason, objectives of the study

1.1 The Title of the assessment.
1.2 The reason for the study (e.g., required by law, to summarise previous research, etc.) as distinct from its objectives.
1.3 The objectives of the study.
1.4 The intended audience.
1.5 The original language.
1.6 References to your PA study (when was it issued, by whom, for whom, when was the work done, etc.).

2. Regulatory framework

2.1 Specify if the study took into account specific regulatory requirements.
2.2 Specify the applicable regulatory requirements.

3. Lists of contents

3.1 Discuss the list of contents.
3.2 Specify/discuss how much material was put in each section and at what cost (person/year).
3.3 Specify/discuss: does the report build on a system of sub-reports? does it work?
3.4 Specify/discuss: outline for each item success/in success and level of difficulty which was encountered.
3.5 Provide a walk-through of the report structure in relation to the reason for the study, its objectives, intended use, audience, and the regulatory requirements (if applicable).

4. Terminology

4.1 Specify: if and how the following words are defined in the assessment; “performance assessment”, “safety assessment”, “integrated safety assessment”, “total system performance assessment” and “scenario”.

5. Disposal concept

5.1 Specify: type and amount of waste, activity inventory and its distribution in the waste forms, canister design, repository design, host rock, site (actual or assumptions), local biosphere and other relevant data of the disposal concept.
5.2 Why was a specific design chosen.

5.3 Was engineering feasibility, as applied to all barriers, taken into account.
5.4 Type of field data used (generic, from boreholes, from tunnels...).
5.5 Address: To which extent site evaluation was considered part of the assessment.
5.6 New/future source terms, such as high burn-up or MOX fuels: were they considered.

6. Assessment/System boundaries

6.1 Was there more attention to the phenomena in some barriers than in others and, if the answer is positive, was it considered if there was a risk of "biasing" this way the results from the assessment?
6.2 Is there an explicit discussion on where to place the primary system boundaries or was the system defined each time implicitly by the different models used in the assessment?
6.3 If applicable: What/where are the system boundaries and what has influenced your choice of system boundary (legal requirements, defensibility of assessment, resources...)?

7. Treatment/Addressing of some specific features/issues

Site features:

7.1 Spatial heterogeneity: was it acknowledged and treated? How?
7.2 The normal geodynamics of the site: was it taken into account? How?
7.3 Migration pathways: were any excluded and why?
7.4 Excavation damaged zone: was it accounted for?

Chemistry features:

7.5 Radionuclide partitioning (dissolution, precipitation, sorption etc.) in the various barriers: How was it modeled? Why?
7.6 Chemically toxic elements other than radionuclides: were they included in the analyses? Why not?
7.7 Effects from extraneous chemicals, e.g., concretes and shotcretes, and from non-HLW: were they taken into account? Why not?

Conceptual features:

7.8 Which idealizations of the geosphere and EBS were implemented and which one disregarded?
7.9 Did you analyze consequences from not observed (and, therefore, conceptual) negative potential features? Which ones and why?
7.10 Does your study mention any conceptual which was initially considered and then discounted? If yes, which were they and which arguments were used?

Some important issues:

7.10 bis Criticality: Does your study mention/address it?
7.11 The resaturation period: How did you treat it? Why?
7.12 Human intrusion: How did you treat it? Why?
7.13 The critical group: how was it defined? Why?
7.14 Expert judgment: to what extent is it acknowledged and used
7.15 Natural analogue data and analyses: were they used? How?
7.16 Common failure modes analysis: did you perform one and report it
7.17 Probabilistic vs deterministic approach to PA: did you select one over the other? what determined your choice?

8. Classification of uncertainty

8.1 Which types of uncertainties have you addressed? what is their definition or, alternatively, how did you separate between different types of uncertainty?

9. Propagation of uncertainty

9.1 How do you propagate uncertainties in your assessment? Do you treat different classes of uncertainty differently
9.2 If applicable, please also address if you have used a mixture of probabilistic techniques and deterministic analyses. If so for which analyses and why have you preferred one approach over the other?
9.3 If applicable, how did you transfer the information of a large number of FEPs into a set of consequence models and from there to a set of data for these models (see also question 13)
9.4 How do you address completeness problems?
9.5 Do you treat non-quantifiable uncertainties in a specific way?

10. Documentation of uncertainty

10.1 How have you documented your support for statements on uncertainty and validation?

11. The safety case

11.1 What is meant by "safety case"? Is it how the results of the analysis are argued, i.e. a demonstration of confidence in the results, or simply a step-by-step follow up methodology codified in, say, the NEA's 1992 booklet on safety assessments?
11.2 Is the safety case reflected in the report outline?

11.3 Will exploration of conditions when system fails and exploration of points of weakness contribute to the safety case? Is confidence level, completeness and traceability part of the safety case?

11.4 Is confidence level, completeness and traceability part of the safety case?

11.5 Do you recognize any unavoidable uncertainties in your assessment? Which are they and how do you handle them when making a safety case?

11.6 Some programmes require "reasoned arguments" as performance is evaluated further in time. Have you faced these requirements? In particular, are your arguments totally qualitative (starting from when)? Is there always room for quantitative analysis?

12. Identification of key positive/negative factors and their justification

12.1 Please list the key positive factors that contributed to safety and give a short elaboration (qualitative) on why.

12.2 Please list also the key potentially detrimental factors together with a short elaboration on how these factors could be taken care of.

13. Mass and activity flows in the "reference scenario"

13. Mass and activity flows in the "reference scenario": describe, in some detail and supplied with examples with numbers in them, how the quantitative calculations were put together.

IPAG EXTRA QUESTIONS

1. Can you suggest a "hit-list" of safety features?

2. Can one justify, and how, condensing uncertainty, in general, into parameter uncertainty?

3. In your assessment, when considering the combination of data availability and sensitivity analysis, which are the most critical uncertainties associated with predictions of radionuclide migration in the geosphere? Can these uncertainties be resolved by more site specific data?

4. How sensitive is your safety case to the assumptions on canister failure distribution?

5. In your safety case, how significant are the transients on the overall performance of the repository (e.g., resaturation, changing of flow direction, climate evolution, etc.)?

6. Biosphere: can it be used as safety barrier?

7. How was quality assurance applied to codes and to the whole analysis? Is this mentioned in your study?

8. Is the input from international projects used in integrated assessments? How?

9. Which assumptions were made to make calculations easy?

10. Were some analyses dictated by quirks of available computer codes? Which ones?

11. How did you assure consistency of data and assumptions across various analyses

12. Conservative assumptions: if they are used to simplify PA models, are they identified and justified? Is the magnitude of their effect quantified?

13. Role of PA in cost/benefit optimisation: Have you used, or can you cite, practical examples where PA has been used to select design options, optimise repository lay-out, or derive site/design constraints?

14. Why are we trying to simplify calculations? Is this likely to satisfy the technologists and the public?

APPENDIX III

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