A Joint Report by the OECD Nuclear Energy Agency
and the International Atomic Energy Agency

An International Peer Review of the Yucca Mountain Project TSPA-SR

Total System Performance Assessment for the Site Recommendation (TSPA-SR)

INTERNATIONAL ATOMIC ENERGY AGENCY

NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

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- to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has a Co-operation Agreement, as well as with other international organisations in the nuclear field.

INTERNATIONAL ATOMIC ENERGY AGENCY

The International Atomic Energy Agency (IAEA) was established in 1957. Its statutory objective is to seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world. One of the IAEA’s functions is “to establish or adopt, in consultation and, where appropriate, in collaboration with the competent organs of the United Nations and with the specialized agencies concerned, standards of safety for protection of health and minimization of danger to life and property (including such standards for labour conditions), and to provide for the application of these standards to its own operations as well as to the operations making use of materials, services, equipment, facilities, and information made available by the Agency or at its request or under its control or supervision; and to provide for the application of these standards, at the request of the parties, to operations under any bilateral or multilateral arrangement, or at the request of a State, to any of the State’s activities in the field of atomic energy.” Moreover, with respect to any IAEA project, or other arrangement where the IAEA is requested by the parties concerned to apply safeguards, the IAEA has the right and responsibility, to the extent relevant to the project or arrangement, “to require the observance of any health and safety measure prescribed by the Agency” and “to send into the territory of the recipient State or States inspectors … to determine whether there is compliance with [such] health and safety measures”. The Standards are intended inter alia to facilitate the discharging of these functions, rights and responsibilities of the IAEA.

Foreword

Peer reviews are part of the services that the Nuclear Energy Agency (NEA) of the Organisation for Economic Co-operation and Development and the International Atomic Energy Agency (IAEA) of the United Nations provide to their Member countries. The NEA provides peer reviews as part of its mandate to help improve and harmonise the technical basis for dealing with nuclear waste issues in its Member countries. The IAEA provides peer reviews within its statutory functions to perform services useful in research on, and development or practical application of, atomic energy for peaceful purposes, and to establish international standards of safety and provide for their application.

The Department of Energy of the United States of America (USDOE) has been studying the Yucca Mountain site in Nevada for more than 15 years to determine whether it is a suitable place to construct the first underground repository for US spent nuclear fuel and high-level radioactive waste of commercial and military origins. In addition to site characterisation work and development of the system concept, a number of performance assessments have been carried out over the past decade, the latest of which is the Total System Performance Assessment supporting the site recommendation process (TSPA-SR) of December 2000. This report presents the results of the jointly organised NEA-IAEA international peer review of the TSPA-SR.

The review was requested by the USDOE and was carried out and documented over the period from June to December 2001. The Joint NEA-IAEA Secretariat negotiated and agreed terms of reference for the review with the USDOE and assembled an independent team of ten international specialists, including two members of the Joint Secretariat. The team members represented several scientific and technical disciplines relevant to assessing the performance of underground radioactive waste repositories.

The primary intended readership of this report is USDOE high-level management and relevant technical staff. However, it is hoped that this review will also be of value to the regulators, various ongoing review groups and other stakeholders including the public.

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Summary

This Summary presents the key results of the international peer review of the US Department of Energy (USDOE) Total System Performance Assessment supporting the site recommendation process (TSPA-SR) issued in December 2000 for the Yucca Mountain site. The review was carried out at the request of the USDOE Yucca Mountain Project (YMP) and was jointly organised by the Nuclear Energy Agency (NEA) of the Organisation for Economic Co-operation and Development (OECD), and the International Atomic Energy Agency (IAEA) of the United Nations. The primary intended audience for this review is USDOE higher level management and relevant technical staff. However, it is hoped that this review will also be of value to the regulators, various ongoing review groups and other stakeholders including the public.

This review is the outcome of the work of an international review team of ten members, over a period of about four months. The main focus of the review is the TSPA-SR document, with partial review of some supporting documents. Given the limited time available, the IRT was primarily concerned with the higher level features of the methodology rather than with details of individual sub-models that are subject to change and that are undergoing detailed peer reviews by specialists in the relevant areas. It is therefore an expression of findings based on a brief review and cannot be considered as an in-depth analysis of all of USDOE's work on Yucca Mountain over the last ten years.

1. Objectives

The primary objective given to the International Review Team (IRT) was to review and critically analyse the performance assessment methodology and rationale used by the USDOE in support of the current site-recommendation decision process in order to:

- Identify consistencies and inconsistencies between methods that were implemented by the USDOE and those being considered or developed in international recommendations, standards and practices.
- Provide a statement regarding the adequacy of the overall performance assessment approach for supporting the site recommendation decision.

- Provide detailed recommendations for specific technical and other improvements that would help performance assessment better support the next programmatic decision point, if the site is recommended and subsequently approved, which entails the preparation and submission of a license application.

Those three aspects are considered below.

2. International perspective

2.1 Yucca Mountain setting

The conditions prevailing at Yucca Mountain are significantly different to those considered in other national repository programmes in that Yucca Mountain is in a closed basin and the repository is in an oxidising environment above the water table. The IRT has taken due account of these differences in conducting the review.

2.2 Rationale

The rationale chosen by the YMP in support of the site-recommendation process was as follows. A total system performance assessment was carried out to determine whether it is likely that the selected repository concept at the Yucca Mountain site will be able to meet the quantitative licensing requirements of the USEPA standard and the USNRC proposed rule. The dose rate requirement for the 10 000-year period was met by designing the engineered barriers (with redundant features) so that, based on available corrosion data, there would be no release from the waste package under normal conditions.

This rationale is capable of addressing many important issues. However, at present, the extensive knowledge accumulated in many years of characterisation and analysis of the site is not utilised to its fullest extent. The IRT is also of the opinion that it would have been desirable to have placed greater emphasis in the TSPA-SR on the performance of the geological barriers in their own right. Moreover, a broader safety case should have been developed to support the site recommendation decision.

2.3 Methodology

The overall structure of the TSPA-SR methodology, and the USDOE approach of building on an iterative series of performance assessments, conform to international best practice. Moreover, the structured abstraction process linking process-level models to assessment models is at the forefront of international developments.

One of the first steps in a safety/performance assessment is identification of the potentially relevant features, events and processes (FEP). The IRT has found the FEP methodology used in the TSPA-SR to be in agreement with international best practice, and recognises the contributions to the international development that has come from work within the YMP.

The YMP places far greater emphasis on probabilistic assessment than equivalent programmes in other countries. Some known issues, and particularly "risk dilution", considered in the international fora such as the Probabilistic System Assessment Group of the NEA, have not been fully addressed in the TSPA-SR.

The YMP TSPA does not emphasise natural analogues as much as in some other international studies.

2.4 Regulation

The regulatory requirements set down and proposed[1] for the YMP are somewhat more prescriptive than in many other countries, both in specifying compliance requirements and in directing how these must be met. Particularly relevant in this regard is the specification of a period of 10 000 years for which the applicant must provide reasonable assurance (USNRC proposed regulation) or reasonable expectation (USEPA) that a radiation dose limit will not be exceeded. Other examples are: (i) the detailed specification of a stylised human intrusion scenario; (ii) the precise specification of the distance to the receptor area; (iii) specification of the representative volume of groundwater to be used in human uptake and dose rate calculations; and (iv) the requirement that events with probability of occurring as low as 10^{-8} per year should be modelled and assessed numerically.

The way the regulations are formulated has contributed to the tendency of the TSPA-SR to focus more on demonstrating numerical compliance with quantitative criteria than on demonstrating an understanding of repository performance. Also, the US approach to regulation has focused attention on the presentation of aggregated results that can be compared directly with regulatory requirements. The IRT considers that more intermediate results and disaggregated end results should be given. This would provide more information to decision-makers, a point emphasised in recent international recommendations on the safety of radioactive waste disposal.

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1. Since the work of this review, both the NRC and DOE have finalised their regulations. The IRT considers that its conclusions and recommendations are not called into question by the changes made. See Appendix 4.

2.5 Statement by the International Review Team

In response to the request by the USDOE to provide a statement regarding the adequacy of the overall performance assessment approach for supporting the site recommendation decision, the IRT considers that:

While presenting room for improvement, the TSPA-SR methodology is soundly based and has been implemented in a competent manner. Moreover, the modelling incorporates many conservatisms, including the extent to which water is able to contact the waste packages, the performance of engineered barriers and retardation provided by the geosphere.

Overall, the IRT considers that the implemented performance assessment approach provides an adequate basis for supporting a statement on likely compliance within the regulatory period of 10 000 years and, accordingly, for the site recommendation decision.

On the basis of a growing international consensus, the IRT stresses that understanding of the repository system and its performance and how it provides for safety should be emphasised more in future iterations, both during and beyond the regulatory period. Also, further work is required to increase confidence in the robustness of the TSPA.

3. Recommendations for future assessments

To provide better support to the next programmatic decision point, namely the preparation and submission of a license application, the IRT recommends that a number of improvements should be made in the USDOE approach to assess the performance of the repository system. Detailed recommendations on specific technical issues and subsystem analysis are provided in the main report. The most important recommendations in regard to overall system performance, subsystem performance and other issues are summarised below.

3.1 Overall system methodology

Features Events and Processes (FEP) – The IRT has carried out some spot checks of the FEP identification and screening process. This has identified two additional potentially important FEPs. This points to some shortcomings in the routines and procedures for the FEP identification and screening processes and in the QA of assessment input, which should be revisited and revised as necessary. While the regulatory compliance period is 10 000 years, the YMP team are to be commended for extrapolating some of the TSPA-SR simulations out to longer times in order to estimate the time and magnitude of the maximum expected dose. However, FEPs have been screened out on the basis of demonstrating compliance up to 10 000 years and so the assessment is less reliable at longer times. Thus the IRT recommends that in future the screening of FEPs should be made in two stages. The first stage should retain all FEPs required for a full understanding of repository performance, while the second stage should include regulatory compliance considerations in the screening criteria.

Uncertainty – A comprehensive and systematic methodology for identifying and treating all types of uncertainty should be formulated and implemented. This should include the classification of uncertainties as to whether they are due to intrinsic variability or to lack of knowledge, since the latter can lead to non-conservative results when incorporated into a probabilistic framework. This is termed "risk dilution" and is discussed further in the main report. It is recommended that a study should be carried out of the quantitative importance of risk dilution for the expectation value of dose. The reduction of uncertainty should be a major goal of the YMP, focusing attention on obtaining good laboratory and field data in those areas where uncertainty has the greatest effect.

Probabilistic methodology – Given the regulatory requirements in the USA, it is appropriate to make use of a probabilistic systems analysis framework for the potential repository at Yucca Mountain. However, the IRT is of the opinion that some particular aspects of the methodology require further consideration. The key concern of the IRT is the potential problem of risk dilution. This arises because the parameter distributions used in the TSPA-SR represent the combined effects of stochastic variability and subjective probability due to incomplete understanding of the system. Under some situations the inclusion of subjective uncertainty can lead to non-conservative estimates of the expectation value of dose (so-called risk dilution or uncertainty dilution). When this occurs it means that increased ignorance leads to lower expected doses, which does not appear to be a sensible basis for decision-making, and requires further scrutiny. The IRT is of the opinion that the TPSA-SR presents conditions where risk dilution may have occurred, but that this issue has neither been addressed nor analysed. Consequently, the IRT recommends that an assessment should be carried out of the quantitative importance that risk dilution might have on the magnitude of the performance measure. Also, the limitations and strengths of the probabilistic method need to be addressed as pre-conditions for a defensible analysis.

Sensitivity analysis – The IRT was favourably impressed by the methods and quality of the sensitivity analysis used in the TSPA-SR and supporting documents. The IRT recommends that sensitivity analysis be developed further into a tool to build an integrated and comprehensive understanding of the relative importance and role of different barriers and processes.

Safety Case – A Safety Case should be developed as a higher level document, and include the articulation of a strategy to achieve safety as distinct from the strategy for demonstrating compliance, with an emphasis on obtaining and communicating understanding and facilitating dialogue with the relevant stakeholders. A Safety Case is the integration of relevant arguments in support of the long-term safety of the repository. In particular, a statement of confidence should be included, to elucidate the means that were adopted to achieve sufficient confidence, and to acknowledge the remaining issues, together with a suggested strategy for resolving those issues. This should build upon the current Repository Safety Strategy document.

System understanding – Within the TSPA-SR report most attention is given to demonstrating quantitative compliance with regulatory criteria. Relatively little emphasis is placed on the important issue of presenting an understanding of system behaviour, which is required to enable decisions to be made based on the full body of evidence. The IRT considers that demonstrating understanding should be complementary to demonstrating compliance and of at least equal importance. Two approaches are needed.

The first is to present what is considered to be a realistic (i.e., non-conservative) analysis of the likely performance of the repository using realistic model assumptions and data. This could usefully draw on evidence from natural and archaeological/historical analogues and should aim to communicate the likely evolution of the repository and its surroundings to a range of stakeholders and give an indication of the safety margins inherent in the analysis.

The second approach is an analysis for compliance purposes where conservative assumptions and parameter values are used to make the case more defensible. Specific assumptions and models are needed for this and should be identified separately from the less conservative analysis. Finally, in order to communicate understanding, the USDOE should take steps to improve its corporate memory and make more use of the extensive archive of technical and non-technical reports produced during earlier phases of the programme.

3.2 Subsystem methodology

Repository design – There have been major changes in repository design between TSPA iterations (e.g., since the TSPA-VA) but no clear rationale for these changes was discernible from the TSPA-SR report. In a future safety case it would be helpful to include a section in the main body of the report describing the evolution of the disposal concept. In addition to indicating how design changes have responded to safety concerns, this would provide continuity and would enhance confidence by demonstrating that the project is maturing and developing in a logical and systematic manner.

Engineered barrier materials – The selection of materials for the waste package outer barrier (alloy-22) and drip shield (titanium Grade 7) are in line with international best practice, having regard to the specific chemical environment at Yucca Mountain. However, in order to build further confidence in the performance of these materials over thousands of years in the anticipated Yucca Mountain repository environment, it is recommended that long-term corrosion tests using multiple specimens are carried out. These should investigate the effects of gamma radiation field, salt deposits, microbes and ageing. A key challenge is to improve confidence in the extrapolation of corrosion measurements to long times. In order to accomplish this, it is recommended that efforts be made to help improve the scientific understanding of the kinetics of pitting and crevice corrosion, and of stress corrosion cracking.

Waste form – The procedure used for screening the radionuclide inventory may have resulted in some potentially important radionuclides (e.g., ^{36}Cl, ^{135}Cs) being omitted from detailed analysis and thus the IRT recommends that this procedure should be reviewed and amended as appropriate. In the TSPA-SR, the fuel cladding remains a significant barrier up to 100 000 years and beyond. The IRT was impressed with the depth of thought given to this issue but found one process (effects of the corrosion of basket components) that was not taken into account and which might compromise the performance of the cladding. Thus further efforts are recommended to strengthen confidence in this area.

Some of the solubility limits for elements (especially Np, Th and Ra) given in the TSPA-SR are simplifications made in the absence of reliable data. It is recommended that more experimental data be obtained to validate thermodynamic modelling, especially with regard to the complex interactions between the degrading waste form and components of the waste package.

Transport within the engineered barrier system – The proposed mechanism of radionuclide diffusion through stress-corrosion cracks, which is assumed to be dominant for many millennia after the waste package is breached, appears to be overly conservative and complex, and possibly not credible. The model requires a continuous film of water to allow diffusion that extends all the way from the waste form to the cracks in the degrading waste package and to the bottom of the invert. In applying the model, the TSPA-SR assumes very conservatively that the process of diffusion occurs even when there is no dripping in the location and the drip shield is intact. The engineered barrier transport model should be independently reviewed. Moreover, questions remain about the likely extent of drift collapse and its effect on engineered barrier performance.

A key issue concerning the near-field repository environment is whether liquid water is likely to exist in and around waste packages, as assumed in the TSPA-SR. Very little water should be able to reach the drifts because of the repository design, causing diversion around the emplacement drifts, or by Nature due to limited precipitation, infiltration and seepage. At the same time, the evaporation potential of water due to heat output from the waste packages is substantial: much more than 1 000 litres per year per package before 10 000 years has been postulated. Thus except in areas where seepage is extraordinarily high, waste packages may remain dry due to evaporation. Design modifications, such as capillary barrier backfill, could be considered in areas of high seepage.

Unsaturated zone – Confidence in the modelling of flow and radionuclide transport in the unsaturated zone should be increased through further experimentation, and the influence of temperature on capillary suction should be accounted for. The TSPA-SR determined that some of the dose comes from colloidal transport of Pu, Th and possibly other actinides, in both the unsaturated and saturated zones. However, this assumption is possibly over-conservative and should be reviewed.

Moreover, natural dripping of groundwater from fractures or pores in the matrix has never been clearly observed,[2] primarily as it is affected by drift ventilation, and yet it plays an important role in the analysis. This begs the question as to whether the assumptions about dripping are too conservative. In view of its critical role in the assessment, the IRT recommends that the postulated dripping process should be better understood and quantified.

Saturated zone – The IRT expresses concern about the level of knowledge available for assessing the role of the saturated zone (SZ) in the TSPA-SR, both at the regional scale and at the site scale. Further hydrogeological and hydrogeochemical data are required. Moreover, the treatment of this information to construct and calibrate a regional groundwater flow model is considered by the IRT not to be state-of-the-art. It is therefore recommended that a significant effort be made to improve the regional SZ flow model by collecting new data and improving the calibration. This effort should be closely integrated with the improvement of the site flow model, in order that these two models are made consistent with one another. Once improved flow models have been constructed, calibrated and validated, they should be run in a spatial variability analysis, not by using a large uncertainty factor.

Biosphere – The Yucca Mountain biosphere modelling programme has recently been the subject of a comprehensive international review and thus in general it has not been thoroughly scrutinised by the IRT. However, the IRT

2. Clarification made. See Appendix 4.

considers that a realistic understanding of the long-term fate of radionuclides in the Yucca Mountain basin should be developed.

Natural analogues: The IRT recommends that the USDOE should carry out further work at the Peña Blanca uranium deposit in northern Mexico as a natural analogue for Yucca Mountain and use its characteristics to increase the confidence of both the public and the scientific community in the system performance over very long times. Also, investigations of naturally-occurring uranium and its radioactive progeny in the tuffs at Yucca Mountain should be continued to improve understanding of their mobility within the flow systems of the mountain. Overall, natural analogues should receive more prominent attention as instruments for increased understanding and confidence building.

3.3 Disruptive events and human intrusion

Disruptive events – Volcanism at Yucca Mountain is a very low probability event. With regard to volcanism, more explosive rhyolitic eruptions can occur at the same time as basaltic eruptions (so-called "bimodal volcanism"). That was not discussed in the TSPA-SR. It is recommended that the probability of bimodal basaltic-rhyolitic volcanism should be estimated and, if relevant, the consequences should be analysed. The IRT considers that the TSPA-SR adequately addresses seismological influences and finds the analysis in line with other international studies.

Human intrusion – The stylised human intrusion scenario, as specified by the regulatory agencies, involves drilling of a borehole through the waste package and into the saturated zone. The IRT recommends that in future assessments direct surface water flow into the assumed borehole should be included so that water flows into the degraded waste package in every realisation of the computer model.

3.4 Documentation

The full set of documentation, including supporting reports, provides a comprehensive and impressive analysis of relevant issues, models and data. In areas where the IRT has examined supporting documents, they were found to exhibit adequate traceability. Moreover, the documentation has clearly been prepared in a systematic fashion with great care and attention to detail.

Nevertheless the TSPA-SR report has some shortcomings in terms of overall clarity and comprehensibility. This may be due to it being written for a number of different types of readers and is an area where improvement could be made. To address this problem in future, it would be appropriate to produce documents for different sets of stakeholders including a summary document where the whole YM concept, context and safety case is presented in a form suitable for a more general audience.

1. Introduction

This document presents the results of the international peer review of the US Department of Energy (USDOE) Total System Performance Assessment (TSPA) issued in December 2000 supporting the site recommendation process (TSPA-SR) for the Yucca Mountain site (*CRWMS, 2000a*). The review has been carried out at the request of the USDOE Yucca Mountain Project (YMP) and has been jointly organised by the Nuclear Energy Agency (NEA) of the Organisation for Economic Co-operation and Development (OECD) and the International Atomic Energy Agency (IAEA) of the United Nations.

The report is intended primarily for a USDOE readership of technical managers and senior management, but is likely to be useful to other individuals with similar backgrounds and interests and to the broader range of interested stakeholders including members of the public. The review comments are offered in a constructive spirit in order to help the USDOE assess its achievements and better steer its working programme in the development of a repository for spent nuclear fuel and high level waste.

1.1 Background to the Yucca Mountain Project

The USDOE has been studying the Yucca Mountain site in Nevada for more than 15 years to determine whether it is a suitable place to construct the first underground repository for US commercial and defence spent nuclear fuel and high-level waste.

In addition to a large amount of site characterisation work and development of the system concept, a number of performance assessments have been carried out over the past decade, the latest of which is the TSPA-SR (*CRWMS, 2000a*).

The relevant draft[3] regulatory requirements by the United States Nuclear Regulatory Commission (USNRC) and the standards of the United States Environmental Protection Agency (USEPA), which will apply for licensing if the

3. Since the work of this review, both the NRC and DOE have finalised their regulations. The IRT considers that its conclusions and recommendations are not called into question by the changes made. See Appendix 4.

site is recommended by the President and accepted by Congress, are summarised in the TSPA-SR report. For the purposes of this review, key requirements are the use of the probabilistic expectation value of individual dose as the primary quantitative performance measure, and the specification of a compliance timeframe of 10 000 years following disposal. The standard of proof is that of "reasonable assurance" (USNRC, proposed regulation) and of "reasonable expectation" (USEPA). In this context it is noted that the final decision to be made by the USNRC is based not only on the results of the performance measures but on the "full record" before the regulatory authority.

1.2 Terms of reference, objectives and scope of the review

This review has been conducted according to Terms of reference (Appendix 1) agreed between the USDOE, IAEA and NEA.

According to the Terms of reference, the objective of the review is to provide an independent assessment of the methodology developed by the USDOE-YMP as presented in the TSPA-SR report (*CRWMS, 2000a*). It is a technically oriented and consensus review conducted by an International Review Team (IRT).

The primary objective is to review and critically analyse the performance assessment methodology and rationale being used in support of the current site-recommendation decision process in order to:

- Identify consistencies and inconsistencies between methods being used by the USDOE and those being considered or developed in international recommendations, standards and practices.
- Provide a statement regarding the adequacy of the overall performance assessment approach for supporting the site-recommendation decision.
- Provide detailed recommendations for specific technical and other improvements that would help performance assessment better support the next programmatic decision point, if the site is recommended and subsequently approved, which entails the preparation and submission of a license application.

Based on the expertise and international experience of the team, these three aims are addressed throughout the report and the key issues are summarised in Section 5.

The primary report reviewed was the TSPA-SR document, with each section being reviewed by at least two members of the IRT. Where deemed appropriate to meet the aims of the review, ancillary reports were also reviewed. These included Revision 4 of the Repository Safety Strategy (RSS)

(*CRWMS, 2000b*) and certain Process Model Reports (PMR) and Analysis Model Reports (AMR).

The IRT has not reviewed in detail the recent Supplemental Science and Performance Analyses (*BSC, 2001*) because it was outside the scope of the Terms of reference and because of assurances from the USDOE that it follows the same basic methodology as the TSPA-SR. In this context, it should be noted that the IRT was primarily concerned with the higher level features of the methodology rather than with details of individual sub-models that are subject to change and that are undergoing detailed peer review by specialists in the relevant areas.

In keeping with the Terms of reference, in reviewing the relevant reports the IRT has given consideration to the:

- Technical basis for the performance assessment, including identification and justification of the conditions and characteristics modelled at the system level; this includes a review of the abstractions of the adopted design and the scientific basis for determining future environments in the system and its materials and natural systems behaviours.
- Development of the key conceptual models, including the assumptions made with respect to the representations of relevant features, events and processes (FEP).
- Adequacy of the treatment of the undisturbed and disturbed system performance.
- Adequacy of the methods used, and the cases considered, in sensitivity and uncertainty evaluations.
- Overall clarity and completeness of the technical report describing this system-level performance evaluation.

With this background, the IRT considered that it was empowered to comment on any matter discussed in the main TSPA-SR report, including the technical and scientific basis for the assessment, scenario development, and the development, abstraction and integration of mathematical models. In particular, the review team focused on the overall question:

- From an international perspective, does the TSPA methodology have the potential to support a credible long-term post-closure safety case?

The conditions prevailing at Yucca Mountain are significantly different to those considered in other repository programmes because the repository is above the water table, in an oxidising environment and in an effectively closed basin. The IRT has taken due account of these differences in conducting the review.

1.3 Conduct of the review

The review was conducted over the period June to October 2001 by ten members of an International Review Team (IRT). It is therefore an expression of findings based on a brief high-level review, and cannot be considered as an in-depth analysis of all of USDOE's work on Yucca Mountain over the last 10 years.

The IRT members have experience in aspects of system-level long-term performance assessment evaluations (Appendix 2). The team members were selected by the Joint NEA-IAEA Secretariat in accordance with a written criteria statement. The team members participated as individuals, rather than representing their organisations.

The review team met for the first time in Las Vegas on 21-23 June 2001 where they held a number of closed-door meetings where team members discussed the conduct and schedule of the review together with their first impressions of the TSPA-SR report. On 21 June, the review team visited the Yucca Mountain site including viewing the surface geology and characterisation experiments within the mountain. An Orientation Meeting was held on 22 June 2001, where USDOE staff and contractors made a series of presentations on the TSPA-SR, each of which was followed by a question and answer session. The Orientation Meeting was open to members of the public, three of whom were invited to make brief presentations at the end of the meeting.

Following the Orientation Meeting, the review team sent an initial list of questions to the USDOE based primarily on the presentations by USDOE staff and contractors. Two further sets of questions were prepared following scrutiny of the TSPA-SR report and some supporting reports. The USDOE responded in writing to each of these sets of questions.

A second set of meetings was held in Las Vegas from 26 August to 1 September 2001. Plenary meetings were held with USDOE staff and contractors in order to develop a deeper understanding of the issues raised in the written questions and answers. Observers from the general public, the State of Nevada, and the USNRC were present at all open meetings. Closed-door meetings of the review team were held to discuss substantive issues. At the close of the plenary meeting on 31 August, the IRT Chairman, Tönis Papp, made an oral presentation of preliminary observations by the IRT to USDOE staff and contractors at an open meeting.

Following the second Las Vegas meeting, the IRT members compiled and reviewed this final report, which was then submitted to USDOE in November 2001, for fact-checking only. Following that examination by USDOE, the IRT received comments, included in Appendix 4, which have been incorporated in this final version.

1.4 Organisation of the report

The organisation of the report is as follows. Section 2 presents some general considerations on the regulatory environment, the performance assessment rationale and approach, and documentation. The methodology and scientific basis for subsystems, corresponding primarily to Chapter 3 of the TSPA-SR report, are reviewed in Section 3. Section 4 reviews the integrated TSPA methodology corresponding primarily to Chapters 1 and 2 and parts of Chapter 5 of the TSPA-SR report. Finally, the most important conclusions and recommendations of this review are collected together in Section 5. Appendix 1 sets out the Terms of reference for the review and Appendix 2 presents brief CVs for members of the IRT. Appendix 3 contains detailed comments on the TSPA approach to the saturated zone hydrogeology of the Yucca Mountain area. Appendix 4 contains the comments received from USDOE after fact checking of the draft report, and the IRT responses.

2. General Considerations

2.1 Regulatory perspective

The regulatory requirements set down and proposed for the YMP are somewhat more prescriptive than in many other countries, both in specifying safety requirements and in directing how these must be met. Particularly relevant in this regard is the specification of a period of ten thousand years for which the applicant must provide reasonable assurance (USNRC proposed regulation) or reasonable expectation (USEPA) that a radiation dose limit will not be exceeded. Other examples are: (i) the detailed specification of a stylised human intrusion scenario; (ii) the precise specification of the distance to the receptor area; (iii) the specification of the representative volume of groundwater to be used in human uptake and dose rate calculations; and (iv) the requirement that events with probability of occurring as low as 10^{-8} per year should be modelled and assessed numerically. *The IRT acknowledges and accepts that these regulations are the product of extensive debate in the US and represent a considered view that provides a legal basis for accepting, challenging and implementing decisions.*

Furthermore it is recognised that the role of the USDOE is to provide impartial advice to elected officials, who are responsible for decision making. In this context the IRT has been impressed with the openness of YMP staff in explaining the points of view of project opponents and critics.

The regulations require that a risk-informed approach should be adopted in demonstrating compliance with the dose limit, in recognition of the uncertainties inherent in making assessments over long time frames in the future. It is also required that the assessment should reveal an understanding of the relationship between the performance of the repository subsystems and the total system performance. Nevertheless despite the prescriptive nature of the regulations, the IRT notes that the proposed licensing regulation 10 CFR 63 states that "*consistent with a performance based philosophy, the Commission proposes to permit DOE the flexibility to select the approach for demonstrating this relationship that is most appropriate to its analysis*".

In its review of the TSPA-SR, the IRT has observed a tendency for more focus to be given to the demonstration of numerical compliance with the proposed regulatory requirements than on developing and presenting an understanding of repository performance. Whilst it is completely understandable that the TSPA-SR should give due attention to demonstrating compliance with the prescribed dose limit, an in-depth understanding of the performance of the repository system is necessary to develop confidence in the overall design and safety of the repository and in the results of the assessment. In this regard, there is an emerging international consensus that building confidence in repository performance is of comparable importance to demonstrating compliance with criteria. *Thus it is recommended that in the future equal attention should be given to system understanding as to numerical compliance with regulatory criteria if the project proceeds to the licensing stage.*

In presenting the outcome of the performance assessment, probabilities and consequences are generally combined together emphasising compounded performance measures. Examples of such compound performance measures are the expectation value for an ensemble of calculations, and the combined results for the nominal-evolution scenario and the probability-weighted disruptive-event scenario. Whilst this is appropriate for demonstrating numerical compliance with regulatory requirements, it tends to obscure the interpretation of results. For example, it would have been helpful if the TSPA-SR had shown more intermediate results as a means of improving the understanding of system performance, for example the dose-time curves for realisations in which volcanic disruption takes place.

International recommendations recognise the validity of presenting assessment results in both an aggregated and a disaggregated manner. Disaggregated results provide an aid to understanding, for example by displaying probabilities and consequences separately and enhancing the understanding of the effectiveness of subsystems (*ICRP, 2000*). They therefore provide more information for making subsequent decisions on the acceptability of repositories. *Thus it is recommended that in future assessments more emphasis is placed on disaggregation of the results.*

Finally it is noted that the US regulations are currently the subject of legal challenges. Thus it would be prudent to ensure that any TSPA is robust to possible regulatory changes, such as the 10 000-year compliance period. As this review considers the TSPA-SR from an international perspective, it is hoped that it might contribute to an understanding of such regulatory robustness.

2.2 Performance assessment rationale

The Terms of reference require the IRT to review the *"rationale being used in support of the current site-recommendation decision process"*. The rationale chosen by the YMP was to carry out a TSPA and determine whether it is likely that the selected repository design at the Yucca Mountain site will be able to meet the quantitative licensing requirements of the USEPA standard and the USNRC proposed rule. With this rationale, the question of site suitability requires a preliminary evaluation of compliance over 10 000 years. The YMP chose to meet this by designing a waste package that, based on current corrosion data, would last 10 000 years without any release. While the IRT accepts this as one logical way to proceed, it has resulted in a bias towards performance of the engineered barrier system. It is not the only rationale that could have been used. The effect is to undervalue the considerable potential of the geological barriers.

For example, the YMP assessment could have focused more on the role of the site in assuring total repository safety. The robustness of the site suitability could have been illustrated by examining possible conditions that would make the site unsuitable and showing that they have low probability.

The TSPA is not an isolated exercise but involves an iterative process where engineering design is adjusted in order to demonstrate compliance with the regulatory requirements. In view of this the flexibility of the engineered barrier concept could have been demonstrated by showing how design adjustments could compensate for reasonable discrepancies between the real and assumed site characteristics.

Alternative rationales for site suitability evaluation could also have been based around the development of a "safety case" to support the decision at hand. Performance assessment is only one component of the safety case, other components being development of a strategy to achieve safety as distinct from the strategy for demonstrating compliance, with an emphasis on obtaining and communicating an understanding of the integrated system ant its performance and favouring dialogue with the relevant stakeholders. The demonstration of the existence of multiple barriers in the repository design and natural system is also a part of a safety case. In addition a safety case should include a statement of confidence in its findings at each stage that acknowledges the existence of any unresolved issues and provides guidance for work to resolve these issues in future development stages (*NEA 1999*).

The TSPA-SR has in itself some elements of a safety case, but the focus on demonstrating numerical compliance with regulations has taken the foremost priority vis-à-vis understanding and confidence building aspects.

The IRT is of the opinion that it would have been preferable to have incorporated the TSPA within a safety case in support of the site recommendation decision, and to have formulated this within well-developed strategies to achieve safety and to demonstrate compliance. It is recommended this approach be followed for the next decision point in the programme.

2.3 General approach to performance assessment

The objective of a TSPA is to provide an understanding of the overall system performance and to provide a safety-related basis for decision making, in this case for site suitability. Compared with the evolving international trends in performance assessment, the contents and focus of the TSPA-SR have been more directly influenced by the prescriptive nature of the proposed US regulations than is typically the case. This has caused tension between the objective to develop and demonstrate understanding and the objective to evaluate the likelihood of compliance with quantitative criteria.

The general approach used in the TSPA-SR is set out clearly in Chapters 1 and 2 of the TSPA-SR report together with a useful summary of the regulatory context. In essence the general approach consists of the following five major steps:

- Identifying and screening potentially relevant features, events and processes (FEP) to develop scenarios.
- Developing models.
- Estimating parameter ranges and uncertainties.
- Performing calculations.
- Interpreting results.

At this level of detail, the general approach to TSPA, and the USDOE approach of building on an iterative series of performance assessments, conform to international best practice (NEA, IAEA and CEC, 1991).

A sixth step is also mentioned in the TSPA-SR report, namely the development of a repository safety strategy and the principal factors. This step is discussed within a separate Repository Safety Strategy (RSS) document (*CRWMS, 2000b*) which is potentially the most important safety case report but whose status is somewhat unclear. This represents a move towards implementing the NEA Confidence Document (*NEA, 1999*), as discussed in Section 2.2 above.

As with any system approach, the first requirement is to define what is included in the system and is modelled explicitly, and what lies outside the system and influences its evolution through initial and boundary conditions. Given the regulatory requirement to perform a probabilistic assessment the TSPA-SR makes the choice of including virtually all relevant FEPs within the system model, and thereby only considering two scenario classes (nominal and disruptive) reflecting differing external conditions. This has necessitated the development of a complex system model incorporating hundreds of FEPs and their interactions. It is to the credit of the Yucca Mountain Project (YMP) that this has been carried out in a systematic, scientifically competent and professional manner.

In particular, a bottom-up approach has been adopted, linking process-level models to assessment models, which is at the forefront of international developments. In future assessments this might usefully be complemented by a top-down approach in which models are developed to be as simple as necessary from the outset. While most of the Process Model Reports (PMR) and Analysis Model Reports (AMR) have not been scrutinised in detail by the IRT, it is clear that they constitute an impressive body of work leading from fundamental science to the system-level models used in the TSPA-SR.

The IRT notes that a complementary more-deterministic approach could have been used, as has been done in a number of other countries, namely to base the assessment on a best-estimate model of system behaviour with major uncertainties addressed by examining scenarios derived from the effects of external FEPs.

While the IRT acknowledges that the broad sweep of the TSPA-SR performance assessment methodology is in line with international best practice, it has encountered some issues worthy of further consideration for future iterations, and these are discussed in later sections of this report.

2.4 Documentation

The full set of documentation, including supporting reports, provides a comprehensive and impressive account of relevant issues, models and data. In areas where the IRT has examined supporting documents, they were found to exhibit a good level of traceability. Moreover, the documentation has clearly been prepared with great care and attention to detail.

A good attempt has been made to integrate the total system performance assessment: it is logical and well structured but the story of the repository evolution is not told particularly well.

The overall clarity and comprehensibility of the report could have been better, and may have been affected by the report being aimed at a number of audiences with different needs. In future it would be appropriate to produce documents aimed at different sets of stakeholders in order to overcome this problem.

In its current form, the length and complexity of the documentation make it rather impenetrable to all but specialists. Moreover, in some cases, the descriptions of the subsystems are incomplete and the interpretation of results could be improved. The Executive Summary could also have been more appropriately written at a higher level and in a more readable style. Some of the illustrations are excellent, some unnecessary and some more appropriate for an oral presentation rather than a scientific report.

The IRT recommends that, at an appropriate point, the USDOE should produce a document of a few tens of pages where the whole YM concept, context, and safety case is presented in a form amenable *to a more general audience. This should emphasise the expected performance of the repository up to and beyond the compliance period. A relevant example is the summary of the Canadian Environmental Impact Statement* (AECL, 1994).

3. Subsystem Methodology

3.1 Repository design

There seem to have been rather large changes in repository design between iterations (e.g., since the TSPA-VA) but no clear rationale for these changes was discernible from the TSPA-SR report. Design changes are often made to improve safety or provability. However, in the TSPA-SR it was not clear why backfill was not considered when it has many favourable aspects from a safety perspective. Also, the reasons for changing the sequence of metals used in the waste package and introducing drip shields were not discussed in the TSPA-SR. In previous disposal concepts, cement was to be used in large quantities as a barrier and a seal in the repository, but this now appears to have been abandoned. One result of these changes in design is that it slows the convergence of the iterative series of performance assessments. *The IRT recognises the need for a performance assessment to be well focused on a given design. However, the IRT recommends that a discussion of design improvements and their role in the safety strategy should be included in future safety case documentation. This would provide continuity and would enhance confidence by demonstrating that the project is maturing and developing in a logical and systematic manner.*

Contingencies for dealing with poor ground conditions and heavy fracturing in the repository area, that had not been recognised from prior drilling and excavation of the ESF and Cross Drift tunnels, appear to have developed in a rather *ad hoc* manner. There appears to be only a limited amount of data from boreholes and the present drifts on which to base predictions for rock conditions in the repository area. Thus, plans for waste loading, container and drift spacing, etc., may need to be revised once excavation has begun. More borehole drilling is needed to verify the suitability of the emplacement site.

The proposed USNRC regulation (10 CFR Part 63) requires that the repository design allows for retrieval. However, retrievability is not discussed in the TSPA-SR apart from listing in the FEPs. The potential impacts of the provisions made for retrievability should be discussed in future assessments, including degradation of waste packages and drifts and possible damage to the drip shield carriage system prior to closure.

The IRT also notes that changes in the thermal loading and spacing of waste packages within the repository are under consideration. Changes in design, if adopted, will require a reassessment of the total system performance.

3.2 Engineered-barrier materials

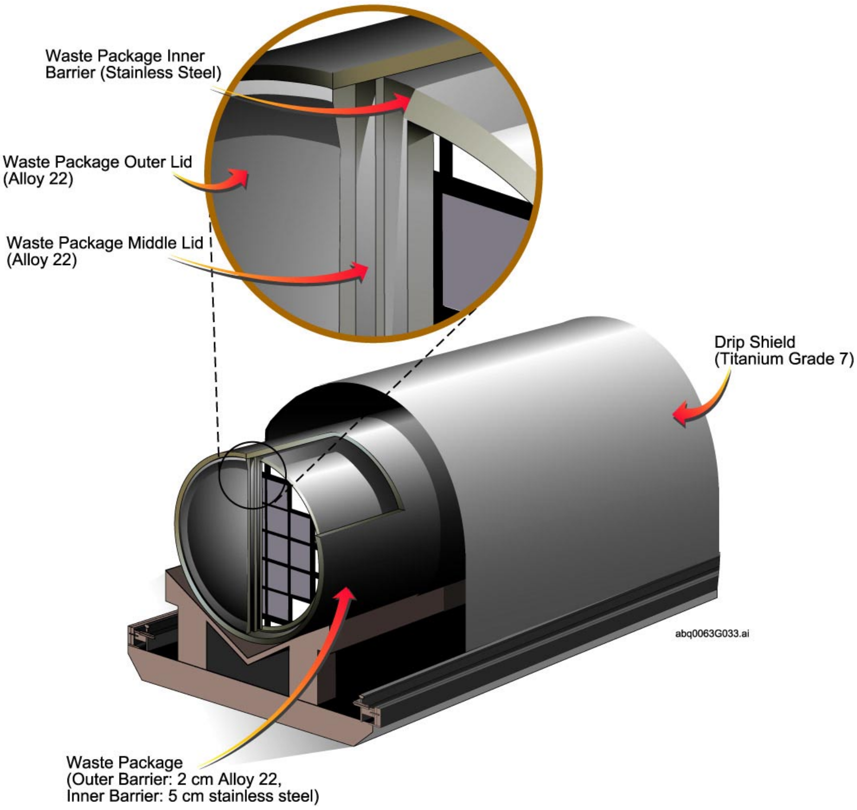
The primary components of the engineered barrier system, namely the drip shield and waste package, are depicted in Figure 1. The materials selected for the waste package outer barrier (alloy-22) and drip shield (titanium Grade 7) are in line with international best practice, having regard for the specific chemical environment at Yucca Mountain. Also, the waste package design shows a good balance between mechanical strength and corrosion protection. These materials are well known to be highly resistant to general corrosion, local corrosion and stress corrosion cracking (SCC) under a variety of disposal conditions including rock salt, granite and clay.

In the current design, the drip shield is largely redundant since the alloy-22 barrier is somewhat more effective. However, the use of dual barriers of dissimilar materials provides defence-in-depth and contributes to the overall confidence in the system.

The present investigations under Yucca Mountain conditions indicate good corrosion resistance. The general corrosion rate is extremely low and the experiments performed to date do not indicate a susceptibility to local corrosion. However, these experiments have not covered the full range of conditions expected in the repository. The available limited experimental results on SCC of welds of the alloy-22 do not allow a statement on the long-term resistance of this alloy to SCC. Moreover, the tests performed to date have been of relatively short duration compared to typical incubation times for localised corrosion in such corrosion resistant materials. In order to build confidence in the performance of these materials over thousands of years in the anticipated Yucca Mountain repository environment, *it is recommended that long-term corrosion tests using multiple specimens are carried out to investigate the effects of:*

- Gamma radiation field, especially on alloy-22.
- Kinetics of pitting and crevice corrosion.
- Salt deposits on local corrosion.
- Stress corrosion cracking, especially on welds of alloy-22.
- Microbially enhanced corrosion.
- Ageing especially for alloy-22.

Figure 1. Schematic design of the drip shield and waste package
*(*CRWMS, 2000a*)*



These experiments need to examine the effects of water chemistry (including pH and Eh) and temperature over ranges relevant to anticipated repository conditions.

In addition to the testing of small-scale coupons, it is recommended that larger specimens from real and model containers (including welds) should be investigated in order to determine the impacts of manufacturing processes and surface area.

A key challenge is to improve confidence in the extrapolation of corrosion performance to the 10 000-year regulatory compliance period and beyond. In order to accomplish this, *it is recommended that:*

- *To the extent possible, improved experimental methods are developed for accelerated testing.*
- *Measurements of the microscopic structure and composition of the passive oxide layers are made as an aid to scientific understanding of corrosion mechanisms.*
- *Models are developed, refined and validated based on scientific understanding, as an aid to extrapolating experimental results in time.*

In order to improve the understanding of the robustness of the system, it would be worthwhile to investigate the consequences of a "what-if" case in which there are a small number of early canister failures. This would address the concern that early failure of waste packages has not been properly considered and modelled. Coupled with this could be further discussion on the effectiveness of the drip shield and waste form to resist the effects of drip movement, and tunnel deformation and collapse.

3.3 Waste form

Twenty-six radionuclides are considered in the TSPA-SR report based on an initial screening process. The IRT notes that some radionuclides (such as ^{36}Cl and ^{135}Cs) that feature as important in other international studies (*NEA 1997a*) were screened out after the TSPA-1995. It is possible that changes in the disposal concepts or models since 1995 could affect the relative importance of radionuclides.

For instance, ^{36}Cl has been screened out because it is not a fission product. However, it is produced by neutron activation of contaminating Cl in the fuel. It has been shown to be an important contributor to dose in, for instance, the Canadian program (*Johnson* et al., *1995*). Although USDOE calculations appear to have been made to determine its contribution from this source, further examination is required to resolve this issue together with laboratory measurements in spent fuel leaching tests.

The IRT recommends that the inventory screening procedure should be reviewed and amended as appropriate.

Furthermore, it is noted that the biosphere dose conversion factors used in screening out radionuclides did not properly account for short-lived daughters of long-lived parents when determining whether to screen out the parent. However, the USDOE has assured the IRT that plans are in place to deal with this issue.

In the TSPA-SR, the cladding remains a significant barrier up to 100 000 years and beyond. This is not the same as in other international studies where different conditions exist and little credit is given for the cladding. In discussion with the IRT, the USDOE has argued that conditions at Yucca Mountain are more favourable to long-term maintenance of the cladding barrier. The IRT was impressed with the depth of thought given to this issue but found one process (effects of the degradation of basket components on cladding integrity) that was not taken into account and which could compromise the performance of the cladding. *The issue of cladding performance is important because it is one area of possible optimism and because it has a major effect on system performance beyond 10 000 years. Thus further efforts are recommended to strengthen confidence in this area.*

The degradation of the Commercial Spent Nuclear Fuel (CSNF) controls the source term because it dominates the inventory and because it is less durable than the HLW. As modelled in the TSPA-SR, the degradation of the CSNF is relatively rapid because of the oxidising conditions and the presence of carbonates in the water which complexes the uranyl species.

The release of some radionuclides from the waste package is governed by solubility limits, which are given in Table 3.5-8 of the TSPA-SR. Some of the solubility limits for elements (especially Np, Th, and Ra) are simplifications made in the absence of reliable data. The most important area of uncertainty is neptunium solubility and the degree of incorporation of neptunium into secondary phases. Neptunium solubility is a strong function of pH and Eh in the water within the degrading waste package.

The pH and redox potential of the water in equilibrium with the waste package are extremely important variables in determining the release of radionuclides from the near field. The degradation of the CSNF will occur within the same timeframe as other components in the waste package: the steel, alloy 22, titanium drip shield, etc. These processes will consume oxygen and, in some cases, protons and will tend to push the system towards reducing conditions. There is a wide variation in the predicted pH in computer simulations (below pH 3 is some cases), the reason for this variability appears to be due to the presence of sulphur in the carbon steel. If this is a problem it could be overcome by using low sulphur steel. Having regard to the above factors, *it is recommended that more experimental data be obtained to build confidence in the thermodynamic modelling, especially with regard to the complex interactions between the waste form and components of the waste package.*

There is some uncertainty as to whether the fast release fraction of volatile radionuclides has been adequately investigated and included in TSPA-SR. Further discussion on this topic should be included in future assessments.

3.4 Transport within the engineered barrier system

Figure 2 depicts the engineered barrier system during the initial stages of water ingress and degradation. In the TSPA-SR, water ingress and radionuclide transport within the engineered barrier system (EBS) is assumed to occur by the following mechanisms:

- Advection through the degraded container.[4]
- Diffusion through stress-corrosion cracks.

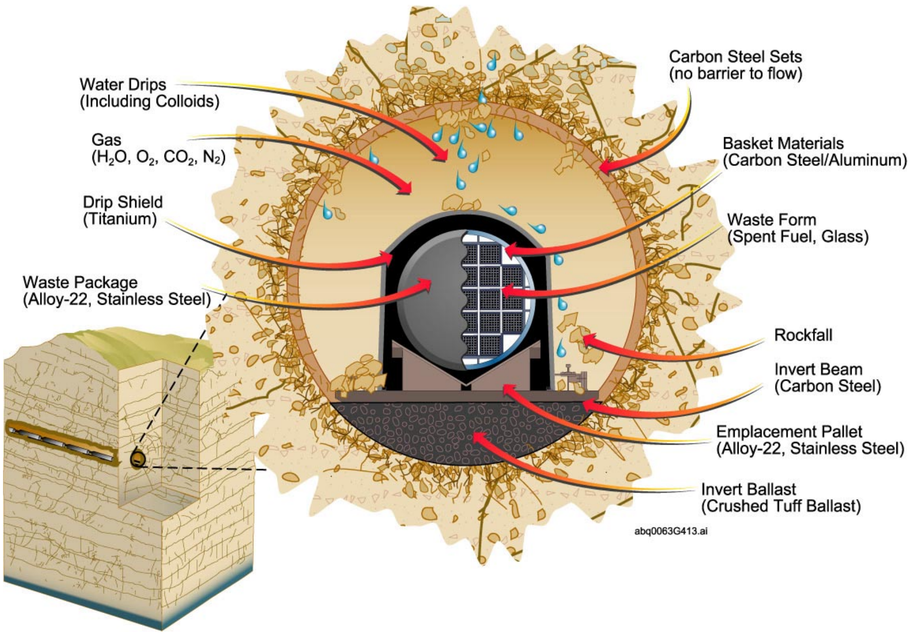
The second mechanism, which is dominant for many millennia after the waste package is breached, is overly conservative and complex and possibly not credible. The model requires a continuous film of water to allow diffusion that extends all the way from the waste form to the cracks in the degrading waste package and to the bottom of the invert. In applying the model, the TSPA-SR assumes very conservatively that the process of diffusion occurs even when there is no dripping in the location and the drip shield is intact. Furthermore, as discussed below, the existence of a continuous water film seems most unlikely because of evaporation. Moreover, the presence of the emplacement pallet (see Figure 2) is ignored and the waste package is assumed to be lying on the invert.

The model for spatial flow in the engineered barrier system is so complex that it is not easy to determine the effect of the conservative assumptions. The TSPA-SR lists (in Section 3.6.3.1) six noteworthy conservatisms but concludes that the magnitude of the conservatisms cannot be estimated because of the complexity and statistical nature of the model.

One aspect that has not been given sufficient attention is the possibility and probability for any liquid water to exist on and within waste packages over long time scales. The evaporation potential of water due to the decay heat of the waste is in fact substantial, exceeding 1 000 litres per year per container before 10 000 years and will still be of the order of 100 litres per year per container at 100 000 years. It appears that the USDOE have not taken this factor into account. Indeed, it is questionable whether larger seepage rates than the evaporation potential could ever occur over reasonable time scales for assessment of performance. The probability of extraordinarily high seeps should be better investigated. Design fixes, such as capillary barrier backfill, could be considered for any areas where seepage could be too high.

4. Diffusion through degraded waste packages was also considered in the TSPA-SR. See Appendix 4.

*Figure 2. General engineered barrier design features, initial water movement, and rock fall (*CRWMS, 2000a*)*



The overall conclusion from the analysis of engineered barrier transport is that the model is at the same time too complex and too conservative. In particular, the IRT recommends that the inclusion *of a diffusion pathway in the absence of any advective flow onto or into the waste package, or indeed the presence of any liquid water, should be independently reviewed to determine if it is credible and whether the complexity serves a valid purpose.* If this apparent over-conservatism is removed, the calculated repository performance beyond 10 000 years could improve substantially.

The corrosion of engineered barriers and components of the waste package (steels) could result in localised reducing conditions within the degrading waste package (see discussion in Section 3.3). Moreover the iron oxides formed by corrosion processes are known to be highly retentive of radionuclides. Both these factors should retard the release of uranium and actinides from the near field environment and should be considered in future waste package modelling studies.

Concentration limits assumed for the various radionuclides are regarded as a principal factor affecting post closure safety, both with regard to requirements for defence in depth and for contribution to performance. For many radionuclides this factor is, among other things, sensitive to the materials used in the repository. The materials intentionally brought into the repository are of course listed, but there should also be a systematic search for stray materials that could be spilled or unintentionally left in the repository and an identification of sensitive substances that would not be allowed to be brought into the repository.

The possibility of drift degradation by collapse of steel support sets and the tunnel roof appears to have been thoroughly examined in the supporting documents of the TSPA-SR and the integrity of the drip shield is claimed to be maintained throughout at least the first 10 000 years. Those conclusions are largely derived from the results of a model that describes the formation and collapse of "key blocks" in the emplacement drifts. The model shows that largest key block that may form (~50 tonnes)[5] is not expected to breach the drip shield although verification and validation of the model has yet to be performed. Therefore, the caveat "to be verified" applies to these conclusions. The work proposed by USDOE to identify suitable natural analogues for code verification and validation is, accordingly, important and welcome.

3.5 Unsaturated zone

Figure 3 shows a conceptual drawing of water flow within Yucca Mountain. The unsaturated zone (UZ) is the region above the repository and below the repository but above the water table.

Infiltration into the unsaturated zone has been a difficult parameter to quantify at Yucca Mountain (YM). The IRT understands that several methods have been used to determine infiltration but it would have been helpful if these had been described and the level of confidence in each discussed. In the TSPA-SR, fracture flow becomes increasingly important with increase in depth and is allowed to dominate at repository level to simplify calculations while remaining conservative. This approach appears to be appropriate although it is not clear whether the assumption of linear behaviour of flow-path characteristics (e.g., capillary suction pressures in the rock matrix) can be expected throughout the range of infiltration cases and climate scenarios.

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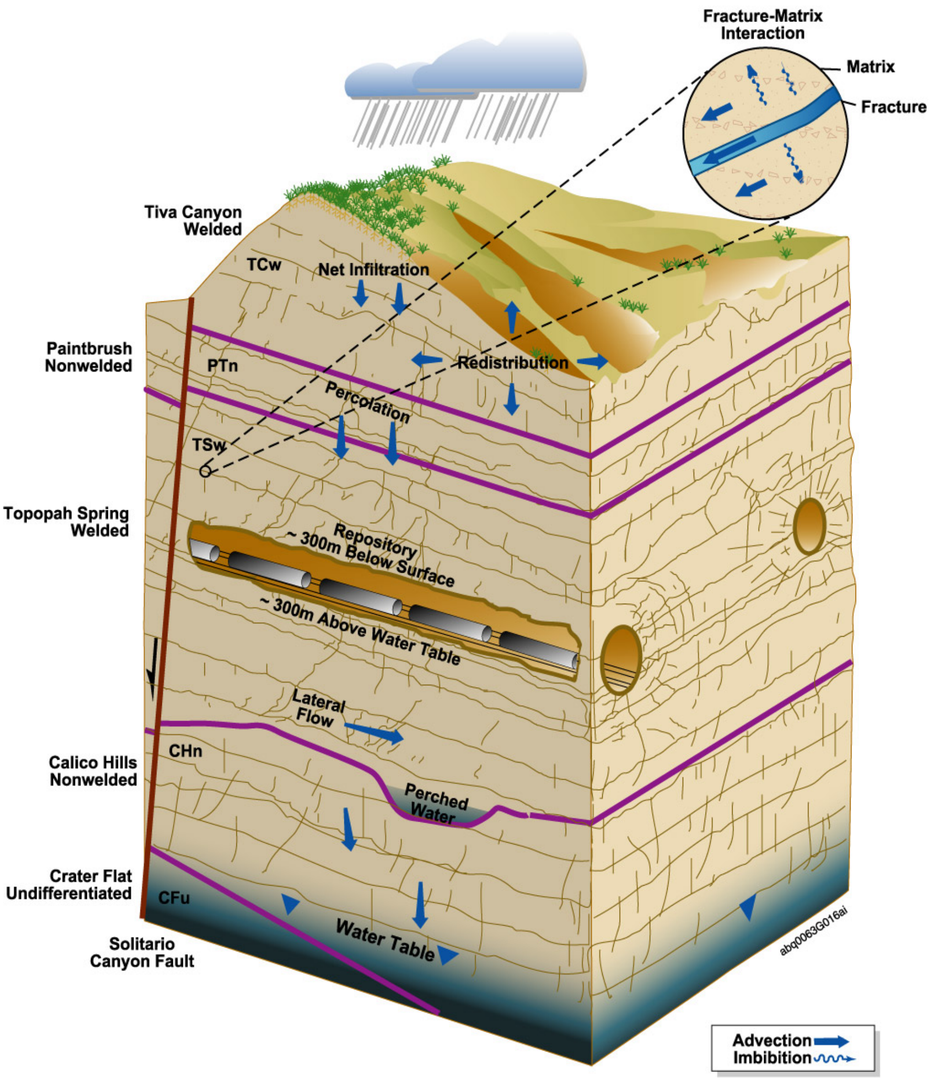
5. The maximum expected key-block size is 37 tonnes, and calculations indicate that no cracks will form in the drip shield up to a key-block size of 52 tonnes. See Appendix 4.

*Figure 3. Conceptual drawing of mountain-scale flow processes (*CRWMS, 2000a*)*



Evidence of past climate has been determined, appropriately, from nearby locations (Devil's Hole, Owen's Lake) to derive the three climate states for the next 10 000 years. That approach fulfils the requirement expressed in the review of the TSPA-Viability Assessment that wetter climates be incorporated in the model.

Water leaving the EBS flows through the UZ to the water table a vertical distance of 175-365 m (depending on climatic conditions). Flow calculations within the UZ are done ahead of time for input into the radionuclide transport model.

Modelling of fluid flow and radionuclide transport in the UZ utilises the dual-permeability[6] approach in which flow through fractures is relatively fast whereas most of the porosity resides within the rock matrix. Sorption processes are neglected in the fractures but occur within the rock matrix. Colloidal transport is also modelled for radionuclides that are either reversibly or irreversibly-attached to the colloids. That treatment is similar to that used in other repository studies where disposal occurs into fissured rock.

The description of transport in the UZ is clearly written and the illustrative figures (see Figures 3.7-9, 10 and 12 in the TSPA-SR) are useful. They show that the average transit times in the UZ are typically 500 to 1 000 years for non-sorbing species such as ^{99}Tc, 1 000 to 10 000 years for ^{237}Np and >100 000 years for irreversibly and reversibly-bound Pu, respectively. This illustrates the ability of the Yucca Mountain geological strata to retain radionuclides, a fact that is otherwise masked in the TSPA-SR by the dominance of engineered barriers for the first 10 000 years and more.

One important caveat needs to be given. The modelling of flow and radionuclide transport in unsaturated media is complicated by the presence of both air and water in the void space. The major uncertainty in the current model is the extent of continuity between water in the fractures and matrix. This can have an important effect on the output of the model. Also, the fracture-matrix exchange-reducing parameter, which is supposed to account for channelling into and clogging of the fracture planes, needs to be validated by additional field tests both for the migration of water and nuclides. *The only real way of resolving these issues is by experimentation and thus it is recommended that experiments be conducted to validate the model of flow and transport in the unsaturated zone.*

Independent evidence of the groundwater flow rate through both the UZ (and SZ) can be obtained by use of groundwater "dating" (residence time) techniques, such as the measurement of the naturally occurring isotopes ^{3}H, ^{14}C and ^{36}Cl. Little indication of this work is given in the TSPA-SR although there are citations to excellent AMRs on this topic, in which these and other techniques have been applied. What is not clear, however, is whether and how these results have been incorporated in the flow models for the UZ (and SZ).

For representing flow and transport in the UZ, the TSPA-SR has developed a full 3-D model of the site. However, this model has not used the existing large-scale experiment that the present ventilation of the exploratory tunnel is providing. *The IRT suggests that head measurements in the rock matrix and water extraction by the ventilation system should be used to test the 3-D UZ model, and thus potentially confirm the estimate of the present large-scale permeability of the rock and also infiltration rate into the mountain.*

6. Terminology corrected. See Appendix 4.

The TSPA-SR determined that some of the dose comes from insoluble or relatively insoluble species of Pu, Th and possibly other actinides. These species are transported, in part, by colloids generated by corrosion of the waste form or in the invert below the waste form. The support for colloidal transport appears to come largely from measurements of Pu at the Nevada Test Site (NTS) although the amounts transported were extremely small in that study. The TSPA-SR supporting documents give a somewhat confusing picture as to whether colloidal transport is at all important. It is possible that it is over-rated as a transport mechanism, but this needs to be clarified. It is noted that the mobility of biological species is treated differently to colloids.

Natural dripping of groundwater from fractures or pores in the matrix has never clearly been observed[7] in the drifts at Yucca Mountain, because it is affected by drift ventilation, and yet it plays an important role in the analysis. This begs the question as to whether the assumptions about dripping are too conservative. Also, the time and spatial dependence of dripping, if dripping occurs, needs to be understood better. One possibility is that dripping could be controlled by installing a capillary barrier backfill. *In view of its critical role in the assessment, the IRT recommends that the postulated dripping process be better understood and quantified. Also, the influence of temperature on capillary suction should also be taken into account, as the surface tension of water decreases with temperature*[8].

One possible approach to understanding seepage into drifts is to make use of the analogy of stalactites in caves caused by drips from the cave roof. Limestones are fractured in a similar manner to YM tuffs and it is possible that a study of drip frequency, volume and distribution has already been made by speleologists and may be found in the karst or speleological literature. This could form the basis of a model for describing dripping and migration of the drip source.

3.6 Saturated zone

For the purposes of radionuclide modelling, the saturated zone (SZ) extends from the point at which radionuclides reach the water table to the receptor point in the model farming community (see Figure 4). The farming community is assumed to be 20 km downstream in the TSPA-SR but this will need to be adjusted to 18 km following finalisation of the EPA regulation, 40 CFR 197 (*EPA, 2001*).

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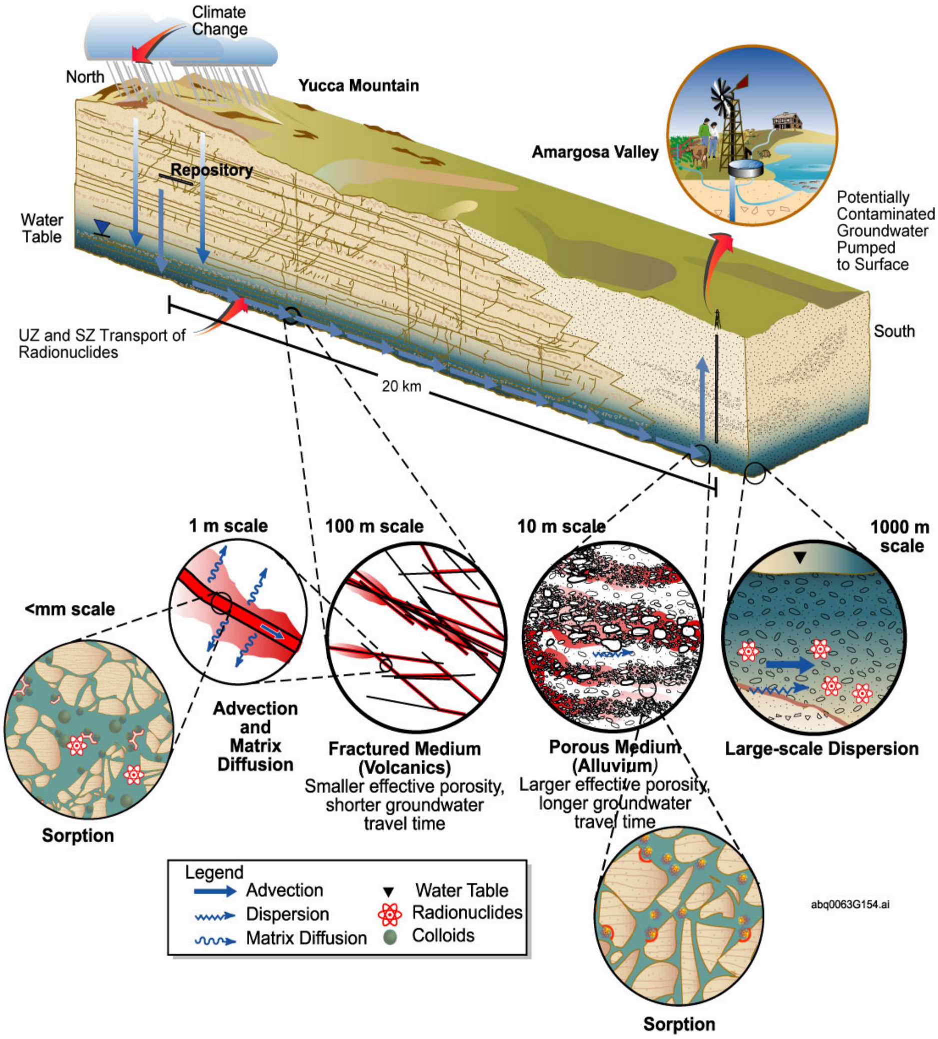
7. Clarification made. See Appendix 4.
8. 10% decrease over the temperature range of 20 to 60°C.

*Figure 4. Conceptualisation of features and processes important to saturated zone transport (*CRWMS, 2000a*).*



The IRT expresses concern about the level of knowledge available for assessing the role of the saturated zone (SZ) in the TSPA-SR, both at the regional scale and at the site scale. The geological structure and hydrogeological properties of the Death Valley Basin and of the Yucca Mountain region are clearly very complex. The amount of data that has been collected by the USGS and USDOE, particularly on the site and its surroundings, is significantly too low for adequately supporting the role that is to be played by transport in the SZ, in a multi-barrier approach of a TSPA.

The IRT observes that the SZ flow system at YM is very complex and not sufficiently understood to propose a conceptual model for a realistic transport scenario. A number of site specific features have to be investigated in the continued site investigations before a realistic flow model can be built. This is discussed in detail in Appendix 3 and summarised below.

3.6.1 Regional scale flow model

At the regional scale, the USGS has assembled a significant amount of information. However, the treatment of this information to construct and calibrate a regional groundwater flow model is considered by the IRT not to be state-of-the-art, and to be below what has been done in the US at other sites (e.g., WIPP) or in the oil industry. A reliable regional SZ flow model is necessary to provide the boundary conditions of the site model, and also the predicted regional hydrology in different climatic conditions. *It is recommended that a significant effort be made to improve the regional SZ flow model. This effort should be closely integrated with the improvement of the site model, in order that these two models be made consistent with each other, which is not the case at present.*

3.6.2 Site scale flow model

At the site scale, there is a gap of information between the location of the repository and the potential receptor, 20 km downstream. Furthermore, there are indications from the C-holes study that the single-well tests that have been made so far in the area do not provide results consistent with those of the multi-well tests. This introduces a very significant uncertainty in the understanding of the system, which needs to be resolved in order to qualify the existing single-well data. Finally, there are indications, which need to be confirmed, that the fractured volcanic rocks can display a significant horizontal anisotropy.

The USDOE has built a site scale flow model that, in its description of the geology of the site, is a much better approach than that used in the regional model, but which is very difficult to make consistent with the information extracted from the regional model. However, there is still room for improvement. *It is recommended that the site flow model should be improved based on the new data that is to be collected, and better calibrated, using* for *instance additional information such as the temperature data that is available in the area.* By interactive adjustments with the regional model, a coherent picture of the SZ flow at both scales should be obtained. Once this model has been adequately calibrated, a conditional approach to the residual spatial variability of the system should be implemented, analogous for instance to work carried out for WIPP. This variability analysis should incorporate both the distribution of permeability and that of recharge, in a consistent way.

3.6.3 Treatment of uncertainty

In the TSPA-SR, the USDOE has fully recognised the large uncertainty that is inherent in the lack of data and the poor quality of the regional model. This uncertainty has been accounted for by assuming an uncertainty range of a factor of 100 in the velocity in the aquifers, and by further assuming that two different conceptual models (isotropic and anisotropic) can be used alternatively with equal probability. Such a large uncertainty in the velocity of the aquifer has been extracted from the judgement of an Expert Elicitation Panel, which thus acknowledges the unreliability of the estimates provided by the regional model.

The IRT has also observed that the uncertainty factor on the velocity in the aquifer creates an equal uncertainty factor in the regional groundwater flux entering into the model. However, in the Monte-Carlo sampling, no correlation has been introduced between the magnitude of this flux and the magnitude of the recharge estimate, which is also randomly sampled in the TSPA. The SZ model can thus have a very large groundwater velocity associated with a very low recharge rate, and vice versa, which *a priori* seems inconsistent. While there may be potential reasons explaining this decision, nowhere in the TSPA-SR nor in the AMRs that the IRT reviewed has this feature been addressed. It thus gives the impression that the TSPA-SR contains undefined and unjustified decisions that can potentially affect the outcome of the analysis, and thus the credibility of the results.

The IRT considers that introducing such a large uncertainty in the TSPA is likely to induce "risk dilution" effects (see discussion in Section 4.3), thus impairing a reasonable understanding of the role of the SZ barrier in the system performance measure, and further generating non-conservative biases in the calculated expectation value of dose. This potential effect has not been analysed in the sensitivity study of the system, and is presently unquantified. The IRT consider that it would have been preferable, in the absence of additional data, to have reconsidered the range of uncertainty derived from the Elicitation Panel. This could have been done by reconvening the panel, and then, as in other parts of the TSPA, to have used a conservative model of the SZ rather than the potentially non-conservative approach used in the present TSPA-SR. *For future analyses, the IRT recommends that additional data should first be collected, and an improved model constructed, calibrated and validated, and then run in a spatial variability analysis, not by using a large uncertainty factor.*

3.6.4 Radionuclide transport

Section 3.8 of the TSPA-SR report on transport in the saturated zone is well written and logically ordered. There is, however, a general reluctance to seek out and clearly display hydrogeological/geochemical evidence that could build confidence in the models. Examples of this are the validation of assumed water types that reflect different climates over the last 10 000 years and measurements of the mobility of naturally occurring radionuclides that are also contained in the waste (e.g., ^{14}C, ^{36}Cl, ^{99}Tc, ^{129}I, ^{238}U) in both natural analogues and Yucca Mountain itself. Evidence is needed in the TSPA-SR to support proposed hydrogeological flow paths, modelled groundwater residence times and flow rates, and groundwater redox conditions at discharge zones.

The importance of colloids is again discussed in the TSPA-SR for transport of low solubility radionuclides in the SZ. As noted for the UZ, however, the importance of colloids in contributing to dose may be overrated. Several conservatisms have been made with respect to the role of colloids: filtration of reversible (surface-sorbed) colloids is not considered, minimum values of K_d are used for the highly sorbing radionuclides (Am, Pu, Th) in the SZ, chemical equilibrium is assumed so that mobility is maximised, and K_d values for the least sorbing rock unit in the SZ are used. This likely results in an overly conservative assessment of the importance of colloids in the SZ.

3.7 Biosphere

The outputs from the SZ transport model are the fluxes of radionuclides crossing into the receptor area. In the biosphere model, radionuclide concentrations in the receptor area are calculated simply by dividing the mass of each radionuclide by the volume of water that is assumed to be used by the model farming community. The volume used in the TSPA-SR will have to be adjusted to the EPA regulation, which is 3,000 acre-feet (3.7 million m^3). Also, as the assumption of a constant pumping rate is an extreme stylisation, other credible evolutions of the pumping rate should be considered.

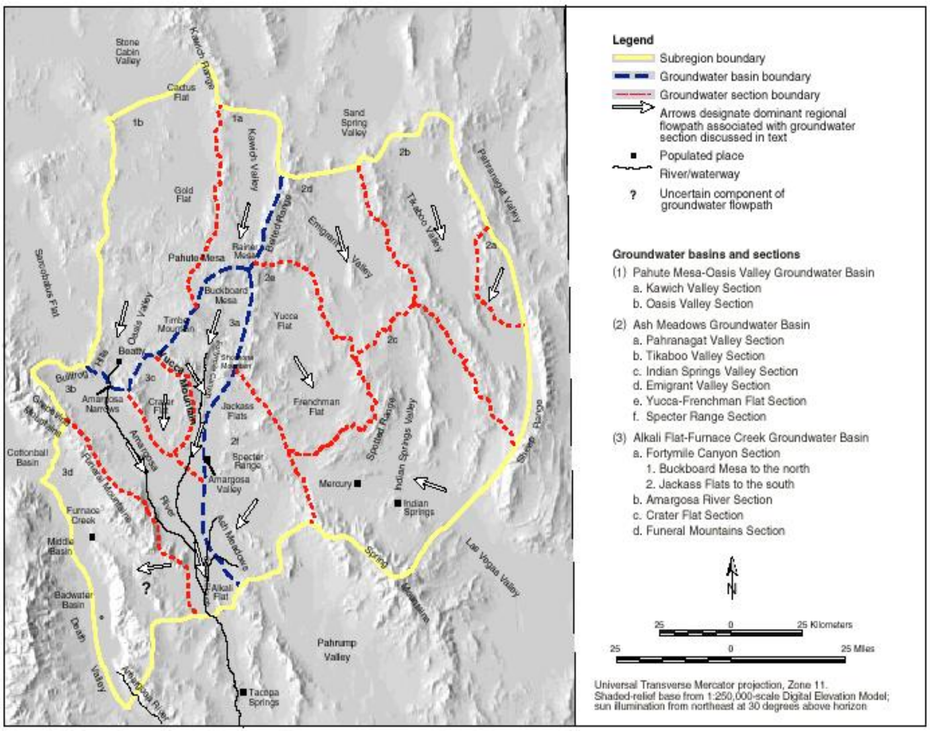
The biosphere model assumes that all contaminated water from the repository is utilised by the model farming community. Thus no accumulation occurs apart from irrigation of soils for production of crops.

The Yucca Mountain biosphere modelling programme has recently been the subject of a comprehensive international review (*IAEA, 2001*) and thus in general it has not been thoroughly scrutinised by the IRT. However, one geosphere-biosphere interface issue has arisen in connection with the review of saturated zone hydrology, and this is discussed below.

The TSPA-SR focuses on calculating doses to individuals making use of water from a specified receptor well located 20 km from the proposed repository, as prescribed by regulation. As such, the TSPA-SR document does not address the issue of the long-term fate of the radionuclides leaving the repository in the groundwater.

The IRT considers that this may be a relevant issue in the case of Yucca Mountain, because, contrary to most international planned repositories whose final outlet is the sea, Yucca Mountain is a closed basin system. Thus all releases will eventually end up in some location within the basin (see Figure 5). There is therefore a risk that accumulation and possible reconcentration of radionuclides could occur, leading to potential non-trivial doses.

*Figure 5. Groundwater basins in the Yucca Mountain vicinity (*DOE, 1999*)*



The TSPA has identified one FEP consistent with this concern, namely "the role of playas". Playas can indeed be final recipients of contaminated groundwater, where it would evaporate and accumulate the transported radionuclides. This FEP has been screened out as "low consequence" by the TSPA-SR. The USDOE is of the opinion that the potential doses in the long term to an exposure group living near a playa would be lower than those from the regulatory farming community wells, located 20 km away from the repository, thus closer to the source.

The IRT considers that this opinion and the screening out of this FEP are probably valid for the regulatory period of 10 000 years, and the regulatory "farming community" receptor. It is however unsatisfactory for longer periods, such as the 1 000 000 year period included in the TSPA-SR, where the long-term consequences of the repository are presented, independently of the regulatory compliance measure. The IRT encourages the USDOE to formulate and analyse such a scenario in order to exhibit its in-depth understanding of the long-term consequences of the construction of the repository.

It is possible that natural analogues could help to determine the long-term fate of radionuclides at Yucca Mountain. For example, uranium at Peña Blanca has not moved very far. This is also the case for uranium at Alligators Rivers even though the conditions are oxidising and far wetter than at YM. This illustrates the importance of making realistic assessments in order to understand the safety margins inherent in the TSPA-SR.

The IRT recommends that long-term fate of radionuclides from the YM repository *should be considered in future assessments*, including addressing the following questions:

- For the present climate, what is the final fate of the radionuclides reaching the farming community, and supposedly extracted from the groundwater? Since most of the water is used for irrigation, where do the nuclides end up after they leave the soil compartment of the biosphere? Can they reconcentrate and where, and at what rate? Is there a potential pathway to man linked to this potential reconcentration?
- If the water is not extracted by the farming community, what is the fate of the radionuclides? Where do they go, do they reconcentrate, is there again a potential pathway to man?
- For a wetter climate, the TSPA-SR indicates that Death Valley would become a lake again (Lake Manley), and that Fortymile Wash and the Amargosa Valley (see Figure 5) would become perennial streams and eventually discharge into this lake. Will the radionuclides leaving the repository end-up also in this lake? Over what time scales? What would be the fate of the radionuclides in this water, can they reconcentrate, and is there a potential pathway to man?
- The IRT also questions the rationale for keeping constant the volume of water extracted by the farming community, when the climate becomes more humid.

3.8 Disruptive events

3.8.1 Probability of eruption

Recent volcanic activity in the Yucca Mountain Region (YMR) is clearly limited to basaltic eruption of the Strombolian type. Probabilistic analysis of volcanic vent alignments in the YMR leads to the conclusion that there remains the possibility of a basaltic dike intersecting the repository during the next 10 000 years. The description in the TSPA-SR of this possibility is rather vague, compared to that of the consequences, and should have been treated in more detail. Details of the probabilistic methods used in estimating the probability of a dike intersecting the repository are covered in supporting documents, but it would have been advisable to have included a brief discussion of the probabilistic volcanic hazard analysis models in the TSPA-SR report.

The volcanic event used in the calculations was defined as a dike, rather than a point process or fissure eruption, for example. Again, even though the reasoning for this assumption is mentioned elsewhere, it should be stated in future safety reports.

The low rates of volcanic activity in the region of Yucca Mountain yield insufficient data to make a precise determination of the probability of volcanic activity affecting the repository. Condit and Connor (*1996*) were able to make comparisons of actual eruption locations, and probability maps were calculated from a spatio-temporal model developed for the YMR (*Connor and Hill, 1995*) in the larger Springerville volcanic field, Arizona. The results of such studies applying models developed for the YMR to other larger volcanic fields should be included in future reports.

3.8.2 Consequences of volcanic disruption

The type of eruption assumed in the ASHPLUME model needs to be stated. In the case of Strombolian type eruptions (the most probable type in the YMR) few fine-grained particles are produced because fragmentation is not very efficient and only minor amounts of ash are produced. The eruption results in the formation of a scoria cone where pyroclastic fall deposits are generally limited to the close vicinity of the vent, mostly less than 10 km. The probability of fine-grained particles of volcanic or radioactive waste material reaching a distance of 20 km from the eruption source (as depicted in the ASHPLUME model) is extremely low. A Strombolian type eruption may rarely become violent, which is more intense with fall deposits having a wider distribution than that of Strombolian eruptions. Therefore, a violent eruption is acceptable as a conservative assumption.

However, there are some examples in other volcanic fields, where basaltic volcanic activity is associated with amounts of rhyolitic volcanic activity (e.g., the Newberry Volcano Group in Oregon, and the Higashi-Izu Monogenetic Volcano Group in central Japan). Such association of two different kinds of magma is known as bimodal. Rhyolitic eruptions can form a lava dome at and occasionally under the surface. They are more explosive than basaltic eruptions and would lead to significantly greater amounts of waste particles that are more widely distributed. Also there exists the possibility that the thermal influence would be more intense and of longer duration than that for basaltic eruptions.

Bimodal volcanism was not mentioned or discussed in the TSPA-SR. *It is recommended that future assessments should estimate the probability of bimodal volcanism and, if relevant, should analyse its consequences.*

3.8.3 Seismological influences

The IRT consider that the TSPA-SR adequately addresses seismological influences on the performance of the proposed repository. The TSPA-SR analysis is in line with other international studies. For example a study at the Kamaishi Mine in Japan (*Shimizu* et al., *1996*) showed that earthquakes are likely to have an insignificant impact on the performance of a repository.

3.9 Human intrusion

Human intrusion has the potential to impair the performance of a geological repository. Since the nature of future human activities at a repository is subject to great uncertainty, it is common for regulatory authorities to require assessment of a stylised (i.e., simplified) human intrusion scenario (*NEA, 2000*).

Both the USEPA and proposed USNRC regulations require assessment of a stylised scenario involving drilling through the waste package to the saturated zone. Although this scenario is unrealistic in several respects, the IRT accepts it as an indication of the resilience of the system to a breach of a waste package coupled with accelerated transfer to the environment.

The TSPA-SR assumes penetration of the waste package (including cladding) by an 8-inch (20 cm) diameter drill 100 years after closure (a 10 000-year intrusion event is also considered as part of the sensitivity analysis). In the conceptual model, the borehole does not remain open but is degraded by inward collapse of surrounding material. The model allows increased infiltration of water into the hole but not direct flow of surface water. The calculation of mean dose rate is based on probabilistic analysis as in the nominal scenario.

The mean dose calculated by the model rises to about 0.01 mrem/a after 1 000 years and remains fairly constant thereafter. The peak dose is insensitive to the time of intrusion and, significantly, ^{137}Cs and ^{90}Sr make no contribution to the dose since they decay before reaching the accessible environment. This is a powerful demonstration of the resilience of the system to a significant disturbance or early failure by any mechanism of a significant number of waste packages.

However, there is one caveat that should be noted. Insufficient information is provided in the TSPA-SR or supporting documents to determine the extent to which infiltration is increased by the borehole. However, it appears that infiltration remains zero in many realisations. *The IRT recommends that this optimism be removed by allowing direct surface water flow into the borehole so that water flows into the degraded waste package in every realisation of the computer model.*

Current regulations do not require any consideration of deliberate intrusion or sabotage. In this context, the IRT notes that the repository will contain large quantities of uranium, plutonium, titanium, and nickel and that it is conceivable these could be targeted for economic, proliferation or other reasons.

3.10 Natural analogues

Natural analogues are naturally-occurring systems that experience processes similar to those that might occur in a nuclear waste repository. They have typically been used to represent the whole of the repository but the current view is that they are best used to represent specific processes or subsystems of the repository. Natural analogues may provide data that is useful in: (i) understanding long-term processes such as corrosion and mineral dissolution/precipitation; (ii) determining the important parameters of radionuclide migration such as radionuclide flux, sorption sites and groundwater residence times; and (iii) modelling the performance of the repository. However, a more important use is the increased confidence they can give to the assessment of long-term performance of a repository that generally cannot be obtained in laboratory or field studies. The USDOE has identified several sites for natural analogue study and, in 1999, selected the Nopal I uranium deposit in the Sierra Peña Blanca in northern Mexico for limited investigation. The site is very relevant because of the remarkable number of characteristics it shares with Yucca Mountain. These include climate, precipitation, rock types and their mineralogy, presence of both an unsaturated zone and a saturated zone, occurrence of faults, and the predomination of oxidising conditions. A few differences exist (depths, U inventory, and distance to discharge point) but these are not important to the analogy.

Despite prior investigation by other groups, the amount of data and the level of understanding of the analogue are relatively low in comparison with international analogue studies such as Oklo and Cigar Lake. *The IRT feel that the USDOE should now make use of the opportunity to improve understanding of the analogue and use its characteristics to increase the confidence of the public and scientific community in the Yucca Mountain programme*. In particular, to give a better understanding of radionuclide mobility in these conditions, groundwaters, fracture-filling minerals and host rock should be analysed for naturally occurring isotopes, such as ^{14}C, ^{36}Cl, ^{129}I and U-series nuclides, some of which also occur as major contributors to dose in the TSPA-SR model. The concentration of ^{99}Ru in the playa could be used to investigate long-term accumulation of ^{99}Tc.

In parallel with the Peña Blanca study, the use of naturally occurring U and its radioactive daughters in the tuffs at Yucca Mountain should continue to be investigated by USDOE to improve understanding of the mobility of U and analogue elements within the flow systems of the mountain. A large suite of data have been obtained on the calcites and opals found in fractures at the ESF level and this has given a good understanding of the mechanisms of fracture infilling, processes of seepage flow and ages of secondary infillings. $^{234}U/^{238}U$ activity ratios for perched waters and saturated zone groundwaters have recently been found to be significantly higher than off-site groundwaters indicating that U-series radionuclides are a potential useful tracer for Yucca Mountain recharge as well as providing insight to the migration of U in the mountain. More data are needed for pore fluids in the tuff matrix to verify the preliminary analyses that have shown ratios to be much lower than the other Yucca Mountain groundwaters. Analysis of ^{226}Ra is also suggested to provide analogue data and understanding of radium mobility as well as to indicate the likely source of radon gas which occurs in high concentrations in the Exploratory Studies Facility (ESF) and Cross Drift tunnels in the absence of ventilation.

The IRT recommends that natural analogues should be used throughout the programme to provide long-term data to assist in understanding the important processes and to increase the level of confidence in the assessment, particularly for the public and scientific community.

4. Integrated Total System Methodology

The broad features of the total systems methodology used in the TSPA-SR are set out clearly in Chapters 1 and 2 of the report and are generally in line with international best practice. This section considers some issues where developments of the methodology would be beneficial for future assessments of Yucca Mountain.

4.1 Features, events and processes

From an international perspective a key aspect of performance assessment is the identification and selection of features events and processes (FEP) that influence repository safety. This is partly due to the fact that it is the starting point for defining the evolution of the repository system, and partly because of the recognised difficulties arising from the long time spans addressed. The IRT has found the FEP methodology used in the TSPA-SR to be in agreement with the international state-of-the-art, and recognises the important contributions to the international development that has come from work within the YMP.

However, the IRT has observed that the regulatory requirements have had a large impact on the FEPs included in the TSPA-SR analysis. This has resulted in certain FEPs that are important for a full understanding of the system behaviour being screened out (e.g., see Section 3.7).

The IRT has carried out some spot checks of the TSPA-SR FEP identification and screening process. This has identified a potentially important FEP that has not been included, relating to cladding/basket interaction, as is noted in Section 3.3. Also, the effect of temperature on capillary suction should be considered, as noted in Section 3.5. This points to some shortcomings in the routines and procedures for the FEP identification and screening process and in the QA of assessment input, which should be revisited and revised as necessary.

While the regulatory compliance period is 10 000 years, the YMP team are to be commended for extrapolating some of the TSPA-SR simulations out to longer times in order to estimate the time and magnitude of the maximum expected dose. For example, this is valuable for comparison with the results of performance assessments in other countries. However, in the TSPA-SR FEPs have been screened out on the basis of demonstrating compliance up to 10 000 years and thus the assessment is less reliable at longer times. The YMP may wish, therefore, to carry out a performance assessment iteration that is focused more specifically on the long-time behaviour. In view of this, *the IRT recommends that in future the screening of FEPs should be made in two stages. The first stage should retain all FEPs required for a full understanding of repository performance, while the second stage should include regulatory considerations in the screening criteria.*

This dual approach is consistent with having a strategy for building confidence in the safety of the repository together with a strategy for demonstrating compliance with regulatory requirements.

4.2 Uncertainty

4.2.1 Need for a comprehensive framework

Consideration of uncertainty lies at the heart of the TSPA-SR. This is appropriate since uncertainty is inevitable in the assessment of the long-term performance of a repository. However, a consistent overall strategy and approach to the management and treatment of uncertainties appears to be lacking in the TSPA-SR, with uncertainties being treated in a somewhat *ad-hoc* way. This is also the conclusion reached by an internal DOE audit (*Rogers* et al., *2001*), which reviewed and evaluated the adequacy of the uncertainty treatment in the suite of TSPA-SR technical documents including PMRs and AMRs.

The IRT considers that the current treatment of uncertainty in the TSPA-SR needs to be improved. *It is recommended that future* iterations *of the TSPA should aim to set out and follow a comprehensive and systematic framework for treating all types of uncertainty.* This should involve the systematic identification, classification and quantification of uncertainty and its effects on the results. Also there should be an identification and ranking of the possibilities to avoid or reduce uncertainty. *The YMP needs to classify uncertainty on the basis of type and in particular whether it is due to intrinsic variability or to lack of knowledge. It is important to identify these latter uncertainties since they can lead to risk dilution* as discussed elsewhere in this review (see especially Section 4.3).

When uncertainty exists there is a tendency to skew the model or values of parameters towards conservatism. This is appropriate for demonstration of compliance but results in embedded conservatism. It is appropriate to attempt to identify conservatisms and possible optimisms (this has been done to some extent by the YMP) and then, additionally, to run the model for the most likely situation (that has not been attempted). Conservatisms and possible optimisms should also be ranked in terms of their importance to overall performance and confidence in the system.

Unnecessary complexity in models is a possible source of uncertainty because it involves the introduction of additional parameters, each of which is subject to uncertainty. The IRT considers that some of the subsystem models especially those that may be difficult to validate within the in-drift environment (see Section 3.4) are unnecessarily complex. Simplification of a model facilitates understanding, reduces computer time and allows effort to be focused on the most important issues. It could also assist in presentations to the public and acceptance of the facility.

Finally, it is observed that currently there is a very large range of estimated doses based on probabilistic analysis (often extending to four orders of magnitude or more). This large range presents a credibility problem. *The IRT recommends that reduction in uncertainty should be a major goal of the YM project and that attention should be focused on obtaining good laboratory and field data in those areas where uncertainty has the greatest effect.*

4.2.2 Model uncertainty

Quantification of uncertainty involves running of models to determine the effect of input uncertainty on the output of the model. The sensitivity analyses performed to date have been very useful in identifying the importance of parameter uncertainty for the various barriers in the system, but not for model uncertainty.

Model uncertainty has in general been treated by attempting to select the model that is intrinsically the most conservative. However, it is very difficult to prove that this is the case *a priori*. Thus it is suggested that where appropriate in future assessments, alternative models (with their associated parameters) should be examined as separate calculation cases to determine which is the most conservative when embedded in the full system model. In particular, alternative models suggested by other interested organisations (e.g., EPRI, State of Nevada) should be evaluated in a systematic way. This is an important issue, as model uncertainty can often be the dominant source of uncertainty, but can be overlooked as parameter uncertainty is more easily quantified. In some situations it is likely that deterministic rather than probabilistic calculations would be appropriate for assessing model uncertainties, and would have the added benefit of the results being more readily comprehensible.

4.2.3 Evolution of uncertainty with time

Intuitively one would expect uncertainty in performance measures to increase with time. However, this does not generally appear to be the case with the TSPA-SR. One reason for this is that the relevant FEPs are chosen primarily to be relevant to the 10 000-year compliance period (see Section 4.1) whereas in practice new uncertainties would be introduced over time. However, it is acknowledged that uncertainty related to the engineered barriers can decrease with time as their importance for the performance of the total system decreases with time. This question deserves further investigation by the YMP.

4.2.4 The meaning of numerical calculations and results

At present, the TSPA nominal case is treated probabilistically yet it involves a mixture of embedded conservatism and statistical analyses to determine the mean, median and the various percentiles of the dose distribution. The reported "mean" is therefore not the true mean in a statistical sense. This issue is discussed further in Section 4.3. Moreover, that value is reported in the Executive Summary of the TSPA-SR and elsewhere as the expected value of effective dose, without any qualification. This stretches credibility especially as the discrete numerical values are given for times in the far future. The USDOE needs to indicate that, for compliance purposes, a performance indicator has been chosen that is meant to illustrate the safety of the system and argue the compliance with regulation. However "probability" does not indicate the actual probability of occurrence and "dose" has a different interpretation from its usage in operational radiation protection.

The IRT recommends *that the USDOE more clearly indicate the meaning of the calculational approach that is taken and of the quantities that are used to report its results.*

4.3 Probabilistic methodology

Given the regulatory requirements in the US, it is appropriate to make use of a probabilistic systems analysis framework for analysing a potential repository at Yucca Mountain. However, the IRT is of the opinion that there are some issues that require further consideration. These have previously been considered within the NEA Probabilistic System Assessment Group and are reviewed in (NEA, 1997b). These issues pertain to the most effective use of the Monte Carlo method, its numerical convergence, and the potential for risk dilution.

The IRT considers *that issues raised by the Probabilistic System Assessment Group, especially risk dilution, should be addressed in future assessments.*

4.3.1 Realism or conservatism

At a fundamental level, it is useful to resort to a probabilistic analysis of a system evolution in time if a realistic model can be attempted but legitimate uncertainties persist. However, if the starting model is built *a priori* to be conservative, exercising it probabilistically has little or no added value, as one would still obtain conservative results. If the modelling attempts to be realistic, one may claim that some probabilistic measures (e.g., the 99^{th} percentile) constitute, *a posteriori*, a conservative measure of performance. In the TSPA-SR a hybrid conservative/probabilistic methodology is used, which causes assumptions and reality to be mixed in a confusing way. *In the future it may be appropriate to present: (i) a probabilistic analysis based on a realistic or credible representation; and (ii) a set of* complementary *analyses with different conservatisms, in order to place the best available knowledge in perspective.* These ancillary analyses could be given a probabilistic weight as well. This should satisfy the regulatory requirements whilst providing a better basis for dialogue and decision-making.

Besides, as is shown elsewhere, constantly invoking conservatism (e.g., in establishing probability distributions) has the potential to lead to risk dilution.

The IRT recommends that when a best estimate/best knowledge probabilistic analysis is performed, the best estimate or the most probable range of the calculated "dose" should also be given. This should be in addition to the current upper limiting values at an appropriate *percentile, as a measure of the maximum reasonably expected value.*

The IRT notes that while the final licensing decision requires a probabilistic approach, this is not necessarily the case for the site recommendation decision, and some complementary deterministic analyses would have been appropriate as an aid to understanding system behaviour.

Finally, it is noted that assumptions and parameters that are conservative for one performance measure may not be conservative for another. For example a calculation that is conservative for the compliance period may not be conservative for longer times.

4.3.2 Convergence

There are questions as to whether the 300 realisations used in the TSPA-SR are sufficient for the mean dose and other statistical measures to be fully converged. With such a low number of realisations, some high-consequence low-probability realisations may be missed. Convergence cannot be judged simply by sight, as it was done for TSPA-SR. *The IRT recommends that in future a more formal approach should be taken to deciding whether the results have converged. Also, alternative sampling schemes (e.g., Monte Carlo rather than Latin Hypercube) and much larger numbers of realisations should be considered. More importantly, the probability density function (PDF) of calculated doses should be presented. A peer review by experts in statistics should be considered.*

4.3.3 Risk dilution

The probability density functions (PDF) for parameters used in the TSPA-SR represent the combined effects of stochastic variability and subjective probability representing uncertainty (incomplete understanding). There is a tendency to broaden the PDFs especially when experts are polled and subjective uncertainty is important. This is not necessarily a conservative approach and can lead to a situation where increasing ignorance leads to lower expected doses.

The Probabilistic System Assessment Group of the Nuclear Energy Assessment (NEA, 1997b) stressed that risk dilution is an issue that deserves attention in probabilistic safety assessments. In assigning PDFs to describe the uncertainty in the parameters there may be a tendency to overestimate the uncertainty, that is, to overestimate the width of the parameter distributions. The term "risk dilution" is used to describe a situation in which an increase in the uncertainty of the input parameters of a model may lead to a decrease in the mean of an output quantity. If over-estimation of uncertainty results in mean consequences being reduced, the unfortunate effect is that what appears to be a conservative step (enlarging the range of uncertainty, or advancing the occurrence of unfavourable outcomes) lead to an over-optimistic assessment of mean system performance.

One circumstance in which risk dilution is a concern is when the performance measure in question has a peak in time, and the time of the peak is affected by uncertain parameters. Averaging over the range of values of the model inputs amounts to averaging over alternative situations in which the peak value of the performance measure occurs at different times. At any given time, the mean value of the performance measure is obtained by averaging cases that lead to the peak occurring at around that time with others for which the consequence is smaller. The wider the distribution of the uncertain inputs, the more the averaging process mixes in smaller values. Hence the term "dilution".

A second case arises when increasing the uncertainty range of an input parameter leads to an increase in the time over which radionuclides are released. This can lead to a reduction in the maximum release rate and mean dose.

Finally, averaging over cases or scenarios that have very different probabilities of occurrence leads to a risk dilution effect for the high consequence situation. In this case, disaggregation of the results is necessary.

The IRT is of the opinion that the TPSA-SR presents conditions for risk dilution to have occurred, but that this issue has not been addressed nor analysed. This requires further scrutiny.

Consequentl*y, the IRT recommends that an assessment should be carried out of the quantitative importance that risk dilution might have on the magnitude of the performance measure. In future, the measures taken to avoid risk dilution should be carefully described.*

4.4 Sensitivity analysis

The IRT was favourably impressed by the methods and quality of the sensitivity analysis used in the TSPA-SR and in the supporting documents especially CRWMS *(2000b*). Sensitivity analysis is necessarily performed to determine the relevance to performance of different components and processes. *The IRT recommends that sensitivity analysis be further developed into a tool to build an integrated and comprehensive understanding of the relative importance and role of different barriers and processes.* This should be an iterative process within the project, which eventually should help to build confidence in the robustness of the barriers and provide a guide for removing complexity when the latter is not necessary.

4.5 Safety case

The development of a deep geological repository is typically characterised by several stages within a step-wise process and, overall, requires several decades for completion. The long duration of this process reflects the desire to proceed by cautious steps with due regard to technical issues and societal acceptance. At the end of each development stage a decision is taken whether to move forward, and whether the requirements for the next development stage need to be adjusted.

The various decisions must be supported by performance assessments with regard to the possibilities of achieving acceptable post-closure safety. To be complete, the decision basis must contain both comprehensive technical material, and less technical information discussing how the remaining unresolved issues, excessive uncertainties or unquantified safety margins are to be resolved. An international consensus has developed over the past few years (*NEA 1999, NEA 2001, IAEA 1997*) that it is advantageous to present the more technical arguments in respect to repository performance in a TSPA document, and the broader safety arguments in a more generic “safety case” document.

As noted in Section 2.2 *the IRT recommends that if the Yucca Mountain* project *proceeds to the licensing stage, a safety case should be developed along the lines discussed in the NEA Confidence Document (*NEA, 1999*), rather than primarily focusing on TSPA.* The key aspects of such a development are discussed below.

The safety case that presents arguments relating to the long-term safety of the repository is one of the key bases in support of the decision that is to be made. International developments in the last decade have progressively emphasised the need for a safety case in addition to more quantitative performance assessment considerations. For example the IAEA (*1997*) have described a range of considerations aimed at achieving reasonable assurance of the safety of a disposal system including multiple lines of reasoning and the use of a range of indicators.

The NEA Confidence Document (*NEA, 1999*) describes the general features of a safety case. The growing international consensus that a broadly based safety case document should be produced is further documented in NEA (*2001*), which expresses the consensus of experts from 20 national programmes. According to this and other NEA documents, the safety case is the integration of relevant arguments, at a given stage of repository development, in support of the long-term safety of the repository. The basis for a safety case lies in science and good engineering practice, and this is reflected in the detailed and rigorous modelling of the disposal system, as well as in semi-quantitative and qualitative arguments made to support long-term safety. The strategy for coupling design adjustments, research and development work and performance assessment methods in order to achieve and prove an acceptable degree of safety should be addressed.

In addition, the safety case must provide a statement of confidence in the overall assessment of long-term safety, and argue the adequacy of the present science, engineering and modelling work for the stage of repository development or function being addressed. The existence of redundant multiple barriers in the system to assure safety in cases where the performance of one or more of the barriers is not realised should also be discussed. The statement of confidence should include an acknowledgement and discussion of uncertainties and unresolved issues, and provide a road map to the work being planned to resolve those issues.

The IRT recommends that key messages from the NEA Confidence Document should be addressed in a safety case report for Yucca Mountain aimed at both the strategy to achieve safety and to demonstrate compliance. In particular, a statement of confidence should be produced, which is an elucidation of the means that were adopted to reach sufficient confidence in the current analyses, an acknowledgement of the remaining issues, and the suggested strategy for resolving the remaining issues in support of the next decision.

The IRT recognises that the YMP has been participating in developing the international recommendations in this area and that in future efforts the area of confidence documentation and communication will receive heightened attention in line with the international trends. The current version of the Repository Safety Strategy (RSS) (*CRWMS, 2000b*) is a first commendable attempt at outlining the strategy for achieving safety and for demonstrating compliance with the regulations as well as the basis for confidence in the analyses. *The IRT suggests that the information contained in the RSS should be updated and extended, and used as a basis for developing the proposed safety case document for the next phase of the programme*.

4.6 System understanding

The TSPA-SR methodology embodies a comprehensive computational framework for estimating possible doses to future generations using a complex systems-level model accounting for hundreds of features, events and processes and related parameter ranges. A key issue with this approach is the difficulty in understanding the meaning of the numerical results. In particular, it is often difficult to understand how the system is likely to evolve and which process and parameters are the most important.

Within the TSPA-SR report most attention is given to quantitative results of the performance analysis. Relatively little emphasis is placed on the important issue of developing and communicating an understanding of system behaviour. However, the sensitivity analysis techniques described in Chapter 5 of the TSPA-SR report shed some light on this question. Also, the Repository Safety Strategy report (*CRWMS, 2000b*) is a useful starting point for developing and demonstrating a comprehensive system understanding. The IRT considers that demonstrating understanding should be complementary to demonstrating compliance and of equal importance.

Two types of assessment are needed to build an overall understanding of system performance. First, *a realistic (i.e., non-conservative) assessment of system evolution and radionuclide migration should be made, regardless of whether this can be demonstrated with reasonable assurance. This would be able to communicate the likely evolution of the repository to a range of stakeholders beyond the regulators, for example by drawing on natural and historical analogues.*

Secondly, *the understanding of the TSPA results should be improved, making use of a range of approaches*, for example, the following:

- Development of an overall understanding of the key safety-relevant factors and arguments, and documentation of this in a fashion that is accessible to a wide range of stakeholders.
- Disaggregation of dose results in order to explain which factors or sub-scenarios can lead to large potential doses, explaining as well that the likelihood of occurrence would be small and also that dose – beyond a few hundred years – is not really a measure of detriment in the operational sense of radiation protection (see *ICRP, 2000*).
- Use of additional performance measures, for example showing the effects of each barrier and the spatial and temporal distribution of radionuclides within each component (e.g., waste package, EBS, UZ, SZ, receptor area) of the system.

- Development of a simplified interpretative or insight model containing only the key processes affecting safety, which can be used by people within and outside the YMP.
- Development of an understanding of the major conservatisms and optimisms in the analysis, and quantification of their impact with respect to more realistic assumptions.
- Development of an understanding of what extreme conditions might give rise to doses above prescribed regulatory criteria, and a description of the factors that make these situations unlikely.
- Description and prioritisation of the features (barriers in a broad sense) that are considered important to keep the releases and doses low;
- Documentation of where the major uncertainties are and how they might be dealt with in the future.
- Documentation of a sensitivity case where some or all engineered barriers are rendered ineffective.
- Presentation of the features and results for sub-scenarios as an aid to understanding and dialogue.
- Comparison of results with related assessments performed elsewhere.

The IRT recommends that a safety case produced in support of licensing *should incorporate an improved demonstration of system understanding to counterbalance the present emphasis on uncertainty.*

Finally, greater use should be made of the extensive archive of technical *reports produced during earlier phases of the programme. In this regard the USDOE needs to ensure that it retains a corporate memory of the YMP.*

5. Conclusions and Recommendations

The primary objective given to the IRT was to review and critically analyse the performance assessment *methodology* and *rationale* used by the USDOE in support of the current site-recommendation decision-process from an international perspective and to provide a statement regarding the adequacy of the overall performance assessment approach, and recommendations for future assessments. These three aspects are considered below.

5.1 International perspective

5.1.1 Yucca Mountain setting

The conditions prevailing at Yucca Mountain are significantly different to those considered in other national repository programmes in that Yucca Mountain is in a closed basin and the repository is in an oxidising environment above the water table. The IRT has taken due account of these differences in conducting the review.

5.1.2 Rationale

The rationale chosen by the YMP in support of the site-recommendation process was as follows. A total system performance assessment was carried out to determine whether it is likely that the selected repository concept at the Yucca Mountain site will be able to meet the quantitative licensing requirements of the USEPA standard and the USNRC proposed rule. The dose rate requirement for the 10 000 year period was met by designing the engineered barriers (with redundant features) so that, based on available corrosion data, there would be no release from the waste package under normal conditions.

This rationale is capable of addressing many important issues. However, at present, the extensive knowledge accumulated in many years of characterisation and analysis of the site is not utilised to its fullest extent. The IRT is also of the opinion that it would have been desirable to have placed greater emphasis in the TSPA-SR on the performance of the geological barriers in their own right. Moreover, a broader safety case should have been developed to support the site recommendation decision.

5.1.3 Methodology

The overall structure of the TSPA-SR methodology, and the USDOE approach of building on an iterative series of performance assessments, conform to international best practice. Moreover, the structured abstraction process linking process-level models to assessment models is at the forefront of international developments.

One of the first steps in a safety performance assessment is identification of the potentially relevant features, events and processes (FEP). The IRT has found the FEP methodology used in the TSPA-SR to be in agreement with international best practice, and recognises the contributions to the international development that has come from work within the YMP.

The YMP places far greater emphasis on probabilistic assessment than equivalent programmes in other countries. Some known issues, and particularly "risk dilution", considered in the international fora such as the Probabilistic System Assessment Group of the NEA, have not been fully addressed in the TSPA-SR.

The YMP TSPA does not emphasise natural analogues as much as in some other international studies.

5.1.4 Regulation

The regulatory requirements set down and proposed for the YMP are somewhat more prescriptive than in many other countries, both in specifying compliance requirements and in directing how these must be met. Particularly relevant in this regard is the specification of a period of 10 000 years for which the applicant must provide reasonable assurance (USNRC proposed regulation) or reasonable expectation (USEPA) that a radiation dose limit will not be exceeded. Other examples are: (i) the detailed specification of a stylised human intrusion scenario; (ii) the precise specification of the distance to the receptor area; (iii) specification of the representative volume of groundwater to be used in human uptake and dose rate calculations; and (iv) the requirement that events with probability of occurring as low as 10^{-8} per year should be modelled and assessed numerically.

The way the regulations are formulated has contributed to the tendency of the TSPA-SR to focus more on demonstrating numerical compliance with quantitative criteria than on demonstrating an understanding of repository performance. Also, the US approach to regulation has focused attention on the presentation of aggregated results that can be compared directly with regulatory requirements. The IRT considers that more intermediate results and disaggregated end results should be given. This would provide more information to decision-makers, a point emphasised in recent international recommendations on the safety of radioactive waste disposal.

5.2 Statement by the International Review Team

In response to the request by the USDOE to provide a statement regarding the adequacy of the overall performance assessment approach for supporting the site recommendation decision, the IRT considers that:

While presenting room for improvement, the TSPA-SR methodology is soundly based and has been implemented in a competent manner. Moreover, the modelling incorporates many conservatisms, including the extent to which water is able to contact the waste packages, the performance of engineered barriers and retardation provided by the geosphere.

Overall, the IRT considers that the implemented performance assessment approach *provides an adequate basis for supporting a statement on likely compliance within the regulatory period of 10 000 years and, accordingly, for the site recommendation decision.*

On the basis of a growing international consensus, the IRT stresses that understanding *of the repository system and its performance and how it provides for safety should be emphasised more in future iterations, both during and beyond the regulatory period. Also, further work is required to increase confidence in the robustness of the TSPA.*

5.3 Recommendations for future assessments

To provide better support to the next programmatic decision point, namely the preparation and submission of a license application, the IRT makes the following recommendations.

5.3.1 Understanding

1. The understanding and explanation of the behaviour of the TSPA-SR systems model should be improved, for example by placing more emphasis on disaggregation of the results. Also, a realistic (non-conservative) analysis should be made of the likely performance of the repository.

2. The USDOE should take steps to improve its corporate memory and make more use of the extensive archive of technical reports produced during earlier phases of the programme.

5.3.2 Safety case

3. A safety case report should be developed along the lines discussed in the NEA confidence document.

5.3.3 Uncertainty

4. A comprehensive and systematic methodology should be formulated and implemented for identifying and treating all types of uncertainty.

5. A study should be carried out of the quantitative importance of risk dilution for the expectation value of dose.

6. The reduction of uncertainty should be a major goal of the YMP, focusing attention on obtaining good laboratory and field data in those areas where uncertainty has the greatest effect.

5.3.4 Modelling

7. The engineered barrier transport model should be independently reviewed and improved.

8. A significant effort should be made to improve the regional saturated zone flow model, by collecting new data and improving the calibration. This effort should be closely integrated with the improvement of the site flow model. The improved flow models should be run in a spatial variability analysis, not by using a large uncertainty factor.

9. A realistic understanding, utilising natural analogues, should be developed of the likely long-term fate of radionuclides and potential pathways to man in the closed basin.

5.3.5 Documentation

10. Documents should be produced summarising the performance assessment aimed at distinct sets of stakeholders, including a summary document for the whole YM concept, context, and safety case in a form amenable to a public of informed readers.

11. A discussion of design improvements and their role in the safety strategy should be included in future safety case documentation.

5.3.6 Engineered-barrier materials

12. Long-term corrosion tests should be carried out on waste package and drip shield materials and the scientific understanding of corrosion mechanisms should be improved.

5.3.7 Waste form

13. The inventory screening procedure should be reviewed and amended as appropriate, so that all potentially important radionuclides are included in the analysis.

14. Further work should be carried out to strengthen confidence in the role of the cladding as a long-term containment barrier.

15. More experimental data should be obtained to validate thermodynamic modelling, especially with regard to the complex interactions between the waste form and components of the waste package.

5.3.8 Unsaturated zone

16. Additional experiments should be performed to enhance confidence in the model of flow and transport in the unsaturated zone.

17. Head measurements in the rock matrix and water extraction by the ventilation system should be used to test the 3-D unsaturated zone model.

5.3.9 Disruptive events

18. The probability of bimodal basaltic-rhyolitic volcanism should be estimated and, if relevant, its consequences analysed.

5.3.10 Human intrusion

19. Direct flow of surface water into the human intrusion borehole should be considered in future assessments.

5.3.11 Natural analogues

20. The USDOE should carry out further work at the Peña Blanca uranium deposit in northern Mexico.

21. Investigations of naturally occurring uranium and its radioactive progeny in the tuffs at Yucca Mountain should continue to be investigated.

5.3.12 Features, events and processes

22. The screening of FEPs should be carried out in two stages. The first stage should retain all FEPs required for a full understanding of repository performance, while the second stage should include regulatory considerations in the screening criteria.

5.3.13 Probabilistic methodology

23. A best estimate or the most probable dose range plus the upper limit value at an appropriate percentile should be presented as a measure of the maximum reasonably expected value.

24. A probabilistic analysis should be made based on a realistic rather than conservative representation.

25. A more formal approach should be taken to deciding whether the probabilistic results have converged. Also, alternative sampling schemes and much larger numbers of realisations should be considered.

26. The probability density function (PDF) of calculated doses should be presented.

5.3.14 Sensitivity analysis

27. The sensitivity analysis should be further developed into a tool to assist in building an integrated and comprehensive understanding of the relative importance and role of different barriers and processes.

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Appendix 1

Terms of reference of the Joint Nuclear Energy Agency/International Atomic Energy Agency International Peer Review of the Yucca Mountain Site Characterisation Project's Total System Performance Assessment Supporting the Site Recommendation Process

1. Introduction

The purpose of these Terms of reference is to formulate the conditions for the international peer review service to be rendered by the IAEA and the NEA to USDOE (YMP). The international peer review will be a consensus review conducted by an Expert Team that is to be organised by a Joint Secretariat formed by the NEA and IAEA. The IAEA participates in the context of that Agency's statutory functions to perform services useful in research on, and development or practical application of, atomic energy for peaceful purposes, and to establish international standards of safety and provide for their application. The NEA participates under its mandate for improving and harmonising the technical basis for dealing with nuclear waste related issues among its Member countries.

2. Objectives

The objective of this international peer review is to provide, consulting the bases of available international standards and guidance as appropriate, an independent assessment of the methodology developed by the USDOE's Yucca Mountain Site Characterization Project, as reported in the document: Total System Performance Assessment for the Site Recommendation, TDR-WIS-PA-000001 Rev. 00, ICN 01.

The international peer review will entail a review and critical analysis of the performance assessment methodology and rationale being used in support of the current site-recommendation decision-process. It will be conducted taking account of the international experience in preparing for and conducting system-level post-closure performance assessments. In addition, the relevant international standards and practices, and specifically the requirements proposed by the U.S. Environmental Protection Agency and the U.S. Nuclear Regulatory Commission, should also be considered as bases.

This should be a technically oriented review. One aspect of the review would, however, be to identify consistencies and inconsistencies between methods being used in this USDOE project and those being considered or developed in international recommendations, standards or practices.

In requesting this international peer review, the USDOE is asking for a statement regarding the adequacy of the overall performance assessment approach for supporting the programmatic decision at hand (a site recommendation). In addition, detailed recommendations are expected to be provided for specific technical and other improvements that would help performance assessment better support the next programmatic decision point, if the site is recommended and subsequently approved, which entails the preparation and submission of a License Application.

3. Scope

The review will be primarily based on the document TDS-WIS-PA-000001 Rev.00, ICN 01, that describes the performance assessment modelling methodology and approach, and its scientific basis. Consideration of any updates to this document, and its supporting documents, during the review period will require prior agreement between the USDOE and the Joint Secretariat.

Several key Process Model Reports (PMR) and associated Analysis and Model Reports (AMR) will need to be consulted for this review. This material is to be supplied by the USDOE as requested by the joint Secretariat.

A list of documents to be reviewed and considered as deemed appropriate by the reviewers is given in the annex to this document.

In conducting the review, consideration will be given to:

- The technical basis for the performance assessment, including identification and justification of the conditions and characteristics modelled at the system level; this would include a review of the abstractions of the adopted design and the scientific basis for determining future environments in the system and its materials and natural systems behaviours.
- The development of the key conceptual models, including the assumptions made with respect to the representations of relevant features, events and processes (FEPs).
- The adequacy of the treatment of the undisturbed and disturbed system performance.
- The adequacy of the methods used, and the cases considered, in sensitivity and uncertainty evaluations.
- The overall clarity and completeness of the technical report describing this system-level performance evaluation.

4. Process and deliverables

The review will be conducted by a team of international experts (the Expert Team) with experience in aspects of system-level long-term performance assessment evaluations. The team members will be selected by the Joint Secretariat.

The Expert Team will prepare an International Peer Review Report that documents its proceeding, findings, and recommendations. The International Peer Review Report will be delivered to the USDOE, for fact checking only, prior to finalisation. The USDOE will not comment on the substance of the draft report, but will suggest corrections where facts are misstated. All meeting records and correspondence involving the USDOE are to become part of the USDOE records system.

The USDOE is, for its own purposes, preparing a document called the "Plan for the International Review of the Total System Performance Assessment in Support of the Site Recommendation Process (TSPA-SR Review Plan). A draft is attached as Reference 1.

The TSPA-SR Review Plan will make several demands on the Department of Energy in terms of the transparency of the process, its openness to public observation, and its documentation. These demands require certain specific but reasonable actions by the Joint Secretariat. Those who have signed the cover page of this document have agreed in principle to these actions. In summary, the required actions are:

1. To select the members of the Expert Team in accordance with a written criteria statement, and to provide to the USDOE the criteria statement and why the selected person meets the applicable criteria (a curriculum vitae or other statement of experience usually suffices).
2. To allow public observers at any meetings involving the USDOE and its contractors where technical questions are asked and technical information is exchanged.
3. To provide the USDOE a draft of the interim and final reports for fact checking only.
4. To acknowledge that all correspondence involving the USDOE or its contractors, including by e-mail, will become part of the USDOE records system; public access thus becoming possible.

5. Schedule

May to early June 2001

Planning activities. TSPA-SR documentation is received by the Joint Secretariat. Agreement is reached on the Terms of reference. Cost estimates are provided by the Joint Secretariat. Contract papers are prepared by USDOE and submitted to the IAEA, a grant application is prepared by NEA and submitted to USDOE.

Expert Team and its Chairman are identified by the Joint Secretariat. USDOE identifies potential objections to any nominated members based on conflicts of interest or other documentable objections, only if absolutely necessary, and does so in an official USDOE project record. Contract/grant papers are finalised. Signature of agreement (DOE, IAEA, NEA) is finalised. The Joint Secretariat provides the relevant documentation to the members of Expert Team.

Mid-June 2001

Orientation Meeting of Expert Team in Las Vegas or Paris, (a) to allow the Expert Team to gain a common in-depth understanding of the objectives of the peer review; (b) to have the Expert Team briefed on contents of the main document for review along with its supporting documents; (c) to establish subject-matter expertise between team members and agree to an internal modus operandi. If the meeting is held in Las Vegas, (d) to visit to the YM site.

June to mid-August 2001

Expert Team reviews documentation received and receives any draft supplementary materials discussed in the Orientation Meeting or requested by Expert Team. Sets of questions will be formulated by the Expert Team and provided to USDOE by the Joint Secretariat. Responses will be provided in writing by the USDOE.

End of August to mid-September 2001

A second one-week review meeting will be held in Las Vegas where members of the Expert Team will interact with DOE staff and contractors. The preliminary findings will be presented orally to the USDOE at the end of the week. If the first meeting was not held in Las Vegas, there will be a whole day visit to the YM site as part of this meeting.

October 2001

Completion of an executive summary report that firms up and finalises the preliminary findings, and gives a preview of the final Peer Review Report. The purpose of this report is to notify higher level managers in the USDOE of the results of the review at a less detailed level. The final Peer Review Report should add the detail needed to make the review of use to the technical levels of the USDOE in planning new work to improve the product for the next iteration of TSPA.

November 2001

Completion of the draft final Peer Review Report and submission of it to USDOE for fact checking only, with written comment response to be received from the USDOE within 30 days. The report will be finalised taking into consideration the response.

January 2002

Final Peer Review Report to USDOE and Chairman's briefing to USDOE on highlights from the report. Acknowledgement of receipt by USDOE of the final Peer Review Report.

Reference

1. (Draft of) "Plan for the International Review of the Total System Performance Assessment in Support of the Site Recommendation Process" (TSPA-SR Review Plan, a document binding on the US Department of Energy only).

Members of the International Review Team

From left to right: Phil Metcalf, Yasuhisa Yusa, Claudio Pescatore, Tönis Papp, Ghislain de Marsily, Mel Gascoyne, Des Levins, Emmanuel Smailos, Jesús Alonso, David Hodgkinson.

Appendix 2

Members of the International Review Team

Tönis Papp (RwS Konsult, Sweden) – IRT Chairman

Tönis Papp was until March 2001 Research Director of SKB, Swedish Nuclear Fuel and Waste Management Company, and is now after his retirement working as a private consultant.

Tönis Papp graduated in Physics and Chemistry at Stockholm University in 1966 and became involved with nuclear issues when joining the Swedish State Power Board, the present Vattenfall, in 1967. He was appointed to the KBS-project, the radioactive waste management project operated by the Swedish nuclear utilities, when it was formed in 1976. Mr Papp has stayed with that programme after it was transformed to a company with the responsibility to implement a safe management and final disposal of the Swedish radioactive waste until his retirement in March 2001. He was in 1981 appointed manager of the SKB Safety Assessment Programme, and in 1991 Research Director of SKB, including both the Research Programme and the Safety Assessment Programme.

Tönis Papp has been a member of the NEA Committee on Radioactive Waste Management during the periods of 1981-1989 and 1997-2001. From 1986 to 1999 he was also a member of the RWMC Performance Assessment Advisory Group, and during the period 1986-1989 as a chairman. In 1989 he participated in the IAEA–WATRP Peer Review of the NIREX R&D programme, and has from the SKB side been involved in the international peer reviews of the SKB safety reports of 1978, 1979, 1983 and 1999.

Tönis Papp is a member of the Nordic Society for Radiation Protection and has from 1998 until his retirement in 2001 been a member of the Research Council for the Centre for Safety Research within the Royal Institute of Technology, Stockholm.

Jesús Alonso (ENRESA, Spain) – Panel Member

Jesús Alonso holds a degree in engineering of energy by the Politechnical University of Madrid (Spain) and a specialisation certificate by the École supérieure d'électricité, Paris (France). He has about 30 years of professional experience in the nuclear field, including 14 years in power plant industry. He has devoted the last 15 years to radioactive waste management (both low and high level).

Jesús Alonso started his professional career in 1972 when he joined the French Nuclear Power Plant Constructor, Framatome. In 1976, when he joined Empresarios Agrupadosas in Madrid as a senior engineer where he participated in the design, construction and operational analysis of several nuclear power plants (both PWR and BWR).

In 1986 he joined ENRESA, the Spanish agency for the management of radioactive wastes, which had been created the year before. His initial commitment was the safety analysis, construction follow up and licensing of the El Cabril near surface disposal facility, and subsequently the analysis of operation and first renewal of the operation permit.

From the start he was also involved in the safety studies for the management of high level radioactive waste. He was in charge of the first generation of safety assessment studies for geological disposal concepts carried out by ENRESA, and conducted the participation of the latter in European R&D projects on the safety assessment of geological repositories (SPA, BENIPA, SPIN), as well as for other R&D international projects in the area of disposal of radioactive wastes. Since 2001 he has been the head of ENRESA's Engineering Team in charge of the design and safety assessment of the Deep Geological Disposal Project (AGP). In late 1999 Jesús. Alonso was appointed a member of the Conseil scientifique de l'ANDRA, advisory group to the French agency for the management of radioactive wastes on the programme for the development of repositories for high and intermediate level wastes.

He has represented ENRESA in the NEA-PAAG Working Group, and is also a member of the Integrated Group for the Safety Case and of its Core Group. He has also participated in a number of NEA-RWMC Working Groups. In addition he has been appointed as an expert to a number of IAEA advisory groups, and the RADWASS Programme.

Ghislain de Marsily (University Paris VI, France) – Panel Member

Ghislain de Marsily graduated as a Mining Engineer in 1963 at the Paris School of Mines, and received his Doctoral degree from the University Paris VI in 1978. He initially worked as a drilling engineer in oil fields in the Sahara, and as a civil engineer in dam construction in France.

In 1966, he founded a new research group in hydrogeology at the Paris School of Mines in Fontainebleau, which he headed until 1985. During that time he also taught hydrogeology and environmental sciences at this school. In 1987 he was appointed Professor at the University of Paris VI and head of the Applied Geology Department.

The interests of Ghislain de Marsily range from water resources to waste management, with special emphasis on nuclear waste issues. He is the author of three books, more than one hundred publications in refereed journals, and two hundred articles in conference proceedings and other journals.

Ghislain de Marsily has served on expert committees relating to nuclear waste issues for the Swedish Nuclear Inspectorate, the Swiss Paul Scherrer Institute, the European Commission, the UK Environment Agency, the US WIPP project, the US-NRC TPA international review group, the French nuclear safety authorities, and the French CNE (equivalent to the US NWTRB). He was a member of the IAEA international study on the radiological situation at the atolls of Mururoa and Fangataufa in French Polynesia. Prof. de Marsily has served on two US National Academy of Sciences/National Research Council reports on nuclear waste issues. He is a member of the French Academy of Technology, a Foreign Associate of the US Academy of Engineering, a Member of the Academia Europea, an Associate Member of the French Academy of Sciences, and an American Geophysical Society Fellow.

Melvyn Gascoyne (Gascoyne GeoProjects, Canada) – Panel Member

Mel Gascoyne has been a geochemical consultant since 1998. For 16 years prior to that, he was a Senior Scientist with Atomic Energy of Canada Limited, and Head of the Hydrogeochemistry Section of the Applied Geosciences Branch, at the Whiteshell Laboratories, Manitoba.

Mel Gascoyne was responsible for obtaining and interpreting geochemical data for the Canadian Nuclear Fuel Waste Management Program for the characterisation of several crystalline rock formations in Canadian Shield. His particular areas of expertise include the use of naturally occurring stable and radioactive isotopes in groundwater to determine its residence time (age), sources of dissolved salts and geochemical evolution, and the application of uranium decay methods for dating fracture minerals and determining the timing of recent alteration.

Since leaving AECL, Mel Gascoyne has performed consulting work for document review, report preparation, isotopic analysis of groundwaters, short course presentation and laboratory analysis, with the British Geological Survey, SKB (Sweden), POSIVA OY (Finland), Ontario Power Generation, AECL (Canada), the US Geological Survey (Denver), Duke Engineering (Canada), and NOVA Chemicals (Canada).

Mel Gascoyne obtained his B.A. (Honours) in chemistry (1969) and M.Sc. in Environmental Sciences (1974) at the University of Lancaster, U.K., followed by his Ph.D. in geology at McMaster University, Hamilton, Ontario, Canada. After two years of post-doctoral work at McMaster, he joined AECL to work on geochemical aspects of nuclear waste disposal. He was a contributing author to the Environmental Impact Statement for nuclear waste disposal submitted to the Canadian Federal Government in 1995 and subsequently defended in public hearings.

Mel Gascoyne is the author of over 60 journal and conference papers and over 45 technical reports and QA documents for commercial projects. He has been an Associate Editor of the journal Applied Geochemistry since 1988, Secretary of the International Association of Geochemistry and Cosmochemistry since 1992, and member of the Board of Directors of the ISOTRACE Accelerator Mass Spectrometry facility, University of Toronto since 1997.

David Hodgkinson (Quintessa, UK) – IRT Scientific Secretariat

David Hodgkinson has a B.Sc. in physics from Bristol University and a Ph.D. in theoretical physics from Cambridge University. In 1972-1973 he was, a NATO Research Fellow in the Theoretical Physics Division at the European Centre for Nuclear Research (CERN) in Geneva where he worked on theoretical approaches to understanding pion-pion and pion-nucleon scattering based on the general principles of unitarity and analyticity. The following year was spent at Lawrence Berkeley Laboratory in California as a Lindemann Trust Fellow working on the interpretation of data for pion-nucleon reactions.

In 1974, he joined the Theoretical Physics Division of the United Kingdom Atomic Energy Authority at Harwell, initially working on the development and application of theories for atomic collisions and the excitation of atoms by intense laser beams, in connection with atomic vapour laser isotope separation. In the following years, this work expanded to include theoretical aspects of the molecular route to laser isotope separation including the development and application of theories relating to the non-linear excitation of polyatomic molecules by intense laser beams.

In 1977, David Hodgkinson started his involvement with radioactive waste disposal assessment, initially developing and applying models for assessing the local and global temperature fields associated with the disposal of high-level waste, and the effects of thermal stresses and thermal buoyancy driven groundwater flow.

In the early 1980s, his work on radioactive waste disposal modelling and assessment expanded to include the interpretation of tracer experiments in fractured rock, the development of models for the transport of water-borne radionuclides through permeable and fractured rocks, and the development and application of source-term models for intermediate-level waste. In addition he participated in a number of international exercises including INTRACOIN and HYDROCOIN.

In 1986, David Hodgkinson was appointed as project manager for the Nirex Safety Assessment Research Programme and the Nirex Disposal Safety Assessment Team. In regards to the research programme he was responsible for the scientific direction of a multidisciplinary research programme including experimental and modelling work on chemical, physical and microbiological processes. Also the assessment team produced a comprehensive radiological assessment for the disposal of low-level waste at four potential near-surface disposal sites.

In 1987 David Hodgkinson founded the UK Environmental Division of Intera Information Technologies (later renamed QuantiSci) where as Vice-President he built an international business related to radioactive waste disposal performance assessment. During the following decade he carried out a wide range of projects related to the development and application of performance assessment methodologies and models. In particular he acted as chairman of the Scenarios Working Group of the OECD Nuclear Energy Agency, and was a member of steering committees for the international Stripa, Project-90 and INTRAVAL projects, and participated in a management committee of the Paul Scherrer Institute in Switzerland.

In 1999, David Hodgkinson founded Quintessa Limited as an Anglo-Japanese employee-owned scientific consultancy specialising in strategic and scientific aspects of the disposal of radioactive and other hazardous wastes. At Quintessa he has been involved in a number of projects including the review and documentation of performance assessments and associated research, the quantification of impacts associated with retrievability provisions for geological repositories, and the development of new approaches to the structure, content and presentation of safety cases.

Des Levins (Consultant, Australia) – Panel Member

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

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

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

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

In 1996-98, he was a member of the international study, organised by the IAEA, on the radiological situation at the atolls of Mururoa and Fangataufa in French Polynesia. As chairperson of Task Group B, he was responsible for co-ordinating the scientific assessment of the long-term releases of radionuclides from the underground cavities where nuclear tests had been conducted.

Phil Metcalf (IAEA) – IRT Secretariat

Phil Metcalf is presently head of the Disposable Radioactive Waste Unit within the Department of Nuclear Safety of the International Atomic Energy Agency. His responsibilities include development of international standards for the safety of radioactive waste management and a range of activities providing for application of the standards. The latter include peer review missions, technical assistance missions, information exchange activities and training courses. Prior to joining the IAEA early in 2001 he was Deputy General Manager of the South African National Nuclear Regulator where he was responsible for the scientific and technical aspects of licensing nuclear fuel cycle facilities within South Africa. The latter included uranium mining and processing activities, uranium conversions, enrichment and fuel fabrication, power and research reactors and radioactive waste management facilities.

He has been actively involved in the development of international standards for radiation and waste safety over the past twenty years. He was Chairman of the IAEA Waste Safety Standards committee for a period of six years and was actively involved in the development of the Joint Convention on the Safety of Spent Nuclear Fuel and the Safety of Radioactive Waste Management. He is presently Vice President of the International Radiation Protection Association

Phil Metcalf holds an honours degree in physics and a masters degree in radiation health and safety from the University of Salford in the UK.

Claudio Pescatore (OECD/NEA) – IRT Secretariat

Claudio Pescatore holds a Ph.D. in nuclear engineering from the University of Illinois, Urbana-Champaign (USA). He has over 20 years' experience in the field of nuclear waste covering low-level waste, high-level waste and spent-fuel storage and disposal.

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

Claudio Pescatore joined the OECD/NEA in 1992 in the Division of Radioactive Waste Management and Radiation Protection, where he is the Deputy Head for Radioactive Waste management. He has been at the centre of several recent international initiatives such as the ASARR and GEOTRAP projects, and the IPAG studies, and co-author of several NEA reports on the status of and issues in radioactive waste management world-wide. He is a co-author of the NEA Confidence Document. He assures the technical secretariat of several NEA committees: the Radioactive Waste Management Committee (RWMC), the RWMC Regulators' Forum, the Working Party on Decommissioning and Dismantling, and the Forum on Stakeholder Confidence. On behalf of the NEA he has organised numerous international peer reviews of national safety studies. These include: SKI's Project-90 (Sweden), AECL's Environmental Impact Statement of the Disposal of Canada's Nuclear Fuel Waste, the 1996 Performance Assessment of the US Waste Isolation Pilot Plant (WIPP), the SKI's SITE-94 project (Sweden), the Nirex methodology for scenario and conceptual model development (UK), the JNC's H-12 Project to establish the technical basis of HLW disposal in Japan, and the SR 97 study by SKB the Swedish spent fuel management company.

Emmanuel Smailos (Institut für Nukleare Entsorgung, Germany) – Panel Member

Emmanuel Smailos received his Doctor Engineer in Mechanical Engineering in 1974 from the Technical University of Karlsruhe in Germany. He joined the Forschungszentrum Karlsruhe in the Institute for Material Research in 1968 and gained six years' experience in the material sciences, especially in the Powder Metallurgy. The theme of his dissertation was

"Chemical Reactions of Radionuclides in Simulated Uranium Nitride and Uranium Carbide Nuclear Fuels".

Emmanuel Smailos changed in 1974 to the Institut für Nukleare Entsorgung of the Forschungszentrum Karlsruhe where he is since 1980 Head of the Corrosion Group. He has very long experience on corrosion of metallic container materials for high-level waste and nuclear spent fuel as well as in the field of disposal of radioactive wastes in geological formations. He is the author of over 100 publications and conference proceedings, and he has co-ordinated for more than 10 years international corrosion programmes in the frame of the Research and Development programmes of the European Commission in Brussels, Belgium. He has also served as an expert consultant to international programmes of the IAEA in Vienna.

Yasuhisa Yusa (Japan Nuclear Cycle Development Institute, Japan) – Panel Member

Yasuhisa Yusa is the Chief Senior Scientist of Tono Geoscience Center, Japan Nuclear Cycle Development Institute (JNC), where he is responsible for geoscientific studies including those on geological environments and their long-term stability in Japan. He began his experience in radioactive waste management at the Power Reactor and Nuclear Fuel Development Corporation (PNC, now JNC) in April 1987.

Yasuhisa Yusa obtained a B.Sc. in chemistry at Shizuoka University in 1969 and a M.Sc. in earth science at Nagoya University, followed by his Ph.D. in earth science at Nagoya University in 1981. His main area of study was volcanic activity.

After seven years of work as a research associate at Nagoya University, he joined PNC in 1977. From 1977 to 1986, his job was related to uranium mineralogy and ore petrology for uranium exploration.

From 1987 to 1991 he was a deputy general manager of the geological isolation technology section of Tokai Works, PNC. After 1991, he moved to Tono Geoscience Center, where geoscientific studies are carried out leading to reports such as the second Progress Report (referred to as the H12 report).

Yasuhisa Yusa was a member of the OECD/NEA Site Evaluation and Design of Experiment (SEDE) Group during 1992 to 1996.

Appendix 3

Saturated zone hydrogeology

In Section 3.6 of this report, the IRT observed that the SZ flow system at YM is very complex and not sufficiently understood to propose a conceptual model for a realistic transport scenario. A number of site-specific features should be further investigated before realistic flow models can be built. This appendix presents a critical review of the present level of understanding and modelling of the hydrogeology at YM and of the features that require further investigation.

The comments in this appendix are based essentially on a review of USGS reports R96-4300 (*D'Agnese* et al., *1997*) and R96-4077 (*Luckey* et al., *1996*)), which are referred to as forming the basis of the hydrogeology of the site used in the TSPA-SR report.

In general the level of understanding of the hydrogeology of the site, based on these documents, is low, unclear, and insufficient to support an assessment of realistic performance. Furthermore, the modelling that has been carried out so far at the regional level, is not up to international standards and does not make optimal use of all the available data. This regional modelling is important as it provides boundary conditions for the local model and helps to determine the conditions at the site for future climates.

A better understanding of the flow through the saturated zone is necessary for at least two reasons:

- Estimating the groundwater travel time, and the nuclide travel time and flux at the regulatory limit, potential retardation mechanisms being taken into account, both in present-day conditions, and for a more humid climate.
- Estimating the potential dilution, which could occur between the repository and the selected abstraction zone.

From the evidence presented in USGS reports R96-4300 and R96-4077, it seems that these objectives cannot be met today, with any degree of confidence. With the present level of understanding it is a question of conceptual model uncertainty, not of parameter uncertainty. Therefore, the approach used in the TSPA-SR, namely to assume that a lack of exact knowledge can be compensated for by assigning a range of parameter uncertainties to a selected conceptual model assumed to represent the uncertain mechanisms, is not applicable. The conceptual model of flow in the saturated zone at YM is as yet undecided and uncertain and does not permit the building of a local model of flow and transport that would adequately address the two requirements listed above.

The site is obviously very complex, and the series of stratigraphic units in which flow is taking place is interbedded, fractured, highly variable both vertically and horizontally, and undersampled. The USGS Report R96-4300 describes the regional hydrogeology of the Death Valley system, and will be reviewed first. The USGS Report R96-4077 describes the local hydrogeology of the site, embedded in the regional setting. The first report is at best a preliminary attempt at quantifying this regional system, for which the IRT has some severe reservations. It cannot be viewed as a framework in which the local hydrogeology can be understood nor does it constitute the scientific basis on which to understand the flow system. The second report is more comprehensive and offers a better view of the local hydrogeology. However, it raises a large number of issues and presents several alternative conceptual models of the site, which cannot be judged at the present level of knowledge.

In general, the development of a conceptual model of the hydrogeology of a given area goes through the following steps:

1. Determination of the boundaries of the system;
2. Description of the major lithofacies in the domain, with their geometry, major properties, measured heads, etc;
3. Estimation of the recharge and discharge fluxes;
4. Development of a numerical model of the complex system;
5. Calibration of the model using all existing data;
6. Sensitivity studies.

This logic is followed when reviewing both USGS reports.

1. Review of Report USGS R96-4300

1. Boundaries. In the USGS report, the selection of the boundaries of the system seems relatively appropriate, although it is not a closed system. It would have been more satisfactory to extend the limits up to the actual physical boundaries of the system being drained by Death Valley; i.e., no-flow boundaries. However, the studied area is already very large, and the fluxes which have to be estimated on some parts of the boundaries which are not “no flow” must be relatively small, and would probably not greatly affect the global hydrologic balance and the understanding of the system.

2. Lithofacies. The description of the lithology is good in general terms, and the building of a Geoscientific Information System (GIS) to store and represent all the information on the 3-D geology of the site is a very good step. There are serious gaps in the knowledge because of the existence of large areas with few or no borehole data, or insufficient depth of the boreholes. One absence of data appears to be in geophysics. There is no reference to the use of geophysical data in the report, nor mention of the existence of such data. It is likely that much geophysical data have been gathered as part of the work done towards constructing the geologic model, prior to developing the flow model, because, a lot of useful information can be obtained from aeromagnetic surveys, gravimetric maps, seismic profiling, electromagnetic soundings, electric resistivity maps, etc. At other sites, studied for regional and local hydrogeology, particularly in nuclear waste disposal projects, such geophysical surveys have been made and used. This is all the more true as the second report R96-4077 mentions the existence of a large number of geophysical surveys of the area. The 3-D geologic model should have been consistent simultaneously with the borehole information, the surface geology, and the geophysics.

The information on the head distribution is inappropriately lumped into one single "average" system. There is only one piezometric map for the ensemble (Figure 27), and no attempt was made to present information on the differences in heads between the various units. It is understood that this is difficult, as the position of the screens in the wells is not well known, but some attempts at describing the head differences between hydrogeological units should have been made. Are there vertical head gradients? Which are the units receiving or releasing water by vertical leakage? Are there low-permeability layers separating the various units? Only one such layer is mentioned, the Eleana formation separating the upper and lower carbonate aquifers (Palaeozoic rocks). The analysis of the piezometric data is not detailed enough to obtain an understanding of the vertical exchanges between the different lithological units, nor a realistic understanding of the physics of the system.

When such important data are lacking, a detailed geochemical analysis of the water composition can help understand the importance of leakage (particularly when there are rocks as different as volcanics, carbonates, alluvia, etc). The geochemical signature of the waters could help to better understand the flow system. None of this appears to be considered in the report. By contrast, the second USGS Report R96-4077 puts a lot of effort into analysing the differences in heads between the various hydrogeological units, and particularly between the volcanics and the carbonates, which seems to be a very important issue. The use of the geochemical data is also mentioned and used in this second report.

3. Recharge/Discharge. Concerning recharge and discharge, it is understood that the problem is difficult, since neither is easily measured. But the presented work is not convincing. For one thing, direct evaporation of water from the water-table, even without any vegetation, is not discussed nor estimated. In arid areas, it is well known that evaporation can withdraw water even if the water-table is very deep. There are measures available with water-tables as deep as 10 m below ground, and empirical rules that relate evaporation to depth. In some areas, in Africa, in the 200 mm/a rain-depth area, there are closed depressions where the water-table is more than 70 m deep (it is not however proven that evaporation is the only cause of these depressions). Similarly, the estimation of recharge as percentages of rainfall, which vary with altitude, or classification of vegetation, slope or soils looks very arbitrary.

Furthermore, in arid climates, recharge often occurs by runoff followed by re-infiltration in wadis or gullies. This is not discussed in the report, nor is it evaluated. Moreover, in such systems, the recharge is often episodic, and occurs only in a few extreme years (e.g., every 30 years in North Africa, on average). If these episodic recharge events are not considered, the global water balance of a large system may be strongly biased. By contrast again, the USGS second report R96-4077 mentions both the infiltration in the Fortymile Wash, and the importance of major flows, the last major flow that occurred was in 1969, but extreme events occurring at frequencies such as every 500 years are mentioned.

When such uncertainties on recharge and discharge are present, it is necessary to use additional sources of information to try to estimate fluxes. Environmental tracers are used, e.g., the salt balance, the ensemble of natural tracers, and the "age" of water is used to determine velocities, and hence fluxes and hence recharge. Temperature anomalies in borehole profiles are sometimes used to estimate fluxes, both vertically and horizontally. These are not discussed in USGS reports R96-4300 and R96-4077.

Finally, the hypothesis is made that the system is in steady state. Until calculations have been made that show that a steady state is relatively rapidly established in such a large system, which would be surprising, the assumption of equilibrium seems largely arbitrary: the system may still be reacting to past climate changes. By contrast again, the second USGS report R96-4077 specifically points out that the regional system may not be at equilibrium. Indeed the Winograd and Doty (*1980*) and Claassen (*1985*) references in USGS R96-4077 have precisely suggested that the system is still in a transient condition resulting from pluvial cycles during the Quaternary. This is not considered in the report.

4. Modelling. The modelling attempt that follows is unsatisfactory. Even if it may be an improvement on previous models, by being partly 3-D, the presented work is rudimentary and not up to standard international practice. For modelling of that complex system, two options were available:

1. To construct a very detailed geologic grid in 3-D from the GIS, supplemented with all the available geophysical information, using millions or even billions of nodes. In general, this grid is very thin

in the vertical direction (e.g., 10 cm) and on the order of 10 m horizontally. This scale was for instance used in the study of the London Basin. The exact (or assumed) geometry of each lithological unit is thus finely described and discretised. Each unit is assigned its estimated anisotropic hydraulic conductivity value. Then, a 3-D calculation grid is superimposed on the previous geologic one, with as many nodes as feasible given the available computing power (but currently closer to a million cells than on the order of 75,000 used by the USGS). A rigorous upscaling of the geologic model hydraulic conductivities to the scale of the flow model is made, giving the anisotropic hydraulic conductivity of the flow model (see for instance *Renard and Marsily, 1997*). Calibration of such a model is made by changing the hydraulic conductivity of lithofacies of the detailed model, and upscaling again, not by adjusting the flow model conductivity. The importance of each layer can then be assessed individually.

2. To construct a very detailed multi-layer model, where each aquifer lithological unit is represented by a layer of meshes, and vertical links representing leakage are introduced between layers, with estimated vertical permeabilities. The extension of each layer is not necessarily continuous, and each layer is not necessarily present on all sites. It is common to use up to several tens of superposed layers, if necessary. The fitting of such a model is then based on treating each layer as a more or less homogeneous zone, (or subdividing it if it has known large variations e.g., of thickness, density of fractures, etc) and on calibrating the vertical conductivity between layers as well. This approach is consistent with, for instance, the detailed description of the hydrogeological units at the site scale given in USGS R96-4077.

Neither of these two options was followed by USGS R96-4300. Instead, an arbitrary coarse mesh of three continuous layers was built. The hydraulic conductivity was assigned to each mesh in a crude fashion, by using the 50 percentile K value for each of the zones in the model, each zone having been defined by limiting the permeability to four different classes in the whole domain. These permeabilities were used as initial guesses, and then an automatic inverse procedure based on linear regression theory was used to improve the hydraulic conductivity distribution in the model. The selected grid size is elementary. Uniform squares were used over the whole domain, whereas it would have made much more sense to have variable size meshes, e.g., nested squares meshes, and to focus the grid on the areas of interest, i.e., the Yucca Mountain area and the downstream area towards Death Valley. This was not done.

The transmissivity in the model is assumed to be constant, and not a function of the saturated thickness of the aquifer. While this may be an acceptable starting point, it is not sufficient and should have been turned into a variable saturated thickness model, in order to study (as a complementary calibration exercise) what happens in the model during a humid period, when the recharge is higher. Such a calculation is for instance suggested in the second USGS Report R96-4077. Since a few indications of past elevation of the water-table are available, this would have been a second independent test of the plausibility of the model. This was not done.

At this stage of the development of the model, using an automated calibration method to improve the fitting is not useful. It may well decrease the discrepancy between observed and calculated heads. However, the structure of the model is so poor that it does not improve in any way the understanding of the actual functioning of each of the lithological units of the system (whereas the methods (i)or (ii) above would have). The IRT also has strong reservations on the method of calibration. The hydraulic conductivity values have been initially grouped into four zones, each zone being assigned an initial hydraulic conductivity, as indicated above, and then this value is improved by automatic calibration. But the pattern of each zone is kept constant in space. These patterns are given in Figures 44, 46 and 47 for each of the three layers of the model. In fact, more than four zones were introduced, to account for some local complexities, a maximum of nine zones was finally selected. But the essence of the fitting is the following: if two areas of the model, tens miles apart or more, happen to belong to the same zone, the model calibration is forced to assign the same hydraulic conductivity to both zones. This does not make sense, and could be called “under-parameterisation”. If a zone could be identified with a lithology, this could have been a defensible approach, but given the arbitrary uniform discretisation that was used, a “zone” is a complex assemblage of different lithologies. When the role of faults, the variability of facies, the thickness of each layer are so variable, this arbitrary calibration constraint does not make sense. The grid is inappropriate, but even with this grid, an initial manual trial-and-error fitting would have been more reasonable than this automatic calibration. Moreover, the fitting of the model is poor, the head residuals are large, 20 m is considered a good fit, a moderate fit is between 20 and 60 m of residuals, and a poor fit has residuals greater than 60 m. The same applies to spring flow.

5. Sensitivity. The sensitivity study that follows adds very little, given all the reservations on the structure of the model, the parameterisation, and the fitting. Its only merit is that it is concluded from this analysis that the model is highly non-linear, and that the linear regression analysis that is presented is only a rough indicator of simulation uncertainty. It does not give any clues to the important pathways for the water in the system (e.g., is most of the water flowing in the palaeozoic carbonates? How important is vertical leakage? Are the alluvial sequences draining the system? What is the role of faults? Are the volcanic rocks anisotropic?, etc.).

2. Review of Report USGS R96-4077

This report is a much better description of the hydrogeology of the site (at the local scale) than the previous one (at the regional scale). It provides a comprehensive description of the major hydrogeological units, their relations, and the various conceptual models, which have been proposed to explain the observations. Although this work has been superseded by the new local SZ model developed by USDOE (*TRW, 2000*), the IRT's concerns about this report are as follows:

- Page 3. The IRT disagrees with the statement that "because ground-water travel time in the saturated zone probably is much shorter than travel time in the unsaturated zone (*USDOE, 1988*) only limited characterisation of it may be appropriate". For one thing, the transfer in the unsaturated zone is no longer considered to be very long, and second, the dose to man is assumed essentially to occur through receptor wells at the regulatory limit, the flux to this limit cannot be accurately determined if the hydrogeology is not understood.
- Although the existence of geophysical data is mentioned (page 7), it is not clear how much of it was used to construct a detailed geological model of the site at the local scale, neither in this report nor in TRW (2000). To prepare for a model of the site, a GIS would be needed, as was done for the regional scale, but with a finer scale and intensive use of geophysics.
- The existence of an impervious (or semi-pervious) layer between the volcanics and the carbonates is very important to the understanding of the site, and the presence or absence of the Eleana formation needs to be more firmly established. It is realised that this would be a costly analysis.
- On page 36, it is mentioned that the fractured volcanic rocks are probably anisotropic. The work of Erickson and Waddell (*1985*, pp. 24-29, reference in R96-4077) is reported which gives an anisotropy ratio of 5 to 7 in the only case where an attempt was made at measuring this anisotropy (well USWH-4). That is an extremely important issue, because with such an anisotropy, the direction of flow may be very different from what is assumed today based on the gradient direction. This uncertainty was recognised in the TSPA-SR as a random choice (50%-50%) alternative, but was not resolved.

- Concerning the interpretation of the well tests, it is surprising that the dimensionality of the flow tests was never determined. Reference is made to the work by Barker (*1988*) who showed that the analysis of pumping tests could be done by also fitting the spatial dimensionality of the medium being investigated (this spatial dimension may vary between 1 and 3, and is sometimes referred to as fractal). Such an analysis is particularly relevant for fractured media, and can indicate the degree of connectivity of the fractures and, if the assumption of equivalent porous medium is applicable, to the fractured system. This method has been successfully applied in Sweden to characterise fractured granite.
- The IRT fully support the statement (page 44) that "hydrochemical and isotopic data, where adequate data are available, can provide qualitative information for checking numerical flow models", and would have liked to see this done, at the regional scale and at the local scale.
- The IRT disagrees with some of the suggestions (page 55 and following) that some of the uncertainties about the conceptual model of the site can be lifted with adequate numerical simulations. A particular case in point is the statement on page 56 that *"investigations as to whether the system can be treated as an equivalent porous medium or if discrete features need to be accounted for can best be carried out using a series of numerical simulations"*. If one type of model can give better numerical results compared with the existing data, it will necessarily only deal with flow, and not with transport. Since the objective of the numerical simulations will, in the end, in the TSPA, be to predict transport of nuclides, it is not correct that, with the existing data, numerical simulations can adequately answer that question.
- The IRT fully supports the statements about the need for additional data.

3. Conclusions

The overall conclusion after reviewing USGS reports R96-4300 and R96-4077 is that the flow system at YM in the saturated zone is really very complex, and not sufficiently understood to propose a conceptual model on which scenarios of radionuclide transport from the repository can be made with any degree of realism. The major issues seem to be:

1. The role of the palaeozoic carbonate (is water coming from or going to the carbonate, or both, as suggested in the report to explain the zones of high and low gradients, as an alternative to a perched water-table local aquifer).

2. The horizontal anisotropy of the fractured volcanics, to determine the direction of flow, the velocity in the fractures.
3. The connectivity of the fracture network, to determine how much mixing could occur in the system.
4. The recharge in the regional system, for different climatic conditions.
5. The relation between the volcanics and the alluvium. How layered are the alluvial deposits? Is there vertical mixing in the alluvium? At the contact between the volcanic tuffs and the alluvium, how is the flow distributed? Is it along the whole thickness of the alluvium, over a fraction only, mostly at the surface, or at depth?
6. What is the exact geometry of the alluvium in the area lying between YM and the Amargosa Farms area?

Until these questions are answered, it is not possible to develop a realistic conceptual model of the site, or to build a probabilistic SZ local model.

The local flow model developed by the USDOE of the SZ at Yucca Mountain (*TRW, 2000*) is a piece of work of much higher quality, up to international standards. But this model uses the USGS regional model as boundary conditions, and is therefore biased by the poor quality of the USGS work. This translates in the TSPA to an uncertainty factor of 100 in the flux coming form the regional model to the local model, as discussed in Section 3.6 of the IRT report. The preliminary modelling work developed by the State of Nevada (*Lehman and Brown, draft, August 2001*) is an interesting alternative that proposes to use temperature data to calibrate the model, and to improve the description of the faults and fractures in the system. Such an effort should be continued.

The regional and local modelling efforts should be combined and the two models recalibrated, once a realistic model of the regional hydrogeology of the site has been constructed. It is advisable that the same group of hydrogeologists develops both models at the same time, as the iterative interaction of both models is necessary during the calibration phase.

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Appendix 4

USDOE fact checking

This Appendix sets out the comments made by the USDOE on the factual content of the final draft of this report, and indicates how the IRT has responded to this feedback.

1. DOE Comments

Please note that we are providing feedback on your draft report on what we perceive to be errors of fact or implication. This is in keeping with our Terms of reference. There is no intent to engage in a dialogue regarding these items, the IRT's independence is very important to the DOE and to its sponsoring agencies, the IAEA and NEA, as well as to its expert members.

1. Section 1.1, first paragraph. Although it is true that DOE has been studying YM for more than 15 years, it is also true that DOE has been studying YM for more than 20 years. The first borehole may have been as early as 1978.
2. Section 3.7, third bullet point. It is Lake Manley, not Menley, and Fortymile Wash.
3. Note that the following is a comment on an implication of the report's language, not on an actual error in fact, but an error in implication. In Section 1.2 it says that the details of the individual sub models are undergoing detailed peer review by specialists in the relevant areas. This implies ALL the submodels are being reviewed in this meticulous fashion. But only the biosphere and waste package submodels have been subjected to formal peer review for this (TSPA-SR) iteration. Formal expert elicitations and reviews were carried out on all the important models several years ago, and every model received an independent review for this iteration, but not necessarily a formal review by an outside, independent panel. It may be more factually correct to say that two of the submodels were reviewed by independent peer review panels for this iteration, and that all of the important submodels

were reviewed for the present iteration using internal experts not involved in the production of the model.

4. Section 3.4 bullet points on transport mechanisms: We also consider diffusion through a degraded waste package, i.e., diffusion through patches.
5. Section 3.4 indicates that the maximum key block size is 50 tonnes: The following discussion from the DE FEPs AMR indicates that the largest key block is 37 MT. The 50 tonne size is postulated as a block size that would still not breach the drip shield, and exceeds the calculated key block size.

   The Disruptive Events FEPs AMR states on page 105 that based on the results of CRWMS M&O (*2000j*), the maximum key-block size expected is 37 MT. The impact of rock fall on the drip shield is discussed in Rock Fall on Drip Shield, CAL-EDS-ME-000001 (*CRWMS M&O 2000t*). The calculation indicates that no cracks develop in the drip shield (i.e., no breaching) due to the dynamic impact of a rock fall on the drip shield for an effective rock mass of 10 MT over a 3-m length of drip shield, or up to a key-block size of 52 MT.
6. Section 3.5 indicates the UZ model is dual-porosity: It may be just a fine difference between dual-porosity and dual-permeability, but the UZ model is usually described as dual-permeability.
7. *This comment requests a clarification in language and not a correction per se*: In the "Unsaturated Zone" sub-section of the Summary it is stated, "Moreover, dripping has never really been observed, primarily as it is affected by ventilation, and yet it plays an important role in the analysis." And then again in *Section 3.5* it is stated, "Dripping has never been observed in the drifts at Yucca Mountain, because it is affected by drift ventilation, and yet it plays an important role in the analysis." These statements are probably true if clarified to refer to "in situ water dripping naturally from the rock". However, given the way these statements are written, it was not clear if the panel was given information on the number of observations of dripping in the tunnels. When ventilation is shut off in the ESF, dripping has been observed from rock bolts. Dripping was observed outside of the Drift-Scale heater Test bulkhead where warm moist air met colder rock. In response to tests introducing water, dripping was observed in alcove 3/niche 8, and dripping is observed in some of the Seepage tests. There was some evidence for dripping in the ECRB behind the bulkhead, thought to be the result of temperature gradients causing condensation in that sealed off tunnel. All of these

observations probably do not reflect simply the natural system behaviour, however they are information that the IPT should have. Although these observations may not be direct analogues of the natural ambient Seepage expected, they do provide some insight into the processes relevant to Seepage and dripping into the tunnels.

8. The document is potentially dated since the regulations that were "proposed" during the review are now final. A suggestion (only) would be to add a footnote explaining that "Since the work of the review, both the NRC and the DOE finalised their regulations. An examination of the changes made between the draft and final regulations shows that the technical recommendations made by the IRT are not called into question by the relatively minor changes in language and requirements." We see no impact from the change in language, the dropping of "reasonable assurance" and replacing it with "reasonable expectation," or from changes in requirements that matter like the compliance boundary being at 18 km from the repository rather than 20, and the prescribing of a 3,000 acre-foot/a dilution volume for the groundwater protection requirement. The IRT, of course, needs to reach this same conclusion for itself if it is to make this suggested clarification at all.

2. IRT Responses

1. No change is necessary.
2. Spelling corrections made.
3. No comment.
4. The following footnote has been added to Section 3.4: "Diffusion through degraded waste packages was also considered in the TSPA-SR."
5. The following footnote has been added to Section 3.4: "The maximum expected key-block size is 37 t and calculations indicate that no cracks will form in the drip shield up to a key-block size of 52 tonnes."
6. In Section 3.5, "dual-porosity" has been replaced with "dual-permeability". Also, a footnote has been added noting that the terminology has been corrected.
7. The third sentence of the "Unsaturated zone" subsection of the Summary has been changed to: "Moreover, natural dripping of groundwater from fractures or pores in the matrix has never been clearly observed…" Also a footnote has been added noting that a clarification has been made.

8. The first sentence of the tenth paragraph of Section 3.5 has been changed to: “Natural dripping of groundwater from fractures or pores in the matrix has never clearly been observed…”. Also, a footnote has been added noting that a clarification has been made.
9. The following footnotes have been added to the “Regulation” sub-section of the Summary, and to Section 1.1: “Since the work of this review, both the NRC and DOE have finalised their regulations. The IRT considers that its conclusions and recommendations are not called into question by the changes made.”

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Printed in France.