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TRANSMITTAL OF REPORT "UNCERTAINTY ANALYSES AND STRATEGY, REVISION 00"

The enclosed report, "Uncertainty Analyses and Strategy, Revision 00," is provided for your information. This report was produced by Bechtel SAIC Company, LLC, with oversight from my staff.

The U.S. Department of Energy (DOE) identified a variety of uncertainties from different sources during its assessment of the performance of a potential geologic repository at the Yucca Mountain, Nevada, site. The three main goals of the report are:

1. To briefly summarize and consolidate the discussion of much of the work that has been done over the past few years to evaluate, clarify, and improve the representation of uncertainties in the Total System Performance Assessment (TSPA) and performance projections for a potential repository. This report does not contain any new analyses of those uncertainties, but it summarizes in one place the main findings of that work.

2. To develop a strategy for how uncertainties may be handled in the TSPA and supporting analyses and models to support a License Application, should the site be recommended. The strategy may be modified pending receipt of additional pertinent information.

3. To discuss issues related to communication about uncertainties, and propose some approaches the DOE may use in the future to improve how it communicates uncertainty in its models and performance assessments to decision-makers and to technical audiences.

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Uncertainty Analyses and Strategy

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CONTENTS

FIGURES

FIGURES (continued)

Page

TABLES

ACRONYMS AND ABBREVIATIONS

AMR	Analysis and Model Report
BSC	Bechtel SAIC Company, LLC
CFR	Code of Federal Regulations
CRWMS	Civilian Radioactive Waste Management System
DIRS	Document Input Reference System
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
HLW	High-Level Waste
HTOM	high-temperature operating mode
IPCC	Intergovernmental Panel on Climate Change
IRT	International Review Team
LTOM	low-temperature operating mode
M&O	Management and Operating Contractor
MTS	Management and Technical Services
NRC	U.S. Nuclear Regulatory Commission
NWTRB	Nuclear Waste Technical Review Board
OCRWM	Office of Civilian Radioactive Waste Management
PMR	Process Model Report
REV	Revision
S&ER	Science and Engineering Report
SCC	Stress Corrosion Cracking
SR	Site Recommendation
SSPA	Supplemental Science and Performance Analysis
SZ	Saturated Zone
TSPA	Total System Performance Assessment
UZ	Unsaturated Zone
WP	Waste Package
YMP	Yucca Mountain Site Characterization Project

1.0 INTRODUCTION

Confronting and dealing with uncertainty is one of the key issues, and key difficulties, in policy analysis and risk management. Although uncertainty is often seen as a purely technical issue, one that can be resolved with more time and more study, societal and policy decisions can rarely be postponed until all uncertainties are resolved. Indeed, resolution of all uncertainties relevant to a complex decision is most often not feasible. Estimating the post-closure performance of a repository utilizing a total system performance assessment approach is no exception: the complexity of any repository and the associated long time frame over which projections must be made make uncertainties unavoidable.

The U.S. Department of Energy (DOE) recognizes the importance of assessing, managing, and communicating uncertainties in the assessment of the performance over thousands of years of a potential geologic repository at Yucca Mountain, Nevada. Although extensive scientific studies have been conducted, important uncertainties in the performance assessment are expected to remain. Uncertainties and uncertainty treatment are addressed in several reports that were released by DOE between May and August 2001 to support the consideration of the possible recommendation of the Yucca Mountain site. The *Yucca Mountain Science and Engineering Report* (S&ER) (DOE 2001 [DIRS 153849]) presents technical information supporting the consideration of the possible site recommendation. The report summarizes the results of more than 20 years of scientific and engineering studies and is based on numerous supporting reports. These include the *Total System Performance Assessment for the Site Recommendation* (TSPA-SR) (CRWMS M&O 2000 [DIRS 153246]) and the analysis and model reports and process model reports cited therein. The *FY01 Supplemental Science and Performance Analyses* report (SSPA) presents additional information and analyses developed following completion of the S&ER (DOE 2001 [DIRS 153849]) and its supporting documents. The SSPA report consists of two volumes: *FY01 Supplemental Science and Performance Analyses: Vol. 1, Scientific Bases and Analyses* (BSC 2001 [DIRS 155950]) and *FY01 Supplemental Science and Performance Analyses: Vol. 2, Performance Analyses* (BSC 2001 [DIRS 154659]). Volume 1 focuses on the technical work conducted in each process model area, encompassing uncertainty quantification, updated science and models, and lower-temperature operating mode analyses. Volume 2 describes the total system performance assessment (TSPA) analyses conducted using the updated information documented in Volume 1.

One part of the DOE approach to recognizing and managing uncertainties is a commitment to continued focused testing and analysis and to the continued evaluation of the technical basis supporting the possible recommendation of the site, including the significance of uncertainties. This report has been prepared to briefly summarize available information on uncertainties in reports prepared to date, to provide strategies for the future treatment of uncertainties, and to explore alternatives for the communication of uncertainties.

1.1 GOALS OF REPORT

The DOE identified a variety of uncertainties, arising from different sources, during its assessment of the performance of a potential geologic repository at the Yucca Mountain site. In general, the number and detail of process models developed for the Yucca Mountain site, and the complex coupling among those models, make the direct incorporation of all uncertainties difficult. The DOE has addressed these issues in a number of ways using an approach to uncertainties that is focused on producing a defensible evaluation of the performance of a potential repository. The treatment of uncertainties oriented toward defensible assessments has led to analyses and models with so-called "conservative" assumptions and parameter bounds, where conservative implies lower performance than might be demonstrated with a more realistic representation. The varying maturity of the analyses and models, and uneven level of data availability, result in total system level analyses with a mix of realistic and conservative estimates (for both probabilistic representations and single values). That is, some inputs have realistically represented uncertainties, and others are conservatively estimated or bounded. However, this approach is consistent with the "reasonable assurance" approach to compliance demonstration, which was called for in the U.S. Nuclear Regulatory Commission's (NRC) proposed 10 CFR Part 63 regulation (64 FR 8640 [DIRS 101680]).

In this approach, the most important application of the performance assessment is the demonstration of the *margin* between the calculated performance result and the regulatory standard. In contrast, a risk-informed approach would consider the "expected" (mean) result and compare that to the standard as well as to any additional "compliance" case to demonstrate *conservatism*. There are instances where more than one conceptual model for part of the system may be consistent with available data and observations. In the absence of definitive data or compelling technical arguments for a specific conceptual, process, or abstracted model, a conservative representation was chosen to provide defensibility in a regulatory sense.

A risk analysis that includes conservatism in the inputs will result in conservative risk estimates. Therefore, the approach taken for the TSPA-SR provides a reasonable representation of processes and conservatism for purposes of site recommendation. However, mixing unknown degrees of conservatism in models and parameter representations reduces the transparency of the analysis and makes the development of coherent and consistent probability statements about projected repository performance difficult. Likewise, a demonstration of the magnitude of conservatisms in the dose estimates that result from conservative inputs is difficult to determine. To respond to these issues, the DOE explored the significance of uncertainties and the magnitude of conservatisms in the SSPA Volumes 1 and 2 (BSC 2001 [DIRS 155950]; BSC 2001 [DIRS 154659]).

The three main goals of this report are:

1. To briefly summarize and consolidate the discussion of much of the work that has been done over the past few years to evaluate, clarify, and improve the representation of uncertainties in the TSPA and performance projections for a potential repository. This report does not contain any new analyses of those uncertainties, but it summarizes in one place the main findings of that work.

2. To develop a strategy for how uncertainties may be handled in the TSPA and supporting analyses and models to support a License Application, should the site be recommended. It should be noted that the strategy outlined in this report is based on current information available to DOE. The strategy may be modified pending receipt of additional pertinent information, such as the Yucca Mountain Review Plan.

3. To discuss issues related to communication about uncertainties, and propose some approaches the DOE may use in the future to improve how it communicates uncertainty in its models and performance assessments to decision-makers and to technical audiences.

1.2 OUTLINE OF REPORT

The contents of each of the sections of this report are as follows:

- Section 1 describes the goals and scope of the report, including brief descriptions of information available on uncertainties in the documents prepared to support the Site Recommendation.
- Section 2 summarizes information on uncertainties from previously prepared reports, specifically those evaluating the uncertainty treatment in the technical documents supporting the TSPA-SR and the SSPA. The results of these studies and their significance are provided at the total system level in Section 2.2.1. A review of key remaining uncertainties at the subsystem level is presented in Section 2.3 and a discussion is provided regarding implications of these uncertainties to the site recommendation decision process.
- Section 3 provides a strategy for future treatment of uncertainties. It first provides a framework for developing strategies based on current regulations and written comments from various oversight groups regarding how uncertainties have been treated in the analyses to date. Based on this review, a possible strategy is provided for treating uncertainties in the development of the license application.
- Section 4 addresses the communication of uncertainties. The discussion includes recognition of the needs of different audiences, including technical audiences and decision-makers; a review of how uncertainties have been communicated in other contexts; and examples of how uncertainties in potential repository performance can be communicated to different audiences

2.0 EVALUATION OF UNCERTAINTY TREATMENT IN TSPA-SR AND THE SIGNIFICANCE OF UNCERTAINTIES

Total System Performance Assessment (TSPA) is a method of forecasting how a potential repository system, or parts of this system, designed to contain radioactive waste is expected to behave over long periods of time. One goal of TSPA is to aid in determining whether the potential repository system can meet established performance requirements. Other applications include identifying which barriers and processes significantly affect performance, explicitly presenting uncertainty in projections, and providing information to guide future design and testing activities. The TSPA is a comprehensive quantitative analysis where the results of detailed conceptual and numerical models of each of the individual and coupled processes are combined into a single probabilistic model that can be used to project how a potential repository will perform over time. Detailed background on the definition, philosophy, regulatory requirements for, and the development and use of a TSPA is described in the TSPA-SR (CRWMS M&O 2000 [DIRS 153246], Section 1.1.1).

DOE's goal in conducting detailed evaluations of uncertainty treatment has been to evaluate the significance of uncertainties in TSPA and to assess the magnitude of conservatism that is included in the TSPA-SR results. A number of activities were undertaken to accomplish these goals: a systematic review of how uncertainties were treated in the TSPA-SR, quantification of some previously unquantified uncertainties and an evaluation of the impact of that quantification on process-level and system-level results, and consideration of the implications of this work for the total level of conservatism in the TSPA-SR. The review of TSPA-SR uncertainty treatment (YMP 2001 [DIRS 155343]) conducted by the Management and Technical Services contractor to DOE is summarized below in Section 2.1. The SSPA report (BSC 2001 [DIRS 155950]; BSC 2001 [DIRS 154659]) documents the effort to quantify some previously unquantified uncertainties, to update process models, and to examine the effect of these uncertainties at the subsystem level and the total system level. The results of the SSPA evaluations are summarized below in Sections 2.2.1. Implications to the conservatism in total system results are also summarized in Section 2.2.1. An evaluation is made of the significance of the remaining subsystem uncertainties in Section 2.3. Concluding remarks on TSPA-SR treatment of uncertainties are made in Section 2.4.

2.1 REVIEW OF UNCERTAINTY TREATMENT IN TSPA-SR

With the development and evolution of TSPAs over the past ten years has come the progressive improvement in the portrayal of physical processes. These improvements come because of collection and analysis of additional pertinent data, consideration of appropriate analogue information and processes, and improved modeling approaches. Concurrent with these improvements has been improvement in the acknowledgement and treatment of uncertainties. Inputs treated by assumption in early TSPAs have evolved into explicit consideration in more recent assessments such as TSPA-SR (CRWMS M&O 2000 [DIRS 153246]). For example, consideration of seepage into the drifts has evolved from simplified assumptions to more realistic models that incorporate uncertainties in the inputs. Recognizing the importance of addressing uncertainties, as well as communicating their significance, the DOE sponsored a review of the degree to which various inputs to the TSPA-SR are representative (Cline 2000 [DIRS 153193]) and of the uncertainty treatment in the TSPA-SR (YMP 2001 [DIRS 155343]). The goal of the latter review was to provide lessons learned and recommendations for the future treatment of uncertainties. The results of the study are summarized below.

The *"Evaluation of Uncertainty Treatment in the Technical Documents Supporting TSPA-SR"* (YMP 2001 [DIRS 155343]) contains a review and evaluation of the uncertainty treatment in the TSPA-SR (CRWMS M&O 2000 [DIRS 153246]), the supporting Process Model Reports (PMRs), and Analysis Model Reports (AMRs). The study was conducted by a team of Management and Technical Services (MTS) technical specialists who were generally not involved in the work reported in the documents.

YMP (2001 [DIRS 155343]) identified a suite of process models and described how these models relate to each other and to the AMRs (for example, five AMRs comprise the overall model of groundwater flow in the saturated zone). An internal structure of key models was then developed by identifying the conceptual model(s) that describe the process, the parameters/inputs that support the model, the representational model that implements the conceptual model, and the model results, particularly those to be used in the TSPA. The uncertainty treatment and incorporation of variability were then evaluated for each model.

The evaluation focused on the completeness, transparency, and traceability of the uncertainty treatment. Some of the specific characteristics of the uncertainty treatment that were reviewed include: documentation of critical assumptions; technical bases for distributions, ranges, and bounding values; and discussions of data limitations. The final step in the review involved evaluating the propagation of uncertainty through the suite of process models and into TSPA. This involved developing a hierarchy of the AMRs that constitute a single detailed process model (for example, one AMR may provide output information that becomes input information to another AMR). Seventeen key models were evaluated in the study. The findings of this study are summarized below.

Conceptual Model Uncertainty

Conceptual model uncertainties arise from incomplete understanding of the processes being modeled. Alternative conceptual models may be considered equally likely or be considered equally capable of explaining the available data. The principal way of addressing this type of uncertainty is to develop and evaluate alternative models that include a spectrum of viable conceptualizations. The analysis of stress corrosion cracking (SCC) in the waste package (WP) area is a good example of this approach. Two models for SCC are formulated and the most conservative (i.e., most pessimistic with respect to performance) is propagated forward for use with the TSPA. In the probabilistic seismic hazard analysis, alternative tectonic models are developed and they are incorporated directly into the hazard analysis. Only rarely on the YMP are alternative conceptual models incorporated directly into a probabilistic analysis.

YMP (2001 [DIRS 155343]) concludes that for most key models a clear description of the overall conceptual model(s), its bases, and the uncertainties, is lacking or difficult to find. For some models, short descriptions are provided in the PMR. For other models, limited discussions are presented in the AMRs. However, several AMRs lack a discussion of conceptual model(s) addressed in that AMR. This is believed to be partly due to the way that work is organized within a PMR area. For instance, the discussion of conceptual models for unsaturated zone (UZ) flow are contained in a separate AMR, while in the saturated zone (SZ) the conceptual model is discussed in the PMR and subcomponents are discussed in the AMRs.

Representational Model Uncertainty

Translation of a conceptual model into a representational, or mathematical, model produces additional uncertainties because of simplifications and approximations that typically must be used to make the problem tractable. Also, representational models are implemented in computer programs, which introduces another set of uncertainties related to numerical representation of the representational/mathematical model. YMP (2001 [DIRS 155343]) concludes that there are examples where representational model uncertainty has been treated well, including evaluation of different computer codes, like NUFT and TOUGH2, using test data to evaluate how well a model represents a process, and evaluating submodels embedded within larger models.

Parameter Uncertainty

Uncertainty in model parameters arises from imperfect knowledge or limited data. The uncertainty may be related to measurement error, imperfect knowledge of spatial variability, or other sources. For parameters that are based on data that can be measured directly, and at the appropriate scale, the uncertainty treatment could include discussions of measurement errors, representativeness, and related issues. Standard error analysis of measured parameter values is important to document, and parameter distributions should be developed and analyzed whenever possible. YMP (2001 [DIRS 155343]) concludes that the YMP has numerous good examples of this type of treatment.

Developed parameters have their values derived via some interpretive or analytical process involving scaling to appropriate dimensions, such as laboratory measurements of hydrologic properties, or conceptualization in terms of a model, such as incorporating lithophysal cavities into values for thermal conductivity. Error analysis of the values used for developed parameters is important, but it is also important to evaluate and discuss the uncertainties associated with the model and/or analysis bases for the parameter value. In order to fully characterize and evaluate uncertainties associated with developed parameters it is important to provide a clear discussion of the technical activities involved in deriving the parameter values.

YMP (2001 [DIRS 155343]) concludes that the bases for the selection of the specific values or distributions are unevenly presented. There are a number of cases in the AMRs where parameter uncertainty is not characterized and a bounding parameter value is chosen. In other cases, parameter values are chosen that are indicated to be representative. Some parameter ranges are shown by probability distributions.

Uncertainty In Model Results

The main purpose of modeling is to simulate the future consequences of processes that cannot be directly observed. Model results serve either as input to subsequent models or as direct input to the TSPA model through abstraction or direct linkage. The results of modeling are uncertain because the model components (i.e., the conceptual models, representational models, and parameters) are themselves uncertain. YMP (2001 [DIRS 155343]) concludes the AMRs vary widely in portraying how uncertainties in the model components affect the results. Some AMRs explicitly show how such uncertainties affect the results. Good examples exist in the WP degradation, SZ transport, and biosphere areas. Other technical areas are less developed, for example SZ flow. For most technical areas, the reviewers concluded that additional sensitivity analyses at the total system level would help demonstrate which uncertainties, at the process level, affect the model results.

Modeling of a particular process typically culminates with the development of abstraction models. These abstracted models are then implemented into the overall TSPA model. For most technical areas, the development of the abstracted models and their links to supporting process model results are clear. Examples of this are the abstracted models for WP degradation, waste form degradation, and dissolved concentration limits.

Propagation of Uncertainty

Uncertainties propagate from field data, laboratory data, and literature information, through process-level modeling, into abstracted models, and ultimately into the TSPA. The clear propagation of uncertainty is essential to demonstrate that the TSPA is complete and robust. YMP (2001 [DIRS 155343]) concludes that all identified uncertainties appear to have been propagated into the TSPA. However, it was found that the manner in which this has been done is not always clear. For example, it is difficult to understand that all the uncertainties associated with UZ flow are contained within three calibrated sets of flow fields. It also may not be clear at the TSPA level that alternative conceptual models have been evaluated at the process-level with the most conservative one chosen. An example of this is SCC of the WP outer barrier. In addition, it was found that the TSPA-SR (CRWMS M&O 2000 [DIRS 153246]) document does not contain comprehensive discussions of the bases supporting the treatment of important uncertainties within the abstracted models. An example of this is matrix diffusion in the UZ. Pointers to these discussions in the AMRs would assist the reader.

The principal conclusions and recommendations made in YMP (2001 [DIRS 155343]) are given below.

PRINCIPAL CONCLUSIONS

- The YMP could benefit from a systematic process for identifying, documenting, categorizing, evaluating, and quantifying uncertainties.
- Conceptual model, representational model, parameter/inputs, and results provide categories that are effective for evaluating and discussing uncertainty treatment.
- Distinguishing between parameter values derived from acquired and developed data could improve parameter uncertainty treatment.
- Representational model uncertainty is addressed well in several YMP documents, and these should serve as examples for others to follow.
- The YMP could benefit from a consistent approach to the propagation of uncertainty through the TSPA model hierarchy.

PRINCIPAL RECOMMENDATIONS

- Consider developing a systematic process for identifying, documenting, categorizing, evaluating, and quantifying uncertainties.
- Provide better discussions of the bases for determining parameter values and probability distributions.
- Provide more robust and consistent justification for parameter and model bounds.
- Develop an overall conceptual model AMR for large, complex models. Improve the conceptual model discussions within AMRs.
- Describe how uncertainties from upstream models have been incorporated into AMRs for the downstream models.

The review of the TSPA-SR in YMP (2001 [DIRS 155343]) provides a valuable set of observations and recommendations that the DOE may use to develop a strategy for the future treatment of uncertainties. The review was commissioned in the spirit of continuous improvement, taking advantage of the strengths and weaknesses of past work. Accordingly, guidance for future treatment of uncertainties given in Section 3 is mindful of this effort. Likewise, the lessons learned helped set the scope of the analysis of unquantified uncertainties given in the SSPA. Acknowledging room for improvement in TSPA-SR does not imply that TSPA-SR is not appropriate or sufficient to support a site recommendation decision process. As shown in the SSPA Volume 2, Section 4 (BSC 2001 [DIRS 154659]), the analysis of conservatisms and nonconservatisms shows that the peak dose results from the TSPA-SR nominal scenario are conservative (i.e., doses are greater and earlier) than those developed from more realistically quantified uncertainties. Doses due to igneous eruptions at the site are higher in the SSPA than in the TSPA-SR, as are the very small doses in the nominal scenario resulting from early failures of a small number of packages with initial flaws. As will be discussed in detail in Section 3, several oversight groups have difficulty understanding the implications of uncertainties to total system results when the inputs are a mix of conservative and realistic inputs. The DOE acknowledges that uncertainty treatment in the future needs to better quantify and document the bases for that treatment. Likewise, it is acknowledged that some inputs to TSPA-SR have been shown to be nonconservative (e.g., early waste package failures and igneous consequences). However, as shown in the SSPA, the vast majority of inputs were either realistically or conservatively estimated, and the dose results are likewise conservative.

2.2 EVALUATION OF SIGNIFICANCE OF UNQUANTIFIED UNCERTAINTIES

For the SSPA Volumes 1 and 2 (BSC 2001 [DIRS 155950]; BSC 2001 [DIRS 154659]), the DOE identified, considered, and evaluated the most recent and relevant information about Yucca Mountain and the potential repository system that was available from all sources, inside and outside the YMP. This information was used to quantify uncertainties, update conceptual and numerical models, and provide additional lines of evidence about the possible future behavior of a repository. To the extent possible, the information was incorporated in an updated supplemental TSPA model and evaluated for two thermal operating modes: for a repository operated as described in the S&ER (DOE 2001 [DIRS 153849]) and for a repository operated at temperatures where the average maximum temperature on the surface of the waste packages do not exceed an average waste package surface temperature of 85°C after closure. The former is termed the higher temperature operating mode (HTOM) and the latter is the lower temperature operating mode (LTOM).

The process for evaluating unquantified uncertainties involved: (1) identifying unquantified uncertainties to be evaluated; (2) developing more representative, quantified descriptions of those uncertainties; and (3) evaluating the implications of those newly quantified uncertainties for repository performance.

The first step in the process of quantifying uncertainties was to identify a set of process models and parameter inputs to the TSPA model for which significant uncertainty has not been quantified (i.e., where a conservative or nonconservative representation exists in the TSPA-SR). Recent studies have focused on identifying potentially important unquantified uncertainties (CRWMS M&O 2000 [DIRS 153246], Appendix F; YMP 2001 [DIRS 155343]). From this set of models and parameters, a subset was identified that is expected to include those most important to annual dose estimates, either annual dose during the 10,000-year period covered by the proposed regulations or longer-term annual dose, out to hundreds of thousands of years (see Section 2.1.1 in SSPA Vol. 1 (BSC 2001 [DIRS 155950])). The longer time period was considered because annual doses over long time periods may produce insights about uncertainty in annual dose that are relevant to all time periods. In selecting uncertainties to address in these supplemental analyses, consideration was given to both the potential impact on TSPA results and the feasibility of modifications to the model and parameter inputs to the TSPA.

To quantify the uncertainties associated with the identified models and parameters, technical investigators developed unbiased (i.e., neither conservative nor nonconservative) representations of the specified uncertainties. To assist them, an iterative series of interviews were held with representatives from each of the main process model areas affecting performance. The interviews were followed in some cases by supplemental calculations and analyses, which are documented in Volume 1 of the SSPA. The emphasis in the discussions was on the physical realism of the models and parameter estimates. The technical investigators used their knowledge of project-specific data, literature data, analogue systems or processes, and the technical judgment of the broader scientific and engineering community to develop the representations. Specific implementation of the representations took a variety of forms, as described in Sections 3 through 14 of SSPA Volume 1 (BSC 2001 [DIRS 155950]). Those forms range from new or updated parameter distributions to new or updated conceptual and mathematical models.

The impacts of the new representations for previously unquantified uncertainties were then evaluated through updated process models, sensitivity analyses, and supplemental TSPA analyses using the updated uncertainty treatment. The representations were implemented and the form and rationale for them documented. The implications of these new representations for process-level model results are also discussed in Sections 3 through 14 of Volume 1 of the SSPA. For many of these newly quantified uncertainties, supplemental TSPA sensitivity analyses were also conducted, as described in Volume 2 of the SSPA (BSC 2001 [DIRS 154659]). These included subsystem performance analyses, TSPAs, and analyses similar to those documented and discussed in the TSPA-SR (CRWMS M&O 2000 [DIRS 153246]). The calculated annual doses from the revised representations have been compared to the estimates from the TSPA-SR.

Table 2-1 shows the supplemental analyses that have been produced, the rationale for obtaining the supplemental information (i.e., unquantified uncertainties, updated scientific information, or lower-temperature operating mode analyses), and the section in Vol. 1 where the work is documented. The last two columns of the table indicate how the supplemental information described in Vol. 1 of the SSPA is evaluated in the performance assessment analyses described in Volume 2 of the SSPA.

Table 2-1. Summary of Supplemental Models and Analyses[a]

Key Attributes of System	Process Model (Section of S&ER)[b]	Topic of Supplemental Scientific Model or Analysis	Reason for Supplemental Scientific Model or Analysis			Section of Volume 1, SSPA[c]	Performance Assessment Treatment of Supplemental Scientific Model or Analysis (Discussed in Volume 2)	
			Unquantified Uncertainty Analysis	Update in Scientific Information	Lower-Temperature Operating Mode Analysis		TSPA Sensitivity Analysis[d]	Included in Supplemental TSPA Model[e]
Limited Water Entering Emplacement Drifts	Climate (4.2.1)	Post-10,000-year climate model		X		3.3.1	X	X
	Net Infiltration (4.2.1)	Infiltration for post-10,000-year climate model		X		3.3.2	X	X
	Unsaturated Zone (UZ) Flow (4.2.1)	Flow in PTn		X		3.3.3		
		Three-dimensional flow fields for lower-temperature design; flow fields for post-10,000 yr climate, lateral flow; variable thickness of PTn; fault property uncertainty		X	X	3.3.4		
		Effects of lithophysal properties on thermal properties		X		3.3.5		
	Coupled Effects on UZ Flow (4.2.2)	Mountain-scale thermal-hydrologic (TH) effects		X	X	3.3.5		
		Mountain-scale thermal-hydrologic-chemical (THC) effects		X	X	3.3.6		

Table 2-1. Summary of Supplemental Models and Analyses (Cont.)

Key Attributes of System	Process Model (Section of S&ER)[b]	Topic of Supplemental Scientific Model or Analysis	Reason for Supplemental Scientific Model or Analysis			Section of Volume 1, SSPA[c]	Performance Assessment Treatment of Supplemental Scientific Model or Analysis (Discussed in Volume 2)	
			Unquantified Uncertainty Analysis	Update in Scientific Information	Lower-Temperature Operating Mode Analysis		TSPA Sensitivity Analysis[d]	Included in Supplemental TSPA Model[e]
Limited Water Entering Emplacement Drifts	Coupled Effects on UZ Flow (4.2.2)	Mountain-scale thermal-hydrologic-mechanical (THM) effects		X	X	3.3.7		
	Seepage into Emplacement Drifts (4.2.1)	Flow-focussing within heterogeneous permeability field; episodic seepage	X		X	4.3.1, 4.3.2, 4.3.5	X	X
		Effects of rock bolts and drift degradation on seepage	X			4.3.3, 4.3.4		
	Coupled Effects on Seepage (4.2.2)	Thermal effects on seepage	X		X	4.3.5	X	X
		THC effects on seepage	X		X	4.3.6		
		THM effects on seepage		X	X	4.3.7		

Table 2-1. Summary of Supplemental Models and Analyses (Cont.)

Key Attributes of System	Process Model (Section of S&ER)[b]	Topic of Supplemental Scientific Model or Analysis	Reason for Supplemental Scientific Model or Analysis			Section of Volume 1, SSPA[c]	Performance Assessment Treatment of Supplemental Scientific Model or Analysis (Discussed in Volume 2)	
			Unquantified Uncertainty Analysis	Update in Scientific Information	Lower-Temperature Operating Mode Analysis		TSPA Sensitivity Analysis[d]	Included in Supplemental TSPA Model[e]
Long-Lived Waste Package and Drip Shield	Water Diversion Performance of engineered barrier system (EBS) (4.2.3)	Multiscale TH model, including effects of rock dryout	X		X	5.3.1		X
		Thermal property sets	X	X		5.3.1		X
		Effect of in-drift convection on temperatures, humidities, invert saturations, and evaporation rates	X		X	5.3.2		
		Composition of liquid and gas entering drift	X		X	6.3.1	X	X
		Evolution of in-drift chemical environment	X		X	6.3.3	X	X
		Thermo-Hydro-Chemical model comparison to plug-flow reactor and fracture plugging experiment		X		6.3.1		
		Rockfall		X		6.3.4		

Table 2-1. Summary of Supplemental Models and Analyses (Cont.)

Key Attributes of System	Process Model (Section of S&ER)[b]	Topic of Supplemental Scientific Model or Analysis	Reason for Supplemental Scientific Model or Analysis			Section of Volume 1, SSPA[c]	Performance Assessment Treatment of Supplemental Scientific Model or Analysis (Discussed in Volume 2)	
			Unquantified Uncertainty Analysis	Update in Scientific Information	Lower-Temperature Operating Mode Analysis		TSPA Sensitivity Analysis[d]	Included in Supplemental TSPA Model[e]
Long-Lived Waste Package and Drip Shield	In-Drift Moisture Distribution (4.2.5)	Environment on surface of drip shields and waste packages	X			5.3.2 7.3.1		
		Condensation under drip shields	X			8.3.2	X	
		Evaporation of seepage	X		X	8.3.1 5.3.2	X	X
		Effect of breached drip shields or waste package on seepage	X		X	8.3.3	X	X
		Waste package release flow geometry (flow-through, bathtub)	X			8.3.4	X	
	Drip Shield Degradation and Performance (4.2.4)	Local chemical environment on surface of drip shields (including magnesium and lead) and potential for initiating localized corrosion	X			7.3.1		

Table 2-1. Summary of Supplemental Models and Analyses (Cont.)

Key Attributes of System	Process Model (Section of S&ER)[b]	Topic of Supplemental Scientific Model or Analysis	Reason for Supplemental Scientific Model or Analysis			Section of Volume 1, SSPA[c]	Performance Assessment Treatment of Supplemental Scientific Model or Analysis (Discussed in Volume 2)	
			Unquantified Uncertainty Analysis	Update in Scientific Information	Lower-Temperature Operating Mode Analysis		TSPA Sensitivity Analysis[d]	Included in Supplemental TSPA Model[e]
Long-Lived Waste Package and Drip Shield	Waste Package Degradation and Performance (4.2.4)	Local chemical environment on surface of waste packages (including magnesium and lead) and potential for initiating localized corrosion	X			7.3.1		
		Aging and phase stability effects on Alloy 22	X	X		7.3.2	X	
		Uncertainty in weld stress state following mitigation	X			7.3.3	X	X
		Weld defects	X			7.3.3	X	X
		Early failure due to improper heat treatment	X		X	7.3.6	X	X
		General corrosion rate of Alloy 22: temperature dependency	X		X	7.3.5	X	X
		General corrosion rate of Alloy 22: uncertainty/variability partition	X			7.3.5	X	X

Table 2-1. Summary of Supplemental Models and Analyses (Cont.)

Key Attributes of System	Process Model (Section of S&ER)[b]	Topic of Supplemental Scientific Model or Analysis	Reason for Supplemental Scientific Model or Analysis			Section of Volume 1, SSPA[c]	Performance Assessment Treatment of Supplemental Scientific Model or Analysis (Discussed in Volume 2)	
			Unquantified Uncertainty Analysis	Update in Scientific Information	Lower-Temperature Operating Mode Analysis		TSPA Sensitivity Analysis[d]	Included in Supplemental TSPA Model[e]
Long-Lived Waste Package and Drip Shield	Waste Package Degradation and Performance (4.2.4)	Long-term stability of passive films on Alloy 22	X			7.3.4		
		Stress threshold for initiation of stress corrosion cracking (SCC)	X	X		7.3.3	X	X
		Probability of non-detection of manufacturing defects		X		7.4.3	X	X
		Number of defects		X		7.3.5	X	X
		Distribution of crack growth exponent (repassivation slope)	X	X		7.3.7	X	X
Limited Release of Radionuclides from the Engineered Barriers	In-Package Environments (4.2.6)	Effect of high-level waste (HLW) glass degradation rate and steel degradation rate on in-package chemistry	X		X	9.3.1	X	X

Table 2-1. Summary of Supplemental Models and Analyses (Cont.)

Key Attributes of System	Process Model (Section of S&ER)[b]	Topic of Supplemental Scientific Model or Analysis	Reason for Supplemental Scientific Model or Analysis			Section of Volume 1, SSPA[c]	Performance Assessment Treatment of Supplemental Scientific Model or Analysis (Discussed in Volume 2)	
			Unquantified Uncertainty Analysis	Update in Scientific Information	Lower-Temperature Operating Mode Analysis		TSPA Sensitivity Analysis[d]	Included in Supplemental TSPA Model[e]
Limited Release of Radionuclides from the Engineered Barriers	Cladding Degradation and Performance (4.2.6)	Effect of initial perforations, creep rupture, SCC, localized corrosion, seismic failure, rock overburden failure, and unzipping velocity on cladding degradation	X		X	9.3.3	X	X
	DOE high-level radioactive waste Degradation and Performance (4.2.6)	HLW glass degradation rates	X	X	X	9.3.1		
	Dissolved Radionuclide Concentrations (4.2.6)	Solubility of neptunium, thorium, plutonium, and technetium	X	X	X	9.3.2	X	X
	Colloid-Associated Radionuclide Concentrations (4.2.6)	Colloid mass concentrations	X			9.3.4	X	
	EBS (Invert) Degradation and Transport (4.2.6, 4.2.7)	Diffusion inside waste package	X	X		10.3.1	X	X
		Transport pathway from inside waste package to invert	X	X		10.3.2		

Table 2-1. Summary of Supplemental Models and Analyses (Cont.)

Key Attributes of System	Process Model (Section of S&ER)[b]	Topic of Supplemental Scientific Model or Analysis	Reason for Supplemental Scientific Model or Analysis			Section of Volume 1, SSPA[c]	Performance Assessment Treatment of Supplemental Scientific Model or Analysis (Discussed in Volume 2)	
			Unquantified Uncertainty Analysis	Update in Scientific Information	Lower-Temperature Operating Mode Analysis		TSPA Sensitivity Analysis[d]	Included in Supplemental TSPA Model[e]
Limited Release of Radionuclides from the Engineered Barriers	EBS (Invert) Degradation and Transport (4.2.6, 4.2.7)	Sorption inside waste package	X	X		10.3.4	X	X
		Sorption in invert	X	X		10.3.4	X	X
		Diffusion through invert	X			10.3.3	X	X
		Colloid stability in the invert	X			10.3.5		
		Microbial transport of colloids	X	X		10.3.6		
Delay and Dilution of Radionuclide Concentrations by the Natural Barriers	UZ Radionuclide Transport (Advective Pathways; Retardation; Dispersion; Dilution) (4.2.8)	Effect of drift shadow zone - advection/diffusion splitting	X		X	11.3.1	X	X
		Effect of drift shadow zone – concentration boundary condition on EBS release rates	X			11.3.1		
		Effect of matrix diffusion	X			11.3.2, 11.3.3		

Table 2-1. Summary of Supplemental Models and Analyses (Cont.)

Key Attributes of System	Process Model (Section of S&ER)[b]	Topic of Supplemental Scientific Model or Analysis	Reason for Supplemental Scientific Model or Analysis			Section of Volume 1, SSPA[c]	Performance Assessment Treatment of Supplemental Scientific Model or Analysis (Discussed in Volume 2)	
			Unquantified Uncertainty Analysis	Update in Scientific Information	Lower-Temperature Operating Mode Analysis		TSPA Sensitivity Analysis[d]	Included in Supplemental TSPA Model[e]
Delay and Dilution of Radionuclide Concentrations by the Natural Barriers	UZ Radionuclide Transport (Advective Pathways; Retardation; Dispersion; Dilution) (4.2.8)	Three-dimensional transport			X	11.3.2		
		Effect of coupled thermo-hydrologic, thermo-hydro-chemical, and thermo-hydro-mechanical processes on transport		X	X	11.3.5		
	SZ Radionuclide Flow and Transport (4.2.9)	Groundwater specific discharge	X	X		12.3.1	X	
		Effective diffusion coefficient in volcanic tuffs	X			12.3.2	X	
		Flowing interval spacing				12.3.2	X	
		Flowing interval (fracture) porosity	X			12.3.2	X	
		Effective porosity in the alluvium	X			12.3.2	X	
		Correlation of the effective diffusion coefficient with matrix porosity	X			12.3.2	X	

Table 2-1. Summary of Supplemental Models and Analyses (Cont.)

Key Attributes of System	Process Model (Section of S&ER)[b]	Topic of Supplemental Scientific Model or Analysis	Reason for Supplemental Scientific Model or Analysis			Section of Volume 1, SSPA[c]	Performance Assessment Treatment of Supplemental Scientific Model or Analysis (Discussed in Volume 2)	
			Unquantified Uncertainty Analysis	Update in Scientific Information	Lower-Temperature Operating Mode Analysis		TSPA Sensitivity Analysis[d]	Included in Supplemental TSPA Model[e]
Delay and Dilution of Radionuclide Concentrations by the Natural Barriers	SZ Radionuclide Flow and Transport (4.2.9)	Bulk density of the alluvium	X	X		12.3.2	X	X
		Retardation for radionuclides irreversibly sorbed on colloids in the alluvium	X	X		12.3.2	X	
		No matrix diffusion in volcanic tuffs case				12.5.2	X	
		Presence or absence of alluvium				12.5.2	X	
		Sorption coefficient in alluvium for iodine and technetium	X	X		12.3.2	X	X
		Sorption coefficient in alluvium for neptunium and uranium	X	X		12.3.2	X	
		Sorption coefficient for neptunium in volcanic tuffs	X			12.3.2	X	

Table 2-1. Summary of Supplemental Models and Analyses (Cont.)

Key Attributes of System	Process Model (Section of S&ER)[b]	Topic of Supplemental Scientific Model or Analysis	Reason for Supplemental Scientific Model or Analysis			Section of Volume 1, SSPA[c]	Performance Assessment Treatment of Supplemental Scientific Model or Analysis (Discussed in Volume 2)	
			Unquantified Uncertainty Analysis	Update in Scientific Information	Lower-Temperature Operating Mode Analysis		TSPA Sensitivity Analysis[d]	Included in Supplemental TSPA Model[e]
Delay and Dilution of Radionuclide Concentrations by the Natural Barriers	SZ Radionuclide Flow and Transport (4.2.9)	K_c model for groundwater colloid concentrations plutonium and americium		X		12.5.2	X	
		Enhanced matrix diffusion in volcanic tuffs				12.5.2	X	
		Effective longitudinal dispersivity	X	X		12.3.2	X	
		New dispersion tensor		X		12.3.2		
		Flexible design			X	12.3.2		
		Different conceptual models of the large hydraulic gradient and their effects on the flow path and specific discharge		X		12.3.1		
		Hydraulic head and map of potentiometric surface		X		12.3.1		

Table 2-1. Summary of Supplemental Models and Analyses (Cont.)

Key Attributes of System	Process Model (Section of S&ER)[b]	Topic of Supplemental Scientific Model or Analysis	Reason for Supplemental Scientific Model or Analysis			Section of Volume 1, SSPA[c]	Performance Assessment Treatment of Supplemental Scientific Model or Analysis (Discussed in Volume 2)	
			Unquantified Uncertainty Analysis	Update in Scientific Information	Lower-Temperature Operating Mode Analysis		TSPA Sensitivity Analysis[d]	Included in Supplemental TSPA Model[e]
Delay and Dilution of Radionuclide Concentrations by the Natural Barriers	Biosphere (4.2.10)	Receptor of interest	X			13.3.1		
		Comparison of dose assessment methods	X			13.3.2		
		Radionuclide removal from soil by leaching	X			13.3.3		
		Uncertainties not captured by the GENII-S computer code	X			13.3.4		
		Influence of climate change on groundwater usage and biosphere dose conversion factors (BDCF)	X			13.3.5, 13.3.7		
		BDCF for groundwater and igneous releases		X		13.3.6, 13.3.8 13.4	X	X
Low Mean Annual Dose Considering Potentially Disruptive Events	Volcanism/Igneous Activity (4.3.2)	Probability of dike intersection of repository for the operating mode described in S&ER		X		14.3.3.1		X

Table 2-1. Summary of Supplemental Models and Analyses (Cont.)

Key Attributes of System	Process Model (Section of S&ER)[b]	Topic of Supplemental Scientific Model or Analysis	Reason for Supplemental Scientific Model or Analysis			Section of Volume 1, SSPA[c]	Performance Assessment Treatment of Supplemental Scientific Model or Analysis (Discussed in Volume 2)	
			Unquantified Uncertainty Analysis	Update in Scientific Information	Lower-Temperature Operating Mode Analysis		TSPA Sensitivity Analysis[d]	Included in Supplemental TSPA Model[e]
Low Mean Annual Dose Considering Potentially Disruptive Events	Volcanism/Igneous Activity (4.3.2)	Scaling factors to evaluate impacts of repository design changes			X	14.3.3.2		
		Contribution to release of Zone 1 and Zone 2		X		14.3.3.3	X	
		Sensitivity to waste particle size distribution		X		14.3.3.4	X	
		New wind speed data		X		14.3.3.5	X	X
		Explanation of method for handling ash/waste particle size and density		X		14.3.3.6		
		Volcanism inputs for supplemental TSPA model		X		14.3.3.7		X
		New aeromagnetic data		X		14.3.3.8		

[a] BSC 2001 [DIRS 155950]
[b] DOE 2001 [DIRS 153849]
[c] BSC 2001 [DIRS 155950]
[d] BSC 2001 [DIRS 155023]
[e] BSC 2001 [DIRS 155023]

2.2.1 Total System Significance of Unquantified Uncertainties and Updated Models

One of the goals of the SSPA (BSC 2001 [DIRS 155950]; BSC 2001 [DIRS 154659]) is to provide insights into the significance of the unquantified uncertainties and the impact of updated scientific results and models. Section 3 of Volume 2 of the SSPA documents results of one-off sensitivity analyses conducted using modifications of the TSPA-SR model that incorporate newly quantified uncertainties, new models, or new input parameter values for some components. The following section of this report, taken from Section 4 of Volume 2 of the SSPA, summarizes the system-level results to provide additional insight into the significance of the previously unquantified uncertainties and updated scientific information, as well as the degree of conservatism in the overall assessment of the performance of the potential repository. Subsequent to the SSPA and in light of the recently-released EPA standard, additional TSPA calculations were conducted that use a distance of 18 km, rather than the 20 km in the SSPA calculations (BSC 2001 [DIRS 156460]). These new calculations do not change the conclusions regarding the significance of uncertainties and conservatism expressed in the SSPA.

2.2.1.1 Annual Dose at Particular Times for Nominal Case

In the nominal case, defined as performance that does not include very low-probability events, such as igneous events, or human intrusion scenarios, the range of uncertainties incorporated into the TSPA (CRWMS M&O 2000 [DIRS 148384]) is captured by the range of 300 realizations of sampled models and parameters. Further, the mean, median, 5th, and 95th percentiles of the annual dose probability distribution provide information regarding the expected dose rate at a given time and the time to attain a given annual dose. Uncertainties in those mean estimates, represented by the percentiles, can provide insight on the differences between the TSPA-SR (CRWMS M&O 2000 [DIRS 153246]) and the supplemental TSPA models documented in SSPA (BSC 2001 [DIRS 155950]; BSC 2001 [DIRS 154659]).

An important consideration in the interpretation of the annual dose probability distribution is the sensitivity of the mean estimate to the number of realizations having zero or nonzero annual doses. This is illustrated by the dose rate histories showing the mean annual dose and individual realizations (Figures 2-1 through 2-4). At earlier times, most of the 300 realizations provide estimates of zero dose, while a relatively small number of realizations provide estimates of nonzero doses. Because the mean estimate is an average of all realizations at any given point in time, if any realizations have a nonzero dose, the mean estimate will likewise be nonzero. Further, if only a few realizations have annual doses that are significantly higher than the remaining realizations, the mean will likely be closer in value to the few higher values. This effect is seen in the annual dose histories. At early times when relatively few realizations have a finite dose rate, the mean lies close in value to the upper percentiles of the distribution. At later times, the number of realizations having finite dose rates increases and the mean moves closer to the central part of the distribution (that is, toward the median estimates). However, in the case of the supplemental TSPA model (Figures 2-1 and 2-2), even at times as late as several hundred thousand years there are still many realizations leading to zero dose and, as a result, the difference between the mean and median estimates is notable. In the subsequent discussion, it is important to keep in mind these characteristics of the mean estimates.

Examining the annual dose histories from the standpoint of the probability distribution of realizations can provide insights into the aggregate or system-level significance of the uncertainties in the inputs. Consider first the distribution of dose rates at particular times, which is the same as taking "vertical slices" through the annual dose history plots (Figures 2-1 through 2-4). Figures 2-5 through 2-7 are plots showing the distribution of realizations at three particular points in time: 10,000 years, 30,000 years, and the time of the peak in the mean dose (approximately 1,000,000 years). These plots are constructed by looking at the distribution of realizations at a given time and progressively summing the number of realizations at particular dose rates to form a cumulative distribution function or summing the number of realizations within various dose-rate increments to form histograms.

The nominal performance annual dose at 10,000 years is zero for all (100 percent) realizations in TSPA-SR, and for about 77 percent of the realizations for the supplemental TSPA model (Figure 2-5). The supplemental TSPA model includes a consideration of the uncertainty associated with possible improper heat treatment of the lid welds, and this leads to waste package failures prior to 10,000 years. The wider range of quantified uncertainty in the supplemental TSPA model, in this case, leads to a broader range of outcomes, expressed by the range of realizations.

By 30,000 years (Figure 2-6), waste package failures begin to occur according to the TSPA-SR model. A comparable percentage of realizations show failure (about 20 percent), but the annual doses for the TSPA-SR model are significantly higher. This is primarily because the TSPA-SR model shows failures occurring in tens to hundreds of packages by 30,000 years (BSC 2001 [DIRS 154659], Figure 4-2.5-2), while the early failures in the supplemental TSPA model due to improper heat treatment of welds are limited to one or two packages.

The distribution of annual doses at the time of the peak of the mean annual dose is shown in Figure 2-7. The peak of the mean dose rate during the period of simulation occurs at about 276,000 years for the TSPA-SR model, and it is close to 1,000,000 years for the supplemental TSPA model, with doses still climbing slightly (Figure 2-1). All of the realizations in the TSPA-SR model show a nonzero dose, as do about 90 percent of the realizations for the supplemental TSPA model. The median (50^{th} percentile) dose rate for the supplemental TSPA model is about 10 mrem/yr, and it is about 200 mrem/yr for the TSPA-SR model. As can be seen in the plots, the additional quantified uncertainties and updated models in the supplemental TSPA model lead not only to a reduction in the peak dose at this time, but also a broader spread in the range of annual doses. An alternative way to express this result is that the conservative models of the TSPA-SR Rev 00 ICN01 lead to a higher peak dose with a narrower range of annual doses.

2.2.1.2 Time to Particular Annual Doses for Nominal Case

Another way to compare the results of the TSPA-SR model (CRWMS M&O 2000 [DIRS 148384]) and the supplemental TSPA model (BSC 2001 [DIRS 155950]; BSC 2001 [DIRS 154659]) for nominal performance is to examine the distribution of realizations for the time to reach particular annual doses. This is comparable to taking a series of "horizontal slices" through the dose history plots (Figures 2-2 through 2-4) at given dose rates. Shown in Figures 2-8 through 2-11 are cumulative distribution functions and histograms that were constructed in the same way as discussed in BSC (2001 [DIRS 154659], Section 4.1.3.1) using the distribution of 300 realizations for each case. Shown are the times at which each realization first reaches a particular annual dose for dose rates of 0.00001, 0.001, 0.1, and 10 mrem/yr. These values are chosen to provide insight into trends, and do not carry specific programmatic or regulatory connotations. The cumulative distribution function is first shown, followed by histograms out to 1,000,000 years, and in order to discern finer detail, out to 100,000 years.

Beginning with the time to reach 0.00001 mrem/yr (Figure 2-8), in general, the time for most of the realizations to reach this annual dose in the TSPA-SR model is considerably shorter than for the supplemental TSPA model. For example, the median or 50 percent of the realizations reach this dose rate by about 50,000 years for the TSPA-SR model, and it is about 400,000 years for the supplemental TSPA model. Similarly, over 90 percent of the TSPA-SR (CRWMS M&O 2000 [DIRS 153246]) realizations reach 0.00001 mrem/yr in the first 100,000 years, whereas only approximately 20 percent of the realizations in the supplemental TSPA model reach this value in the first 100,000 years (Figure 2-8b). Most of realizations in the supplemental TSPA model that reach 0.00001 mrem/yr during the first 100,000 years, do so during the first 50,000 years, with the largest number occurring in the first 10,000 years (Figure 2-8c). These early releases are due to improper heat treatment of the waste package lid welds (See Section 3.2.5.4 of SSPA Volume 2(BSC 2001 [DIRS 154659])). The earliest annual doses of 0.00001 mrem/yr are generally from the unrealistically rapid transport of carbon-14, and if results were adjusted to show only the early doses due to technetium-99, there would be fewer realizations reaching this level in the first 10,000 years. In contrast, the TSPA-SR model has no releases in the first 10,000 years. The net effect of the additional quantified uncertainties and updated models in the supplemental TSPA model is to broaden the range of times at which this dose is reached, relative to the TSPA-SR model.

The same conclusion holds true at the other annual doses (Figures 2-9 through 2-11). As the dose rate of interest increases from 0.001 to 10 mrem/yr, the difference between the two models in the time to reach that dose level remains about one order of magnitude at the 50^{th} percentile level. At the relatively lower doses of 0.00001 and 0.001 mrem/yr, the supplemental TSPA model has early realizations that reach these levels; at relatively higher doses of 0.1 and 10 mrem/yr, only the TSPA-SR model has early realizations that reach these levels. The first realizations of the supplemental TSPA models do not reach these levels until 200,000 years or later.

2.2.1.3 Conclusions Regarding Uncertainties and Conservatism in Simulations of Nominal Performance

Comparisons at the system and subsystem levels between the TSPA-SR process models (CRWMS M&O 2000 [DIRS 148384]) and the supplemental TSPA models (BSC 2001 [DIRS 155950]; BSC 2001 [DIRS 154659]) and unquantified uncertainties developed for this SSPA provide insight into the ways that uncertainties have been addressed and quantified. Likewise, the one-off sensitivity analyses (see Section 3, Volume 2 of the SSPA (BSC 2001 [DIRS 154659])) provide information regarding the potential effects of the uncertainties and supplemental TSPA models on performance at an individual process model level. In this section, the aggregate effect of all quantified uncertainties and updated scientific information on system performance are presented and compared to the TSPA-SR model. Further, the effects of thermal operating mode on the supplemental TSPA model results are compared.

Comparison of dose histories over 1,000,000 years for the TSPA-SR nominal case and the supplemental TSPA model shows the following two characteristics. First, the supplemental TSPA model shows significantly wider ranges of doses at a given time, and of times to reach given doses. Second, except at early times, the magnitude of the dose rate is less for the supplemental TSPA model and it occurs later in time.

The first observation is best illustrated by the comparisons in Figures 2-5 through 2-11. In every case, the supplemental TSPA model produces a broader range of annual doses or times to specific annual dose values than does the TSPA-SR model. This is represented quantitatively by the distribution of realizations at particular dose rates and particular times. The broader range is a result of the additional uncertainties and updated models that have been incorporated into the supplemental TSPA model. In many cases, simplified or bounding models have been replaced with more physically representative models that include quantified uncertainties in their parameters. For example, a bounding solubility model for neptunium in TSPA-SR (CRWMS M&O 2000 [DIRS 153246], Section 3.5.5) has been replaced with a more complex model that accounts for the solubility of secondary phases that control the solubility (BSC 2001 [DIRS 155950], Section 9.3.4). The updated solubility model is believed to be more realistic, but the uncertainties in the model lead to a broader range of neptunium concentrations than the previous model. Propagation of these uncertainties, as well as those of all of the other updated process models, results in the broad ranges that are seen in results of the supplemental TSPA model.

The second observation is based on a comparison of the estimates of mean performance (dose rate and time to dose) for the TSPA-SR case (CRWMS M&O 2000 [DIRS 153246]) and the supplemental TSPA cases (Figure 2-1), which shows that, after approximately 10,000 years, the mean annual dose for the supplemental TSPA model is always less than the mean for the TSPA-SR model. The difference between the mean estimates is one measure of the magnitude of the conservatism in the TSPA-SR model. For example, at 30,000 years, the difference between the mean estimates of dose rate is about three orders of magnitude (Figure 2-6a), and at time of peak mean dose the difference is about one order of magnitude (Figure 2-7a). The magnitude of conservatism can also be estimated by the difference in the mean time to reach particular dose levels. For example, the delay in reaching a mean annual dose of 0.1 mrem/yr in the supplemental TSPA model is about 200,000 years, and the delay in reaching 10 mrem/yr is more than 400,000 years (Figures 2-1, 2-10a and 2-11a).

During the period prior to 10,000 years, the small annual doses (less than about 0.0002 mrem/yr) indicated by the supplemental TSPA nominal model clearly exceed the zero annual doses calculated in TSPA-SR, and the TSPA-SR model is interpreted as being slightly nonconservative with respect to the supplemental TSPA model during this time. The small doses result from the revised treatment of uncertainty regarding the potential for improper heat treatment of lid welds on waste packages.

From the standpoint of uncertainties at the total system level, the supplemental TSPA model HTOM and LTOM cases show essentially comparable nominal performance, and both are significantly different from the TSPA-SR model. One potentially significant difference between the two operating modes is seen in the plots of the time for individual realizations to reach 0.1 and 10 mrem/yr (Figures 2-10a and 2-11a). Supplemental TSPA model LTOM realizations reach those levels several tens of thousands of years later than HTOM realizations. This is due to the temperature dependency of the general corrosion rate for the waste package, resulting in lower corrosion rates for the LTOM. Due to an error in an input file, radiation heat transfer processes were only partially included in the lower-temperature operating mode (LTOM) process model results presented in SSPA Volume 1, Section 5.4. This error resulted in overprediction of waste package peak temperatures by about 5 degrees centigrade and underprediction of relative humidities by about 5-10 percent for early time periods in the information used to develop the supplemental TSPA analyses reported in SSPA Volume 2.

Results of the supplemental TSPA model higher-temperature operating mode case are not affected by the error, and the overall conclusion that the performance of the HTOM and LTOM cases are comparable and indistinguishable at the mean level remains valid.

2.2.1.4 System-Level Analyses of Igneous Disruption Performance

An uncertainty importance analysis was carried out for the TSPA-SR results (CRWMS M&O 2000 [DIRS 153246], Section 5.1) using various statistical methods to identify the most important contributors to the spread in the igneous disruption model results and to identify contributors to the extreme, or outlier, outcomes in the model results. The analysis showed that the most important parameters affecting the spread in model results are annual frequency of igneous intrusion and wind speed. The model and parameter changes for the supplemental TSPA model (BSC 2001 [DIRS 155950]; BSC 2001 [DIRS 154659]) for the igneous disruption scenario class are described in detail in SSPA Volume 1 (BSC 2001 [DIRS 155950], Sections 13 and 14) and system-level calculations reflecting those changes are given in SSPA Volume 2 (BSC 2001 [DIRS 154659], Sections 3 and 4).

A number of revisions were made to the igneous disruption scenario in the SSPA including: the biosphere dose conversion factors (BDCFs) for eruptive and groundwater pathways were modified to account for new information developed since completion of the TSPA-SR; changes were made in the volcanic eruptive BDCFs; the conditional probability of an eruption at the potential repository and the probability distribution for an intrusive event were revised, consistent with revisions in the potential repository footprint since inputs were compiled for TSPA-SR; new distributions were provided for the number of waste packages affected by eruptive and intrusive events, consistent with the new event probability information; and changes have been made in the input data used to determine the wind speed during an eruption.

The TSPA-SR model for igneous disruption calculates doses from eruptions that entrain waste in volcanic ash and from igneous intrusions that damage waste packages and allow releases of radionuclides into groundwater. Figure 2-12 shows the probability-weighted mean annual dose for igneous disruption for the supplemental TSPA model for the HTOM and the LTOM. The 100,000-year supplemental analyses use 5,000 realizations for each case, and are compared to the 5,000-realization, 50,000-year base case from the TSPA-SR (CRWMS M&O 2000 [DIRS 153246], Figure 4.2-1). Figure 2-13 shows 500 of the 5,000 realizations (i.e., every tenth realization) for HTOM.

The probability-weighted annual dose for the igneous disruption scenario class is significantly different in the supplemental model as shown in Figure 2-12. Eruptive doses, which dominated in TSPA-SR for only approximately the first 2,000 years are now the main contributor to annual dose for more than 10,000 years. Peak mean annual eruptive dose still occurs approximately 300 years after closure, but it is increased by a factor of approximately 25, to approximately 0.1 mrem/yr. Doses from groundwater transport following igneous intrusion are decreased (generally by a factor of 5 or more), and the peak mean intrusive dose (which occurs in the LTOM case between 40,000 and 50,000 years) is approximately 0.05 mrem/yr, roughly one-quarter of the comparable peak mean dose in the TSPA-SR. The time of the peak mean annual igneous dose corresponds to the onset of the first full glacial climate at 38,000 years.

The largest single contributor to the 25-fold increase in the probability-weighted mean eruptive dose comes from changes in BDCFs (a factor of approximately 2.5). Other major factors are the change in wind speed (a factor of approximately 2), and the increase in the conditional probability of an eruption at the location of the potential repository (a factor of approximately 2, from 0.36 to 0.77). An increase in the total number of eruptive conduits possible within the potential repository (from 5 to 13) accounts for most of the remainder of the change (parameter values from CRWMS M&O 2000 [DIRS 153246], Table 3.10-4; BSC 2001 [DIRS 155950], Table 14.3.3.7-1).

Decreases in the probability-weighted annual dose due to igneous intrusion are due to changes in the nominal performance models for radionuclide mobilization and transport. The distributions used to characterize uncertainty in the number of waste packages affected by igneous intrusion were modified, resulting in a larger number of packages damaged for the supplemental analyses (BSC 2001 [DIRS 155950], Section 14.3.3.7 and Table 14.3.3.7-2). This increase, however, is more than offset by decreases in radionuclide mobilization and transport. As modeled, thermal operating conditions have no effect on the eruptive doses, and the curves for the HTOM and LTOM cases overlie each other until groundwater pathway releases cause minor divergence beginning at about 10,000 years.

2.2.1.4.1 Conditional Igneous Events

All dose histories for the igneous disruption scenario in the TSPA-SR (CRWMS M&O 2000 [DIRS 153246], Sections 4.2 and 5.2.9) were displayed as probability-weighted annual doses resulting from events occurring at uncertain times throughout the period of simulation. As described in the TSPA-SR (CRWMS M&O 2000 [DIRS 153246], Section 4.2), this approach to calculating and displaying the probability-weighted annual doses is consistent with the approach specified by the NRC (NRC 2001 [DIRS 156893]) and is required for determination of the overall expected annual dose. However, displays of the probability-weighted annual dose do not allow direct interpretation of the conditional annual dose, which is the annual dose an individual would receive if a volcanic event occurred at a specified time. For conditional analyses, the probability of the event is set equal to an unrealistic value of 1 (i.e., the calculation is conditional on the occurrence of the event), and the time of the event must be specified. Because the probability of occurrence is ignored, conditional results do not provide a meaningful estimate of the overall risk associated with igneous activity at Yucca Mountain, but they provide insights into the magnitude of possible consequences for specific sets of assumptions. The SSPA Volume 2, Section 3.3.1.2.4 (BSC 2001 [DIRS 154659]) presents several conditional igneous cases, which are briefly summarized here.

Three hundred realizations of eruptive annual doses were calculated assuming that an eruption intersects the potential repository 100 years after closure (Figure 2-14). The distribution in annual doses in the first year is due entirely to uncertainty in the sampled values for input parameters in ASHPLUME V1.4LV-dll (CRWMS M&O 2000 [DIRS 154748]) and BDCFs. The rapid decline in annual dose in subsequent years is due primarily to soil removal and, to a lesser extent, to radioactive decay. Variability in the rate at which annual dose decreases is caused by uncertainty in the soil removal rate. A discussion of ASHPLUME inputs, eruptive BDCFs, and soil removal is presented in the TSPA-SR (CRWMS M&O 2000 [DIRS 153246], Sections 3.10.2 through 3.10.4).

Conditional mean annual dose histories were also calculated for eruptive events at 100, 500, 1,000, and 5,000 years in the SSPA Volume 2 (BSC 2001 [DIRS 154659]). The mean annual dose history for an event at 100 years is repeated from Figure 2-14, and the mean annual dose histories for events at later times are each derived from 300 realizations analogous to those shown for the 100-year event. The conditional mean dose in the first year for an eruptive event at 100 years is approximately 13 rems/year (1.3×10^4 mrem/year). The first-year conditional dose decreases to approximately one half this level by 500 years after closure, and is approximately 10 percent of this value after 5,000 years.

Calculation and display of the conditional doses resulting from groundwater transport following igneous intrusion is simpler than that for the eruptive releases because of the approach taken in TSPA-SR (CRWMS M&O 2000 [DIRS 153246], Section 4.2.1.2) to incorporate event probability by sampling on the time of the event. Figure 2-15 shows 500 out of the 5,000 realizations of 50,000-year igneous intrusion annual dose histories calculated for TSPA-SR (CRWMS M&O 2000 [DIRS 153246], Section 4.2) without probability-weighting. Peak mean annual dose from the igneous intrusion pathway increases from approximately 0.1 mrem/year in the probability-weighted case to approximately 500 mrem/year, consistent with the overall mean probability of an intrusive igneous event during the 50,000-year simulation of 8×10^{-4}.

2.3 UNCERTAINTIES IN PROCESS MODELS AND IMPLICATIONS FOR SR

The purpose of the activities conducted for the SSPA (BSC 2001 [DIRS 155950]; BSC 2001 [DIRS 154659]), and documented therein was to update models and parameter values in light of new data and analyses since the time of the TSPA-SR (CRWMS M&O 2000 [DIRS 153246]), to quantify many key uncertainties that had not been quantified in the TSPA-SR, to evaluate the significance of previously unquantified uncertainties, and to assess the magnitude of conservatisms in the TSPA-SR. The updates and newly quantified uncertainties are summarized in Table 2-1 and the evaluation of those uncertainties followed a tiered approach. All updated and newly quantified uncertainties are discussed in Volume 1 of the SSPA. This discussion includes the technical basis for model refinements and, if uncertainties have been modified, for the new representation of uncertainty. In many cases, conservative models were replaced with more realistic models, and bounding or conservatively-biased parameter distributions were updated with more representative probability distributions. The implications of the updates and newly quantified uncertainties are evaluated at the subsystem level in the one-off sensitivity analyses, and, for a subset of those elements, at the total system level through the TSPA calculations in Volume 2 of the SSPA.

The total set of TSPA calculations and sensitivity analyses given in the TSPA-SR, Repository Safety Strategy (CRWMS M&O 2001 [DIRS 154951]), SSPA, and previous TSPAs provides considerable insight into the relative importance of various inputs to the analysis and their significance to performance results. Despite continuing efforts to reduce uncertainties through data collection and analysis, and to quantify uncertainties, there continue to exist key remaining uncertainties. These uncertainties, their potential implications to performance/risk, and the planned approach to address them are given in Table 2-2. The uncertainties are in the areas of seepage, in-drift thermal-hydro-chemistry (THC), drift degradation, waste package degradation, waste form degradation, radionuclide concentration, unsaturated zone transport, saturated zone transport, and igneous consequences.

Table 2-2. Key Remaining Uncertainties

Components of TSPA	Uncertainties	Perceived Significance of Risk	Possible Analysis Treatment
Seepage	Effect of infiltration, heterogeneity, drift degradation and coupled THMC processes on seepage distribution and amount	Low	Consider range of seepage fluxes including bound that 100% of drift area receives 100% of percolation flux.
In-Drift THC	Effect of local heterogeneity and coupled THC processes on in-drift chemistry. This includes the likelihood of forming near neutral pH brines or high pH brines.	Medium	Develop probability and weighting functions for the likelihood of forming different brines based on potential starting water compositions / Consider range of in-drift chemistries and bounding salt content on drip shield and waste package surfaces.
Drift Degradation	Effect of seismically -induced and THM processes on rock degradation and rock fall	Medium	Develop site-specific ground motion time histories appropriate for the post-closure period. Develop appropriate thermal and mechanical properties of rock blocks and joints. Consider range of rock fall sizes including bounding sizes.
Waste Package Degradation	Local chemistry on waste package and drip shield surface (NaF, $CaCl_2$, or $MgCl_2$)	High	Characterize scale and deposits likely to form on metal surfaces. Consider likely range of chemical environments for range of dust/hygroscopic salt contents.
	Stability and degradation of passive films on waste package surface, including effects of defect/debris accumulation	High	Continue to characterize passive film under repository relevant conditions. Consider low probability of instability and combine with performance of drip shield barrier and more realistic water ingress models.
	Possibility of concentrated trace ionic species on waste package (Pb, Hg, As) and corrosion consequences	Medium	Consider low probability of such aggressive species and combine with more realistic water ingress models.
	Post-welding residual stress distribution of closure welds and manufacturing flaws in waste package	Medium	Consider low probability of improper heat treatment and develop reasonable representation of the consequences.
Waste Form Degradation	Initial cladding state	Low	Consider taking no credit for cladding or increase the uncertainty distribution on the initial cladding perforation.

Table 2-2. Key Remaining Uncertainties (cont.)

Components of TSPA	Uncertainties	Perceived Significance of Risk	Possible Analysis Treatment
Radionuclide Concentration	Radionuclide solubility and colloid formation/stability	Low	Consider range of solubilities and colloid formation/stability.
Unsaturated Zone Transport	Presence and distribution of low advective transport times (PTn lateral flow, active fracture model, drift shadow zone)	Low	Consider distribution of advective transport times.
Saturated Zone Transport	Saturated zone specific discharge	Low	Constrain rock permeability estimates with data collected from the Nye County Drilling Program.
Igneous Consequences	Interaction between magmas and repository structures; response of waste packages and waste forms to igneous conditions; eolian and fluvial remobilization of contaminated volcanic ash	Medium	Consider range that includes NRC bound as low probability consequence.

While there is a proposed strategy for managing the remaining uncertainties (see Section 3), for the purposes of Site Recommendation, the potential implications of these remaining uncertainties must be discussed. The sections below provide a discussion of why, even in the presence of the remaining uncertainties, the Project has sufficient confidence in our current analysis to support a Site Recommendation decision process. The arguments focus on the conservatism built into our models, supplemental literature surveys in similar topics, importance to performance, and that the models bound potential uncertainties.

2.3.1 Seepage: Effect of Infiltration, Heterogeneity, Drift Degradation and Coupled THMC Processes on Seepage Distribution and Amount

The remaining uncertainties in processes affecting seepage, including infiltration, heterogeneity, drift degradation and coupled processes, have been evaluated. These uncertainties have been determined to be insignificant. The evaluation of existing uncertainties is detailed in the following.

Infiltration

Infiltration and hydrogeologic stratigraphy directly control seepage rates. Uncertainties remain in our current understanding of the infiltration processes at Yucca Mountain. It is not expected, however, that these uncertainties will have any significant impact on the TSPA-SR (CRWMS M&O 2000 [DIRS 153246]) because of the following considerations:

A wide range of infiltration rates has already been incorporated into the UZ flow and transport models (BSC 2001 [DIRS 155950]).

It has been shown that the presence of the nonwelded units such as the PTn tends to re-distribute flow fluxes below them, resulting in a rather uniform distribution of percolation rates (and hence seepage).

Small, local variations in infiltration rates, a likely result of updated infiltration information, would not dramatically impact percolation and seepage because of the above reason.

Heterogeneity

The hydrogeology of the region is spatially variable, or heterogeneous, which gives rise to uncertainties in their properties. Hydrostratigraphic units (such as the PTn) and features (such as faults) govern large-scale flow patterns, and thus lead to a redistribution of infiltration and percolation fluxes. On an intermediate scale, flow through the fracture network may be focused (funneling effect) or dispersed (bifurcation). The funneling effect leads to zones of locally higher percolation fluxes and areas of reduced water flow between them. Water within such a high-flux zone may be further channeled by variabilities in the fracture network. Finally, heterogeneity and flow instabilities within individual fractures lead to small-scale flow channels (rivulets or fingers). Recent treatments of uncertainties in the effect of heterogeneity on seepage have been documented in SSPA Volume 1, Section 4.3 (BSC 2001 [DIRS 155950]). The results indicate that the flow focusing factors used in the TSPA-SR are conservative since they tend to produce higher radionuclide doses because of increased total seepage (BSC 2001 [DIRS 155950], p.4-23).

In addition, data collected from ongoing field tests are also being evaluated using process level models to assess this effect. The relevant tests include the systematic hydrologic characterization of the TSw lower lithophysal unit, the seepage threshold testing at Niche 5 (also in the lower lithophysal unit), the ECRB/ESF moisture monitoring program, and the Alcove 8-Niche 3 water and tracer injection tests. The systematic hydrologic characterization involves borehole testing at regular intervals along the Enhanced Characterization Repository Block (ECRB) Cross Drift, to characterize hydrological attributes within the lower lithophysal unit of the Topopah Spring welded tuff (TSw).

Test data in the lower lithophysal unit confirm the understanding of UZ flow in the repository units as described in TSPA-SR, based previously on niche test results in the middle nonlithophysal unit. The data indicate that the seepage threshold concept is valid in the lower lithophysal zone. The data indicate that small fractures are well connected, giving rise to air-permeability values on the order of 10^{-11} m^2. The small fractures connected by lithophysal cavities constitute the main contribution to liquid flow, and the water drainage is expected to be good. The Cross Drift is shown to divert some fraction of the prevailing percolation flux around the drift. These additional data serve to limit the impact of the uncertainties remaining in the area of heterogeneity.

Coupled Processes

The uncertainty in seepage associated with coupled processes has been evaluated. Following TSPA-SR, recent treatments of effects of THMC coupled processes on seepage were documented in SSPA Volume 1, Sections 4.3.5 (TH), 4.3.6 (THC), and 4.3.7 (THM).

In the studies supporting the TSPA-SR (CRWMS M&O 2000 [DIRS 153246]), effects of repository heat on seepage were deduced indirectly from results presented in Mountain-Scale Coupled Processes (TH) Models (CRWMS M&O 2000 [DIRS 144454]). In Section 4.3.5 of SSPA Volume 1, a refined modeling study was performed to reduce conceptual uncertainties regarding grid resolution and heterogeneity. The study also examined the impact of lithophysal cavities on thermal properties; the potential for liquid water to penetrate a superheated region, causing episodic seepage events; and the development of a vaporization barrier. Moreover, percolation flux was calculated for a range of thermal operating modes. The results obtained show that it is very difficult for water flow to reach the emplacement drifts when the drift walls are above the boiling temperature. Under these conditions, seepage into the drifts is greatly reduced and possibly eliminated entirely. The analyses conducted with the mountain-scale coupled-process model and the mountain scale thermal hydrology (MSTH) model found no seepage into the drift during the thermal period for the high temperature operating mode (HTOM), even with heterogeneity included. The analysis of penetration of episodic pulses through superheated rock showed that it is possible for seepage to occur, but it also found that water did not reach the drift wall under most parameter combinations.

Thermal-hydrologic-chemical (THC) processes may impact seepage through thermally induced changes in unsaturated hydrogeologic properties. The TSPA-SR (CRWMS M&O 2000 [DIRS 153246]) was based on an abstraction of the data documented in *Drift-Scale Coupled Processes (DST and THC Seepage) Models* (CRWMS M&O 2000 [DIRS 142022]). Additional validation studies were performed (BSC 2001 [DIRS 155950], Section 4.3.6), enhancing the confidence in the THC modeling approach. Sensitivity analyses were performed to examine different in-drift designs, different heterogeneous host rock units, different systems of components and minerals, different kinetic models for mineral-water interactions, different permeability-porosity relations during precipitation and dissolution, and changed thermodynamic data and initial conditions. All these studies, which are fully documented in Drift-Scale Coupled Processes (DST and THC Seepage) Models (BSC 2001 [DIRS 154677]), helped reduce conceptual uncertainties in the THC models. Additional studies of coupled processes were performed for an extended range of temperatures covering various thermal operating modes. The studies show that the effects of THC processes on porosity and permeability were slight (less than 1 percent change in porosity over 20,000 yrs under LTOM) because amorphous silica, the primary phase that results in porosity loss during boiling, is generally undersaturated except in areas adjacent to the drift wall where substantial evaporation has taken place.

A distinct-element analysis was performed to examine thermal-mechanical (TM) effects of drift excavation and repository heat on hydrogeological properties (CRWMS M&O 2000 [DIRS 149040]). This analysis has been revised and extended in SSPA Volume 1, Section 4.3.7 to provide a more robust estimate of TM effects in fracture permeability. In addition, a fully coupled thermal-hydrologic-mechanical (THM) continuum model was developed and calibrated against air-permeability data from three niches and the Drift Scale Test area. The successful calibration increased confidence in the conceptual model and reduced uncertainties in the subsequent prediction runs, which included two thermal operating modes. The results found so far indicate that percolation flux values and distribution immediately above the drift are not significantly affected by the THM processes. Further, permeability changes caused by THM effects, apart from the immediate neighborhood of the drift that is part of the drift degradation analysis, are about one order of magnitude, which is within the much larger measured range of permeability that is the basis of the ambient seepage model. Thus, results to date do not indicate a significant THM induced impact on the performance as represented in the TSPA-SR.

In addition to work captured in SSPA Volume 1, new data collected from the DST and natural analogue studies generally support the UZ models included in the TSPA-SR concerning the TH, THC, and THM effects on seepage.

In regard to the THM data, Plate Loading Test results indicate higher bulk elastic moduli than earlier tests. This result has no effect on the drift-degradation (rockfall) analysis because that analysis uses independent data for rock joint properties and does not rely on bulk rock elastic modulus as an input. For thermal-hydrologic-mechanical effects, the main question concerns the effects on seepage. If thermal-hydrologic-mechanical effects (such as an increase in permeability due to shear strain) result in a permanent change in permeability around the drift, then there is a potential effect on long-term performance. However, increases in permeability near the drift will result in lower seepage, according to the seepage model. Reductions in permeability are expected to be due to normal stresses, which are not expected to produce permanent changes. Furthermore, the magnitude of the thermal-hydrologic-mechanical changes in permeability are smaller than the natural spatial variability of permeability. Thus, if there are effects on dose, they are not expected to be significant.

Concerning the THC effects, recent CO_2 gas-concentrations data support the near-field environment model and therefore have no impact. In addition, four recent water samples condensed from high temperature vapor in the Drift Scale Test show fluoride concentrations as high as 66 ppm and pH values as low as 3.1 at the sample collection temperature of over about 50°C (120°F). At present, the source of this solution is unknown, but it is considered likely to be a sampling artifact, from fluoride leached either from Viton used in borehole packers or from Teflon-lined sampling tubes. All of these samples came from boreholes where the packers had failed. Another possibility for the source of this solution that cannot be ruled out until further information is collected on the behavior of the introduced materials is that the presence of fluoride may have resulted from the interaction of steam with fluoride-bearing minerals in the rock. If this is the case, hydrogen fluoride gas could be produced within the host rock at sustained temperatures as low as 138°C (280°F). If the hydrogen fluoride gas is transported to the engineered barrier system and dissolved into an aqueous phase, this could have the potential to enhance corrosion on the drip shields and waste packages. Analyses have not been conducted to determine the extent of such corrosion or the resulting potential impact on performance.

Thermal-hydrologic-chemical model simulations have suggested that precipitates are volumetrically small, but over long time frames a question remains concerning the potential for fracture sealing. Natural analogue observations suggest that only a small portion of the fracture volume needs to be sealed to effectively retard fluid flow in low-permeability rocks. Although a laboratory test involving a boiling aqueous solution in a single fracture resulted in sealing of the fracture over a period of a few days (BSC 2001 [DIRS 155950], Section 4.3.6.7.4), the fluid flux was several orders of magnitude greater than those expected in the near field environment under the HTOM. From a TSPA perspective, the potentially important effect of this sealing would be if it were to result in greater flow focusing above waste emplacement drifts. (If all fractures above the drifts became sealed, seepage could be reduced to zero. However, if only some of the fractures became sealed, it could possibly result in funneling of flow into the unsealed ones.) The effects of a wide range of flow-focusing factors have been considered in TSPA, and the calculated dose is not particularly sensitive to flow focusing (see Figure 5.2-2 in the TSPA-SR report (CRWMS M&O 2000 [DIRS 153246])).

Based on the previous analyses, improvements in these coupled processes models are not expected to significantly impact seepage results included in the TSPA-SR.

2.3.2 In-Drift THC: Effect of Local Heterogeneity and Coupled THC Processes on In-drift Chemistry

There are uncertainties in calculated in-drift water compositions that may contact the waste packages and drip shields and in the kinds and quantities of salts that could precipitate from those waters due to evaporation. The water and salt compositions directly influence waste package and drip shield degradation rates due to corrosion. Therefore, those uncertainties are significant, because they introduce uncertainties in calculated waste package and drip shield degradation rates, i.e., times to breach due to corrosion. In-drift water and salt compositions depend on the compositions of seepage water and gas that enter the drifts, which in turn depend on the values of thermal-hydrologic parameters in the host rock. In-drift water and salt compositions also depend on in-drift thermal-hydrologic parameters. Therefore, the sequence of uncertainties is as follows: (1) host rock thermal-hydrologic (TH) uncertainty, (2) host rock thermal-hydrologic-chemical (THC) uncertainty, (3) in-drift thermal-hydrologic (in-drift TH) uncertainty, (4) in-drift water and salt compositions (in-drift chemistry) uncertainty, and finally (5) waste package and drip shield corrosion rate uncertainty. These uncertainties were evaluated as follows.

Thermal hydrologic parameters in the host rock are important because they directly affect equilibrium constants and reaction rates, the degree of water evaporation and boiling, and the amount of carbon dioxide volatilization from pore water, with direct implications on computed water and gas chemistries. Ranges of values for these parameters and their effects on the chemical environment within the drifts were evaluated by simulating high- and low-temperature operating modes as described in Sections 5 and 6, Volume 1, SSPA.

The THC seepage models predict the composition of fluids entering the emplacement drifts. THC simulations were performed for the SSPA using two significantly different input water chemistries (UZ-14 perched water and Alcove-5 pore water) with significant differences in initial pH and carbon dioxide partial pressures. Using both waters under a higher- and a lower-temperature operating mode, the scatter or uncertainty defined by predicted water compositions that may enter drifts over time fell largely within the variability of water compositions that could be used for input into the PC&E models. Evaluation of uncertainties associated with seepage rates and seepage and gas compositions are presented in detail in *Drift Seepage Model* (CRWMS M&O 2001 [DIRS 154291]) and *Drift-Scale Coupled Processes (DST and THC Seepage) Models* (CRWMS M&O 2000 [DIRS 142022]; BSC 2001 [DIRS 154677]), respectively.

Thermal hydrologic parameters evaporation rate, relative humidity, and temperature within the emplacement drifts are provided to the EBS physical and chemical environment (PC&E) models (CRWMS M&O 2000 [DIRS 151951]) by the multiscale thermohydrologic (MSTH) model. The calculation of these quantities and their associated uncertainties are presented in detail in the *Multiscale Thermohydrologic Model* (MSTH) (CRWMS M&O 2000 [DIRS 149862]) and in Section 5 of the SSPA, Volume 1 (BSC 2001 [DIRS 155950]). Incoming rates of seepage from the host rock and compositions of incoming seepage and gas are boundary conditions for the EBS PC&E models.

To assess the effect of uncertainty in seepage compositions on in-drift water composition, evaporation calculations were performed for several waters observed at Yucca Mountain using the In-Drift Precipitates/Salts Model described in *In-Drift Precipitates/Salts Analysis* (BSC 2001 [DIRS 156065]). The results, documented in detail (Mariner 2001 [DIRS 155041]), show that the various waters fall into two types of brine, carbonate-based and low-carbonate based brines. These brines tend to evolve upon evaporation into high pH brines and near-neutral pH brines, respectively. In these calculations, pH values generally range between 5 and 9. In that pH range, and the calculated chloride concentration range, general corrosion rates are adequately represented by a fixed range of values used in TSPA. The range of general corrosion rates used in the SR assessment includes expected rates for pH range of 3 to 13.

Uncertainty in precipitated salt composition was assessed by considering the effects on localized corrosion of $NaNO_3$, $CaCl_2$, and $MgCl_2$ salts. Descriptions of those assessments follow.

$NaNO_3$ salt is the most hygroscopic salt that can form on drip shield and waste package surfaces when contacted by carbonate-based brines. The threshold relative humidity used in TSPA-SR for initiation of corrosion of drip shield and waste package is based on the deliquescence point of $NaNO_3$ salt, which is a function of temperature and is as low as 50% RH at 120°C. The TSPA-SR (CRWMS M&O 2000 [DIRS 153246]) assumed that the salt is present on the drip shield and waste package surfaces for the entire simulation period. A series of short-term potentiodynamic polarization tests showed that both Alloy 22 (waste package) and Ti Grade 7 (drip shield) are not subject to localized corrosion for the entire range of temperature and pH that are expected in the repository. This results from the inherent resistance to localized corrosion of the alloys and inhibiting effect of nitrate ion (NO_3^-) present in the solution. Waste package and drip shield materials were shown not to be subject to localized corrosion. The range of general corrosion rates used in the SR assessment includes expected rates for pH range of 3 to 13.

If low-carbonate concentration based pore water comes into contact with drip shield and waste package, $MgCl_2$ and $CaCl_2$ salts could form on the drip shield and waste package surface from evaporative concentration of the solutions. These salts are more hygroscopic and their saturated solution is more corrosive than $NaNO_3$ salt. For example, the deliquescence point of $CaCl_2$ salt is as low as 15% RH at 165 degrees C. The deliquescence point of the salts is also a function of temperature. More details of this water chemistry evolution scenario are discussed in Section 6 of SSPA Volume 1. Preliminary short-term potentiodynamic polarization tests in nearly saturated calcium chloride solutions at 120°C showed that Alloy 22 is not subject to localized corrosion in the presence of the mitigating nitrate ion. The test showed that the alloy could be subject to localized corrosion in the absence of nitrate ion.

However the possibility of developing saturated solutions of $MgCl_2$ and $CaCl_2$ salts without significant nitrate and other anion concentrations is very unlikely. The formation of an aqueous film containing $MgCl_2$ and $CaCl_2$ salts will also result in the dissolution of other soluble anions that will be present, such as nitrates and sulfates. Project data confirm that the presence of anions such as nitrate, carbonate, and sulfate reduces the aggressiveness of chloride ions for Alloy 22 corrosion.

In order to investigate potential effects of the possible presence of $MgCl_2$ and $CaCl_2$ salts on the waste package and drip shield surfaces, a sensitivity analysis was conducted using a relative humidity threshold for the initiation of general corrosion based on the deliquescence points of $MgCl_2$salt. Use of this threshold allows general corrosion to initiate at an earlier time, i.e., general corrosion initiating at lower relative humidities and higher temperatures (around 15 percent RH at 165°C). The temperature-dependent general corrosion model for Alloy 22 was used for the sensitivity analysis allowing increased general corrosion rates at higher temperatures. It was assumed that Alloy 22 is not subject to localized corrosion, because of the reasons discussed above. Results show that the effect of using a critical relative humidity for the initiation of general corrosion based on the deliquescence points of magnesium chloride salt is a minor effect and is neglected because waste package lifetime is much longer than the time duration during which the waste package temperature is high and the waste packages are subject to higher general corrosion rates. More details of the sensitivity analysis are discussed in Section 7 of SSPA Volume 1.

Based on the rationale presented above, the TSPA-SR assessment for drip shield and waste package degradation is defensible and appropriate, even with the uncertainties in the TSPA-SR assessments of water and salt chemistry, including water chemistry parameters such as pH.

2.3.3 Drift Degradation: Effect of Seismically-induced and THM Processes on Rock Degradation and Rockfall

Another key remaining uncertainty is the extent of drift degradation through time due to seismically induced and THM processes. The deterioration of the rock mass surrounding the potential repository emplacement drifts was predicted based on a probabilistic key-block analysis. Key blocks are formed at the surrounding rock mass of an excavation by the intersection of three or more planes of structural discontinuities. The *Drift Degradation Analysis* (BSC 2001 [DIRS 156304]) provides an assessment of the possible formation of key blocks within the potential repository horizon that is based on the orientations of discontinuities present in the ESF main loop and in ECRB Cross Drift. Block failure due to seismic and thermal effects has also been analyzed.

The rockfall analyses provide data to the EBS postclosure performance assessment that may modify estimates of seepage into the emplacement drifts due to the mechanical effects of rock fall during the first 10,000 years postclosure (BSC 2001 [DIRS 155950], Section 4.3.4). These data also support disruptive events analyses (BSC 2001 [DIRS 155950], Section 14.4). Additionally, the rock fall analyses provide data and information to support repository design, including both waste package and subsurface design. The effects of rock fall on drip shield performance are discussed in a white paper (see BSC 2001 [DIRS 156747]).

A primary uncertainty in rock fall analysis is the uncertainty in the change in rock joint properties due to time-dependent, seismic, and thermal effects. This uncertainty is accounted for in the *Drift Degradation Analysis* (BSC 2001 [DIRS 156304]) by applying a conservative reduction in joint strength over time. This conservative use of joint properties bounds this uncertainty.

It is well known that the long-term strength of rock specimens is significantly lower than the short-term strength. For example, degradation of rock mass mechanical properties was observed at the Underground Research Laboratory of Atomic Energy of Canada Limited. Time-dependent cracking in rock related to load, temperature and moisture (stress corrosion) was found to be the mechanism for degradation (Potyondy and Cundall 2001 [DIRS 156895]). The strength reduction in this case is around 50%. The degradation of the host rock at the Yucca Mountain has not been observed from the short-term laboratory testing or field investigation for site characterization activities.

Cohesion degradation of joints was assumed in the Drift Degradation Analysis for long-term effects on rock strength. Cohesion was degraded from 0.1 MPa (14.5 psi) at the beginning of emplacement to 0.01 MPa (1.5 psi) at 10,000 years after waste emplacement, which is a 90% reduction in joint cohesive strength.

Uncertainties associated with the effect of seismic loading on drift degradation are bounded by comparison to case history examples of the performance of underground structures. Underground structures near major earthquakes reported no significant damage (BSC 2001 [DIRS 156304], Attachment VII). Case studies where underground facilities subjected to an earthquake received significant damage are in general characterized by either shallow overburden (Sharma and Judd 1991 [DIRS 154505]), poor ground condition (Rowe 1992 [DIRS

156898]), or fault intersection (Rowe 1992 [DIRS 156898]; Raney 1988 [DIRS 147173]). These conditions are not characteristic of the repository horizon.

The assessment of seismic effects in the *Drift Degradation Analysis* (BSC 2001 [DIRS 156304]) is consistent with case history examples, and is therefore defensible and appropriate. Additional conservatism for the key block approach in the *Drift Degradation Analysis* is that lateral confinement due to the in situ and thermal loads are not included in the model.

2.3.4 Waste Package Degradation: Local Chemistry on Waste Package and Drip Shield Surface (NaF, $CaCl_2$, or $MgCl_2$)

A key uncertainty in the potential degradation of the waste package is the formation of aqueous solutions of $MgCl_2$ or $CaCl_2$, which may enhance the degradation of the waste packages. Potential sources of these minerals have been evaluated. Entrained matter in the ventilation air is not expected to be a source of these ions based on analysis of deposition studies. The soluble salt content of drift dust is also not expected to contribute to significant quantities of these ions. Carbonate base seepage waters preclude the formation of $MgCl_2$ or $CaCl_2$ type brine. Non-carbonate base seepage waters may result in the $MgCl_2$ or $CaCl_2$ type brines. The quantities of these types of brines will be limited due to the formation of insoluble magnesium and calcium minerals, and have a limited effect on the waste package performance. Thus, this uncertainty is expected to be bounded by the current modeling that contains significant uncertainty already.

Another potential source of waste package degradation is the presence of fluoride ions in near-neutral or acidic pH aqueous solutions that are aggressive corrosively if present in sufficient quantity. The most significant source of fluoride ions would be seepage waters. Evaporative concentration of carbonate base water results in significant precipitation of fluoride minerals with fluoride remaining in solution at the 1000 to 2000 mg/kg concentration level, but at high pH. The high pH of these aqueous solutions negates the very aggressive nature of the fluoride. Evaporative concentration of non-carbonate base waters, would result in solutions containing Ca and Mg ions. These ions form relatively insoluble minerals with fluoride, hence significant quantities of fluoride are not expected in the near-neutral solutions, so the overall uncertainty is expected to be low.

2.3.5 Waste Package Degradation: Stability and Degradation of Passive Films on Waste Package Surface, including Effects of Defect/Debris Accumulation

Another key uncertainty in the waste package degradation analysis is the stability and degradation of passive films on the waste package surface. As discussed in SSPA, there are many industrial analogues for Alloy 22 where it is used in aggressive environments because of its resistance to localized corrosion and stress corrosion cracking. Passive materials, such as Alloy 22, are seen to remain passive over long time periods and, when the passive film is damaged, it heals (or repassivates). As long as environmental conditions do not evolve into those in which the passive material is susceptible to localized corrosion, there is no indication from industry that passive materials would not remain passive over long time periods.

An uncertainty in this area is the possibility for passive film degradation due to continual growth of the passive film to a thickness where cracking or spalling might occur. As discussed in the Technical Update Information Letter Report (TUILR) (BSC 2001 [DIRS 156747], Appendix E), thickness measurements thus far suggest that growth of the passive film at relevant temperatures quickly levels off at a steady-state thickness. Another degradation possibility is an increase in the corrosion potential beyond the critical potential for localized corrosion due to changes in the passive film. As discussed in the TUILR, the corrosion potential of Alloy 22 quickly increases by an amount that is small compared to the difference between the corrosion potential and the critical potential and levels off, thus, indicating stability of the passive film. The corrosion potential of samples exposed to the test environments of the long-term corrosion test facility at LLNL for approximately 4 years are, in most cases, only a couple hundred mV higher than they were initially. Samples from one test environment showed a much larger increase in corrosion potential, but this is believed to be due to dissolved metallic ions such as iron, which are known to increase the corrosion potential and most likely came from iron-rich samples other than Alloy 22 that were tested at the same time.

Finally, international experts from a wide range of disciplines and institutions, can find no plausible reason why a passive film would not last for the very long times required by a geologic repository. On July 19 and 20, 2001, the Nuclear Waste Technical Review Board (NWTRB) held a workshop with international experts in the area of corrosion to discuss possible mechanisms for breakdown of the passive film over long time periods. Although, the NWTRB has not formally published its conclusions from this workshop, the Waste Package Performance Peer Review panel (national experts in the areas of metallurgy and corrosion with assistance from an international group of subject matter experts) commented in their interim report that they concluded from this workshop that a passive film could in principle survive over a geologic time scale (Beavers et al 2001 [DIRS 156406]). Further, in their interim report, the panel states that it has not found any technical basis for concluding that the waste package materials are unsuitable for long-term containment. It was also concluded that the approaches used for modeling waste package degradation are sound and consistent with the current corrosion science and engineering practice.

2.3.6 Waste Package Degradation: Possibility of Concentrated Trace Ionic Species on Waste Package (Pb, Hg, As) and Corrosion Consequences

The uncertainty of aqueous solutions in contact with the waste package containing significant trace ionic species, and contributing to waste package degradation is another key remaining uncertainty. Metals at trace concentrations in aqueous solutions are known to have an effect on corrosion processes affecting metallic alloys. For example, trace amounts of lead (Pb) may affect the corrosion of Alloy 600, a nickel-chromium alloy, as an oxidation-reduction couple (Byers et al 1997 [DIRS 156519]), and trace amounts of arsenic (As) are known to assist in hydrogen embrittlement of type 304 stainless steel (Hermas 1999 [DIRS 156591]). To assist in characterizing the extent that trace metals may affect corrosion of candidate materials, the trace metal geochemistry in ambient Yucca Mountain groundwater was evaluated with regards to generating elevated dissolved lead, arsenic, and mercury levels in the potential repository environment. The chemical composition of water that might come in contact with engineered components at Yucca Mountain is expected to be an oxidizing, neutral to alkaline brine, that evolves as fairly neutral (pH 5-8). Dilute ambient groundwater interacts with the Yucca Mountain geology at elevated temperature. End-member brines are expected to be alkaline (pH 10) Na-HCO_3-CO_3 brines and/or more neutral (pH 5) Na-K-Ca-Mg-Cl-NO_3 and Na-K-Mg-Cl-SO_4-NO_3 brines.

Lead. Ambient levels of dissolved lead are at trace levels in groundwater in the vicinity of Yucca Mountain ~9 ppb (Perfect et al 1995 [DIRS 101053]).) In general, dissolved lead concentrations in groundwater are controlled by precipitation of lead containing minerals (e.g., carbonates and oxides in oxidized waters and sulfides in reduced waters) as well as lead adsorption onto mineral surfaces (Drever 1997 [DIRS 140067]). Ambient lead levels in groundwater, which would evolve into near neutral to alkaline brines, have the potential to concentrate in these brines, however concentration levels are expected to be limited to at or below the ppm level. Depending on brine pH and anion levels, lead-chloride, -carbonate and -hydroxyl complexes can either decrease or increase lead solubility.

Arsenic. A potential source of arsenic in Yucca Mountain groundwater is volcanic glass, which slowly dissolves and releases arsenic (Welch et al 1988 [DIRS 156568]). The trace arsenic levels in ambient Yucca Mountain groundwater ~1 ppb (Perfect et al 1995 [DIRS 101053]) have the potential to concentrate in repository brines as the groundwater evaporates because dissolved arsenic has few solubility controls in oxidizing groundwater (Hem 1992 [DIRS 115670]). This conclusion is supported by high dissolved arsenic concentrations measured in geothermal waters and in alkaline lakes, which can contain arsenic at the ppm level (Stauffer and Thompson 1984 [DIRS 156536]; Anderson and Bruland 1991 [DIRS 156515]; Maest et al 1992 [DIRS 156528]; Oremland et al 2000 [DIRS 156531]). It should be noted that arsenic is a minor constituent in these waters. Sorption processes may limit dissolved arsenic concentrations from pH 4-7 in dilute groundwater (Hingston et al 1971 [DIRS 106038]; Anderson et al 1976 [DIRS 156514]; Frost and Griffin 1977 [DIRS 156522]; Pierce and Moore 1980 [DIRS 156532]; van der Hoek et al 1994 [DIRS 156567]; Wilkie and Hering 1996 [DIRS 156570]). However arsenic sorption will be diminished in more concentrated brines, containing high dissolved silica or phosphate that compete for surface sorption (Hingston et al 1971 [DIRS 106038]; Swedlund and Webster 1998 [DIRS 156537]). It is possible for some cement minerals to remove As (V) from alkaline water above pH > 10.7 (Myneni et al 1997 [DIRS 156894]).

Mercury. Ambient Yucca Mountain groundwater mercury concentrations are expected to be quite low based on the composition of other pristine groundwaters (10^{-2} to 10^{-3} ppb) (Krabbenhoft and Babiarz 1992 [DIRS 156523]; Zelewski et al 2001 [DIRS 156571]). Similar to arsenic, mercury has few solubility controls (Hem 1992 [DIRS 115670]). However, the ability of mercury to concentrate in brines will be limited because it is volatile and transfers to the atmosphere, especially at elevated temperatures anticipated in the potential repository environment. Although mercury does sorb to clay minerals, its role in concentrated brines will be diminished because mercury forms chloride complexes that do not sorb effectively to mineral surfaces (MacNaughton and James 1974 [DIRS 156394]; Barrow and Cox, 1992 [DIRS 156518]; Tiffreau and Trocellier 1998 [DIRS 156566]).

In summary, based on a literature review of trace element geochemistry, these elements are not expected to have a significant effect on corrosion either because of limited solubility (Pb and Hg) or because the enhancement of the corrosion process is not significant (As). Arsenic enhances hydrogen embrittlement but only when the material is already susceptible to hydrogen embrittlement under the conditions where arsenic is present. This is not the case in the EBS at Yucca Mountain.

2.3.7 Waste Package Degradation: Post-Welding Residual Stress Distribution of Closure Welds and Manufacturing Flaws in Waste Package

The manufacture of the waste packages and its effect on waste package degradation is another area with potential uncertainty. In particular, post-welding stress profiles at the closure welds and the number, size, and distribution of manufacturing flaws in the waste package remain the sources of uncertainty.

Post-Welding Residual Stress Uncertainty on Waste Package Closure-Lid Welds

Stress corrosion cracking (SCC) is a potential degradation mode that can result in breach of the waste package. SCC of materials may occur when an appropriate combination of material susceptibility, tensile stress, and environment is present. An approach to eliminate the threat of SCC and the resultant through-wall cracking in the waste package is to implement a stress mitigation process to either remove residual tensile stresses in the materials or reduce them below threshold values for SCC initiation and growth.

The closure of the waste package outer barrier is designed to include two lids with two separate post-welding stress mitigation processes: local induction annealing of the outer closure-lid welds and laser peening of the inner closure-lid welds.

The TSPA-SR analysis assumes that SCC is possible only in the regions around the closure-lid welds of the waste package outer barrier because the residual stress in the closure-lid welds may not be relieved by the stress mitigation techniques to the extent that potential for SCC is eliminated (CRWMS M&O 2000 [DIRS 151566], Section 5.6). Additional analyses have been conducted since the completion of the TSPA-SR (CRWMS M&O 2000 [DIRS 153246]) to better quantify uncertainties in the residual stress and corresponding stress intensity factor profiles for the weld regions of the outer and inner closure-lids of the outer waste package barrier.

In the absence of measured data for the waste package design, those analyses focused on relevant literature data for similar stress mitigation techniques applied to similar materials (EPRI 1983 [DIRS 154454]; Chrenko 1980 [DIRS 154451]; Shack and Ellingson 1980 [DIRS 154456]; Pasupathi 2000 [DIRS 149968]). It is assumed in the analysis that the stress measurement uncertainty is the primary contributor to the total uncertainty in the residual stress. Based on an analysis of literature data, the worst case is a case that might result from inadequate control of the processes, represented with the stress uncertainty range of +/- 30 percent of the yield strength (CRWMS M&O 2000 [DIRS 151564], Section 6.2.2.5). The TSPA-SR (CRWMS M&O 2000 [DIRS 153246]) considers conservatively the worst case (+/- 30 percent of the yield strength) as the base case. In addition, a sensitivity analysis was conducted to evaluate the impact on the waste package performance of the updated uncertainty in the residual stress and corresponding stress intensity factor profiles for the outer and inner closure-lid weld regions. The analyses indicate that the earliest possible first waste package failure is delayed by about 5,000 years compared to the TSPA-SR base case model.

Based on the rationale presented above, the TSPA-SR assessment for the waste package degradation is conservative, even with the uncertainties in the TSPA-SR assessments of the residual stress and stress intensity factor profiles and their uncertainty bounds for the closure-lid weld regions of the waste package outer barrier.

Uncertainties in the Number, Orientation and Shape of Manufacturing Flaws in the Waste Package SCC Analysis

Pre-existing manufacturing flaws in the closure-lid welds are the most likely sites for waste package failure by stress corrosion cracking (SCC). Therefore, characteristics (e.g., number, size, orientation and shape) of flaws in the waste package closure-lid welds are important input to the waste package SCC analysis. In the TSPA-SR analysis (CRWMS M&O 2000 [DIRS 153246]), the frequency and size distributions for manufacturing flaws in the closure welds were developed based on published data for stainless steel pipe welds in nuclear power plants (CRWMS M&O 2000 [DIRS 152097], Section 6.2.1.1). The TSPA-SR analysis employed a set of conservative assumptions on the number, orientation and shape of manufacturing flaws as input to the SCC analysis, which are discussed below.

In the TSPA-SR analysis (CRWMS M&O 2000 [DIRS 153246]), pre-existing flaws in the outer 25 percent of the weld thickness (both surface-breaking and embedded) of the closure-lids are assumed to be potential sites for SCC crack growth (CRWMS M&O 2000 [DIRS 151549], Section 5.2). This is a highly conservative assumption and provides that the flaws maintain the original size and shape and propagate into the interior at the rate of general corrosion as the general corrosion front advances. As general corrosion progresses, some of the existing surface-breaking flaws may disappear, and some of the embedded flaws may become surface-breaking flaws. The assumption made in the TSPA-SR and subsequent SSPA analyses, results in a greater number of flaws that are sites for crack initiation and growth by SCC than would be expected.

The hoop stress is the dominant stress in the closure-lid weld region, which drives radial cracks through the closure lid weld region. This analysis indicates that only radial flaws are potential sites for through-wall SCC, if it occurs. The TSPA-SR analysis (CRWMS M&O 2000 [DIRS 153246]) assumes conservatively that all manufacturing flaws are oriented in such a way that they could grow in the radial direction in the presence of hoop stresses (CRWMS M&O 2000 [DIRS 151566], Section 5.6). This is a highly conservative assumption. More realistically, most weld flaws, such as lack of fusion and slag inclusions, would be expected to be oriented in the circumferential direction (CRWMS M&O 2000 [DIRS 151564], Section 6.5.1).

A sensitivity analysis was conducted to evaluate the impact on the waste package performance of the revised model for the orientation of manufacturing flaws. The analyses indicate that the earliest possible first waste package failure is delayed by approximately 5,000 years compared to the TSPA-SR base case model. Details of the analysis are discussed in Section 7.4.2.1 of SSPA Volume 1 (BSC 2001 [DIRS 155950]).

Based on the rationale presented above, the TSPA-SR (CRWMS M&O 2000 [DIRS 153246]) assessment for the waste package degradation is conservative, even with the uncertainties in the TSPA-SR assessments of the number, size, orientation and shape of the manufacturing flaws in the waste package.

2.3.8 Waste Form Degradation: Initial Cladding State

Cladding is being modeled in TSPA-SR (CRWMS M&O 2000 [DIRS 153246]) as an integral part of the waste form. One of the important uncertain parameters in the cladding degradation model is the fraction of cladding that is initially failed. The TSPA-SR uses an expected (mean) value for 9.7%. Table 2-3 gives both the best estimate and values used for the components of this parameter and shows that the expected value used in TSPA-SR is a factor of 190 larger than the best estimate. A discussion of the components follows. In a study for the EPA, S. Cohen & Associates (1999 [DIRS 151783]) estimated the rod failure rate for all causes as less than 0.1%, consistent with the best estimates given below.

Table 2-3. Percent and Cause of Rods Failed as Received at YMP

Rod Failure Mode	Best Estimate [a] (%)	TSPA-SR (%)
Reactor Operation Failures	0.036	0.47 (0.02 – 1.29)
Pool Storage	0.0	0.0
Dry Storage	0.012	7.68 (1.1-19.4)
Transportation (Vibration, Impact)	0.0	0.01
Stainless Steel Cladding	0.002	1.1
Stress Corrosion Cracking	0.0	0.47
Total	0.05%	Expected = 9.7%

[a] S. Cohen & Associates 1999 [DIRS 151783]

Cladding failure during reactor operations have been reduced over time. For the last ten years, the reactor operational failures for the rods have averaged 0.018% (1.69% of the assemblies) (Yang et al 2000 [DIRS 156804]). Table 2-4 gives the failure rate reported by others for various times and conditions. These support the values used in the cladding model.

Fuel degradation during pool storage has been studied and no degradation is expected. The dry storage failure rate used in TSPA-SR included 0.033% failure from rod consolidation, a practice that was studied but never used by utilities. ANL is currently testing rods that have been in dry storage for 17 years and have reported no anomalies. The transportation failure rate is based on half of the shipping casks undergoing a nine-meter fall, an unlikely condition. Studies of the condition of the stainless steel cladding have concluded that 5% of the assemblies and 0.06% of the stainless steel rods (0.002% of the total rods) contain damaged rods but no credit is taken for the remaining 95% of the assemblies. These assemblies are also included in the reactor operation failures so they are being double counted. The NRC believes (NRC 2001 [DIRS 156893]) that failures from iodine induced stress corrosion cracking are unlikely.

In summary, the initial cladding state has been conservatively modeled in the TSPA-SR, is expected to encompass the uncertainty, and no further revisions beyond that described in the SSPA (BSC 2001 [DIRS 155950]; BSC 2001 [DIRS 154659]) are expected until additional data necessitates it.

Table 2-4. Comparison of Fuel Reliability from Various Sources

Fuel	Period	Reference	Failure Rate[a], %
BWR	Through 1990	DOE 1992 [DIRS 102812], p. 2.5-4, Table 2.5.2	4.9 (assembly)
W-PWR	Through 1990	DOE 1992 [DIRS 102812], p. 2.5-5, Table 2.5.3	1.6 (assembly)
PWR-all	Through 1990	DOE 1992 [DIRS 102812], p. 2.5-3,Table 2.5.1	4.2 (assembly)
All	1988	Bailey and Wu 1990 [DIRS 109192], p. 4.2	0.0022
GE-8 × 8	1983	Bailey et al 1985 [DIRS 109191], p. 1-3	0.007
PWR-French	1979 –1984 1984	Dehon et al 1985 [DIRS 109197], p. 2-24	0.001 - 0.01 0.005
BWR-Japan PWR-Japan	To 1997	Sasaki and Kuwabara 1997 [DIRS 102074], p. 13, 14	0.01 0.002
GE-BWR, 8 × 8	4/74 – 8/1993	Potts and Proebstle 1994 [DIRS 107774], p. 92, Table 1	0.016
PWR-CE	To 11/1984	Andrews and Matzie 1985 [DIRS 109190], Table 2, p. 2-42	0.011
All	Through 1984	EPRI 1997 [DIRS 100444], p. 4-1	0.02–.07
All	After 1984	EPRI 1997 [DIRS 100444], p. 4-2	0.006-0.03
BWR PWR	To 1986	Sanders et al 1992 [DIRS 102072], p. I-36	0.15-0.68 0.035-0.44
PWR-Westinghouse	1 core, debris damage after SG replacement	McDonald and Kaiser 1985 [DIRS 101725], pp. 2-5	0.26
All	1969 – 1976	Manaktala 1993 [DIRS 101719], p. 3-2 and 3-3, Fig 3-1	0.01-2+
PWR-Mark B-B&W	1986–1996	Ravier et al 1997 [DIRS 102068], p. 34, Fig. 4	0 - 0.055
All	To 1995	EPA (S. Cohen & Associates 1999 [DIRS 151783])	< 0.05
PWR	1990-1998	EPRI (Yang et al 2000 [DIRS 156804])	2.66 (assembly), 0.018
BWR	1990-1998	EPRI (Yang et al 2000 [DIRS 156804])	0.46 (assembly) 0.008
BWR	2000	Edsinger 2000 [DIRS 154433]	0.0005

[a] Failure rates are on a rod basis unless noted as assembly-based.

2.3.9 Radionuclide Concentration: Radionuclide Solubility and Colloid Formation/Stability

The primary uncertainties associated with radionuclide solubilities are the controls on Np and Pu dissolved concentration limits. The solubilities of both elements are extremely sensitive to system redox state and pH. At the same time, dissolved concentrations depend critically upon the nature of the solid likely to form inside of a breached WP. For example, dissolved Pu levels in equilibrium with PuO_2 are predicted to be several orders of magnitude lower than Pu levels controlled by equilibrium with $Pu(OH)_4$, even if the pH and Eh are exactly the same. That being said, it is hard to unambiguously predict the Eh likely to exist inside of a breached WP. If conditions are oxic due to free exchange of atmospheric O_2 into the WP environment, Np and Pu solubilities will be several orders of magnitude higher than if the high volumes of steel cause the redox state to be appreciably lower than atmospheric. The current approach is to assume Pu solubility–controlling solids of low crystallinity and high hydration – in essence the most soluble of phases, and to assume oxic conditions will prevail inside the WP. The net effect is to cause the likely overprediction of dissolved Pu levels. The conservative nature of the Pu calculation, and the neglect of in-package sorption (see below), provides the requisite confidence to support the site recommendation decision process.

Experimental results from drip tests suggest that a solid-solution between U and Np in spent fuel alteration phases will control dissolved levels of Np inside a breached WP. There is considerable uncertainty in the chemical state of Np in altered spent fuel and this uncertainty is the source of uncertainty in the estimates of dissolved Np levels. Although the former remains unclear, preliminary thermodynamic modeling of the proposed solid-solution predicts dissolved Np levels consistent with drip-test results from actual spent fuel. For this reason the uncertainty in dissolved Np controls is not considered to be an obstacle to proceeding with the site recommendation decision process. Lastly, note that in-package sorption of both Pu and Np to iron oxide degradation products - a powerful limit to transport – is neglected in current analyses, indicating that predictions of dissolved Np and Pu levels are almost certainly substantially larger than would actually occur.

The colloid model (BSC 2001 [DIRS 155950]) has several areas of uncertainty. Two obvious ones are the nature and magnitude of potential colloid release from CSNF and DSNF. Note though that the colloid model relies on a series of exceedingly conservative assumptions that tend to maximize calculated releases and minimize colloid retardation/filtration. The multiple layers of conservatism, combined with natural analogue evidences suggesting only minor transport of radionuclides in many situations, provides confidence that the colloid model is appropriate for the site recommendation decision process.

2.3.10 Unsaturated Zone Transport: Presence and Distribution of Low Advective Transport Times (PTn Lateral Flow, Active Fracture Model, Drift Shadow Zone)

The key uncertainty in the unsaturated zone transport is the presence and distribution of low advective transport times from processes not fully incorporated into the analyses. These uncertainties have been conservatively masked in the current unsaturated zone transport model, and any further inclusion of them would serve to increase transport times and improve the overall performance of the unsaturated zone. The following discussion identifies three areas (lateral flow in the Paintbrush Tuff (PTn), active fracture model, and drift shadow) where the potential uncertainty toward a more realistic representation of the unsaturated zone is being evaluated. However, in spite of these new areas, the overall unsaturated zone transport modeling appears to appropriately capture the uncertainty from the perspective of conservatively bounding the performance of the system.

Lateral Flow in PTn

Recent simulations with the UZ transport models indicate that refinement of the numerical grid leads to redistribution of advective/dispersive transport fluxes (e.g. the PTn unit). Since the TSPA-SR (CRWMS M&O 2000 [DIRS 153246]), new geochemical field data have been used to calibrate the spatial distribution of net infiltration and the anisotropy of permeability of the PTn in UZ flow model simulations (BSC 2001 [DIRS 155950], Section 3.3.3). Detailed PTn flow models have been constructed to evaluate lateral flow within the PTn caused by capillary barrier effects.

Flow in the PTn is important because the new flow simulation results from this study suggest that water flow within and through the PTn likely will be matrix dominated except, possibly, in the vicinity of major through-going fault zones that may create fracture-dominated preferential flow pathways through the unit. The PTn acted as a buffer, damping out variations in the transient net infiltration, so that flow beneath the PTn was essentially steady-state. The PTn redistributed percolation flux in space as well as in time. Lateral flow diverted net infiltration above the potential repository area eastward to the Ghost Dance and Drill Hole Wash faults. Flow thus diverted bypassed the potential repository block. More detailed simulations subsequent to SSPA using a grid of multi-million cells confirm the SSPA results of the PTn study.

The results indicate that the process modeling and associated model abstractions used to represent this component in the TSPA-SR are conservative in that no credit is taken for the effects of this lateral flow component on total system performance.

Active Fracture Model

Of concern to both NRC and NWTRB is the validation of the Active Fracture Model (AFM), which is implemented in all UZ flow, seepage, and transport models (BSC 2001 [DIRS 155950]). The validation of AFM requires field and lab evidence, in addition to numerical consistencies demonstrated by the UZ models. Recent reviews by an internal peer review panel have raised serious concerns about the validation of the AFM. Both the ongoing flow and transport test at Alcove 8-Niche 3 and multi-fracture tests of the 1-m^3 block from the TSw will provide data for validating this key conceptual model. UZ process and abstraction models will be updated if test results require significant revisions of the AFM. Uncertainties in the AFM are not expected to significantly affect the UZ flow model since the model is well constrained after a series of independent calibration and validation against field measurements of water potential and saturation. The impact of the uncertainty of AFM on seepage and UZ transport remains less clear as fewer data have been available for validation. Nevertheless, abstractions of the UZ transport calculations included in the TSPA-SR are not expected to be adversely impacted since they tend to be conservative (BSC 2001 [DIRS 155950], Section 11).

Drift Shadow Zone

Uncertainties in the drift shadow effects on flow beneath the drifts (including dryout during the thermal period), associated diffusion-dominated transport from the drift to the rock, and the transport behavior of radionuclides that initially enter the matrix from the drift remain a challenge. Recent calculations (BSC 2001 [DIRS 155950], Section 11.3.1) show that flow in the UZ tends to be diverted around an opening such as an emplacement drift because of capillary forces. Owing to the shadow zone effect, radionuclide transport times through the UZ tend to be thousands of years longer.

Regardless of how the drift shadow zone is treated for the purpose of TSPA-LA, the TSPA-SR is conservative without incorporating this effect.

2.3.11 Saturated Zone Transport: Saturated Zone Specific Discharge

The key remaining uncertainty in the saturated zone transport analysis is the specific discharge (flow over a specified area) from the saturated zone. TSPA calculations for SR represented a broad range of values for specific discharge in the Saturated Zone (SZ). A single, spatially varying, distribution of specific discharge was obtained from the SZ calibrated flow model. This field of specific discharge values was then scaled over a broad range as part of SZ transport calculations in order to represent uncertainty in this parameter. It is prudent to determine the level of confidence in the SZ flow model (BSC 2001 [DIRS 155950]) given the relatively large uncertainty in specific discharge that is represented in TSPA calculations.

The reason for the large uncertainty in specific discharge is clear from its definition. It is the product of the gradient of hydraulic head and rock permeability. The gradient of head is reasonably well known from field measurements and does not vary spatially over large ranges. However, rock permeability commonly varies spatially over several orders of magnitude in a single rock unit. Consequently, a large number of observations are required to greatly reduce uncertainty in this parameter. The relatively large uncertainty in specific discharge in the TSPA calculations is mainly due to uncertainty in permeability. It is somewhat helpful, however, that specific discharge is constrained by amounts of natural recharge and discharge, and patterns of groundwater flow in natural systems.

The YMP has taken several steps to develop confidence that the site-scale model appropriately (or conservatively) represents actual flow conditions. First, modeled (calibrated) values of permeability are reasonably consistent with available permeability data. Second, there have been efforts to ensure that the site-scale flow model is reasonably consistent with the regional-scale flow model developed by the USGS. This second step adds additional constraints on specific discharge that are based on estimates of natural recharge rates, and regional flow patterns. These two steps add to confidence that the site scale model adequately represents actual conditions at the resolution of the hydrogeologic framework model. However, it is possible that geologic features or local variations in permeability that are not represented in the base calibrated flow model could result in faster flow rates along a potential release pathway. Alternative calibrations are required to examine the impact of plausible features or local variations in permeability. The alternative calibrations discussed below have been performed for this purpose. These alternative calibrations included:

- Different conceptualizations of the Solitario Canyon Fault
- Different conceptualizations of the Large Hydraulic Gradient
- Vertical gradient
- Anisotropy effects
- Repository temperature effects.

The additional calibrations evaluate the effect of these factors on the value of specific discharge that is predicted by the model.

Studying different conceptualizations of the Solitario Canyon fault was important because this fault regulates flow from Crater Flat to the west of the fault to Fortymile Wash on the east of the fault. Different conceptualizations investigated included a shallower representation of the fault that originally went to the bottom of the SZ site-scale model, well into the carbonate aquifer. The shallower representation went only to the top on the carbonate aquifer. The calibrated permeability of the fault changed very little as did the results fluid pathlines for fluid leaving the repository area. This is primarily the result of the fluid particles remaining in the volcanic units due to an upward gradient in the carbonate aquifer. Varying the ratio of vertical to horizontal permeabilities also had little effect. The important fault property was simply the East-West (across-the-fault) permeability.

Different conceptualizations of the Large Hydraulic Gradient were important because all previous models of the saturated zone near Yucca Mountain needed a low permeability feature North of Yucca Mountain to explain the abrupt drop in heads (1200m to 730m) in this area. An excellent calibration was obtained by postulating that changes in the head were due to geochemical alteration and ring faulting as a consequence of the formation on the Claim Canyon Caldera north of Yucca Mountain. The fluid pathlines and specific discharge were very similar for both models. The important conclusion here was that the conceptualization on the Large Hydraulic Gradient had little effect on specific discharge when the model was properly calibrated.

The mapping of the vertical gradient at the contact between the volcanic and/or alluvial aquifer and the carbonate aquifer showed that the vertical gradient was upward along the fluid pathlines from the repository area. For all reasonable climate scenarios, the fluid paths will travel in the most permeable volcanic unit (likely the Bullfrog Tuff), until it reaches the alluvial aquifer, where it will remain in that aquifer. This investigation therefore limits the possibilities for flow pathlines and groundwater specific discharge

The anisotropy study focused on investigating the effect of anisotropy on fluid pathlines. If there was a calibrated directional permeability associated with the fault, the other directional permeabilities contributed much less to the uncertainty of the model. The prime example here is the Solitario Canyon fault where the across-the fault permeability was important. Varying the vertical permeability from 10 to 1000 times the across-the fault value had little effect. The investigation of an anisotropic zone to the east of Yucca Mountain, used to represent the multitude on North-South trending faults showed a slightly better calibrated model was obtained using a 5:1 ratio between the North-South and East-West permeabilities. Overall specific discharge values changed little.

With the exception of the Solitario Canyon fault, fault anisotropy contributed primarily to preferential flow in the North-South direction and was the motivation for investigation a zone of anisotropy to the east of Yucca Mountain. This zone, representing the multitude on North-South trending faults showed a slightly better calibrated model was obtained using a 5:1 ratio between the North-South and East-West permeabilities. Overall specific discharge values changed little. The importance on the Solitario Canyon fault to the SZ model was to regulate flow from Crater Flat to the west of Yucca Mountain to Fortymile Wash on the east side of Yucca Mountain. Here the across-the-fault (East-West) permeability was important. Varying the vertical permeability from 10 to 1000 times the across-the fault value had little effect.

Incorporating increases in saturated zone water temperature changed the specific discharge in a very predictable manner. Creating a zone of elevated temperature near the repository simply decreased the travel time (and thus increasing the specific discharge) in proportion to the decrease in the fluid viscosity due to temperature change. Increasing the average temperature from 30°C to 80°C along a 5-kilometer path decreased the viscosity and travel time by a factor of two, however, this is not expected for current repository design.

Each of these analyses has led to a more complete understanding of the uncertainties that influence the prediction of groundwater specific discharge. The philosophy of the saturated zone model development was to bracket the possible range of key parameters such as the groundwater specific discharge. The model currently bounds the potential travel times, especially by providing a solid lower bound on arrival time at the compliance boundary, and any incorporation of the uncertainty from the above-mentioned topics would serve to lengthen the travel time.

2.3.12 Igneous Consequences: Interaction between Magmas and Repository Structures; Response of Waste Packages and Waste Forms to Igneous Conditions; Eolian and Fluvial Remobilization of Contaminated Volcanic Ash

In the area of igneous activity, the main areas of uncertainty are in igneous consequences, assuming an igneous event occurs. These fall into three main topics.

(1) Interaction between rising magmas and repository structures. Would magma in dikes that intersect repository drifts, after expanding and flowing into drifts, continue upward toward the surface directly above the initial intersection point(s)? Or, alternatively, would magma erupt from some point(s) along intersected drifts that do not correspond with the initial intersection point? Additional uncertainties lie in determining whether current YMP estimates of magmatic conditions within drifts during a potential igneous event are adequate bounding values.

(2) Response of waste packages and waste forms to conditions that might be caused by igneous activity (e.g., high temperature, contact with magma, presence of magmatic gases). For eruptive releases, no credit is taken for the waste package and waste form of intersected materials. The waste package and waste form are assumed to be totally degraded in the affected area. For igneous groundwater releases (no surface eruption), uncertainties exist in the response of waste packages/forms to igneous conditions. Within this realm, a currently unaddressed area of uncertainty is the effect of simple exposure of waste package materials to dilute or concentrated igneous gases on long-term corrosion. The analysis attempts to bound this in its determination of affected waste package and degradation of those waste packages.

While the performance of the waste packages under exposure to corrosive magmatic gases has not yet been addressed explicitly, the effects of this exposure can be discerned from a review of published data on materials such as Alloy 22 in aggressive environments. Assuming that the magmatic gas consists of a mixture water vapor containing volatile SO_2, H_2S, S_2, HCl, HF, CO_2, and CO, the environment is expected to be a reducing one and also highly corrosive. Corrosion performance of Alloy 22 in this type of environment is not readily available but can be inferred from the information available on emission control equipment industries. Components of flue gas desulfurization and waste incineration equipment are exposed to high temperature gases containing sulfuric and sulfurous acids, HCL, chlorine, HF and phosphorus compounds. Under these conditions, high nickel alloys (such as Alloy 276 and Alloy 625) and titanium are the materials of choice and they perform very well (ASM International 1987 [DIRS 133378], p. 1368). While specific corrosion rates for gaseous environment are not available, high nickel alloys such as Alloy 22 will likely corrode at rates no higher than 5 mm/y when exposed to individual acid environments (such as HCL, H_2SO_4, and HF) (ASM International 1987 [DIRS 133378], p. 1152, figure 33 and p. 1162, figure 66). Assuming about 50 days duration for the igneous event (BSC 2001 [DIRS 155950]), a typical duration for an event after which the corrosive gases will dissipate, the loss of metal due to corrosion is expected to be less than 1 mm. Even given that information, a brief review of available published information suggests that exposure to magmatic gases is not expected to result in a significant amount of corrosion of the waste package barrier during the event.

Another area of uncertainty yet to be addressed is the potential degradation of impact properties of the Alloy 22 barrier due to exposure to high temperatures for up to several thousands of hours during an igneous event. Such exposures may result in significant changes in metallurgical characteristics of the material accompanied by loss in ductility and impact strength. Reductions in impact strength from about 260 ft-lb to about 5 to 10 ft-lb have been observed when Alloy 22 was exposed to 760°C for about 2000 hours (Rebak et al 2000 [DIRS 146910]), an environment similar to that expected during an igneous event. This, however, does not necessarily lead to failure of the waste packages and additional events such as rockfall and seismic activity are needed to cause failures.

(3) The fate and transport of potentially contaminated ash from a repository-penetrating eruption. There is currently uncertainty associated with the possibility of remobilization of contaminated ash into fluvial and eolian transport systems. Although this needs to be better quantified, it is unlikely that new results will strongly affect doses relative to the regulatory limits.

The expected low probability of an igneous event intersecting the potential repository (approximately 1.6×10^{-8}/yr) leads to low potential for occurrence. Identification of new aeromagnetic anomalies that might be buried volcanic centers is unlikely to have a significant impact on probability of occurrence. In addition, recent analysis is likely to reduce the probability of explosive eruptive phenomena and therefore to reduce the dose to a control population at the 18 km regulatory boundary. This will likely (at least partially) offset the possibility of increased quantities of waste being erupted as a result of improved magma-repository interaction models.

2.4 CONCLUSIONS REGARDING TSPA-SR TREATMENT OF UNCERTAINTIES

The focus of this report is the treatment of uncertainties in TSPA, both conducted for the TSPA-SR and that planned for the LA. TSPAs in general are the unanimous choice by the Nuclear Energy Association, International Atomic Energy Agency, Environmental Protection Agency, NRC, and the National Academy of Sciences for evaluating the complex processes that may occur over the long time periods of a geologic repository system. Over the past decade, several TSPAs have been developed for the Yucca Mountain Project TSPA 91 (Barnard 1992 [DIRS 100309]), 93 (CRWMS M&O 1994 [DIRS 100111]), 95 (CRWMS M&O 1995 [DIRS 100198]), VA (CRWMS M&O 1997 [DIRS 100842]; CRWMS M&O 1998 [DIRS 108000]), and SR (CRWMS M&O 2000 [DIRS 153246]) and this has led to progressive improvement in the analysis of the performance of the potential repository. Many oversight groups have reviewed the TSPAs conducted for the Project and any obvious problems in methods, assumptions, or approach have been identified during these reviews, and subsequently corrected. The NRC and the Electric Power Institute conduct independent TSPAs and, despite different approaches, they arrive at comparable results and insights. Finally, as discussed by the NRC in the Supplementary Information to final Part 63 (64 FR 55732 [DIRS 156671]), quality assurance and performance confirmation are defenses that help to deal with the uncertainties associated with performance projections.

The discussion above is aimed at the TSPA model as a whole, but the same arguments apply to individual components of the model as well. For example, process models have undergone multiple reviews by internal and external groups, and they have been compared to models developed by other organizations, such as NRC, EPA, EPRI, and other countries. Unreasonable approach, assumptions, or methods should have been eliminated over the course of these reviews.

Hence, the use of a TSPA and its component parts provide reasonable and appropriate bases for supporting a site recommendation decision. The reviews and analyses of uncertainty summarized in this section provide valuable information for understanding the significance of uncertainty to the TSPA results. As will be seen in Section 3, they are also part of the framework for deciding how uncertainties in TSPA should be addressed in the future.

3.0 STRATEGY FOR THE FUTURE TREATMENT OF UNCERTAINTIES

Previous TSPAs have incorporated the evolving information and understanding of the site during the site characterization phase of the Yucca Mountain project. TSPA-VA (CRWMS M&O 1997 [DIRS 100842]; CRWMS M&O 1998 [DIRS 108000]) and TSPA-SR, as well as the previous YMP TSPA's, provided important opportunities for refining models to describe important processes affecting repository performance, for identifying the most significant contributors to dose estimates, and for prioritizing the site characterization and engineering activities toward those issues having greatest importance to performance. The principal goal of performance assessments up to this time has been to capture important physical processes in the process models and abstractions (e.g., unsaturated zone flow, seepage into drifts, corrosion of components of the engineered barrier system) such that *defensible* estimates of system performance can be made. As discussed in Section 2, the maturity of the data and models and approaches taken in the TSPA-SR (CRWMS M&O 2000 [DIRS 153246]) have resulted in a TSPA that consists of a mix of realistic, conservative and, in a few cases, nonconservative models and parameter values. The significance of this mix on performance has been evaluated in the SSPA (BSC 2001 [DIRS 155950]; BSC 2001 [DIRS 154659]). Beginning with the review of the uncertainty treatment in the TSPA-SR (Cline 2000 [DIRS 153193]) and culminating in the evaluation of unquantified uncertainties and conservatism in the SSPA, much has been learned about the importance and influence of uncertainties. These insights provide a supplement to the TSPA-SR and, taken together, provide a firm basis for evaluating the suitability of the site for SR. Further, the insights developed from this past work will be utilized in outlining the approaches that may be explored in the future to treat uncertainties.

This section builds on the insights produced from the existing analyses combined with reviews of these analyses to provide possible strategies for the treatment and communication of uncertainties in future TSPAs. The discussion below begins with considerations of the framework for developing an uncertainty strategy from the standpoint of the views expressed by regulatory and oversight groups. This is followed by a summary of the issue as discussed in the risk analysis literature from the general perspective of treating and understanding uncertainties for decision-making. As noted in the discussion, detailed lower-level guidance for uncertainty treatment will be necessary for process modelers and model abstracters.

3.1 FRAMEWORK FOR DEVELOPING STRATEGY

A number of regulatory and oversight groups have provided their advice and views on the approaches that DOE has followed and should consider following in addressing uncertainties. Likewise, the risk analysis literature provides insights into the manner in which uncertainties could be expressed in order to provide for effective decision-making. The views of regulatory and oversight groups, as derived from written position statements and regulations, are summarized first in this section, as they provide a framework for the subsequent development of a strategy for uncertainty treatment. This will be followed by a summary of the positions voiced in the risk analysis literature.

Since the time of the SSPA, the U. S. Environmental Protection Agency (EPA) has issued its final standard (40 CFR 197 [DIRS 155238]) and the U.S. Nuclear Regulatory Commission (NRC) has issued its final regulation 10 CFR Part 63 (66 FR 55732 [DIRS 156671]). Unlike the draft NRC regulation (64 FR 8640 [DIRS 101680]), these documents and their associated statement of considerations call for a "reasonable expectation" approach, rather than reasonable assurance, for compliance demonstration. This approach focuses on developing a TSPA that represents the reasonably expected behavior of the system and comparing the expected dose value (mean) with the standard in demonstrating compliance. This approach to risk analysis calls for a greater emphasis on quantifying the uncertainties in the inputs to the TSPA, which represent the expected values and associated uncertainties. The new regulations provide a framework for developing strategies for future compliance demonstrations.

The analyses of uncertainties contained in the SSPA Volumes 1 and 2 (BSC 2001 [DIRS 155950]; BSC 2001 [DIRS 154659]) provide valuable information for understanding the significance of previously unquantified uncertainties and the magnitude of conservatism in TSPA-SR. Possible differences in uncertainties between thermal operating modes are also provided in the SSPA. This information, which is summarized in this report, is used to form the basis for the development of a strategy for the future treatment of uncertainties, and analysis of the possible ways to communicate and manage uncertainties in the TSPA.

3.1.1 U.S. Environmental Protection Agency (EPA)

The EPA recently issued its Public Health and Environmental Radiation Protection Standards for Yucca Mountain, Nevada (40 CFR 197 2001 [DIRS 155238]). The regulation provides a definition of the individual protection standard that DOE must meet and a description of "reasonable expectation," which is the context for understanding the standard and its implementation.

> **"Individual Protection Standard**
>
> **"§ 197.20 What standard must DOE meet?**
>
> The DOE must demonstrate, using performance assessment, that there is a reasonable expectation that, for 10,000 years following disposal, the reasonably maximally exposed individual receives no more than an annual committed effective dose equivalent of 150 microsieverts (15 millirems) from releases from the undisturbed Yucca Mountain..."
>
> **"§ 197.14 What is a reasonable expectation?**
>
> Reasonable expectation means that NRC is satisfied that compliance will be achieved based upon the full record before it. Characteristics of reasonable expectation include that it:
>
> a) requires less than absolute proof because absolute proof is impossible to attain for disposal due to the uncertainty of projecting long-term performance;
>
> b) accounts for the inherently greater uncertainties in making long-term projections of the performance of the Yucca Mountain disposal system;
>
> c) does not exclude important parameters from assessments and analyses simply because they are difficult to precisely quantify to a high degree of confidence;
>
> d) focuses performance assessments and analyses upon the full range of defensible and reasonable parameter distributions rather than only upon extreme physical situations and parameter values."

The discussion in the Supplementary Information to Part 197 (pp. 69-73) provides clarifications and additional insights into EPA's intent in the use of the term "reasonable expectation."

> **"III.B.2.c. What Level of Expectation Will Meet Our Standards?**
>
> "We use the concept of "reasonable expectation" in these standards to reflect our intent regarding the level of "proof" necessary for NRC to determine whether the projected

> performance of the Yucca Mountain disposal system complies with the standards (see §§ 197.20, 197.25, 197.30). We intend to convey our position that unequivocal numerical proof of compliance is neither necessary nor likely to be obtained for geologic disposal systems." (p. 69)

The EPA makes a clear distinction between their "reasonable expectation" approach and the "reasonable assurance" approach that the NRC has used for licensing. They conclude that the reasonable expectation approach is more appropriate for demonstrating compliance for a geologic repository.

> "We believe that for very long-term projections where confirmation is not possible, involving the interaction of natural systems with engineered systems complicated by the uncertainties associated with the long time periods involved, an approach that recognizes these difficulties is appropriate. Although NRC has adapted the reasonable assurance approach from the reactor framework and has applied it successfully in regulatory situations related to facility decommissioning and shallow-land waste burial, it has not been applied in a situation as complex as the Yucca Mountain disposal system. We believe that reasonable expectation provides an appropriate approach to compliance decisions; however, with respect to the level of expectation applicable in the licensing process, NRC may adopt its proposed alternative approach. We expect that any implementation approach NRC adopts will incorporate the elements of reasonable expectation listed in § 197.14." (p. 69)

At the time the EPA issued its standard, the proposed 10 CFR part 63 regulation issued by the NRC proposed that the technical criteria for evaluating the DOE's compliance demonstration include a finding of reasonable assurance (63.101). As will be discussed below in Section 3.1.2.1, the final rule now calls for the application of a reasonable expectation approach for evaluating post-closure performance, and reasonable assurance for preclosure safety.

Responding to public comments on the regulation, the EPA outlines its views that the reasonable expectation approach has a sufficient basis in precedent, does not imply less rigorous science and analysis, and is not solely an implementation concern that should be left to the NRC:

> "With respect to the legal authority and use of the reasonable expectation concept in the regulatory process, we believe that the reasonable expectation concept is well established in both the regulatory language in standards, as well as in actual application deep geologic disposal of radioactive wastes, and has been judicially tested." (p. 70)

> "...We do not believe that the reasonable expectation approach either encourages or permits the use of less rigorous science in developing assessments of repository performance for use in regulatory decision making. On the contrary, the reasonable expectation approach takes into account the inherent uncertainties involved in projecting disposal system performance, rather than making assumptions that reflect extreme values instead of the full range of possible parameter values. It requires that the uncertainties in site characteristics over long time frames and the long-term projections of expected performance for the repository are fully understood before regulatory decisions are made...Elicited values for relevant data should not be substituted for actual field and laboratory studies when they can be reasonably performed, simply to conserve resources or satisfy scheduling demands. The gathering of credible information that would allow a better understanding of the uncertainties in site characterization data and engineered barrier performance that would bear on the long-term performance of the repository should not be subjugated simply for convenience. We do not believe that reasonable expectation in any way encourages less than rigorous science and

analysis. In contrast, adequately understanding the inherent uncertainties in projecting repository performance over the time frames required must involve a rigorous scientific program of site characterization studies and laboratory testing." (p. 71-72)

"... Relative to implementation, the primary task for the regulatory authority is to examine the performance case put forward by DOE to determine "how much is enough" in terms of the information and analyses presented, i.e., implementation involves how regulatory authority determines when the performance case has been demonstrated with an acceptable level of confidence. We have proposed no specific measures in our standards for that judgment...The implementing agency is responsible for developing and executing the implementation process and, with respect to the level of expectation applicable in the licensing process, is free to adopt an approach it believes is appropriate, but we believe whatever approach is implemented must incorporate the aspects of reasonable expectation we have described in the standards and amplified upon in the Response to Comments document." (p. 72-73)

From the standpoint of developing a strategy for the treatment of uncertainties in performance assessments for the LA, the EPA makes their view clear that they prefer an approach that quantifies uncertainties realistically, rather than one that involves conservative or bounding estimates. It is important to also note, however, that the EPA recognizes that any performance assessment that is used in long-term projections of a complex system will involve simplifying assumptions and models. Hence, an approach that aims at a realistic representation of uncertainty does not need to be all-inclusive or provide "proof" that all models and parameters are correct. Also, in the following discussion, the EPA indicates possible factors that a "bounding" approach to uncertainty treatment needs to consider from the standpoint of understanding the importance of uncertainties or using the results of the performance assessment in decision making.

"The primary means for demonstrating compliance with the standards is the use of computer modeling to project the performance of the disposal system under the range of expected conditions...Simplifications and assumptions are involved in these modeling effort out of necessity because of the complexity and time frames involved, and the choices made will determine the extent to which the modeling simulations realistically simulate the disposal system's performance. If choices are made that make the simulations very unrealistic, the confidence that can be placed on modeling results is very limited. Inappropriate simplifications can mask the effects of processes that will in reality determine disposal system performance, if the uncertainties involved with these simplifications are not recognized. Overly conservative assumptions made in developing performance scenarios can bias the analyses in the direction of unrealistically extreme situations, which in reality may be highly improbable, and can deflect attention from questions critical to developing an adequate understanding of the expected features, events, and processes. For example, a typical approach to addressing areas of uncertainty is to perform "bounding analyses" of disposal system performance. If the uncertainties in site characterization information and the modeling of relevant features, events, and processes are not fully understood, results of bounding analyses may not be bounding at all. The reasonable expectation approach is aimed simply at focusing attention on understanding the uncertainties in projecting disposal system performance so that regulatory decision making will be done with a full understanding of the uncertainties involved." (p. 69-70)

3.1.2 U.S. Nuclear Regulatory Commission (NRC)

The NRC has issued its final Rule 10 CFR Part 63, which includes consideration of uncertainties, both in the rule itself and in its rulemaking discussion (66 FR 55732 [DIRS 156671]). It is expected that more detailed implementation guidance will eventually be provided in the Yucca Mountain Review Plan, which is not yet available. The discussion below begins with a summary of the pertinent parts of the final rule and associated discussion. This is followed by a summary of the NRC staff's review of the subissues associated with Total System Performance Assessment and Integration Key Technical Issue (TSPAI KTI) and the agreements reached with DOE on a number of issues related to uncertainty treatment.

3.1.2.1 Final Rule 10 CFR 63 "Disposal of High-Level Radioactive Wastes in a Proposed Geologic Repository at Yucca Mountain"

Three sections of the final rule are particularly pertinent to the issue of the treatment of uncertainties in a TSPA for a license application. The first deals with the basic treatment of uncertainties that need to be addressed in a TSPA:

> **"§ 63.114 Requirements for performance assessment**
>
> Any performance assessment used to demonstrate compliance with § 63.113 must:
>
> ...(b) Account for uncertainties and variabilities in parameter values and provide for the technical basis for parameter ranges, probability distributions, or bounding values used in the performance assessment.
>
> (c) Consider alternative conceptual models of features and processes that are consistent with available data and current scientific understanding and evaluate the effects that alternative conceptual models have on the performance of the geologic repository
>
> (d) Consider only events that have at least one chance in 10,000 of occurring over 10,000 years.
>
> (e) Provide the technical basis for either inclusion or exclusion of specific features, events, and processes in the performance assessment..."

The second calls for the applicant to provide sufficient information such that the Nuclear Regulatory Commission can apply the notion of "reasonable expectation." Note that this concept and the associated definition are adopted without modification from the EPA's radiation protection standards (§ 197.14) discussed previously.

> **"§ 63.304 Reasonable expectation**
>
> Reasonable expectation means that the Commission is satisfied that compliance will be achieved based upon the full record before it. Characteristics of reasonable expectation include that it:
>
> (a) requires less than absolute proof because absolute proof is impossible to attain for disposal due to the uncertainty of projecting long-term performance;
>
> (b) accounts for the inherently greater uncertainties in making long-term projections of the performance of the Yucca Mountain disposal system;
>
> (c) does not exclude important parameters from assessments and analyses simply because they are difficult to precisely quantify to a high degree of confidence;

(d) focuses performance assessments and analyses upon the full range of defensible and reasonable parameter distributions rather than only upon extreme physical situations and parameter values."

This part of the regulation is important to developing an uncertainty strategy for LA that will meet approval of the Commission. In particular, subparagraph (c) suggests that attempts should be made to quantify important parameters and associated uncertainties, even for those parameters having relatively few data to constrain them. Subparagraph (d) suggests that reasonable parameter distributions would be preferable to "conservative" or "bounding" models and parameter values for input to the TSPA. The word "only" in subparagraph (d), however, allows for the possibility of applying "extreme" models and parameters in some cases. Subparagraph 63.114 (b) also expresses the expectation that there may be bounding values used in the analyses.

In the third pertinent section, Subpart E—Technical Criteria, the regulation discusses the manner in which an assessment will be made that the performance objectives have been met, drawing on the characteristics of reasonable expectation:

"§ 63.101 (a)(2) Purpose and nature of findings

"Although the post-closure performance objectives specified at § 63.113 are generally stated in unqualified terms, it is not expected that complete assurance that the requirements will be met can be presented. A reasonable expectation on the basis of the record before the Commission, that the post-closure performance objectives will be met, is the general standard required. Proof that the geologic repository will conform with the objectives for post-closure performance are not to be had in the ordinary sense of the word because of the uncertainties inherent in the understanding of the evolution of the geologic setting, biosphere, and engineered barrier system. For such long-term performance, what is required is reasonable expectation, making allowance for time period, hazards, and uncertainties involved...The performance assessments and analyses should focus upon the full range of defensible and reasonable parameter distributions rather than upon extreme physical situations and parameter values. Further, in reaching a determination of reasonable expectation, the Commission may supplement numerical analyses with qualitative judgments..."

As discussed earlier in Section 3.1.1, the EPA provides as part of its discussion of Part 197 a definition of the concepts of "reasonable expectation" and "reasonable assurance" and contrasts in their application. As noted by the EPA, reasonable assurance has been applied by the NRC in their licensing, while reasonable expectation has been applied in EPA's certification of the Waste Isolation Pilot Plant. As illustrated by the paragraphs below, the NRC in its regulation also calls for a reasonable expectation in evaluating *post-closure*. Consistent with power plant licensing, the NRC also calls for a reasonable assurance standard to be used in evaluating *preclosure* safety:

"§ 63.101 (b) Purpose and nature of findings

"...Prior to closure, § 63.31(a)(1) requires a finding that there is reasonable assurance that the types and amounts of radioactive materials described in the application can be received, possessed, and stored in a geologic repository operations area of the design proposed without unreasonable risk to the health and safety of the public. After permanent closure § 63.31(a)(2) requires the Commission to consider whether there is a reasonable expectation the site and design comply with the post-closure performance objectives. Once again, although the criteria may be written in unqualified terms, the demonstration of compliance must take uncertainties and gaps in knowledge into account so that the Commission can make the specified finding with respect to paragraph (a)(2) of § 63.31."

As discussed in the supplementary information accompanying final 10 CFR 63 (66 FR 55732 [DIRS 156671], p. 55736), these criteria are consistent with the NRC's overall philosophy of risk-informed, performance-based regulation (60 FR 42622 [DIRS 103662]).

3.1.2.2 NRC/DOE Agreements Related to Uncertainty Treatment

The treatment of uncertainty is part of the Total System Performance Assessment and Integration Key Technical Issue (TSPAI KTI). The DOE has had two Technical Exchanges with the NRC to review the status of activities to resolve various subissues of this KTI. In order to achieve a status of "closed-pending" for the various TSPAI KTI subissues, the DOE and NRC developed a series of agreements that call for the DOE to conduct certain activities prior to the submittal of a license application (Cornell 2001 [DIRS 156408]). The NRC/DOE agreements provide insights into possible approaches to addressing uncertainties. An example subset of the agreements that deal with the uncertainty issue is given in Table 3-1.

Many of the agreements deal with evaluating the effects of uncertainties in particular process model inputs to the TSPA, or the appropriate propagation of uncertainties in process models through the abstraction process into TSPA. Others deal with the distinction between the representation of uncertainty and variability in process models, or with documentation of the technical basis for the representations and abstractions. Two of the agreements deal with the development of written guidance for the model abstraction process (TSPAI.3.38) and for the methodology for addressing alternative conceptual models into the performance assessment (TSPAI.4.01). The purpose of the written guidance would be to ensure consistent, systematic approaches across the project to representing uncertainties, selecting conservatism, and representing alternative conceptual models without underestimating the risk.

3.1.3 Advisory Committee on Nuclear Waste (ACNW)

The Advisory Committee on Nuclear Waste is part of the NRC and provides strategic advice to the Commission. The ACNW's most recent discussion of uncertainty treatment is included in their letter to NRC Chairman Meserve regarding their vertical slice review of the TSPA-SR (Hornberger 2001 [DIRS 156892]). Regarding the inclusion in the TSPA-SR of a combination of conservative estimates and realistic estimates, the Committee concludes that the approach does not lead to a realistic assessment of the risk and, therefore, is not conducive to risk-informed decision-making:

Table 3-1. Examples of NRC/DOE Agreements Related to Uncertainties

Key Technical Issue On Total System Performance Assessment And Integration (From DOE 2001 [DIRS 153849])

Subissue Title	Agreement No.	Example Preliminary NRC/DOE Agreements
System description and demonstration of multiple barriers	TSPAI.1.01	Provide discussion of capabilities of individual barriers in light of existing parameter uncertainty and model uncertainty
Model abstraction within the total system performance assessment methodology	TSPAI.3.01	Propagate significant sources of uncertainty into projections of waste package and drip shield performance included in future performance assessments, including: measurement uncertainty, alternative explanations for decrease in corrosion rate with time, limited numbers of samples, confidence in upper corrosion rate limit, and alternative statistical representations of empirical rates.
	TSPAI.3.05	Provide technical basis for representation of uncertainty/variability in general corrosion rates
	TSPAI.3.17	Provide uncertainty analysis of the diffusion coefficient governing transport of radionuclides through the invert, including uncertainty in modeled invert saturation
	TSPAI.3.32	Provide the technical basis that the representation of uncertainty in the saturated zone as essentially all lack-of-knowledge uncertainty (as opposed to real sample variability) does not result in an underestimation of risk when propagated to the performance assessment
	TSPAI.3.38	Develop written guidance in the model abstraction process for model developers so that (1) the abstraction process, (2) the selection of conservatism in components, and (3) representation of uncertainty, are systematic across the TSPA model. These guidelines will address: (1) evaluation of non-linear models when conservatism is being utilized to address uncertainty, and (2) utilization of decisions based on technical judgment in a complex system.
	TSPAI.3.41	To provide support for the mathematical representation of data uncertainty in the TSPA, the DOE will provide technical basis for the data distributions used in the TSPA. An example of how this may be accomplished is the representation on a figure or chart of the data plotted as an empirical distribution and the probability distribution assigned to fit these data.
Demonstration of overall performance objective	TSPAI.4.01	Document the methodology that will be used to incorporate alternative conceptual models into the performance assessment, ensuring that the representation of alternative conceptual models in the TSPA does not result in an underestimation of risk. Document guidance given to process-level experts for the treatment of alternative models. The implementation of the methodology will be sufficient to allow a clear understanding of the potential effect of alternative conceptual models and their associated uncertainties on the performance assessment.
	TSPAI.4.03	Document the method to demonstrate that the overall results of the TSPA are stable. Provide documentation that submodels are also numerically stable, and address in the method the stability of the results with respect to the number of realizations.
	TSPAI.4.04	Conduct appropriate analyses and provide documentation that demonstrates the results of the performance assessment are stable with respect to discretization (e.g. spatial and temporal) of the TSPA model.

"The TSPA-SR relies on modeling assumptions that mask a realistic assessment of risk...Other assumptions that mask a realistic assessment and reasonableness have to do with mixing conservative and nonconservative bounding analyses and the general treatment of uncertainty. While the TSPA-SR analysts clearly recognize the masking problem and the modeling inconsistencies with respect to realistic assumptions, they fail to convey the expected risk, based on the available evidence.

"The Committee believes that the TSPA-SR is driven more by an attempt to demonstrate compliance with the standards than by the need to provide an assessment designed to answer the question: What is the risk? The result is that the assessment does not really risk-inform the safety of the repository..."

The Committee notes that there may be issues in finding a consistent definition of the term "conservative" and in understanding its implications to performance:

"The stated DOE practice is to choose parameter distributions that are "deliberately conservative" where uncertainty "cannot be adequately justified based on available information." To suggest that the distributions are conservative implies some knowledge about the underlying processes, and how the results are affected by parameter values. While this approach may be suitable under some circumstances, when modeling involves linear systems and independent processes, the application of this approach to the high-level waste (HLW) repository at Yucca Mountain may be flawed. This is because the underlying processes in the near field of the repository, for example, are not entirely linear or independent. To the contrary, significant coupling is expected among nonlinear hydrological, chemical, and thermal processes. Determining what is conservative and what is not under these conditions is neither intuitive nor straightforward."

The Committee concludes that the approach taken to deal with uncertainties may not provide sufficient information for decision-making:

"The masking of realism in the TSPA-SR precludes providing a clear basis to estimate the margins of safety, or making an objective regulatory decision that is in the best public interest."

From the standpoint of developing a strategy for handling uncertainties in the future, the Committee offers recommendations:

"On the basis of its vertical-slice review of the TSPA-SR, the Committee recommends that the NRC staff take the necessary action to be assured that:

The performance assessment of the proposed Yucca Mountain repository is, in fact, risk-informed.

DOE has adopted an evidence-supported approach and realistic modeling assumptions to use in the TSPA-SR while reducing the dependence on parameter bounding and conservatism to overcome uncertainty and increase the reliance on such available evidence as site-specific field and laboratory data, natural analogs, and expert knowledge..."

3.1.4 Nuclear Waste Technical Review Board (NWTRB)

Over the past few years, the Nuclear Waste Technical Review Board (NWTRB) has provided a critical review and evaluation of DOE's total system performance assessments including specific reference to the manner in which uncertainties have been treated. The Board has also expressed its views regarding the manner in which uncertainties should be identified, quantified, and communicated for decision-making. Such decision-making can include regulatory decisions regarding the use of TSPA in demonstrating compliance and communicating confidence in the results. Therefore, the Board's views in this area, as exemplified by their written positions, provide a meaningful framework for considering a strategy for uncertainty treatment in the LA. A summary of those comments is given below.

A recurring theme throughout the Board's comments on uncertainties over the past few years has been a link between the characterization of uncertainties related to performance and decision-making using that characterization. In their March 20, 2000 letter (Cohon 2000 [DIRS 148739]), whose subject was the January, 2000 Board meeting, the Board identifies the need for information that could be useful for decision-makers, and the types of information that should be provided:

> "A central theme of the January meeting was the challenge of describing uncertainties in ways that will be meaningful in the decision-making process..."
>
> "At the same time, the Board believes that addressing PA's uncertainties and the sources of these uncertainties as clearly as possible is essential for technical credibility and sound decision-making. Therefore, the Board recommends that the DOE include in its representation of performance uncertainty a description of critical assumptions, an explanation of why particular parameter ranges were chosen, a discussion of possible data limitations, an explanation of the basis and justification for using expert judgments (whether or not they are elicited formally), and an assessment of confidence in the conceptual models used. In addition, the Board recommends that the uncertainties associated with the performance estimates be identified and quantified well enough so that their implications for the performance estimates can be understood."
>
> "Multiple lines of argument and evidence—combined with a clear and complete description of uncertainty—will present a much more technically defensible demonstration of repository safety than will any individual component of the safety case"

An important component of the "package" of information that the Board describes as important for decision-making is a quantification of uncertainties. The need to *quantify* uncertainties, rather than just to describe them or bound them in the TSPA, is described in several correspondences by the Board:

> "The Board believes that meaningful quantification of the uncertainties associated with performance, clearly and understandably presented, is an essential element of performance characterization. The complexity of the repository system and the length of time over which performance must be estimated make uncertainty both large and unavoidable (although perhaps reducible). Especially important in such a situation is that policy-makers and other interested parties understand the uncertainty associated with key decisions." (Cohon 2000 [DIRS 156461]). Note: In this letter also sent on March 20, 2000, the Board responds to DOE's rulemaking in Part 963.
>
> "The next step, important for the fast-approaching site recommendation by the Secretary of Energy, is to analyze and explain quantitatively the size and significance of those uncertainties for performance and how they vary with repository temperature...Similarly, quantifying uncertainties in variables and processes that pertain to fluid flow and transport in the repository rock over the temperature range from ambient to the maximum predicted temperature in the rock is very important" (Cohon 2000 [DIRS 156462]).

"The Board believes that the quantification, analysis, integration, and communication of uncertainty need to be addressed in a more rigorous manner than shown in the presentations at the Board meeting [in August, 2000]. Any projections of repository performance will be incomplete unless the DOE also provides a description and a meaningful quantification of the level of uncertainty associated with its predictions" (Cohon 2000 [DIRS 152574]).

"...the Board has recommended that DOE focus significant attention on four priority areas dealing with managing uncertainty and coupled processes, which, in the Board's view, are essential elements of any DOE site recommendation.

(1) Meaningful quantification of conservatisms and uncertainties in DOE's performance assessments..." (NWTRB 2001[DIRS 156474]).

"The Board also realizes that policy-makers can make a decision on whether to recommend the site at any time, depending in part on how much uncertainty they find acceptable. The Board believes, however, that developing methods for quantifying uncertainties in the DOE's performance assessments should be a priority area of work for the Yucca Mountain Project so that policy-makers will have a clearer basis for making their decisions" (NWTRB 2001 [DIRS 156474]).

Partly in response to the Board's request to quantify uncertainties and partly because of the need to understand and communicate the conservatisms being included in the TSPA for SR, the DOE embarked on the "Unquantified Uncertainties" activity that was specifically designed to quantify the previously-unquantified uncertainties in the TSPA and to evaluate the significance of uncertainties and conservatisms (PORB Position Papers 000531-01 (Brocoum 2000 [DIRS 156874]) and 000913-02 (Brocoum 2000 [156875])). Multiple presentations were made to the Board to gain their insights and the efforts were generally well received:

"The Board is pleased with the efforts made so far to quantify better the uncertainties and conservatisms present in the performance assessments of the proposed Yucca Mountain repository..." (Cohon 2001 [DIRS 156891]).

"The Board is encouraged by the work being undertaken by the Project to quantify uncertainties and conservatisms in it performance assessments (PA). The work appears to be responsive to the concerns that the Board has voiced in the past. The Board will have more detailed comments on this issue when it completes its review of the *Supplemental Science and Performance Analyses (SSPA)* report." (Cohon 2001 [DIRS 156890]).

Although the TSPA-SR contains a number of quantified uncertainties and the supporting AMRs describe the uncertainties associated with the models and analyses, there are a number of inputs that are bounded or conservatively estimated. The treatment of uncertainty in the TSPA-SR can be summarized as the following: Provide a *defensible* selection from among alternative conceptual models and explain the technical basis for your selection in your AMR; when there are sufficient data to do so defensibly, quantify uncertainties in parameters (e.g., with probability distributions); otherwise, in the absence of sufficient data, develop conservative or bounding estimates that can be defended technically. This approach is in accord with the recommendations made by the TSPA Peer Review Panel (Budnitz et al 1999 [DIRS 102726]), who provided their perspectives after review of the TSPA-VA (see Section 3.1.5 below). The consequence of this approach is a "mix" of conservative and realistic (quantified uncertainty) inputs that, the Project contends, results in conservative performance estimates. Note that a few unintended nonconservatisms have also been identified. But on the whole, the approach to treating uncertainties in the TSPA-SR is aimed at providing defensible inputs that result in a conservative estimate of doses.

Similar to the ACNW and other oversight groups, the Board has difficulty in understanding how this approach to treating uncertainties can be understood in terms of the significance of the uncertainties that have not been quantified and the magnitude of the conservatisms that result:

> "For the PA being prepared for its site recommendation, the DOE is using a methodology in which uncertainties are addressed differently for different input assumptions and parameters. According to presentations made to the Board at its January 2000 meeting, some of these assumptions and parameters will be single-valued conservative estimates, and others will be represented probabilistically. The Board understands the value of using conservative estimates, but it strongly urges the DOE to work with statisticians and other experts to develop coherent and consistent probability statements about projected repository performance based on those conservative estimates" (Cohon 2000 [DIRS 156461]).

> "Another issue requiring further thought is the adoption of a mix of conservative, realistic, and optimistic assumption in models and parameters: for example, the "conservative" estimates of diffusion through the invert and the "optimistic" estimate of the extent of THC coupling. Determining the overall level of conservatism for a mix of conservative, realistic, and optimistic assumptions will be very difficult. If the DOE wants to argue that the TSPA is conservative, an effort must be made to provide a defensible estimate of the overall level of conservatism" (Cohon 2000 [DIRS 152574]).

Because of this concern, the Board's four priority items provided at the January, 2001 Board meeting (Cohon 2001 [DIRS 156891]) includes a call for "meaningful quantification of conservatisms and uncertainties in DOE's performance assessments." As the ACNW indicates in their comments, the quantification of conservatism in risk assessments is typically based on a comparison between the *expected* risk (i.e., mean dose) and a *compliance* risk estimate that might include conservatisms. The Board indicates that having only the latter—as is the case for the TSPA-SR—does not provide a basis for quantifying the conservatism that it might contain. An aim of the Unquantified Uncertainties activity was to develop an expected risk estimate and to compare that to the TSPA-SR. The results of that effort are given in the SSPA (BSC 2001 [DIRS 155950]; BSC 2001 [DIRS 154659]) and summarized in Section 2 of this report.

Closely coupled with the concept of quantifying uncertainties, the Board indicates that such quantification will provide direct information that decision-makers can use in making trade-offs, assessing the credibility of DOE's positions, and developing confidence. Their view is very similar to the risk-informed decision-making concept advanced by the NRC, where the notion of "risk-informed" includes both the expected risk and a quantitative description of the uncertainty associated with the expected risk.

> "The Board is concerned that the PA approach now envisioned by the DOE could deprive policy-makers of critical information on possible trade-offs between projected performance and the uncertainty in those projections. For example, one policy-maker might be willing to accept development of a repository that would release half of the permitted dose, with only a 1 in 1,000 chance of exceeding that permitted dose. However, that same policy-maker might decline to develop a repository that is expected to release only a tenth of the permitted dose, but has a 1 in 4 chance of exceeding that permitted dose. Another policy-maker's preferences might be the opposite. Because the uncertainties about repository system

> performance may be substantial, estimates of uncertainty about doses are at least as important as estimates of performance." (Cohon 2000 [DIRS 156461])

> "The Board believes that meaningful quantification of the uncertainties associated with performance, clearly and understandably presented, is essential to provide policy-makers who are deciding on a site recommendation with critical information on trade-offs between projected performance and uncertainty in those projections...Eliminating all the uncertainties will never be possible (although they can be reduced). In fact, the Board has noted that a decision on whether to recommend the site can be made at any time, depending in part on how much uncertainty policy-makers are prepared to accept." (Cohon 2000 [DIRS 152574])

> "At the time a decision is made on site recommendation, the Board and scientific community are likely to be asked at least two questions: (1) Is the underlying science broadly regarded as technically sound? and (2) Are the uncertainties in estimates of performance displayed clearly and openly, especially about the major factors that may lead to a potential radioactive release? A major question for policy-makers at that point may be whether the site is suitable, given the level of uncertainty associated with the DOE's site-suitability determination. The Board believes it is critical that the DOE not only offer estimates of performance but also clarify the extent and significance of the technical and scientific uncertainties. Understanding uncertainties is vital for sound decision-making." (Knopman 2000 [DIRS 156783])

Another recurring Board theme related to uncertainties is the need to communicate uncertainties and risk information in a clear, meaningful manner to decision-makers and stakeholders.

> "Accurately portraying the nature of uncertainties about the performance of a complex system like a Yucca Mountain repository is a formidable challenge. As you are aware, the DOE will need to communicate effectively to a wide variety of audiences as the project moves forward. The DOE's initiative to develop a simplified performance-assessment capability is a commendable effort to make the "black box" of performance assessment more transparent to nonspecialists...We also urge the DOE to seek other innovative ways of improving communication with all stakeholders." (Cohon 2000 [DIRS 148739])

> "In the Board's view, the DOE has not yet developed a consistent and transparent approach to representing the uncertainty in its estimates of long-term repository performance." (Cohon 2000 [DIRS 156461])

> "Finally, even if a technically credible performance assessment is carried out, poor communication can hurt the perception of credibility." (Cohon 2000 [DIRS 152574])

3.1.5 Total System Performance Assessment Peer Review Panel

During a two-year period from February, 1997 until February, 1999, a TSPA Peer Review Panel (PRP) undertook a review of the TSPA for the Viability Assessment (TSPA-VA) (CRWMS M&O 1997 [DIRS 100842]; CRWMS M&O 1998 [DIRS 108000]), which culminated in their final report and recommendations (Budnitz et al 1999 [DIRS 102726]). Although the panel focused on the TSPA-VA, which differs in many respects from the TSPA-SR, the observations and recommendations made by the PRP provide a context for the approaches taken by the Project to address uncertainties in the TSPA-SR. In fact, many of the approaches taken in the SR accord well with the advice given by the Panel. Note that the Viability Assessment and the PRP review occurred prior to the issuance of the EPA standard and final NRC regulations discussed above. Therefore, the PRP was providing its comments in the absence of an EPA standard and in the context of the draft proposed Part 63 regulation, which was focused more on the demonstration of compliance using a reasonable assurance, rather than a reasonable expectation, approach. This is reflected in the Panel's general description of managing complexities and component model limitations:

> "On the basis of its review, the Panel has concluded that there are two types of processes that should be analyzed as part of the possible upcoming TSPA-LA, particularly in terms of meeting the anticipated "reasonable assurance" requirements of the USNRC. These are (1) those for which analytical models are available, and (2) those that may be essentially intractable given current analytical capabilities, or intractable within the time constraints under which the TSPA staff is operating."

Recognizing that some technical inputs to the TSPA may be readily addressed using available data, or that new data may be gathered to address some processes in a timely matter, the Panel states that other processes may be impossible to treat probabilistically:

> "...the applicability of a given approach to a specific type of process will depend on the nature of the process. In the case of processes for which analytical models are available, significant improvements can be made through updating the component models and the acquisition and use of additional data. In the case of processes that may be essentially intractable, the only available option may be to treat them through the use of bounding analyses and/or design changes...
>
> In contrast to the goal in the preparation of the TSPA-VA, the objective for the TSPA-LA should be to provide sufficient documentation so that it can be more readily defended as being either realistic or conservative."

In its discussion of the use of "bounding analyses," the Panel states the view that traditionally such analyses provide assurance to the NRC and, therefore, assuming a "reasonable assurance" regulation, should prove acceptable for the LA. The Panel is clear, however, that bounding analyses should always be technically supported and should be applied judiciously to those inputs that do not have a large impact on the TSPA results.

> "Applications of bounding analyses generally produce results that are conservative. For this reason, the outcomes of such analyses are generally assumed to be highly credible by regulatory agencies. In addition, such analyses are commonly less data-intensive than those conducted on a more realistic basis. As a result, bounding analyses are particularly useful in cases where the existing analytical models have significant deficiencies that would be difficult and time consuming to correct. A good example of processes that fall into this category is those that are highly complex and extensively coupled. The application of bounding analyses would appear to be especially appropriate as the project staff approaches the preparation of the anticipated TSPA-LA. The chosen applications must, however, be defensible, and care should be taken to ensure that the performance of the systems to which the analyses are applied have only a minor effect on the results of the overall assessment. Otherwise, the use of bounding analyses may result in unacceptably conservative projections of the performance of the overall repository system."

Additional cautions are provided regarding the use of bounding analyses:

> "There are other cautions that should be observed in the application of bounding analyses. For a complex, non-linear system, it is not always readily apparent how conditions that

bound performance should be defined. This makes it difficult to judge whether, and the degree to which, the generated results are conservative. Because of the difficulties inherent in developing fully-coupled models for analyzing the flow and transport in the unsaturated zone, it may prove advantageous to begin with a simpler set of models, and then to evaluate the more complex issues through either sensitivity studies or bounding evaluations. If these efforts demonstrate that certain aspects of the complex coupled phenomena can be ignored or treated one-dimensionally, the overall analysis will be vastly simplified. More effort, however, needs to be directed to defending this approach and ensuring that coupled effects, that are potentially detrimental to repository performance, are addressed in this manner."

Finally, the Panel's recommendation can be viewed as a pragmatic approach that calls for reducing uncertainties with data collection and making the most significant elements of the model more realistic, while providing defensible bounds and not devoting limited resources to the elements of lesser importance.

"Our comments are not meant to excuse the Department of Energy from meeting its obligation of demonstrating with the required degree of confidence that the repository will meet or exceed the specified performance targets, should a license application be submitted the USNRC... For cases in which it is feasible to improve either the component models or their underlying data, the Panel recommends that efforts be made to implement such improvements wherever such changes would affect the overall assessment. Where conservative bounding analyses do not result in unduly pessimistic estimates of the total system performance, the Panel recognizes that it may not be cost-effective to spend additional time and effort refining the assessments and making them more realistic. For those issues for which, by virtue of their complexity, it is not feasible to produce more realistic models supported by data, the Panel recommends that a combination of bounding analyses and design changes be applied."

3.1.6 Joint NEA-IAEA International Review Team

During the summer of 2001, a Joint NEA-IAEA International Review Team (IRT) conducted a review of the TSPA-SR. A summary report detailing the findings of the IRT is expected in mid November. The Executive Summary for the report has been made available to the DOE (Riotte 2001 [DIRS 156782]). Conclusions from the Executive Summary are summarized here.

In the "Statement by the International Review Team" (Riotte 2001), the IRT provides its overall assessment of the adequacy of the performance assessment for supporting the site recommendation decision:

"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 emphasized 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."

The need to develop an understanding of the system as well as to demonstrate compliance is articulated in the IRT's "Recommendations for Future Assessments." The IRT's suggested approach also addresses the issue of developing a realistic performance assessment and a conservative assessment.

> "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 presenting an understanding of the 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. 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 surrounding to a range of stakeholders and give an indication of the safety margins inherent in the TSPA-SR. A second complementary analysis should then be undertaken and presented which is aimed at reinforcing or arguing reasonable assurance of compliance with regulations. Specific assumptions and models will be needed for this and should be identified separately from the less conservative analysis." (p. 5)

The IRT notes the importance of establishing a comprehensive strategy for uncertainty treatment for the LA, which should include consideration of the distinction between intrinsic variability (also called aleatory uncertainty [e.g., Budnitz et al 1997 [DIRS 103635]) and lack of knowledge (also called epistemic uncertainty). The IRT also notes that the issue of "risk dilution" arising from the probabilistic inclusion of alternative conceptual models needs to be addressed.

> "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 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." (p. 5)

3.1.7 Insights from the Risk Analysis Literature

In a general sense, a TSPA is part of a decision process where one is attempting to minimize risk to the workers, the public, and the environment within the limits of available resources, design options and policy constraints. As such, there are analogies to other quantitative assessments of risk posed by alternatives that provide important inputs to decision processes. Review of the risk analysis literature indicates a preference for the use of realistic representations of uncertainty as inputs to the decision process for the following reasons.

A meaningful comparison between alternatives for maximizing risk reduction for the expended resources requires that the risks posed by each alternative be assessed on a comparable basis. The use of "conservative" or "plausible bound" inputs instead of quantification of the uncertainty in the inputs will produce results of a risk assessment that are known to be biased from what is expected based on current knowledge (e.g. Helton et al 2000 DIRS [156549], p. 445). However, the degree of this bias will be unknown and may vary widely between the assessments for different alternatives (Paté-Cornell 1996 DIRS [107499], p. 100). As a result, a meaningful comparison between the costs and benefits of alternatives cannot be made when the assessments of the risks posed by the various options have unknown degrees of conservatism (Paté-Cornell 1996 [DIRS 107499], p. 100-101; Rechard 1999 [DIRS 156544], p. 799; Helton et al 2000 [DIRS 156549], p. 445; Paté-Cornell 1999 [DIRS 156550], p. 998). As stated by Garrick and Kaplan (1999 [DIRS 156546], p. 906):

> "For output of PPA (probabilistic performance assessment) to be trustworthy, i.e., useful for decision purposes, these curves should be based 'on the evidence,' and not on any individual's opinion, position, politics, mood, special interests, or wishful thinking."

Another reason for preference of the full characterization of uncertainties over the use of conservative assumptions is in communication of the results of an uncertainty analysis. Introduction of conservative assumptions in place of uncertainty distributions for some key parameters leads to a *conditional* uncertainty analysis (Paté-Cornell 1999 [DIRS 156550], p. 995). The challenge is then to remind the reader of the conditional nature of the results and the fact that they should not treated as "expected results" in decision making.

The literature also contains references to "aversion to ambiguity" exhibited by decision makers (e.g., Mumpower 1991 [DIRS 156551], p. 519; Paté-Cornell and Fischbeck 1969 [DIRS 156560], p. 200; Paté-Cornell and Davis 1994 [DIRS 156554], p. 267). These authors discuss evidence that when faced with two alternatives with equal expected consequences (both calculated over the epistemic uncertainties in the process), decision makers often prefer the alternative with the narrower epistemic uncertainty distribution. These choices need to be made in light of true, unbiased assessments of uncertainty.

3.1.8 Direction from DOE to Bechtel SAIC Company, LLC (BSC)

A final piece of the framework for developing guidance for the future treatment of uncertainties is direction provided by DOE to BSC related to fiscal year 2002 Multi-year Plan through License Application (Dyer 2001 [DIRS 156480]). In the description of the Strategic Planning Basis for the Science and Analysis Project, the issue of uncertainty characterization to support a conservative or a realistic representation of TSPA-LA is addressed. Rather than have two TSPAs, one bounding and one realistic, the DOE calls for a single TSPA and describes its' attributes:

> "There will be a single, fully qualified TSPA developed and documented as part of the technical basis for the LA. This will avoid potential problems associated with bringing two different analyses, based on different sets of modeling assumptions (e.g., bounding versus realistic), into the licensing review process...
>
> "Models used for the TSPA to evaluate compliance with regulatory requirements for repository system performance after closure should reflect a credible representation of the system and its natural and engineered components...To the extent possible, this representation should reflect the reasonably expected behavior of the system and its components, and the uncertainty associated with modeling such behavior..."

The DOE also notes that the data and software used to characterize the uncertainties in inputs to the TSPA need to be qualified:

> "The data and software used in support of model development and TSPA analyses must be fully qualified, and all models must be validated (i.e., information presented to provide confidence that the models are valid for their intended use)."

3.1.9 Summary of Framework for Developing Strategy

Review of the written positions and comments of various oversight groups provides a framework for a high-level strategy regarding the future treatment of uncertainties in TSPA. A number of common themes emerge from the review provided in Sections 3.1.1—3.1.8, which are summarized here:

- The "reasonable expectation" approach to evaluating performance is viewed as an appropriate framework for evaluating the projected performance of the repository. The reasonable expectation approach focuses performance assessments upon the full range of defensible and reasonable parameter distributions, rather than on extreme physical situations and parameter values. Both the EPA, which developed the standard, and the NRC, which is responsible for the regulation and review of the applicant's compliance demonstration, have now endorsed the reasonable expectation concept. Guidance to the NRC staff for review of the LA in this regard may be included in the Yucca Mountain Review Plan, but is not yet available.
- Review of the uncertainty treatment in TSPA-SR (YMP 2001 [DIRS 155343]) indicated that the treatment of uncertainties was not uniform. Further, reasonable representations of models and parameters should be developed with the importance of the model or parameter in mind. Transparency is not enhanced by developing extreme detail in models that do not have an impact on the total system performance.
- The reasonable expectation concept, as defined identically by the EPA and NRC, recognizes that long-term projections in a TSPA will involve simplifying assumptions and models. Therefore, an approach that aims at a realistic representation of uncertainty does not need to be all-inclusive or provide absolute "proof".
- Several oversight groups conclude that a TSPA containing a mixture of "realistic" and "conservative" inputs presents several concerns, including: obscuring an understanding of uncertainties and their importance; potentially masking the expected performance determined in the TSPA such that a clear basis for estimating margins of safety is complicated, and making quantitative risk-informed decision-making difficult.
- One reason for the incorporation of conservatisms into TSPA-SR is to have a performance assessment that is focused on *compliance* rather than on *expected* risk. However, oversight groups have observed that more than a compliance-based TSPA will be necessary to provide a basis for quantifying the conservatism that it might contain. DOE has asked for a single fully qualified TSPA that "reflects the reasonably expected behavior" of the system to be used for establishing compliance for the LA.
- Approaches need to be developed that preserve the focus on reasonable expectation (i.e., mean estimates and their associated uncertainties) while placing the most emphasis on those inputs that are most important to the performance estimates.
- Future assessments of uncertainties should provide the technical basis for all parameter ranges, probability distributions, and bounding values used in the performance assessment.
- Alternative conceptual models of features and processes that are consistent with available data and current scientific understanding must be considered. The effects that alternative conceptual models have on the performance of the repository should be evaluated. An

NRC/DOE agreement has been reached to document a methodology that will be used to address alternative conceptual models in the performance assessment.

- Written guidance on uncertainty treatment that can be consistently communicated and applied across the project should be developed. The goal is to have uniform implementation of an uncertainty strategy for the LA.
- If "conservative" or "bounding" assessments will be included in the TSPA, a consistent set of definitions and methods for implementation should be developed. Definitions must take into account possible non-linearities between conservatism in input parameters and their effects on performance. Consideration should be given to traditional notions of conservatism in risk analyses, whereby conservatism is applied to the final dose distribution for use in subsequent applications.
- The use of performance assessment for decision-making requires that uncertainties be reasonably quantified or appropriately bounded with adequate justification. Such quantification will provide information that decision-makers can use in making trade-offs, assessing the credibility of DOE's positions, and developing confidence. NRC's concept of "risk-informed" decision-making includes both the expected risk and a quantitative description of the uncertainty associated with the expected risk.
- There is a need to communicate uncertainties and risk information in a clear, meaningful manner to decision-makers and stakeholders.

3.2 STRATEGY FOR TREATMENT OF UNCERTAINTIES FOR LICENSE APPLICATION

An eight-part strategy for treatment of uncertainties is provided in this section, based on the framework developed from review of the views of oversight groups, as well as the lessons-learned from the review of the uncertainty treatment for the TSPA-SR (YMP 2001 DIRS [155343]) and the SSPA (BSC 2001 [DIRS 155950]; BSC 2001 [DIRS 154659]). This strategy is designed to be at a high level in order to provide basic concepts for approaches that may be implemented in a reasonable time frame and are likely to be found acceptable to regulatory and oversight groups. Subsequently, as planned in FY02 activities and as agreed with the NRC, detailed guidance can be developed that can be used consistently by those responsible for characterizing uncertainties in process models and abstractions for the TSPA. This implementation level guidance may require some modification from the strategic level guidance, as variants in models and analyses are incorporated. In other words, a "one-size fits all" approach to treatment of uncertainty may not be completely possible.

1. General Framework for Uncertainty Treatment: Develop a TSPA that meets the intent of "reasonable expectation."

The EPA and NRC define the four characteristics of reasonable expectation (e.g., § 197.14 (40 CFR 197 [DIRS 155238])), which provide a basis for understanding how the concept should be implemented. The first two characteristics acknowledge that no projection of long-term performance will ever be "proved" or not subject to assumption and simplification. The third suggests that a reasonable attempt should be made to include potentially significant uncertainties, even those very difficult to quantify. Finally, the *expected* models and parameter values and full *range* of uncertainties should be the focus of the uncertainty treatment, rather than extreme models and parameters. The goal of the reasonable expectation approach is to have a sufficient basis to compare the expected (mean) results of the performance assessment with the dose standard, and to be in a defensible position to assert that uncertainties in inputs that would contribute significantly to the expected results have been incorporated quantitatively into the analysis. The elements of the strategy given below are consistent with this goal.

2. Quantify Uncertainties in Inputs to the Performance Assessment

Because the notion of reasonable expectation is founded on proper development of *mean* risk, quantification of significant uncertainties is necessary. It is well known that mean estimates of risk, unlike median or other central tendencies, are usually quite sensitive to the range of uncertainty. Therefore, it is important to quantify significant uncertainties in the input models and parameters to the performance assessment to the extent possible. This does not mean that *all* processes need to be represented or even that all uncertainties *can* be included. Several of the oversight groups note that simplifying assumptions and models will be necessary, given the complexity of the system and the long time-frames involved, and there are some uncertainties that are simply not possible to anticipate or quantify meaningfully.

The standards, regulations, and guidance suggest that a reasonably expected analysis should be developed, which is based on a reasonable quantification of uncertainties and results in a supportable mean dose estimate and its associated distribution. This dose estimate and the associated propagated uncertainties can then be used to compare with the standard. The regulations do not preclude simplifications being made in the treatment of uncertainties in some inputs, as long as those inputs can be shown to have an insignificant effect on the expected dose.

Insight-producing analyses may then be developed that include a range of alternative assessments or assumptions and can be used for various purposes during licensing, such as demonstrating margins, evaluating "what-if" scenarios, or reaching agreement with the NRC staff on specific issues. Fundamentally, however, to address the concerns associated with previous TSPAs regarding a mix of realistic and conservative assessments, a performance assessment focused on expected behavior is the principal tool for expressing the risk and for decision-making.

3. Identify Processes that Encourage the Quantification of Uncertainties and Gain Concurrence on Approaches with the NRC

Many of the review comments from various oversight groups expressed concern that the Project had chosen to encourage a "defensible, compliance case" rather than seek to understand the nature and importance of uncertainties. Within the context of a probabilistic risk analysis, the reasonable approach to the treatment of uncertainties is to quantify and incorporate them to the extent practical into the analysis in order to determine their effect on the result. Traditional statistical methods for analyzing uncertainties rely on unbiased representations of uncertainty in the inputs. This means that the Project should encourage the quantification of uncertainty, *especially* in those cases where uncertainties are considerable. However, approaches may be developed that allow for simplifying uncertainty treatment for those inputs that can be shown to have no significant effect on the expected dose.

One approach to quantifying uncertainty may be the use of expert judgment to define the shape, range, and parameters of probability distributions. In their guidance on the use of expert judgment, the NRC has indicated that they expect the DOE to use expert judgment (Kotra et al 1996 [DIRS 100909]). This is further supported in their discussion of the manner in which compliance should be demonstrated using reasonable expectation:

> "Demonstrating compliance will involve the use of complex predictive models that are supported by limited data from field and laboratory tests, site-specific monitoring, and natural analog studies that may be supplemented with prevalent expert judgment...the Commission may supplement numerical analyses with qualitative judgments..." (§ 63.101 (a)(2) (66 FR 55732 [DIRS 156671]))

The NWTRB reflects its position:

> "Expert judgment and careful interpretation of data will be needed to accurately characterize and quantify the uncertainties associated with data and their use in predicting repository performance." (Cohon, 2000 [DIRS 148739]).

The point here is that processes and procedures need to be advanced that provide for the open and unbiased expression of uncertainties by the experts who develop the process models for the performance assessment.

NRC notes that simplifications and assumptions about complex processes are expected. However, the NRC also states that *important* parameters should not be excluded simply because they are difficult to quantify, and that the focus of performance assessments will be "upon the full range of defensible and reasonable parameter distributions" (§ 63.101 (a)(2) (66 FR 55732 [DIRS 156671])). Presumably, then, the NRC will accept an assessment of uncertainty that attempts to capture the reasonably expected behavior of a process and its associated uncertainty. Likewise, parameters that are unimportant to mean dose can be treated in a simplified manner (e.g., single values or simple probability distributions) in order to focus resources toward the more important inputs.

It should be noted that the approach outlined here for quantifying uncertainties is in direct response to the recently-released EPA standard and final NRC regulation that identify reasonable expectation as the basis for compliance. As the intent of this basis becomes clear, structural changes in processes and procedures to accomplish this goal may need to be identified. These changes may need to be implemented by the DOE as the license applicant. At the same time, it is expected that the NRC will modify its approach to post-closure license review away from notions of reasonable assurance and toward reasonable expectation. This will mean evaluating the applicants' compliance arguments on the basis of whether the *expected* risk and associated uncertainties have been properly portrayed, acknowledging that no performance assessment will ever include all possible physical processes that may affect a complex system over thousands of years and that proof of the performance assessment models is not to be had in the ordinary sense of the word. Likewise, extreme scenarios or conservative assessments should only be considered in the context of insight-producing sensitivity analyses and not as inputs to the reasonably expected performance assessment.

4. Provide the Technical Basis for All Uncertainty Assessments

Uncertainty descriptions of inputs to the TSPA will span a range from statistically-defined distributions coming from extensive datasets to judgmentally-defined distributions based primarily on experience and judgment that are supported by more limited datasets. In any case an important part of the uncertainty assessment will be documentation of its technical basis. It is generally acknowledged that all technical interpretations require some type of support or justification, but this is particularly true in discussing uncertainties. Detailed guidance should be developed and distributed to all individuals responsible for uncertainty characterization such that consistent documentation will be accomplished.

5. Address Conceptual Model Uncertainty

As discussed in the SSPA (BSC 2001 [DIRS 155950], Section 1.2) the uncertainty associated with alternative conceptual models can be a significant component of the total uncertainty in inputs to a performance assessment. In paragraph 63.114 (66 FR 55732 [DIRS 156671]), the NRC requires that performance assessments "consider" alternative, potentially viable, conceptual models and "evaluate the effects" on performance. Taken literally, this means that the applicant is only required to identify viable alternative conceptual models and then test each individually to determine their effect on performance. It is not clear in the regulation whether it is expected that alternative conceptual models be *included* in the performance assessments or be *considered* individually, followed by selection of a single model. The TSPA-SR approach was to describe alternative models and their technical basis in the AMRs, and then to select a single, most defensible, model. When faced with alternative representations that reasonably explained the available information, the analysts in some cases choose the more conservative representation. The principal arguments against the incorporation of multiple models are the additional computational effort that this would introduce, the possibility of risk dilution, and the potential difficulty in defending the relative weights that would need to be assigned to each of the alternatives to incorporate them.

In many probabilistic hazard analyses where conceptual model uncertainties tend to dominate the total uncertainty, the incorporation of conceptual model uncertainties using weighted alternatives has become common (Budnitz et al 1997 [DIRS 103635]). For example, probabilistic seismic and volcanic hazard analyses for the Yucca Mountain site incorporate explicitly conceptual model uncertainties (e.g., tectonic models) into the probabilistic analyses using this approach (Wong and Stepp 1998 [DIRS 103731]; CRWMS M&O 1996 [DIRS 100116]). The justification for the relative weights ascribed to alternative models is based on expert judgment regarding the consistency of each model with available information and data. As per the NRC/DOE agreement TSPAI 4.01 (Cornell 2001 [DIRS 156408], Table 3-1), guidance needs to be developed for the manner in which conceptual model uncertainties should be addressed for the TSPA-LA.

6. Develop a Consistent Set of Definitions and Methods for "Bounds" and "Conservative" Estimates

It is anticipated that the approach to demonstrating compliance using a reasonable expectation concept will involve quantifying uncertainties in the inputs to the TSPA that most significantly affect the mean dose. However, it is also anticipated that sensitivity analyses and other insight-producing analyses will be conducted during the course of the licensing process. For example, scenario or "what-if" type analyses might be carried out that assume certain conservative or non-conservative models or parameter values as a basis of comparison with the reasonably-expected models and parameters. Such assessments could be used to demonstrate margin with the standard, or to show that some assessments, even when conservatively bounded, are not important to the performance results. Likewise, inputs to the performance assessment that can be shown to have no significance to the mean dose could be conservatively and simply defined. This could, in turn, help limit the scope of the license review to just those assessments that are most important to mean dose.

Reviews of the TSPA-SR indicate that a variety of approaches were used by process modelers to develop bounds and conservative estimates, reflecting different perceptions about the meaning of these concepts. In some cases, a "bound" was interpreted to be a value lying within a distribution of data at the tails of the probability distribution; in other cases, a "bound" was identified that lay well outside of any observed data to account for uncertainties that were not explicitly quantified in the direct observations. Another issue identified by the review groups was the use of the term "conservative" when referring to the value of an input parameter, when the effect of the parameter on the integrated performance was not clear. It was noted that nonlinearities in risk assessments could mean that a marked "conservatism" in bounding the data pertaining to an input parameter might not necessarily result in a large or even noticeable difference in the risk results.

In order to provide for a more consistent and defensible use of bounds and conservatism, a clearly documented set of definitions and methods should be developed. This is part of the NRC/DOE agreement TSPAI 3.38 (see Table 3-1) (Cornell 2001 [DIRS 156408]).

7. Develop and Communicate Uncertainty Information that Can Be Used by Decision-Makers

Assuming that information about the *uncertainty* associated with performance assessment is just as important as the *mean* estimate, considerable effort needs to continue to be devoted to understanding the significance of uncertainties and to finding the best ways to communicate that information to regulators, stakeholders, and the public. The move to a reasonable expectation approach to performance assessment means that many uncertainties will be quantified and traditional statistical approaches to evaluating the significance of uncertainties can be applied. These and other analyses, which could include regression analyses, contributions to variance, sensitivity studies, and the "dominant event sequence" used in reactor probabilistic risk analyses, should continue to be used. Further, methods for communicating the significance of uncertainties in ways that are understandable for decision-makers should be developed. These can include quantitative and qualitative evaluations of confidence. See Section 4 of this report for an expanded discussion of uncertainty communication.

8. Develop Detailed Guidance and Provide for Its Implementation

To ensure consistency and to promote adherence to a common strategy for licensing, detailed guidance should be developed that describes how uncertainties should be treated for the TSPA. The recipients for this guidance would be process modelers and those responsible for abstraction of models for the TSPA. Per agreement with the NRC (TSPAI 3.38) (Cornell 2001 [DIRS 156408]), the guidance should include consistent methods for representing uncertainty, selecting conservatism in components, and the abstraction process. Also, the approach to treating conceptual model uncertainties needs to be included (TSPAI4.01) (Cornell 2001 [DIRS 156408]). Further, the guidance should review methods for developing statistical expressions of uncertainty supplemented with expert judgment to develop probability distributions. Guidance for documenting the technical bases for the uncertainty assessments should also be included.

The development of written guidance can take advantage of similar guidance developed for risk analyses. For example, Budnitz et al (1997 [DIRS 103635]) provide guidance for addressing uncertainties in probabilistic analyses and specifically address the issue of distinguishing variability (aleatory) and uncertainty (epistemic) components. Likewise, the EPA (EPA 1997 [DIRS 103834]) provides a series of guiding principles or steps in carrying out a probabilistic risk assessment. The sixteen steps include guidance for selecting input data and distributions for use in a Monte Carlo analysis, evaluating uncertainty and variability, and presenting the results.

In addition to written guidance, effort should be devoted to assisting project participants in developing their uncertainty descriptions. This effort might include workshops to review the uncertainty guidance and discuss examples, interactions to assist process modelers as they consider their available data, and early review of the documentation of uncertainty assessments to ensure completeness and consistency.

Plans for implementing the strategy presented here for treating uncertainties are being included in the overall planning process for the license application. The detailed implementation approach will be provided in the TSPA License Application Methods and Assumptions document.

4.0 COMMUNICATION OF UNCERTAINTIES

The TSPA is a comprehensive quantitative analysis of the potential performance of a repository at Yucca Mountain. Detailed background on the TSPA is described in the TSPA-SR (CRWMS M&O 2000 [DIRS 153246], Section 1.1.1). The TSPA combines the results of detailed and complex conceptual and numerical models of individual and coupled processes into a single probabilistic model for projecting how a potential repository will perform over time. The major output of such a probabilistic analysis is a range of estimates of the projected annual dose rate to the specified receptor population, and an associated likelihood for each projected annual dose rate. As illustrated in Section 3, the results may be presented as a series of plots of dose rate over time. These plots display the results of multiple realizations of the model on a single plot, as well as the expected (mean or median) value, and the fifth and the ninety-fifth percentiles. It is incumbent on the analysts to communicate these quantitative modeling results in a way that most clearly represents the information conveyed by the model results, including the uncertainty in those results, and to communicate in such a way that audiences can derive appropriate qualitative insights.

4.1 COMMUNICATION IN DOE'S OVERALL APPROACH TO UNCERTAINTY

DOE has developed and is implementing a consistent overall strategic approach for handling uncertainties in assessing the performance of a potential repository at Yucca Mountain. The approach involves assessing uncertainties, analyzing quantified uncertainties, managing uncertainties, and communicating uncertainties. The management of uncertainties and assessment of uncertainties are highly interactive. For example, initial assessment of the impact of an uncertainty may lead to the selection of a particular uncertainty management technique for that issue. Implementing the management technique can then change the level of the uncertainty or the impact of that uncertainty on performance. Communication of the uncertainties and their impacts is crucial to all the other components of the strategy for handling uncertainties; and understanding and communicating the impact of uncertainties will allow DOE to assess the importance of those uncertainties and to select an appropriate uncertainty management approach.

Effective communication about uncertainties and their potential impacts when dealing with the performance of a first-of-a-kind system over tens and hundreds of thousands of years is a unique challenge. Communicating about uncertainties means discussing and documenting what uncertainties exist, how they have been accommodated in the design of the repository, how they are accounted for in modeling system performance, and what impact they may have on the estimates of performance. Perhaps most importantly, effective communication of the basis for a decision on a potential site recommendation requires DOE to communicate their understanding of the uncertainties about the ability of a potential Yucca Mountain repository to protect the public from health risks associated with radiological exposures.

For Yucca Mountain, the performance assessment models have provided the framework for organizing and describing the site and the repository design. The modeling paradigm of following water, as it would flow through the system, is useful and greatly facilitates communication about many aspects of the system. However, within this paradigm it is difficult for even a well-informed and involved observer to understand how crosscutting issues are treated. Uncertainty is one of those crosscutting issues: it is relevant for every process component and model. As discussed in Section 2.1, descriptions of each process model include descriptions and illustrations of uncertainties within the model, but those descriptions have not always been consistent, or easy to trace. Sections 2.1 and 2.2 of this report summarize the uncertainty treatment in the current process models and total system performance assessments. The displays illustrated there are representative of the Program's standard displays for illustrating and communicating uncertainties.

Communicating uncertainties in the performance assessment is not a stand-alone task. It is part of the broader obligation of DOE to communicate effectively with multiple stakeholders about the Program, the Yucca Mountain site, and how the potential repository will meet the regulatory requirements protecting public health and safety, if the site is recommended and designated, a license issued, a repository constructed, a license update granted, and waste emplaced in the mountain. This obligation to communicate how the site will meet regulatory requirements does not end at the site recommendation, but continues throughout the entire project, including the multiple milestones just described. DOE has attempted to meet this obligation to communicate about the Program and the Site through the numerous Project documents described elsewhere in this document, and also through summary documents, such as the Executive Summary for the Science and Engineering Report (DOE 2001 [DIRS 153849]), for those who do not have the time to read and digest thousands of pages of technical detail. In part because of its crosscutting nature, in part because of the mixed treatment of uncertainty, and in part because outside reviewers felt DOE had not yet communicated clearly and succinctly how uncertainties have been treated and how they affect and are reflected in the performance assessment results, the SSPA reports were prepared, focusing heavily on uncertainty. The SSPA, however, was primarily a technical summary, which placed more emphasis on communicating technical results than on summarizing the uncertainties for policy makers.

Because uncertainty is not a separate topic but rather a component of the modeling effort and results, much of the discussion of communicating uncertainty that follows will place that communication into the broader topic of the general communication of results. Section 4.2 discusses some general issues in risk and uncertainty communication. Section 4.3.1 describes examples of how uncertainty has been communicated in other contexts. Examples of how the Project has communicated uncertainties in performance estimates to date are presented in Section 4.3.2. The next subsection (Section 4.3.3) offers some potential approaches to improve how DOE communicates uncertainty to policy- and decision-makers and to technical audiences. Section 4.4 provides a brief discussion of several open issues related to communicating uncertainty. Finally, Section 4.5 closes with potential guidelines for communication with different audiences.

4.2 GENERAL COMMUNICATION NEEDS FOR DIFFERENT AUDIENCES

There are numerous different potential audiences that are interested in the performance of a potential repository, including DOE, Executive and Congressional decision-makers, State and local governments, technical review groups such as the NWTRB and the ACNW, the NRC, and the general public. Each group has different interests and different needs for understanding model results, and different levels of familiarity with the methods for expressing quantitative analyses and their results. It is essential that DOE understand its target audiences and their needs, so that they can select effective methods and appropriate content for presentation to each. The NWTRB, for example, would require a more technically detailed depiction of uncertainty than might a high-level decision-maker or the general public. Differences in audience needs, coupled with the varied ways that different people process information, suggest that multiple presentation formats should be considered for different target audiences. In fact, the project has attempted to accomplish this in its overall documentation through use of multi-level documentation and multi-media presentation of analysis and results.

One of the key insights from recent research by psychologists on risk communication is that the first and most important step in effective communication is to understand what the audience knows and what they need to know. The "mental models" approach to risk communication (Fischhoff et al 1993 [DIRS 156562]) emphasizes detailed discussions and interviews with members of the target audience(s) to develop "maps" of their current perception of the hazard and risks of interest. Similar interviews are conducted with subject matter experts to develop maps of the "expert" model of the hazard or risk. Then the different representations are compared and the communication vehicle is designed to complement what people currently know, and to correct any misconceptions that may lead to poor decision making. This method has been employed by the EPA (1997 [DIRS 103834]) and other groups to develop communication tools to explain the risks of radon, of climate change, and of low-frequency electric and magnetic fields (see Bostrom et al 1992 [DIRS 156525]; Bostrom et al 1994 [DIRS 156517]; Bostrom et al 1994 [DIRS 156553] for examples).

In defining a communication package covering uncertainty in repository performance for different audiences, DOE must first understand why uncertainty is relevant or potentially important to any particular audience. What message or scope of understanding is required to meet the objectives of the recipient of the information? For example, a risk manager will care very much about uncertainty, and will require information that conveys a more complete understanding of the nuances of the results. On the other hand, the general public may not care about this level of technical detail. Their needs are usually more directly stated in language like "Will it be safe to live near the repository?" "How do you know?" And, perhaps "Why should we trust your answers?" To answer this last question, DOE will have to explain that there is uncertainty and that uncertainties will remain, but that the range of uncertainty is such that one can still have confidence in the overall safety of the repository. Understanding the audience's needs and objectives is critical for framing the presentation of results.

Before uncertainty can be communicated, audiences need to have or need to gain a common understanding of terms and methods. In some cases, this can be done through workshops or other training. In other cases, there may not be an opportunity outside of the presentation of results itself to provide any introduction to methods or terms, in which case selection of presentation format becomes even more important. The ultimate decision-makers must be willing to consider the scientific evidence together with its limitations. Ideally, they should be educated in understanding common graphical representations of uncertainty, rather than in black-and-white answers on topics beset with uncertainty. This may require a cultural shift for some decision-makers, many of which are uncomfortable with the level of sophistication practiced by risk analysts.

4.3 METHODS FOR EXPRESSING AND COMMUNICATING UNCERTAINTY

The major outputs of a performance assessment and an uncertainty analysis are quantitative or pictorial descriptions of uncertainty in risk or some other quantity. Although there are dozens of ways of depicting uncertainty, only a few are commonly used. These methods differ along several dimensions, including: 1) the amount of information expressed, which to some extent determines how faithful the depiction is to the "true" state of uncertainty; 2) the clarity of the description and ease of understanding the information therein; and 3) the ability of the method to convey particular subsets of information about uncertainty. Some methods are good at informing the decision-maker about the relative likelihood of different values being the true value, others are better at describing the probabilities of the true value being within certain defined ranges, whereas still others are better at describing the effect on summary indices of the absolute magnitudes of all potential values. The first two dimensions are often at odds with each other – clear and simple depictions, unfortunately, can rob the decision-maker of needed information or nuance. Similarly, graphical displays that capture the full detail and nuances of the analyses may take training and experience to interpret. This fact, combined with the varied and idiosyncratic ways that different people process visual information, suggests that where resources and space permit, uncertainty analysts should provide more than a single depiction of each uncertain quantity.

4.3.1 Examples from non-Project Areas and Applications

Although most analysts would agree that graphical techniques play an indispensable role in communicating uncertainty, remarkably little attention has been devoted to this topic in the literature. Ibrekk and Morgan (1987 [DIRS 156510]) conducted one of the few empirical studies exploring how readers interpret and respond to various types of one-dimensional displays. The absence of more empirical studies of the relative value of alternative displays means that the choice of displays remains largely a matter of personal judgment.

Ibrekk and Morgan's study (1987 [DIRS 156510]) was directed to "semi- and non-technical subjects" and evaluated nine different methods in terms of their popularity among the readers and their ability to convey specific information about probabilities, ranges, and values. They recommended that a particular pair of methods be used, with one adjustment, but cautioned that "one should not depend on all users correctly interpreting this or any other display."

Their recommendation for one-dimensional displays provides decision-makers with access to the most information-rich depictions of uncertainty that analysts can provide. Their proposal involves presenting a cumulative distribution function (cdf) directly above a probability density function (pdf), using the same horizontal scale to facilitate comparisons. In addition, they recommend that the mean of the distribution should be clearly indicated on both plots. The simultaneous display of the cdf and pdf takes advantage of the strengths of each type of display. With this information in hand, the audience could evaluate the consequences of any desired summary statistic, with full knowledge of the probabilities of potential errors of underestimation and overestimation.

However, decision-makers may be overwhelmed by such a graphical presentation, whether one is talking about one-dimensional displays or more complicated multi-dimensional displays, and in some cases would be better served if someone performed the task of compressing the information into textual descriptions. Finkel (1990 [DIRS 107717]) argues than any reduced description should include as many of the following as is practicable:

- Numerical values of the median, mean and mode of the uncertainty of the quantity of interest.
- The values of the 5^{th} and 95^{th} percentiles. If other percentiles (e.g. the 1^{st} and 99^{th}) differ dramatically from these, both sets should be included.
- The percentile location of the mean. This is rarely reported, but its omission may lead to the mistaken belief that the mean and median are always coincident.

- An estimate of the standard deviation of the coefficient of variation (standard deviation divided by the mean).
- A qualitative description of the shape of the distribution, pointing out important discontinuities, asymmetries, or multimodal behavior.
- A numerical measure of any distributional inequality.

The above studies provide useful guidance for the representation of one-dimensional displays and discussions of uncertainty. However, these often don't apply to the types of information that must be displayed for YMP. When attempting to display multi-dimensional representations, the problem becomes even more difficult and one needs to look for other examples.

Perhaps the closest analogy to the problems in communicating uncertainties for the YMP are those faced by the Intergovernmental Panel on Climate Change (IPCC) (Albritton and Miera Filho 2001 [DIRS 156545]; Albritton and Miera Filho 2001 [DIRS 156611]]). Both the IPCC and YMP are faced with modeling of complex systems through aggregation of sub-models, high levels of uncertainty, relatively long time frames for prediction (though the IPCC's time frames of 100+ years are still orders of magnitude smaller than those required for YMP), and the need to communicate results to multiple and varied audiences.

The IPCC has taken the approach of creating documents of differing levels of detail aimed at different target audiences. For each of the three main parts of the study, a suite of three reports is created. The full report of approximately 1000 pages provides a high level of detail, similar in scope to that of the Yucca Mountain Science and Engineering Report (S&ER) (DOE 2001 [DIRS 153849]). Next, a Technical Summary (Albritton and Miera Filho 2001 [DIRS 156545]) report of approximately 60 pages provides an overview aimed at a technically knowledgeable audience. Finally, a Summary for Policymakers (Albritton and Miera Filho 2001 [DIRS 156611]) of approximately 20 pages provides the most condensed version aimed at decision-makers that may not have a sophisticated understanding of the technical issues or of risk and uncertainty analysis. The Executive Summary of the S&ER is similar in size and scope to this document.

To illustrate some of the approaches used by the IPCC, the following discusses the summary reports created in 2001 by the IPCC's Working Group 1 (WG1), covering "Climate Change 2001: The Scientific Basis" (Albritton and Miera Filho 2001 [DIRS 156545]). The Summary for Policymakers (Albritton and Miera Filho 2001 [DIRS 156611]) is a 20-page document that uses a mix of graphical and textual methods to condense and convey the results of the large volume of work. The following are some observations on the IPCC approach.

- The document is structured as 8 broad result statements. For example, "Emissions of greenhouse gases and aerosols due to human activities continue to alter the atmosphere in ways that are expected to affect the climate", and "Confidence in the ability of models to project future climate has increased" are two of these. Under each of these are sub-statements and bullet points in support of the broad conclusion. The report is essentially structured as a hierarchy of result statements and supporting commentary.
- There is a strong reliance on stating results in textual form. This includes statements that discuss modeling approaches and uncertainties in the results.

- When discussed in the text, confidence estimates are usually stated as descriptive words that have an associated quantitative definition. A footnote in the report provides the linkage -- "In this Summary for Policymakers (Albritton and Miera Filho 2001 [DIRS 156611]) and in the Technical Summary (Albritton and Miera Filho 2001 [DIRS 156545]), the following words have been used where appropriate to indicate judgmental estimates of confidence: *virtually certain* (greater than 99% chance that a result is true); *very likely* (90-99% chance); *likely* (66-90% chance); *medium likelihood* (33-66% chance); *unlikely* (10-33% chance); *very unlikely* (1-10% chance); *exceptionally unlikely* (less than 1% chance). The reader is referred to individual chapters for more details."
- Graphical results are used somewhat sparingly. There are only a few graphical figures in the document. Uncertainties on graphs are conveyed in various ways.
  - In some cases, uncertainty is represented by error bars showing 95% confidence bands (Figure 4-1).
  - In one case, uncertainty is represented two different ways on the same figure: error bars showing the spread in published values for a number of system variables, and each is also assigned a qualitative measure of the level of scientific understanding for that parameter (Figure 4-2).
- Simulation results are displayed in a summary fashion:
  - The results over time of multiple simulations are shown, but are displayed as a shaded range on the graphs, rather than displaying the precise time histories of each model run (Figure 4-3).
  - Displays for specific individual scenarios, as well as uncertainty across scenarios are included for multiple metrics of interest. For example, there are presentations of CO_2 emissions over time as well as presentations of temperature change over time (Figure 4-4).
  - Bars showing the range of model predictions at the end of the modeled time period are included on the plots showing the predictions of temperature over time, giving an indication of how much uncertainty there is after 100 years (Figure 4-4).

The following are observations for use of these approaches for YMP:

- The use of reports of differing levels of detail are useful for targeting audiences with different needs and differing levels of technical understanding. Note that YMP has done some of this already.
- The structure of the Summary for Policymakers (Albritton and Miera Filho 2001 [DIRS 156611]) document may be a useful model for DOE in conveying results to policymakers (i.e., a list of broad summary statements, followed by additional supporting statements and graphical displays where necessary). YMP has used this method of mixing graphical and textual messages, though the IPCC seems to place a greater emphasis on text-based messages with graphical displays in support of those statements, at least for policymaker level documents.
  - Use of descriptive terms for confidence levels should be considered. As long as the terms are clearly defined, this provides for simpler sentence structure for the reader than repeatedly stating the numerical confidence bands.

Another source of guidance for the communication of uncertainties is provided by *The Risk Assessment Forum of the EPA*, which has published guidelines for presenting the results of a Monte Carlo analysis (EPA 1997 [DIRS 103834]). Their recommendations are:

- Provide a complete and thorough description of the exposure model and its equations (including a discussion of the limitations of the methods and the results).
- Provide detailed information on the input distributions selected. This information should identify whether the input represents largely variability, largely uncertainty, or some combination of both. Further, information on goodness-of-fit statistics should be discussed.
- Provide detailed information and graphs for each output distribution.
- Discuss the presence or absence of dependencies and correlations.
- Calculate and present point estimates.
- A tiered presentation style, in which briefing materials are assembled at various levels, may be helpful. Presentations should be tailored to address the questions and information needs of the audience.

The YMP has utilized many of these approaches in presenting such information about the TSPA. It also has objectives in KTI agreements to deal with many of the items on this list.

Extreme or rare events, such as volcanic or seismic events at Yucca Mountain, pose unique challenges for communication. Audience members are often unfamiliar with what is meant by an extreme event and are unaccustomed to considering the impact of such events in decisions. In these cases, the frequencies and uncertainties should be discussed explicitly. Communication should include multiple presentation formats containing both a quantitative and qualitative component. One proposed approach (Matalas and Bier 1999 [DIRS 156524]) calls for the inclusion of graphical displays in both linear and logarithmic scales as well as textual descriptions of recurrence times of events (e.g., one is 95% confident that a certain incident of a certain magnitude may occur every 1 million years).

4.3.2 Examples of Presentation of Uncertainties in TSPA Results

As discussed in Section 2 of this report, the most common method used by the Project to display uncertainty in projected performance is a log-log plot showing estimated annual dose rate over 100,000 years for multiple runs of the TSPA model (the "horsetail plots"). On top of the simulation results, the mean, the median, and the 5th and 95th percentile dose rate estimates are plotted. A typical plot showing 300 realizations of the TSPA model is provided as Figure 4-5. These plots contain a very large amount of information. The Project is developing ways of highlighting the information to allow the reader to access it.

The text accompanying the "horsetail" plot in the S&ER provides some condensation of the results into textual statements. For example, "At 40,000 years, there is about a 5% probability of the dose rate being on the order of 1 mrem/yr or higher. At 60,000 years, there is about a 50% probability of the predicted dose rate being less than 1 mrem/yr. At 100,000 years, there is about a 50% probability of the predicted dose rate being on the order of 10 mrem/yr." This type of condensation may prove to be a useful communication technique, especially to less technical audiences.

The overall confidence in the TSPA results is also alluded to in the accompanying S&ER text. "Because of the large uncertainty in applying the models to 100,000-year time frames, these projections should not be interpreted as predictions of probable future performance. They are simply indicators of the possible range of performance." Such statements are used to provide the reader with an appropriate context for interpreting the estimated ranges or other statistical measures.

A few plots of the performance of repository subsystems are also shown in the S&ER. Figure 4-6 shows one example of drip shield performance. This plot, like the horsetail plots, shows the mean, median, and 5th and 95th percentiles. It does not, however, show the individual realizations. These plots are useful for conveying the uncertainties at the subsystem level that contribute to the overall uncertainties in dose to a receptor.

Finally, the S&ER also includes plots of stochastic sensitivity analyses run to identify parameters having the greatest impact on the uncertainty in calculated results. Figure 4-7 is an example, showing the contribution to total uncertainty from the uncertainty in key input parameters. The figure illustrates that the largest single contributor to overall uncertainty in the performance assessment results is the uncertainty in how susceptible the other lid of the waste package is to stress corrosion cracking. This information is valuable to technical audiences, especially those directly involved with the Project, because it is useful in identifying areas where additional work will have the greatest impact in reducing remaining uncertainties. It is less clear whether the information shown on these plots will be useful to policymakers. There may be cases where the inclusion of these plots would help to alleviate concerns about what can be done regarding existing uncertainties. For example, if such a plot showed that the climate over the life of the repository is one of the major remaining uncertainties, there is little that can be done to reduce that uncertainty. Communicating that to a policymaker can help to identify areas where delaying the decision in hopes of getting more information will not be fruitful.

In the SSPA (BSC 2001 [DIRS 155950]; BSC 2001 [DIRS 154659]), and in recent presentations at public meetings of the NWTRB, several additional displays have been developed and used to communicate specific uncertainties.

The SSPA incorporated a number of previously unquantified uncertainties and consideration of high-temperature (HTOM) and low-temperature (LTOM) operating modes. Figure 2-1 (from SSPA Volume 2, Figure 4.1-1) shows a comparison of the original nominal scenario (base case) from the S&ER with the new HTOM and LTOM cases. For clarity, only the mean for each case is shown.

Figure 2-7 (from SSPA Volume 2, (BSC 2-001 [DIRS 154654], Figures 4.1-11a and b)) shows the fraction of realizations reaching particular annual dose rates at the time when mean dose rate peaks. Two companion plots are shown; a cumulative distribution function and a probability mass function (histogram), plotted at the same horizontal scale. This follows Ibrekk & Morgan's (1987 [DIRS 156510]) recommended approach of supplying both a cumulative density function (cdf) and probability density function (pdf) or probability mass function (pmf) to provide a large amount of information regarding uncertainty. Proper interpretation of these plots requires significant technical knowledge or familiarity with these types of plots from the viewer. Therefore, these plots are appropriate for communications specifically directed at a technical audience, but perhaps not for a less knowledgeable group.

Figure 2-10 (from SSPA Volume 2, (BSC 2001 [DIRS 154654], Figures 4.1-14a, b and c)) shows the time that the fraction of realizations reaches a dose rate of 10^{-1} mrem/yr. Three companion plots are shown, a cumulative distribution function and a two probability mass functions (histograms), one plotted at the same horizontal scale as the cdf and the other an expansion of the data for the first 100,000 years. Like the two previous plots, these are information rich, but will require significant technical knowledge by the viewer in order to interpret the results.

Figure 4-8, a graph that has been shown to the NWTRB, but has never been published, shows dose rate means for combined nominal and igneous as both log and linear plots. These plots are effective in their use of both log and linear scales to better inform the viewer of the information provided by the different scales. While these particular plots lack any information on uncertainty, that information could be added.

4.3.3 Additional Options for Communicating Uncertainties

Recognizing the need to improve the ways in which the Project communicates about uncertainties, TSPA and other project staff have been developing additional ideas and options for communicating uncertainties. These ideas are informed by comments, questions, and feedback from various review groups, and by the review of other communications approaches described above. Some alternative displays and communication methods are described in this section, but none of them have yet been tested with potential audiences outside the Project.

The following graphs show examples of alternate ways to present results. Figure 4-9 gives the fraction of realizations below mean dose for a scenario, that is similar to the suggestion from Finkel (1990 [DIRS 107717]) that the percentile location of the mean estimate be presented. This is one way to demonstrate the asymmetric information contained in the horsetail plots by showing that the expected value is generally much closer to the 95^{th} percentile than to the 50^{th}.

Figure 4-10 shows an example alternative way to display the uncertainty in dose rate at specified times. The figure shows a histogram of dose rates at three distinct points in time, and illustrates the general trend of increasing dose rate estimates over time, as well as increasing uncertainty in the dose rate estimates.

Figure 4-11 provides an example visual comparison of the uncertainty in the time it takes to reach a specified dose rate, for three different specified dose rates. This plot illustrates the general trend that higher doses are reached at greater time periods, but also illustrates that the uncertainty in the time to reach a specified dose rate is greater for lower doses than for higher doses. The time to reach 0.1 mrem/year ranges from less than 20,000 years to 90,000 years, but the time to reach 10 mrem/year ranges only from 50,000 to 90,000 years.

The following are some additional ideas and guidelines generated for consideration in presenting uncertainties in graphs:

- For clarity, it will sometimes be advisable to show only the mean or median values on a plot, and not show uncertainty. In those cases, a companion chart that has confidence bands or some other representation of uncertainty may be developed so that the information is available to the reader.
- To overcome unfamiliarity with log-log plots, consider showing "horsetails" as a pair of plots, one in the previously shown log-log form, and another in either log-linear form (log time scale, linear dose scale) or linear-linear form.
- Where confidence bands are shown, consider annotating in a footnote or associated text that the percentiles are based only on quantified uncertainties and that they exclude the

impact of conservatisms and other unquantified uncertainties. Provide discussion to the extent known on what potential impact these exclusions might have on stated results.

The Project has been considering how to best communicate uncertainty with non-graphical descriptions of dosage probabilities, either as statements or in table form. For example, in statement form: "There is a XX% likelihood that the dosage will exceed XX mrem/yr within the first XX years." To the extent possible, this should be accompanied by a qualifying statement regarding any uncertainties that were not quantified during generation of the result and their potential impact on the stated result

A suggested example of representing uncertainty information for Annual Dose in table form is as Table 4-1. The table condenses information from the full "horsetail plots," and presents them in a non-graphical form. The table can be used to find the likelihood of exceeding a specified dose at any point in time. Note that the numbers used in the row and column headers are illustrative only.

Table 4-1. Probability of Exceeding a Given Annual Dose in a Given Time Frame (example table structure)

Probability of exceeding >>	.01 mrem/yr	.1 mrem/yr	1 mrem/yr	10 mrem/yr	15 mrem/yr
In 1,000 years					
In 10,000 years					
In 100,000 years					
In 500,000 years					
In 1,000,000 years					

At the decision-maker level, it will be important to develop means of expressing results and their uncertainties in a concise, summary manner. A possible method for communicating these issues is to provide discussions of the following pieces of information, both for the entire model, and for key component parts of the model:

1. **Uncertainty**: Provide a brief discussion of uncertainties in results, referring to the appropriate reports and graphs where the detailed results can be found.

2. **Confidence**: Provide a discussion of the level of confidence the Project has that the calculated uncertainties accurately reflect the "true" uncertainties. This would include discussion of the state of understanding of physical processes, amount and quality of data available, accuracy of models used to represent the physical system, and so on.

3. **Impact of Unknowns**: Provide a discussion of how much it matters if the estimates are incorrect. Another way to frame this would be in terms of how far off the estimates would have to be for it to "matter." What "matters" would also need to be defined: it could be defined as a specified percent difference in annual dose rate estimate, as a specified probability of exceeding the regulatory limits, or a number of other ways.

The combination of these three pieces of information should allow the decision maker to understand how much uncertainty exists in the results, how much confidence they can place in those results, and how much it matters if the results are incorrect. In a broad context, this provides a forum for DOE to summarize their level of confidence, and importantly, to show where the largest gaps remain in understanding. Communication of both of these areas is critical for technical and policymakers level audiences to be able to gain sufficient confidence in the results.

4.4 OPEN ISSUES WITH COMMUNICATING UNCERTAINTIES

As discussed earlier, effective communication about uncertainties and their potential impacts when dealing with the performance of a one-of-a-kind system over tens of thousands of years is a unique challenge.

In particular, the problem of how to communicate "structural" (i.e., model) uncertainty as opposed to "parametric uncertainty" in probabilistic analyses is still an open issue in the risk analysis literature. In constructing the scenarios for TSPA analyses, Project scientists have typically selected one conceptual model for each process of interest from a suite of alternative conceptual models. The use of specified conceptual models in Monte Carlo simulations leads to an analysis where parametric uncertainty drives the uncertainty in the model results. Model or structure uncertainty (i.e., uncertainty related to the question of whether or not the correct models have been chosen) is simply not displayed in the TSPA results. This has led some reviewers to believe that uncertainties in model coefficients are more important than the uncertainties in the models themselves. This is not the case, and the overall level of confidence to be placed in the TSPA results must consider both the parametric uncertainty included explicitly in the TSPA and the model uncertainty that has not been captured in the TSPA results. Model uncertainty is dealt with by the choice of the specific conceptual models, typically conservative, from the suite of available alternatives.

Selection of the conceptual models for inclusion in the TSPA is a subjective process, and, for each process of interest, begins with the recognition of a suite of alternative conceptual models that may be appropriate for that particular process. In some cases, available information and current understanding of the system may be sufficient to identify a single alternative model that is most appropriate and consistent with all available information. For such a case, all uncertainty can, in principle, be fully quantified through parametric means. However, in many cases multiple alternative conceptual models may be consistent with available information. One approach for this situation is to address "all" plausible models, and determine the implications of each for the decision. One of the difficulties of this approach is that explicit consideration of multiple alternative conceptual models at model subsystem levels can rapidly lead to computational intractability when sub-model alternatives are combined to calculate all possible combinations in the larger TSPA model. The approach of including "all" feasible models in not used in the TSPA analysis. Choosing which models deserve inclusion in the assessment, then, is essentially a policy decision. Rational thinking helps, but risk analysis is both a policy and a technical tool, and the decision can not always be justified as being empirically based on science. In some cases, selected alternative conceptual models have been included explicitly in the TSPA with probabilities, or weights, assigned to their occurrence, allowing some measure of the associated uncertainty to be carried forward in the parametric analysis. More often, Project scientists have chosen conservative models when faced with equally viable alternatives, and have therefore introduced conservatisms into the TSPA analysis that cannot be readily recognized through examination of the TSPA results.

Given the choices that must be made for how and which models to include in the TSPA, the Project is left with the difficult task of communicating the level of uncertainty that these choices impart on the final results. Without an explicit means of quantifying those uncertainties, it is critical that any communication of results includes a discussion of the consideration of alternative conceptual models, for both technical and policymaker audiences. This should include the rationale for the models chosen, and a description of those unmodeled conditions that the assessment does not consider. This would include items excluded for various reasons or events deemed to be implausible. The qualitative description of what is not explicitly modeled extends a higher level of confidence to what is being modeled. Furthermore, the implications on results of what is excluded should be identified as much as is possible. Much of this communication has already been created and documented by the Project, however the information is currently dispersed among a variety of different Project documents.

The report, *"Evaluation of Uncertainty Treatment in the Technical Documents Supporting TSPA-SR"* (YMP 2001[DIRS 155343]) provides one example of existing documentation of the consideration of conceptual model uncertainty. "For SCC [Stress Corrosion Cracking], conceptual model uncertainty is considered through the use of two alternative conceptual models, a threshold stress intensity model and a slip dissolution model. Both models were fully developed and documented, including uncertainties in parameters. Bounding analyses were conducted and the results indicated that the threshold stress intensity factor approach would never result in failure of the waste packages due to SCC. As such, a decision was made to only consider the slip dissolution model in TSPA. These results are clearly documented and the decision supported." Ready access for audiences to these dispersed discussions would result in enhanced confidence in modeled results.

In addition to access to the detailed discussions, a method for communicating a summary of the current understanding of model uncertainty to decision-makers is the proposed discussion in Section 4.3.3. Under the topic headed *Confidence*, the estimated impact of model uncertainties on the confidence in calculated results can be communicated, at least in a qualitative way. Reference can also be made back to the more detailed discussion of models considered and the rationale for choices that are contained in other documents.

4.5 POTENTIAL COMMUNICATION GUIDELINES FOR DIFFERENT AUDIENCES

The following two subsections provide examples and suggested guidelines for preparing communication materials for decision-maker and technical audiences. The decision-maker audience is assumed to be Executive or Congressional level policymakers. The technical audience is assumed to be technical review groups such as the NWTRB and the ACNW, and the NRC.

4.5.1 For Decision-Makers

Consider creation of a summary document for policy makers, similar in scope to the Executive Summary prepared for the Science and Engineering Report, or the Summary for Policymakers (Albritton and Miera Filho 2001 [DIRS 156611]) prepared for the larger IPCC reports.

Use bullets and text-based descriptions of results, including uncertainties. This will be an important vehicle for policymakers who are accustomed to looking at the bottom line. Graphical representations will certainly be an important aspect of a policymaker report, but should be used more as support of key result statements.

For example, the text summarizing key results of the "horsetail" plots might be stated as a series of statements similar to those presented in the S&ER (DOE 2001 [153849]) (see section 4.3.2 of this report), but somewhat more bottom-line oriented. "For the low-temperature operating mode case, there is a less than 0.01% probability of exceeding 0.1 mrem/yr in the first 100,000 years." Or, "At 1 million years, there is about a 5% probability of the predicted dose rate being on the order of 15 mrem/yr."

Consider using a table like the proposed Table 4-1 to summarize the likelihood of reaching some specific dose level in some specific time frame.

In selected cases, consider presenting multiple graphical representations of results that each in turn convey an aspect of uncertainty about that result. The use of multiple formats provides information and simultaneously provides a learning vehicle for the audience to better understand the usefulness of different types of plots.

Where feasible, show confidence bands, and provide descriptions of what is and is not included in the uncertainty estimates. The NWTRB and others have consistently raised questions about whether stated probabilities reflect the true probabilities. Providing complete and transparent explanations, as companions to graphs will lend confidence to the reader in interpreting these plots.

4.5.2 For Technical Audiences

Consider creation of a summary document for technical audiences, similar in size and scope to the Technical Summary prepared for the larger IPCC reports (Albritton and Miera Filho 2001 [DIRS 156545]).

Use bullets and text-based descriptions of results, including uncertainties.

Present multiple graphical representations of results that each in turn convey an aspect of uncertainty about that result. The use of multiple formats provides information and simultaneously provides a learning vehicle for the audience to better understand the usefulness of different types of plots. For example, showing the horsetails in log and linear versions with consistent horizontal axes provides a better understanding of the true relative magnitudes of dose over time.

Where feasible, show confidence bands, and provide descriptions of what is and is not included in the uncertainty estimates. The NWTRB and others have consistently raised questions about whether stated probabilities reflect the true probabilities. Providing complete and transparent explanations, as companions to graphs will lend confidence to the reader in interpreting these plots.

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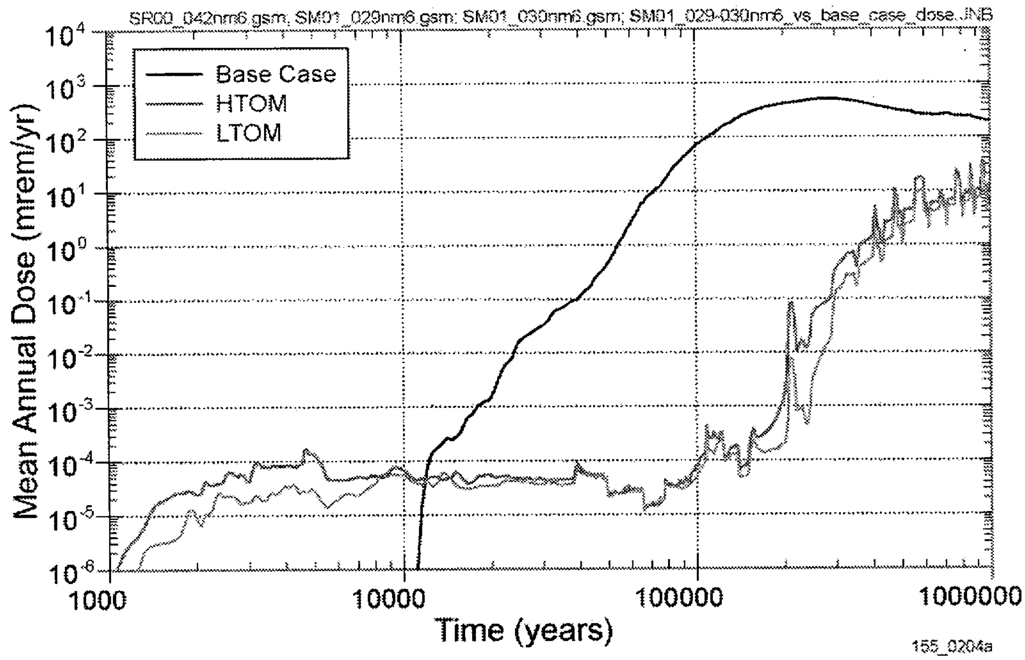
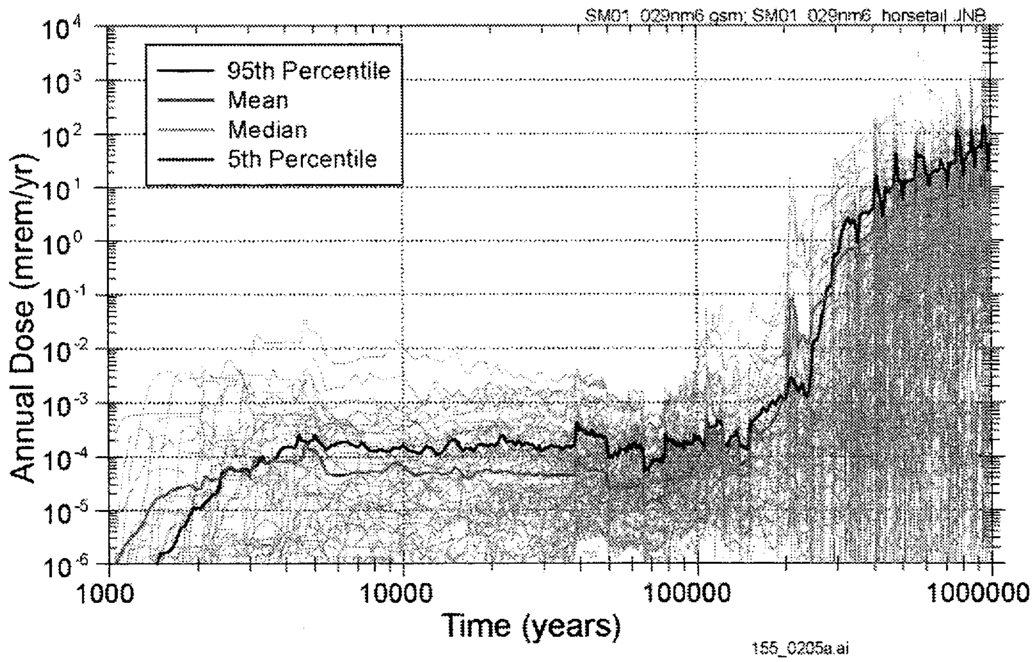
FIGURES



Source: SSPA Volume 2 (BSC 2001 [DIRS 154659]).

NOTE: Mean annual dose histories are shown for the supplemental TSPA model for HTOMs and LTOMs, and are compared to a base case showing the mean annual dose for nominal performance from the TSPA-SR.

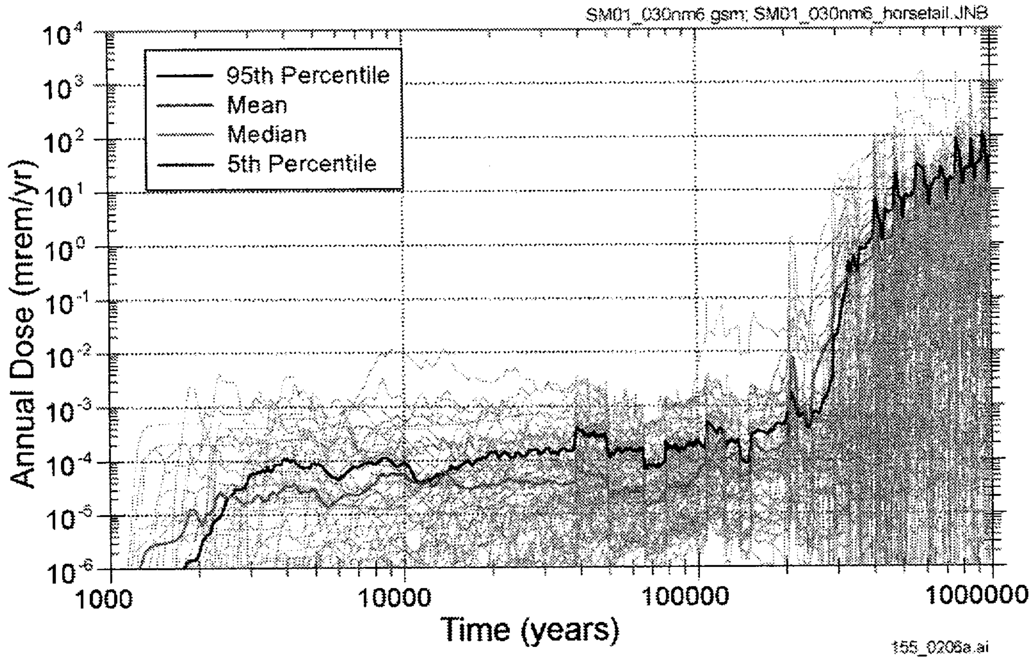
Figure 2-1. Supplemental TSPA Model: Mean Million-Year Annual Dose Histories for Nominal Performance



Source: SSPA Volume 2 (BSC 2001 [DIRS 154659]).

NOTE: Summary curves show the 95th and 50th (median) percentiles, as well as the mean. The 5th percentile curve plots below the lowest values shown.

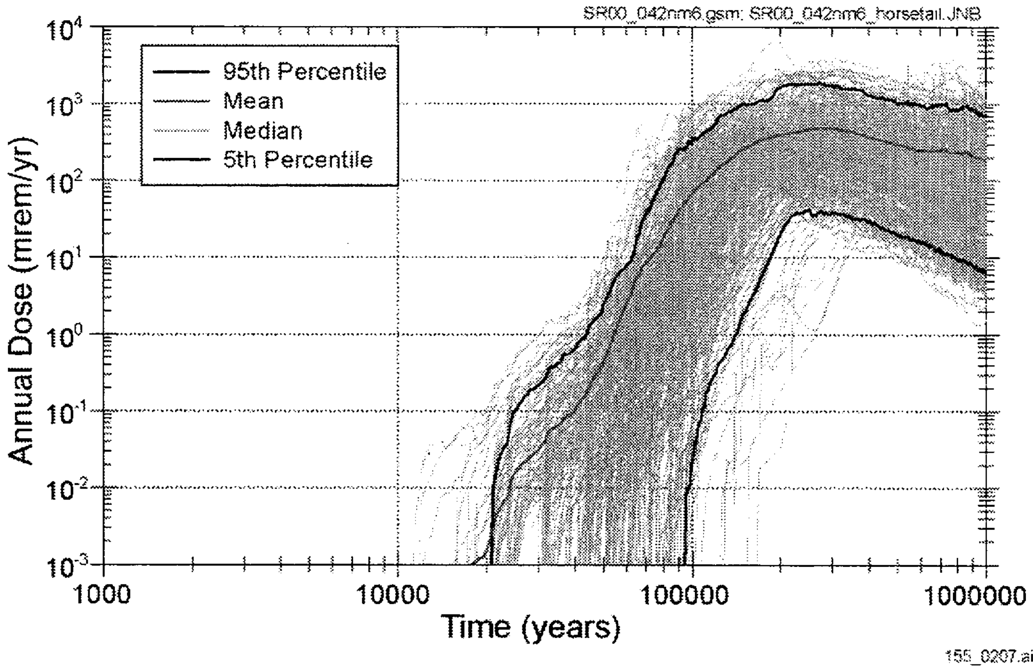
Figure 2-2. Supplemental TSPA Model: 300 Realizations of Million-Year Annual Dose Histories for Nominal Performance, Higher-Temperature Operating Mode



Source: SSPA Volume 2 (BSC 2001 [DIRS 154659]).

NOTE: Summary curves show the 95th and 50th (median) percentiles, as well as the mean. The 5th percentile curve plots below the lowest values shown.

Figure 2-3. Supplemental TSPA Model: 300 Realizations of Million-Year Annual Dose Histories for Nominal Performance, Lower-Temperature Operating Mode



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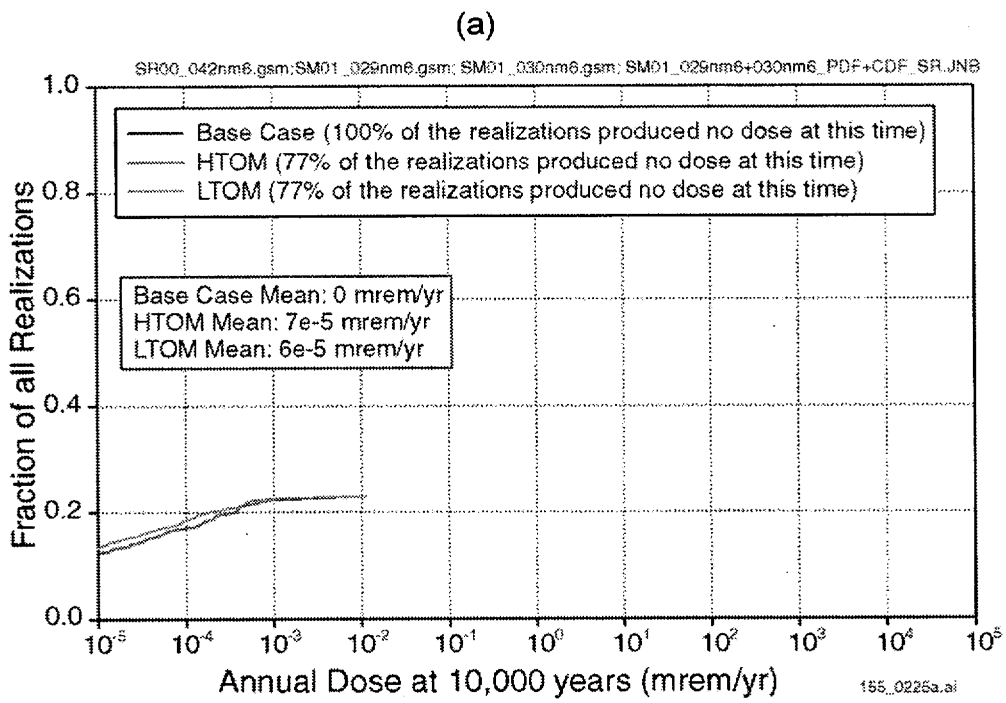
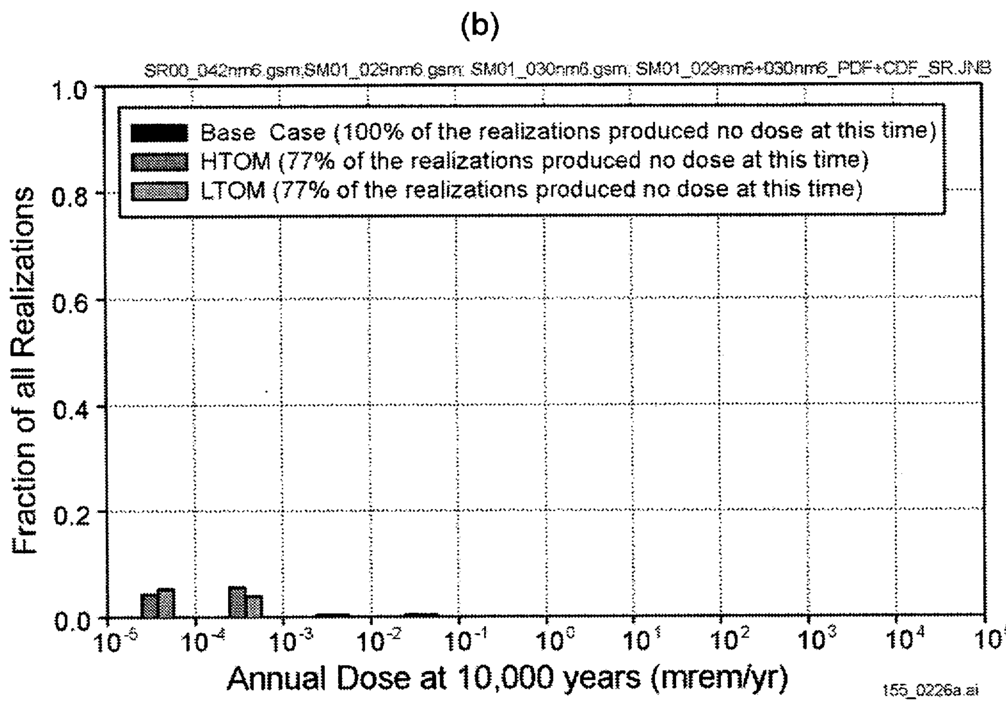
Source: SSPA Volume 2 (BSC 2001 [DIRS 154659]).

NOTE: Summary curves show the 95th, 50th (median), and 5th percentiles, as well as the mean. Results based on the TSPA-SR base-case model.

Figure 2-4. TSPA-SR Base-Case Model: 300 Realizations of Million-Year Annual Dose Histories for Nominal Performance

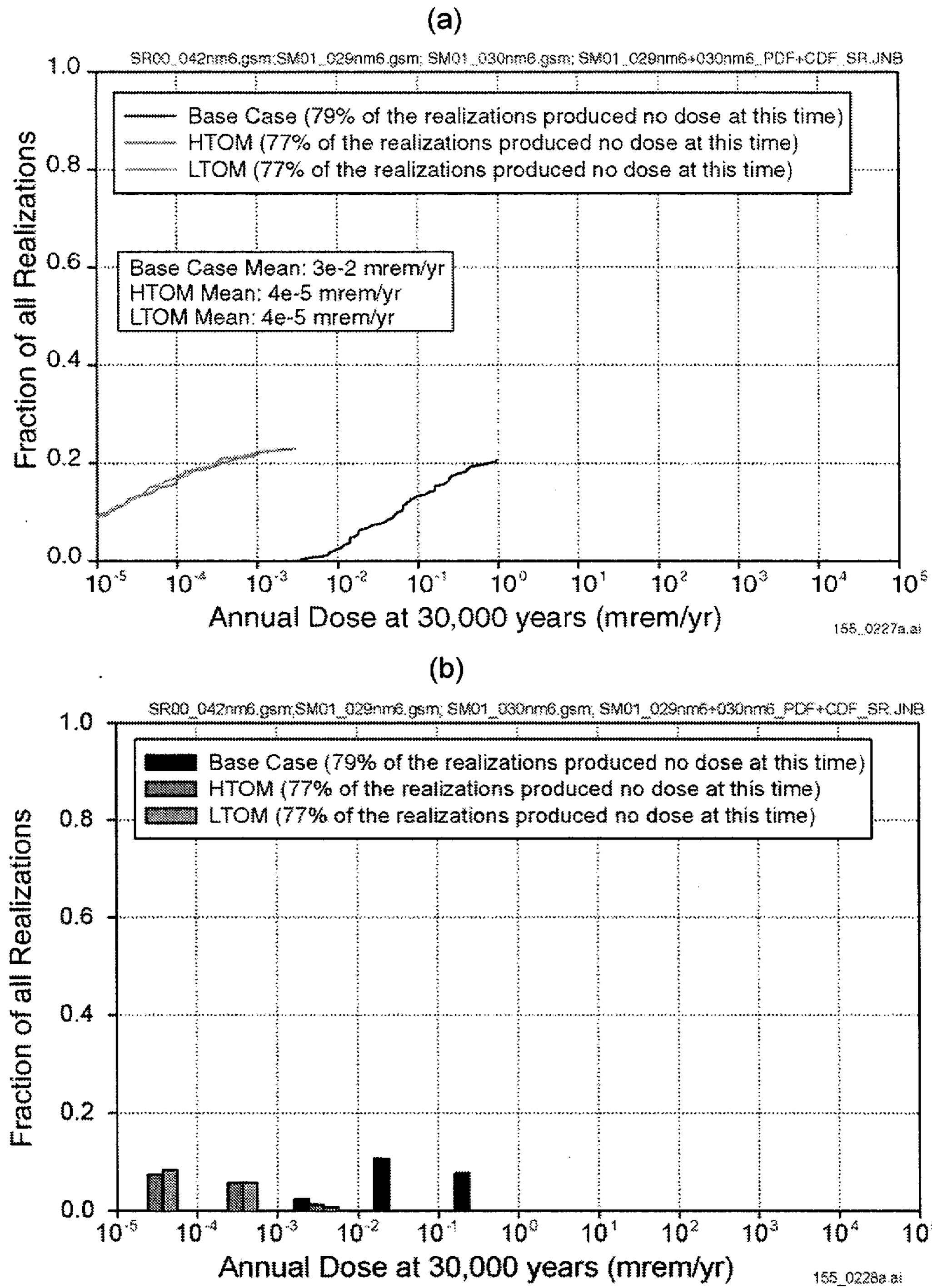




Source: SSPA Volume 2 (BSC 2001 [DIRS 154659]).

NOTE: (a) Cumulative distribution function of fraction of realizations. (b) Histogram of fraction of realizations.

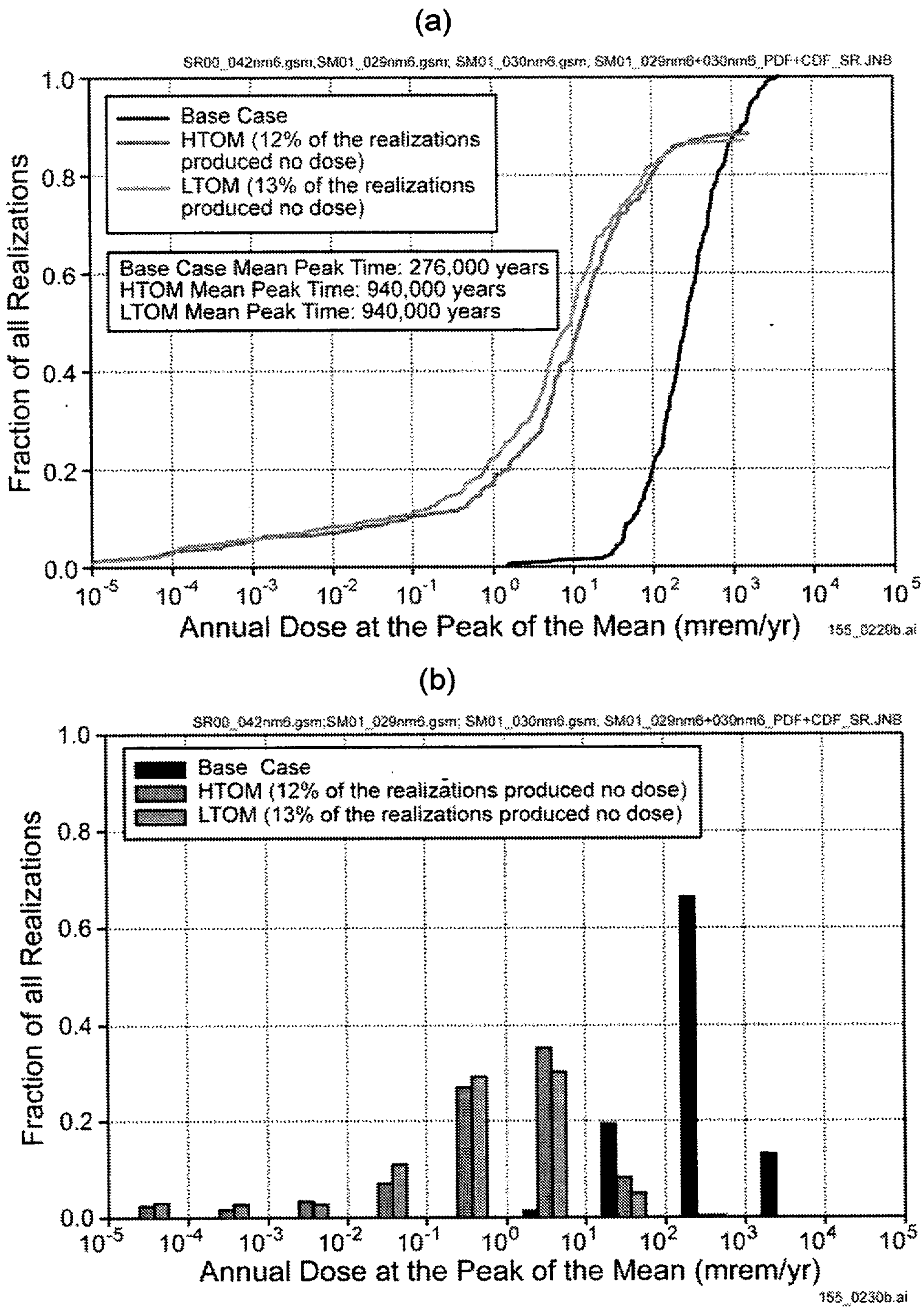
Figure 2-5. Fraction of Realizations Reaching Particular Annual Dose Rates at 10,000 Years



Source: SSPA Volume 2 (BSC 2001 [DIRS 154659]).

NOTE: (a) Cumulative distribution function of fraction of realizations. (b) Histogram of fraction of realizations.

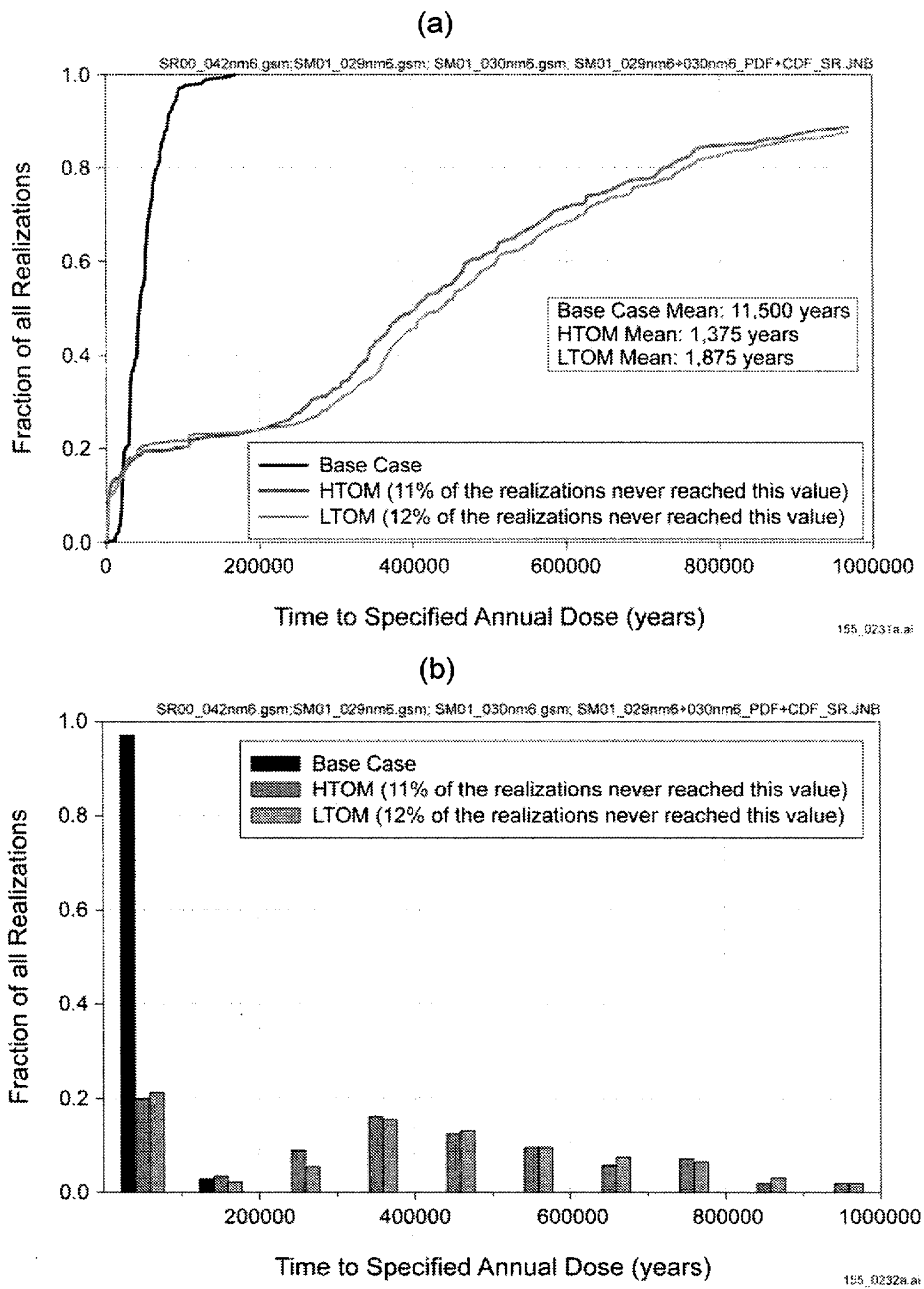
Figure 2-6. Fraction of Realizations Reaching Particular Annual Dose Rates at 30,000 Years



Source: SSPA Volume 2 (BSC 2001 [DIRS 154659]).

NOTE: (a) Cumulative distribution function of fraction of realizations. (b) Histogram of fraction of realizations.

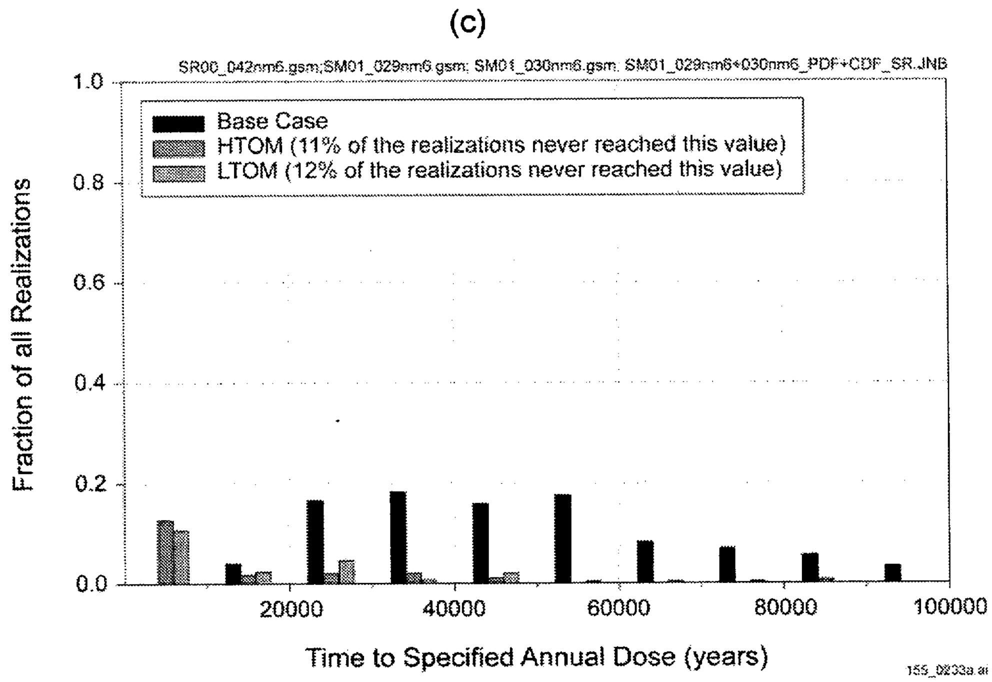
Figure 2-7. Fraction of Realizations Reaching Particular Annual Dose Rates at Time When Mean Dose Rate Peaks



Source: SSPA Volume 2 (BSC 2001 [DIRS 154659]).

NOTE: (a) Cumulative distribution function of time to dose rate of 10^{-5} mrem/yr. (b) Histogram of time to dose rate of 10^{-5} mrem/yr (to 1,000,000 years).

Figure 2-8a and b. Time that Fraction of Realizations Reaches Dose Rate of 10^{-5} mrem/yr

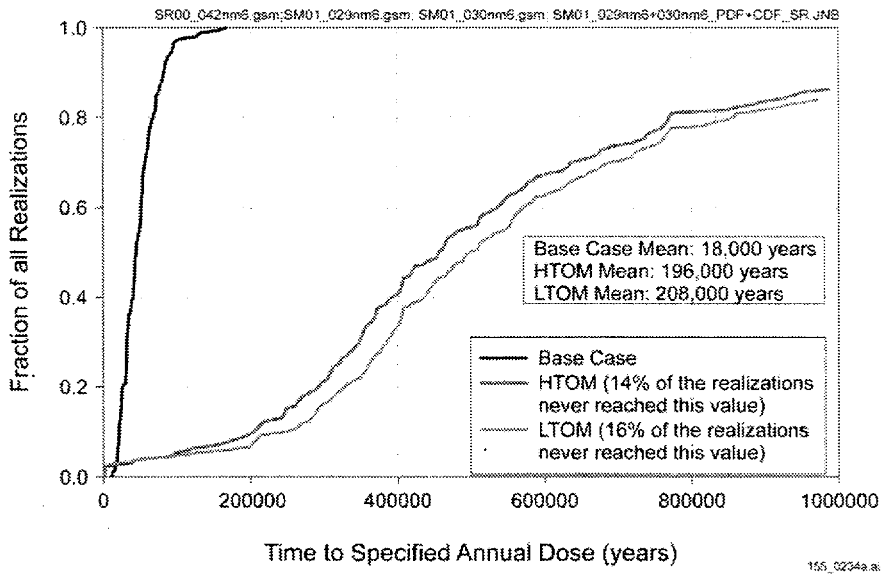


Source: SSPA Volume 2 (BSC 2001 [DIRS 154659]).

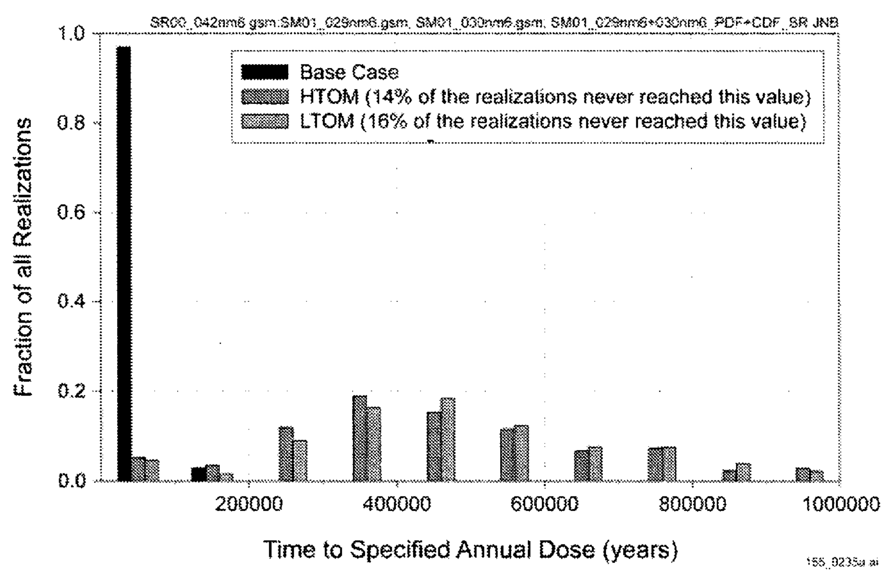
NOTE: (c) Histogram of time to dose rate of 10^{-5} mrem/yr (to 100,000 years).

Figure 2-8c. Time that Fraction of Realizations Reaches Dose Rate of 10^{-5} mrem/yr

(a)



(b)

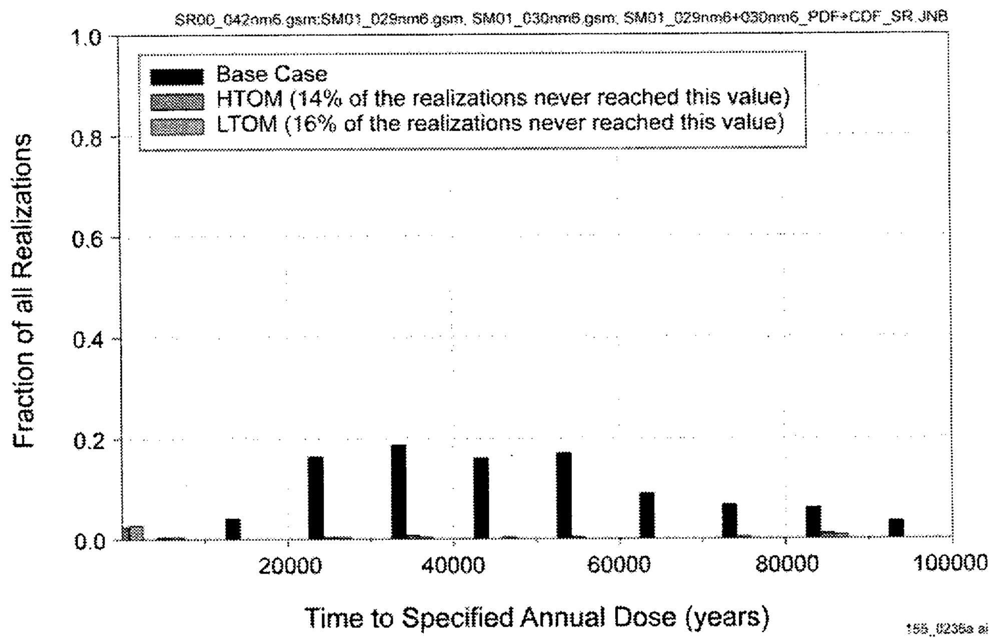


Source: SSPA Volume 2 (BSC 2001 [DIRS 154659]).

NOTE: (a) Cumulative distribution function of time to dose rate of 10^{-3} mrem/yr. (b) Histogram of time to dose rate of 10^{-3} mrem/yr (to 1,000,000 years

Figure 2-9a and b. Time that Fraction of Realizations Reaches Dose Rate of 10^{-3} mrem/yr

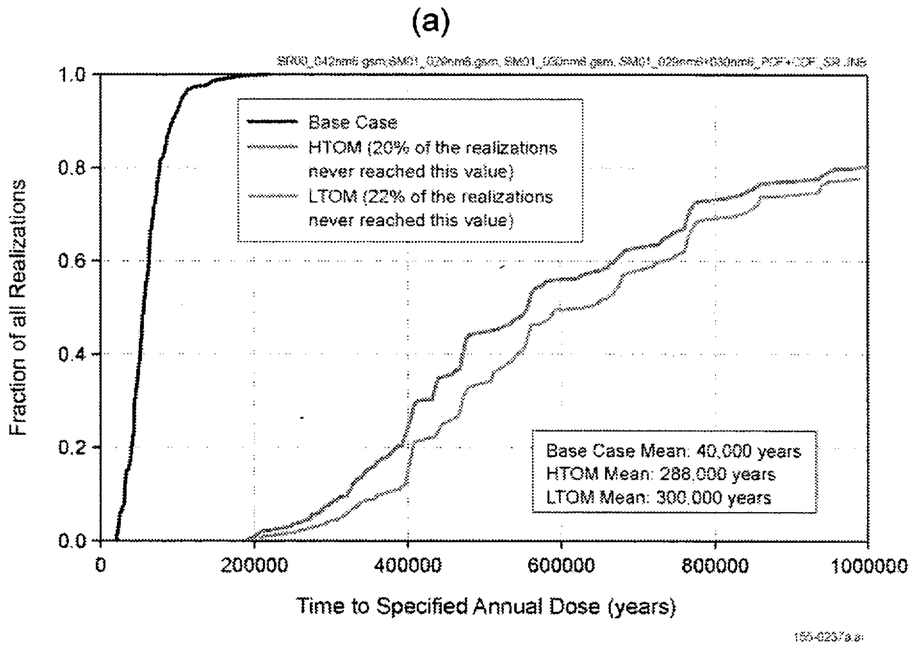
(c)

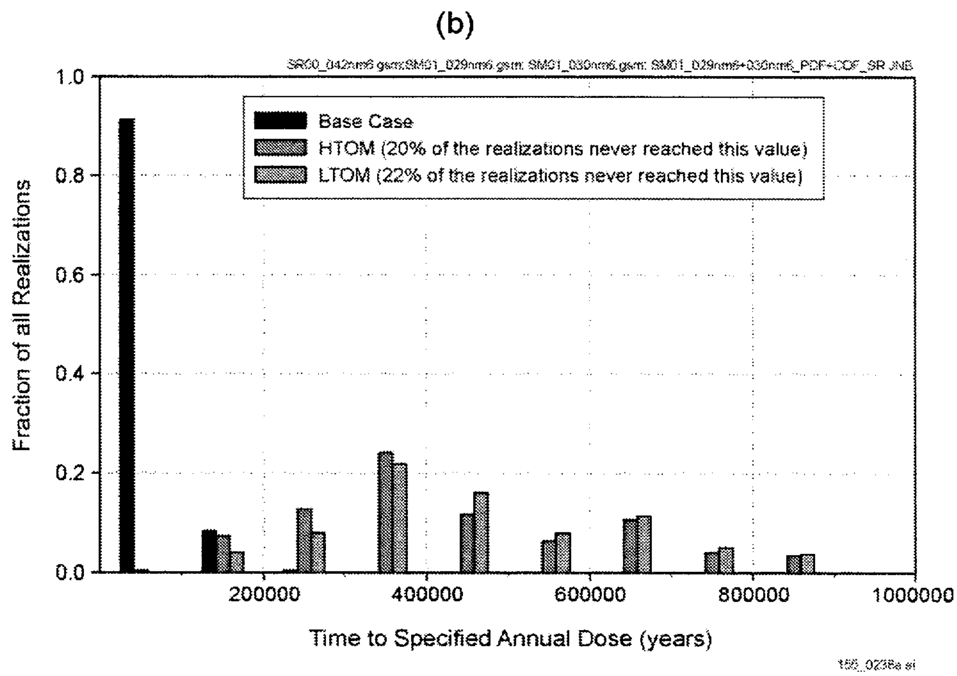


Source: SSPA Volume 2 (BSC 2001 [DIRS 154659]).

NOTE: (c) Histogram of time to dose rate of 10^{-3} mrem/yr (to 100,000 years).

Figure 2-9c. Time that Fraction of Realizations Reaches Dose Rate of 10^{-3} mrem/yr

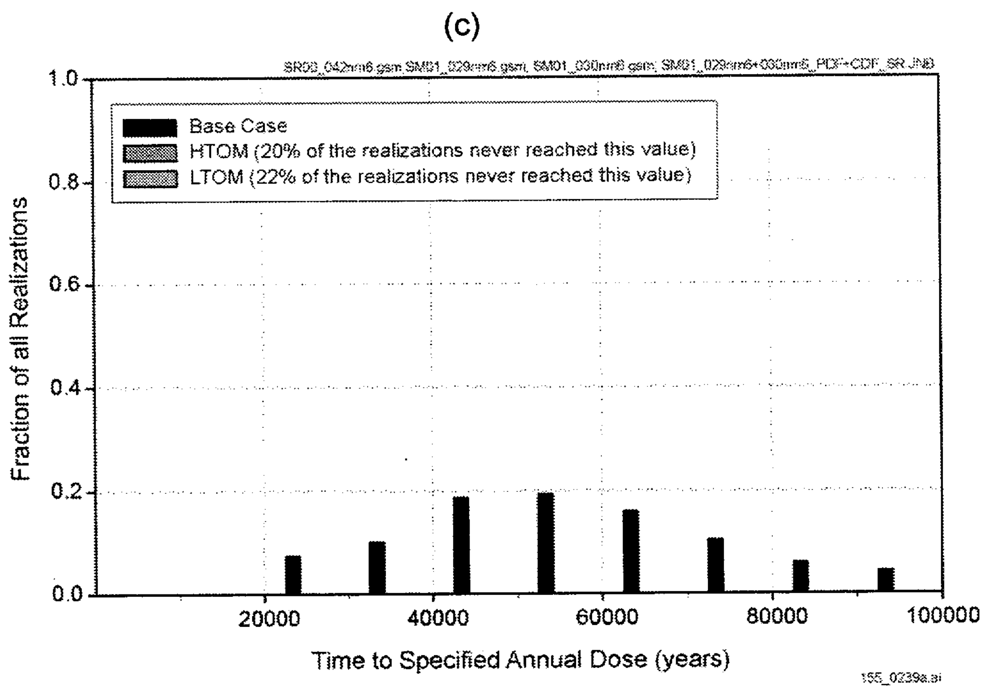




Source: SSPA Volume 2 (BSC 2001 [DIRS 154659]).

NOTE: (a) Cumulative distribution function of time to dose rate of 10^{-1} mrem/yr. (b) Histogram of time to dose rate of 10^{-1} mrem/yr (to 1,000,000 years).

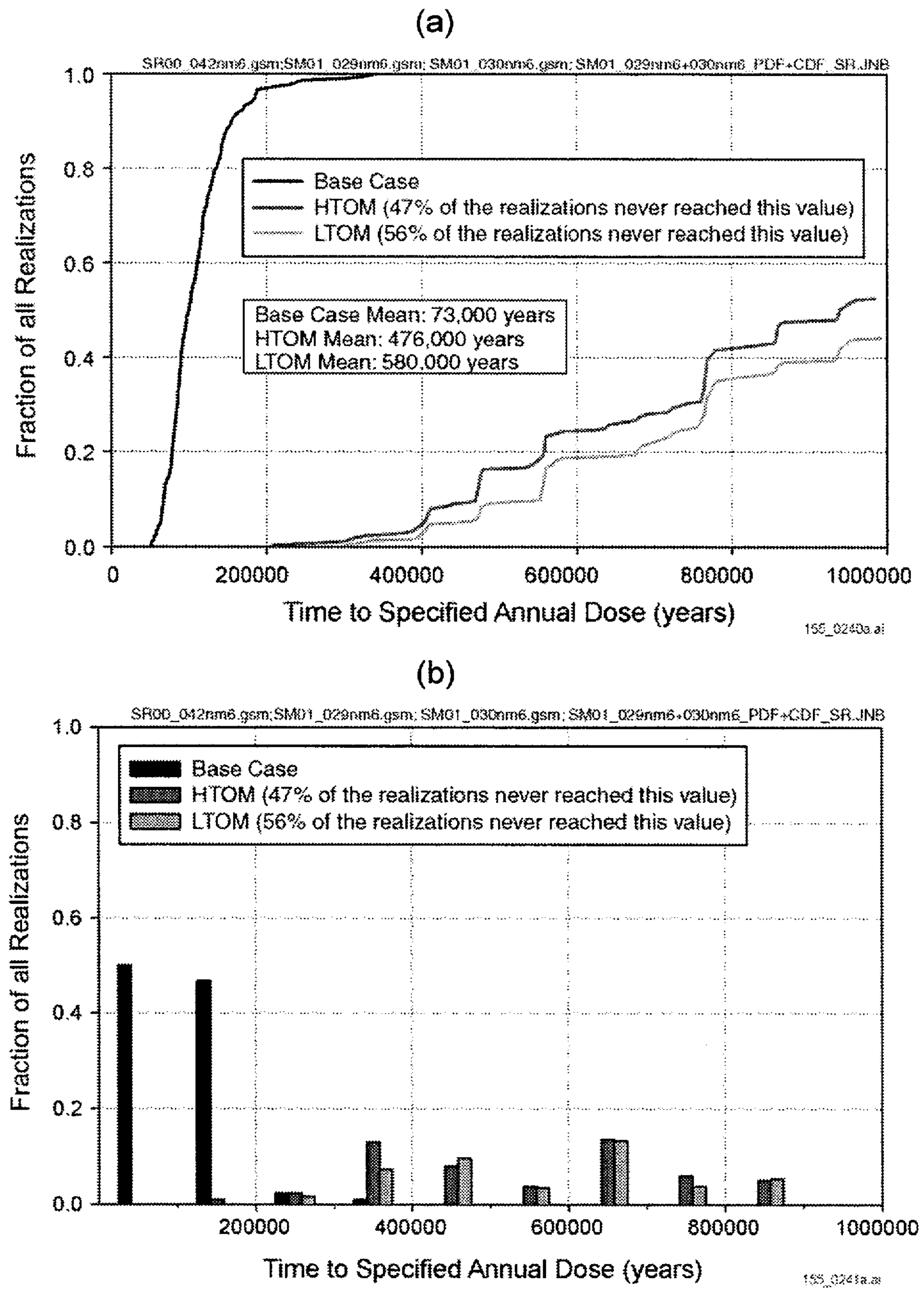
Figure 2-10a and b. Time that Fraction of Realizations Reaches Dose Rate of 10^{-1} mrem/yr



Source: SSPA Volume 2 (BSC 2001 [DIRS 154659]).

NOTE: (c) Histogram of time to dose rate of 10^{-1} mrem/yr (to 100,000 years).

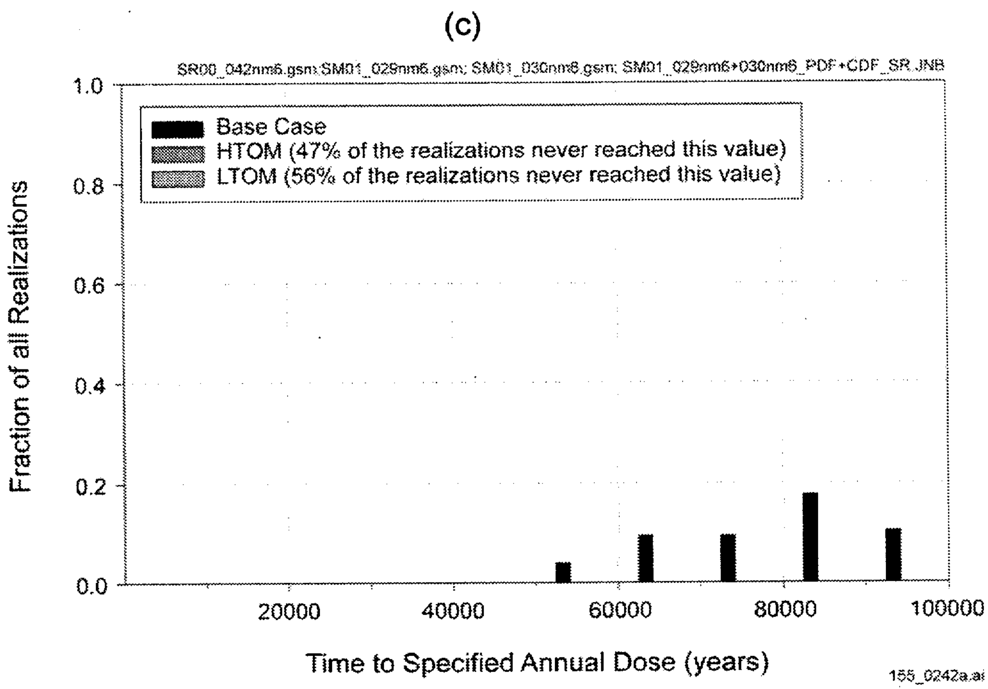
Figure 2-10c. Time that Fraction of Realizations Reaches Dose Rate of 10^{-1} mrem/yr



Source: SSPA Volume 2 (BSC 2001 [DIRS 154659]).

NOTE: (a) Cumulative distribution function of time to dose rate of 10 mrem/y. (b) Histogram of time to dose rate of 10 mrem/yr (to 1,000,000 years).

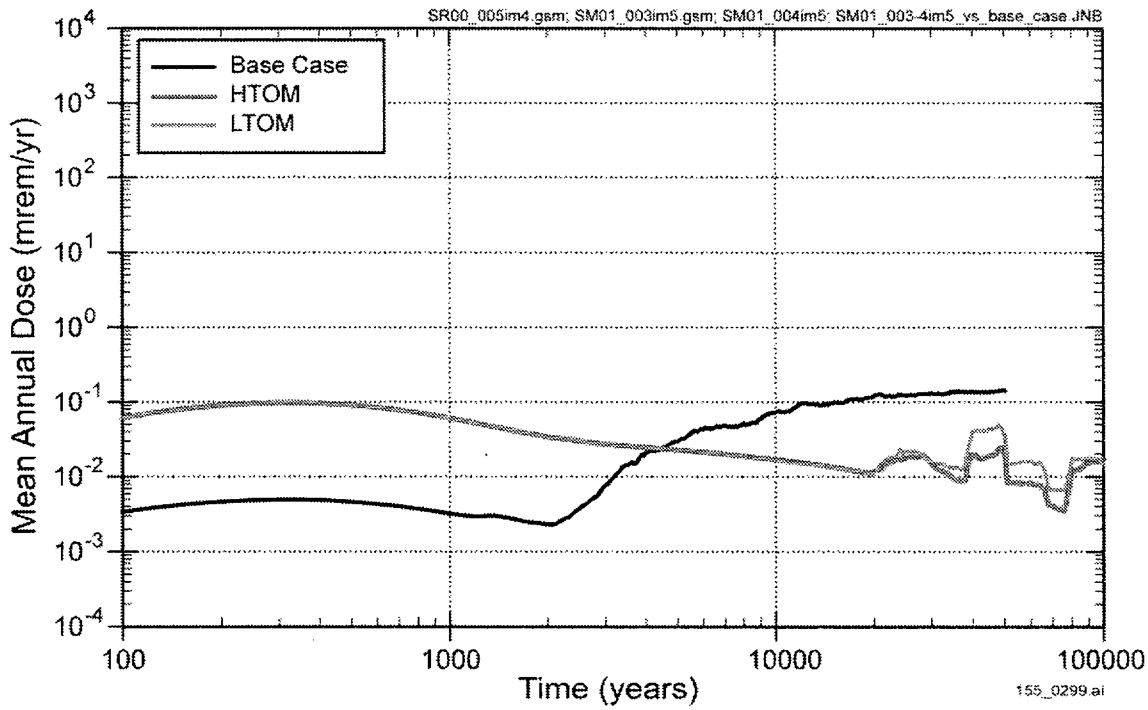
Figure 2-11a and b. Time that Fraction of Realizations Reaches Dose Rate of 10 mrem/yr



Source: SSPA Volume 2 (BSC 2001 [DIRS 154659]).

NOTE: (c) Histogram of time to dose rate of 10 mrem/yr (to 100,000 years).

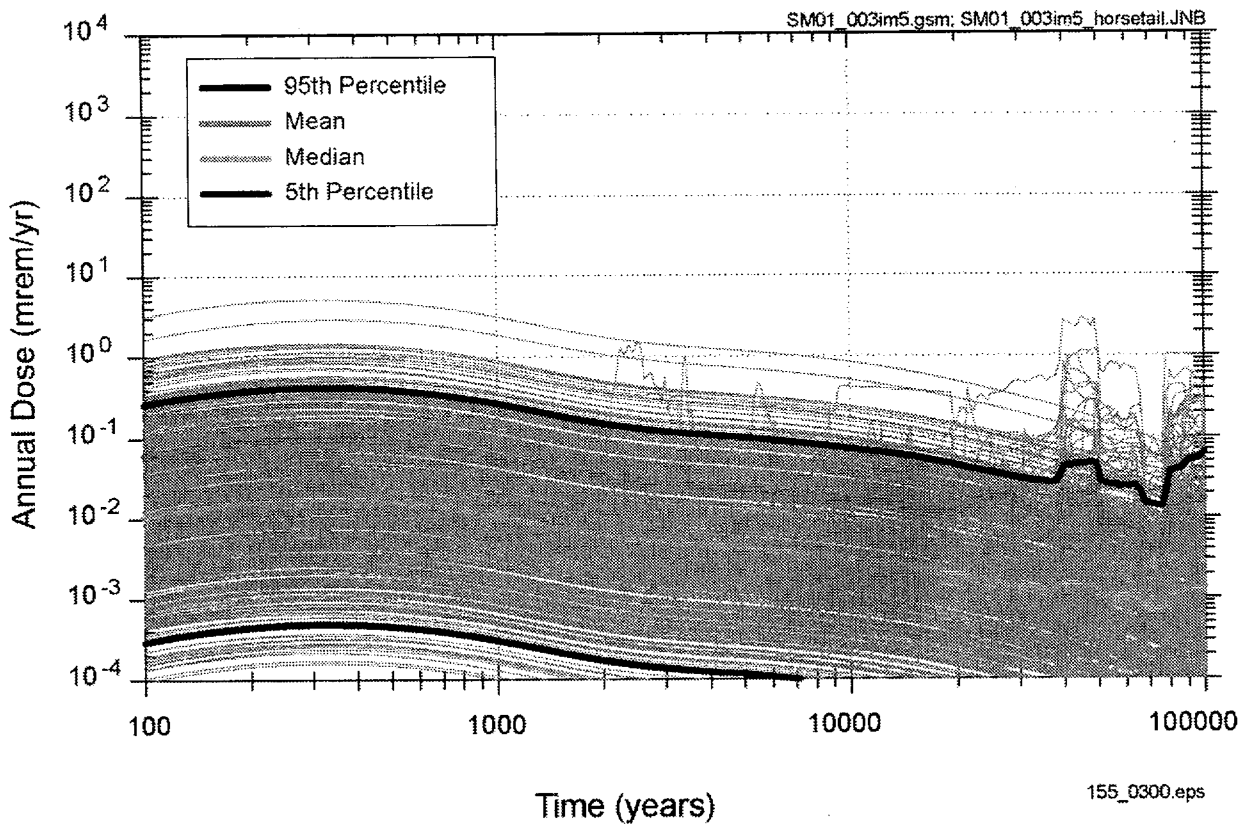
Figure 2-11c. Time that Fraction of Realizations Reaches Dose Rate of 10 mrem/yr



Source: SSPA Volume 2 (BSC 2001 [DIRS 154659]).

NOTE: Comparison of the mean annual does for three cases: TSPA-SR base-case HTOM, supplemental TSPA model HTOM, and supplemental TSPA model LTOM.

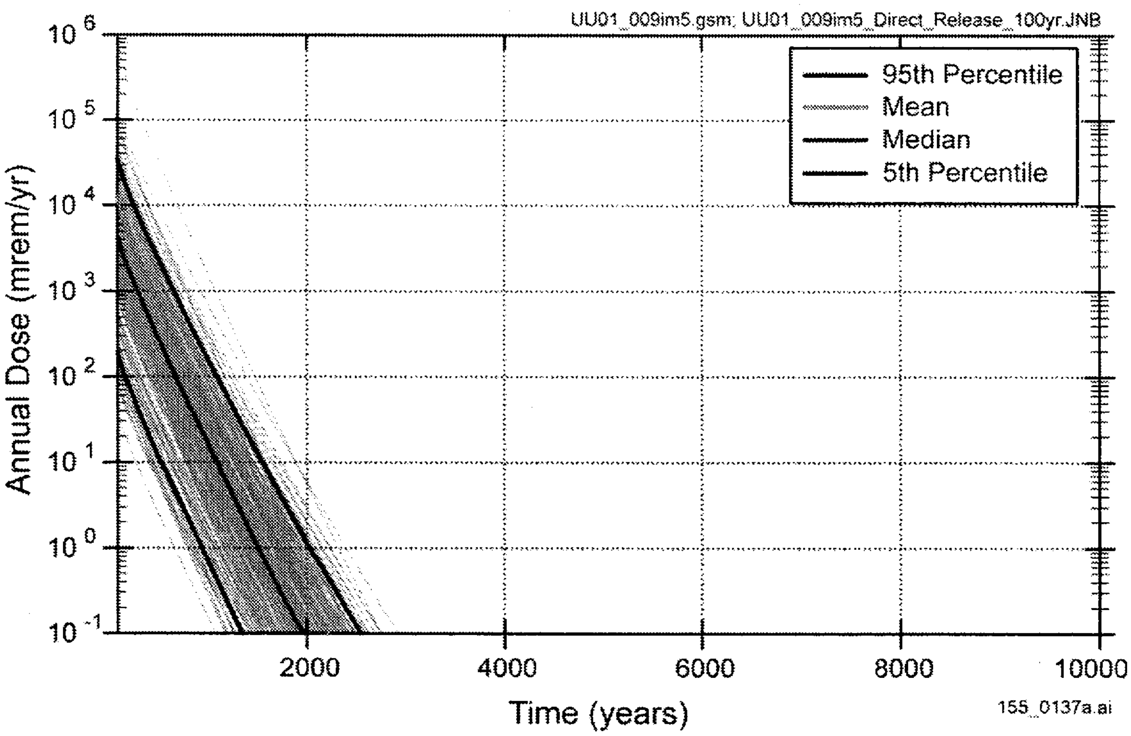
Figure 2-12. Probability-Weighted Mean Annual Dose for Igneous Disruption



Source: SSPA Volume 2 (BSC 2001 [DIRS 154659]).

NOTE: Summary curves show the mean and the 95th, 50th (median), and 5th percentiles.

Figure 2-13. Supplemental TSPA Model: 500 (of 5,000) Realizations of Probability Weighted Annual Dose Histories for Igneous Disruption, Higher-Temperature Operating Mode

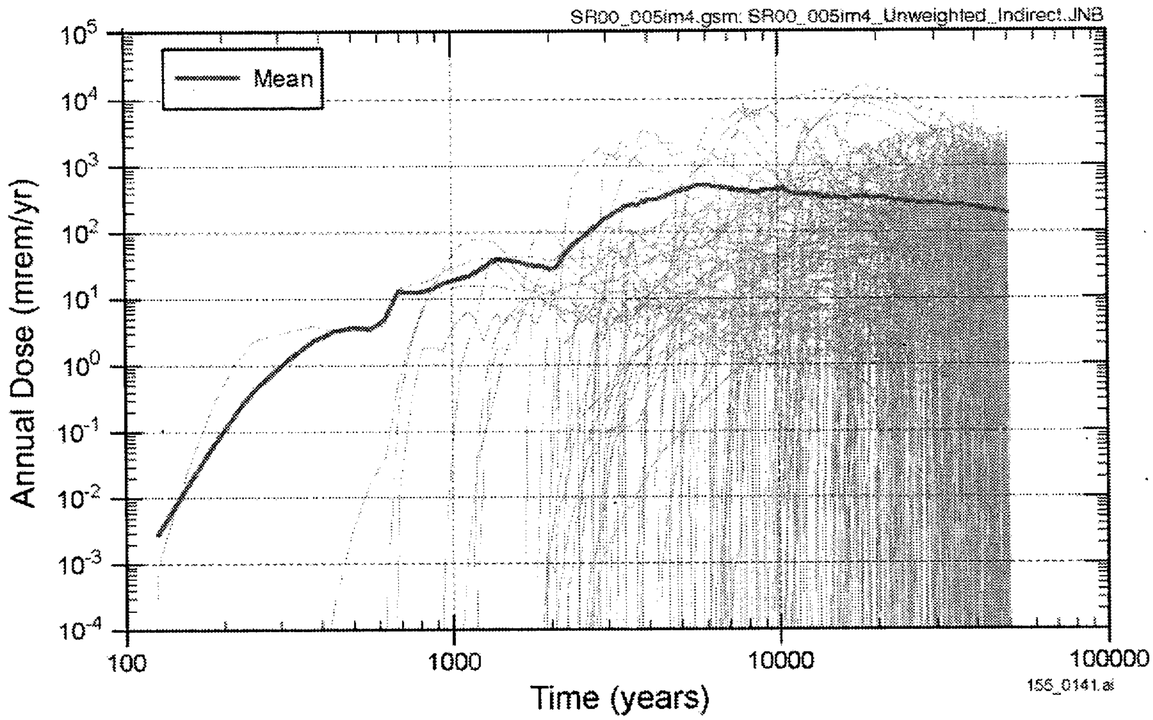


155_0137a.ai

Source: SSPA Volume 2 (BSC 2001 [DIRS 154659]).

NOTE: Conditional annual doses due to a volcanic eruption 100 years after closure of the potential repository. Annual doses calculated using the TSPA-SR models and parameters, with the probability of an eruptive event at the repository set to 1. Because annual doses are not shown weighted by the probability of the occurrence of the eruptive event, they are not suitable for comparison to proposed regulatory standards.

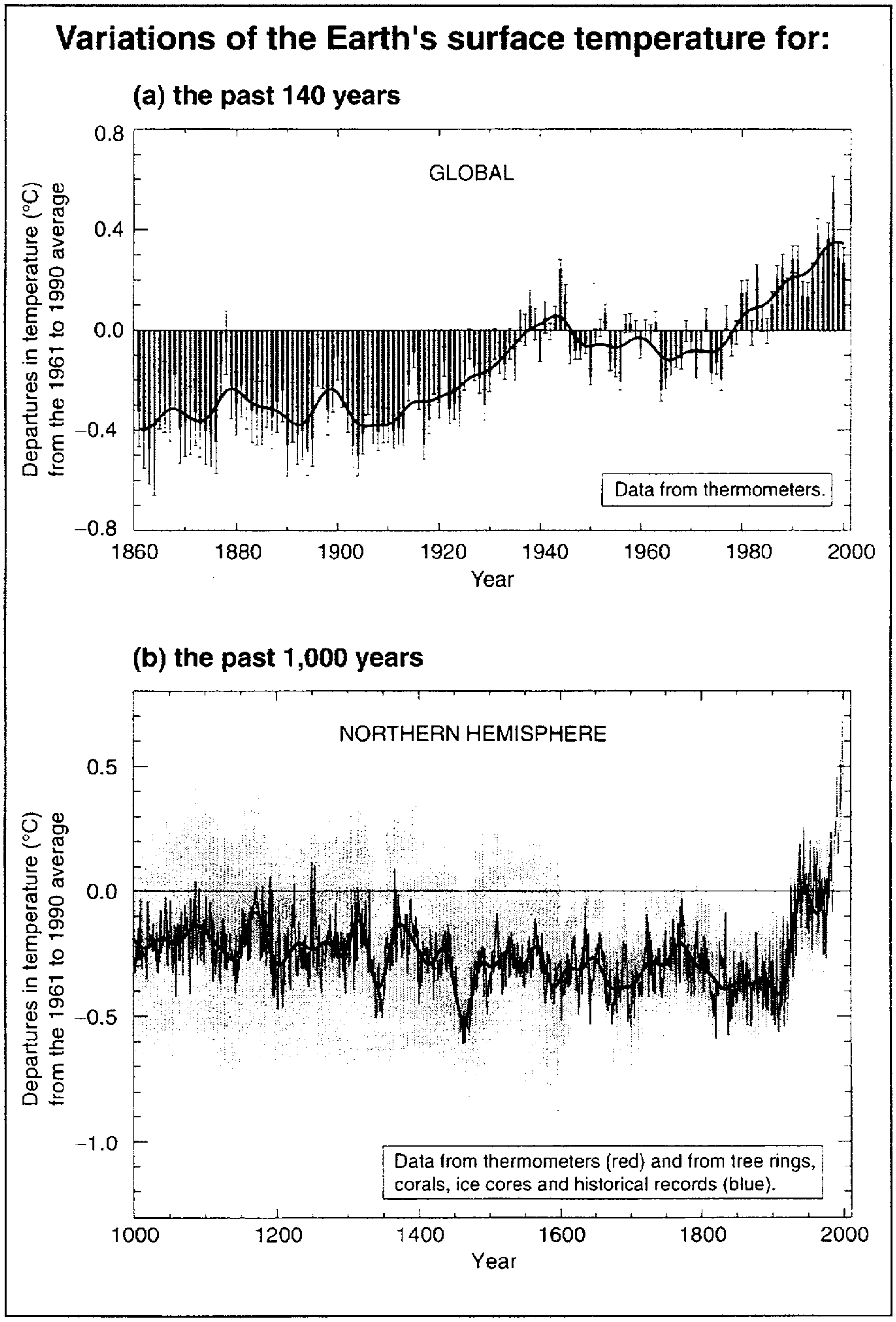
Figure 2-14. Non-Probability Weighted Mean Annual Dose Due to Volcanic Eruption



Source: SSPA Volume 2 (BSC 2001 [DIRS 154659]).

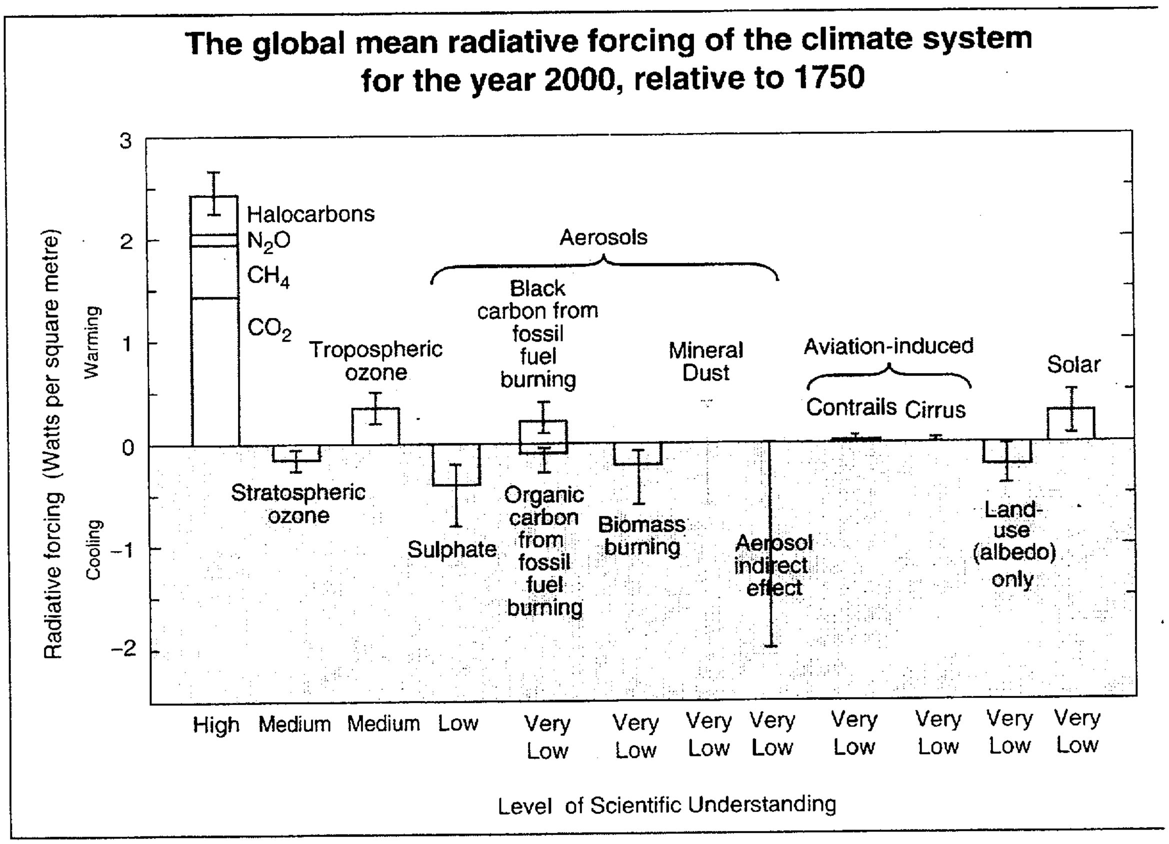
NOTE: Conditional annual dose histories due to groundwater transport following an igneous intrusion. This figure assumes the probability of the occurrence of an igneous intrusion during the simulation is set to 1. Because annual doses are not shown weighted by the probability of the occurrence of the eruptive event, they are not suitable for comparison to proposed regulatory standards.

Figure 2-15. Unweighted Dose for Igneous Groundwater Release Scenario



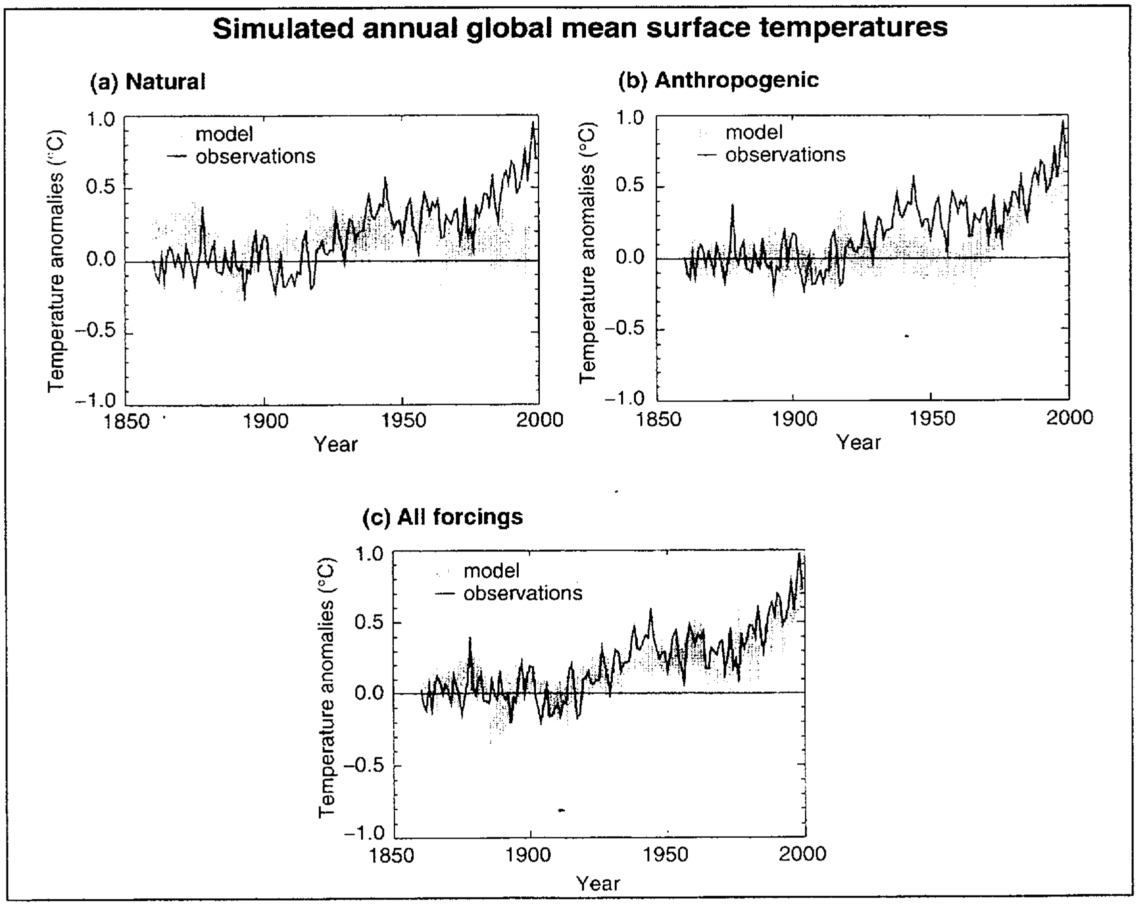
Source: (Albritton and Miera Filho 2001 [DIRS 156611])

Figure 4-1. Variations of the Earth's surface temperature over the last 140 years and the last millennium.



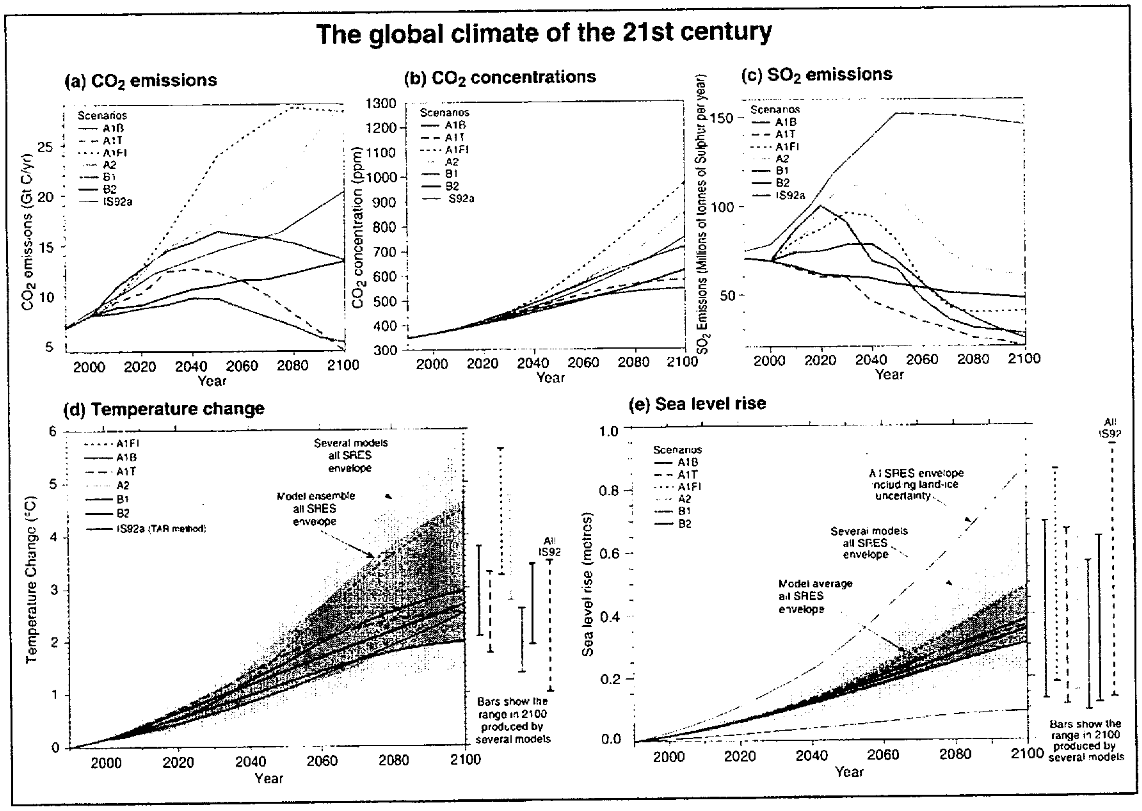
Source: (Albritton and Miera Filho 2001 [DIRS 156611])

Figure 4-2. Many external factors force climate change.



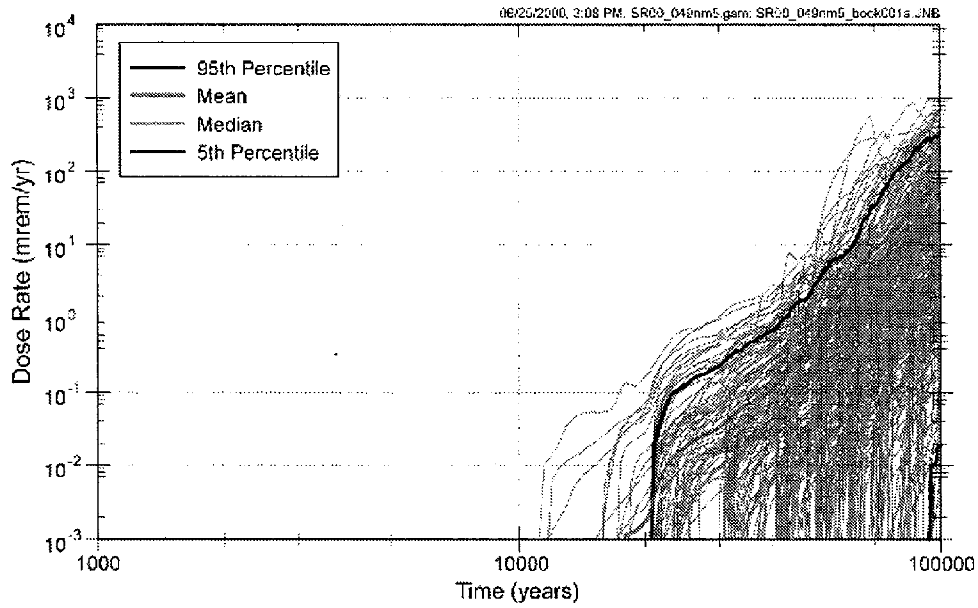
Source: (Albritton and Miera Filho 2001 [DIRS 156611])

Figure 4-3. Simulating the earth's temperature variations, and comparing the results to measured changes, can provide insight into the underlying causes of the major changes.



Source: (Albritton and Miera Filho 2001 [DIRS 156611])

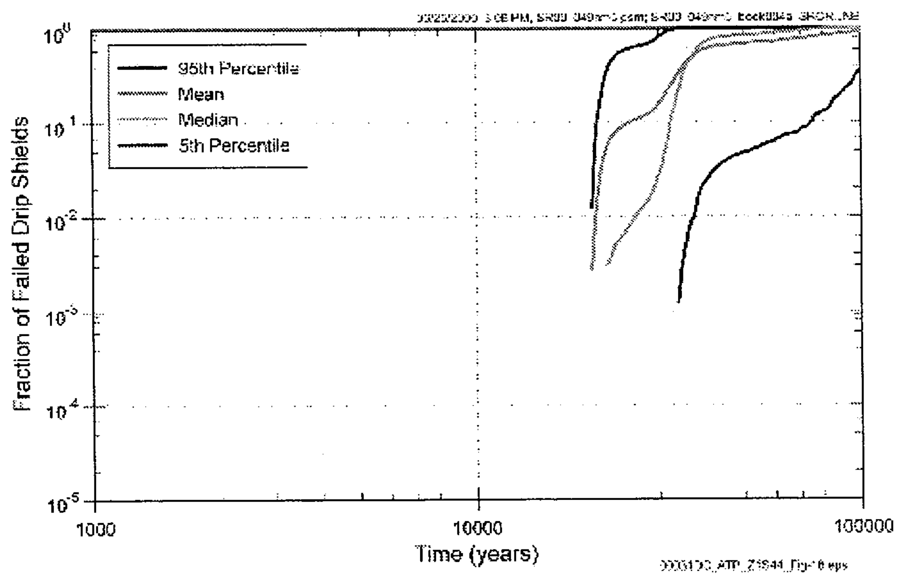
Figure 4-4. The global climate of the 21st century will depend on natural changes and the response of the climate system to human activities.



00031DC_ATP_Z1S44_Fig-15.ai

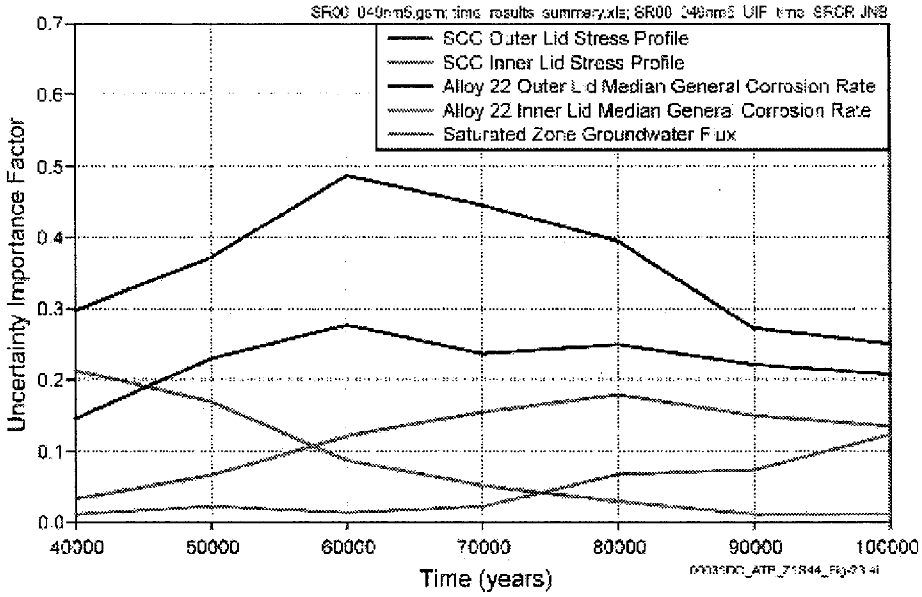
Source: S&ER (DOE 2001 [DIRS 153849]).

Figure 4-5. TSPA Results of Annual Dose to a Receptor for the Nominal Scenario



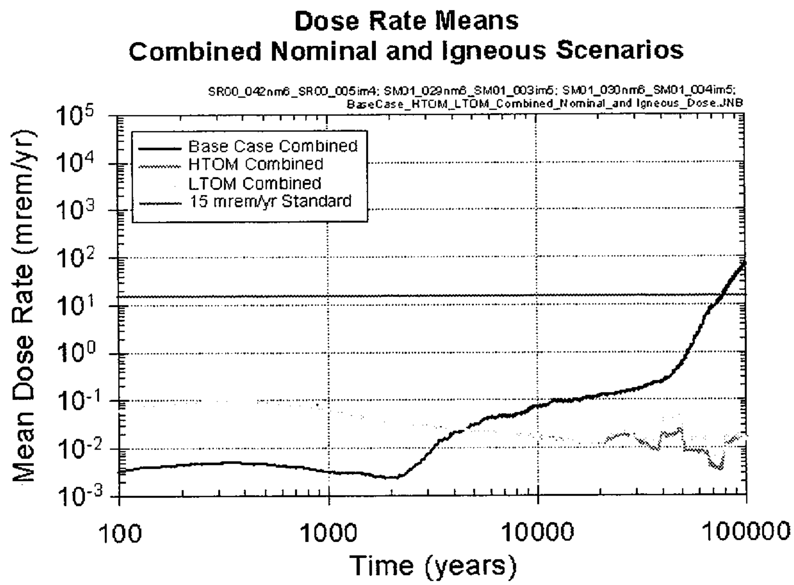
Source: S&ER (DOE 2001 [DIRS 153849]).

Figure 4-6. Cumulative Fraction of Drip Shields Degraded for the Nominal Scenario



Source: S&ER (DOE 2001 [DIRS 153849]).

Figure 4-7. Summary of Stochastic Sensitivity Analyses for Nominal Scenario



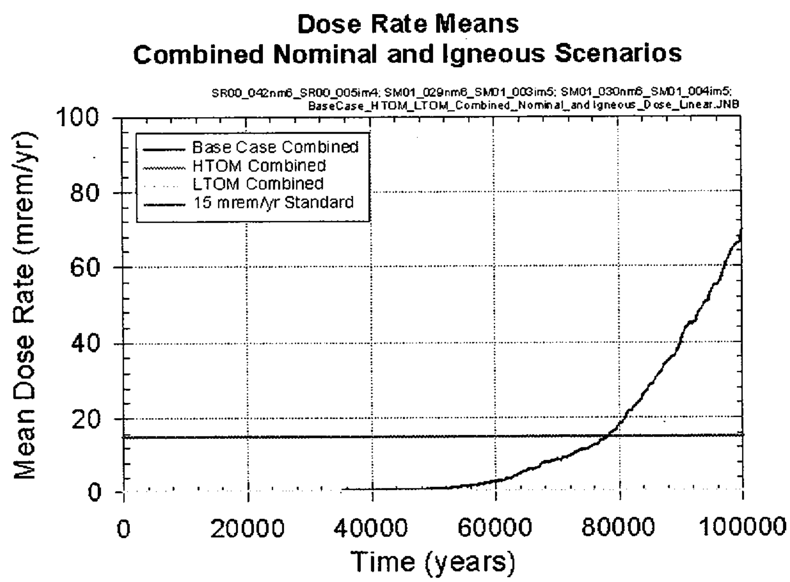


Figure 4-8. Example Dose Rate Means

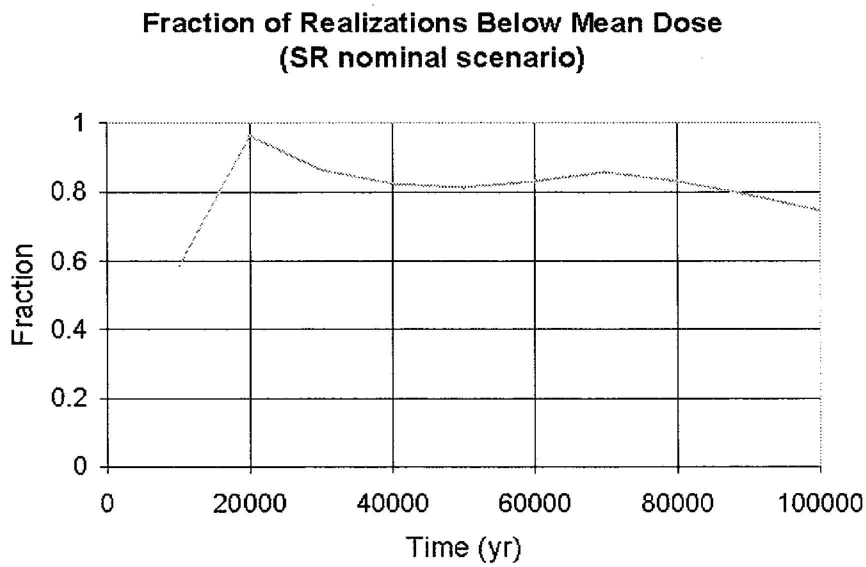


Figure 4-9. Example Fraction of Realizations Below Mean Dose

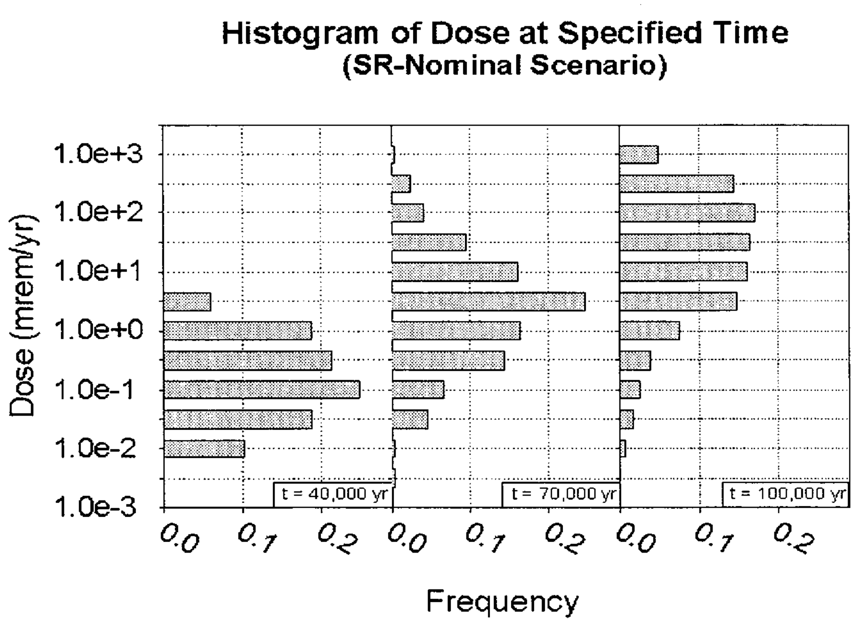


Figure 4-10. Example Histogram of Dose at Specified Time

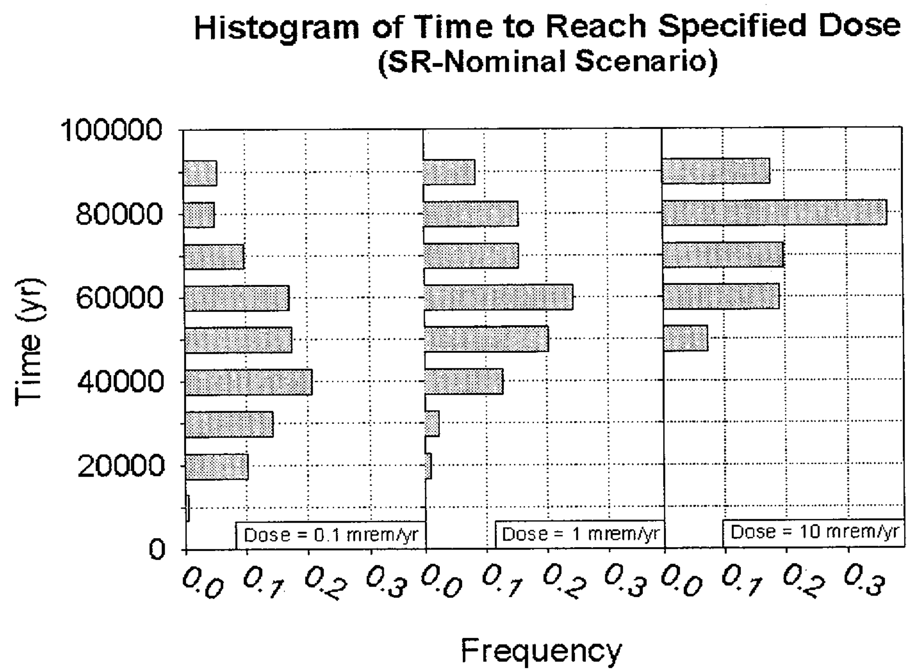


Figure 4-11. Example Histogram of Time to Reach Specified Dose