WBS: 1.2.5.4
QA: L

Civilian Radioactive Waste Management System
Management & Operating Contractor

Chapter 1
Total System Performance Assessment-Viability Assessment (TSPA-VA) Analyses Technical Basis Document

Introduction

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August 14, 1998

Prepared for:

U.S. Department of Energy
Yucca Mountain Site Characterization Office
P.O. Box 30307
North Las Vegas, Nevada 89036-0307

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Management & Operating Contractor

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August 14, 1998

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ACRONYMS

AML	areal mass load
CAM	corrosion allowance material
CRM	corrosion resistant material
DOE	U.S. Department of Energy
EBS	Engineered Barrier System
EPA	U.S. Environmental Protection Agency
FEPs	features, events, and processes
LA	License Application
NRC	U.S. Nuclear Regulatory Commission
PA	performance assessment
PACE	Performance Assessment Calculated Exercise
SCP	Site Characterization Plan
SNF	Spent Nuclear Fuel
TSPA-VA	Total System Performance Assessment for the Viability Assessment
UZ	unsaturated zone
VA	Viability Assessment
WP	waste package

1. INTRODUCTION TO THE TSPA-VA TECHNICAL BASIS DOCUMENT

This report was prepared for the specific purpose of augmenting the documentation of the Total System Performance Assessment (TSPA) methodology, results, and information contained in Volume 3 of the Viability Assessment (VA) (DOE 1998). While Volume 3 represents a relatively comprehensive compendium of analyses and results, this Technical Basis Document goes further into the technical details regarding modeling approaches, assumptions, data base, computer codes, and process-level model sensitivity analyses. This document was primarily written for regulatory agencies and scientific review groups such as the U.S. Nuclear Regulatory Commission (NRC) and their contractors, the U.S. Department of Energy (DOE) TSPA-VA Peer Review Panel, the Nuclear Waste Technical Review Board, the Advisory Committee on Nuclear Waste, the State of Nevada and affected units of government groups, as well as for other interested parties in industry and academia. A directed effort was made to document the component performance analyses in a manner that would be transparent, traceable, and thus facilitate its review.

This first chapter discusses the broad objectives of the TSPA-VA as defined in Public Law 104-206. To aid the reader, this introductory chapter explains the primary objectives of the TSPA-VA Technical Basis Document. It outlines the organization of this document, and explains how various chapters of this document are correlated with corresponding sections of Volume 3 of the VA. In addition to defining terms such as "performance assessment" (PA) and "total-system performance assessment" (TSPA), this chapter also describes the general TSPA process as implemented by the DOE and NRC repository programs in the United States and by high-level waste programs and regulatory agencies elsewhere in the world. The chapter also discusses the role of TSPA as a tool for integrating the knowledge base from diverse disciplines and its use as a systematic process for analyzing a nuclear waste repository system. To provide a historical background, this chapter discusses the evolution of TSPA iterations for the Yucca Mountain site, starting with the Performance Assessment Calculated Exercise (PACE 90) exercise (Barnard and Dockery 1991) and the progressions of the TSPA iterations to the current TSPA-VA. The last part of this chapter describes the current reference design for the proposed repository and provides the specific design data used in TSPA calculations for the VA.

1.1 OBJECTIVE OF THE TSPA-VA TECHNICAL BASIS DOCUMENT

The Technical Basis Document provides the supporting documentation for Volume 3 of the VA. In the TSPA-VA, the results of the total-system analyses and the supporting sensitivity analyses were reported in detail. However, documentation of the component models was written at a generalized level to only provide a synopsis of the development, implementation, and results of the subsystem analyses. Also, the details of the TSPA code architecture and the methodology associated with the sensitivity and uncertainty analyses were not described in Volume 3 of the VA. The purpose of this document is to provide the underlying details for the topics that were only briefly covered in Volume 3.

1.1.1 Objectives of Total System Performance Assessment for the Viability Assessment

The overall scope and objective of the TSPA for the VA are contained in the 1997 Energy and Water Development Appropriations Act (Public Law 104-206):

> ...a total system PA based upon the design concept and the scientific data and analysis available by September 30, 1998, describing the probable behavior of the repository in the Yucca Mountain geological setting relative to the overall system performance standards.

Assessing the overall performance of the proposed repository system at Yucca Mountain required the following:

- Assimilating all the available scientific data and examining prior analyses for the geological setting
- Preparing a discrete representation of the reference design concept for the repository facility, waste package (WP), and hydrogeologic setting for use in the assessment
- Developing appropriate models and input data sets to forecast the probable behavior of the proposed repository system
- Selecting the interim performance standards to be used in comparisons with the TSPA results.

Since the inception of the DOE Yucca Mountain project, the scientific data produced by site characterization activities have been compiled, documented, analyzed, and reviewed by both internal and external groups. This data and information is largely contained in several computer data bases under the Yucca Mountain Project's Technical Data Management system, which is accessible through the internet. These and more recent data have been examined by project scientists and input data sets developed for use in the TSPA-VA.

Concurrent with the collection of site data, the design efforts have produced a reference design for the underground facility, the WP, as well as for the emplacement geometry to achieve the appropriate thermal design. The reference design for the proposed repository is described in Volume 2 of the VA (DOE 1998). Some of the major aspects of the reference design are summarized at the end of this chapter.

Since the early 90s, DOE PA model development efforts have produced a set of process-level models applicable to different components and subsystems of the proposed repository. These sophisticated and detailed models have been used in developing a system-level model that integrates all the component models, accounts for major phenomenological couplings, and propagates uncertainty (i.e., using a probabilistic technique) for both input parameters and future system states (i.e., disruptive scenarios). In addition to analyzing the isolation capability of the natural and engineered barriers of the repository system, the total system model produces statistical distributions of the performance indicator (e.g., peak dose) for the designated receptor location (e.g., 20 km) and containment period (e.g., 10,000 yr).

At present, the U.S. Environmental Protection Agency (EPA) is continuing to develop and finalize the new environmental standard for the proposed Yucca Mountain high-level waste repository. Similarly, the NRC is preparing a new high-level waste regulation which will revise the technical criteria in 10 CFR Part 60. In order to fulfill the objective mandated in Public Law 104-206, the DOE has adopted an interim postclosure performance goal for the proposed repository system. Specifically, the interim goal consists of an expected dose to an average individual in a critical group at a location 20 km from the repository not to exceed 25 mrem/yr from all pathways and all radionuclides during the first 10,000 years after closure (Barnes 1997). In addition, TSPA calculations beyond 10,000 years are to be performed to gain insight into longer term system performance.

1.1.2 Organization of This Document

Following this introductory chapter, the technical basis for each of the component models that comprise the TSPA-VA is presented. The TSPA-VA components presented in Chapters 2 through 9 consist of (1) unsaturated zone (UZ) flow, (2) thermal hydrology, (3) near-field geochemical environment, (4) WP degradation, (5) waste form alteration and mobilization, (6) unsaturated zone transport, (7) saturated zone flow and transport, and (8) biosphere. For each of these components, the associated chapter:

- Introduces the conceptualization of each individual process
- Discusses the key issues associated with the process model for that component
- Describes the abstraction approach and implementation in the TSPA analysis
- Provides the TSPA base case description for that component
- Describes the data sources
- Models parameter development and computer simulation methods
- Shows results and interpretation of the results
- Provides the approach, assumptions, description, results and interpretation of any sensitivity analyses performed for that component.

Chapter 10 describes the analyses and results associated with disruptive events (i.e., seismicity, volcanism, nuclear criticality, and human intrusion). Chapter 11 defines the TSPA-VA base case and then describes how the information produced in Chapters 2–10 is incorporated into the total-system model to provide evaluations of system performance. This chapter also includes a detailed discussion of the TSPA-VA model and computer code architecture and describes the uncertainty and sensitivity analysis methods used to determine the components and parameters contributing the most uncertainty to the evaluation of system performance. Finally, Appendix A gives the parameter values and distributions used in the TSPA-VA.

Table 1-1 cross-correlates the location of various types of information in Volume 3 of the VA (DOE 1998) and the chapters and subsections of this Technical Basis Document. As stated above, the sections on the individual TSPA components and some of the details of the total-system codes and methods are reported in much more detail in this volume. However, Volume 3 of the VA is the primary source for the results and interpretations of the total-system analyses and the associated sensitivity and uncertainty analyses. Volume 4 of the VA is also the primary reference containing the DOE guidance for PA model development for the License Application (LA).

1.2 DEFINITION AND USES OF PERFORMANCE ASSESSMENT AND TOTAL SYSTEM PERFORMANCE ASSESSMENT

As used in the nuclear waste management field, the terms PA and TSPA have very specific meanings. PA, the more generic term, is a method of forecasting how well a disposal or storage system (or component of that system) will isolate the nuclear waste (e.g., low-level, high-level, transuranic) over time. Its goal is to aid in determining whether the system or component being analyzed can achieve the specified design and/or regulatory requirements. A TSPA is a special type of PA in which all of the components of a system are linked into a single analysis.

1.2.1 What is a Total System Performance Assessment?

A TSPA, like other systematic safety assessment methodologies, is an analytic tool to aid decision making. It is unique from other methodologies, however, in that a TSPA for a geologic repository considers the combined behavior of disposal system as a function of significant features, events, and processes (FEPs), for time periods of thousands of years. These FEPs are represented in models of varying complexity for both the engineered and the natural system. The uncertainty and variability inherent in FEPs must also be included and evaluated. With these concepts in mind, a TSPA can formally defined as:

> A systematic analysis methodology that: (1) identifies the significant FEPs that may significantly affect the isolation capability of the system, (2) examines the effects of the FEPs on overall performance, and (3) estimates the radiologic risk to a hypothetical receptor group, taking into account the uncertainties associated with the FEPs , and (4) for the regulatory period of concern, provides a quantitative estimate of the regulatory risk measure and/or performance indicator in the form a probability distribution.

Another important output of a TSPA is a rank ordering of the FEPs, which delineates those components, scenarios classes, and uncertainties that determine overall repository performance.

The process of constructing and implementing a TSPA for a specific repository system is often explained using a pyramid, where detailed information representing the various processes and components of a total system are distilled and linked into progressively more abstracted models used to analyze system performance. The findings of a TSPA are also used to prioritize the information gathering activities of site characterization and design investigators. The results from prior TSPAs such as sensitivity studies performed on individual parameters or processes

give insight into the areas in which additional information will decrease uncertainty to the greatest extent. This process is usually iterative, so incorporation of the revised and updated information into the subsequent TSPAs allows a progression toward more reasonable and defensible total-system models. The evolution of this process for the proposed Yucca Mountain repository is described in more detail in Section 1.3 of this chapter.

The word "forecast" rather than "predict" is used to describe the expected outcome of a TSPA. "Predict" implies "inference from facts or accepted laws of nature." Forecast has a similar meaning but also implies anticipating eventualities and differs from predict in being usually concerned with probabilities instead of certainties (Merriam-Webster 1993, pp. 457). As discussed in Section 1.3, incorporation of probabilities and uncertainty is a critical aspect of TSPA, which allows determination of reasonable assurance, as defined by regulatory agencies.

In certain respects, the process of TSPA is distinct from that of safety assessments and probabilistic risk assessments. Safety assessments generally use a conservative "bounding" assessment of the entire system; PAs analyze the best understanding of the system and its components (NEA 1995 pp. 28-36). In a safety assessment, which is often based on a deterministic approach, a set of FEPs are assumed to occur, regardless of the likelihood of their occurrence. A TSPA incorporates more information than a safety assessment because it assumes some processes or events are more likely to happen than others. They are then treated accordingly using mathematical models (however, for some processes or events where information is limited, bounding analyses may be used in the PA). The benefit of a TSPA in this case, is that a more realistic and, therefore, more defensible case is used.

It must be noted that, in the community of nuclear waste management professionals, this distinction between a safety assessment and a PA has become blurred, such that in informal usage they are often used interchangeably. However, it is important to differentiate the two philosophies, that is, the use of a "conservative" bounding cases versus using the most realistic models possible. In addition, a safety case, as made before a licensing authority, could include both safety assessments and PAs, as defined above.

"Probabilistic risk assessment" (PRA) is a term generally applied to safety studies of nuclear power plants (Lewis 1997) or other engineered systems, (Henley and Kumamoto 1991) but can be applied to any system that could fail in well-known and identifiable ways. Although this type of analysis incorporates variations in probability for different processes, the system and the time periods are very different between a reactor system and geologic repository system as studied by a PA. A PRA is usually considers discrete events of limited duration involving an engineered system and its components. Natural events such as earthquakes and volcanic eruptions are considered initiating events that may have an effect on overall system behavior, but are not a part of the system. Many reactor components, such as pumps and valves, can be tested on a time scale similar to that for the operational life of the system.

A PA for a geologic repository system includes both engineered and natural components as integral parts of the system. The variability and heterogeneity introduced in the system is much larger than that in a reactor system. Also, unlike the reactor system, the responses of the total-system extend over periods of time for which completely representative data has not or can not be obtained. It is important to emphasize that a TSPA, although based on the use of

sophisticated computational models and probabilistic methods, only provides a rationale means of demonstrating a "reasonable expectation" of repository compliance with safety requirements. It can not be expected to provide a unique answer about the specific state of the repository system during various points in the future.

1.2.2 Philosophy of Total System Performance Assessment

The TSPA has become the internationally recognized method for analyzing system behavior for nuclear waste repositories. It is important to understand why TSPAs are performed, why a TSPA is unique, when compared to other types of analyses, and why the confidence in TSPA as a process has been established at such a global level.

1.2.2.1 Why Total System Performance Assessments are Performed

Performance assessments are used to forecast how a specific system and all of its components evolve over time. Comparing the results to performance requirements allows analysts to estimate whether the amount of harmful material that may become accessible in the environment is acceptably low. The requirements, usually in the form of regulatory criteria, are generally established by governmental oversight agencies. The ultimate determination of whether a system complies with the requirements lies with the legally responsible regulatory group. The task of those proposing a nuclear waste repository is to provide reasonable assurance that the safety standard will be met, which in turn requires that they:

- Understand the behavior of the proposed system and all of its components
- Can demonstrate the capability to model the system
- Can adequately account for and treat the uncertainties in the analysis
- Can show that the information in the model provides reasonable assurance that safety standards will be met.

In addition to providing a tool for demonstrating the disposal system's ability to meet regulatory requirements, TSPA also provides a rigorous method for aiding management in establishing the priority of information-gathering activities during the site selection, site characterization, and design phases. As more information is gathered, the TSPA process iterates to incorporate revised and updated information into successive TSPA models and allows a program to progress toward more reasonable and defensible total-system models. Results of each TSPA, particularly the sensitivity and uncertainty studies, provide information about the relative importance of ongoing or proposed information-gathering activities addressing site characterization and design development. Each successive TSPA requires that the total system models become more representative of the site and engineering design. Several TSPAs by the YMP have been completed to date on the Yucca Mountain repository system (Sinnock et al. 1984; Barnard and Dockery 1991; Barnard et al. 1992; Eslinger et al. 1993; Wilson et al. 1994; Andrews et al. 1994; CRWMS M&O 1995). These efforts, along with studies done by other organizations (NAS/NRC 1995; Kessler and McGuire 1996), have contributed to the iterative process of the TSPA for the VA.

A TSPA is unique because it is the analysis that links all the system components together. This linkage is important because it allows each component to be viewed in the context of the behavior of the entire system. Even the simplest system has various aspects that are easier to understand when studied separately. For example, WP material degradation may be characterized by laboratory tests of corrosion. However, the geologic system in which the WP is to be emplaced is analyzed using field studies of the host rock for properties that are only observed on a large scale (such as fracture density), as well as laboratory studies of other aspects (such as water chemistry). In a functioning system, these elements provide feedback to one another. The interaction of the water with the corroded WP would likely change the water chemistry, which may in turn change the fractures and the way water flows through them. This very simple example shows an obvious potential for feedback. When a very complex system with numerous components is simulated as a single system in a TSPA, interactions among the components that would not otherwise be observed are often found in the analysis.

As discussed in Volume 1 of the VA, the repository safety strategy for the YMP relies on a multiple barrier system. This isolation strategy means that all the components of the natural and engineered systems work together to form a series of barriers. Because the behavior of each component in the series is governed by a different set of physical or chemical processes, this strategy provides a strong argument that the entire system is very unlikely to fail in response to a single mechanism. Also, the use of different types of barriers lessens reliance on complete knowledge about any one process. Therefore, the incorporation of multiple barriers helps to answer the question that frequently arises, how can the analysis account for what is not known? Given the uncertainty inherent in a forecast, one way to deal with an unanticipated response by one component of the system is to have multiple additional components that will still operate as barriers.

"The concept of reasonable assurance" does not require absolute certainty in the results of an analysis. The incorporation of uncertainty into the TSPA, using various mathematical methods, allows the regulator and others to determine if the goal of reasonable assurance has been met. The study of uncertainty is documented in chapters of this document; however, some of the general methods of treating uncertainty include developing distributions to represent various types of data and also assigning probabilities to different conceptual models to encompass a range of potential behaviors or responses of certain components.

1.2.2.2 Why Total System Performance Assessments are the Appropriate Tool for Analyzing Repository Systems

A question that often arises is whether or not PA is a useful tool for the purpose of analyzing safety. The consensus of the international waste management community is that, PA is an adequate tool in the realm of providing reasonable assurance. In support of this consensus, the Nuclear Energy Agency Radioactive Waste Management Committee and the International Atomic Energy Agency International Radioactive Waste Management Advisory Committee issued a collective opinion (NEA 1991 p. 7) that they:

> "confirm that safety assessments are available today to evaluate adequately the potential long-term radiological impacts of a carefully designed radioactive waste disposal system on humans and the environment, and consider that appropriate use of

safety assessment methods, coupled with sufficient information from proposed disposal sites, can provide the technical basis to decide whether specific disposal systems would offer to society a satisfactory level of safety for both current and future generations."

Although TSPAs can never provide precise predictions, there are still many environmental problems that require modeling of the long-term interactions between man-made and geologic systems. Using the term "model" acknowledges that only approximate descriptions of geologic FEPs are possible and how well they represent absolute reality cannot be fully demonstrated. "Validation" of a long-term assessment model means that, on the basis of tests of the assumptions, inputs, outputs, and sensitivities, the model adequately reflects the recognized behavior of the portion of the system it is intended to represent. Adequacy of model is driven by the needs of the application for which it is specifically developed (Boak and Dockery 1998, pp. 178-180.).

Scientists assessing long-term risk (Kaplan and Garrick 1981) use the following mechanisms to establish the adequacy of their models (Boak and Dockery 1998, pp. 181-182):

- Expert judgment to assign appropriate ranges of parameters where data are sparse, controversial, or unobtainable

- Conservatism in assigning parameter values and process descriptions, including ignoring some potentially mitigating processes

- Stochastic simulation to assess the effect of uncertainty in descriptions and the sensitivity of performance predictions to uncertainty and to examine alternative scenarios and process models.

The following measures are undertaken to demonstrate that the effort to ensure validity has been comprehensive (Boak and Dockery 1998, p. 182):

- Documentation of the model structures, including justification for assumptions and simplifications as well as the examination of alternative conceptualizations for the system

- Review by the scientific community and those who have a stake in the decisions that these models support.

Uncertainty is an inherent part of all total system studies and, to the extent possible, is captured in statistical distributions selected to represent the randomness in future system states and variability of media properties. In some cases, information gathering activities are directed at reducing uncertainty as much as is practical, while in others, it is aimed at better characterizing the statistical representation of random behavior.

1.2.3 Role of Performance Assessment in the Nuclear Waste Management Program

The analysis of the Yucca Mountain total-system was performed, in part, to determine whether the system, using a reference design and current understanding of the natural system processes, is

expected to comply with regulatory requirements. However, another goal of the YMP is to assess total system performance quantitatively defining the significance of each of the key components in the repository-safety strategy to assist in a systematic refocusing of Project resources in the areas of site characterization and system design. The statutory goal of the TSPA-VA is to address the probable behavior of the repository system. However, the available scientific information can also suggest alternative interpretations that may also be plausible. When propagated through a quantitative tool such as PA, these alternative interpretations can illustrate the significance of the uncertainty in the base-case interpretation chosen to represent the repository's probable behavior. The information about uncertainty will assist the U.S. Department of Energy (DOE) in defining the work required either to minimize uncertainty or to modify the repository design to accommodate for this uncertainty before submitting the LA for constructing the repository system. The quantitative performance analyses assist in identifying those areas where additional scientific and technical work are required to evaluate the site and to prepare a complete, cost-effective, and timely LA. The additional scientific investigations and design analyses necessary for developing the LA are summarized in Volume 4 of the VA (DOE 1998).

Another indirect use of the TSPA is to provide a vehicle for pre-licensing discussions with NRC. The NRC pre-licensing program focuses interactions on the key technical issues most important to repository performance. An important role of the TSPA is to evaluate the potential significance of these issues to find a common basis for understanding the need for additional scientific and technical work.

Although the goal of the TSPA is to provide a quantitative assessment of the probable behavior of the repository system, it is important to recognize the uncertainties inherent in such analyses. The EPA and NRC have recognized the care required in defining the degree of confidence needed from the analyses. EPA says that:

> "Because of the long time period involved and the nature of the events and processes of interest, there will inevitably be substantial uncertainties in projecting disposal system performance. Proof of the future performance of a disposal system is not to be had in the ordinary sense of the word in situations that deal with much shorter time frames" (EPA 1985; 40 CFR 191.13[a]).

According to NRC—The Commission anticipates that licensing decisions will be complicated by the uncertainties that are associated with predicting the behavior of a geologic repository over the thousands of years during which HLW [high-level waste] may present hazards to public health and safety (NRC 1983, 10 CFR 60).

These inherent uncertainties were recognized in developing the analysis tools that are described in Chapters 2–11 of this volume. The potential effects of many of these uncertainties are presented in Sections 5 and 6 of the Volume 3 of the VA.

An important goal of a post-closure PA is to produce document that is transparent with regards to the assumptions, results, and conclusions of the analyses. External review groups have defined what they mean by transparent. The Nuclear Waste Technical Review Board states that "transparency is the ease of understanding the process by which a study was carried out, which

assumptions are driving the results, how they were arrived at, and the rigor of the analyses leading to the results" (Nuclear Waste Technical Review Board 1997, p. 21). The TSPA Peer Review Panel notes that "transparency is achieved when a reader or reviewer has a clear picture of what was done in the analysis, what the outcome was, and why" (Whipple et al. 1997, p. 10).

For there to be broad confidence in the PA, the presentation of the methodology and results must illustrate with sufficient clarity the following attributes:

- The conceptual basis for the individual components in the quantitative analyses
- How the individual components are combined into an assessment of system behavior
- The scientific understanding used to develop the quantitative analysis tools that describe the system's expected evolution
- The system's expected evolution as defined by the spatial and temporal response of the system to waste emplacement
- Uncertainty in the system's expected evolution and the significance of that uncertainty to the system performance goals.

This Technical Basis Document attempts to achieve the level of transparency expected by these oversight groups and the regulatory agencies. However, the YMP PA staff and management realize that there still remains a significant amount of work to be done to fully accomplish the level of traceability and transparency required for a defensible LA.

1.3 EVOLUTION OF YUCCA MOUNTAIN TSPA

A number of comprehensive but preliminary TSPAs (Sinnock et al. 1984; Barnard and Dockery 1991; Barnard et al. 1992; Eslinger et al. 1993; Wilson et al. 1994; Andrews et al. 1994; and M&O 1995) have been performed and documented for the proposed repository system at Yucca Mountain. In addition, several subsystem analyses have been performed. As more information about the site and design components of the potential repository system has become available, these TSPA analyses evolved into progressively more complex representations of the system.

The representation of some of the elements of the total system analysis included in each of the iterations has remained fundamentally the same, although the models and parameters have been revised and refined each time. However, as the collective scientific understanding of the FEPs specific to Yucca Mountain has progressed, the representation of certain process areas has been significantly updated. Perhaps the largest change has occurred in the understanding of unsaturated-zone groundwater flow at the potential repository site. Clearly, the rate and distribution of the movement of groundwater through the unsaturated-zone is important to the performance of the system. In every TSPA, regardless of the details of the performance measure used, performance is highly correlated to unsaturated-zone flow. In earlier assessments of Yucca Mountain, groundwater was assumed to flow downward, almost exclusively in the matrix. This assumption resulted in extremely slow flow through the entire system, and thus to very low cumulative releases during the regulatory period. Sensitivity studies at higher fluxes suggested it

to be an important parameter. The evolution of the understanding of unsaturated-zone groundwater flow has required changes in the DOE models and the representation of the system. The most current model for this process is described in detail in Chapter 2 of this document and in Section 6.1.

In addition, the design has been evolving in response to experimental data and a changing understanding of site characteristics. In particular, TSPA analyses have been required to change from representation of a small, in-floor, vertically emplaced WP, as specified in the Site Characterization Plan (SCP), to a significantly larger WP emplaced horizontally in the drift. For a postclosure TSPA, this change has required inclusion of analyses concerning

- Drift stability with time
- Performance effects of backfill, pedestals, and invert materials
- Amount and location of seepage into the drift
- Lifetime of alternative container materials
- The possibility of single or common mode failures of multiple WPs due to circumstances in the drift.

Another large change in the design has been establishment of a high temperature region, utilizing the thermal output of the large WPs. In an attempt to form a long-lived "dry-out zone" from the heat of the packages, and thus to extend package lifetimes by curtailing corrosion from inflowing groundwater, areal power densities of up to 114 kW/acre have been studied. The change to higher thermal load and larger WPs, as well as other design changes related to use of concrete drift liners, drip shields, etc., have all required accommodation by the TSPA models.

Changes in regulatory guidelines have also resulted in major changes in the TSPA modeling activities. For instance, TSPA analyses that assessed the release of gaseous C-14 against the guidelines in 10 CFR Part 60 and 10 CFR Part 960 showed that this process provided the major contribution to the TSPA results when expressed in terms of cumulative releases over 10,000 years. However, the upper limit on releases of C-14 in these standards are far below annual release limits established by the Clean Air Act. If the new regulations, when repromulgated, are consistent with the Clean Air Act, C-14 is no longer expected to contribute significantly to the TSPA results. Another major change in TSPA models has resulted from the possibility of conversion to a dose standard, resulting in increased significance of the saturated-zone flow. The analyses presented here were predicated on the assumption that the Yucca Mountain repository system would be regulated using a dose-based standard. When the performance standard only addressed cumulative release, details of saturated-zone flow (e.g., dispersion, dilution) were relatively unimportant. Under a dose standard however, radionuclide transport through the saturated zone is very important. Thus, TSPA models and analyses have changed to reflect these and other changes required by the dose standard that is expected to be promulgated by the EPA in response to the Energy Policy Act of 1992. Table 1-2 contains a synopsis of the various features in each of the YMP TSPAs (including the TSPA-VA) to allow

for comparison. This table generally shows an increase in sophistication in the model representation, however, this is not universally true.

1.3.1 Precursors to Recent YMP TSPA Modeling Activities

One early study of the Yucca Mountain repository system utilized deterministic calculations of radionuclide release from the system using a one-dimensional transport code (Sinnock et al. 1984). This study also included some additional analyses to estimate the importance of the effects of dimensionality, particularly in terms of lateral diversion of unsaturated flow. This study considered primarily "nominal conditions", based on the then current site knowledge. However, it also assessed the effects of increasing groundwater flux up to 20 mm/yr and of decreasing radionuclide retardation (due to interaction with the rock minerals) to zero. The releases calculated along the groundwater pathways under nominal conditions were more than seven orders of magnitude below the EPA release limits. Uncertainties were not explicitly included in the TSPA, nor were gaseous releases. The authors recognized that both incorporation of fast-path flow and changes in the assumptions about fracture-matrix interactions, as well as different treatment of geochemical retardation and of the source term could have major implications in terms of meeting the standard then applicable (EPA 1985). No disruptive processes or events were included in this calculation. Analyses performed for the Environmental Assessment (DOE 1986) evaluating the postclosure system guideline also concluded that releases, even over a period of 100,000 years, would not exceed the EPA's 10,000 year release guideline. However, it was recognized that a great deal of uncertainty remained in the representation of the groundwater flow system and in the performance of the engineered system in oxidizing conditions in the unsaturated-zone.

A number of subsystem analyses were performed in the subsequent years, including initial assessment of disturbances such as volcanism and human intrusion (Sinnock 1989; Doctor et al. 1992), WP lifetime (Farmer and McCright 1989), and performance of spent fuel (Apted et al. 1989). However, the predecessors to the current set of iterative PA were the PACE-90 conducted in 1989 and 1990 (Barnard and Dockery 1991) and the initial total systems analyses (Doctor et al. 1992, reporting 1988 work). PACE-90 was defined to simulate nominal-case groundwater flow and transport over a modeling period of 100,000 years. Deterministic analyses were run in both one- and two- dimensions. Four radionuclides were used to represent classes of behavior of long-lived nuclides present in the inventory (Np-237, Tc-99, I-129, and Cs-135). Percolation flux through the repository horizon was set at 0.01 mm/yr. Waste was mobilized from two major water-contact modes: "wet-drip" and "moist-continuous." The nuclides then traveled through a 19-layer hydrostratigraphy with laterally homogeneous properties that was developed from limited information from four boreholes. There were no calculated releases to the water table during the specified time period; therefore, movement in the saturated zone was not included. Also, gaseous releases, thermal effects, and disturbed scenarios were not included.

1.3.2 TSPA-91

The first in the "comprehensive" TSPA studies conducted by YMP was TSPA-1991 (Barnard et al. 1992; Eslinger et al. 1993) constructed using PACE-90 as a basis. Its objective was to develop a framework for probabilistic total-system calculations and it was the first set of stochastic analyses for YMP. The analyses were run in one- and two-dimensions using

distributions of hydrogeologic parameters based on site and analog data. Two conceptual models for UZ flow were analyzed: composite porosity that represented fracture-matrix equilibrium, and the "weeps" model that assumed flow occurred exclusively in the fractures. The calculations also included disturbances to the nominal system caused by basaltic volcanism, human intrusion, and climate change. The radionuclide inventory was expanded to include those nuclides prevalent in the inventory (Pu, U, and Am isotopes), those expected to be important to dose (Se-79, Sn-126), and C-14 to represent the gaseous component. Radionuclide transport from the WP also included some near-field interactions. The saturated zone was also included explicitly and modeled out to the accessible-environment (5 kilometers). A simple drinking water dose was calculated, in addition to the cumulative releases.

No attempt was made to evaluate regulatory compliance. Qualitatively, however, comparisons were made with the EPA standard and NRC technical criteria. Results for TSPA-91 suggested that aqueous releases for both the weeps and composite porosity models and gaseous release using the weeps model did not exceed the EPA standard's (EPA 1985) cumulative release limits. Gaseous release, calculated with the composite porosity model, did exceed these limits. However, it was anticipated that a more realistic Engineered Barrier System (EBS) model for WP and waste form failure (i.e., taking credit for gradual degradation of these engineered components) would reduce these releases to below the EPA limit. Releases due to human intrusion and to volcanism were also both well below these regulatory limits.

1.3.3 TSPA-93

The primary purpose of TSPA-1993 (Wilson et al. 1994; Andrews et al. 1994) was to provide feedback concerning the relative importance of specific site-characterization and design information. Its secondary goal was to make progress in developing more defensible TSPA models for use in a demonstration of compliance.

There were a number of enhancements and revisions of the TSPA-1991 models and information including:

- A more geohydrologically representative model of the repository
- A 3-D geostatistically correlated stratigraphy
- An expanded hydrologic data set, explicit inclusion of wetter future climates
- Discrete modeling of individual stratigraphic units in the saturated zone
- Modification of retardation and sorption parameters
- Introduction of thermal dependence, spatial and temporal variation in fracture apertures (in the Weeps model)
- Inclusion of waste-package failure modes due to corrosion and dry oxidation
- Updated waste-form dissolution and oxidation models

- Analysis of both the SCP containers and the multi-purpose canisters, and inclusion of spent fuel and vitrified waste.

The analyses investigated sensitivities using both cumulative releases and dose results for up to 1,000,000 years. Percolation flux was the single most sensitive parameter. Again, as in TSPA-1991, all releases were below the EPA's 1985 standard, except for gaseous C-14 releases. However, longer-term (>100,000 years) peak doses for drinking water pathways were shown to be significantly above background. These analyses were being performed prior to the remanded EPA 1985 standard (i.e., 40 CFR Part 191), and were not designed to evaluate regulatory compliance with a dose or risk-based standard.

1.3.4 TSPA-95

The objectives of TSPA-1995 (M&O 1995) were primarily to enhance the representation of the engineered system, although some improvements of the natural system models were also incorporated. Specific changes to TSPA-1995 models included:

- Inclusion of a drift-scale thermohydrologic environment to derive relative humidity and temperature information adjacent to the WP
- A more detailed waste-package-degradation model, including corrosion of both inner and outer waste-package layers and galvanic protection of the inner layer
- Calculation of releases both with and without backfill
- Modification of solubility and retardation values for radionuclide transport
- Consideration of two alternative ranges of percolation flux (high flux: 0.5– 2.0 mm/yr; low flux: 0.01–0.05 mm/yr).

Disruptive events and gaseous releases were not included in TSPA-1995. A simple climate-change model was also incorporated into the analyses. The time period for the calculation of release and dose was up to 1,000,000 years.

TSPA-1995 also reported percolation flux to be the single most important factor to performance of a Yucca Mountain repository in the context of a 10,000-year standard. However, many elements of the EBS also were key to performance, as shown through sensitivity analyses such as galvanic protection, varying thermal load and backfill configurations, and assumptions about radionuclide transport through the EBS. As in TSPA-1993, sensitivities were calculated in terms of system-level performance measures (such as dose and cumulative release), and no attempt was made at evaluating regulatory compliance with a dose or risk-based standard.

1.3.5 Other Recent Yucca Mountain TSPAs

A number of other organizations have performed TSPAs for Yucca Mountain in the past several years. The most recent iterations include TSPAs run by the NRC (NUREG-1464) and by the Electric Power Research Institute (Kessler and McGuire 1996). A TSPA was also conducted by

Sandia National Laboratories (Rechard 1995) on a hypothetical "Yucca Mountain-like" tuff site. The suite of scenarios analyzed by each of these groups was essentially the same as those used in the YMP TSPAs. In each case, assumptions about conceptual models and parameter distributions differed somewhat from those used in the YMP TSPAs. However, the conclusions reached about the importance of particular processes and parameters (with the possible exception of basaltic volcanism in the case of the NRC analysis) with respect to performance of the repository system were very similar to those determined by the various YMP TSPA analyses.

1.4 SUMMARY DESCRIPTION OF TSPA-VA REFERENCE DESIGN

The base case repository design (i.e., underground facility a, WP, and thermal loading) used for TSPA-VA analyses is described in this section. The basis for the base case design is presented in this section. It is also described in detail in Volume 2 of the VA (DOE 1998). Design options analyses are included in Volume 3 of the VA (DOE 1998). Much of the text that follows was extracted from CRWMS M&O (1997). The design has been formulated with the intention of enhancing system performance with respect to the attributes of the repository safety strategy including (1) limited water contacting WPs, (2) long WP lifetime (containment), (3) low rate of release of radionuclides (mobilization) from breached WPs, and (4) radionuclide concentration reduction during transport from the WPs. The design strategy seeks to use engineered components to tailor the environmental variables (i.e., temperature, relative humidity, seepage flux) to be as benign as possible.

A schematic of the base case design at the time of repository closure is presented in Figure 1-1. In general, the major components of the base case design include a high areal mass load (AML) (85 MTU/acre), with "point loading" of the WPs. Figure 1-1 shows the repository layout design that covers ~740 acres and a schematic of the WP layout in the drift. The EBS will include a drift liner (concrete), an initial air gap in the drift (no backfill), two-layer WP (10 cm corrosion allowance material [CAM] and 2 cm corrosion resistant material [CRM]), in-drift emplacement of the WPs, placement of the WPs on steel support system, and a concrete invert at the base of the drift. Figure 1-2 shows representative WPs and waste forms for the reference design. The following discussion provides more detail as to the basis for each of these design components.

Drift Liner (Normal Concrete) - A drift liner (10 cm thick) has been included in the design, primarily in support of pre-closure safety. While it is intact, the liner is a potential barrier to water seeping into the drift. An intact liner could allow the water that might otherwise seep into the drift to drain along the perimeter of the drift in the small space between the liner and the host rock, or to flow as a film directly along the inside surface of the liner. Both of these modes of flow could reduce or eliminate dripping directly onto the WP. Normal concrete is used in the current reference design for lining 9 out of 10 drifts, with steel liner in the other drifts.

Air Gap (Capillary Barrier) - The air gap between the liner or drift wall and the WPs provides a means by which the percolating water may be diverted around the opening as matrix or film flow. This advantageous property will be in effect until the drift collapses and fills with rubble.

Waste Package—Corrosion Allowance Material - Because the WP is the single component that is expected to have absolute containment at the time of emplacement, the design strategy is to make the WP robust. The outer layer of the WP is 10 cm thick and serves three functions.

First, it provides structural strength to resist falling rock, to support the internal components, to be supported by the steel support systems, and to allow handling without damage. Second, the CAM provides radiation shielding to reduce the WP exterior surface contact dose rate. Coupled with the transportation overpack, the shielding is expected to be sufficient to protect workers during handling. Third, the CAM, in conjunction with the inner layer described below, acts as a containment barrier for the radioactive waste inside the WP. The current CAM material in the design is a carbon steel, Alloy A516.

Waste Package—Corrosion Resistant Material - The inner layer of the WP is a nickel-based alloy that is very resistant to aqueous corrosion and almost completely resistant to humid-air corrosion. The current reference CRM is 2 cm of Alloy 22. Because the CRM is inside the CAM, the corrosion environment can be much different than that induced by the ambient seeping water (potentially higher pH and crevice corrosion), thus requiring a more corrosion-resistant material than the outer barrier.

Large Waste Packages - A large WP reduces cost, handling, closure operations, non-destructive evaluation operations, and allows efficient use of the drift length. The current large WP reference design is based on a 21 PWR Spent Nuclear Fuel (SNF) Assembly WP. Roughly the same size WP can also accommodate 44 of the smaller Boiling Water Reactor SNF Assemblies or five Defense High-Level Waste glass "logs" surrounding a central canister of DOE SNF. For high heat producing or high criticality potential assemblies, a smaller WP, for 12 PWR SNF Assemblies, is used.

In-Drift Emplacement of Waste Packages - The design calls for in-drift emplacement. This is a consequence of large WPs being well suited to in-drift emplacement; consequently, the amount of excavation is minimized. Non-drift emplacement would require additional excavation.

Invert - The invert is designed to provide support for the WP pedestals during the pre-closure period. It will be composed of normal concrete.

Steel Support System for Waste Packages - The carbon steel support system provides support for the WPs during the pre-closure period. The support systems will be installed at a pre-determined spacing such that each WP is guaranteed to have at least three support systems under it, independent of WP spacing. Because the support system thickness is less than the CAM, it is expected that the support system will degrade prior to complete degradation of the CAM.

Thermal Design—Areal Mass Load (High) - The AML for the base case is 85 MTU/acre. This was determined by consideration of cost, expectation of water driven away during the high temperature period, and preservation of the zeolites below the repository. Clearly, if performance were independent of AML, it would be most cost effective to load the waste as densely as possible (high AML). Thus, the goal is to load the repository at as high an AML as feasible for acceptable performance, in order to minimize cost. In May 1995, the Office of Civilian Radioactive Waste Management Director decided to focus on a reference AML range of 80–100 MTU/acre, while maintaining the flexibility to use alternate AMLs should performance calculations find the reference range to be unacceptable. The current reference design AML is set by the temperature maximum which won't degrade the zeolites below the repository, which are a class of minerals that can potentially retard radionuclide transport.

Thermal Design—Waste Package Spacing (Point) - Once an AML is determined, the repository design team has the option to either place closely spaced WPs in widely spaced drifts or to place the WPs farther from each other in drifts that are more closely spaced. The latter option is termed "point loading" because each WP acts relatively independently of its neighbors in shedding its heat (this independence is strongest at very early times, before the rock between the WPs becomes hot). There is a large range of combinations of WP spacing and drift spacing that meets this definition of "point." The current reference design has a drift spacing of 28 m, which was determined by setting a limit of 200°C on the drift wall temperature.

Thermal Design—SNF Assembly Blending—To Meet 18 kW Limit - Each SNF assembly has a specific set of characteristics: enrichment, burnup, and age. These characteristics determine the amount of thermal power each assembly produces. A limit of 18 kW has been set for the thermal power produced by the collection of assemblies in a WPs to prevent heating the cladding beyond 350°C, which could cause the cladding to split. For the 18 kW "Design Basis" WP at a drift spacing of 28 m, enough aluminum is used in the basket design to ensure the cladding does not exceed the temperature limit. SNF assemblies will be packaged appropriately to meet the thermal power limit of 18 kW.

Thermal Design—SNF Assembly Blending—To Meet Criticality Limit - Each SNF assembly also has a specific potential to contribute to nuclear criticality, again based on enrichment, burnup, and age. This potential is quantified by the criticality constant in an infinite lattice, "k." Based on the finite number of assemblies in the WP and the overall effective criticality constant constraint, $k_{eff} < 0.95$, limits have been set for assembly values of k . SNF assemblies will be packaged to meet the limit.

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Chapter 1
Figures

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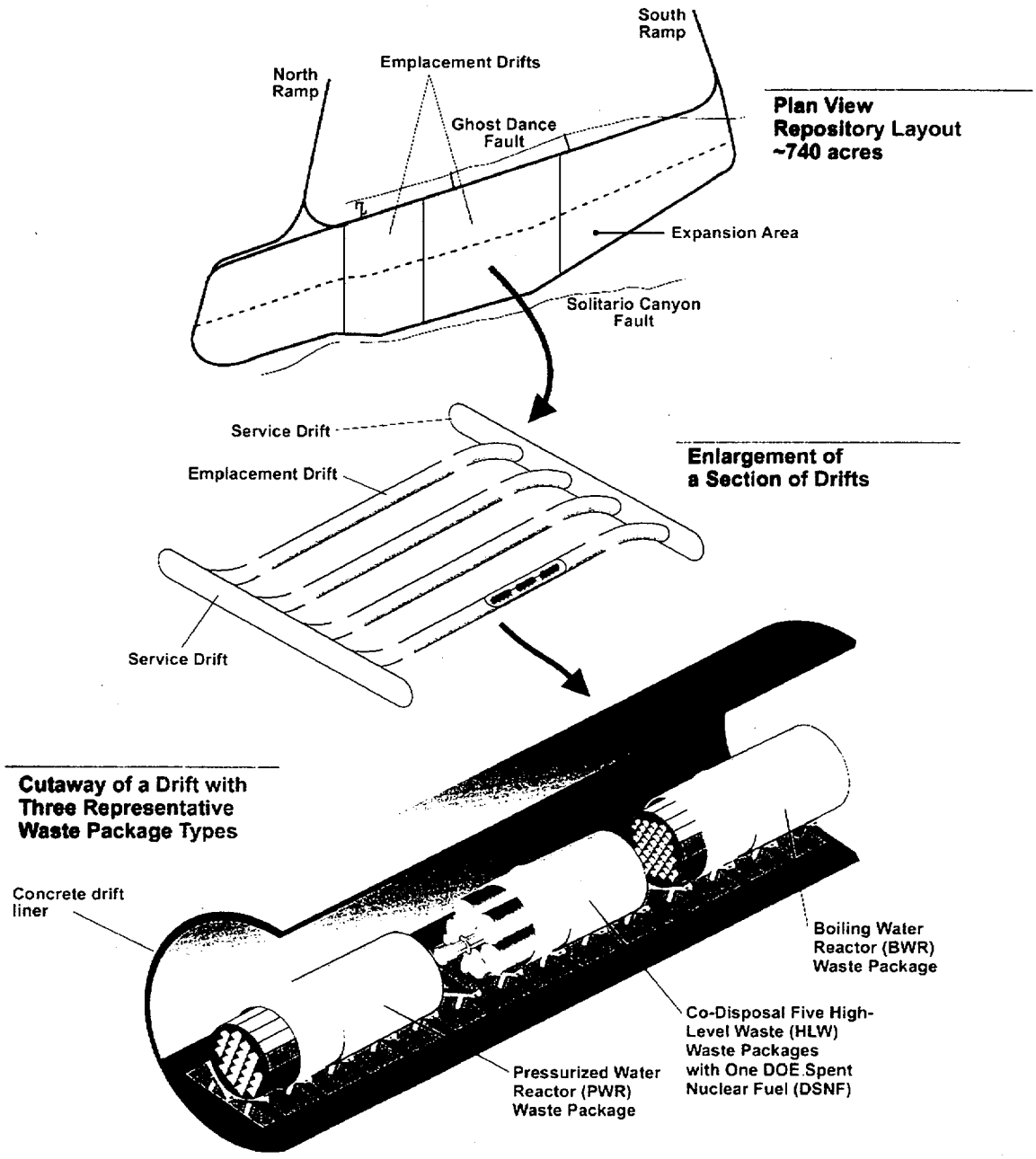

Figure 1-1. Schematic of the Reference Repository and Engineered Barrier System Designs used in the TSPA-VA. This figure illustrates the general drift layout within Yucca Mountain to contain the 70,000 metric tons of waste. Also illustrated is the emplacement of the waste packages on support system placed on the drift inverts.

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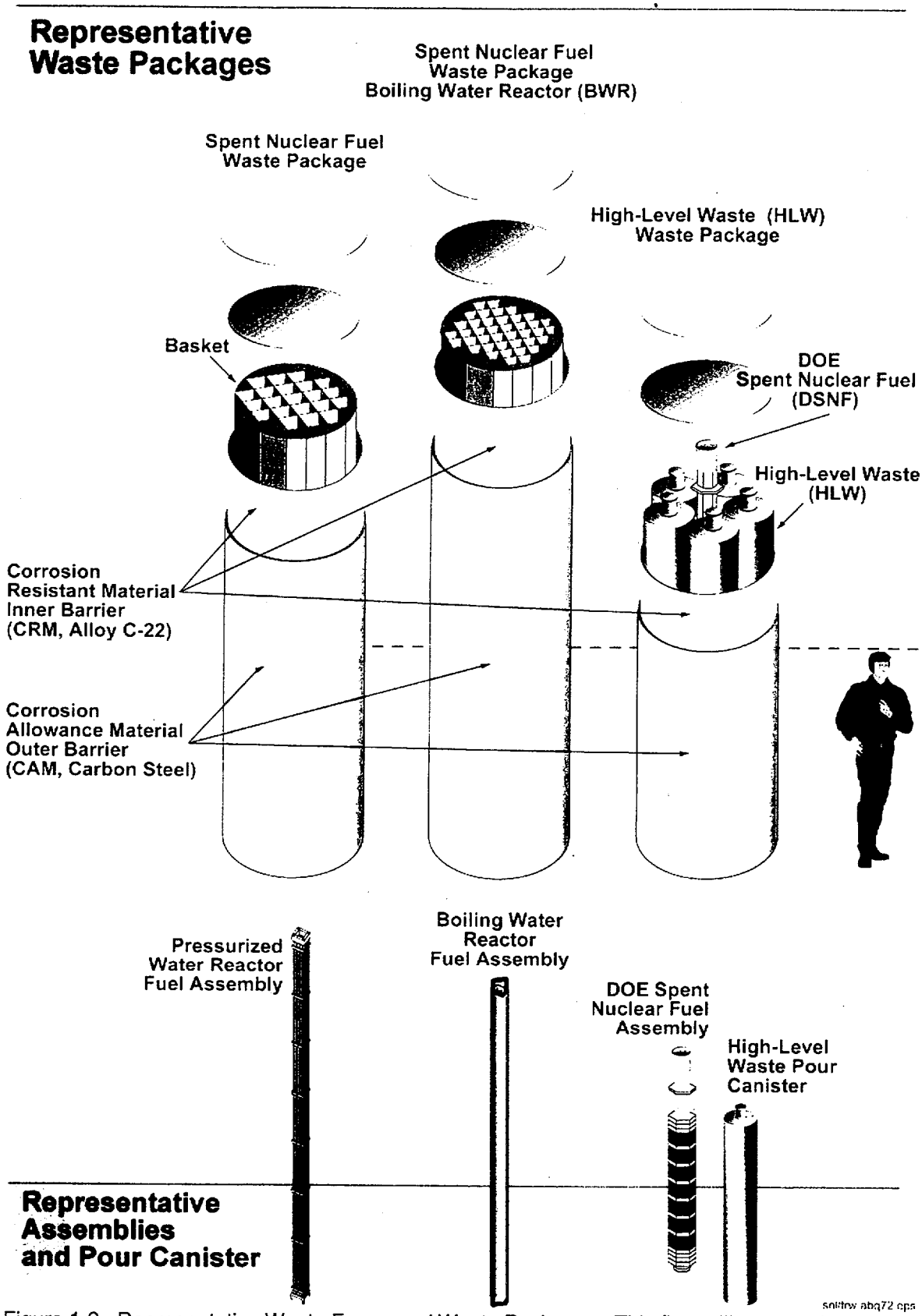

Figure 1-2. Representative Waste Forms and Waste Packages. This figure illustrates the three major waste form types: commercial spent nuclear fuel (CSNF), [existing as either Pressurized Water Reactor (PWR) fuel or Boiling Water Reactor (BWR) fuel], high level waste (HLW), or DOE-owned spent nuclear fuel (DSNF).

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Chapter 1
Tables

Table 1-1. Correlation of location of specific information in the TSPA in Volume 3 of the V-A Technical Basis Document.

Information	Location in Viability Assessment-Volume 3	Location in Technical Basis Document
Definition and Uses of TSPA	Sections 1.1-1.2	Chapter 1.2
Evolution of YMP TSPA	NA	Chapter 1.3
Description of Reference Design	Section 4.1	Chapter 1.4
Definition of TSPA-VA Base Case	Section 4.1	Chapter 11.1
Unsaturated-Zone Hydrology Model	Section 3.1	Chapter 2
Thermal Hydrology Model	Section 3.2	Chapter 3
Near-Field Geochemical Environment Model	Section 3.3	Chapter 4
Waste Package Degradation Model	Section 3.4	Chapter 5
Waste Form Degradation and Mobilization and EBS Transport Model	Section 3.5	Chapter 6
Unsaturated Zone Transport Model	Section 3.6	Chapter 7
Saturated Zone Flow and Transport Model	Section 3.7	Chapter 8
Biosphere Model	Section 3.8	Chapter 9
Disruptive Events Models	Section 4.4	Chapter 10
Effects of Design Options	Section 4.5	NA
TSPA-VA Methodology	Section 2.3	Chapter 11.1-11.2
Deterministic TSPA-VA Results	Section 4.2	Chapter 11.4
Probabilistic TSPA-VA Results	Section 4.3	Chapter 11.4
Uncertainty/Sensitivity Analyses	Section 5	NA
Uncertainty/Sensitivity Analysis Methods	Section 2.3.3	Chapter 11.3
TSPA-VA Conclusions	Section 6.4	NA
TSPA Model Development for the LA	Section 6.5	Chapter 11.5
Base Case Parameter Distribution	NA	Appendix A

Table 1-2. Analysis Approach to Selected Previous TSPA Evaluations.

Feature	Sinnock et. al. 1984	Pace-90	TSPA-91	TSPA-93	TSPA-95	TSPA-VA
Infiltration	Up to 20 mm/yr	Min: .01 mm/yr Max: 0.5 mm/yr	0 - 39 mm/yr	dry: 0.5 mm/yr mean wet: 10 mm/yr mean	lo: 0.01-0.05 mm/yr hi: 0.5-2.0 mm/yr	dry: 7.7 mm/yr mean LTA: 42 mm/yr mean SP: 110 mm/yr mean
Number of Radionuclides	17	4	10	43 (direct) 8 (aqueous)	39	9
Time Period of evaluation	up to100,000 yrs	up to 100,000 yrs	up to 100,000 yrs	up to 1,000,000 yrs	up to 1,000,000 yrs	up to 1,000,000 yrs
Waste Forms	CSNF	CSNF	CSNF	CSNF and HLW	CSNF and HLW	CSNF, HLW, DSNF
Distance to AE	5 km	n/a	5 km	5 km	5 km 30 km	20 km
Saturated Zone	yes	n/a	single composite medium	multiple layers	single composite medium	effective continuum, 1-D, six stream tubes
Stratigraphic Discretization in UZ	n/a	19 layers	5 layers	10 layers	5 layers	28 layers
UZ flow model	1-D, matrix	1-,2-D 5 codes	1-,2-D; ECM and Weeps	1-,2-D; ECM and Weeps	2-D; ECM	3-D; DKM
Release Model	n/a	2 water contact modes	simple failure distribution for WP	simple failure distribution for WP	3 alternative conceptual models in EBS	diffusive, advective release from dripping and no dripping zones
^{14}C gaseous release	no	no	2-D steady state	2-D transient	no	no
Thermal effects	no	no	no	dry-out zone	dry-out zone	mountain and drift scale T-H
Disruptive Events	no	no	volcanism, human intrusion	volcanism, human intrusion	no	volcanism seismicity, human intrusion, nuclear criticality
Fracture Flow	no	in ECM	ECM, weeps	ECM, weeps	yes	DKM
Dose	no	no	no	Drinking water and irrigation	Drinking water	3 receptor scenarios, all pathways
Climate Change	through range of fluxes	no	through range of fluxes	100,000-year random periods	100,000-year random periods	3 climate cycles: Dry, LTA, SP

Table 1-2. (continued).

Feature	Sinnock et. al. 1984	Pace-90	TSPA-91	TSPA-93	TSPA-95	TSPA-VA
Galvanic Protection	no	no	no	no	yes	no
Uncertainty	through range of analysis parameters	no	in pdf's and flow models	in pdf's and flow models	in pdf's and flow models	in pdf's and flow models
Near field Geochemistry	no	no	no	no	no	limited

AE = Accessible Environment

LTA = Long Term Average Climate

SP = Super-Pluvial Climate

CSNF = Commercial Spent Nuclear Fuel

DSNF = Defense Spent Nuclear Fuel

HLW = High-level Waste

ECM = Equivalent Continuum Model

Weeps = Unsaturated flow model assumes stochastic flowing fractures

DKM = Dual-Permeability Model

WP = Waste Package

EBS = Engineered Barrier System

T-H = Thermal Hydrology

pdf = Probability Distribution Function