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11. Remarks

ANL-WIS-PA-000004 REV 00 was issued as TDR-WIS-PA-000011 REV 00. Because the report contains calculations and because the work was done under AP-SIII.9Q and not under AP-3.11Q, a new document identifier was issued for this document. Also, after the release of TDR-WIS-PA-000011 REV 00, two Technical Errors, see TER-03-0001, were discovered in the model formulation used to perform the analyses contained in the report. The model formulation was corrected, the analyses were redone, and the results used to update the report. Non-substantive editorial changes are also included. Per AP-SIII.9Q, Sects. 1.0 and 1.1 were renamed and Section 8 of TDR-WIS-PA-000011 REV 00 became Sect. 7.15 of ANL-WIS-PA-000004 REV 00. The supporting data analysis were submitted to the Yucca Mountain Project Technical Data Management System and the Data Tracking Number is in the Inputs and References Section. Because these data are not Quality Affecting and do not have any impact on the Yucca Mountain Project License Application or the Total System Performance Assessment being performed for the License Application, a formal review under AP-2.14Q was deemed unnecessary. For similar reasons, change bars are not included in ANL-WIS-PA-000004 REV 00.

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Revision History

12. Revision/ICN No.	13. Description of Revision/Change
TDR-WIS-PA-000011 REV 00	Initial Issue transmitted to Department of Energy under a cover letter with the Analysis Report as an attachment.
ANL-WIS-PA-000004 REV 00	Initial Issue of Revision to TDR-WIS-PA-000011. The original model formulation used to develop the data and graphical plots for the initial issue were found to have technical errors (TER-03-001). Therefore, all model simulations were redone and the results included in ANL-WIS-PA-000004 REV 00. This document contains revised tabulated data and text references to that data based on the output of the corrected analysis model. In addition, all graphical plots of the data developed in the model simulations were replaced. Also, Sections 1.0 and 1.1 were renamed and Section 7.15, Summary of Results, containing Section 8.0 of TDR-WIS-PA-000011 was added to Section 7.0. Nonsubstantive text edits were also included in this issue. Lastly, Case 8 was re-classified as a Natural-System Barrier changing Figures 6-3 and 6-4.

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1. PURPOSE

1.1 INTRODUCTION

This report presents the results of analyses of the hypothetical performance of the various configurations of selected natural and engineered elements of the proposed Yucca Mountain nuclear-waste repository. These analyses were conducted upon the recommendation of the Nuclear Waste Technical Review Board (NWTRB) regarding an alternative approach to investigate the identified natural and engineered barriers and associated processes with respect to the postclosure performance of the proposed Yucca Mountain repository.

The analyses were conducted per Technical Work Plan (TWP) TWP-MGR-PA-000011 REV 00, Section 3.2.4, Task 2, which states that the task involves "Identification of barriers that are important to repository performance:" by means of "one-on" analyses to gain a better understanding of repository performance relative to previously identified barriers." The "One-on Analysis" was performed per Administrative Procedure AP-SIII.9Q.

The NWTRB previously reviewed similar analyses conducted by Electric Power Research Institute (EPRI) (EPRI 2002 [158069]). The approach of the investigation was to simulate the hypothetical performance of the repository after an arbitrarily chosen successive addition of each of the selected natural and engineered barrier components and associated processes that provide for the overall safety of the repository. Because the repository system will behave as an integrated system, the combined interaction of all the processes and barriers identified in this report will provide the ultimate repository performance as indicated in various performance-assessment analyses for the Civilian Radioactive Waste Management System (CRWMS) M&O 2000 [153246]; Bechtel SAIC Company, LLC (BSC) 2001 [155950]; and Williams 2001 [157307]). The analyses presented in this report should not be construed as an indication, for the chosen additive sequence, of the relative importance on any one barrier or process. Rather, the results of these analyses provide an indication of the relative performance of those barriers and processes and an understanding of their contribution to the overall performance of the proposed repository system. The analyses in this report considered the nominal-performance scenario only, and did not address performance following unlikely disruptive events (e.g., volcanic activity) (10 Code of Federal Regulations (CFR) 63.342).

1.2 SCOPE

These "One-on" Analyses were stylized analyses in the sense that the modeled sequence of the various barriers and associated processes was a hypothetical construct designed to facilitate the analysis of the potential influence of those barriers and associated processes. The sequence of stylized analyses should not be construed to be representations of the actual system of features and processes contained in the Total System Performance Assessment for the Site Recommendation (TSPA-SR) and the Total System Performance Assessment-Final Environmental Impact Statement (TSPA-FEIS) performance-assessment model. Rather, the stylized sequence for these analyses was hypothetical and was chosen to emphasize the potential contributions of the natural and engineered systems and processes to overall repository performance. These analyses were different than previous "One-off" sensitivity analyses that investigated a selective "turning off" of certain model features and processes to determine their

relative contributions to repository performance. The analyses in this report start with bare waste and analyze performance after the addition of the natural and engineered barriers and associated processes in an attempt to assess their influence on to overall repository performance. In that sense, these analyses are called "One-on" analyses.

The progress of the investigation involved testing of the analysis model outside of the previous modes of analysis, turning model features on and off, and directly connecting model elements that were previously integrated. The process of the investigation was designed to view the influence of barriers related to the waste form, natural processes, and engineered systems as described below in Section 6.3.

For these analyses, a "barrier" was understood to be in the context of the Nuclear Regulatory Commission (NRC) final rule at 10 CFR 63.2 [156605] or "Barrier means any material, structure, or feature that, for a period to be determined by the NRC, prevents or substantially reduces the rate of movement of water or radionuclides from the Yucca Mountain repository to the accessible environment, or prevents the release or substantially reduces the release rate of radionuclides from the waste". Barriers evaluated in this report are consistent with those identified for the Yucca Mountain Site Recommendation in the Yucca Mountain Science and Engineering Report U.S. Department of Energy (DOE) 2001 [155943] Section 4.5.1, p. 4-519 as follows:

4.5.1 Identification and Description of Barriers

The barriers important to waste isolation at Yucca Mountain may be broadly categorized as natural barriers (associated with the geologic and hydrologic setting) and engineered barriers. The engineered barriers complement the natural barriers by prolonging the containment of radionuclides within the repository and limiting their eventual release.

The natural barriers consist of the following:

- *Surficial soils and topography, which limit water infiltration*
- *Unsaturated rock layers above the repository horizon, which limit water flux into repository drifts*
- *Unsaturated rock layers below the repository horizon, which limit radionuclide transport*
- *Volcanic tuffs and alluvial deposits below the water table, which limit radionuclide transport in the saturated zone.*

The engineered barriers consist of the following:

- *A drip shield, which limits the water contacting the waste package and the water available for advective transport through the waste package and invert*
- *A waste package, which limits the water contacting the waste form*

- *Cladding, which limits the water contacting the commercial spent nuclear fuel portion of the waste*
- *A waste form that limits the rate of release of radionuclides to the water that contacts the waste*
- *A drift invert, which limits the rate of release of radionuclides to the natural barriers.*

However, in this report, the waste-form barrier has been separated into two components (degradation rates and concentration limits) to provide a better understanding of the relative contributions of the different processes included in the waste-form barrier. Identification of barriers and the analyses documented here are not presented in the context of the NRC's requirements at 10 CFR 63.115 regarding multiple barriers, a subject that will be addressed in documentation supporting a license application. The performance measure of these analyses was the mean annual dose to the reasonably maximally exposed individual (RMEI) calculated after the stylized addition of each successive barrier and/or process.

The most recent performance-assessment analyses (Williams 2001 [156743] and 157307]) indicate general conformance with final rules of both the Environmental Protection Agency (EPA) (40 CFR Part 197 [155238]) and the NRC (10 CFR Part 63 [156605]). However, it is also important to identify the potential influence of each natural and engineered barrier in reducing exposure to the RMEI. These analyses utilize the most recent performance-assessment model, i.e. the TSPA-FEIS model, and assess the role of each barrier and/or associated process with respect to total system performance. The barriers were analyzed sequentially and the results provide calculations of mean annual dose from radionuclides that could potentially be released from the repository, and the sum of the doses from all the released radionuclides modeled, i.e. the total mean annual dose, which provides an indication of the contribution of that barrier.

The analysis of the roles of the natural and engineered barriers and associated processes considered in this report for their roles in the performance of the proposed Yucca Mountain repository can be conducted in a variety of hypothetical, stylized sequences. The EPRI report "Evaluation of the Proposed High-Level Radioactive Waste Repository at Yucca Mountain Using Total System Performance Assessment" (EPRI 2002 [158069], Section 10.2, p. 10-15 to 10-67]) describes several different sequences of applying natural and engineered barriers in analyzing barrier contributions to performance assessment. That analysis indicated that the order of the analysis appears to demonstrate a greater or lesser contribution of individual barriers depending on the model sequence of the application of the barriers to the performance assessment. No matter what sequence was chosen, the magnitude of the sum total contribution of all the barriers, i.e. the total-system performance model, was the same regardless of the sequence. That is, the total dose reduction was the same regardless of the sequence, although the different sequences demonstrated that the order of analysis can mask the relative influence of the different barriers and/or processes.

For this report, the "One-on" analysis was conducted by "adding on" barriers one by one in order to estimate the successive performance-assessment influence as each barrier was added to the repository system. The stylized sequence chosen was to consider first the processes and barriers associated with waste-form degradation, then add the natural barriers, and finally add the engineered barriers. The hypothetical order of the analysis of the natural and engineered systems

was conducted in a sequence designed to approximately follow the flow of water through the “natural system”, followed by the addition of engineered barriers as they enhance the performance of the repository system. The idea was to mobilize the radionuclides from the waste form, then assess the role of the natural environment, and then determine the effect of the addition of engineered systems that serve to protect and isolate the waste form from the natural system. For previous TSPA investigations, the TSPA-FEIS model configuration served to protect the waste form from the natural system until the engineered systems degraded. However, if the “One-on” analysis started with the engineered system, the effect of the natural barriers on flow and transport would be masked and obscured. Because the EPRI analysis (EPRI 2002 [158069], Section 10.2, p. 10-15 to 10-67)) indicates that some barriers/processes may mask one another’s performance depending on the order of analysis, this report adds an additional analysis designed to examine the potential masking effects of the unsaturated and saturated zones relative to one another.

2. QUALITY ASSURANCE

A Technical Work Plan and Activity Evaluation (Graves and Sevougian 2002 [159174]) was developed, issued, and used in the preparation of this document. The activity evaluation determined that these “One-on” analyses serve to support management decision-making, and are therefore not required to be subject to quality assurance requirements (Graves and Sevougian 2002 [159174], Attachment, p. 4). This report will not produce either qualified or baseline outputs. However, to ensure complete traceability of these analyses, the software was obtained from Software Configuration Management (SCM) as prescribed in AP-SI.1Q, and the files, data, and parameters were carefully controlled and documented in the same manner as prescribed in AP-SIII.9Q. The results of the analyses were submitted for archival retrieval to the Technical Data Management System (TDMS). Each of the analyses was prepared by a qualified originator and documented in sufficient detail that they could be verified without recourse to the originator. In addition, each analysis was conducted using a controlled version of the TSPA-FEIS model and all changes applied to the TSPA-FEIS model were implemented in a controlled manner and fully documented in a manner similar to that described in AP-SIII.10Q, REV 0, ICN 2. The analyses and their documentation and the checking of the output of the analyses were documented and controlled in the same manner as performed under AP-SIII.9Q and the analysis results, including the model file, were submitted to the Technical Data Management System (TDMS) as described in AP-SIII.3Q, REV 01, ICN 02. If needed for future baseline analyses, the outputs prepared for this report will be revisited and developed in a qualified technical product using qualified software and will be submitted to the TDMS also.

A qualified checker different from the originator reviewed the analyses and the analysis document. The analyses were checked for correctness and accuracy and the results of that checking exercise were fully documented and the results submitted to the Yucca Mountain Project's Technical Data Management System (TDMS). The supporting documentation for this submittal to the TDMS includes the model file, the input files for the associated dynamic-link libraries, descriptions of each analysis, a checklist documenting the changes from the master TSPA-FEIS model, and a flow chart showing the relationship between the “One-on” Analyses and the base cases for those analyses.

3. USE OF SOFTWARE

The studies were performed using GoldSim Version 7.17.200 (BSC 2001[155182]). This numerical code is the same as that used for the FY01 Supplemental Science and Performance Analyses (SSPA) (BSC 2001 [154659]), the Letter Report in support of the final EPA regulations (Williams 2001 [157307]), and the Letter Report in support of the final NRC regulations (Williams 2001 [156743]). The documentation for this report, including the detailed description of the model variations, records of model checking, and input and output files are stored in the Technical Data Management System with the Data Tracking Number MO0211MWDTS11.014 (BSC 2002 [160680]).

The GoldSim software (BSC 2001 [155182]) was developed by Golder Associates as an update to the baseline software, RIP v.5.19.01 (Golder Associates, 1999 [151395]). GoldSim is designed so that probabilistic simulations can be conducted and represented graphically. GoldSim fulfills the specific functional requirements for Total System Performance Assessment (TSPA) analyses. Although not currently qualified in accordance with AP-SI.1Q, *Software Management*, GoldSim Version 7.17.200 (STN: 10344-7.17.200-00 [155182]) was used for this application and used within an acceptable specified range. The software was obtained from Software Configuration Management and is considered appropriate for the analyses in this report.

The nominal multi-realization TSPA simulations were performed at the Performance Assessment Department, 1180 Town Center Drive, Building 3, Las Vegas, Nevada) on Dell Precision 620 Workstations with Dual Pentium III Xeon Processors, Dell PowerEdge 2200 Workstation with Dual Pentium Processors, and Dell PowerEdge 6350 and 6450 Servers with Pentium III Xeon and Pentium II Xeon Quad Processors. The hardware was operated under Windows NT 4.0 Operating System.

4. INPUTS

4.1 DATA AND PARAMETERS

The data and parameters used in the analyses presented in this report are based on those used in the TSPA-FEIS model. The model structure was essentially the same as used for the TSPA-SR and later modified for the SSPA (BSC 2001 [154659]) and subsequently for the TSPA-FEIS (Williams 2001 [157307]). The most recent documentation of the model used in the "One-on Analysis" for this report, including model structure and complete parameter listing can be found in the TSPA-SR model document (CRWMS M&O 2000 [148384] Sections 6.3 and 6.4, p.112 to 541). The TSPA-FEIS model was developed to address certain regulatory criteria in the EPA Final Rule 40 CFR 197 [155238] and the NRC Final Rule 10 CFR Part 63 [156605]). Because the final rules were published subsequent to the issuance of the SSPA, the Letter Reports describe the analyses performed in support of the final EPA and NRC regulations (Williams 2001 [157307]; and Williams 2001 [156743]). The model used for these calculations required modifications to the TSPA-SR model as described in detail in the Letter Reports written in response to the publication of the final rules (Williams 2001 [157307] and Williams 2001 [156743]). In a similar manner, modifications to the TSPA-FEIS model were required to perform the analyses presented in this report. The modifications to the TSPA-FEIS model that

were effected in order to conduct these “One-on” analyses are described in Section 6.2 of this report.

4.2 CRITERIA

There are no criteria applicable to these analyses. The calculations in this report were performed to examine the contributions of barriers to waste isolation and quantify the impact of these barriers in terms of changes in dose as was done using the TSPA-SR model and the TSPA-FEIS model. These analyses are not intended to address compliance to regulations or specific acceptance criteria in draft Yucca Mountain Review Plan (YMRP) (CNWRA 2002 [158449]).

4.3 CODES AND STANDARDS

There are no codes and standards applicable to this analysis. Analyses of dose from potential radionuclide release from the proposed repository at Yucca Mountain considering the different combinations of barriers and associated processes are used to provide insight regarding the relative contribution of different barriers and or processes by calculating dose at approximately 18 kilometers downgradient from the proposed Yucca Mountain repository (10 CFR 63.302 [156605]) as was done using the TSPA-SR and TSPA-FEIS nominal-case models (CRWMS M&O) 2000 [153246] and Williams 2001 [157307], respectively).

5. ASSUMPTIONS

The TSPA model analyses utilized for the evaluations in this report are stylized "One-on" analyses based on previous calculations performed for the FEIS Letter Report (Williams 2001 [157307]) based on the final EPA rule and the Letter Report in support of the final NRC regulations (Williams 2001 [156743]). The key assumptions used in the calculations and in this report are listed here for completeness.

5.1 ASSUMPTION 1

The TSPA-FEIS model was assumed to be the most appropriate performance-assessment tool to perform these analyses. This model was the basis for the most recent TSPA analyses for the EPA and NRC final rules, 40 CFR Part 197 and 10 CFR Part 63, respectively. The nominal-case model configuration for the calculations in this report is based on the same model configuration used in the FEIS Letter Report (Williams 2001 [157307]). The model used for the calculations in Sections 6.0 below includes the modifications from the SSPA and TSPA-SR models as described in Section 5 of the FEIS Letter Report (Williams 2001 [157307], Section 5). Additional model modifications and/or activation of model/software options used to obtain the analytical results presented in this report are described in Section 6.2 below. This assumption was used throughout.

5.2 ASSUMPTION 2

The radionuclide inventories used to produce the results presented in Section 7 are those developed in the *Inventory Abstraction* (BSC 2001 [154841], Table 36, p.38). The per-package inventories for the commercial spent nuclear fuel (CSNF), and co-disposed (CDSP) waste packages are the same as those used in the TSPA-SR (CRWMS M&O 2000 [153246], Section

3.5.1, p. 3-94 to 3-100) but the DOE-owned spent nuclear fuel (DSNF) inventory does not include the U.S. Navy spent nuclear fuel which is instead modeled as CSNF. This assumption was used throughout.

5.3 ASSUMPTION 3

The first four analyses were modeled as if the bare waste were assumed to have been placed at land surface and the released radionuclides were delivered directly to the RMEI using the 3,000 acre-ft annual water demand specified at 10 CFR 63.312 [156605]. This assumption was used in Sections 6.3.1 through 6.3.4.

6. SCIENTIFIC ANALYSIS DISCUSSION

6.1 BACKGROUND

The scope of the calculations presented in this report includes the evaluation of long-term repository performance after the eventual closure of the proposed Yucca Mountain repository. Figure 6-1 shows the location of the proposed repository. In particular, these analyses focus on a proposed Yucca Mountain repository for the disposal of 70,000 MTHM (metric tons of heavy metal) of nuclear material allowed by the Nuclear Waste Policy Amendments Act of 1987 (NWPAA) (NWPAA, Public Law 100-203 [100016]). These analyses considered the nominal-performance scenario only, and did not address performance following very unlikely disruptive events (i.e., volcanic activity).

This report utilizes the TSPA-FEIS (Williams 2001 [157307]) modeling of the 70,000-MTHM-case repository configuration. The analysis is provided only for the release of radioactive material from the Primary Block of the proposed Yucca Mountain repository, the area designated for the 70,000 MTHM inventory under the higher-temperature operating mode (Williams 2001 [157307]).

The GoldSim numerical code simulates transport of radionuclides from the repository, through the unsaturated zone (UZ), and through the saturated zone (SZ) to the accessible environment. The structure and organization of the model and its incorporation of the different process models included in the GoldSim code is described in the TSPA-SR (CRWMS M&O 2000 [153246]). The analyses in this report use the TSPA-FEIS model modified to allow the successive calculations by sequentially turning on model features as described in Sections 6.3.1 through 6.3.13. These analyses are consistent with the NRC final regulations in the use of a 3,000 acre-ft annual water demand (10 CFR 63.312 [156605]).

6.2 MODEL MODIFICATIONS AND ACTIVATION OF MODEL FEATURES

The analyses described in this report were conducted using the TSPA-FEIS model (Williams 2001 [157307]). However, because the scenarios simulated for this report are quite different than the TSPA-FEIS base case, modifications to the TSPA-FEIS model were required, and some features of the GoldSim software were implemented that were not implemented for the TSPA-FEIS analyses. Following are descriptions of the implementation of these modifications and

features. (Note that the simulations are referred to as “Cases 1 through 13” and these are further described in Section 6.3.)

- The GoldSim software utilized logic switches to globally turn on and off various barriers, allowing the use of only one base-case file, the modified TSPA-FEIS base-case file to run all the Cases 2 through 13. For Case 1, additional water was introduced to allow all the dissolved radionuclides to be released to the RMEI within the first two time steps.
- The base-case TSPA-FEIS model water flux was modeled as drift seepage calculated from the thermal-hydrologic process model. Before adding the UZ above the repository barrier for Case 8, water flux was added to the model using the average precipitation flux for the various climate states for Cases 1 to 4 and average infiltration fluxes for various climate states for Cases 5 to 7 and Case 13. These data were derived from the same database used in the thermal-hydrologic process model. Cases 8 to 12 used water flux from the same seepage-rate model as in the TSPA-FEIS model.
- The analyses in this report modeled the transport of Cs-137 and Sr-90. In the TSPA-FEIS model, although included in the model inventory, Cs-137 and Sr-90 were not modeled because the short half-lives of these radionuclides and their sorption properties did not computationally justify their inclusion in the model.
- The model used the same annual water demand of 3,000 acre-ft as used in the TSPA-FEIS model formulation used in support of calculations for the final NRC regulations (Williams 2001 [156743], Section 5.3) and for ground-water protection in accordance with the EPA Final Rule (Williams 2001 [157307], Section 6.6).

In addition to the model modifications described above, Cases 1 through 11 and 13 were simulated without accessing the diffusion model to effect the release of radionuclides. Individual cases described in Section 6.3 below indicate whether or not diffusive transport was implemented in the cases. Diffusive transport was not incorporated into individual cases other than Case 12 for the following reasons.

- The analyses were performed in a manner consistent with the EPRI-style “One-on” barrier analysis (See EPRI 2002 [158069], Section 10.2, p. 10-15 to 10-67), which emphasized the barrier effect on advective releases.
- In the TSPA-FEIS base case, the diffusive-transport model is thought to be conservative and combines the effects of all the barriers and both diffusive and advective releases. Because the majority of these “One-on” analyses had no waste-package, the dominant transport mechanism was advection, not diffusion. Therefore, diffusive transport was not modeled except in Case 12, which includes all barriers and diffusion, i.e. the TSPA-FEIS base case model (Williams 2001 [157307]).

6.3 ADDITION OF NATURAL AND ENGINEERED BARRIERS AND ASSOCIATED PROCESSES

The natural and engineered barriers and associated processes were added sequentially in an arbitrarily chosen order designed to mimic the EPRI multiple-barrier analysis (EPRI 2002 [158069]). The barriers/processes can be considered in three broad categories; a) waste-form barriers/processes (Figure 6-2), b) natural system barriers/processes (Figure 6-3), and c)

engineered system barriers/processes (Figure 6-4). In modeling successive barriers and processes, the modeling sequence was configured as if water passes sequentially from one barrier to the next and the order of barriers within each group approximates the travel path of fluid through portions of the hydrogeologic system and the proposed repository.

The analysis process begins with the waste dissolved in 3,000 acre-feet of water in order to estimate the maximum possible dose to the RMEI in accordance with the NRC rule (10 CFR 63.332 [156605]). These analyses were modeled as if the bare waste were placed at land surface and the released radionuclides were delivered directly to the RMEI using the 3,000 acre-ft annual water demand. The waste-form barrier, i.e. the degradation of the waste material, is the first "barrier" added that affects the releases of radionuclides with time.

The natural-system hydrogeologic barriers, describing the barrier effects of the UZ above and below the repository and the SZ, were added following the evaluation of the waste-form barriers. The natural-system hydrogeologic barriers were added before the engineered-system barriers because the robust nature of the engineered systems, as seen in the TSPA-FEIS calculations (Williams 2001 [157307]), would result in a very late-time release of radionuclides to the natural system. Thus, if, for this stylized analysis, the engineered systems were added before the natural barriers, they could mask the effects of the natural-system barriers.

The engineered-system barriers were added after the natural-system barriers were added to assess the effects of the engineered elements of the repository, the invert, the drip shield, and the waste package. The order of the addition of the engineered barriers accounts for the successively later degradation of these systems as established in the TSPA-SR (CRWMS M&O 2000 [153246]). Following the addition of the engineered systems, the analysis adds the effect of the diffusion-transport mechanism to account for the diffusive release via the fluid associated with waste-form and waste-package corrosion products, the invert, and no-drip waste packages. The analyses also consider an alternate barrier sequence by analyzing the direct addition of the SZ, without the UZ, to the repository to assess its contribution independently from the UZ.

The TSPA model elements adapted and/or modified for the stylized scenarios for these "One-on" analyses are summarized as follows, with the order of the "One-on" simulations referred to as Cases 1 through 13:

- ***Waste-form barriers/processes (Figure 6-2)***

Case 1: No barriers, waste dissolved in 3,000 ac-ft of water.

Case 2: Add Waste-Form Degradation Barrier Component: Constitutes a partial waste-form barrier, i.e. degradation rate of the waste form.

Case 3: Add Solubility Constraints and Colloidal Stability Barrier Component: Constitutes a complete waste-form (high-level waste (HLW))/partial waste-form (CSNF) barrier which includes waste-form degradation-rate limits, solubility limits, and colloid-stability limits.

Case 4: Add CSNF Cladding: Constitutes the full waste-form barrier which includes Case 1 and 2 plus cladding.

- ***Natural-system barriers/processes (Figure 6-3)***

Case 5: Add Surficial Soils: This case adds percolation through the surface soils and the UZ above the repository.

Case 6: Add Unsaturated Zone Flow and Transport: This case adds the UZ beneath the repository and the effects of advection and sorption in the UZ.

Case 7: Add Saturated Zone Flow and Transport: This Case adds the SZ between the UZ and the biosphere and the effects of advection and sorption over the 18 kilometers between the repository and the RMEI.

Case 8: Add the UZ Barrier Above the Repository: This barrier calculates seepage into the repository and accounts for the capillary effect on groundwater flow around a large engineered tunnel. This case also includes thermal effects of decay heat on flow and flow focussing due to preferential flow through fractures and the heterogeneity of material properties in the geologic media above the repository.

- ***Engineered-system barriers/processes (Figure 6-4)***

Case 9: Add the Invert Barrier: This case adds the invert barrier, affecting colloid stability, radionuclide solubility, and sorption of radionuclides.

Case 10: Add the Drip-Shield Barrier: This case adds the drip-shield barrier, which diverts seepage around the waste packages.

Case 11: Add the Waste-Package Barrier: This case adds the waste-package barrier, which accounts for the waste-package failure.

Case 12: Add Diffusive Transport: The diffusion process incorporates transport of radionuclides along concentration gradients in the waste package and invert. Unlike advective transport, diffusive transport does not require flowing water.

Case 13: Add Saturated Zone below the Repository without the Unsaturated Zone: In addition to the first 12 cases, an additional case, Case 13, was added to test the relative effectiveness of the UZ and SZ. Case 13 adds the SZ to the model directly after Case 5 and is thus called, “Add SZ without the UZ”. The case tests the concept that by first adding the UZ below the repository to the sequence of barriers, the UZ performance may mask the barrier contribution of the SZ below the repository.

Figure 6-5 is a flow chart that describes the order of the cases and shows the sequential addition of the barriers. Cases 1 to 13 are described in more detail in the following sections.

6.3.1 Case 1: No Barriers, Waste Dissolved in 3,000 acre-feet of Water

In this case, the waste is simulated as being at land surface above the repository horizon at the start of the “One-on” set of simulations (Case 1). The release of radionuclides is modeled as being dissolved directly into groundwater from the waste form. The simulation assumes instantaneous dissolution of the complete radionuclide inventory into the water precipitating on Yucca Mountain, and transported without delay to the biosphere using the precipitation rates used in the TSPA-FEIS model. The precipitation rates used in the analyses in this report are

presented in Table 6-1. The entire waste inventory that would be placed in waste packages was made available for advective transport only because radionuclide transport by diffusion was not activated. In Case 1, all the waste reaches the representative groundwater volume during the first time step. Therefore, the representative groundwater volume, being defined as the amount of water used by the RMEI in one year, receives all the waste in the first time step. Because the representative groundwater volume receives all the waste in the first time step, and that volume of waste and water is fully utilized by the RMEI, the entire representative groundwater volume is replaced with fresh water in the next time step.

6.3.2 Case 2: Add Waste-Form Degradation Barrier Component:

Case 2 introduces the waste-form barrier to the system, impeding the release of radionuclides from the waste form. The rate of radionuclide release is controlled by the degradation rate of the waste form. The annual representative groundwater volume in this scenario is the same volume as that in Case 1 and the radionuclide release is due to degradation and dissolution of the waste form rather than the instantaneous release in Case 1. In Case 2, the simulation of waste-form degradation and dissolution uses the same rate equations and dissolution models used in the base case of the TSPA-FEIS model. The release of the radionuclides is governed by the decay rate of the simulated waste forms under drift-boundary chemical conditions. Once released from the waste form, the simulation instantaneously releases the degradation products, including associated radionuclides, from the repository to the representative groundwater volume. In Case 2, only that fraction of the waste that is released from the waste form reaches the groundwater volume used by the receptor within each simulated time step. The introduction of radionuclides from the repository for the remainder of the simulation is governed by the continual degradation of the waste forms.

6.3.3 Case 3: Add Solubility Limits and Colloidal Stability Barrier Component

In Case 3, the release of radionuclides to the representative groundwater volume from the waste form as presented in Case 2 is constrained by imposing radionuclide-solubility and colloidal-stability constraints on certain radionuclides and colloid-forming radionuclides derived from the dissolution of the waste form. These constraints are the same as those used in the base case of the TSPA-FEIS model. These solubility limits are, in part, functions of the chemical conditions in the waste form and the geochemistry of the groundwater used in the simulation. The solubility constraints are determined by the drift-boundary chemistry. In this scenario, colloid stability is also governed by drift-boundary chemistry. According to the application of colloidal stability in Case 3, the higher the mass concentration of colloids, the greater the mass of radionuclides that can partition, either reversibly or irreversibly, onto the colloids. This mechanism can enhance mass transfer out of the waste form. When colloidal-stability constraints are imposed in Case 3, the mass concentration of colloids may decrease from the maximum stable concentrations used in Case 1 and Case 2, thus reducing the mass transfer of each radionuclide species associated with colloids.

6.3.4 Case 4: Add CSNF Cladding

Case 4 adds in the effect of CSNF waste form cladding to further impede and slow the release of radionuclides to the representative groundwater volume. In the model, Case 4 is developed from Case 3 by activating a cladding-degradation model representing the stability of cladding that

normally coats the CSNF waste form. Activating the cladding-degradation model delays the release of radionuclides from CSNF waste forms. In Cases 1, 2, and 3, the waste-form cladding was represented as having been 100% perforated at time zero, and the release of radionuclides from CSNF waste was governed by the degradation of the CSNF matrix and impeded only by chemical constraints related to radionuclide solubility and by the stability of colloid formation. Under Case 4, the CSNF cladding fails according to the cladding model used in the base case of the TSPA-FEIS model. Radionuclide release from the waste form is governed by the unzipping rate of the cladding after its perforation. Note that the model configuration used for the TSPA-FEIS analysis included a subsystem model to simulate cladding damage from rockfall; however, this model was not implemented in Case 4. In Case 4, the waste form is considered to be placed at land surface without being enclosed in a waste package. Therefore, there would be no rockfall under these conditions.

6.3.5 Case 5: Add Surficial Soils: Including Topography, and UZ above the Repository

Cases 5 through 8 describe the addition of the natural barriers to the system. For these cases, the waste form is still not in waste packages nor “in” a repository per se. Case 5 adds various features and processes, including the UZ between land surface and the repository. These factors and processes serve to reduce the advective flow rate through the repository horizon, and subsequently through the waste form, thus slowing the advective release of radionuclides to the representative groundwater volume. In the previous cases, the advective flow rate through the repository was equivalent to the average precipitation rate at Yucca Mountain (Table 6-1). In Case 5, the inclusion of the surface soils and topography and associated natural processes and barriers to flow reduces the flow rate reaching the repository from the average Yucca Mountain precipitation rate to the average infiltration rate at Yucca Mountain. Table 6-2 shows the infiltration rates used in the analyses in this report. Because the average infiltration rate is lower than the average precipitation rate, the addition of this barrier reduces the advective releases of radionuclides from the repository horizon. Similar to the previous cases, this scenario includes the requirement that all waste forms are dripped upon and diffusion is not allowed to occur because the diffusive-transport model element is not accessed as described above in Section 6.2.

6.3.6 Case 6: Add Unsaturated Zone Flow and Transport below the Repository

Case 6 adds the effect of the UZ beneath the repository to the radionuclide-release pathway. In this scenario, the radionuclides that are released by advection from the waste form are effectively placed into the fractures beneath the repository and allowed to flow through the UZ. Sorption in the UZ beneath the repository and partitioning into the rock matrix is governed by the partition coefficients for fracture flow which are the same coefficients used in the base case of the TSPA-FEIS model. Diffusion through the UZ is not simulated in Case 6 and all the radionuclides released from the repository horizon are released by advection.

6.3.7 Case 7: Add Saturated Zone Flow and Transport

The water and associated radionuclides flowing from the UZ in Case 6 are then passed to the SZ in Case 7. The travel distance through the SZ is approximately 18 kilometers from the models capture zone in the SZ beneath the repository to the representative groundwater volume at the receptor’s well. In Case 7, radionuclides are advectively transported from the waste form, allowed to flow through fractures in the UZ beneath the repository and through the SZ to the

RMEI. Sorption in both the UZ and SZ is governed by the partition coefficients for fracture flow in the UZ and groundwater flow and transport in the SZ as found in the base case of the TSPA-FEIS model. Similar to Case 6, diffusion through the repository horizon and UZ is not simulated in this scenario and all radionuclide transport from the repository horizon and through the UZ occurs by advection only.

6.3.8 Case 8: Add the Unsaturated Zone above the Repository Barrier

Case 8 is the last natural-system barrier added and is associated with the repository drift. Case 8 specifies the areal distribution of seepage through the drift walls and onto waste forms emplaced in the repository. The presence of this excavation provides a capillary barrier to flow into the drift and thus could affect the amount of water that might contact the waste form. This scenario and Cases 9 through 12 remove the requirement of the previous cases that all waste be dripped upon. The percentage of waste receiving seepage and the drip rate onto the waste are those calculated by the seepage model included in the TSPA-FEIS model. The seepage rate is further modified and/or reduced by the conditions present during the evaporation and boiling period expected during the first several hundred years after waste emplacement. Due to spatial variability, the model implementation of the drift barrier specifies environments in which some waste forms are not exposed to dripping water. As discussed in Section 6.2, diffusion through the waste form and UZ is not simulated in this scenario and all the releases from the waste form and UZ are advective releases.

6.3.9 Case 9: Add the Invert Barrier

Cases 9 through 11 describe the principal engineered components of the Yucca Mountain repository system. Case 9 adds the engineered barrier consisting of the drift invert below the waste-emplacement level. The invert affects radionuclide release in a number of ways. The chemistry in the invert is different than that in the waste forms and hence colloid stability, solubility and sorption can be affected. In addition, advective radionuclide transport from the waste form is now delayed by passage through the invert. Case 9 does not include diffusion through either the invert or the UZ.

6.3.10 Case 10: Add the Drip-Shield Barrier

Case 10 calculates the release of radionuclides from the repository just as in Case 9 but the release scenario is modified by the addition of the drip-shield engineered barrier placed in the drifts above the emplaced waste form. In Case 10, the waste form was still not in a waste package. The drip shield was added before the waste package so that the drip shield's additive effect as a barrier in the context of 10 CFR 63.2 [156605] could be discerned. The drip shields reduce the groundwater release of radionuclides to the representative groundwater volume because adding the drip-shield barrier diverts seepage around the waste forms, effectively reducing the amount of dripping water that could contact the waste form. Activating the drip-shield barrier delays the initiation of advective releases of radionuclides from both CSNF and CDSP waste that are placed in dripping environments. Case 10 does not include diffusion through the waste form, the invert, or the UZ.

6.3.11 Case 11: Add the Waste-Package Barrier

Case 11 adds the engineered barrier consisting of the waste packages containing the CSNF waste and the CDSP waste packages containing the DSNF waste and HLW waste glass. The waste packages are placed in the repository between the drip shields and the invert. The release of radionuclides to the invert cannot occur until the waste packages fail. Adding the waste-package barrier regulates the amount of mass that can be released to the invert by advection after the waste packages and drip shields in preceding Case 11 have failed. The release of the radionuclides from the waste packages is governed by the failure of the waste packages as calculated in the manner as was used in the TSPA-FEIS model. Case 11 adds the potential for early waste-package failure (juvenile failure) with one waste-package failure assumed for each realization. However, because Case 11 does not include diffusion, there is no radionuclide release from early waste-package failure until the drip shields have failed. In addition, the in-package chemistry model used in the TSPA-FEIS model governs the chemical conditions inside the waste packages. The in-package chemistry potentially affects solubility and colloidal stability of radionuclide species subject to flow and transport to the representative water volume. Furthermore, corrosion products generated by the degradation of the waste packages themselves and their internal components contribute to the release of mass from the repository. In addition, the porosity of the corroded material provides additional water storage that provides for additional dissolution of radionuclides. Case 11 does not include diffusion through the EBS and UZ.

6.3.12 Case 12: Add Diffusive Transport

Case 12 effectively adds the TSPA-FEIS treatment of diffusion to Case 11. Case 12 is effectively the TSPA-FEIS base case and provides an end-point comparison after the addition of the suites of waste-form, natural, and engineered barriers and associated processes. Diffusion was not added until after all the natural and engineered barriers were added for several reasons.

1. Diffusion is not a barrier but a release mechanism. It is more consistent to consider all the barriers one-to-another without this added release mechanism.
2. These “One-on” analyses were patterned after the EPRI analyses (EPRI 2002 [158069] Section 10.2) and the EPRI model does not include diffusion.
3. Because advection was the dominant transport mechanism in all the cases until Case 8 (Add the UZ above the Repository Barrier), there was more consistency in the comparison of the cases with only advection as the transport mechanism for the remaining barriers.
4. All cases until the addition of the waste package (Case 11) are concerned with release from the waste form and would not include diffusive transport through the corrosion products as calculated by the TSPA-FEIS model.

The model calculates the release of radionuclides from the repository just as in Case 11 but the case is modified by the addition of diffusion as a release mechanism from the waste packages containing the CSNF waste and CDSP waste packages containing the DSNF waste and HLW waste glass. Adding diffusion to the releases from the waste-packages affects the mass of radionuclides that can be released to the invert by advection and/or diffusion after the waste packages have failed. Further, the additional water storage in the porosity of the corroded

material is subsequently added to the diffusive flow from the repository providing carrying capacity for the transport of radionuclides and corrosion products from the repository. The zero boundary condition for the diffusion model is set at the bottom edge of the invert below the waste as in previous TSPA model simulations in general, and the TSPA-FEIS model in particular.

6.3.13 Case 13: Add Saturated Zone without the Unsaturated Zone below the Repository

Case 13 was developed to assess the contribution of the SZ barrier in the same manner that Case 6 assessed the UZ barrier. Both the UZ and the SZ are barriers that contribute to the reduction of the peak mean annual dose and the contributions to that peak dose by certain radionuclides. Assessing the contribution of the SZ after adding the UZ could indicate that the SZ was “less significant” because some of the benefits of the SZ are redundant with the UZ. Case 13 analysis was investigated to directly assess the role of the SZ as a natural barrier without the masking effect of the UZ.

Case 13 models the SZ, as described in Section 6.3.7, as if it were the radionuclide-release pathway directly beneath the repository. In this scenario, the radionuclides are released by advection from the waste form. The radionuclides are then effectively transported into the SZ beneath the repository with no transport through the UZ. The released radionuclides are then allowed to flow through the SZ to the groundwater volume utilized by the RMEI. Processes affecting transport through the SZ beneath the repository, including sorption, are governed by advection and associated partitioning coefficients that are included in the base case of the TSPA-FEIS model.

Table 6-1 Average Precipitation Rates (mm/yr) Implemented in the “One-on” Analyses

Climate State	Low Precipitation	Mean Precipitation	High Precipitation
Interglacial ^a	186.8	190.6	268.6
Monsoon ^a	190.6	302.7	414.8
Intermediate ^a	202.2	317.8	433.5
Glacial, Stage 8/10 ^b	433.5	429	529
Glacial, Stage 6-16 ^b	330	429	529
Glacial, Stage 4 ^b	269	330	429

^a (BSC 2001 [155950] Table 3.3.1-1)

^b (BSC 2001 [155950] Table 3.3.1-5)

Table 6-2   Average Infiltration Rates (mm/yr) Implemented in the “One-on” Analyses

Climate State	Low Infiltration	Mean Infiltration	High Infiltration
Interglacial ^a	1.3	4.6	11.1
Monsoon ^a	4.6	12.2	19.8
Intermediate ^a	2.5	17.8	33
Glacial, Stage 8/10 ^b	33	87.9	151
Glacial, Stage 6-16 ^b	24.4	87.9	151
Glacial, Stage 4 ^b	12.9	24.4	87.9

^a (BSC 2001 [155950] Table 3.3.2-1)

^b (BSC 2001 [155950] Table 3.3.2-3)

Figure 6-1 Location of the Proposed Yucca Mountain Repository

Figure 6-2 Schematic Diagram Illustrating Waste-Form Barriers/Processes

Figure 6-3 Schematic Diagram Illustrating Natural-System Barriers/Processes

Figure 6-4 Schematic Diagram Illustrating Engineered-System Barriers/Processes

Figure 6-5 Flow Chart Showing the Successive Addition of the Barriers

7. CONCLUSIONS

The results of the “One-on” analyses are presented in plots of total annual dose (millirem (mrem)/yr) to the RMEI for one million years after repository closure. Consistent with the TSPA-FEIS and the evaluation of the NRC final rule (Williams 2001 [157307 and 156743, respectively]) the one-million-years simulation time was chosen as the period of geologic stability and used as the simulation time period. The plots show the change in estimated total annual dose with the addition of each barrier or associated process and the individual plots are intended to be viewed relative to one another.

The results for the cases described in Sections 6.3.1 through 6.3.13 are presented in Figures 7-1 through 7-13. These figures show the mean annual dose versus time calculated from 300 realizations for the full simulation period as well as the median, and 5th and 95th percentiles of the 300 realizations. To provide an indication of the degree of uncertainty associated with the calculations, Figures 7-1 (no Barriers) and 7-12 (all Barriers plus diffusive transport) include the simulation results of all 300 realizations (a.k.a. “horsetail” plots). The results for each case include a plot of the fractional contribution of selected radionuclides that contribute to the total dose as shown in the legend of each figure. Although the model calculates the dose due to 26 radionuclides (CRWMS M&O 2000 [148384], Section 6.3.4.1, Table 6-26), the calculated values of dose for most of the radionuclides do not provide a significant contribution to fractional dose and are therefore not shown. In addition, the results for the total dose due to all radionuclides modeled are tabulated in Table 7-1. Table 7-1a shows the cases modeled, the magnitude of the peak mean annual dose for each case, and the time at which the simulation calculated the peak mean annual dose. Table 7-1b shows the same information for the 95th percentile dose. Table 7-2 shows the range of total mean annual dose by time period and case. Note in viewing the tabulated results and the figures displaying the results, that the TSPA-FEIS model employs variable time stepping. The first four time steps in all the model runs are 31.25, 62.5, 125 and 187.5 years. The time step length is 62.5 years from 187.5 years to 5000 years. From 5,000 to 10,000 years, the time-step length is 250 years. From 10,000 to 100,000 years, the time-step length is 500 years. From 100,000 to 120,000 years, the time step-length is 1,000 years. From 120,000 to 152,000 years, the time-step length is 2,000 years, and thereafter to 1,000,000 years, the time-step length is 4,000 years. The time-step lengths shown in Table 7-1 are as they appear in the model output. These time-step lengths were given for ease of use of the model results in the TDMS but the tabulated values on Table 7-1 should not be assumed to be indicative of the level of significance of these values.

7.1 CASE 1: NO BARRIERS, WASTE DISSOLVED IN 3,000 ACRE FEET OF WATER

Figure 7-1 shows that for Case 1, the peak mean annual dose occurs at 31.25 years. The peak mean annual dose has a value of 2.66×10^{10} mrem/yr. The peak of the 95th-percentile dose also occurs at 31.25 years and has a value of 3.50×10^{10} mrem/yr. The only differences between the mean and 95th-percentile dose rate are due to the sampling the distributions for the biosphere dose-conversion factors. The peak value is seven orders of magnitude less than the correlative case in EPRI (EPRI 2002 [158069] Section 10.2) because the EPRI dissolved all the waste in 600 liters of water and Case 1 dissolved all the waste in 3,000 acre-feet of water (3.7×10^9 liters). The mean dose drops to essentially zero at 125 years. All the radionuclides are released

in the first time step. However, due to the mechanics of the model, one additional time step, after the first time step, is needed to move all the radionuclides from the waste-form cell. Because 99.99% of all the dose due to Case 1 occurs in the first time step and all the dose occurs within the first two time steps (62.5 years), the result is judged to be satisfactory.

Figure 7-1 also shows that the time of the peak mean annual dose, the percent of the total dose contributed by Am-241 is 32.9%, Cs-137 is 30%, Pu-238 is 17.4%, and Sr-90 is 12.6%. Other radionuclides that together contribute less than 7% of the mean annual dose but are either not shown or not easily discernible on Figure 7.1 are Pu-240, Pu-239, Am-243, Pu-242, Np-237, and U-234.

7.2 CASE 2: ADD WASTE-FORM DEGRADATION BARRIER COMPONENT

Figure 7-2 shows that the peak mean annual dose for Case 2 occurs at 62.5 years. The peak mean dose has a value of 1.30×10^{10} mrem/yr. The peak of the 95th-percentile dose also occurs at 62.5 years and has a value of 2.13×10^{10} mrem/yr. The differences between the mean and 95th-percentile dose rate are due to the sampled values for the biosphere dose-conversion factors and stochastic sampling of waste-form degradation-rate parameters. Figure 7-2 indicates that at the time of the peak mean annual dose, the percent of the total dose contributed by Am-241 is 43.6%, Cs-137 is 19.8%, Pu-238 is 18.7%, Sr-90 is 8%, Pu-240 is 6%, and Pu-239 is 4%. Other radionuclides that together contribute less than 0.5% of the mean annual dose but are either not shown or not easily discernible on Figure 7-2 are Am-243, Pu-242, Np-237, and U-234. The mean annual dose does not drop to zero mrem/yr in 1 million years because, in some realizations, the waste forms have not completely degraded after one million years. At one million years, the mean annual dose rate is 1.30×10^{-1} mrem/yr.

Compared to the Case 1, the peak of the mean annual dose is delayed in time by adding the waste-form matrices. However, the peak mean annual dose is decreased by approximately 51% relative to Case 1, indicating that the dose due to the total mass of the waste inventory is beginning to be spread over postclosure time. Another difference between Case 1 and Case 2 is that the Case 2 simulation shows dose contribution for this case continues for the full one-million-year simulation time. In Case 1, there was no annual dose after 250 years postclosure. The continued dose shown for Case 2 occurs because of the slower degradation of the waste forms and the subsequent later release of radionuclides.

7.3 CASE 3: ADD SOLUBILITY CONSTRAINTS AND COLLOIDAL STABILITY BARRIER COMPONENT

Figure 7-3 shows that the Case 3 peak mean annual dose occurs at 62.5 years. The peak mean dose has a value of 3.63×10^9 mrem/yr. The peak of the 95th-percentile dose also occurs at 62.5 years and has a value of 7.16×10^9 mrem/yr. At the time of the peak mean annual dose, Figure 7-3 shows that the percent of the total dose contributed by Cs-137 is 71.5%, Sr-90 is 28%, and Am-241 is 0.2%. Other radionuclides that together contribute less than 0.5% of the mean annual dose but are either not shown or not easily discernible on Figure 7-3 are Pu-238, Pu-240, Pu-239, Am-243, Tc-99, Pa-231, and C-14.

Compared to Case 2, the Case 3 peak mean annual dose is not delayed in time by adding the solubility constraints and colloidal-stability criteria because this barrier affects only the dissolved mass of radionuclides and does not add delay transport with respect to time. However, the peak mean dose for Case 3 is approximately 72% less than calculated for Case 2. In addition, the rank of the major nuclides contributing to dose is different for Case 3 relative to Case 2. The calculated dose values in mrem/yr for Cs-137 and Sr-90 in Case 3 are identical to those calculated for Case 2 indicating that both Cs-137 and Sr-90 are not constrained by solubility limitations or colloidal stability. Alternatively, the dose contribution of Am-241 has decreased by more than 99%, accounting for almost approximately 60% of the reduction in the peak mean-annual dose of the Case 3 results. In addition, the dose from Pu-238 accounted for 26% of the dose reduction.

At one million years, the Case 3 mean annual dose rate is 4.88 mrem/yr, a value higher than that calculated for Case 2. This higher dose rate is likely due to early-time retention of species in the waste form because of the solubility constraints added for Case 3. The model allows the radionuclides in the waste form to dissolve up to their solubility limits, leaving the remaining mass in the solid phase and not available for transport until later times when the solubility limits allow transport. At one million years postclosure, Pu-242 accounts for 98% of the total dose for Case 3, and 99% of the dose increase relative to the Case 2 dose is due to Pu-242.

7.4 CASE 4: ADD CSNF CLADDING

The Case 4 peak mean annual dose occurs at 62.5 years as shown on Figure 7-4. The peak mean dose has a value of 1.59×10^8 mrem/yr. The peak of the 95th-percentile dose also occurs at 62.5 years. The peak 95th-percentile dose has a value of 3.45×10^8 mrem/yr. At the time of the peak mean annual dose, the percent of the total dose contributed by Cs-137 is 64%, Sr-90 is 33.5%, and Am-241 is 2.4% (Figure 7-4). Other radionuclides that together contribute less than 0.5% of the mean annual dose but are either not shown or not easily discernible on Figure 7-4 are Pu-238, Pu-239, Pu-240, Am-243, Pa-231, Ac-227, and Tc-99.

The peak of the mean annual dose for Case 4 is not delayed in time relative to Cases 1, 2, and 3 by adding the CSNF cladding barrier. However, the peak mean annual dose is 96% less than that calculated for Case 3. Note that this barrier affects only the CSNF waste not the CDSP waste that effectively is unclad. The simulation results also show that the order of the major radionuclides contributing to total mean annual dose is the same as that calculated for Case 3 although the relative contributions of these radionuclides are different. The calculated dose values in mrem/yr for Cs-137 and Sr-90 in Case 4 are identical to those calculated for Case 3 at the first time step, indicating release of gap-fraction radionuclides, i.e. the radionuclides present in the gap between the waste form and the cladding. However, a comparison of the mean annual dose rates for each radionuclide at 62.5 years reveals that the mean annual dose rate for Cs-137 and Sr-90 at 62.5 years (the second time step) decreases by 96% when comparing Case 4 to Case 3, indicating that the release of both Cs-137 and Sr-90 is constrained by adding CSNF cladding. These results suggest that the Case 4 dose is likely due to the bound fraction of these radionuclide species. Because CSNF waste accounts for more than 90% of the Sr-90 and Cs-137 in the proposed radionuclide inventory in the repository (Williams 2001 [157307], Section 1.1),

delaying the mass release of these radionuclides by the addition of CSNF cladding appears to be significant relative to the mean annual dose rate at early times.

The Case 4 mean annual dose at one million years is 37.4 mrem/yr, a value higher than that calculated for Case 3. This result is likely due to the CSNF cladding causing a slow release of the CSNF radionuclide inventory, although the total dose does receive a contribution from the unclad CDSP waste inventory. In order for all the repository waste to be available for transport, all the CSNF cladding must be degraded and unzipped. A review of some of the 300 realizations simulated by the model shows that in some realizations, 100% cladding failure is not achieved in one-million years, allowing the CSNF waste forms to serve as continual sources of radionuclides. This slow release occurs because the cladding-failure model does not calculate 100% cladding failure at the same time for every realization. For example, for the group of waste-forms reviewed, 25% reached 100% cladding failure by 264,000 years postclosure and more than 50% of the realizations did not experience 100% cladding failure within the first one-million years postclosure.

7.5 CASE 5: ADD SURFICIAL SOILS

Figure 7-5 shows that the peak mean annual dose for Case 5 occurs at 62.5 years. The peak mean dose has a value of 8.08×10^7 mrem/yr. The peak of the 95th-percentile dose also occurs at 62.5 years and has a value of 1.74×10^8 mrem/yr. At the time of the peak mean annual dose, the percent of the total dose contributed by Cs-137 is 66%, Sr-90 is 34%, and Am-241 is 0.21% (Figure 7-5). Other radionuclides that together contribute less than 0.2% of the mean annual dose but are either not shown or not easily discernible on Figure 7-5 are Pu-238, Pu-231, Ac-227, Pu-240, Pu-239, Am-243, and Tc-99.

The peak mean annual dose for Case 5 is not delayed in time relative to Cases 1 to 4 by adding the surficial-soils barrier (See Figures 7-1 to 7-5) because this barrier primarily affects transport and does not affect which radionuclides are released. However, the peak dose is approximately 51% less than that calculated for Case 4. The mean annual dose values calculated for Case 5 for Cs-137 and Sr-90 are each approximately half what they were in Case 4 indicating that the release of both Cs-137 and Sr-90 is constrained by adding the surficial soils which reduces the advective water flux through the waste form. Because advection is the only active transport mechanism for this simulation, reducing the flow rate through the waste form reduces the mass flux from the waste form, thus eventually leading to a lower peak mean annual dose.

Figure 7-5 shows that the total mean annual dose for Case 5 exceeds the mean dose calculated for Case 4 from approximately 80 to 120 years postclosure and from about 650 to 1,500 years postclosure. There is a climate change at the 625-year time step that causes a 300% increase in the advective flow rate through the waste form in Case 5, but only a 30% increase in flow rate in Case 4. This increased advective flux results plus the addition of colloid species results in a larger fraction of mass transported out of the waste form. The cumulative dose for most Case 5 radionuclides remains below those calculated for Case 4, indicating that the increase in advective flux probably accounts for a flushing of some previously immobilized mass and/or colloids from the waste form.

7.6 CASE 6: ADD UNSATURATED ZONE FLOW AND TRANSPORT BELOW THE REPOSITORY

The results for Case 6 show that the peak mean annual dose has a value of 3.92×10^3 mrem/yr and occurs at 40,000 years postclosure as shown on Figure 7-6. The peak dose of the 95th-percentile dose has a value of 1.13×10^4 mrem/yr and occurs at 42,000 years. Figure 7-6 also shows that at the time of the peak mean annual dose, Pu-239 (including colloids) accounts for 89.5% of the peak mean annual dose and Np-237 accounts for 5.6%. Other radionuclides that together contribute less than 5% of the mean annual dose but are either not shown or not easily discernible on Figure 7-6 are U-234, Pu-242, Pa-231, Ac-227, U-236, Pu-238, and Pb-210.

Compared to the Case 5 results, the peak of the mean annual dose for Case 6 is delayed in time by adding the UZ barrier beneath the repository (Figures 7-5 and 7-6). The delay is nearly 40,000 years. In addition to the delay, the peak mean annual dose decreased to a value over four orders of magnitude less than the previous result. In addition, there was a change in the observed order of the major contributors to dose. The two main contributors to the peak dose in Case 5, Cs-137 and Sr-90 do not contribute anything to the mean annual dose in Case 6 indicating that transport of both Cs-137 and Sr-90 is constrained by adding the UZ. The removal of Cs-137 and Sr-90 is likely due to a combination of retardation in the UZ and the short half-lives (<100 years) of these radionuclides, a factor that becomes more important as the transport time increases.

The addition of the UZ delays the calculated arrival of radionuclides for Case 6 relative to Case 5 for several reasons. The first is the transport distance. The groundwater travel distance was zero meters for Case 5 after the radionuclides left the waste form whereas the Case 6 travel distance is approximately 300 meters, the depth of the UZ beneath the repository. In addition, matrix diffusion and, to some extent, sorption to the geologic media in the UZ, are the likely mechanisms that act to retard the arrival of nuclides at the receptor site. Lastly, the longer the radionuclides remain in the UZ, the greater the reduction in activity due to radioactive decay.

7.7 CASE 7: ADD SATURATED ZONE FLOW AND TRANSPORT

Case 7 adds the SZ and thus the results reflect the combined effect of the addition of the UZ followed by the SZ. The role of the SZ alone is investigated separately in Case 13 as discussed in Section 7.13. Figure 7-7 shows that the Case 7 peak mean annual dose has a value of 2.64×10^3 mrem/yr and occurs at 39,000 years postclosure. The peak annual dose of the 95th-percentile has a value of 7.86×10^3 mrem/yr and occurs at 42,000 years. At the time of the peak mean annual dose, the percent of the total mean annual dose contributed by Pu-239 (including colloids) is 85.6%, and Np-237 contributes 9.8%. (Figure 7-7). Other radionuclides that together contribute less than 5% of the mean annual dose but are either not shown or easily discernible on Figure 7-7 are Pu-240, U-234, Pu-242, U-236, Pa-231, and U-238. The addition of the SZ barrier for Case 7 makes the peak of the mean annual dose occur 1000 years earlier, and the peak is broader and lower than the Case 6 peak mean annual dose (see Figures 7-6 and 7-7). Also, the addition of the SZ most likely lowers the dose and delays the arrival of some early arriving radionuclides relative to Case 6 primarily because of the increase in transport distance. In Case 6, the groundwater travel distance was 300 meters following release of the radionuclides from the waste form at the repository horizon. For Case 7, this travel distance is increased to 18 km, the approximate distance from the edge of the repository to the receptor community (10 CFR 63.302 [156605]).

The data from the Case 7 simulation show that the addition of the SZ leads to an approximately 32.7% reduction in the peak mean annual dose as compared to Case 6. Further, comparing Figures 7.6 and 7-7 shows that approximately 97% of the reduction in the peak mean annual dose after about 40,000 years is due to a reduction in the contribution of Pu-239. The climate change at 38,000 years provides a surge in flow in the UZ and SZ causing a 40% reduction in dose due to Pu-239 after 39,000 years, the time of the peak mean annual dose. Thus, the reduction in the peak mean annual dose is attributed to the performance of the SZ on Pu-239.

7.8 CASE 8: ADD THE UNSATURATED ZONE ABOVE THE REPOSITORY BARRIER

Case 8 is indicative of the influence of the UZ above the repository after the construction of the repository drifts. The Case 8 peak mean annual dose has a value of 2.11×10^3 mrem/yr and occurs at 39,000 years postclosure as shown on Figure 7-8. The peak of the 95th-percentile dose has a value of 7.31×10^3 mrem/yr and also occurs at 39,000 years. At the time of the peak mean annual dose, the percent of the total dose contributed by Pu-239 (including colloids) is 83.9%, Np-237 is 10.3%, and Pu-240 (including colloids) is 3.3% (Figure 7-8). Other radionuclides that together contribute less than 3% of the mean annual dose but are either not shown or not easily discernible on Figure 7-8 are U-234, Pu-242 (including colloids), U-238, and Am-243 (including colloids). Figures 7-7 and 7-8 show that the peak mean annual dose is not delayed in time by adding the interaction of the UZ above the repository and the repository drifts. This interaction essentially constitutes a barrier because the UZ affects seepage into the drift, and consequently the quantity of mass released but does not transport time.

Table 7-1a shows that the peak mean annual dose for Case 8 is decreased by approximately 20% relative to Case 7. The addition of the UZ above the repository barrier reduces the total mean annual dose by changing the seepage rate through the waste form. The seepage rate is further modified and/or reduced by the evaporation and boiling period expected during the first several hundred years after waste emplacement. The subsequent change from the infiltration rate to the seepage rate alters the advective mass flux out of the waste form. The UZ above the repository barrier alters the distribution of seepage such that dripping conditions may not occur over some waste forms and may increase the seepage rate over others. The UZ above the repository barrier implements a flow-focusing mechanism that allows dripping on only some of the waste. Thus, flow focusing could result in an increase in the advective release from some waste forms if the advective flow rate is sufficient to sweep away additional mass from the dripped-upon waste forms. However, because diffusion is not activated, there are no radionuclides released from waste forms not dripped upon.

A review of the Case 8 results shows that the number of no-drip versus dripped-upon waste packages indicates that, on average, 54% of the waste packages in the repository will experience no-drip conditions. Thus, one would expect that there would be a 54% reduction in the mean annual dose. However, the reduced number of no-drip waste packages results in only a 20% reduction in mean annual dose as determined by comparing the results from Case 7 with the results from Case 8. The 20% lower calculated peak total mean annual dose for Case 8 is likely due to the dual effects of evaporation on the amount of available seepage and flow focusing which results in a higher advective flux release from the dripped-upon packages.

7.9 CASE 9: ADD THE INVERT BARRIER

The Case 9 peak mean annual dose has a value of 7.70×10^2 mrem/yr and occurs at 108,000 years postclosure as shown on Figure 7-9. The peak of the 95th-percentile dose has a value of 3.78×10^3 mrem/yr and also occurs at 108,000 years. At the time of the peak mean annual dose, the percent of the total dose contributed by Pu-239 (including colloids) is 82.8%, Np-237 is 12.2%, and Pu-242 (including colloids) is 1.7% (Figure 7-9). Other radionuclides that together contribute less than 4% of the mean annual dose but are either not shown or not easily discernible on Figure 7-9 are U-234, Pa-231, Ac-227, Pb-210, Th-229, and Ra-226. Compared to Case 8, adding the invert barrier delays the time to the peak of the mean annual dose by 69,000 years and reduces the peak mean annual dose by approximately 63.5%.

The addition of the invert barrier reduces the total dose by changing the chemical conditions in the fluid environment affecting the waste forms in the repository horizon. Corrosion products in the invert provide a sorptive site to retard transport. Because there is no diffusive transport in this analysis, the only factors changing the release from the waste form are the chemical conditions in the invert. Once out of the waste form and into the invert, the pH and ionic strength of the transport fluid can change. These geochemical changes affect colloidal stability and the solubility of certain radionuclides. The lower dose is likely due to a combination of radionuclide decay over the 70,000 year peak delay as well as the increased stability of colloids in the invert under the influence of the invert chemistry. At the time of the Case 8 peak dose (39,000 years), the Case 9 contribution by Pu-240 and Pu-239 irreversible colloids is decreased by 2 and 3 orders of magnitude, respectively. These two colloid species were the first and fifth largest contributors to the peak dose in Case 08. The combination of these factors can serve to reduce the mass flux from the invert. In the Case 9 analysis, the advective flow through the waste form is equivalent to the advective flow through the invert. Therefore, there do not appear to be any differences in the advective flux that contribute to the reduction in mass flux as reflected in the dose reduction due to the addition of the invert.

7.10 CASE 10: ADD THE DRIP-SHIELD BARRIER

Figure 7-10 shows that the Case 10 peak mean annual dose has a value of 4.65×10^2 mrem/yr at 108,000 years postclosure. The peak of the 95th-percentile dose occurs at 108,000 years and has a value of 3.19×10^3 mrem/yr. Figure 7-10 also shows that at the time of the peak mean dose, the percent of the total dose contributed by Pu-239 (including colloids) is 85%, Np-237 is 11.5%, and Pu-242 (including colloids) is 1.4%. Other radionuclides that together contribute less than 4% of the mean annual dose but are either not shown or not discernible on Figure 7-10 are U-234, Pa-231, Ac-227, U-233, U-236, Tc-99, and Th-229.

Compared to Case 9, the peak of the mean annual dose for Case 10 is not delayed in time by adding the drip-shield barrier because the peak dose for the invert barrier occurs at about the same time as complete drip-shield failure. However, the addition of the drip-shield barrier reduces the peak of the mean annual dose by approximately 40%. Also, Figure 7-10 shows that the calculated mean annual dose is less than 1×10^{-6} mrem/yr for almost 30,000 years. Until 30,000 years, the drip shields remain intact, prohibiting the advective release of radionuclides from the repository. Once the drip shields begin to fail, the waste can be transported from the waste forms to and through the invert, eventually contributing to dose in the biosphere. The model results show that the first drip shield does not fail until 28,500 years postclosure,

indicating that the dose is essentially zero before this time. However, the simulation results show a low dose prior to this time because the minimum flux rate through the waste form in certain sectors of the model domain is 1×10^{-6} m³/yr, a value added to prevent computational errors in the code. Once the drip shields begin to fail, they fail quickly. In 50% of the realizations, all the drip shields are fully failed by 43,500 years postclosure. By 640,000 years postclosure, all drip shields completely fail in every realization.

Because diffusive releases have not been activated for Case 10, there is no radionuclide release, and, therefore, no dose from the waste forms that do not experience dripping conditions. The model simulations show that the number of no-drip versus dripped-upon waste forms indicates that, on average, 54% of the waste forms in the repository will likely experience no-drip conditions.

7.11 CASE 11: ADD THE WASTE-PACKAGE BARRIER

The peak mean annual dose for Case 11 occurs at 408,000 years postclosure and has a value of 8.10×10^1 mrem/yr as shown on Figure 7-11. The peak of the 95th-percentile dose occurs at 408,000 years postclosure and has a value of 3.42×10^2 mrem/yr. The addition of the waste-package barrier delays the Case 11 peak mean annual dose by 300,000 years postclosure relative to Case 10. In addition, the peak mean dose is approximately 83% less than that calculated for the Case 10 peak mean annual dose (See Figures 7-10 and 7-11). At the time of the peak mean annual dose, the percent of the total dose contributed by Np-237 is 58%, Pu-242 (including colloids) is 14.5%, and Pa-231 (including colloids) is 6.7%, Ac-227 is 5.4%, U-234 is 3.7%, Th-229 is 2.9%, and Pb-210 is 2.3% (Figure 7-11). Other radionuclides that together contribute less than 7% of the mean annual dose but are either not shown or not easily discernible on Figure 7-11 are Ra-226, U-232, U-236, and Th-230.

Not only does the addition of the waste-package barrier reduce the peak of the mean annual dose by 83%, but also the mean dose is below 1×10^{-6} mrem/yr for approximately 40,000 years postclosure. Until approximately 40,000 years, the waste packages remain intact, prohibiting the release of radionuclides from the repository, except for the case of early waste-package failure which occurs once in every realization (i.e., one package per 11,000) (BSC 2001 [154659], Section 8.4). Once the waste packages begin to fail, the waste can be transported from the waste form and the EBS, contributing to an eventual dose to the biosphere. A review of the results reveals that the first waste-package failure occurs due to early failure at 62.5 years into the simulation in some realizations. Additionally, 50% of the realizations have one waste-package early failure by 437.5 years. By 1300 years, there is one failure in every realization. However, without diffusion, the only transport mechanism from the failed waste packages is advection and, therefore, the release from one failed waste package requires drip-shield failure to provide the required fluid before radionuclides can be released to the UZ.

After the initial early waste-package failure within the first 1,500 years postclosure, the next waste-package failure is not experienced in any realization until after 50,000 years postclosure. In 50% of the realizations, all the waste packages are fully failed by 500,000 years postclosure. All the waste packages do not completely fail in every realization within the full one-million-year simulation period.

As was discussed in Section 7.10, diffusive releases were not activated for the Case 11 simulation. Therefore, there is no release from the waste packages that do not experience dripping conditions. Similar to the comparison between Cases 7 & 8 (Section 7.8), a review of the Case 11 results shows that, on average, 54% of the waste packages in the repository will experience no-drip conditions. However, the reduced number of no-drip waste packages results in only a 29% reduction in mean annual dose as determined by comparing the results from Case 10 with the results from Case 11. This difference in dose from that expected to the higher dose calculated by the model is likely due to flow focusing which results in a higher advective flux release from the dripped-upon packages.

7.12 CASE 12: ADD DIFFUSIVE TRANSPORT

The Case 12 calculated results are essentially the TSPA-FEIS model's base-case results used for evaluating the impact of the NRC final rule (Williams 2001 [156743] Section 6). The addition of diffusion increases the dose compared to Case 11 because the mass released was increased by the addition of the diffusive flux from the no-drip waste packages (CRWMS M&O 2000 [148384] Section 6.3.5, p. 350 and Table 6-63). Figure 7-12 shows that the peak mean annual dose for Case 12 occurs at 476,000 years postclosure. The peak mean dose has a value of 8.45×10^1 mrem/yr. The peak of the 95th-percentile dose occurs at 408,000 years and has a value of 3.75×10^2 mrem/yr. Figure 7-12 also shows that at the time of the peak mean annual dose, the percent of the total dose contributed by Np-237 is 60%, Pu-242 (including colloids) is 13%, and Pa-231 (including colloids) is 6.6%, Ac-227 is 5.3%, U-234 is 3.2%, Th-229 is 3%, and Pb-210 is 2.1%. Other radionuclides that together contribute less than 7% of the mean annual dose but are either not shown or not easily discernible on Figure 7-12 are Ra-226, U-233, U-236, U-238, and Th-230.

Compared to Case 11, the diffusion-transport mechanism delays the peak of the mean annual dose by 68,000 years. In addition, Figures 7-11 and 7-12 show that the peak mean annual dose is increased by approximately 4% for Case 12 relative to Case 11. The mean annual dose is greater than 1×10^{-6} mrem/yr for approximately the first 40,000 years which is different than the results for Cases 10 and 11. For Cases 10 and 11, no release from the repository could occur until there was water flux through the drip shields and waste packages. Thus, in no-drip environments, releases never occurred and in dripping environments, releases did not occur until the drip shields failed. By adding the diffusion-transport mechanism, this constraint is removed, allowing early-failure waste packages to immediately release radionuclides into the invert and the UZ. Furthermore, those waste packages which were confined to no-drip environments can now contribute to dose.

Case 12 includes the contribution to dose from no-drip environments, which on average account for one half of the waste packages in the repository. The result is that the dose increases, but the dose does not double despite the 100% increase in waste packages contributing to dose. For Case 12, the addition of diffusion allows the slow release of radionuclides from the EBS throughout the simulation period, eliminating large pulses of the released mass with the onset of advection. Diffusion also results in a reduction of the amount of mass retained in the EBS. In addition, activating diffusion from the EBS affects the treatment of diffusion in the UZ. Without diffusion, 100% of the mass released from the EBS is forced into fractures in the UZ. With diffusion, a fraction, proportional to the ratio of diffusive to advective releases from the EBS, is placed into the UZ matrix and the remaining fluid is transported through fractures by advection.

Also, releases can occur from no-drip environments into the matrix-flow pathway in the UZ. Thus, the time delay in the peak mean annual dose could be due to the slower transport of waste through diffusion-transport pathways from the EBS and through the UZ.

7.13 CASE 13: ADD SATURATED ZONE WITHOUT THE UNSATURATED ZONE BELOW THE REPOSITORY

One additional case, Case 13, was added to the 12 cases described in Section 6.2. For this case, the SZ barrier was added without the UZ barrier and the output from the SZ was transported directly to the biosphere. The purpose of this case was to estimate the relative contribution of the SZ apart from the effect of the UZ just as Case 6 considers the UZ without the effect of the SZ. Case 13 was investigated to assess the concept that part of the contribution of the SZ as a barrier may be masked by the prior addition of the UZ before the SZ in the sequence chosen for these “One-on” Analyses. Thus, Case 13 follows Case 5, does not have diffusion, and the radionuclides released go directly to the receptor.

Figure 7-13 shows that the Case 13 peak mean annual dose occurs at 125 years postclosure. The peak mean dose has a value of 2.45×10^5 mrem/yr. The peak of the 95th-percentile dose occurs at 125 years postclosure as well and has a value of 6.88×10^5 mrem/yr. At the time of the peak mean annual dose the percent of the total dose contributed by Cs-137 is 67%, Sr-90 is 31.8%, and Am-241 is 0.6% (Figure 7-13). Other radionuclides that together contribute less than 1% of the mean annual dose but are either not shown or not easily discernible on Figure 7-13 are Pu-239, Pu-238, Pu-240, Tc-99, Pa-231, Np-237, and Ac-227.

The Case 13 peak of the mean annual dose is delayed in time by 62.5 years postclosure as compared to Case 5 (Figures 7-5 and 7-13). In addition, the peak mean annual dose is 99.7% less than that calculated for Case 5. Because the peak mean annual dose decreases by more than two orders of magnitude, the SZ appears to be an effective barrier. In Case 13, Cs-137 and Sr-90 account for 99% of the peak dose. These two radionuclides contributed approximately 100% of the dose in Case 5, but their dose contribution was two orders of magnitude higher. These results indicate that the SZ effectively removes most of the Cs-137 and Sr-90, thus accounting for most of the drop in the peak dose.

In contrast to Case 13, Case 6 (Section 7.6) adds the UZ transport barrier as the second natural barrier. A comparison of the results of Cases 6 and 13 indicates that the UZ barrier is a more effective barrier in the removal of Cs-137 and Sr-90. These two radionuclides do not contribute any dose in Case 6 whereas these radionuclides account for the largest share of the Case 5 peak mean annual dose. Thus, the changes in the peak dose between Case 6 and Case 13 are attributed to their contrasting performance in removing Cs-137 and Sr-90 by each barrier. When compared to adding the SZ after adding the UZ, as in Case 7, most of the performance benefits experienced by adding the SZ in Case 13 were already included by adding the UZ in Case 6 before adding the SZ in Case 7.

7.14 COMPARATIVE ANALYSES

To further aid in comparing the results of the “One-on” analysis, the mean annual dose results of the simulations for Cases 1 through 13 are plotted together on Figure 7-14. Table 7-1 provides a case-by-case summary of peak mean annual dose and the time at which the peak mean annual dose occurs.

Further insight into the character of the simulated radionuclide transport from the repository is shown in comparative Figures 7-15 through 7-17 which display selected cases to highlight differences in barrier performance for the sequence of the addition of barriers chosen for the “One-on” analyses in this report. Figure 7-15 shows that the largest reduction in the peak mean annual dose in the regulatory period is after the addition of the UZ flow-and-transport barrier (see also Table 7-1.) The figure also shows the contributions of the drip shield and the waste package, which did not allow dose during the regulatory period because diffusion is not included in Cases 10 and 11. Figure 7-16 illustrates the effects due to the addition of the natural-system barriers including Case 13, the SZ without the UZ. The figure shows the natural barriers and the complete waste-form barrier (Case 4) for comparison. The figure shows the results for the cases when the UZ and SZ are connected directly to the repository horizon, Cases 6 and 13 respectively. The figure shows that the UZ appears to have the greater effect on reducing the mean annual dose, although the contribution of the SZ is not negligible. Figure 7-17 illustrates the effectiveness of the engineered-system barriers and Cases 7 and 8, the SZ and the UZ above the repository, respectively, for comparison. The figure shows the contribution of the drip shield when diffusion is neglected. The figure also shows that the addition of the waste package also contributes to an even lower dose. However, although the waste package contributes to a lowered dose, the delay to release allows the waste-package barrier to make a large contribution to lowering and delaying the mean annual dose.

Figures 7-18 through 7-27 show the contributions to the total mean annual dose of the mean annual doses of the nine radionuclides that provide the largest contribution to the total dose of the 26 radionuclides included in the TSPA-FEIS model. The figures show that for radionuclides with half lives of less than a few hundred years, the delay, in terms of radionuclide release, provided by the UZ and SZ is effective in reducing the mean annual dose due to these radionuclides. Figures 7-18 and 7-19 show that Tc-99 and I-129, respectively, still contribute to dose at 1,000,000 years postclosure, but their late-time contributions to total dose are 2 to 3 orders of magnitude less than Np-237 (Figure 7-27). Figures 7-20 and 7-21 show that, regardless of the barrier, Cs-137 and Sr-90, respectively, do not contribute significantly to dose after about 1,100 years postclosure. It should also be noted that the plotted curves for Cs-137 and Sr-90 for Cases 2 and 3 are identical (See Section 7.3) and therefore the blue and red curves cannot be distinguished from one another. The lowered dose for Cs-137 and Sr-90 is the product of the relatively short half-lives of these radionuclides and their removal by the UZ and SZ. Figures 7-22 and 7-23 show that from 10,000 to 100,000 years postclosure, that the plutonium radionuclides are the primary contributors to total dose regardless of the barrier. Figure 7-24 displays the C-14 dose contribution for each case and indicates that despite its 5,700-year half life, C-14 continues to contribute to doses until 100,000 years postclosure, and displays a seven order-of-magnitude decrease in dose. Figures 7-25 and 7-26 show that the americium radionuclides are strong contributors to dose during the regulatory period, primarily for the

natural barriers. After that time, the effect of the engineered barriers effectively reduces the contributions of the americium radionuclides below what was allowed by the natural barriers and processes. At late time, Figure 7-27 shows that Np-237 is the largest contributor to dose for most of the barriers.

7.15 SUMMARY OF RESULTS

Table 7-1 shows that, for the hypothetical barrier-addition sequence used for the analyses presented in this "One-on Analysis" report, the greatest reduction in peak dose and the largest increase in time to peak dose during the regulatory period occurs with the addition of the UZ barrier below the repository. The UZ barrier provides a reduction in peak mean annual dose of approximately 4 to 5 orders of magnitude relative to the preceding case in the chosen sequence. The UZ barrier provides an approximately 300-meter transport length and geochemical and geologic processes to retard the transport of radionuclides. Time and the UZ's geologic media are the principal factors in bringing about the dose reduction. Some of the potential contributing factors are matrix diffusion, sorption and mineral precipitation.

The One-on Analyses provide a closer review of barriers and processes whose effects during the regulatory time period may be masked in the full-scale TSPA model. One illustration of this phenomenon is Case 13 which evaluates the SZ in a similar manner as Case 6 evaluates the UZ. The results are presented in the last row of Table 7-1 and provide a relative perspective on the effectiveness of the SZ barrier. These results indicate that if the waste form were to be placed at the top of the SZ and there were no UZ, there would be a dose reduction of approximately two-to-three orders of magnitude. If this were the configuration of the repository, the SZ would appear to be the barrier providing the most dose reduction. Because of the sequence analyzed for this report, the SZ barrier appears to be less effective than the UZ because some of the protection offered by the SZ is redundant to that provided by the UZ.

The most interesting implication of these results is that, for the sequence of barriers analyzed for this report, the natural geologic barrier presented by the UZ, and the coupled UZ-SZ system, appears to provide significant dose reduction, relative to preceding cases. It is also interesting to note that in the model configuration describing the effect of the waste-package barrier, the UZ and SZ are also operative after waste-package failure. Waste-package longevity delays the onset of dose to a time greater than the half lives of the radionuclides that have a large contribution to total dose in early time, excepting early waste-package failure. Thus, the natural barriers, primarily the UZ and SZ, continue to operate to reduce and/or attenuate dose after the failure of the engineered barriers probably because the natural barriers operate on a geologic time scale.

The TSPA-FEIS base-case model, upon which the "One-on" analyses were developed, calculates the mass transport of radionuclides using both advective-and diffusive-release mechanisms. Diffusion has been a key transport pathway in the TSPA analysis since the SR. However, for all the cases analyzed except Case 12, this mechanism was not appropriate because the current TSPA diffusion-transport model requires the full EBS. Because only advection was used for flow and transport from the waste form and the repository horizon for Cases 1 to 11, and 13 these analyses provide a clearer picture of the relative roles of advection and diffusion relative to the Yucca Mountain repository system. Further, the Case 12 results reiterate the role of diffusion as a transport pathway during the regulatory time period.

The "One-on" analyses highlight the relative contributions of the natural processes and the impact on time to peak mean annual dose provided by the waste-package and drip-shield barriers. As shown on Table 7-1, the UZ and SZ contributed the most to the reduction in the peak mean annual dose during the regulatory time period. The analyses clearly show that the addition of the engineered barriers serves primarily to delay the release of radionuclides from the repository system but has less effect on the peak of the total mean annual dose. Viewed in this context, the natural and engineered barriers are complementary systems serving to both reduce the overall dose and delay arrival of radionuclides to the RMEI. The impact on dose for many of the radionuclides is delayed to times when the half lives of these radionuclides have reduced their concentrations, and thereby their dose, as compared to release within the regulatory time period (See Figures 7-18 to 7-27).

In addition to evaluating the relative contribution of certain natural and engineered barriers, these "One-on" analyses provide additional insight into the interaction of certain components of the TSPA-FEIS model and into the individual performance of other components of the TSPA-FEIS model.

With the removal of the natural and engineered barriers, certain short-lived radionuclides became dominant dose contributors at early times. Specifically, Cs-137 and Sr-90 were not transported to the biosphere in the base-case of the TSPA-FEIS model. These radionuclides were subject to release and transport for the analyses presented in this analysis because of their contributions in Cases 1 through 5. For Cases 1 through 5, the simulated results show that Cs-137 and Sr-90 contribute up to 99% of the early dose in these cases.

In the TSPA-FEIS model, the rockfall subsystem model fails all CSNF cladding when greater than 50% of the waste packages are failed. However, when activated in the absence of a waste package as in Cases 1 to 10 and Case 13, the rockfall subsystem model negates the performance of the cladding barrier. Therefore, the rockfall subsystem model was disabled for the analysis of Cases 1 to 10 and Case 13.

The sequence of "One-on" simulations of the cases presented in Sections 7.1 to 7.13 shows the apparent relative influence of each barrier or associated process. In aggregate, this suite of simulations shows a decrease in peak mean annual dose as each barrier is added to the analysis. Bare waste without natural or engineered barriers could result in a peak mean annual dose of approximately 2.66×10^{10} mrem/year immediately after disposal. Placing this waste into an engineered geologic repository gives an estimated mean annual dose under expected conditions of less than 1×10^{-4} mrem/year at end of the regulatory period. Thus, for this modeled case, "the repository system" provides a dose reduction of more than 14 orders of magnitude during the regulatory period as compared to the dose calculated for only the bare waste. Figure 7-14 and Table 7-1 show that not only does the value of the peak mean annual dose decrease in magnitude with addition of successive barriers, the data also indicate that as the value of the peak mean annual dose becomes lower, the time from postclosure to peak mean annual dose increases.

The results presented in Sections 7.1 to 7.13 are dependent on the order of the addition of the barriers. For the stylized sequence of barriers presented in this Analysis Report, the approach was to assess first the waste form, then the natural-system barriers, and lastly the engineered-system barriers. This approach considers the various systems sequentially, taking account of the potential masking effect of certain barriers relative to one another. Sequencing helped unmask

the relative influence of the SZ and the UZ. Both barriers appear to be effective in retarding the flow and transport of radionuclides but their mechanisms of retardation are to some extent redundant. Therefore, two separate cases, Case 6 and Case 13, considered singularly the effects of the UZ and SZ, respectively. In both of these cases, the radionuclides released from the waste form went directly to either the UZ or the SZ and then directly to the RMEI. The results are highlighted on Figure 7-16. A comparison of these results shows that although both barriers are very effective, in these hypothetical sequences, the addition of the UZ flow-and-transport barrier appears to provide a relatively greater reduction in the peak of the mean annual dose than does the SZ. Overall, however, sequencing may be less important than the totality of the contributions of all barrier systems processes and components, i.e., the total dose reduction due to the entire repository system may be sequence independent. This comparison of the results of these stylized analyses indicates the usefulness of this One-on approach in evaluating subsystem performance

Table 7-1 Summary of Peak Dose and Year of Peak Dose by Case for Various Performance Periods: (a) Peak Mean Annual Dose; (b) Peak 95th Percentile Annual Dose

a) Peak Mean Annual Dose								
Mean Annual Dose (mrem/yr)								
Case	Case/barrier Added	Model File	10,000 yr Peak		100,000 yr Peak		1,000,000 yr Peak	
			Value	Year	Value	Year	Value	Year
1	No Barriers, Dissolve Waste in 3000 AF/yr	SE01_157nm6.gsm	2.66×10^{10}	31.25	2.66×10^{10}	31.25	2.66×10^{10}	31.25
2	Add Waste-form Degradation Barrier Component	SE01_156nm6.gsm	1.30×10^{10}	62.5	1.30×10^{10}	62.5	1.30×10^{10}	62.5
3	Add Solubility Limits and Colloidal Stability Barrier Component	SE01_159nm6.gsm	3.63×10^9	62.5	3.63×10^9	62.5	3.63×10^9	62.5
4	Add CSNF Cladding	SE01_160nm6.gsm	1.59×10^8	62.5	1.59×10^8	62.5	1.59×10^8	62.5
5	Add Surficial Soils	SE01_161nm6.gsm	8.08×10^7	62.5	8.08×10^7	62.5	8.08×10^7	62.5
6	Add Unsaturated Zone Flow and Transport below the Repository	SE01_162nm6.gsm	2.12×10^3	4,940	3.92×10^3	40,000	3.92×10^3	40,000
7	Add Saturated Zone Flow and Transport	SE01_164nm6.gsm	5.05×10^2	7,250	2.64×10^3	39,000	2.64×10^3	39,000
8	Add UZ Barrier above the Repository	SE01_158nm6.gsm	4.44×10^2	9,250	2.11×10^3	39,000	2.11×10^3	39,000
9	Add Invert	SE01_171nm6.gsm	1.16×10^2	10,000	5.08×10^2	39,000	7.70×10^2	108,000
10	Add Drip Shield	SE01_172nm6.gsm	No Trans		9.92×10^1	100,000	4.65×10^2	108,000
11	Add Waste Package	SE01_173nm6.gsm	No Trans		1.97×10^{-1}	99,500	8.10×10^1	408,000
12	Add Diffusive Transport	SE01_167nm6.gsm	3.93×10^{-5}	4,125	2.01×10^{-1}	98,500	8.45×10^1	476,000
13	Add SZ without UZ below the Repository	SE1_174nm6.gsm	2.45×10^5	125	2.45×10^5	125	2.45×10^5	125
b) Peak 95th Percentile Dose								
95th Percentile Annual Dose (mrem/yr)								
Case	Case/barrier Added	Model File	10,000 yr Peak		1,000,000 yr Peak			
			Value	Year	Value	Year	Value	Year
1	No Barriers, Dissolve Waste in 3000 AF	SE01_157nm6.gsm	3.50×10^{10}	31.25	3.50×10^{10}	31.25	3.50×10^{10}	31.25
2	Add Waste-form Degradation Barrier Component	SE01_156nm6.gsm	2.13×10^{10}	62.5	2.13×10^{10}	62.5	2.13×10^{10}	62.5
3	Add Solubility Limits and Colloidal Stability Barrier Component	SE01_159nm6.gsm	7.16×10^9	62.5	7.16×10^9	62.5	7.16×10^9	62.5
4	Add CSNF Cladding	SE01_160nm6.gsm	3.45×10^8	62.5	3.45×10^8	62.5	3.45×10^8	62.5
5	Add Surficial Soils	SE01_161nm6.gsm	1.74×10^8	62.5	1.74×10^8	62.5	1.74×10^8	62.5
6	Add UZ Flow and Transport below the repository	SE01_162nm6.gsm	2.81×10^3	5,000	1.13×10^4	42,000	1.13×10^4	42,000
7	Add Saturated Zone Flow and Transport	SE01_164nm6.gsm	9.97×10^2	4,600	7.86×10^3	42,000	7.86×10^3	42,000
8	Add UZ Barrier above the Repository	SE01_158nm6.gsm	2.45×10^3	8,500	7.31×10^3	39,000	7.31×10^3	39,000
9	Add Invert	SE01_171nm6.gsm	5.01×10^2	10,000	1.48×10^3	80,500	3.78×10^3	108,000
10	Add Drip Shield	SE01_172nm6.gsm	No Trans		7.17×10^2	99,000	3.19×10^3	108,000
11	Add Waste Package	SE01_173nm6.gsm	No Trans		7.75×10^{-2}	100,000	3.42×10^2	408,000
12	Add Diffusive Transport	SE01_167nm6.gsm	2.19×10^{-4}	4,900	1.06×10^{-1}	100,000	3.75×10^2	408,000
13	Add SZ without UZ below the Repository	SE1_174nm6.gsm	6.88×10^5	125	6.88×10^5	125	6.88×10^5	125

The results are shown to three significant figures to checking and use of the data package submitted to the YMP TDMS. However, given the hypothetical nature of these analyses, the results should be considered to be on the order of one significant figure.

Figure 7-1 Case 1: No Barriers, Waste Dissolved in 3,000 Acre Feet of Water. Mean Annual Dose Due to Waste-Form Dissolved in 3,000 acre-ft of water per year, a) Total Dose, b) Major Radionuclide Contributions to the Mean

Figure 7-2 Case 2: Add Waste-form Degradation Barrier Component. Mean Annual Dose due to Waste-Form Degradation, a) Total Dose b), Major Radionuclide Contributions to the Mean

Figure 7-3 Case 3: Add Solubility Constraints and Colloid Stability Barrier Component. Mean Annual Dose after adding Solubility Limits and Colloid Stability, a) Total Dose, b) Major Radionuclide Contributions to the Mean

Figure 7-4 Case 4: Add CSNF Cladding. Mean Annual Dose after adding CSNF Cladding, a) Total Dose, b) Major Radionuclide Contributions to the Mean

Figure 7-5 Case 5: Add Surficial Soils. Mean Annual Dose after adding Surficial Soil, Topography, and Unsaturated Zone above the Repository, a) Total Dose, b) Major Radionuclide Contributions to the Mean

Figure 7-6 Case 6: Add Unsaturated Zone Flow and Transport below the Repository. Mean Annual Dose after Unsaturated-Zone Flow and Transport, a) Total Dose, b) Major Radionuclide Contributions to the Mean

Figure 7-7 Case 7: Add Saturated Zone Flow and Transport. Mean Annual Dose after Saturated-Zone Flow and Transport, a) Total Dose, b) Major Radionuclide Contributions to the Mean

Figure 7-8 Case 8: Add the Unsaturated Zone above the Repository (i.e., Drift) Barrier. Mean Annual Dose after adding the UZ above the Repository and its Interaction with the Repository Drifts, a) Total Dose, b) Major Radionuclide Contributions to the Mean

Figure 7-9 Case 9: Add the Invert Barrier. Mean Annual Dose after adding Invert, a) Total Dose, b) Major Radionuclide Contributions to the Mean

Figure 7-10 Case 10: Add the Drip-shield Barrier. Mean Annual Dose after adding Drip Shields, a) Total Dose, b) Major Radionuclide Contributions to the Mean

Figure 7-11 Case 11: Add the Waste-package Barrier. Mean Annual Dose after Waste Packages, a) Total Dose, b) Major Radionuclide Contributions to the Mean

Figure 7-12 Case 12: Add Diffusive Transport. Mean Annual Dose after adding TSPA-FEIS Treatment of Diffusion, a) Total Dose, b) Major Radionuclide Contributions to the Mean

Figure 7-13 Case 13: Add Saturated Zone without the Unsaturated Zone. Mean Annual Dose after adding Saturated-Zone Flow and Transport without Unsaturated-Zone Flow and Transport, a) Total Dose, b) Major Radionuclide Contributions to the Mean

Figure 7-14 Comparative Plot of Mean Annual Dose after Adding Each Successive Case

Figure 7-15 Comparative Plot of Mean Annual Dose Showing Most Effective Barriers

Figure 7-16 Comparative Plot of Mean Annual Dose showing Comparative Effect of UZ and SZ

Figure 7-17 Comparative Plot of Mean Annual Dose showing Comparative Effect of Engineered-System Barriers

Figure 7-18 Comparative Plot of Mean Annual Dose due to Tc-99 after Adding Each Successive Case

Figure 7-19 Comparative Plot of Mean Annual Dose due to I-129 after Adding Each Successive Case

Figure 7-20 Comparative Plot of Mean Annual Dose due to Cs-137 after Adding Each Successive Case

Figure 7-21 Comparative Plot of Mean Annual Dose due to Sr-90 after Adding Each Successive Case

Figure 7-22 Comparative Plot of Mean Annual Dose due to Pu-239 after Adding Each Successive Case

Figure 7-23 Comparative Plot of Mean Annual Dose due to Pu-240 after Adding Each Successive Case

Figure 7-24 Comparative Plot of Mean Annual Dose due to C-14 after Adding Each Successive Case

Figure 7-25 Comparative Plot of Mean Annual Dose due to Am-241 after Adding Each Successive Case

Figure 7-26 Comparative Plot of Mean Annual Dose due to Am-243 after Adding Each Successive Case

Figure 7-27 Comparative Plot of Mean Annual Dose due to Np-237 after Adding Each Successive Case

8. INPUTS AND REFERENCES

The following is a list of the references cited in this analysis, Column 1 represents the unique six digit Document Input Reference System (DIRS) number, which is placed in the text following the callout (e.g., (BSC 2001 [154659])). The purpose of these numbers is to assist the reader in locating a specific reference. The reference list is ordered numerically by the DIRS number.

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8.3 SOURCE DATA

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ATTACHMENT I ACRONYMS AND ABBREVIATIONS

BSC	Bechtel SAIC Company, LLC
CFR	Code of Federal Regulations
CDSP	Co-disposed
CRWMS	Civilian Radioactive Waste Management System
CSNF	Commercial Spent Nuclear Fuel
DIRS	Document Input Reference System
DOE	U.S. Department of Energy
DSNF	DOE-owned Spent Nuclear Fuel
EBS	Engineered Barrier System
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
FEIS	Final Environmental Impact Statement
HLW	High-Level Waste
mrem	millirem
MTHM	Metric Tons of Heavy Metal
NRC	U.S. Nuclear Regulatory Commission
NWPAA	Nuclear Waste Policy Amendments Act
NWTRB	Nuclear Waste Technical Review Board
RMEI	Reasonably Maximally Exposed Individual
SSPA	Supplemental Science and Performance Analyses
SZ	Saturated Zone
TDMS	Technical Data Management System
TSPA	TOTAL SYSTEM PERFORMANCE ASSESSMENT
TSPA-SR	Total System Performance Assessment for the Site Recommendation
TSPA-FEIS	Total System Performance Assessment-Final Environmental Impact Statement
TSPA-LA	Total System Performance Assessment for the License Application
UZ	Unsaturated Zone
WAPDEG	<u>waste-package-degradation</u> model