THE U.S. NUCLEAR REGULATORY COMMISSION OFFICE OF NUCLEAR MATERIAL SAFETY AND SAFEGUARDS REVIEW OF THE U.S. DEPARTMENT OF ENERGY'S KEY TECHNICAL ISSUE AGREEMENT RESPONSES RELATED TO THE PROPOSED GEOLOGIC REPOSITORY AT YUCCA MOUNTAIN, NEVADA: STRUCTURAL DEFORMATION AND SEISMICITY 2.01, 2.01 ADDITIONAL INFORMATION NEEDED-1, 2.02, 2.04, AND 2.04 ADDITIONAL INFORMATION NEEDED-1; REPOSITORY DESIGN, THERMAL, AND MECHANICAL EFFECTS 2.01, 2.02, AND 3.03; CONTAINER LIFE AND SOURCE TERM 3.10; AND TOTAL SYSTEM PERFORMANCE ASSESSMENT AND INTEGRATION 3.06

1.0 INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) issue resolution goal during this interim prelicensing period is to ensure the U.S. Department of Energy (DOE) has assembled sufficient information about a given issue for NRC to accept a potential license application for review. Resolution by NRC during prelicensing does not prevent anyone from raising any issue for NRC consideration during the licensing proceedings. It is equally important to note that resolution of an issue by NRC during the prelicensing period does not prejudge the NRC evaluation of the issue during the licensing review. Issues are resolved by NRC during prelicensing when the staff has no further questions or comments about how DOE is addressing an issue. Pertinent new information could raise new questions or comments about a previously resolved issue.

By a letter dated June 29, 2004, DOE submitted a report titled "Technical Basis Document (TBD) No. 14: Low Probability Seismic Events" (Bechtel SAIC Company, LLC, June 2004a) to satisfy the informational needs of numerous key technical issue (KTI) agreement items pertaining to ground motion, seismic design, and performance assessment issues that may affect the performance of the emplacement drifts and the engineered barrier system (EBS) of the potential repository at Yucca Mountain, Nevada. The major elements of the EBS are the waste package, drip shield, emplacement pallet, and the fuel rod cladding.

The KTI agreements were reached during technical exchanges with DOE: i) Structural Deformation and Seismicity (SDS), October 2000 (Schlueter, 2000); and ii) Technical Exchange and Management Meeting on Repository Design and Thermal-Mechanical Effects (RDTME), February 2001, in Las Vegas, Nevada (Reamer and Williams, 2001).

The specific agreements addressed in the technical basis document are categorized by DOE according to the following four issues:

(I) Rockfall and Vibratory Ground Motion Effect on Cladding;

(ii) Seismic Input for Preclosure Design;

(iii) Expert Elicitation of Ground Motion; and

(iv) Documentation of Seismic Fragility Curves.

For the eight agreements addressed in TBD 14, DOE stated that it has satisfied the NRC information needs regarding the agreements and that all agreements should be considered complete. Section 4.0 of this report provides the NRC evaluation of the extent to which DOE's submittal satisfies the informational requirements by NRC of these agreements.

2.0 KTI AGREEMENTS

In Appendices A, B, C, and D of TBD 14, DOE identified the following KTI agreements as being satisfied by the information provided in TBD 14 text and appendices: (1) Appendix A in TBD 14 "Rockfall and Vibratory Ground Loading Effects on the Mechanical Failure of Cladding and Methodology Used to Implement the Seismic Effects on Cladding" responds to KTI agreements Container Life and Source Term (CLST) 3.10 and Total System Performance Assessment and Integration (TSPAI) 3.06; (2) Appendix B "Seismic Inputs for Preclosure Design and Analysis: Methodology" responds to KTI Agreements RDTME.2.01, 2.02, 3.03, and SDS.2.02; (3) Appendix C "Expert Elicitation of Ground Motion Interpretations for the Yucca Mountain Probabilistic Seismic Hazard Analysis: Treatment of Uncertainty and Feed back" responds to KTI Agreement SDS.2.01and 2.01 AIN-1; and (4) Appendix D "Documentation of Seismic Fragility Curves and Seismic Risk Analysis" responds to KTI Agreement SDS.2.04 and 2.04 AIN-1.

The wordings of the agreements are:

SDS.2.01

"Regarding ground motion, provide documentation, or point NRC to the documentation on the expert elicitation process, regarding the feedback to the subject matter experts following the elicitation of their respective judgements. DOE will provide documentation demonstrating the adequacy of the elicitation feedback process by December 2000."

SDS.2 01 AIN–1

"DOE needs to provide clear documentation of the expert elicitation process and its implementation, specifically with regard to the feedback process associated with the experts' interpretation, evaluation, and validation of their ground motion models. Documentation of the experts' reasoning is as important as the elicitation process. Therefore, the documentation should include: the experts' rationale for their interpretations, evaluations, and validations based on feedback; rationale for the experts' understanding and acknowledgment of how their results would be used by DOE to develop seismic design input values for pre-closure and post-closure analyses. Documentation should be consistent with the guidelines in NUREG–1563 (e.g., section on post-elicitation feedback, p. 28)."

SDS.2.02

"Provide the updated FEPs [features, events, and processes]: Disruptive Events AMR, the Seismic Design Input Report, and the update to the Seismic Topical Report. DOE will provide the updated FEPs AMR to the NRC. Expected availability is January 2001. DOE will provide STR 3 to the NRC for their review. Expected availability is January 2002. The Seismic Design Inputs Report is expected to be available to the NRC by September 2001."

SDS.2.04

"The approach to evaluate seismic risk, including the assessment of seismic fragility and evaluation of event sequences is not clear to NRC, provide additional information. DOE believes the approach contained in the FEPs AMR will be sufficient to support the site recommendation. The updated FEPs AMR is expected to be available in January 2001."

SDS 2.04 AIN-1

"DOE needs to provide documentation of methodology, technical bases and data for: (1) the development of seismic fragility curves for structures, systems and components used in performance assessments, including assurance that the necessary data will be available for the time period of interest (TPI), when needed. Moreover, this documentation should address: the range of failure modes that can occur for individual components, component interactions, etc.; consideration of component deterioration and its effect on the seismic capacity; the use of a step function to define conditional probability of cladding failure; (2) conducting a seismic risk analysis for the repository, including the assessment of the effect of cladding failure on design bases, barrier or system performance, or performance confirmation. This documentation should describe the identification, modeling and evaluation of the range of accident scenarios that could occur in the repository as a result of a seismic event during the TPI; and (3) any additional points discussed in NRC's review."

RDTME.2.01

"Provide Topical Report 3, Preclosure Seismic Design Inputs for a Geologic Repository at Yucca Mountain. Consistent with SDS Subissue 2, Agreement 2, the DOE will provide Seismic Topical Report 3, Preclosure Seismic Design Inputs for a Geologic Repository at Yucca Mountain, expected to be available to the NRC in January 2002."

RDTME.2.02

"Provide the substantive technical content of Topical Report 3. The DOE will provide the preliminary seismic design input data sets used in Site Recommendation design analyses to the NRC by April 2001. The DOE will provide the draft final seismic design inputs for license application via an Appendix 7 meeting after calculations are complete prior to delivery of Seismic Topical Report 3."

RDTME.3.03

"Provide the Seismic Design Inputs AMR [analysis and model report] and the Preclosure Seismic Design Inputs for a Geologic Repository at Yucca Mountain, Seismic Topical Report 3. Consistent with SDS Subissue 2, Agreement 2, the DOE will provide the Seismic Design Inputs analysis and model report and Preclosure Seismic Design Inputs for a Geologic Repository at Yucca Mountain, Seismic Topical Report 3. These documents are expected to be available to NRC in January 2002."

CLST.3.10

"Provide Analysis of the rockfall and vibratory loading effects on the mechanical failure of cladding, as appropriate. DOE stated that the vibratory effects are documented in Sanders et al. 1992 SAND90-2406, "A method for determining the Spent-Fuel contribution to Transport Cask Containment Requirements." This will be discussed in the SDS KTI meeting. The analysis of the rockfall effects on the mechanical failure of cladding will be addressed if the agreed to updated rockfall analysis in Section# 2, Item 8 and subissue #1, Item 14 demonstrate that the rockfall will penetrate the drip shield and damage the waste package."

TSPAI.3.06

"Provide the technical basis for the methodology used to implement the seismic effects on cladding in revised documentation. DOE will demonstrate that the methodology used to represent the seismic effects on cladding does not result in an underestimation of risk in the regulatory time frame (ENG 2.1.1). DOE will provide the technical basis for the methodology used to implement the seismic effects on cladding in revised documentation. DOE will demonstrate that the methodology used to represent the seismic effects on cladding does not result in underestimation of risk in the regulatory time frame in TSPA-LA. The documentation is expected to be available to NRC in FY 2003."

3.0 TECHNICAL INFORMATION PROVIDED BY DOE

3.1 Response to KTI Agreements SDS.2.01 and SDS.2.01 AIN-1

Additional information to address SDS.2.01 and 2.01AIN–1 was provided by DOE in Appendix C of "Technical Basis Document No. 14: Low Probability Seismic Events, Revision 1" (Bechtel SAIC Company, LLC, 2004a), within which DOE states, "...the experts were adequately prepared and that they received adequate feedback to their interpretations consistent with state-of-knowledge guidance, which seeks to document the unbiased uncertainty of the informed scientific community about ground-motion estimation." In particular, Appendix C provides additional information to address the NRC concerns raised in Reamer (2001) that there is a large range of differences among experts' interpretations of ground motion effects resulting from varied interpretations of aleatory and epistemic uncertainties.

The additional information provided by DOE centers on two aspects of DOE's ground motion expert elicitation process: (i) the training and information provided to the experts to help them develop their interpretations of uncertainty; and (ii) the feedback the experts received from fellow experts and elicitation facilitators that was then used by the experts to refine their interpretations. Tables 1-4 in Appendix C provide: (i) time line of ground-motion elicitation activities; (ii) definitions of the different types of uncertainty that needed to be defined by the experts during the elicitation; (iii) ground-motion elicitation review schedule; and (iv) summary of ground-motion data packages used in the feedback process. Example plots in Appendix C show median horizontal ground motion point estimates (spectral acceleration) with the associated epistemic and aleatory uncertainties. The point estimate is for a magnitude 6.5, shallow, strike-slip faulting earthquake at a distance 1 km [0.6 mi] from the site.

3.2 Response to Agreements RDTME.2.01, 2.02, 3.03, and SDS.2.02

Agreements RDTME.2.01, 2.02, and 3.03 were reached during the DOE/NRC Technical Exchange and Management Meeting on RDTME held February 6–8, 2001, in Las Vegas, Nevada. The RDTME KTI subissues 1, 2, 3, and 4 were discussed at that meeting (Reamer and Williams, 2001).

To partially fulfill Agreement RDTME.2.02, DOE provided preliminary seismic design input data sets used in site recommendation design analyses (Brocoum, 2001). Staff reviewed those data and informed DOE they did not need any additional information pertaining to those data (Reamer, 2002). The status of the agreement was listed as "Partly Received."

To help address these RDTME and SDS agreements, DOE and NRC held an Appendix 7 meeting August 6–8, 2002, at which time DOE provided staff with draft information intended to be documented in the Seismic Design Inputs analysis and model report (AMR) and Seismic Topical Report 3. Topics included results of surface facility geotechnical investigations that support development of seismic design inputs and an overview of the approach to be used.

The geotechnical investigations discussed at that meeting are described in "Geotechnical Data for a Potential Waste Handling Building and for Ground Motion Analyses for the Yucca Mountain Site Characterization Project" (Bechtel SAIC Company, LLC, 2002).

The updated features, events, and processes AMR on disruptive events (CRWMS M&O, 2000a) was provided to NRC in 2001. Staff concluded this aspect of the agreement was complete (Reamer, 2002).

In October 2000, DOE provided staff with an annotated outline for the third seismic topical report (Brocoum, 2000). Since then, DOE has revised its approach to documentation of preclosure seismic information (Ziegler, 2004a) and issued Topical Report YMP/TR-003-NP, Revision 3 (Ziegler, 2004b). The updated topical report (Revision 3) of (Seismic Topical Report #2, CRWMS M&O, 1997) is intended to be more consistent with the regulatory concepts in 10 CFR 63.102 and the performance objectives in 10 CFR 63.111. In addition, DOE no longer intends to issue the third seismic topical report. Instead, DOE intends to provide the seismic information, which originally was to be contained in Seismic Topical Report 3, in three alternative documents: (i) "Characterize Framework for Seismicity and Structural Deformation at Yucca Mountain, Nevada, Revision 0, ANL–CRW–GS–000003" (CRWMS M&O, 2000b); (ii) "Technical Basis Document No. 14: Low Probability Seismic Events, Revision 1" (Bechtel SAIC Company, LLC, 2004a); and (iii) "Development of Earthquake Ground Motion Input for Preclosure Seismic Design and Postclosure Performance Assessment of a Geologic Repository at Yucca Mountain, NV, Revision 01, MDL–MGR–GS–000003" (Bechtel SAIC Company, LLC, 2004f). These documents have been delivered to the NRC staff for review.

3.3 Response to Agreements SDS.2.04 and 2.04 AIN-1

The DOE responses to SDS.2.04 and 2.04 AIN-1 are provided in Appendix D of "Technical Basis Document No. 14: Low Probability Seismic Events, Revision 1" (Bechtel SAIC Company, LLC, 2004a). In their response, DOE summarized the findings of several reports related to the evaluation of seismic risk. In particular, DOE cited analyses and results from "Seismic Consequence Abstraction" (Bechtel SAIC Company, LLC, 2003a) and "Sampling of Stochastic

Input Parameters for Rockfall and Structural Response Calculations under Vibratory Ground Motions" (Bechtel SAIC Company, LLC, 2003b). In these reports, DOE developed a seismic scenario class for Total System Performance Assessment (TSPA) based on damage abstractions for waste package, drip shield and cladding. The abstractions represent the probability of failure as a function of the amplitude of the ground motion or fault displacement. In the abstractions, input ground motions are characterized in terms of peak ground velocity because this parameter is deemed to more accurately predict the response of the host rock and engineering barriers. The abstractions are based on the failure mechanism of accelerated stress corrosion cracking due to high residual stress from mechanical deformation during a seismic event.

The DOE seismic scenario class for TSPA is based on Monte Carlo simulation. The DOE concluded that the Monte Carlo approach is appropriate because, unlike fragility analyses for nuclear power plants, the emphasis in TSPA is on predicting a continuous range of reasonable component behavior in contrast to the approach used in more traditional fragility probability of failure application used for analyses of power plant components. The damage abstractions and computational methodology are defined in *Seismic Consequence Abstraction* (Bechtel SAIC Company, LLC, 2004e), which provides a description of the technical bases and input data for the seismic risk analysis for TSPA.

3.4 Response to Agreement CLST.3.10

The DOE responded to this agreement in: (i) "Technical Basis Document No. 7: In-Package Environment and Waste Form degradation and Solubility, Revision 01" (Bechtel SAIC Company, LLC, 2004b) - Chapter 4 Commercial Spent Nuclear Fuel Cladding Degradation, 4.2.3 Mechanical Failure of Cladding after Placement in the Repository; (ii) Clad Degradation - FEP Screening Argument (Bechtel SAIC Company, LLC, 2004c); (iii) Clad Degradation - Summary and Abstraction for License Application (LA) (Bechtel SAIC Company, LLC, 2004d); and (iv) Seismic Consequence Abstraction (Bechtel SAIC Company, LLC, 2004e). The DOE response is summarized as:

- Cladding damage is assessed to be 0% and 100%, respectively, at the peak ground velocity values of 0.55 m/s and 1.067 m/s. These two peak ground velocities correspond to mean annual exceedance frequencies of seismic events of $5x10^{-5}$/year and 10^{-5}/year, respectively. A total cladding loss with any damage was implicitly assumed.

- Cladding perforation begins when both the fraction of drip shield patch openings and the fraction of waste package patch openings exceed the sampled uncertainty of 0.2 to 0.5 uniform distribution. After perforations commence from static load of rock overburden, the fraction of cladding with perforations will depend linearly on only the fraction of waste package patches open until all the rods are perforated when an additional 50% of the waste package patches are open.

3.5 Response to Agreement TSPAI.3.06

The DOE response to TSPAI.3.06 is provided in Appendix D of "Technical Basis Document No. 14: Low Probability Seismic Events, Revision 01" (Bechtel SAIC Company, LLC, 2004a). In its response, DOE summarized the basis and methodology used to implement the seismic effects on cladding into the TSPA. In particular, DOE's cite analyses and results from *Seismic Consequence Abstraction* (Bechtel SAIC Company, LLC, 2004e). In this report, DOE developed a seismic scenario class for TSPA based on damage abstraction for waste package, drip shield and cladding.

4.0 NRC EVALUATION AND COMMENTS ON DOE'S RESPONSE TO THE AGREEMENTS

4.1 KTI Agreement SDS.2.01 and 2.01 AIN-1

4.1.1 Relevance of SDS.2.01 and 2.01 AIN-1 to Repository Performance

Seismic hazard results are important because seismicity is one of the disruptive events that could impact repository safety and performance. For the preclosure period of performance, systems, structures, and components important to safety must maintain their safety functions during and after an earthquake. For postclosure evaluations, seismicity is an important input to drift stability analysis and overall performance assessment of the engineered barriers, especially drip shields and waste packages. Therefore, assessments of the vibratory ground motions at Yucca Mountain from earthquakes that are used to develop inputs to seismic design, preclosure safety assessments, and postclosure performance assessments need to be developed from a reliable and defensible technical basis. This agreement is ranked as having "low risk significance" in Attachment 3 of Travers (2003).

4.1.2 Staff Evaluation of KTI Agreement SDS.2.01 and SDS.2.01 AIN-1

The DOE conducted a probabilistic seismic hazard assessment for Yucca Mountain (CRWMS M&O, 1998). Results of this assessment were probabilistic assessments of fault displacements and earthquake-induced vibratory ground motions that could affect repository safety and performance at Yucca Mountain. These hazards are defined using fault displacement and seismic hazard curves, in which the increasing levels of fault displacement or vibratory ground motion (usually expressed in units of acceleration and velocity) are plotted as a function of annual exceedance probability. This hazard assessment was accomplished through expert elicitation.

The DOE concluded that the probabilistic seismic assessment expert elicitation followed the guidance provided in both NUREG/CR–6372 (Budnitz, et al., 1997) and NUREG–1563 (NRC, 1996), including treatment of uncertainty and expert feedback. The DOE notes that the only exception where they did not follow the guidance was not documenting the preliminary and intermediate interpretations by the experts. This exception allows the experts to consider information/data that were not previously used in their preliminary assessment and enable them to freely change their interpretations during the elicitation feedback process and, thereby, avoid the possibility that the experts would prematurely anchor their positions on selected topics.

Staff concerns regarding the elicitation process arose from questions about the scientific basis used for several of the experts' ground motion assessment. In particular, staff noted large differences in predicted ground motion estimates and associate epistemic and aleatory uncertainties among experts, as summarized in NUREG–1762 (NRC, 2002, pp. 3.3.2-22 through 3.3.2-25). These differences in approach among the experts and their treatments of uncertainties affect the levels of predicted ground motions at low annual exceedance probabilities (below 10^{-6}). Large differences among the ground motion experts lead to seismic hazard curves with a relatively shallow slopes, large uncertainties about the mean and median values, and a skewed distribution of the mean toward the upper uncertainty limits (e.g., see Figure 10 in Stepp, et al., 2001).

Although the probabilistic seismic hazard assessment was completed in 1998, DOE revised its plans to use the ground motion expert elicitation results, especially as they pertain to postclosure performance assessments. In "Technical Basis Document No. 14: Low Probability Seismic Events, Revision 01" (Bechtel SAIC Company, LLC, 2004a), DOE concluded that the large ground motions predicted by the probabilistic seismic hazard assessment at annual exceedance probabilities of 10^{-6} and below are unrealistic and greatly exaggerate the ground motions that could occur at Yucca Mountain. Thus, DOE has adopted an approach to more accurately assess the upper range of ground motion at Yucca Mountain to values considered more representative of the site conditions. In Bechtel SAIC Company, LLC (2004a), DOE states:

> "Large ground motion predicted by the PSHA [probabilistic seismic hazard assessment] at annual exceedance probabilities of 1.0×10^{-6} and below overestimates the severity of low-probability ground motion at Yucca Mountain. This overestimation of ground motion is being addressed through determination of constraints on maximum ground motion imposed by the stress-release characteristics of seismic sources and by limits on strain that can be propagated by seismic waves through rocks at Yucca Mountain. The constraint on maximum ground motion will be incorporated in the abstraction of seismic consequences that feeds TSPA [Total System Performance Assessment]."

In the performance assessment calculations for the license application, DOE intends to cap the ground motions, limiting peak ground velocities to an upper-bound range of 250–500 cm/sec [8.2 to 16.4 ft/sec]. This approach effectively restricts application of the 1998 probabilistic seismic hazard assessment to ground motions with annual exceedance probabilities greater than 10^{-6}. For ground motions with annual exceedance probabilities between 10^{-6} and 10^{-8}, DOE will use the 250–500 cm/sec [8.2 to 16.4 ft/sec] upper-bound values. Technical bases for these upper-bound values are to be developed by DOE through ongoing studies of the stress-release characteristics of seismic sources and by limits on strain that can be propagated by seismic waves through rocks similar to those at Yucca Mountain.

The DOE is taking this action because most technical experts (including comments from the NRC and Center for Nuclear Waste Regulatory Analyses staffs) conclude that the ground motion values at low annual exceedance probabilities are unrealistically large. For example, in DOE's postclosure performance assessment, strong motion recordings of acceleration scaled to the seismic hazard at 10^{-7} annual exceedance probability, yield peak ground acceleration as high as 20g [~640 ft/s^2]. This value is well beyond the limits of existing earthquake accelerations from even the largest recorded earthquakes worldwide, and the value is nearly one order of magnitude larger than those observed for earthquakes with moment magnitudes between 6.5 and 7.0. These large ground motions also are deemed physically unrealizable because they require a combination of stress drop, strain, and rupture propagation that cannot be sustained without wholesale fracturing of the bedrock (e.g., Kana, et al., 1991).

These unrealistic earthquake ground motions arise in DOE's study because the seismic hazard curves are constructed as unbounded log-normal distributions. In past practice, probabilistic seismic hazard curves were used to estimate mean ground motions with an annual exceedance probability down to 10^{-4} (a typical annual exceedance probability value designated for nuclear power plant design). Ground motions for hazards at the 10^{-4} level matched expected values for the largest earthquakes that could affect a given site in the eastern U.S. For Yucca Mountain, however, the seismic hazard curves are extrapolated to estimate ground motions with annual exceedance probabilities as low as 10^{-8}. At these low probabilities, the seismic hazard estimates are driven by the tails of the untruncated Gaussian distributions of the input ground motion attenuation models (e.g., Bommer, et al., 2004). As pointed out by Anderson and Brune (1999), overestimates of the hazards also may arise because experts improperly distributed uncertainty in the inputs between the aleatory and epistemic uncertainties.

Similar comments and questions about the seismic hazard were raised at the February 24, 2003, Nuclear Waste Technical Review Board Panel (NWTRB) on Natural System and Panel on Engineered Systems joint meeting about seismic issues. The Board's seismic meeting focused on the large vibratory ground motions predicted by DOE's probabilistic seismic hazard assessment at annual exceedance probabilities below 10^{-6} per year. In a letter from the NWTRB to DOE (Coraddini, 2003), the Board stated:

> "…although the probabilistic seismic hazard assessment is, in general, sound, extending it to very low probabilities results in ground-motion estimates about which there are serious technical questions. These relate to the lack of physical realism and the implication of these unrealistic estimates for performance assessment, design, and scientific confidence."

The Board notes that application of a physically unrealistic or highly conservative approach, even if acknowledged as such by DOE, could lead to numerous problems including a skewed understanding of repository behavior and the significance of different events, consideration of events for which there is little or no understanding or engineering practice, and undermined confidence in the scientific basis of the process being considered.

This change in DOE's approach effectively moots the staff concerns raised in SDS.2.01 and 2.01 AIN-1. The staff question regarding the expert elicitation is no longer relevant because DOE no longer relies on expert elicitation results as a basis for estimates of the low probability ground motions, those with annual exceedance probabilities between approximately 10^{-6} and 10^{-8}. Therefore, staff concludes that KTI Agreements SDS.2.01 and 2.01 AIN-1 are closed. At this time, staff has no further questions concerning the probabilistic seismic hazard assessment elicitation process.

4.2 KTI Agreements RDTME.2.01, 2.02, 3.03, and SDS.2.02

4.2.1 Relevance of RDTME.2.01, 2.02, 3.03, and SDS.2.02 to Repository Performance

Similar to SDS.2.01, Agreements RDTME.2.01, 2.02, 3.03, and SDS.2.02 are related to the development of technically defensible seismic information used in both preclosure design and safety assessments and postclosure performance assessment. For preclosure, the seismic inputs are used to support the design and performance analyses of systems, structures and components deemed important to safety. For the postclosure period, seismic motions are used to evaluate seismic effects on the EBS. Seismically-induced damage to the surface or underground facilities including the EBS must be factored into preclosure safety analyses, and total system performance after permanent closure. These agreements are ranked as having "medium risk significance" in Attachment 3 of Travers (2003).

4.2.2 Staff Evaluation of KTI Agreements RDTME.2.01, 2.02, 3.03, and SDS.2.02

Information needs related to these agreements has been recently provided in four DOE reports: (i) Technical Basis Document No. 14: Low Probability Seismic Events, Revision 1, (Bechtel SAIC Company, LLC, 2004a); (ii) Development of Earthquake Ground Motion Input for Preclosure Seismic Design and Postclosure Performance Assessment of a Geologic Repository at Yucca Mountain, NV, Revision 1, (Bechtel SAIC Company, LLC, 2004f); (iii) Preclosure Seismic Design Methodology for a Geologic Repository At Yucca Mountain, NV, Revision 3, CRWMS M&O, 2004a); and (iv) Features, Events, and Processes: Disruptive Events, CRWMS M&O, Revision1, 2004b). These reports outlined DOE probabilistic seismic hazard assessments for both pre-closure and post-closure period of performance as well as the approach for developing seismic inputs for both periods. The approach for developing seismic inputs is based upon the mean seismic hazard curves developed by the probabilistic seismic hazard analysis. To account for the 300 m (984 ft) of material above the repository level, DOE used a one-dimensional, random-vibration-theory-based, equivalent-linear site response method. Random variability in velocity and dynamic properties at the site are incorporated in the site response computations. In its analysis, DOE did not incorporate two- and three-dimensional wave propagation effects (e.g., effects of topography, dipping strata). In its potential license application, DOE should consider accounting for these effects and the non-linear behavior of the horizontal component of motion in the potential licence application. Time histories to support preclosure and postclosure analyses have been developed by DOE for mean annual probabilities of exceedance of 5×10^{-4}, 10^{-4}, 10^{-5}, $10^{-6,}$ and 10^{-7}. In the TSPA-LA, DOE is considering faulting and ground motion as potential disruptive events that will affect the integrity of the repository. The information provided in these reports meets the information needs in KTI Agreements and, thus, the staff considers these agreements to be closed.

4.3 KTI Agreements SDS.2.04, 2.04 AIN-1, CLST.3.10, and TSPAI.3.06

4.3.1 Relevance of SDS.2.04, 2.04 AIN-1, CLST.3.10, and TSPAI.3.06 to Repository Performance

These agreements address the effect of rockfall and ground motion on cladding and the methodology for how seismic information is integrated and abstracted into DOE's safety and performance assessment. The information requested in the agreements is intended to ensure that sufficient information is available to support the technical basis and methodology for the implementation of the seismic effects on spent nuclear fuel cladding damage. This information is abstracted into the TSPA to support a review of a potential license application. This implementation, as part of the TSPA, is expected to affect the estimates for the releases of radionuclides from the spent nuclear fuel following seismic events in the event that waste packages become breached. These agreements are ranked as having "low risk significance" in Attachment 3 of Travers (2003).

4.3.2 Staff Evaluation of KTI Agreement SDS.2.04, 2.04 AIN-1, CLST.3.10, and TSPAI.3.06

Based on the review of "Technical Basis Document No. 14: Low Probability Seismic Events, Revision 01" (Bechtel SAIC Company, LLC, 2004a), NRC staff concludes that DOE's response to the main points of SDS.2.04, 2.04 AIN-1, CLST.3.10 and TSPAI.3.06 have been discussed by DOE. In addition, if the drip shield and waste package maintain their integrity against various modes of corrosion and mechanical failure, radionuclide releases from cladding, regardless of cladding integrity, will be prevented. Although the staff considers the main points of the agreements are discussed, the technical contents of the responses will be enhanced if DOE considers the recommendations in the following sections:

Probabilistic Distribution Function for Seismic Abstractions

The DOE has proposed the use of a uniform distribution for the damage abstractions, which have been modified to bound the results of an independent analysis based on fitted log-normal distributions (Bechtel SAIC Company, LLC, 2004e). The staff notes, however, that since the number of realizations is very small for certain conditions, DOE should address the sufficiency of the number of successful realizations.

Monte Carlo Simulation

The seismic scenario class for TSPA is based on Monte Carlo simulation, which determines the level of damage to EBS components for a given amplitude of earthquake ground motion. For the non-lithophysal zone, 15 ground motions are combined with synthetic fracture patterns; whereas for the lithophysal zone, a Monte Carlo sampling provides 15 combinations of ground motions and rock mass categories. In the available reports, DOE has not addressed how the selection of the number of realizations considers the representation of uncertainty and variability and its implication on the final analysis.

The DOE has considered random variability due to the frequency content of the ground motions and epistemic uncertainty due to metal-to-metal friction and metal-to-rock friction. The DOE has not addressed the reasons for selecting the above parameters as the only random variables. For example, input parameters such as the stiffness and strength of the rubble surrounding the drip shield present large uncertainty, an uncertainty that may largely affect the dynamic interaction between the drip shield and the surrounding rubble.

Multiple Seismic Events

The DOE seismic analyses are based on a single ground motion for each realization. and coupled effects from multiple seismic events are not considered. However, because the earthquake distribution is represented by a Poisson distribution, successive earthquakes with relatively large ground motions could occur. The DOE has not provided adequate rationale to explain why coupled effects from multiple events were not considered. The DOE should consider if integrity of the waste packages and drip shields will be compromised through multiple earthquake events.

Dynamic Interaction Analyses Including Presence of Rubble

The DOE calculations of dynamic interaction between waste packages, or waste package and drip shield, consider that the drift remains intact during the regulatory period. However, rockfall may occur due to existing thermo-mechanical conditions or due to additional stresses that may be superimposed by potential seismic events (Power et al. 1998). The DOE analyses indicate that the column of rock on top of the drip shield is several times larger than the height of the drip shield (Bechtel SAIC Company, LLC, 2004c). The presence of rubble around the drip shield may modify the dynamic performance of the system. This performance of the system is also affected by indirect factors, such as the increase in temperature that modifies the material properties of the engineered barriers. The DOE should address dynamic interaction structural analyses in which the drip shield is surrounded by rubble.

Failure Criteria

The DOE has evaluated several failure modes for the engineering barriers under seismic loading conditions. Some of the failure modes have been considered very unlikely, and they have been screened out of the TSPA (e.g., immediate tensile failure from puncture or tearing). The DOE has concluded that the most likely cause of failure of waste package and drip shield is "...the presence of residual tensile stress that may nonetheless result in enhanced local degradation from stress corrosion cracking." In this scenario, a barrier is assumed to be susceptible to stress corrosion cracking once a predefined residual tensile stress threshold is exceeded. However, this approach implies that plastic deformation does not always generate a failed area in DOE's scenario because the final residual stress state may be compressive or, if tensile, may be below the tensile threshold to initiate stress corrosion cracking. Areas with plastic deformation, which are not considered failed areas in the above failure criterion, could accelerate different types of failure modes. The failure criteria under seismic events should be consistent with the mechanical failure criterion for mechanical loading specified in "Technical Basis Document No. 6: Waste Package and Drip Shield Corrosion" (Bechtel SAIC Company, LLC., 2003c).

These areas may increase creep effects under static loads, or increase the level of damage in subsequent seismic events (see section of "Multiple Seismic Events" above). The DOE should address the methods used to define the credible failure mechanims.

Model Uncertainty

The DOE, in its submittal, presents potential conservatism (e.g., involving the acceleration from end-to-end impacts of adjacent waste packages) associated with the abstraction for cladding damage due to seismicity. The DOE should consider how alternative models might affect the analysis.

5.0 Summary

Based on our review of the information provided by DOE, the staff considers KTI Agreements SDS 2.01, 2.01 AIN-1, 2.02, 2.04, 2.04 AIN-1; RDTME 2.01, 2.02, 3.03; CLST 3.10; and TSPAI 3.06 are closed. The staff has also provided recommendations for DOE consideration. It is up to DOE to decide how to respond to the staff's recommendations. Please note that NRC will make its final determination on any issues relevant to licensing during its review of any potential Licensing Application.

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