THE OFFICE OF NUCLEAR MATERIAL SAFETY AND SAFEGUARDS REVIEW OF THE

U.S. DEPARTMENT OF ENERGY KEY TECHNICAL ISSUE

AGREEMENT RESPONSE TO PRE 7.02

FOR A POTENTIAL GEOLOGIC REPOSITORY AT YUCCA MOUNTAIN, NEVADA

PROJECT NO. WM–00011

1.0 INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) goal of issue resolution during this interim prelicensing period is to ensure the U.S. Department of Energy (DOE) has assembled enough information about a given issue for NRC to accept a license application for review. Resolution by the NRC staff during prelicensing does not preclude anyone from raising any issue for NRC consideration during the licensing proceedings. Also, and just as importantly, resolution by the NRC staff during prelicensing does not prejudge the NRC staff evaluation of that issue before its actual licensing review. Issues are considered resolved by the NRC staff during prelicensing when the staff have no further questions or comments about how DOE addresses an issue. Pertinent new information could raise new questions or comments about a previously resolved issue.

To satisfy the information needs of Key Technical Issued (KTI) Agreement PRE 7.02, DOE submitted a report (Bechtel SAIC Company, LLC, 2003a) which was transmitted with a cover letter.[1]

The agreement response (Bechtel SAIC Company, LLC, 2003a) provides information about the uncertainties and the methodologies DOE proposed to use to address these uncertainties associated with modeling the response of the waste package to various design basis events using the finite element method.

2.0 WORDING OF THE AGREEMENT

Section 2, Response to the KTI Agreement, of Bechtel SAIC Company, LLC (2003a) indicates the submitted documentation provides the basis for the closure of KTI Agreement PRE 7.02. The wording of the agreement is as follows:

PRE 7.02: “Provide the waste package finite element analysis based numerical simulations that represent a significant contribution to DOE’s safety case. Provide documentation demonstrating that a sufficient finite element model mesh discretization has been used and the failure criterion adequately bounds the uncertainties associated with effects not explicitly considered in the analysis. These uncertainties include but are not limited to: (1) residual and differential thermal expansion stresses, (2) strain-rate effects, (3) dimensional and material variability, (4) seismic effects on ground motion, (5) initial tip-over velocities, and (6) sliding and

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[1]Ziegler, J.D. “Transmittal of Information Addressing Key Technical Issue (KTI) Agreement Item, Preclosure Safety (PRE) 7.02.” Letter (December 10) to Document Control Desk, NRC. Las Vegas, Nevada: DOE. 2003.

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inertial effects of the waste package contents, etc. In addition, document the loads and boundary conditions used in the models and provide the technical bases and/or rationale for them. DOE agreed to provide the information. The information will be available in FY03 and documented in "Waste Package Design Methodology Report."

3.0 TECHNICAL INFORMATION PROVIDED IN THE AGREEMENT RESPONSE

Bechtel SAIC Company, LLC (2003a) provided a systematic assessment of the potential uncertainties associated with modeling the response of the waste package to various design basis events. The waste package was modeled using the finite element method. In addition, DOE provided the methodologies it is proposing to use to address these uncertainties.

3.1 Finite Element Model Mesh Discretization

A summary of the methodology employed by DOE to establish the adequacy of the waste package finite element model mesh discretization was provided in Section 3.1.1, Mesh Discretization, of Bechtel SAIC Company, LLC (2003a). Specifically, the finite element model mesh discretization will be considered adequate if the relative difference in results generated by the initial mesh and the refined mesh is approximately one order of magnitude smaller than the relative difference in mesh size in the region of interest. As defined by DOE, the mesh size refers to the volume or the area of the representative element in the region of interest. The mesh refinement process is performed in a sequential manner, one spatial direction at a time. After completion of this process, the mesh acceptance criterion is assessed one last time using the completely refined model (i.e., refined in all applicable spatial directions).

3.2 Structural Failure Criteria

The criteria that will be used by DOE to assess the potential failure of a waste package when subjected to the various design basis events of concern were identified in Section 3.1.2, Selection of the Failure Criterion, of Bechtel SAIC Company, LLC (2003a). In particular, the failure criteria suggested by the ASME International Boiler & Pressure Vessel Code (2001, Appendix F–1341.2) for plastic analysis will be used to interpret the results obtained from the waste package finite element analyses. If these criteria are not satisfied, integral measures will be examined by DOE on a case-by-case basis to determine if a less conservative failure criterion may be used.

3.3 Differential Thermal Expansion Stresses

DOE identified the reports that document the methodology used to establish the axial and radial gaps required between the waste package inner and outer shells in Section 3.2.1.1, Differential Thermal Expansion, in Bechtel SAIC Company, LLC (2003a). DOE indicated the minimum axial gap between the inner and outer waste package shells is 10 mm [0.39 in]. The minimum radial gap was reported to be 1 mm [0.04 in]. The thermal expansion gaps will vary for the different waste package configurations.

3.4 Residual Stresses Attributable to Waste Package Fabrication Processes

A summary of the methodology employed by DOE to assess the potential effects of residual stresses created in the waste package by the various fabrication processing steps was presented in Section 3.2.1.2, Effect of Residual Stresses, of Bechtel SAIC Company, LLC (2003a). Discussion was limited to the potential residual stresses arising from the solution annealing and quenching processes proposed to be used to generate compressive stresses on the exterior surface of the waste package outer shell prior to emplacement of the spent nuclear fuel or high-level waste and installation of the closure lids. Although quenching may be performed on either the exterior surface only or both the interior and exterior surfaces simultaneously, the report only discusses the latter.

DOE acknowledged the study of residual stress effects on waste package performance was limited by the through-wall discretization used for the waste package outer shell in that only four, one-point-integration solid elements were used. Moreover, DOE acknowledged the one-point-integration solid elements are not formulated to represent residual stress distributions in an accurate manner. DOE pointed out, however, this modeling approach for assessment of the effects of residual stresses was chosen because DOE wanted to maintain consistency with the models that have been used to evaluate the response of the waste package to various design basis events that do not explicitly include the presence of these residual stresses.

Because of the mesh discretization deficiencies just described, two different waste package outer barrier residual stress distributions were studied to evaluate their effects on the waste package response to a horizontal drop onto its supporting pallet with an impact velocity of 8 m/s [26 ft/s]. The first distribution assigned the maximum residual stress value anticipated within the volume of material represented by that particular element. The second distribution assigned the average residual stress value to the elements. It was also noted the initial effective plastic strain was assumed to be zero.

The report presents results of the study that compared the maximum stress intensity, maximum effective plastic strain, and the size of the damaged area, with and without residual stresses included in the analyses.

3.5 Strain Rate Effects

A summary of the methodology employed by DOE to assess the potential effects of material strain rates on the waste package response to dynamic loads was presented in Section 3.2.2, Strain Rate Effects, of Bechtel SAIC Company, LLC (2003a). DOE indicated strain rate data for the waste package inner and outer shell materials (i.e., Type 316 SS and Alloy 22) are not readily available. As a result, the potential effects of material strain rate variability were studied parametrically by using the strain rate characteristics of Type 304 SS to establish the adjusted inner and outer shell material constitutive models.

It was assumed the tangent moduli for both materials are unaffected by strain rate, consistent with the behavior of Type 304 SS. The method used to scale the waste package material yield and ultimate tensile strengths was presented. The range of material strain rates evaluated was reported to be 20 – 900 per second. The effects of strain rate on the waste package response to tip-over from an elevated surface was summarized by comparing the results obtained from the finite element analyses of this design basis event.

3.6 Dimensional Variability Effects

DOE indicated in Section 3.2.3, Dimensional and Material Variability, of Bechtel SAIC Company, LLC (2003a) the effects of waste package dimensional variability have been accounted for by assuming the thicknesses of the inner and outer shells are the minimum allowable, as defined by the waste package allowable tolerances, in the finite element models.

3.7 Material Variability Effects

DOE indicated in Section 3.2.3, Dimensional and Material Variability, of Bechtel SAIC Company, LLC (2003a) that the effects of waste package material variability have been accounted for by assuming the minimum yield and ultimate tensile strength values available from the applicable codes and standards [e.g., the ASME International Boiler & Pressure Vessel Code (2001)] for the inner and outer shell materials in the finite element models.

3.8 Seismic Event Ground Motion Effects

DOE indicated in Section 3.2.4, Seismic Effect on Ground Motion, of Bechtel SAIC Company, LLC (2003a) it has been assumed fixtures will be provided to restrain the waste package in the surface facilities during preclosure handling operations so no damage will be incurred by the waste package during a seismic event. Therefore, the evaluation was limited to consideration of the waste package response to seismic events after emplacement within the drift. The report (Section 3.2.4) also indicated the vibratory ground motions used for the evaluation represent seismic events that have an annual exceedance frequency of 5×10^{-4} per year (i.e., a 2,000-year return period).

3.9 Initial Tip-Over Velocity Effects

A summary of the methodology employed by DOE to establish the potential initial tip-over velocities that may be experienced by the waste package if the tip-over is initiated by a seismic event was provided in Section 3.2.5, Initial Tip-Over Velocities, of Bechtel SAIC Company, LLC (2003a). Using the conservation of energy principle, a mathematical relationship was developed to approximate the rotational velocity of the waste package at the time of impact. This relationship includes consideration of the initial tip-over velocity of the waste package.

To assess the potential effects that initial tip-over velocities can have on the response of the waste package, a series of analyses was performed using a range of initial tip-over velocities spanning 0 – 1.62 rad/s. This range of initial tip-over velocities is consistent with horizontal ground motion velocities varying from 0 to 4.38 m/s [0 to 14.4 ft/s].

3.10 Sliding and Inertial Effects of Waste Package Contents

DOE indicated in Section 3.2.6, Sliding and Inertial Effect of Waste Package Contents, of Bechtel SAIC Company, LLC (2003a) the sliding and inertial effects of the waste package contents are evaluated in calculations where they are anticipated to affect the performance of the waste package inner and outer shells.

4.0 NRC EVALUATION AND COMMENT

Staff reviewed Bechtel SAIC Company, LLC (2003a), reference documents, and other technical documents (see Section 7.0 of this document). The results of the staff evaluation are described next.

4.1 Finite Element Model Mesh Discretization

Although the general methodology for establishing the adequacy of a finite element mesh discretization is satisfactory (Bechtel SAIC Company, LLC, 2003a, Section 3.1.1), additional information might be needed to support the proposed convergence criterion in the potential license application. As defined in the report, the proposed convergence criterion requires the difference in results between two mesh discretizations be less than 10 percent of the relative difference in mesh size in the region of interest. However, the report did not explicitly state which particular analysis results are to be used in implementing this convergence criterion. Because displacements are continuous from one element to the next (i.e., displacements exhibit C^o continuity), basing the convergence criterion on this variable may not provide sufficient continuity in the discontinuous displacement derivatives, which are used to calculate the strains and stresses. Moreover, additional justification might be needed for relating the finite element solution results to mesh size. As noted by Bathe (1996, Section 4.3):

> "The element stresses are calculated using derivatives of the displacements …, and the stresses obtained at an element edge (or face) when calculated in adjacent elements may differ substantially if a coarse finite element mesh is used. The stress differences at the element boundaries decrease as the finite element mesh is refined, and the rate at which this decrease occurs is of course determined by the order of the elements in the discretization."

In other words, the appropriate percentage of the difference in results relative to the difference in mesh size needed to achieve a consistent measure of the allowable discontinuity of stress and strain between adjacent elements is dependent on the element formulations used in the model (e.g., single integration point vs. higher order elements). As a result, the proposed mesh discretization convergence criterion should be calibrated for the specific element formulations being used so the allowable discontinuity of the stresses calculated at the node points in the region of interest is reasonably consistent from one model to the next. For example, establishing an allowable difference between the minimum and maximum element results of interest at a shared node could be a basis for calibrating the proposed mesh discretization convergence criterion.

It was also noted during the review of Bechtel SAIC Company, LLC (2003b) that the mesh discretization convergence criteria was not evaluated at all or, in the case of Bechtel SAIC Company, LLC (2003c), that the mesh discretization satisfying the convergence criteria was not used to perform the analytical study.

4.2 Structural Failure Criteria

The proposed structural failure criteria, which is applicable to materials governed by plastic collapse, for the waste package 316 Stainless Steel inner shell and Alloy 22 outer shell are acceptable to the staff. However, it should be noted that the intent of the proposed failure criteria (ASME International Boiler & Pressure Vessel Code, 2001, Appendix F–1341.2) for Level D service limits are intended to assure maintenance of structural integrity but not to prevent leakage (ASME International Boiler & Pressure Vessel Code, 2001, Appendix F–1200). Because the proposed Level D service limits are based on the ASME Boiler and Pressure Vessel Code definitions of primary stresses, the assessment of the results obtained from finite element analyses of the waste package subjected to various design basis events should be characterized in terms of these parameters.

4.3 Differential Thermal Expansion Stresses

Bechtel SAIC Company, LLC (2003a, Section 3.2.1.1), indicated the methodologies used to establish the axial and radial gaps between the waste package inner and outer shells are documented in Bechtel SAIC Company, LLC reports (2001, 2003d). A review of these methodologies determined that the temperature differences between the inner and outer waste package shells were established in a conservative manner and their corresponding thermal expansion was calculated in a manner consistent with standard engineering practice. However, the basis for the exterior surface temperatures of the waste package outer shell used to establish the required thermal expansion gaps should be provided with appropriate consideration of the expected waste form decay heat rate; potential loss of the heating, ventilation, and air-conditioning system within the waste handling facilities; transport to the subsurface facilities (including potential transporter failure); loss of ventilation within the emplacement drift, and so on.

4.4 Residual Stresses Attributable to Waste Package Fabrication Processes

A summary of the methodology used to assess the potential effects of residual stresses in the waste package outer shell on the design basis loads that could cause its breach by plastic collapse was provided in the report (Bechtel SAIC Company, LLC, 2003a, Section 3.2.1.2). The ASTM International standard for Alloy 22 (1998) indicates this material has a minimum elongation in 50 mm [2 in] of 45 percent. If it can be shown that a significant loss of material ductility does not occur because of the residual stresses created within the waste package outer shell during its fabrication, these residual stresses are not likely to appreciably affect the design basis loads that could cause a breach by plastic collapse. The basis for the residual stress distribution used in the assessment was presented in Herrera, et al. (2002). Because the finite element mesh discretization through the thickness of the waste package outer shell used to assess the potential effects of residual stresses was constructed using only four, equally sized, single-integration-point solid elements, the compressive and tensile residual stresses must be defined as having equal magnitudes for the model to be in a state of equilibrium before applying the design basis loads. Thus, the model is not capable of representing the distinct maximum compressive and tensile residual stresses at the same time. Nevertheless, this deficiency is only relevant if a significant loss of material ductility can be expected to occur because of the presence of these residual stresses. Residual stresses in the waste package outer shell will have a significant effect on the potential occurrence of stress corrosion cracking during the postclosure period. However, an assessment of these effects on stress corrosion cracking is beyond the scope of KTI Agreement PRE 7.02.

4.5 Strain Rate Effects

Because the stress–strain curves for the waste package inner and outer shell materials for varying strain rates are not available at the present time, DOE used the behavior of Type 304 SS as the basis to scale the yield and ultimate tensile strengths of these materials. No adjustment was made of the minimum elongation for either material. According to Levin et al. (1999, Figure 5), however, it would appear that a potential loss of ductility for Alloy 22, at least for relatively high strain rates, does in fact exist. As a result, justification for not considering the potential loss of ductility for both 316 SS and Alloy 22 over the full range of strain rates these materials are expected to experience during various design basis events is needed.

It was also not clear in the agreement response whether the constitutive models employed within the finite element models used to assess the potential effects of strain rates on the response of the waste package accommodated the spatial variability of the strain rate. It is expected that the waste package materials will experience significant strain rate spatial variations when subjected to dynamic loads. As a result, the applicable material strengths and corresponding stress-strain relationships will vary spatially. In other words, the constitutive relationships implemented within the finite element models should explicitly define the material yield and ultimate strengths in terms of strain rate. Lastly, the spatially varying material strengths should be considered when assessing the potential for failure. This information should be provided at the time of the potential license application.

4.6 Dimensional Variability Effects

To bound the potential effects that dimensional variability may have on the response of the waste to design basis events, DOE committed to performing all structural calculations using the minimum material thicknesses (Bechtel SAIC Company, LLC, 2003a, Section 3.2.3). Future design drawings will indicate the applicable dimensional tolerances. The proposed approach to bounding the potential dimensional variability effects on waste package response to design basis events is acceptable to the staff.

4.7 Material Variability Effects

To bound the potential effects that material variability may have on the response of the waste package to design basis events, DOE committed to performing all structural calculations using the minimum available material property strengths (Bechtel SAIC Company, LLC, 2003a, Section 3.2.3). The proposed approach to bounding the potential material variability effects on waste package response to design basis events is acceptable to the staff. It was noted, however, that the analyses presented in Bechtel SAIC Company, LLC (2003b, 2003e) used minimum elongation values that are approximately 50-percent greater than the applicable ASTM International standard for Alloy 22. As a result, justification is needed for using minimum elongation values exceeding the applicable ASTM International standards.

4.8 Seismic Event Ground Motion Effects

DOE noted in Bechtel SAIC Company, LLC (2003a; Section 3.2.4) the waste package response to vibratory ground motions with an annual exceedance frequency of 5×10^{-4} (i.e., a 2,000-year return period) was evaluated. This evaluation was limited to consideration of the waste package response to seismic events after emplacement within the drift. The use of a 5×10^{-4} annual exceedance frequency (i.e., a 2,000-year return period) seismic event as the preclosure design basis, which has been informally discussed by DOE during NRC-DOE technical interactions, has not been formally presented by DOE nor formally accepted by NRC.

Justification was not provided for the assumption that restraints will be sufficient to prevent damage to the waste package during preclosure handling operations when subjected to a seismic event.

The finite element modeling methodology used to evaluate the response of the waste package to vibratory ground motions and the concomitant results were documented in Bechtel SAIC Company, LLC (2003b). Although this report presented an evaluation of the waste package response to both pre- and post-closure design basis ground motions, the review was limited to those analyses relevant to the preclosure period. An assessment of the modeling methodology used to evaluate the response of the waste package to postclosure design basis ground motions is beyond the scope of KTI Agreement PRE 7.02.

4.9 Initial Tip-Over Velocity Effects

The methodology proposed by DOE to establish the initial waste package tip-over velocity that could result from a seismic event was found to be acceptable by the staff. The report noted the initial waste package tip-over velocities considered in analyses performed to date have been based on repository horizon vibratory ground motions. However, no discussion was provided in Bechtel SAIC Company, LLC (2003a; Section 3.2.5) addressing the potential effects of the vertical motion of the floor created by the seismic event on the level of damage incurred by the waste package during a tip-over event in the region of impact. This information may be necessary for the staff to make a determination on the adequacy of the potential license application.

4.10 Sliding and Inertial Effects of Waste Package Contents

Depending on whether DOE intends to take credit for the structural integrity of the cladding for preclosure or postclosure performance, explicitly including the sliding and inertial effects of the waste package contents may be necessary to demonstrate the loads incurred by the waste form are not sufficient to cause appreciable damage.

5.0 SUMMARY

Staff reviewed the response to DOE/NRC KTI Agreement PRE 7.02 (Bechtel SAIC Company, LLC, 2003a). Acceptable methodologies were presented for (i) developing adequate finite element model mesh discretizations; (ii) establishing differential thermal expansion gaps between the waste package inner and outer shells; (iii) assessing residual stress, and dimensional and material variability effects on the waste package response to preclosure design basis events; (iv) evaluating the response of the waste package to preclosure seismic events; and (v) approximating the initial waste package tip-over velocities as a function of the ground motion initiating the tip-over. The proposed material failure criteria are also acceptable to the staff.

However, during the review of a proposed licence application, the staff may need to review the following information pertaining to the implementation of these methodologies to gain reasonable assurance that waste package will perform its intended function:

1. Justification for not considering the effect of varying element formulations on the proposed finite element mesh discretization convergence criterion.

2. Basis for the temperatures used to establish the axial and radial gaps between the waste package inner and outer shells.

3. Justification for not considering the potential loss of ductility for both 316 SS and Alloy 22 over the full range of strain rates these materials are expected to experience during various design basis events.

4. Clarification as to how waste package material strain rate effects were implemented within the finite element models and how the spatially varying material strengths are considered when assessing the potential for failure.

5. Justification for using minimum elongation values that exceed the applicable ASTM International standards.

6. Justification for the assumption that restraints will be sufficient to prevent damage to the waste package during preclosure handling operations when subjected to a seismic event.

7. Justification for using a 5×10^{-4} annual exceedance frequency (i.e., a 2,000-year return period) seismic event as the preclosure design basis.

8. Analyses demonstrating the range of tip-over velocities considered in the sensitivity study bound those velocities ultimately determined to be the appropriate design bases.

9. Analyses demonstrating that the vertical motion of the floor created by the seismic event will not significantly affect the level of damage incurred by the waste package during a tip-over event in the region of impact. This discussion should address justification of the ground motion values used to represent the vertical motion of the floor.

10. Analyses demonstrating that the structural integrity of the waste form is not compromised during postulated waste package design basis events. These analyses are only required if credit is to be taken for the structural integrity of the waste form during the preclosure or postclosure performance periods.

6.0 STATUS OF THE AGREEMENT

Based on this review, the staff consider the status of DOE/NRC KTI Agreement PRE 7.02 closed.

7.0 REFERENCES

ASME International. *ASME International Boiler and Pressure Vessel Code*. New York City, New York: ASME International. 2001.

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