THE U.S. NUCLEAR REGULATORY COMMISSION OFFICE OF NUCLEAR MATERIAL SAFETY AND SAFEGUARDS REVIEW OF U.S. DEPARTMENT OF ENERGY'S KEY TECHNICAL ISSUE AGREEMENT RESPONSE RELATED TO POTENTIAL GEOLOGIC REPOSITORY AT YUCCA MOUNTAIN, NEVADA: CONTAINER LIFE AND SOURCE TERM 2.03 ADDITIONAL INFORMATION NEED-1

1.0 INTRODUCTION

By letter dated December 9, 2003, U.S. Department of Energy (DOE) submitted "Technical Basis Document No. 6: Waste Package and Drip Shield Corrosion" (Bechtel SAIC Company, LLC, 2003). Subsequently, by letter dated July 22, 2004, DOE submitted "Technical Basis Document (TBD) No. 6 Appendix S" (Bechtel SAIC Company, LLC, 2004a). The TBD and the appendixes were provided to satisfy the informational needs of numerous Key Technical Issue (KTI) items pertaining to the environmental degradation of the waste package and drip shield materials. In addition, the TBD and the appendices included issues raised by the U.S. Nuclear Regulatory Commission (NRC) related to corrosion processes and the design of the waste package and drip shield for a potential repository at Yucca Mountain (YM), Nevada. The information was requested by the NRC during technical exchanges in September 2000, February 2001, July 2001, August 2001, and September 2001. The specific agreement addressed in this NRC review is Container Life and Source Term (CLST) 2.03, Additional Information Need-1 (AIN-1) (Schlueter, 2000, 2003).

2.0 AGREEMENT

The wording of the agreement and the AIN-1 are provided in the subsequent paragraphs.

CLST.2.03

"Demonstrate how the Tresca failure criterion bounds a fracture mechanics approach to calculating the mechanical failure of the drip shield. DOE stated that it believes its current approach of using ASME Code is appropriate for this application. Additional justification for this conclusion will be included in the next revision of AMR ANL–XCS–ME–000001, Design Analysis for the Ex-Container Components, to be completed prior to License Application."

CLST.2.03 AIN–1

(1) Clarification of the material failure criterion expected to be used for assessing the response of the drip shield and waste package to mechanical loading (i.e., ASME Boiler and Pressure Vessel Code stress intensity or maximum normal stress theory). If the maximum normal stress theory criterion is to be used, its applicability to ductile metals must be justified.

(2) Justification of the fracture toughness values obtained from empirical correlations with Charpy V-notch impact toughness data.

(3) Justification for adjusting the ultimate tensile strengths from engineering stress to Cauchy stress (i.e., true stress) values.

Enclosure

(4) The effect of variations in the fracture toughness and plastic collapse stress of Titanium Grade 7 and Titanium Grade 24 on drip shield failure.

(5) Justification for not considering a combined mode of fracture failure in the Titanium Grade 7 drip shield plate when subjected to rock block impacts.

(6) The effect of fabrication and stress mitigation processes and allowed variations in alloy composition on the fracture toughness of Alloy 22.

3.0 RELEVANCE TO OVERALL PERFORMANCE

Agreement CLST.2.03 is related to the mechanical failure and lifetime of the waste packages and drip shields, specifically how the Tresca failure criterion bounds a fracture mechanics approach to calculating the mechanical failure of the drip shield. Furthermore, information on the effects of fabrication, such as phase instability and initial defects, on the response of the engineered barrier system materials to mechanical loads due to emplacement, retrieval operations, seismic events, rockfall, and drift degradation is necessary to assess overall system performance.

The waste package, composed of the containers and the waste forms, would be the primary engineered barrier controlling the release of radionuclides from spent nuclear fuel and high-level waste glass. Because of uncertainties in the environment of the emplacement drifts after waste package emplacement and permanent closure of the potential repository, the mechanical properties of the engineered barrier system materials should be considered. Fabrication processes for the waste packages and drip shields may alter the strength, and more importantly, the ductility of the engineered barrier materials. Defects, joints, and sectional transitions may act as initiation points for fractures if the materials used to construct the engineered barriers have insufficient fracture toughness.

Drip shield performance is an important factor regarding safety because the drip shields are incorporated into the design of the engineered barrier system to limit the amount of water contacting the waste package from dripping and preventing rockfall damage. Initiation of aqueous corrosion of the waste packages depends on the deliquescence of dust or the contact with seepage water. Presence of the drip shields will delay contact of seepage water with the waste package surface, resulting in a longer container lifetime. In addition, once the containers are breached, the amount of water available for the dissolution of spent nuclear fuel and high-level waste glass and advective transport of the released radionuclides could be limited, even though drip shield may be partially damaged.

The NRC performed a risk insights analysis that indicates the mechanical disruption of engineered barriers has medium significance to waste isolation (NRC, 2004). Sustained rockfall rubble loads and seismic excitations could lead to mechanical failure of the drip shields and waste packages. Penetration of waste packages would allow water to contact the waste forms and potentially release radionuclides. The integrity of the drip shield has medium significance to waste isolation because, while intact, the drip shield would limit the quantity of water contacting the waste packages and waste forms and limit the formation of aggressive environments on the waste package surfaces. The geometry of penetrations in the waste package and the drip shield could be altered by applied loads from external events such as rockfall, seismicity, and drift degradation.

4.0 RESULTS OF THE NRC REVIEW

Agreement CLST.2.03 is included in the integrated subissue for mechanical disruption of engineered barriers. This agreement resulted from a staff review of DOE documentation that is consistent with Review Method 2 in Section 2.2.1.3.2.2 of the YM Review Plan (NRC, 2003). The NRC's review of the response to this agreement was also conducted in accordance with the aforementioned review method. This review method includes evaluation of the sufficiency of the experimental data used to support parameters in conceptual models and process-level models.

The focus of CLST.2.03 was to ensure that the assessment of the mechanical degradation of the waste packages and drip shields properly considered the effects of phase instability and initial defects. In addition, the assessment of mechanical disruption should specifically demonstrate that the Tresca failure criterion bounds a fracture mechanics approach to calculating the mechanical failure of the drip shield. The AIN-1 for CLST.2.03 requested specific information on the mechanical failure criterion, justification for specific aspects of DOE's approach, and information on the expected mechanical properties of the waste package and drip shield materials. The results from the NRC review of DOE's response to the AIN-1 is included in the subsequent sections.

4.1 Clarification of the Material Failure Criterion

In the response to CLST.2.03, AIN-1, DOE stated that the Tresca criterion (maximum shear stress criterion) and the von Mises criterion (distortion-energy criterion) are generally accepted failure criteria for ductile materials. The DOE has indicated that because the Tresca criterion predicts yielding at lower stresses than the von Mises criterion, the Tresca criterion is conservative for the waste package and the drip shield. The limits used for the waste package and drip shield are based on the values provided in the Boiler and Pressure Vessel Code (American Society of Mechanical Engineers, 2001) and on stress classification concepts contained in that code. Details of the tiered screening criteria for mechanical failure are provided in Appendix S of Bechtel SAIC Company, LLC (2004a).

The information provided in DOE's response is satisfactory to address the AIN-1.

4.2 Justification of the Fracture Toughness

The DOE response to the AIN-1 did not include justification for the fracture toughness values obtained from Charpy impact tests using the empirical relationship developed by Barsom, Rolfe and Novak (Barsom and Rolfe, 1970; Rolfe and Novak, 1970). The DOE response indicated that, after review and evaluation of literature data and Charpy test data generated by the project, additional data are unnecessary. Appendix S references Charpy data for both Alloy 22 base material and weldments reported by Haynes International (1997) in the product literature for Alloy C-22.

For the titanium alloys proposed for the drip shield, DOE's response did not include additional data or justification for the approach. The DOE response indicates fracture failure is determined by both material susceptibility and minimum flaw size for propagation. The DOE design approach for the drip shield is to control flaw size to ensure that the drip shields do not contain flaws that can nucleate fractures. The DOE approach to limit flaw size during fabrication of the drip shield may be appropriate; however, staff expects clarification in a potential license application (LA) to enable a complete assessment of this approach.

Recent work conducted at the Center for Nuclear Waste Regulatory Analyses (CNWRA) shows that Alloy 22 retains high fracture toughness over a wide range of metallurgical conditions. Decreased fracture toughness was observed after welding. Thermal aging at temperatures where topologically close-packed phases are known to be thermodynamically stable also decreases the fracture toughness. Solution annealed welds had fracture toughness similar to as-welded specimens. Although decreases were observed, the measured fracture toughness of Alloy 22 for all metallurgical conditions was sufficient to assure failure would be dominated by plastic collapse, hence, fracture or mixed mode failure is not expected. In addition, the measured fracture toughness was greater than the calculated fracture toughness using the empirical relationship developed by Barsom, Rolfe and Novak which indicates that this relationship is conservative for Alloy 22 (Barsom and Rolfe, 1970; Rolfe and Novak, 1970). Similar conclusions were reported by Csontos, et al. (2004) for single phase Ni-based Alloy 600 and 690.

Csontos, et al. (2004) also analyzed Titanium Grade 2, used as a surrogate for Grade 7, and Titanium Grade 5, used as a surrogate for Grade 24. In both cases, the calculated fracture toughness values were greater than the measured values, indicating that the use of the empirical relationship developed by Barsom, Rolfe and Novak (Barsom and Rolfe, 1970; Rolfe and Novak, 1970) may not be conservative for these Titanium alloys. Although this may be the case for Titanium Grade 2 and Titanium Grade 7, sufficient ductility is expected in the annealed condition to prevent brittle and mixed mode failure. In addition, the analyses reported by Csontos, et al. (2004) indicate the possibility of a mixed mode failure for Grade 24 which is dependent on flaw size.

Although DOE’s response does not provide the justification requested in CLST 2.03, AIN-1 (Schlueter, 2003), recent work conducted at the CNWRA and the analyses reported in Csontos, et al. (2004) provide confidence that the methodology of calculating the fracture toughness values from Charpy impact data for Alloy 22 would be sufficiently conservative to actual values. Furthermore, DOE’s approach to evaluate mechanical failure of the engineered barrier system components by constructing failure assessment diagrams is appropriate. For materials susceptible to fracture or mixed mode failure, a failure assessment diagram may be used to evaluate the effect of flaw sizes on component performance. The DOE approach to limit flaw size during fabrication of the drip shield may be appropriate; however, staff expects DOE to provide sufficient information in a potential LA to enable the assessment of this approach including analyses of the drip shield design, fabrication specifications, non destructive evaluation requirements, material properties, inspection criteria, and the expected range of applied stresses.

4.3 Justification for Adjusting the Ultimate Tensile Strengths

The DOE response to the AIN-1 indicated the modification of engineering stress values to true stress is an industry-accepted technique when performing elastic-plastic analysis for ductile material. This approach is used in the ASME Boiler and Pressure Vessel Code [American Society of Mechanical Engineers, 2001, Section III, Division 1, Appendix F, F-1322.3(b)].

The staff recognizes that converting engineering stress-strain curves to their true stress-strain counterparts is a necessary requirement for performing numerical structural analyses. However, DOE's response did not provide the specific values or justification for the engineering strains corresponding to the ultimate strengths for the various engineered barrier system materials needed to calculate this conversion. Furthermore, justification for using the true stress value of the ultimate strength for approximating the collapse stress in the context of the failure assessment diagram analysis was not provided. Although this conversion may not significantly affect the failure assessment diagram material specific models, staff expects DOE to provide sufficient information in a potential licence application to enable assessment of the designs of the engineered barrier system components, including the mechanical property specifications for the materials used for the waste package and the drip shield.

4.4 Effect of Fracture Toughness Variations for Titanium Alloys

The DOE response to the AIN-1 indicates the current evaluations for drip shield buckling under static load have used conservative structural properties from the Boiler and Pressure Vessel Code (American Society of Mechanical Engineers 2001, Section II, Part D). The DOE has also indicated that for future evaluations, either consensus standard values or nominal values may be used. If nominal values are used, then the appropriateness of the values should be justified.

The DOE response did not address potential variations in fracture toughness that may occur as a result of fabrication; i.e., welding and postweld heat treatments. Welding and thermal exposures of duplex (α-β) titanium alloys may result in the formation of microstructures with altered mechanical properties and decreased fracture toughness. Compositional variations in the base alloy and weld filler metals may also contribute to variations in mechanical properties. Hence, staff expects DOE to provide sufficient information in a potential LA to enable staff assessment of the drip shield design considering the effects of fabrication and compositional variability on mechanical properties to include fracture toughness, acceptable flaw sizes, and the expected range of operating conditions. Furthermore, NRC staff believes that DOE will be able to provide this information in a potential LA.

4.5 Combined Mode of Fracture Failure in the Titanium Grade 7

The DOE response to the AIN-1 indicates that the minimum flaw size necessary to propagate a fracture must be considered in the mechanical analysis of the drip shield. In addition, DOE's response indicates that while this flaw size is not available at present, limits on acceptable flaw sizes will be imposed during drip shield fabrication to ensure that ductile failure is maintained for loads generated by rockfall, hence, avoiding the fracture failure regime.

Csontos, et al. (2004) shows that Titanium Grade 2, used as a surrogate for Grade 7, is expected to have sufficient ductility in the annealed condition to prevent brittle or mixed mode failure. However, the addition of cold work can alter the mechanical properties and possibly lead to mixed mode failures. As indicated in Section 4.2, the approach to limit flaw size during fabrication of the drip shield may be appropriate; however, this approach will need to be supported with additional analyses of the drip shield and include the final fabrication specifications, material properties, inspection criteria, and the range of expected applied stress.

4.6 Effect of Variations in Alloy Composition on the Fracture Toughness of Alloy 22

The DOE response to the AIN-1 references the responses to Agreements PRE.7.03 and 7.05 contained in Appendices T and U (Bechtel SAIC Company, LLC, 2004b,c) of TBD No. 6 (Bechtel SAIC Company, LLC, 2003). Although fracture toughness measurements were not included, the effects of compositional variations and fabrication processes were evaluated using tensile and Charpy impact tests. The DOE response indicates that, based on the results shown in Appendixes T and U as well as DOE's ongoing work, the compositional requirements for Alloy 22 and weld filler metals will be optimized to ensure acceptable mechanical properties.

As indicated in Section 4.1, although DOE's response does not provide the justification requested in CLST.2.03, AIN-1 (Schlueter, 2003), recent work conducted at the CNWRA and the analyses reported in Csontos, et al. (2004) provide confidence that the methodology of calculating the fracture toughness values from Charpy impact data for Alloy 22 would be sufficiently conservative to actual values. The DOE approach to optimize the compositional requirements for Alloy 22 and weld filler metals to ensure acceptable mechanical properties of the waste package outer container is sufficient to address the AIN-1.

5.0 SUMMARY

The NRC staff reviewed DOE's KTI agreement responses for agreement CLST.2.03. Although some of the responses were limited in scope, the NRC staff expects DOE to provide sufficient information to assess the design and mechanical response of the drip shield when considering the effects of fabrication and compositional variations in the potential LA. In addition, NRC staff performed an independent assessment to determine whether the information provided would support submission of a potential LA for a geologic repository. On the basis of this review, NRC staff concludes that sufficient information will likely be available at the time of a potential LA to permit assessment of the mechanical degradation of the engineered barrier system materials.

6.0 STATUS OF THE AGREEMENTS

Based on the above review, NRC concludes that the information provided with respect to agreement CLST.2.03, is adequate to support submission of the LA. Therefore, NRC considers agreement CLST.2.03 to be closed.

7.0 REFERENCES

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