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1. PURPOSE

The objective of this analysis is to confirm the selection of appropriate dimensions and materials for the 21 pressurized water reactor (PWR) uncanistered fuel (UCF) waste package (WP) design based on an evaluation of the pressurized system missile impact onto the WP (see Ref. 5.10). Therefore, this document will explore the waste package resistance to dynamic impact of a pressurized system missile. The purpose of this analysis is to provide preliminary input for the WP technical drawings.

Based on Ref. 5.10, it is assumed that no other external or internal missile impact event exists for the waste package (Assumption 4.3.10). This assumption will be verified upon completion of design basis event (DBE) analysis of these events and the structures, systems, and components which they may affect.

2. QUALITY ASSURANCE

The Quality Assurance (QA) program applies to this analysis. The work reported in this document is part of the preliminary WP design analysis that will eventually support the License Application Design phase. This activity, when appropriately confirmed, can impact the proper functioning of the Mined Geologic Disposal System (MGDS) waste package; the waste package has been identified as an MGDS Q-List item important to safety and waste isolation (pp. 4, 15, Ref. 5.1). The waste package is on the Q-List by direct inclusion by the Department of Energy (DOE), without conducting a QAP-2-3 evaluation. As determined by an evaluation performed in accordance with QAP-2-0, *Conduct of Activities*, the work performed for this analysis is subject to *Quality Assurance Requirements and Description* (QARD; Ref. 5.2) requirements. As specified in NLP-3-18, the development of this analysis is subject to QA controls.

All design inputs identified in this document are in support of preliminary design process, and excluding the codes and standards, shall be treated as unqualified data. These design inputs will require subsequent qualification (or superseding inputs) as the waste package design proceeds. This document will not directly support any construction, fabrication, or procurement activity and therefore does not require TBV (to be verified) tracking. However, use of any data from this analysis for input into documents supporting construction, fabrication, or procurement is required to be controlled with TBV tracking in accordance with the appropriate procedures.

3. METHOD

A dynamic low-velocity impact analysis was performed by making use of the basic relations of the strength of materials and empirical relations obtained for the dynamic impact of projectiles onto plates. A quasi-static approach was used to simplify the dynamic load into a static, concentrated force applied at midspan on the outer and inner barriers. The results of the analytical method solution were then compared to the allowable stress obtained for the waste package corrosion allowance (outer) barrier material. A similar comparison was also made

between the design basis accident missile velocity and the minimum missile velocity required to cause perforation of the barriers.

4. DESIGN INPUTS

All design inputs are for preliminary designs; these design inputs, excluding codes and standards, will require subsequent qualification (or superseding inputs) as the waste package design proceeds to the final design.

4.1 Design Parameters

- 4.1.1 Waste package material properties used in the design analysis are listed below. A waste package containment barrier (outer and inner barriers) initial temperature of 93°C (200°F) (see Assumption 4.3.1) is used to determine the material properties.

ASTM A 516 Grade 70 (Outer barrier material, Ref. 5.4):

Since the carbon content of A 516 Grade 70 can be up to 0.31% (Ref. 5.11, p. 138) and the difference between the elastic moduli for steels with carbon contents less than or greater than 0.30% specified at the temperature of interest (see Assumption 4.3.1) is negligibly small,

Modulus of elasticity = 197 GPa (28.6×10^6 psi) (Ref. 5.5, Table TM-1)

Yield strength = 239 MPa (34.6 ksi) (Ref. 5.5, Table Y-1)

ASTM B 443 Inconel Alloy 625 (Corrosion resistant (inner) barrier material, Ref. 5.4):

Modulus of elasticity = 204 GPa (29.6×10^6 psi) (Ref. 5.6, p. 2)

Yield strength = 366 MPa (53.1 ksi) (Ref. 5.5, Table Y-1)

- 4.1.2 Design parameters for the missile are listed below:

Velocity of the missile = 5.7 m/s (Ref. 5.10)

Mass of the missile = 0.5 kg (Ref. 5.10)

Diameter of the missile = 0.01 m (Ref. 5.10)

4.2 Criteria

The following criteria are applicable to the design subject. Each criterion references the relevant Engineered Barrier Design Requirements Document (EBDRD) (Ref. 5.7) requirement; however, it is not the intent of these analyses to show direct compliance with the referenced

requirements from the EBDRD. Rather, they are used as guidelines and design goals for the preliminary design.

- 4.2.1 The design of waste packages is required to include consideration of the mechanical strength and mechanical stress. This document investigates the results of a missile

impact onto the containment barriers by means of the mechanical strength and mechanical stress considerations. These considerations are addressed throughout this document.

[EBDRD 3.7.1.B]

- 4.2.2 One of the accident events considered for the waste package design is the missile impact onto the containment barriers (see Ref. 5.10). The waste package is required to contribute to limiting the dispersal of radioactive waste materials in case of such an accident. Therefore, the resistance of the waste package to the perforation due to a missile impact is analyzed throughout this document.

[EBDRD 3.7.1.H]

4.3 Assumptions

All assumptions are for preliminary designs; all of these assumptions will require qualification/confirmation as the waste package design proceeds.

In the course of developing this document, several assumptions were made regarding the WP structural analysis. These assumptions are identified below.

- 4.3.1 Temperature of the containment barriers is assumed to be 93°C based on the thermal design analysis results provided in Ref. 5.3, p. 49. This reference includes the thermal analysis and temperature distribution results of the waste package. Since the missile impact is a design basis event which can only take place in industrial facilities, such an accident event can only occur prior to emplacement. The surface facilities are assumed to provide ventilation and spacing for the waste packages which will provide similar temperature boundary conditions to the initial emplacement drift air temperatures. Therefore, the waste package temperature prior to emplacement is equivalent to the waste package initial temperature at emplacement due to similar temperature boundary conditions around the waste package. The waste package outer barrier temperature is 101°C (214°F) at the time of initial emplacement; this temperature is approximated to 93°C (200°F) at which the mechanical properties of the subject materials are specified in English Units in the literature. Since the temperature difference in this approximation is significantly less than the specified temperature and the subject material properties do not change significantly between these temperatures, this approximation has no significant effect on the results. This assumption is used in Section 4.1.1.
- 4.3.2 The missile impact is assumed to occur from vertically above at the waste package midspan which is supported at both ends (see Figure 7-1). This configuration will result in the most critical effects of the impact since the waste package is constrained with supports. A quasi-static approach is used to simplify the dynamic load into a static, concentrated force applied at midspan on the outer and inner barriers. This

configuration provides a conservative approach since the load is applied at midspan. This assumption is used in Section 7.1.

- 4.3.3 All of the kinetic energy of the missile is conservatively assumed to be spent on deflecting the containment barriers. Therefore, the strain energy stored in the barriers will be equal to the kinetic energy of the missile. This assumption is used in Section 7.1.
- 4.3.4 The literature of dynamic impact analyses (Ref. 5.9) shows that various empirical equations were developed for the perforation of ductile metal plates; specifically, mild steel plates. For some of the mild steel (low-carbon steel) sheet and strips, the mechanical properties are not significantly different from the carbon steels (see Ref. 5.11, p. 155). Thus, the same empirical relations are used for the carbon steel plate dynamic impact analysis. This assumption is used in Section 7.1.
- 4.3.5 There are two methods of fabrication considered for the outer and inner barriers, either cladding of the inner barrier on the inner surface of the outer barrier or shrink fitting of the outer barrier on the inner barrier. Either method should result in direct contact between the outer and inner barriers. In addition to this, the material properties given in Section 4.1 show that inner barrier yield strength is higher than the outer barrier yield strength. Therefore, the maximum stress on the containment barriers will be determined with a conservative assumption that the outer barrier mechanical properties can be used for both barriers. This assumption is used in Section 7.2.
- 4.3.6 Outer barrier outer diameter = 1.6634 m (Attachment I). The basis for this assumption is that this dimension is used as an initial value in order to be able to determine if it is acceptable in terms of the structural performance of the waste package. This assumption is used in Section 7.2.
- 4.3.7 Outer barrier thickness = 0.1 m (Attachment I). The basis for this assumption is that this dimension is used as an initial value in order to be able to determine if it is acceptable in terms of the structural performance of the waste package. This assumption is used in Section 7.2.
- 4.3.8 Inner barrier thickness = 0.02 m (Attachment I). The basis for this assumption is that this dimension is used as an initial value in order to be able to determine if it is acceptable in terms of the structural performance of the waste package. This assumption is used in Section 7.2.
- 4.3.9 Outer barrier length = 5.335 m (Attachment I). The basis for this assumption is that this dimension is used as an initial value in order to be able to determine if it is acceptable in terms of the structural performance of the waste package. This assumption is used in Section 7.2.

- 4.3.10 Based on Ref. 5.10, it is assumed that no other external or internal missile impact event exists for the waste package. This assumption will be verified upon completion of DBE analysis of these events and the structures, systems, and components which they may affect. This assumption is used in Section 1.

4.4 Codes and Standards

The use of codes and standards for the design of the waste package is restricted to being a source for material properties. Some of the material properties for ASTM A 516 carbon steel and ASTM B 443 (Inconel Alloy 625) were obtained from Ref. 5.5.

5. REFERENCES

- 5.1 *Q-List*, YMP/90-55Q, REV 4, Yucca Mountain Site Characterization Project.
- 5.2 *Quality Assurance Requirements and Description*, DOE/RW-0333P, Rev 7, U.S. Department of Energy (DOE) Office of Civilian Radioactive Waste Management (OCRWM).
- 5.3 *Thermal Evaluation of Preliminary 21 PWR UCF Design - Internal Structures*, Document Identifier (DI) Number: BBAA00000-01717-0200-00018 REV 00, Civilian Radioactive Waste Management System (CRWMS) Management and Operating Contractor (M&O).
- 5.4 *Waste Package Materials Selection Analysis*, DI Number: BBA000000-01717-0200-00020 REV 00, CRWMS M&O.
- 5.5 *1995 American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code*, Section II, American Society of Mechanical Engineers, 1995.
- 5.6 *Huntington Alloys, Inc. Technical Brochure*, Fourth Edition, INCONEL Alloy 625, Huntington, WV, 1978.
- 5.7 *Engineered Barrier Design Requirements Document*, YMP/CM-0024 Rev. 0, ICN 1, Yucca Mountain Site Characterization Project.
- 5.8 *Mechanics of Materials*, SI Metric Edition, Ferdinand P. Beer and E. Russell Johnston, Jr., McGraw-Hill Ryerson Limited, Toronto, Canada, 1987.
- 5.9 *Shock and Impact on Structures*, Eds. C. A. Brebbia and V. Sanchez-Galvez, Computational Mechanics Publications, Southampton, U. K., 1994.

- 5.10 *Waste Package Design Basis Events*, DI Number: BBA000000-01717-0200-00037 REV 00, CRWMS M&O.
- 5.11 *Metals Handbook Ninth Edition, Volume 1, Properties and Selection: Irons and Steels*, American Society for Metals, Metals Park, OH, 1978.

6. USE OF COMPUTER SOFTWARE

Not applicable.

7. DESIGN ANALYSIS

7.1 Background

The pressurized system missile was described in Ref. 5.10 as a cylindrical object which has the dimension, mass, and velocity given in Section 4.1.2. This geometry will be used in subsequent calculations. Since different angles of impact may result in different deformations in either component involved in the impact, for conservatism, a rigid missile can be assumed to impact the containment barriers. The result of such an impact will certainly include a local indentation on the outer surface of the outer barrier even at low impact velocities. However, the intent of this evaluation is to determine the global or through-thickness response of the subject waste package components. Hence, two different approaches can be taken for analysis of a missile impact onto the outer barrier of the waste package.

First, the global effects of the missile impact on the outer barrier should be considered. A quasi-static approach can be used to simplify the dynamic load into a static, concentrated force applied at midspan on the outer and inner barriers. This configuration provides a conservative approach for dynamic impact analysis of the missile impact since the load is applied at midspan (see Figure 7-1, Assumption 4.3.2).

Figure 7-1. Shear force and bending moment diagrams of analytical model

In the analytical model it is assumed that the normal stress varies linearly with the distance from the neutral surface. A compressive normal stress state is active on one side of the neutral axis, and a tensile normal stress state is active on the other side of the neutral axis. Furthermore, the magnitudes of maximum compressive and tensile stresses are identical due to the symmetric geometry of the WP cross-sectional area with respect to the plane passing through the center of the WP.

The strain energy relation for a beam in bending is obtained from Ref. 5.8, p. 477:

$$U = \int_0^L \frac{M^2}{2EI} dx \quad (\text{Equation 7.1})$$

where:

- U = strain energy in the beam
- M = bending moment
- E = modulus of elasticity of the beam
- L = length of the beam

I = area moment of inertia of the beam
 x = independent variable along the beam length

The total strain energy can be determined by performing the above integration in two regions of the beam. The reaction forces on both sides of the beam are the same and equal to half the value of the applied force P since the problem is symmetric about the mid-plane. Therefore, the bending-moment in either of the two regions depends on the relation $(Px/2)$. Placing this into the strain energy relation and making use of the symmetry,

$$U = 2 \int_0^{L/2} \left(\frac{Px}{2} \right)^2 \frac{1}{2EI} dx \quad (\text{Equation 7.2})$$

Therefore:

$$U = \frac{P^2 L^3}{96 EI} \quad (\text{Equation 7.3})$$

Assuming that all of the kinetic energy of the missile is spent deflecting the containment barriers, which is a conservative approach, strain energy stored in the barriers will be equal to the kinetic energy of the missile (see Assumption 4.3.3). Hence:

Kinetic Energy = Strain Energy

$$\frac{1}{2}mv^2 = \frac{P^2 L^3}{96EI} \quad (\text{Equation 7.4})$$

where:

- m = mass of missile
- v = velocity of missile
- P = force on barriers
- L = length of basket assembly
- E = modulus of elasticity of barrier materials
- I = area moment of inertia of barriers

It is also known that:

$$\sigma = \frac{M c}{I} \quad (\text{Equation 7.5})$$

and $M = P \cdot L / 4$ for this problem (Ref. 5.8, p. 157). " σ " is the bending stress, " c " is the outer barrier outer radius, and " M " is the bending moment. Placing these relations into Equation 7.4 and considering L , c , I , and E as constant values, the following is obtained:

$$\frac{1}{2} m v^2 = \left(\frac{4 \sigma I}{c L} \right)^2 \frac{L^3}{96 E I} \quad (\text{Equation 7.6})$$

The bending stress term is factored out of this equation:

$$\sigma = c v \left(\frac{3 m E}{I L} \right)^{1/2} \quad (\text{Equation 7.7})$$

This relation will be used to obtain the maximum global bending stress on the barriers due to missile impact onto the waste package.

A second method of approach is taken in order to determine the effects of dynamic impact through the containment barrier thickness using the empirical relations derived for perforation of plates by a rigid mass. The literature of dynamic impact analyses shows that various empirical equations were developed for the perforation of ductile metal plates (specifically, mild steel plates, see Assumption 4.3.4). Since the containment barriers will have circular geometry after the plates are rolled into cylinders and a circular geometry is more resistant to compressive loads than a plate, it is conservative to use empirical relations of plates for the purpose of analyzing the missile impact problem.

The perforation of a plate by a missile, or projectile, involves a complex mechanism of impact and subsequent failure if the projectile has a large amount of kinetic energy. Thus, no comprehensive theoretical models are available which incorporate all of the phenomena and which are capable of predicting accurately all of the features of an impact perforation event (Ref. 5.9). However, there are some empirical equations developed for the impact analysis of projectiles. One of these fairly simple relations that have been used widely in design is the Ballistics Research Laboratory (BRL) equation. No limitations are associated with the BRL

equation in terms of the missile velocity range or the ratio of the target span to the missile diameter; therefore, the use of BRL equation is more general as opposed to other equations provided. A second reason for using the BRL equation instead of the other equations is that this equation gives reasonable agreement with the experimental results as plotted in Figure 2 in Chapter 3 of Ref. 5.9. This equation is given below:

$$E_p / (\sigma_u d^3) = 1.4 * 10^9 (H / d)^{1.5} / \sigma_u \quad (\text{Equation 7.8})$$

where E_p is the dynamic energy required for perforation (Ref. 5.9, p. 53), σ_u is the ultimate tensile strength of the plate material, d is the diameter of the impact face of a blunt striker (missile), and H is the plate thickness. The term " E_p " is factored out of this equation:

$$E_p = 1.4 * 10^9 (H * d)^{1.5} \quad (\text{Equation 7.9})$$

It is also known that the kinetic energy E_k is:

$$E_k = E_p = m v^2 / 2 \quad (\text{Equation 7.10})$$

in terms of the projectile mass (m) and velocity (v).

Therefore:

$$m v^2 / 2 = 1.4 * 10^9 (H * d)^{1.5} \quad (\text{Equation 7.11})$$

$$v = (2.8 * 10^9 (H * d)^{1.5} / m)^{0.5} \quad (\text{Equation 7.12})$$

This is the minimum velocity of the projectile to cause perforation of the plate.

7.2 Calculations and Results

The outer and inner barriers will be in direct contact. Therefore, the maximum stress on the containment barriers will be determined with a conservative assumption that the outer barrier mechanical properties can be used for both barriers (Assumption 4.3.5).

Inner diameter of the inner barrier = $1.6634 - (2 * (0.1 + 0.02)) = 1.4234$ m (see Assumptions 4.3.6, 4.3.7, and 4.3.8)

Total area moment of inertia of the outer and inner barriers:

$$I = \pi (D_o^4 - D_i^4) / 64 = \pi (1.6634^4 - 1.4234^4) / 64 = 0.1743 \text{ m}^4$$

The global effect of the missile impact on the outer barrier is calculated using Equation 7.7:

$$\sigma = (1.6634 / 2) * (5.7) * (3 * 0.5 * 197 * 10^9 / (0.1743 * 5.335))^{1/2} = 2.7 \text{ MPa (see Section 4.1 and Assumption 4.3.9)}$$

This is the bending stress on the barriers caused by the missile impact. Since the bending stress is significantly less than the material yield strength (239 MPa, Section 4.1.1), it is determined that there is no global failure on the barriers.

A second calculation will be performed to determine if the minimum velocity of the projectile to cause perforation of the plate is exceeded. The empirical relation was given in Section 7.1 as Equation 7.12.

Placing the values into Equation 7.12:

$$v = (2.8 * 10^9 ((0.1 + 0.02) * (0.01))^{1.5} / (0.5))^{0.5} = 482.5 \text{ m/s}$$

This is the minimum velocity of the missile to cause perforation of the plate. Since the missile velocity (5.7 m/s) is significantly below this value, there will be no perforation of the containment barriers due to the missile impact design basis event considered in this document.

Since the empirical relation was derived for plates, the change in the curvature of the containment barriers does not compromise the conservatism as long as the same thickness is used. Therefore, these results are also applicable to the missile impact analyses of similar waste packages with the same thickness.

8. CONCLUSIONS

As identified in Sections 2 and 4, this analysis is based on unqualified/unconfirmed input data, and use of any data from this analysis for input into documents supporting construction, fabrication, or procurement is required to be controlled as TBV in accordance with the appropriate procedures.

The results given in Section 7.2 clearly show that the kinetic energy, which includes the effects of the mass and velocity, of the missile is too low to cause a perforation of the containment barriers. Therefore, the containment barrier structural design is deemed acceptable under the missile impact load design basis event considered in this document.

Structural evaluations of the WP design presented in this document show that the dimensions listed in Section 4.3 (from Attachment I) are acceptable for the WP design basis event of a dynamic impact of a pressurized system missile, and can be used to develop preliminary technical drawings of the subject 21 PWR UCF WP structural components. It should be noted that the results and conclusions of this document are also applicable to similar waste packages which have the same containment barrier thickness.

9. ATTACHMENTS

Attachment I (1 page): Waste package assembly sketch

Figure I-1. 21 PWR UCF Waste Package Assembly Sketch