Preliminary Assessment of Waste Package Response to Rock Block Impacts

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Introduction

The proposed high-level waste geologic repository at Yucca Mountain (YM), Nevada employs an engineered barrier system in concert with the desert environment and geologic features of the site with the intent of keeping water away from the waste for thousands of years[1]. The primary component of the engineered barrier system is a long-lived waste package (WP). The WP design includes materials chosen to be compatible with the underground thermal and geochemical environment.

Through successive evaluations and improvements, the repository design evolved to the Viability Assessment (VA) reference design[1,2]. This reference design represented a snapshot of the ongoing design process, thus providing a frame of reference to describe how a proposed repository at YM could work. The WP in the VA reference design has two layers: a thick outer layer made of carbon steel that provides structural strength and delays contact of water with the inner, thinner layer made from a corrosion resistant alloy after the outer layer is penetrated. After the License Application Design Selection process was completed by the DOE, the Enhanced Design Alternative II (EDA II) version of the WP was identified by the DOE as the preferred design[3]. Unlike the VA WP design, the EDA II WP uses a corrosion resistant high nickel alloy for the outer barrier and stainless steel for the inner barrier.

The performance and safety assessment of the proposed repository at YM must consider both the probability and consequences of potentially disruptive events, such as seismicity, faulting, and igneous activity. Therefore, an assessment of the WP performance over the 10,000 yr lifetime of the repository must consider the different loading conditions on the WP created by these naturally occurring events in conjunction with possible manufacturing defects, residual stresses created at the time of fabrication (e.g., welding and shrink fits), and temporal degradation of the WP materials caused by various corrosion processes.

The objective of this study was to perform a preliminary assessment of the potential consequences of seismically induced rockfall on the WP by using the finite element (FE) method to evaluate the effects of various rock block shapes and impact orientations at different locations on the WP. The VA version of the 21 Pressurized Water Reactor (PWR) WP conceptual design was used as the basis for the study. The impact load caused by seismically induced rockfall may affect the confinement capabilities of the WP in two ways. The first is a catastrophic rupture of the WP. The second is that rockfall may cause damage to the container in a manner that will accelerate the WP corrosion process.

Finite Element Modeling Methodology

The WP is an assemblage of several individual structural components[4] (see figure 1). Table 1 identifies the WP materials, relevant properties of these materials[5, 6], and the specific WP components fabricated from them. These materials were modeled as elastic-perfectly plastic materials at room temperature.

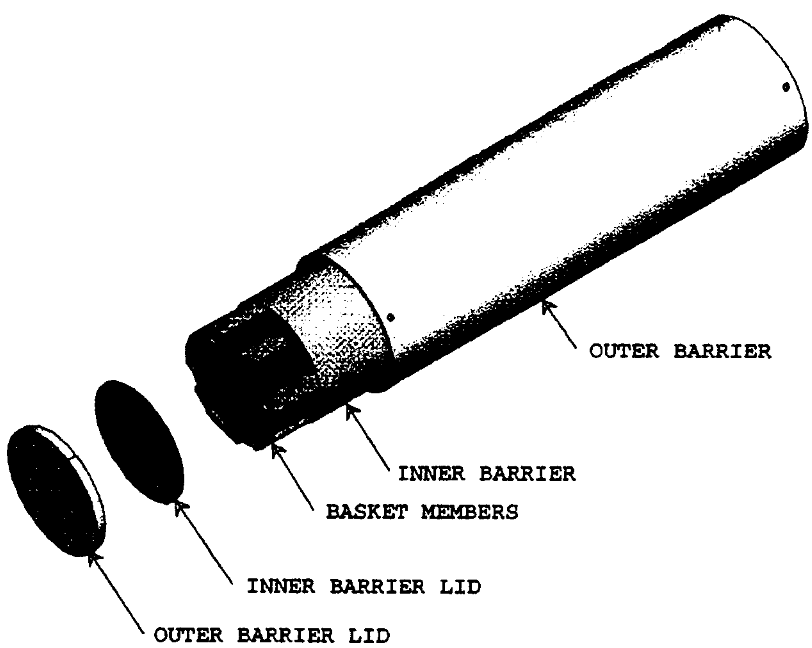

Figure 1. Major components of 21 pressurized water reactor uncanistered fuel assembly waste package

Table 1. Material properties

Material	Components	Yield Strength (MPa)	Young's Modulus (GPa)	Density (kg/m^3)	Poisson's Ratio
A516	Outer barrier and outer barrier lid	205	206	8,131	0.30
Alloy 825	Inner barrier, inner barrier lid, thermal shunt guides/caps, structural stiffener, and basket guides	338	206	8,140	0.42
Al 6063	Thermal shunt	276	68.3	2,690	0.33
316L Stainless Steel	Basket tube	172	195	7,953	0.40

A simple approximation of the effect of seismic ground motion was considered in the FE model by adjusting the rock block and WP impact velocities. Assuming a fall height of 3.2 m and no initial velocity, it can be shown that the velocity of the rock block when it hits the WP will be approximately 7.9 m/s. If the rock block were to begin falling with an initial downward velocity equal to the peak vertical ground velocity of the postulated seismic event, 1 m/s for example, the velocity of the rock block when it impacts the WP will be nearly 8.0 m/s. This represents an increase of only 2.6 percent of the rock block kinetic energy at impact (i.e., from 62.4 kJ to 64.0 kJ for a 2 metric tonne rock block). However, assigning an upward velocity to the WP equal to the peak vertical ground velocity (i.e., 1 m/s) when the impacting rock block makes contact significantly contributes to the total kinetic energy associated with the impact event. Specifically, a loaded 21 PWR WP having a mass of approximately 47.8 metric tonnes[4] moving at 1 m/s represents 23.9 kJ of kinetic energy.

The rock block material was represented as an elastic-perfectly plastic material whose yield strength is equal to its compressive strength. The uniaxial compressive strength used in the FE model of the rock (42.8 MPa) is considerably smaller than that of an average intact rock block (166 MPa) expected to be encountered at YM[7]. This was done in an attempt to account for the lower strength that can be expected for a rock block containing some minor fractures.

Preliminary Rock Block and Waste Package Impact Analysis Results

Preliminary FE analysis results were obtained for six different rock block and WP impact scenarios (see table 2). Each rock block mass, regardless of shape, was 2 metric tonnes. The rock block and WP velocities at the moment of impact were 8 and 1 m/s, respectively, for all six scenarios investigated.

One method for characterizing the response of an elastic-perfectly plastic material, once it has been subjected to a stress level beyond its yield strength, is the amount of plastic distortion or strain that occurs. Consequently, the displacement results obtained from the analyses will be used to convey the amount of plastic distortion that the WP has incurred. In particular, table 2 summarizes the maximum displacements and concomitant residual values for the inner and outer barriers of the WP. Care must be taken when interpreting the significance of the results, however, because displacements reflect rigid body translations and rotations in addition to strain. Of all the scenarios investigated, case 5 clearly represents the most severe condition. In this scenario, the rock block strikes the WP immediately above one of the pedestal supports, causing residual displacements of 5.9 mm for the inner barrier and 6.2 mm for the outer barrier. This is to be expected because a smaller amount of the kinetic energy associated with the impact can be dissipated by way of gross flexural deformation of the WP. For example, case 1 demonstrated relatively large flexural displacements for the inner and outer barriers of the WP with very little residual deformation.

For the cubical rock block scenarios, the face impact was the most critical. This result is somewhat unexpected because the edge and corner impact scenarios would intuitively produce higher stresses at the impact point because of their stress concentration potential. It has been postulated that the edge and corner scenarios did not cause more severe localized residual damage to the WPs because the rock block mass was modeled as a relatively soft elastic-perfectly plastic material to account for minor fractures in its structure.

The results of the study appear to indicate that a spherical rock block shape will cause more damage to the WP than the cubic shape. However, the yield strength for the rock block has been assumed to be much lower than the average compressive strength of an intact rock to account for potential minor fractures within the rock block. As a result, if the rock block is

Table 2. Maximum and residual displacements incurred by the inner and outer barriers of the waste package

Case	Description	Inner Barrier		Outer Barrier	
		Maximum Displacement (mm)	Residual Displacement (mm)	Maximum Displacement (mm)	Residual Displacement (mm)
1	Spherical rock block impact at the midspan and top of the waste package	12.4	1.07	14.8	2.38
2	Cubical rock block corner impact at the midspan and top of the waste package	2.99	0.0531	3.56	0.0916
3	Cubical rock block edge impact at the midspan and top of the waste package	5.30	0.58	5.60	0.180
4	Cubical rock block face impact at the midspan and top of the waste package	6.66	1.02	6.87	0.390
5	Spherical rock block impact over a support and top of the waste package	14.7	5.90	16.5	6.20
6	Spherical rock block impact over an edge and top of the waste package	NA	NA	6.38	0.828

modeled as an intact rock mass, then the localized damage to the WP caused by a cubic rock block shape impact may be more severe than what has been presented here.

Conclusions and Discussion

Six different impact scenarios using spherical and cubical rock block shapes were evaluated. The different scenarios were assessed using maximum residual displacements of the WP as the basis for comparison. It was determined that a spherical rock block impacting the WP directly above one of its pedestal supports (i.e., Case 5) was the most critical scenario of the six analyzed. This is expected because less of the kinetic energy associated with the impact is dissipated by the gross flexural deformation of the WP. Consequently, more energy is available to cause localized damage in the immediate area of the rock block and WP impact zone.

The results presented in this report are based on FE analyses that employ various modeling assumptions, approximations, and simplifications. In particular, the materials were characterized as behaving in an elastic-perfectly plastic manner with properties determined at temperatures significantly lower than those expected within the WP. Higher material temperatures typically lead to overall weaker structures because the yield stress, ultimate strength, and Young's modulus of the materials are reduced. Moreover, the residual stresses within the WP caused by shrink fits and welding procedures during the fabrication process have not been considered. These residual stresses may have a significant influence on the amount of plastic strain that can be incurred by the WP materials before rupturing will occur. Additional effects that may play a role in ~~assessing~~ the ability of the WP to perform its confinement function without disruption from rock block impacts are corrosion degradation, material embrittlement, and initial manufacturing defects.

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References

[1] U.S. Department of Energy. *Viability Assessment of a Repository at Yucca Mountain, Overview*. DOE/RW–0508. Las Vegas, NV: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. 1998.

[2] U.S. Department of Energy. *Viability Assessment of a Repository at Yucca Mountain, Preliminary Design Concept for the Repository*. DOE/RW–0508. Las Vegas, NV: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. 1998.

[3] Civilian Radioactive Waste Management System Management and Operating Contractor. *License Application Design Selection Report*. B00000000–01717–4600–00123.

Revision 01. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor. 1999.

[4] Civilian Radioactive Waste Management System Management and Operating Contractor. *Mined Geologic Disposal System Advanced Conceptual Design Report.* B00000000–01717–5705–00027. Revision 00. Volume III of IV: Engineered Barrier Segment/Waste Package. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor. 1996.

[5] American Society for Testing and Materials. *Specification for Structural Steel.* A36–88C. Philadelphia, PA: American Society for Testing and Materials. 1988.

[6] American Society for Testing and Materials. *Specification for High-Strength Low-Alloy Columbium-Vanadium Steels of Structural Quality.* A572–88C. Philadelphia, PA: American Society for Testing and Materials. 1988.

[7] U.S. Department of Energy. *Consultation Draft Site Characterization Plan.* Yucca Mountain Site, Nevada Research and Development Area, Nevada. Washington, DC: U.S. Department of Energy. 1988.