NUCLEAR WASTE PACKAGE DESIGN FOR THE VADOSE ZONE IN TUFF*

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ABSTRACT

This report presents an overview of the selection and analysis of conceptual waste package designs that will be used by the Nevada Nuclear Waste Storage Investigations (NNWSI) project for disposal of high level nuclear waste (HLW) at the proposed Yucca Mountain, Nevada Site.

The design requirements that the waste packages are required to meet are listed. Concept drawings for the reference designs and one alternative package design are shown. Four metal alloys; 304L SS, 321 SS, 316L SS and Incoloy 825 have been selected for candidate canister/overpack materials, and 1020 carbon steel has been selected as the reference metal for the borehole liners.

A summary of the results of technical and economic analysis supporting the selection of the conceptual waste package designs is included. Post-closure containment and release rates are not discussed in this paper.

INTRODUCTION

Under the direction of the Office of Civilian Radioactive Waste Management, the Department of Energy's Nevada Nuclear Waste Storage Investigations (NNWSI) project is evaluating a candidate site at Yucca Mountain, Nevada, for permanent disposal of high level nuclear waste. Lawrence Livermore National Laboratory (LLNL), a participant in the NNWSI project, is developing waste package designs to meet NRC requirements. Included are designs for the current reference waste form configurations of: 1) spent fuel (SF), which consists of both consolidated and unconsolidated spent fuel rods from pressurized water reactor (PWR) and boiling water reactor (BWR) assemblies, 2) commercial high level waste (CHLW), as a borosilicate glass containing commercial spent fuel reprocessing wastes, and 3) defense high level waste (DHLW) immobilized in borosilicate glass. Reference and alternative designs have been developed for each waste form for both vertical and horizontal emplacement configurations. All designs are for emplacement in a tuff repository located above the water table in the vadose zone.

Conceptual designs and analyses for waste packages in tuff below the water table were developed for Office of Nuclear Waste Isolation (ONWI) by Westinghouse Electric Corporation in 1981-82.[1] The target horizon was changed by NNWSI to the vadose zone in late 1982.[2,3] LLNL has made changes and additions to the conceptual designs, and analyses were performed to determine conformance of the selected design ensemble to NRC design requirements in the currently understood repository environment. Figure 1 shows the current reference conceptual designs. The selected designs[4] include reference and alternative designs which vary in complexity, performance and cost.

From this ensemble, one set of designs (for Spent Fuel, CHLW, and DHLW) will be chosen which should meet NRC/EPA requirements when analyzed with accurate repository data and long term corrosion and leach rate data now being developed.[5,6]

The conceptual designs considered to date do not include considerations for TRU waste packages. These will be developed in the future when more information on the characteristics of TRU waste forms is available.

WASTE PACKAGE ENVIRONMENT

The candidate repository horizon is located in densely-welded tuff, 350 to 400 meters below the surface, and approximately 100 meters above the water table. Our current understanding of the repository environment for expected conditions is: the hydrostatic and lithostatic forces on the waste package will be zero; there will potentially be some load (nominally 0.1 MPa) on canisters due to caving in of borehole walls, or one-meter sized rock blocks falling in; there will be one atmosphere of air; and about 8 mm per year of water dripping on or seeping around the waste packages.[7] When decay radiation heats the borehole wall to temperature above 95°C, the packages will experience a steam-air mixture. When the borehole walls cool to 95°C, if water has resaturated the rock, water may drip onto pour canisters and evaporate for tens of years (spent fuel canisters stay above 95°C for several hundred years in these designs).[8] Gamma radiation may alter the chemistry of the air and water around the canisters.[5]

Pre-Closure Environment and Effects on Canisters

The pre-closure environment for DHLW and CHLW pour canisters begins with the glass pouring operation. For DHLW, the reference canister design is a single barrier, one-cm (3/8 in) thick 61 cm (24 in) diameter 304L container which is filled with a molten glass and waste mixture and emplaced with no overpack. Differential thermal contraction and deformation between the 304L SS wall and hot glass during cooling produces a complicated stress distribution in the canister wall.[9,10] The time/temperature history and accumulated residual stress pattern may cause sensitization (carbide

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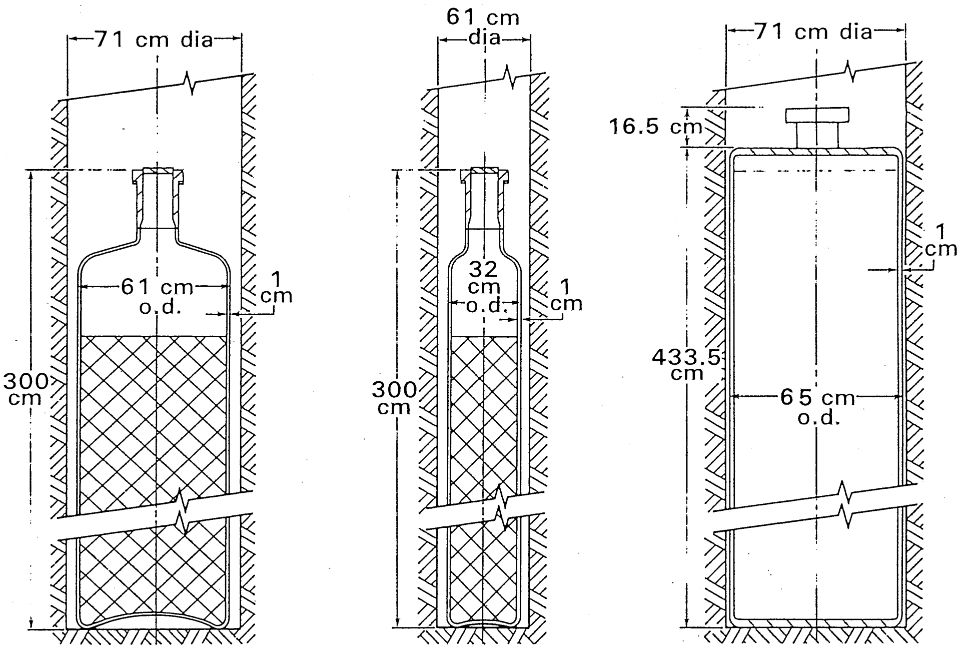

DHLW package emplaced in vertical borehole.

CHLW package emplaced in vertical borehole.

Spent fuel waste package emplaced in vertical borehole.

Fig. 1. Reference Waste Package Design. For defense high-level waste and commercial high-level waste, the reference design consists of 304L pour canisters with no overpacks and no packing. For spent fuel, the reference design canister is one cm thick 304L with no overpack and no packing. The reference emplacement configuration is vertical emplacement beneath drift floors.

precipitation) and create conditions leading to stress corrosion cracking susceptibility after emplacement.[5,10] The reference CHLW pour canister design is identical to the DHLW canister, except for diameter which is 32 cm (12 in). Residual thermal stresses could be minimized in pour canisters by utilizing a thin-walled inner liner with clearance. This would be considerably less expensive than overpacking and could be utilized if the magnitude of residual stresses in pour canister walls proves unacceptable.

The shipping and handling environment of the stressed DHLW and CHLW pour canisters probably will not change the physical or chemical state of the canisters provided the canisters are properly fixed in their shipping casks and shipping procedures are followed. Documented analysis and testing for possible cracking due to fatigue or creep during transportation has not yet been undertaken. At the repository, the normal handling, transporting and emplacement environment should not overstress the pour canisters. Retrieval operations could produce additional stresses in pour canisters depending on the integrity of the emplacement system at retrieval. For pour canisters, stresses imposed during retrieval will be superimposed onto existing thermally induced stresses from glass pouring operations. The reference spent fuel canister is fabricated from 304L stainless steel with a wall thickness of one cm. End caps are 3.8 cm thick. For these spent fuel canisters and for pour canister overpacks the normal emplacement and retrieval operations do not produce stresses above allowable limits.

Fire test and drop test environments for spent fuel canisters and pour canisters will impose high stresses. Calculations and data on fire test stresses[11] and reports on drop tests of spent fuel canisters[10,12] indicate that reference designs for SF canisters and pour canister overpacks will meet requirements for these tests. Plastic deformations occurring during drop tests of unlined pour canisters will be superimposed onto deformations which took place in pouring operations. Temperatures up to 800°C for 30 minutes will occur in fire tests. Fire test heating of pour canisters increases internal gas pressure but may actually lower the residual tensile stress in the canister wall as it expands away from the glass.

DESIGN OBJECTIVES, PHILOSOPHY AND DESCRIPTION

The objective is to develop and analyze waste package designs which incorporate qualified materials and which are fully compatible with the repository design. The designs and analyses are needed to support license application by demonstrating conformance with requirements for safe handling, transportation, emplacement, retrieval, containment and release rate per NRC 10CFR60 and 10CFR71.

The basic design philosophy for waste package conceptual designs is to meet NRC design criteria with flexibility in technical performance and cost. This provides for the present uncertainties in repository environment and corrosion and release rate data. To accomplish this, we have selected reference designs which are simple and economical, and alternative designs with greater technical conservatism but added complexity and higher cost. All designs are generally suitable for vertical or horizontal emplacement with minor modifications.

The simple designs specify direct burial of one-cm wall 304L stainless steel pour canisters and spent fuel canisters. Alternative designs specify more corrosion resistant alloys such as 316L SS, 321 SS and Incoloy 825, for containment barriers. Alternative designs are provided for internally lined pour canisters to reduce residual wall stresses. Designs have been prepared which include overpacks and packing materials.[4] These alternative designs are more conservative and more costly than the reference designs, but may be necessary to meet NRC criteria if long term corrosion and release rate testing produces rates significantly higher than currently available short term data indicate.

DESIGN REQUIREMENTS AND CONSTRAINTS

We are designing waste packages to meet a set of NNWSI requirements derived from NRC 10CFR60 and NRC 10CFR71. Table I lists the requirements.[13]

TABLE I

NNWSI Design Requirements Derived from NRC 10CFR60.

Waste packages shall be designed to:

1. Contain the waste for 300 to 1000 years.
2. Maintain a release rate less than 10^{-5} per year of the radionuclide inventory present at the end of the containment period (300 years minimum).
3. Be retrievable for 50 years after emplacement of the first waste package.
4. Meet nuclear criticality safety standards, i.e., not exceed an effective multiplication factor (K_{eff}) of 0.95.
5. Not exceed temperature limits of the waste forms, which are 773 K (500°C) for DHLW glass, 673 K (400°C) for CHLW glass, and 623 K (350°C) for spent fuel cladding.
6. Not leak radioactive material in excess of applicable federal and state standards after a drop test of two times waste package length onto an unyielding surface, at the minimum anticipated temperature.
7. Not leak radioactive material in excess of applicable federal and state standards after sustaining a 1073 K (800°C), 30-minute fire test.
8. Not leak radioactive material in excess of applicable federal and state standards during or after transportation, handling, emplacement, retrieval, and expected seismic loads. Further, these loads must not compromise long-term performance.
9. Retain legible, externally labeled identification as long as retrievability is required.
10. Meet federal regulatory requirements for transportation of high level nuclear waste.
11. Meet requirements with consideration for cost-effectiveness, including direct package costs and related repository system costs through the operational period.

NUCLEAR CRITICALITY SAFETY ANALYSIS OF CONCEPTUAL DESIGNS

A criticality safety assessment was made for reference DHLW canisters.[9] The results show that the highest calculated criticality coefficient was $k_\infty = 0.147$. This is well below the maximum allowable of 0.95. The calculations had not included flooding conditions which may incrase k_{eff} slightly. However, for DHLW and CHLW, the fissile material content of the waste forms proposed to date is sufficiently low that a criticality accident is not of concern during the containment period.[1]

For various dry and flooded configurations of spent fuel canisters emplaced in the tuff repository, recent criticality calculations show that K_{eff} is always below 0.95 for spent fuel depleted to <1.4 w/o U235.[14] The calculations indicate that k_{eff} will be less than 0.95 unless, as required in NRC 10CFR60, two unlikely, independent, and concurrent changes have occurred in the conditions essential to nuclear criticality safety. The changes necessary to exceed k_{eff} 0.95 are:

1) The emplaced canister is loaded with spent fuel with equivalent (depleted) loading greater than 1.4-1.6 w/o U235. (Undepleted fuel rods will be specially handled in the repository. Fuel assemblies are normally depleted to 1.0-1.5 w/o.) and;
2) The canister is breached and filled with water and;
3) The spent fuel rods or space frame have disintegrated and;
4) a. The spent rods have rearranged into an optimal configuration (>1.6 w/o U235) or;
   b. The Zircaloy cladding has disintegrated and all the spent fuel has fallen into a pile (>1.4 w/o U235).

THERMAL MODELING

Calculated waste package temperatures for all of the reference and alternative designs are within the temperature limits imposed to avoid waste-form degradation.[8] These limits are 350°C for spent fuel (cladding), 400°C for CHLW and 500°C for DHLW. In the canister design for consolidated spent fuel, the same diameter canister (65 cm) will accomodate 18 BWR assemblies (3.05 kW) and 7 PWR assemblies (3.56 kW). For the alternative SF canister with packing, it is necessary to reduce the number of assemblies to 4 PWR (2.0 kW) to avoid exceeding the 350°C limit. The 68 cm canister containing 6 PWR assemblies of pre-consolidated (boxed) spent fuel has a peak temperature of 335°C.

Results of thermal analyes show that the reference package designs for CHLW and DHLW when emplaced in the reference repository geometry (vertical emplacement) are well below waste form temperature limits. In fact, both CHLW and DHLW canisters could be emplaced at higher areal power density without exceeding temperature limits. The analysis also shows that, depending on detailed configurations and fuel loadings, the reference design spent fuel canisters can be emplaced in the reference repository and not exceed waste form temperature limits.

STRUCTURAL ANALYSES OF CANISTER DESIGNS

The pre-closure environmental history of canisters and overpacks begins with canister fabrication and continues through glass pouring (DHLW and CHLW only), transportation, handling, welding, emplacement, and possible retrieval. For prototype canisters, fire and drop tests must be completed without canister leakage. Structural analysis is underway to simulate the normal, test, and unexpected environmental conditions which will be imposed on canisters. Drop tests[10,11,12] and overheat tests[11] have been conducted on these types of canisters by several organizations. Based on these results, NNWSI canister designs are expected to survive such tests.

Fire test computer simulations were performed for a spent fuel canister using TACO2D[15] to calculate internal temperatures from an 800°C, 30 minute boundary condition. These temperatures were used to calculate internal pressures. The internal pressure was applied as a boundary condition to model canister stresses using NIKE2D.[16] Assuming increased pressure from fuel-rod gas release, the maximum stress in the canister was 9,900 psi (68.3 MPa). This results in a safety factor of two on the ultimate strength at 800°C, which is about 20,000 psi (138 MPa).

Structural analysis for lifting loads using NIKE2D gave a maximum stress of 4,400 psi (30.3 MPa) (in the pintle). A retrieval load of 80,000 lb (356 kN) can be applied on the pintle without exceeding the 304L stainless steel yield strength of 30,000 psi (207 MPa) in the pintle or canister.

To simulate the (unexpected) flooding condition in the repository, a hydrostatic pressure was applied to the outside of the canister. The yield strength was not exceeded until 230 psig (1.59 MPa) of water pressure was applied. This pressure would result from a water head of over 500 ft (164 m). Canister strength is therefore sufficient to allow for unlikely flooding incidents, and for significant loadings from local rock failures.

Structural analysis of other canister designs and conditions is continuing. The results thus far indicate that all designs will meet strength requirements over the expected range of pre-closure environments.

DESIGN DESCRIPTION

Reference Designs

The reference conceptual designs represent the least complicated configurations (see Fig. 1). The DHLW 61 cm diameter pour canister and the 32 cm diameter CHLW pour canister are both nominally one cm thick, 304L stainless steel with identical pintles of the Savannah River type.[9]

The reference spent fuel canister is 65 cm diameter with 4.0 and 4.5 m lengths (plus pintle) to accomodate various length spent fuel rods. The canister contains 7 PWR or 18 BWR assemblies. For intact assemblies and preconsolidated boxed spent fuel, the diameter is 68 cm and the lengths are 4.25 and 4.75 m (plus pintle). The canisters are fabricated from 304L stainless steel with wall thickness of one cm. The pintles (16.5 cm) are identical to pour canister pintles.

The internal space-frame for spent fuel canisters provides mechanical stability and enhances heat transfer. For consolidated rods, the space-frame consists of 12-14 one cm thick, carbon steel radial fins in a cylindrical shell with end plates. For preconsolidated or intact assemblies, the space-frame consists of a one cm thick "pigeon-hole" array with square receptacles and end plates. The PWR canister contains three intact or six preconsolidated PWR assemblies. For BWR assemblies, it contains nine intact or 18 preconsolidated assemblies. The 68 cm diameter for preconsolidated boxed assemblies is contingent upon the successful "two for one" volume reduction envisaged and demonstrated for preconsolidation.[17]

None of the reference designs utilizes an overpack container. All are intended for single package emplacement in a vertical borehole.

Alternative Designs

Alternative metals (under long term testing along with 304L) are 316L SST, 321 SST and Incoloy 825 nickel-base alloy. These represent more corrosion-resistant but more expensive metals. Results of long term testing will be used to determine the alloy selection and container thickness.[5,13] A minimum thickness of one cm is required for strength.

The alternative emplacement mode is horizontal emplacement. A carbon steel liner will be used to keep the borehole free from sloughing rock to facilitate emplacement and retrieval. Reference canister designs can be emplaced horizontally. Figure 2 shows the alternative spent fuel package design with packing emplaced vertically.

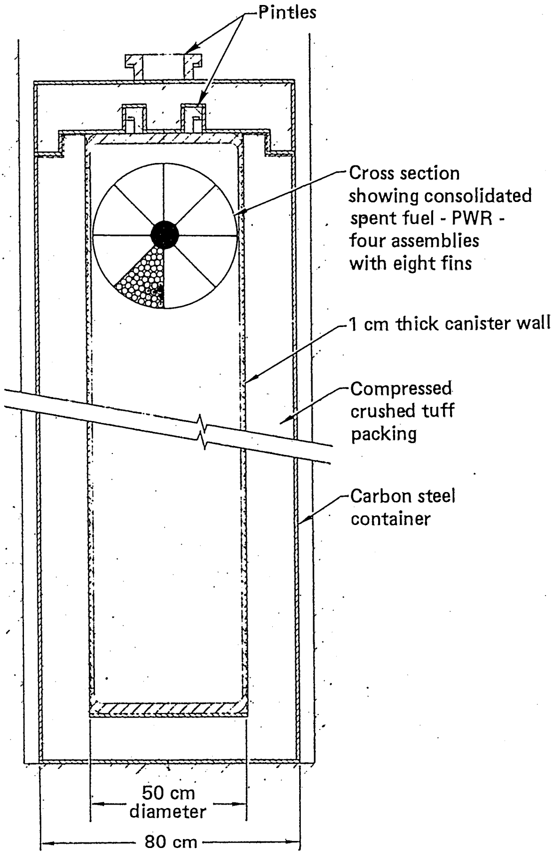

Fig. 2. Alternative design for vertically emplaced spent fuel canisters.

Residual thermal stresses or sensitization in 304L pour canisters may prove unacceptable. If so, three design alternatives have been developed: stress corrosion resistant alloys, internal liners, and overpacks. When testing data and analysis results are obtained, it will become more clear as to which alternative(s) is most appropriate.

ECONOMIC ANALYSIS

Costs have been estimated for all reference and alternative designs. The most cost effective designs are those that maximize the canister size without exceeding waste form temperature limits. The most costly alternative is spent fuel with packing, vertically emplaced (see Fig. 2). Table II gives waste package design related costs of reference designs and the alternative design spent fuel package (4 PWR assemblies) with packing. Most waste package costs are included. Costs for underground and above ground facilities (buildings, equipment, roads, drifts, boreholes, access shafts, etc. are not included).

TABLE II
High Level Waste Package Costs (1983 Dollars)
304L Canister, Vertical Emplacement

	Reference			Alternative
			7 PWR	4 PWR
	DHLW	CHLW	Spent Fuel	Spent Fuel with Packing
Power, kW	0.42	2.21	3.56	2.01
Canister	$5200	3200	9500	7900
Packing	---	---	---	14700
Repository Processing	3800*	3800*	8700*	6600
Consolidation	---	---	24000*	14000
Radiation Plug	6400	5200	7400	10700
Total cost per Pkg	$15400	$12200	$49600	$53900
No. Pkg per yr	500	660	288	504
Annual cost	$7.7M	$8.1M	$14M	$27M

* Schornhorst 1983

CONCLUSIONS

The conceptual design ensemble provides a group of designs from which a set can be chosen for eventual detailed design of waste packages. Within the variations in materials and configurations available, detailed designs should meet all requirements, barring unexpected results from long-term materials testing or package environment characterization activities.

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