Transportation Cask for Bare High Burnup Used Nuclear Fuel – 16362

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ABSTRACT

A conceptual design for a reusable transportation cask (the 6625B-HB) capable of transporting boiling water reactor (BWR) and pressurized water reactor (PWR) used nuclear fuel (UNF) assemblies, including high burnup UNF, was produced for the Department of Energy (DOE) by AREVA. This cask could be configured to ship these assemblies either as bare fuel or fuel loaded into single-assembly damaged fuel cans (DFCs). The 6625B-HB cask has been designed with reasonable assurance it can be certified by the Nuclear Regulatory Commission (NRC) under 10 CFR Part 71 based on AREVA TN's experience with the MP197HB (a transportation cask designed to ship high burnup UNF in a dry storage canister), fabricated within existing facilities, used by most utilities, and transported by rail. The level of detail developed for the 6625B-HB is intended to support analyses and planning activities that DOE is performing in laying the groundwork for an integrated waste management system, which includes preparing for future large-scale transport of UNF to consolidated interim storage or disposal facilities. The details of the conceptual design include cask characteristics (e.g., capacity, dimensions, and masses), characteristics of the UNF that could be shipped in this cask system concept, estimates of costs to fabricate this cask system, an assessment of operational activity durations and associated cumulative doses for loading and unloading this cask system, and identification of potential limitations or anticipated licensing considerations of relevance for this cask system. This design concept for a reusable transportation cask would enhance the high-burnup fuel assembly carrying capacity as compared to other NRC-certified transportation casks and, unlike welded canister systems, could be used for shipment of bare UNF assemblies taken directly from reactor spent fuel pools (SFPs).

INTRODUCTION

In support of operations at a larger Interim Storage Facility (ISF) in the future as described in the Administration's *Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste* [1], DOE wanted to explore options to ship UNF directly from SFPs of nuclear power plants to an ISF. A study to examine design concepts for reusable transportation casks optimized for shipment from the SFPs to an ISF was sought, including a cask concept capable of being loaded with all assemblies enclosed in DFCs.

In response, AREVA developed the 6625B-HB transportation cask concept for DOE. The 6625B-HB would be capable of handling a large range and size of UNF assemblies, including the restrictive short cooled, high burnup UNF assemblies (> 45 GWd/MTU and at least 5 years cooled). The 6625B-HB can contain up to 24 PWR or 61 BWR UNF assemblies placed into baskets designed for holding either bare fuel or fuel packaged into DFCs. The designed transportation package of the 6625B-HB consists of the payload baskets, a lead-shielded cask body, an inner closure lid with lead and steel gamma shielding, an outer steel lid, upper end structure, lower end structure with lead and steel gamma shielding, and upper and lower impact limiters. To ensure reusability, the lids are designed to be bolted to the cask body, and the BWR and PWR baskets are designed to be interchangeable. The following limits, as specified by DOE, were also applied to the conceptual cask design: (1) a gross hook weight of less than 125 tons; (2) a maximum diameter of 128 inches; (3) an accessible surface temperature limit of 185°F; and (4) a normal dose rate of less than 10 mrem/hr at 2 meters.

The conceptual design of the 6625B-HB also took into consideration data collected from the SFPs at the six operating Duke Energy reactor sites. This collected data includes characteristics of the SFP inventory (e.g., burnup, years cooled), duration of activities associated with loading of dry storage casks/canisters, weight capacity of cranes and floors, design information for yokes, and estimation of damaged and failed UNF quantities. This data was used to inform several of the activities performed for the design of the 6625B-HB, including the evaluation of: (1) the ability to efficiently perform loading operations of the 6625B-HB; (2) the effectiveness of the 6625B-HB for offloading the contents of SFPs for both PWR and BWR UNF; (3) alternative loading patterns for UNF into the existing basket structure of the 6625B-HB; and (4) the quantity of DFCs containing damaged UNF that the 6625B-HB should be conservatively designed to load. Results from this study performed with Duke Energy were presented at the 2015 ANS Winter Conference [2].

This paper provides an overview of the following: 6625B-HB conceptual design; the approach taken to satisfy the regulatory requirements; some details of the containment vessel and baskets for the PWR and BWR UNF; and loading maps with corresponding fuel qualification tables for the PWR and BWR UNF baskets. This paper reflects research and development efforts to explore technical concepts which could support future decision making by DOE. No inferences should be drawn from this paper regarding future actions by DOE.

THE 6625B-HB DESIGN CONCEPT

A conceptual cask system, the 6625B-HB, was designed by AREVA to be used for rail transport of UNF, including high burnup UNF, for the DOE under a task order arrangement [3]. The 6625B-HB packaging is designed for direct loading in a commercial nuclear power plant's SFP. The package is designed to be transported singly, with its longitudinal axis horizontal, by rail or highway truck as an exclusive use shipment. When loaded and prepared for transport, the 6625B-HB package can contain up to 24 PWR or 61 BWR UNF assemblies, is 261.5 inches long, 126 inches in diameter (over the impact limiters), and has a nominal weight of 151.1 tons. **Figure 1** provides a general overview of the 6625B-HB and some of its principle dimensions.

The 6625B-HB utilizes bolted inner and outer lids that allow for it to be reused and credited for moderator exclusion under specific conditions as described below in the regulatory section of this paper. By use of four different basket designs, this cask system is designed and optimized to be capable of handling the following UNF arrangements:

- Bare PWR UNF
- Bare BWR UNF
- PWR UNF placed in DFCs
- BWR UNF placed in DFCs

The 6625B-HB is designed to accommodate essentially the entire existing and future inventory of commercial light-water reactor UNF. Within the packaging, bare fuel or fuel in DFCs is contained in the basket structures shown in **Figure 2**, which have been specifically designed for each fuel type to provide for heat rejection and criticality control.

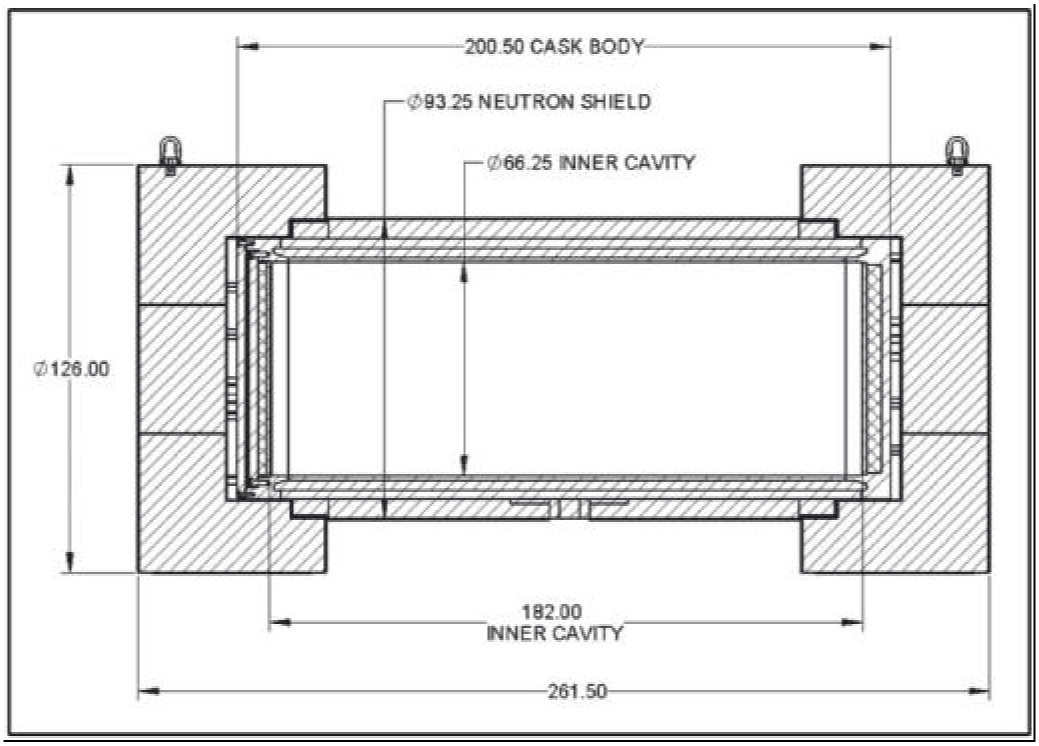


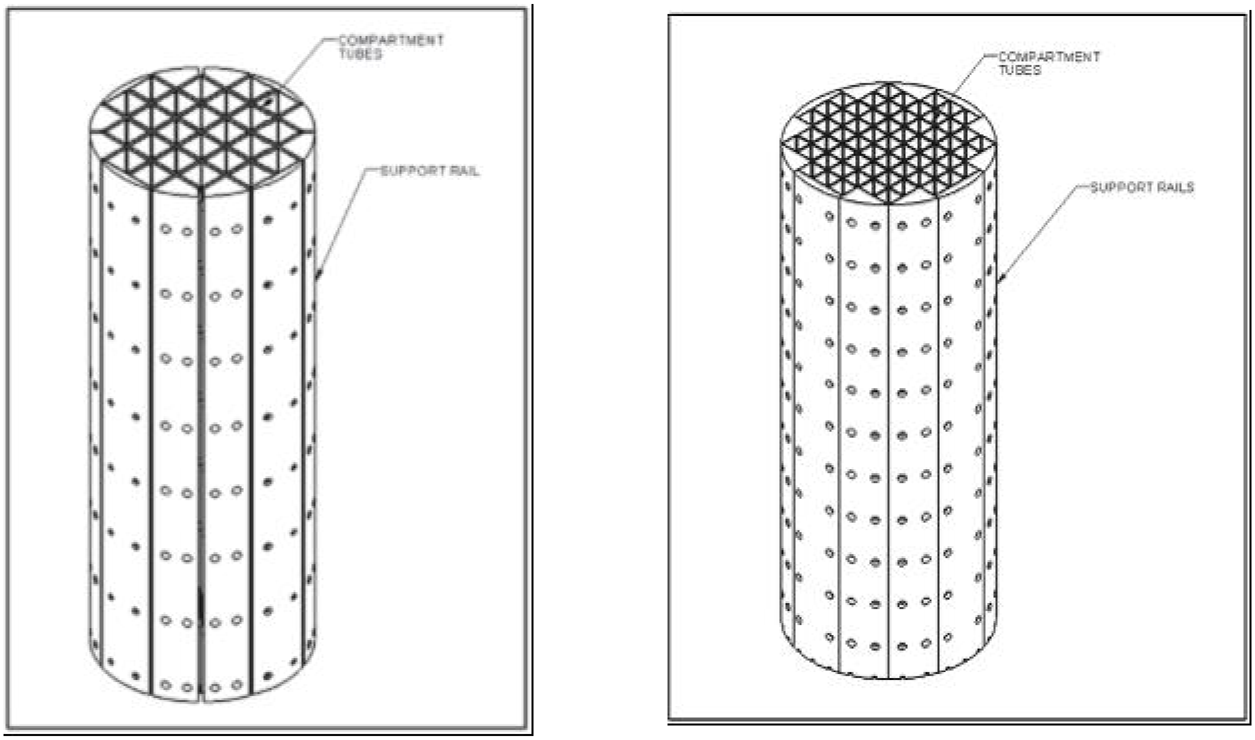
Figure 1. 6625B-HB Package Dimensions

As shown in **Figure 3**, the designed packaging system consists of a payload basket, a lead-shielded cask body, an inner closure lid with lead and steel gamma shielding, an outer steel lid, upper end structure, lower end structure with lead and steel gamma shielding, and upper and lower impact limiters. The packaging is designed to provide leak tight containment of the radioactive contents under all Normal Conditions of Transport (NCT) and Hypothetical Accident Conditions (HAC).

The packaging is of conventional design and utilizes American Society of Mechanical Engineers (ASME) alloy steel as its primary structural material. The 6625B-HB cask is fabricated primarily of nickel-alloy steel (NAS). Other materials include the cast lead shielding between the containment boundary and inner shell, the elastomer O-ring seals (Viton O-rings), the borated resin neutron shield, and the carbon steel closure bolts. Socket-headed cap screws (bolts) are used to secure the inner and outer lids to the cask body. The body of the cask consists of a 1.25 inch thick, 66.25 inch inside diameter, NAS inner (containment) shell and a 2.75 inch thick, 80.25 inch outside diameter, NAS structural shell which sandwich the 3.00 inch thick, cast lead shielding material. Lead shielding is also located in the lower end structure and in the inner lid.

Regulatory Evaluation of the 6625B-HB

The 6625B-HB packaging is designed as a Type B(U)F–96 shipping container in accordance with the provisions of 10 CFR Part 71. Analytical evaluations were performed to ensure adequacy of the structural, thermal, containment, shielding, and criticality design features of the 6625B-HB transport package.



(a) **(b)**

Figure 2. 6625B-HB 24 PWR Basket (a) and 61 BWR Basket (b)

To meet the requirements of 10 CFR 71.55(b) (as-loaded fuel condition with fresh water intrusion), burnup credit will be required for PWR UNF, but is not required for BWR UNF. Taking credit for burnup reduces the system reactivity due to depletion of fissile material and growth of fission product poisons. To meet the requirements of 10 CFR 71.55(d) (packages under NCT), burnup credit is not required because the package is assumed to be dry, as it is leak tight under NCT.

To meet the requirements of 10 CFR 71.55(e) (packages under HAC), moderator exclusion (not burnup credit) is used as the licensing basis because the condition of the fuel is unknown. Burnup credit is not required because moderator exclusion results in a low reactivity. To ensure a robust design, ‘defense-in-depth’ cases are also performed in support of 10 CFR 71.55(e). In the defense-in-depth cases, reasonable fuel damage is assumed with fresh water moderation and burnup credit is applied. For the defense-in-depth cases, the upper subcritical limit (USL) may be based upon an administrative margin of 0.02 (USL ~ 0.98; an administrative margin of 0.05 is used under all other conditions).

Moderator exclusion is employed as a licensing basis to demonstrate compliance with the sub-criticality requirements of 10 CFR 71.55(e). The guidance and criteria provided in Interim Staff Guidance 19 (ISG-19) [4] are employed for this purpose. Specifically, 10 CFR 71.55(e)(2) states that to demonstrate sub-criticality under HAC, it must be assumed that “water moderation occurs to the most reactive credible extent consistent with the damaged condition of the package and the chemical and physical form of the contents.” ISG-19 establishes criteria under which it is possible to demonstrate that the worst-case damaged condition of the package does not result in water in-leakage. This allows the HAC criticality calculations that form the licensing basis to be performed assuming there is no water in-leakage.

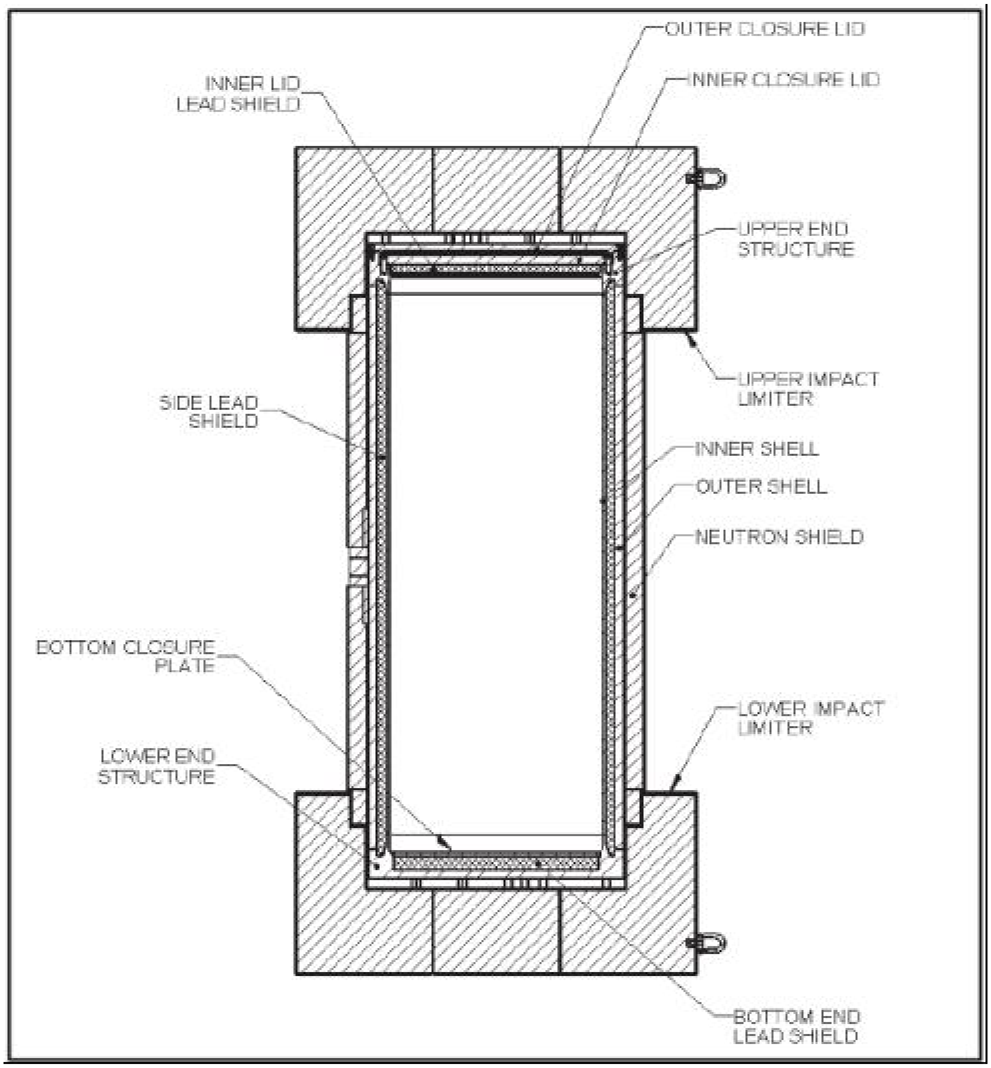


Figure 3. 6625B-HB Package Cross-Section

Containment Vessel

The 6625B-HB cask containment boundary, as shown in **Figure 4**, consists of the 66.25 inch diameter inner shell, a 1.25 inch thick bottom plate, an upper end structure, a 3.00 inch thick inner lid with a 3.50 inch thick shield plug with innermost seals and closure bolts, vent, and drain ports with closure bolts and seals, and containment welds. A 66.25 inch diameter, 182.00 inch long cavity is provided within the containment boundary as shown in **Figure 1**.

A redundant mechanical closure is provided by the 2.50 inch thick outer lid with outermost seals and closure bolts, and the vent port with closure bolts and seals. The outer closure lid along with the space between the lids meets the design and manufacturing criteria such that it can be merged with the inner containment space to define an extended containment boundary. The extended containment boundary will be used only in the unlikely event that the boundary defined by the inner lid ceases to meet leak tight criteria. Both closure lids have been designed to perform the containment function with final qualification by leakage rate testing according to ANSI N14.5 [5].

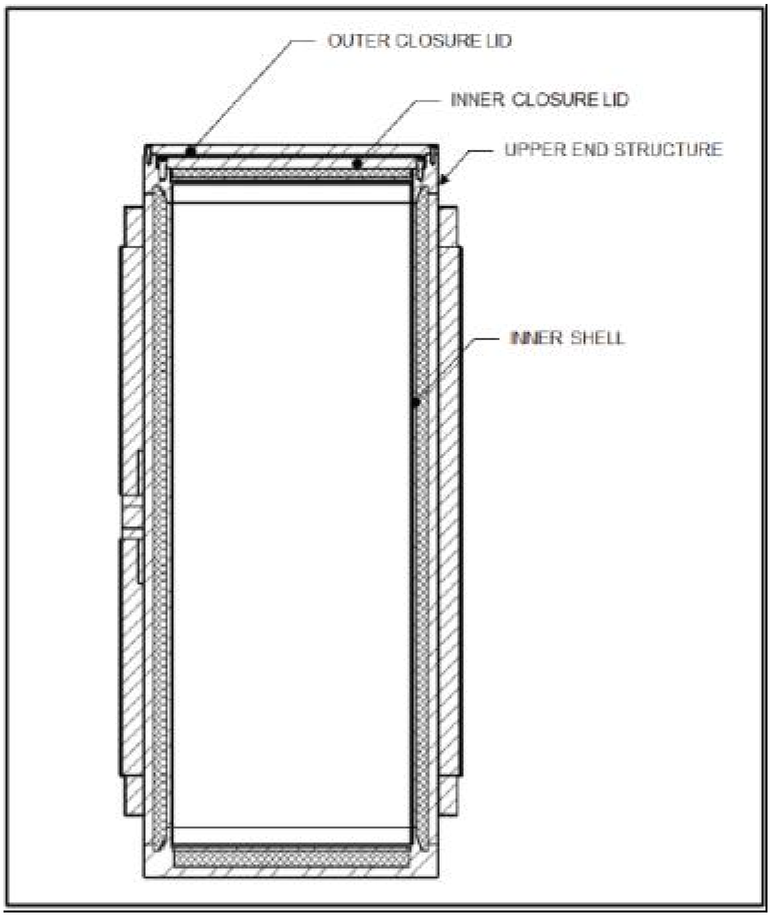


Figure 4. 6625B-HB Package Containment Boundary

The containment vessel prevents leakage of radioactive material from the cask cavity. It also maintains an inert atmosphere (helium) in the 6625B-HB cask cavity. Helium within the cavity assists in heat removal and provides a non-reactive environment to protect fuel assemblies against fuel cladding degradation. To preclude air in-leakage, the cask cavity is pressurized with helium to above atmospheric pressure.

Contents of PWR Basket

The 24 PWR basket is designed to transport PWR UNF with the following limitations:

- maximum irradiated assembly length of 180 inches (does not include thermal growth), fuel spacers are used to accommodate shorter UNF assemblies.
- maximum assembly average initial enrichment of 5.0 wt.% U-235
- maximum allowable assembly average burnup is limited to 62.5 GWd/MTU

The minimum cooling time requirements are given in **Table 1**. The 24 PWR basket is also designed to transport non-fuel assembly hardware (NFAH), which may include burnable poison rod assemblies (BPRAs), thimble plug assemblies (TPAs), control rod assemblies (CRAs), rod cluster control assemblies (RCCAs), axial power shaping rod assemblies (APSRAs), orifice rod assemblies (ORAs), vibration suppression inserts (VSIs), neutron source assemblies (NSAs), and neutron sources.

The basket is divided into inner and peripheral zones, as shown in **Figure 5**. Fuel in each zone is governed by the cooling times presented in **Table 1**. These cooling times are determined to meet temperature and dose rate limits. **Table 2** identifies the maximum decay heat per fuel assembly within a fuel zone. The PWR basket can accommodate 8 damaged and 16 undamaged fuel assemblies with the damaged fuel assemblies loaded in Zone 4.

Table 1. PWR Fuel Qualifications Table for the 6625B-HB 24 PWR Basket

		Minimum Cooling Time (years)		
		Zone 1/4	Zone 2	Zone 3
Maximum Burnup	Minimum Enrichment	Heat ≤ 0.9 kW	Heat ≤ 1.4 kW	Heat ≤ 2.1 kW
≤ 30	≥ 1.8	≥ 5	≥ 5	≥ 5
≤ 37	≥ 2.3	≥ 6.5	≥ 5	≥ 5
≤ 45	≥ 2.8	≥ 10	≥ 5	≥ 5
≤ 53	≥ 3.3	≥ 16	≥ 6.5	≥ 5
≤ 62.5	≥ 3.8	≥ 26	≥ 9	≥ 5

Table 2. PWR Decay Heat Limits for the 6625B-HB 24 PWR Basket

	Zone 1/4	Zone 2	Zone 3
Maximum Decay Heat (kW/FA)	0.9	1.4	2.1
Number of Fuel Assemblies	4/8	8	4
Maximum Decay Heat per Zone (kW)	3.6/7.2	11.2	8.4
Maximum Decay Heat per Basket (kW)	30.4		

Contents of BWR Basket

The 61 BWR basket is designed to accommodate 61 intact BWR fuel assemblies with or without fuel channels or 61 DFCs loaded with intact BWR fuel assemblies with or without fuel channels. The basket can accommodate 12 DFCs loaded with damaged fuel assemblies. The following limitations apply to this basket design:

- maximum irradiated assembly length of 180 inches (does not include thermal growth), fuel spacers are used to accommodate shorter UNF assemblies.
- maximum assembly average initial enrichment of 5.0 wt.% U-235
- maximum allowable assembly average burnup is limited to 62.5 GWd/MTU

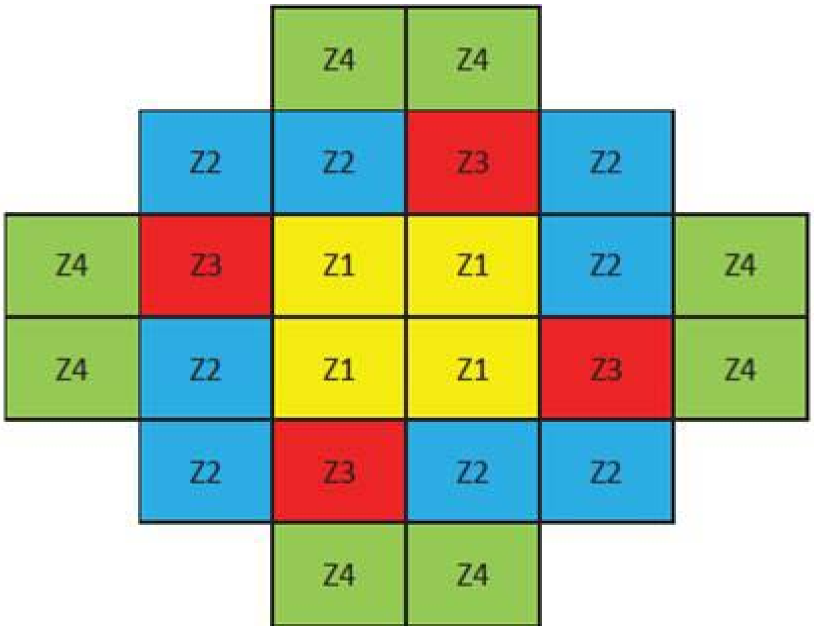


Figure 5. Heat Load Zoning Configuration for 6625B-HB 24 PWR Basket

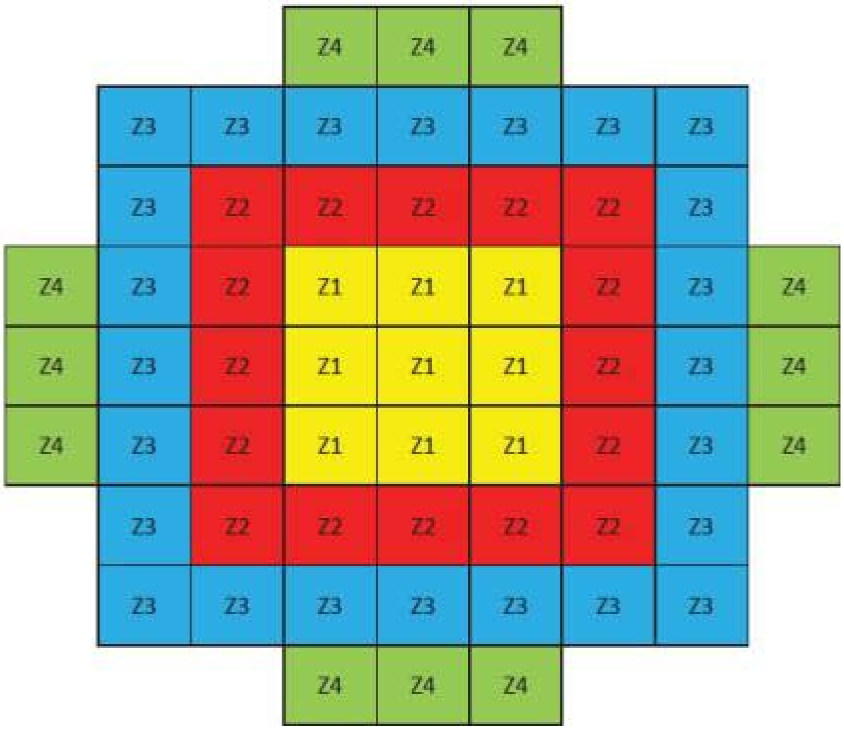
The minimum cooling time requirements are given in **Table 3**. The basket is divided into inner and peripheral zones, as shown in **Figure 6**. Fuel in each zone is governed by the cooling times presented in **Table 3**. These cooling times are determined to meet temperature and dose rate limits. **Table 4** identifies the maximum decay heat per fuel assembly within a fuel zone. The BWR basket can accommodate 12 damaged and 49 undamaged fuel assemblies with the damaged fuel assemblies loaded in Zone 4.

Table 3. BWR Fuel Qualification Table for the 6625B-HB 61 BWR Basket

		Minimum Cooling Time (years)		
		Zone 1 / 4	Zone 2	Zone 3
Maximum Burnup	Minimum Enrichment	Heat ≤ 0.33	Heat ≤ 0.78 kW	Heat ≤ 0.45 kW
≤ 29	≥ 1.5	≥ 5	≥ 5	≥ 5
≤ 35	≥ 2.2	≥ 6	≥ 5	≥ 5
≤ 39	≥ 2.4	≥ 7.2	≥ 5	≥ 5
≤ 45	≥ 2.8	≥ 10	≥ 5	≥ 6
≤ 53	≥ 3.3	≥ 16	≥ 5	≥ 8
≤ 62.5	≥ 3.8	≥ 25	≥ 5	≥ 12.5

Table 4. BWR Decay Heat Limits for the 6625B-HB 61 BWR Basket

	Zone 1 / 4	Zone 2	Zone 3
Maximum Decay Heat (kW / FA)	0.33	0.78	0.45
Number of Fuel Assemblies	9 / 12	16	24
Maximum Decay Heat per Zone (kW)	3.0 / 4.0	12.5	10.8
Maximum Decay Heat per Basket (kW)	30.3		



			Z4	Z4	Z4			
	Z3	Z3	Z3	Z3	Z3	Z3	Z3	
	Z3	Z2	Z2	Z2	Z2	Z2	Z3	
Z4	Z3	Z2	Z1	Z1	Z1	Z2	Z3	Z4
Z4	Z3	Z2	Z1	Z1	Z1	Z2	Z3	Z4
Z4	Z3	Z2	Z1	Z1	Z1	Z2	Z3	Z4
	Z3	Z2	Z2	Z2	Z2	Z2	Z3	
	Z3	Z3	Z3	Z3	Z3	Z3	Z3	
			Z4	Z4	Z4			

Figure 6. Heat Load Zoning Configuration for 6625B-HB 61 BWR Basket

CONCLUSION

The 6625B-HB conceptual design is based on current state-of-the-art industry designs that have been licensed by the NRC. By using proven methodologies that have been utilized in previously licensed casks, a high degree of confidence is obtained for this conceptual design. This approach provides assurance that the design will functionally work, as well as meet the regulatory requirements. The proven methodologies provide confidence that the demonstration of compliance can be made to the current regulatory organization in an acceptable manner. Although detailed analysis was not performed in all areas within the restraints of this conceptual design program, the configurations used in the design are known to be proven acceptable based on very detailed analysis and testing over the years. The design was developed using currently accepted industry practices with the goal of maximizing the package contents within the design basis restrictions. These include a weight limit, a required cavity length, and the thermal, shielding, and criticality restraints of the contents. The selected design was optimized for transporting high burnup fuel while continuing to meet thermal, shielding, criticality, and structural regulatory requirements and also limiting adverse impacts to: operations, the ability to fabricate the system, and fabrication costs. A summary comparison of the basket configurations for the 6625B-HB is shown in **Table 5**.

Table 5. Summary Comparison of Basket Configurations

Characteristic	Bare PWR UNF	PWR UNF in DFC	Bare BWR UNF	BWR UNF in DFC
Fuel Assembly Capacity (#)	24	24	61	61
Total Loaded Weight of Package for Transport (lbs.)	299,121	300,441	292,260	294,151
Maximum Width (inches)	126	126	126	126
Maximum Length with Impact Limiters (inches)	261.5	261.5	261.5	261.5
Maximum Length without Impact Limiters (inches)	200.5	200.5	200.5	200.5
Cask Outisde Diameter without Impact Limiters (inches)	93.25	93.25	93.25	93.25
Cask Cavity Inside Diameter (inches)	66.25	66.25	66.25	66.25
Cask Cavity Length (inches)	182.0	182.0	182.0	182.0
Maximum Heat Load (kW)	30.4	30.4	30.2	30.2
Maximum Fuel Cladding Temperature – NCT (°F)	565	561	375	399
Maximum Fuel Cladding Temperature – HAC (°F)	860[†]			
Maximum Accessible Surface Temperature (°F)	142[†]			
Maximum Dose Rate 2m from Cask Surface – NCT (mrem/hr)	9.3[‡]		9.3[‡]	

Characteristic	Bare PWR UNF	PWR UNF in DFC	Bare BWR UNF	BWR UNF in DFC
Maximum Dose Rate 1m from Cask Surface – HAC (mrem/hr)	875.7‡		920.9‡	
Max. k_{eff} + 2σ - NCT (wet)	0.9144	0.9145	0.9252	0.9316
Max. k_{eff} + 2σ - HAC (wet)	0.9386	0.9386	0.9488	0.9549
Fabrication Costs for Cask System ($)	5.1 – 8.2M	5.2 – 8.3M	5.0 – 8.0M	5.2 – 8.2M
Total Cumulative Dose for Loading & Unloading UNF (mrem)	1002.2	1002.6	1003.1	1004.1
Total Loading and Unloading Duration (hr)	79.1	88.7	101.3	125.7

[†] Listed values are maximum for all basket cases.

[‡] DFCs were not modeled in the shielding analyses as the DFCs provide additional shielding and hence, the bare fuel models are considered to provide bounding values.

REFERENCES

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