Canister for Radioactive Waste Transport, Storage and Disposal in Boreholes – 22033

Rodney Baltzer*, Mark Frei*, David Garrido**, Steve Sisley**

*Deep Isolation, Inc.
**NAC International Inc.

ABSTRACT

Countries around the world continue to work on plans to develop safe, secure, and permanent deep geological disposal facilities for high-level waste, including spent nuclear fuel and other highly radioactive materials. One disposal method uses directional drilling techniques and emplaces disposal canisters in either a vertical, slanted, or horizontal orientation in boreholes deep underground. This provides a more economical disposal solution for spent fuel and high-level waste from advanced reactors, small modular reactors and for countries with smaller waste inventories, but it would also be even more effective to package that waste - when removed from a spent fuel pool - into a disposal canister that could fit into a borehole. Furthermore, a standardized canister designed to include borehole disposal presents an opportunity for greater system efficiencies throughout the fuel life-cycle and maintains options for other disposal methods such as mined repositories.

During the past year, Deep Isolation, Inc., in partnership with NAC International (NAC), further advanced the engineering design of a canister for storage, transportation and disposal, which would eliminate the need for repackaging spent fuel for final disposal, leaving open many waste management options for the lifecycle of the waste. Each canister accommodates a single pressurized water reactor (PWR) fuel assembly, and up to 19 canisters fit within the cavity of the NAC MAGNASTOR concrete cask and NAC MAGNATRAN transportation cask. Preliminary structural, thermal, shielding and criticality safety evaluations were performed for multimodal (storage, transportation, and disposal) for design-limiting conditions to develop a canister design sufficient to satisfy established regulatory requirements for storage and transportation and anticipated regulatory requirements for disposal.

The disposal canister, which is part of an overall engineered barrier system for storage, transport, and borehole disposal, consists of a canister shell assembly, an internal basket assembly, and a removable (bolt-on) lifting fixture. The canister shell assembly consists of a cylindrical shell, an integral welded bottom plate, and a field installed closure lid. The canister includes drain and vent port features that are used in wet-loading operations to drain water, vacuum dry, and inert the canister cavity.

The disposal canister design developed maximizes the use of readily available materials and product forms and eliminates the need for borated neutron absorber materials for criticality control for an economical borehole disposal solution.

The cost of disposal for smaller waste inventories in properly sited horizontal borehole disposal system is estimated to be approximately 50% of the cost of a mined repository. Other factors must be considered but the siting, safety case and technology are sufficiently developed to show that nuclear waste can be safely disposed using borehole disposal repositories while offering cost savings when compared to the status quo.

INTRODUCTION

Countries around the world continue to work on plans to develop safe, secure, and permanent deep geological disposal facilities for high-level waste, including spent nuclear fuel and other highly radioactive materials. One disposal method uses directional drilling techniques and emplaces disposal canisters in either a vertical, slanted, or horizontal orientation in boreholes deep underground. This provides a more economical disposal solution for spent fuel and high-level waste from advanced reactors, small modular reactors and for countries with smaller waste inventories, but it would be even more effective to package that waste - when removed from a spent fuel pool - into a canister that would also be designed for and fit into a borehole. Furthermore, a standardized canister designed to include borehole disposal presents an opportunity for greater system efficiencies throughout the fuel life-cycle and maintains options for other disposal methods such as mined repositories.

Boreholes for disposal can be vertical, horizontal, or deviated and will be customized for the specific geology, waste form and stakeholder requirements. The canister design assumed a generic horizontal borehole as the baseline. The generic horizontal borehole consists of a 1,000 m vertical access hole that gradually transitions to a 1,500 m horizontal section where the waste canisters are emplaced. Previous reports [1] discuss the concept of operations.

During the past year, Deep Isolation, Inc., in partnership with NAC International (NAC), further advanced the engineering design of a canister for storage, transportation and disposal, which would eliminate the need for repackaging spent fuel for final disposal, leaving open many waste management options for the lifecycle of the waste. Each canister accommodates a single pressurized water reactor (PWR) fuel assembly, and up to 19 canisters fit within the cavity of the NAC MAGNASTOR concrete cask and NAC MAGNATRAN transportation cask. Preliminary structural, thermal, shielding and criticality safety evaluations were performed for multimodal (storage, transportation, and disposal) for design-limiting conditions to develop a canister design sufficient to satisfy established regulatory requirements for storage and transportation and anticipated regulatory requirements for disposal.

Canister Overview

The design drawing of the preliminary Drillhole Canister (DHC) design considered in the preliminary analysis is shown below in Figure 1. It consists of at thick-walled shell assembly and a field-installed shield lid, that form a canister cavity sized to accept the largest domestic PWR fuel type. The DHC internals consist of a fuel tube and four side inserts that bridge the gap between the fuel tube and shell, providing both structural and thermal design functions. The DHC includes a field-installed closure ring that provides a redundant confinement boundary in accordance with current NRC guidelines. A lift adapter is bolted to the top end of the DHC to provide a lifting interface for handling at the borehole repository surface facility, including placing the DHC into or retrieving it from the borehole.

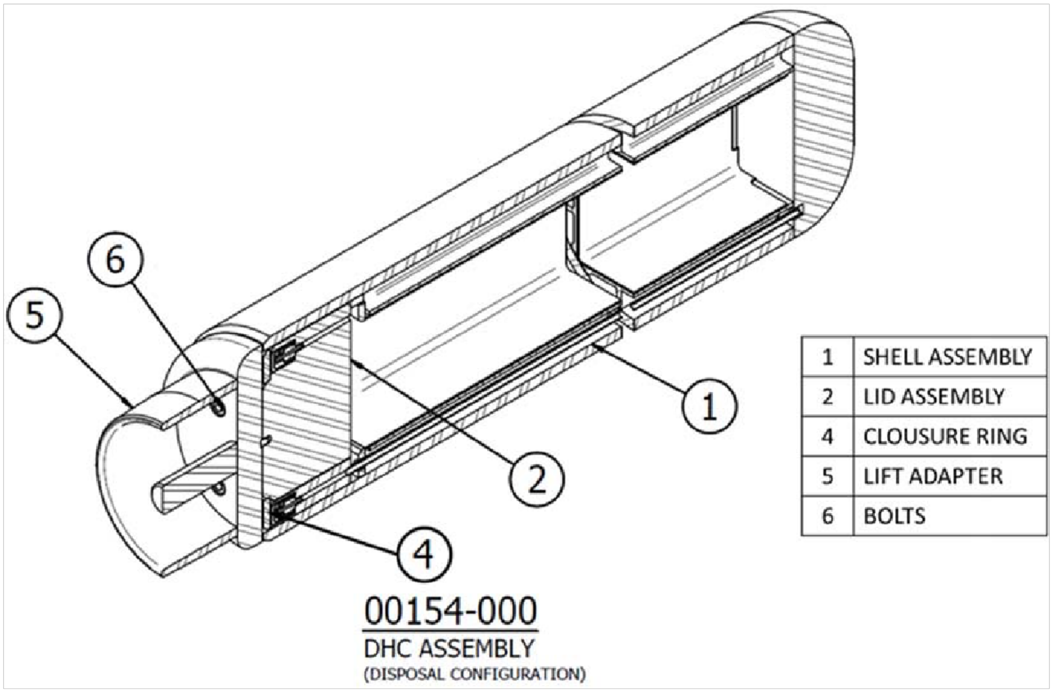


Fig. 1. Drillhole Canister Preliminary Design.

The preliminary design report describes the structural, thermal, shielding and criticality evaluations of the DHC design for borehole disposal of used PWR fuel assemblies. Note that the PWR size was used as it will be larger than most other used fuels from advanced, small modular and legacy reactors. This creates a bounding canister diameter that can be reduced and customized for other fuel types. The DHC is intended to be used for temporary storage and an Independence Spent Fuel Storage Installation (ISFSI) located at a utility site or at a Centralized Interim Storage Facility (CISF), transportation between storage facilities and the repository, and disposal at a borehole repository.

Preliminary evaluations have been performed for those storage, transportation, and disposal conditions expected to govern the design to provide reasonable assurance that the DHC design concept will satisfy the applicable regulatory requirements for storage (US 10 CFR 72 [2] and the equivalent international IAEA regulations) and transportation (US 10 CFR 71 [3] and equivalent international IAEA regulations). Although no regulation for borehole disposal currently exists in the United States, and very few other countries have specific regulations for borehole disposal, the regulatory framework of US 10 CFR 63 [4] for the Yucca Mountain repository has been used as guidance for the DHC design (and equivalent international IAEA regulations). Additional safety analysis will be required to support applications for regulatory certification of the DHC design for storage, transportation, and disposal.

STRUCTURAL EVALUATION

Preliminary structural evaluations of the DHC assembly have been performed for those storage, transportation, and disposal conditions expected to govern the design. These include buckling of the DHC shell due to hydrostatic and lithostatic pressure loading in the borehole, handling loads at the borehole repository including vertical lifting and stuck canister retrieval, a range of postulated free drop condition at the borehole surface facility, and a postulated free drop into the borehole.

External pressure loading on the drillhole canister (DHC) in the borehole repository is expected to govern the thickness of the DHC shell. Preliminary structural analysis of the DHC shell have been performed to determine the shell thickness required to satisfy the applicable buckling criteria for hydrostatic and lithostatic design pressures for repository depths ranging from 1.0 km to 3.0 km.

Hydrostatic Pressure Limit Load Analysis

Structural stability of the DHC shell under hydrostatic pressure loading is evaluated in accordance with the limit analysis acceptance criteria of Subsection NB of the ASME Code. To satisfy this criterion, it is demonstrated that each DHC shell configuration can withstand an external pressure load equal to 150% of the design hydrostatic pressure load at the maximum depth permitted without collapsing. The DHC configurations are designated DHC-2.0, DHC-2.5 and DHC-3.0 for maximum borehole depths of 2.0 km, 2.5 km, and 3.0 km, respectively. All DHC configurations have the same shell inside diameter (i.e., 12.5-inch) and outside diameters of 14.0-inch (i.e., t = 0.75-inch), 14.375-inch (i.e., t = 0.9375-inch), and 14.75-inch (i.e., t = 1.125inch), respectively.

The results of the limit analysis demonstrate that all DHC configurations satisfy the collapse load limit analysis design criteria of ASME Subsection NB [5] Article NB-3228.1 for the design basis hydrostatic pressure loading. Specifically, all DHC shell configurations can withstand at least 165% of the hydrostatic pressure load without collapsing.

Lithostatic Pressure Plastic Instability Analysis

Structural stability of the DHC shell under lithostatic pressure loading is evaluated in accordance with the plastic system analysis acceptance criteria of Appendix F of the ASME Code [6]. To satisfy this criterion, it is demonstrated that each DHC shell configuration can withstand an external pressure load equal to approximately 143% (i.e., 1/0.7) of the design lithostatic pressure load at the maximum depth permitted without collapsing. The DHC configurations are designated DHC-2.0, DHC-2.5 and DHC-3.0 for maximum borehole depths of 2.0 km, 2.5 km, and 3.0 km, respectively. All DHC configuration have the same shell inside diameter (i.e., 31.75 cm) and outside diameters of 35.56 cm (i.e., t = 1.91 cm), 36.51 cm (i.e., t = 2.38 cm), and 37.47 cm (i.e., t = 2.88 cm), respectively.

The results of the plastic instability analysis, demonstrate that all DHC configurations satisfy the plastic instability design criteria of F-1341.4 for lithostatic pressure loading. Specifically, all DHC shell configurations can withstand at least 143% of the lithostatic pressure load without collapsing.

Vertical Lift Analysis

The DHC shell assembly disposal configuration (i.e., with lift adapter attached) has been evaluated for a vertical lift condition in which the DHC is suspended by the threaded post at the center of the lift adapter. The lift load is assumed equal to the dead weight of the DHC assembly increased by 15% to account for possible crane hoist motion. The lift evaluation has been performed for the heaviest fuel assembly type (B&W 15x15) weighing 768 kg. The stresses in the DHC shell and bottom plate due to the vertical lift loading are required to satisfy the Service Level A allowable stress design criteria of Subsection NB of the ASME B&PV Code [5].

The results of the DHC vertical lift analysis demonstrate that the applicable allowable stress design criteria are satisfied.

Stuck DHC Retrieval Analysis

The DHC bolt-on lift fixture (i.e., lift adapter) and its attachments to the DHC shell are designed to withstand a maximum pull force of 26.7 kN if need to attempt to retrieve a stuck DHC from the borehole. The stresses in the DHC for this condition are estimated by scaling the maximum stresses calculated for the vertical lift by the ratio of the applied loads.

Although the stuck DHC retrieval event may be considered an off-normal event that is evaluated in accordance with Level C service limits, it has conservatively been treated as a normal condition and evaluated using the Level A service limits of Subsection NB of the ASME Code.

It is noted that a pull force of nearly 200 kN would be required to reach the applicable stress limit in the DHC closure weld. Therefore, provided that the equipment used to retrieve a stuck canister has the required capacity, the design basis stuck DHC retrieval pull force could be increased significantly.

Repository Drop Analysis

An evaluation of a 1-m end drop; 1-m side drop; and 1-m side puncture drop (a drop onto the upper end of a vertical solid 15 cm diameter steel bar) with the bare (no transfer cask) DHC was performed, as well as a free drop into the borehole. The results of the analysis show that the initial design concept satisfies the applicable design criteria.

The DHC is postulated to be dropped into the borehole from the wellhead, falling in a vertical orientation through the vertical section of the borehole from the surface until it enters the curved section of the borehole, at which time the bottom end of the DHC contacts the borehole casing, redirecting it through the curved section. For this analysis, the deepest borehole (3 km) is considered. Although the curved section for a 3-km deep borehole starts well above 3 km depth, it is conservatively assumed that the vertical section extends the full 3 km depth. Sliding friction between the DHC and the borehole casing and the hydraulic drag force provided by the brine in the borehole dissipate the kinetic energy as the DHC travels through the curved section of the borehole. In order the assure that the dropped DHC does not impact other DHCs already stored in the repository, the DHC is required to stop before it exits the curved section of the borehole.

The drag force increases with velocity and decreases with temperature. The drag force acting on an off-centered DHC is also evaluated using similar methods. The results show that the drag force for the off-center DHC is higher than that for the centered DHC and the differential fluid velocities and pressures at each side of the DHC (i.e., lower velocity and higher pressure at side nearest casing) will center the DHC inside the borehole. Thus, the maximum velocity of the centered DHC will be higher than that of the off-center DHC. Therefore, the remainder of the borehole drop analysis was based on the centered DHC.

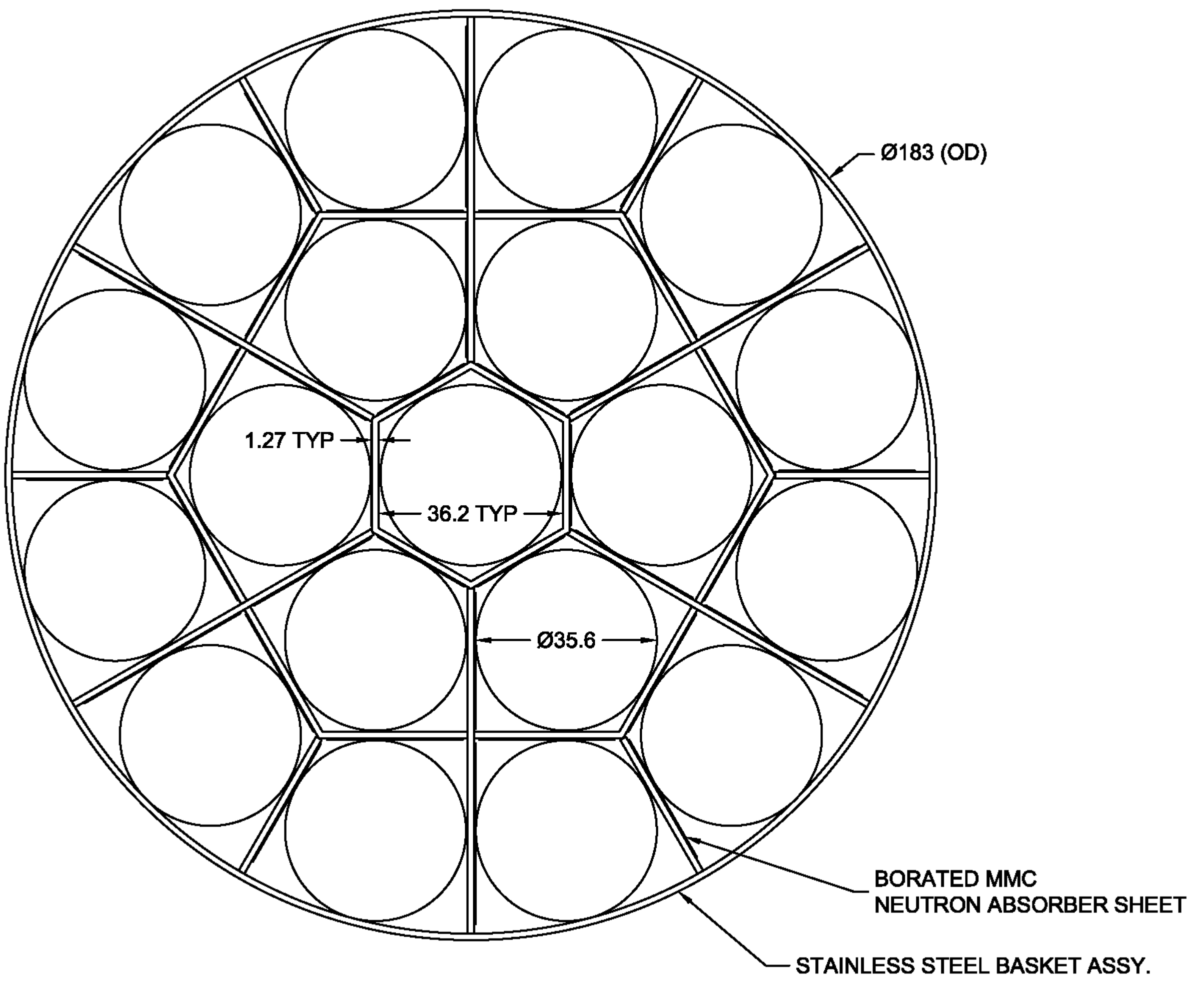
The DHC reaches a maximum velocity of approximately 4.1 m/s at the bottom of the 3.0 km long vertical section. For the lower-bound friction the DHC travels 417 meters (i.e., 82 degrees) through the curved section before coming to rest, whereas for the upper-bound friction the DHC then travels 389 meters (i.e., 76 degrees) through the curved section before coming to rest. The results of the DHC borehole drop stress analysis show that the maximum stresses occur at the top and bottom ends of the DHC shell at the points of contact with the borehole casing. These stresses are highly localized and the stresses in the other parts of the DHC are much lower.

THERMAL EVALUATION

DHC Transport Configuration

For the DHC transport configuration it is assumed that the maximum of 19 DHCs are shipped using the conceptual basket assembly shown in Fig. 2 below inside the cavity of the MAGNATRAN cask. Considering that the maximum allowable heat load in the MAGNATRAN cask is limited to 23 kW, and 19 the number of loaded DHCs inside the cask, the maximum decay heat per fuel assembly d in the calculation is 1.21 kW.

(Note: All dimensions shown in units



of centimeters)

Fig 2. Conceptual DHC Transport Basket Design.

The results show compliance with all temperature limits, except the transportation cask outer surface exceeds the 10 CFR 71.43(g) [3] temperature limit of 85°C on the accessible surface of the package, so a personnel barrier is required to prohibit personnel from contacting the physical surface of the cask.

DHC Disposal Configuration

The emplacement of the DHC into the borehole shall be performed in conjunction with the DHC Dry Transfer System (DDTS). The DDTS/DHC will be transferred to the borehole surface facility's wellhead and docked in vertical orientation to the borehole transfer station. Once the DHC has been connected to the wireline and ready for emplacement, the DDTS doors are opened and the DHC exits the DDTS beginning the DHC surface to subsurface transition in the wellhead, where the environment of the borehole changes from air to drilling fluid. Drilling fluid will most likely be a water-based fluid with additives such as bentonite clay that provide hydrostatic pressure to keep the borehole open prior to casing. For conservatism purposes, the DHC assembly is evaluated considering that the DHC fully exits the DDTS and it is completely exposed to the ambient environment before reaching the drilling fluid.

Once the loaded DHC has been transferred into the borehole, it transcends the borehole until reaching its final horizontal disposal location. To evaluate this scenario, the analysis considers at different depths (1, 1.5, 2, 2.5 and 3 km), three DHCs (to account for the thermal effect of the adjacent DHCs) in horizontal position and in contact with the surrounding media (buffer, casing, cement and EDZ – Excavation Disturbed Zone) which forms the Engineering Barrier System (EBS), and finally the host rock (part of the Natural Barrier System or NBS).

Two transfer modes, radiation and conduction are used to transfer the decay heat from the fuel assembly to the DHC shell (internal gaps have been modeled and filled with helium). At the DHC's external surface, the decay heat dissipation will be dominated by conduction through the rest of the engineer barrier system materials and the host rock in the near-field. The medium between the borehole surface and the DHC surface is assumed to be air, and radiation from the DHC surface to the borehole surface is modeled using a radiation matrix methodology.

The results of the preliminary DHC disposal at depth scenario thermal analysis show compliance with all temperature limits for the worst-case scenario found in the analyses, 1 km depth.

SHIELDING EVALUATION

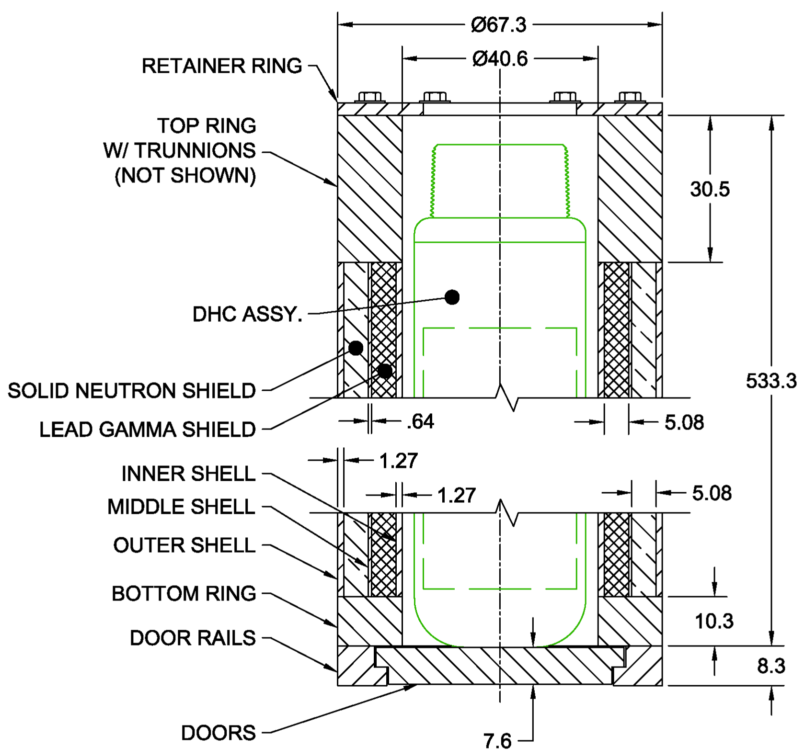
DHC Transfer Configuration

Preliminary shielding analyses of the Drillhole Canister (DHC) assembly have been performed to demonstrate acceptability for the conceptual DHC transfer and transportation configurations. Shielding analyses of the DHC storage configuration are not included in the preliminary evaluation because, except for demonstrating compliance with site-boundary dose rate limits, these dose rates are primarily considered for occupational exposure and the acceptability of the storage configuration shielding results is based on site-specific considerations.

The preliminary shielding analysis for the transfer configuration evaluates a DHC inside the conceptual DHC transfer cask design shown in Fig. 3. The primary concern for the transfer configuration is the dose rates on the top end of the DHC shield lid during canister closure operations, as these affect occupational exposure. The model includes a single Westinghouse 17x17 fuel assembly inside the DHC with representative source terms that are typical for fuel assemblies discharged in the last decade (i.e., 4.3 wt% U-235 initial enrichment, 55 GWd/MTU burnup, 7-year cool time, 1.2 kW decay heat).

The results show that the peak dose rate at the centerline on the top surface of the DHC shield lid is approximately 1.2 mSv/hr. This is considered sufficiently low for occupational exposure rate during canister loading operations considering that there are few, if any, hands-on closure operations that occur on the top center of the DHC shield lid with most hands-on operations occurring near the edge of the shield lid where the dose rates are significantly lower. In addition, when a canister is being placed into a transport cask, temporary/supplemental shielding is typically used to maintain ALARA during closure operations. Therefore, the dose rates on the top surface of the DHC for the transfer configuration are deemed acceptable/manageable.

The dose rates on the surface of the DHC transfer cask are in the range of 0.05 to 0.07 Sv/hr with local maximum dose rates of 0.1 Sv/hr, with most of the dose rate from gamma source radiation. Although these dose rates are too high for transfer operations, and an additional 4 to 5 cm of steel-equivalent shielding added to the transfer cask will reduce the radial surface dose rates to the 0.01 to 0.02 Sv/hr range that is typical for transfer cask designs. For the relatively small size of the DHC transfer cask, the additional shielding will not cause a weight concern.



(Note: All dimensions shown in units of centimeters)

Fig. 3. Conceptual DHC Transfer Cask Design.

DHC Transport Configuration

For the DHC transport configuration it is assumed that 19 DHCs are shipped using the conceptual basket assembly inside the cavity of the MAGNATRAN cask. Dose rates on the exterior of the transportation cask are evaluated to determine if the dose rate limits of 10 CFR 71.47 for normal conditions of transport are satisfied. When the transport index exceeds 10 (i.e., 0.1 mSv/hr at 1 meter from the package surface), the package must be shipped under exclusive-use controls and the dose rates are limited to 10 mSv/hr on the external surface of the package and 0.1 mSv/hr at 2 meters from the edge of the conveyance.

The surface dose rate is 0.3 to 0.4 mSv/hr over the active fuel region, peaking at 0.7 mSv/hr near the cask's lower trunnions due to radiation streaming. The cask surface dose rates are well below the dose rate limit for exclusive-use shipments. The results show that the maximum dose rate at 1-meter from the package surface exceeds 0.1 mSv/hr, confirming that exclusive use shipment is required. The dose rates at 2-meters from the edge of the conveyance are in the range of 0.07 mSv/hr. The 2-meter dose rates are less than the regulatory limit of 0.1 mSv/hr. Therefore, the DHC transport configuration satisfies the dose rate limits of 10 CFR 71 for exclusive-use shipments.

CRITICALITY EVALUATION

Preliminary criticality analyses of the Drillhole Canister (DHC) assembly have been performed to demonstrate acceptability for the conceptual DHC transportation and borehole disposal configurations. Criticality analyses of the DHC transfer and storage configurations are not included in the preliminary evaluation.

The transfer configuration only includes a single fuel assembly and the storage configuration is dry (no moderator) so these configurations will be much less reactive (i.e., low keff) than the DHC transport configuration.

DHC Transport Configuration

DHC transport configuration it is assumed that the maximum of 19 DHC assemblies are shipped using the conceptual basket assembly shown in Fig. 2 inside the cavity of the MAGNATRAN cask.

Based on experience with similar packages, the most reactive preferential flood scenario occurs when the DHCs are fully flooded but the MAGNATRAN cask cavity is completely dry. Although highly unlikely, this scenario is postulated to occur if the package is fully flooded, then the MAGNATRAN cask cavity drains leaving water inside the DHCs.

The preliminary transport criticality analysis models the most reactive PWR fuel assembly type based on criticality evaluations of similar storage and transportation systems (i.e., Westinghouse 17x17) inside the DHC configuration. Criticality analyses are performed assuming fresh fuel and limited burnup credit. An initial enrichment of 4.9 wt % U-235 is assumed for both cases, and 40 GWd/MTU burnup is assumed for the burnup credit evaluation.

The results of the fresh fuel evaluation show that the system reactivity exceeds the regulatory limit, with k_{eff} +2σ = 0.9621 for the fully-flooded configuration and k_{eff} +2σ = 1.0348 for the preferential flood configuration. Therefore, the DHC transport configuration will require burnup credit or moderator exclusion. With burnup credit of 40 GWd/MTU, typical of PWR fuel exposed to 2 or 3 reactor cycles, the system reactivity is substantially lower than the regulatory limit (i.e., k_{eff} +2σ = 0.8064 < 0.95). The preliminary criticality evaluation results for the DHC transport configuration show that the regulatory requirements can be satisfied with less burnup credit than assumed (i.e., 10 GWd/MTU may suffice) and that moderator exclusion should not be required.

An additional preliminary critical analysis was performed in which the neutron absorber sheets were removed from the DHC basket assembly. The system k_{eff} increased by only 0.01, showing that the neutron absorber sheets do not have a significant effect on the system reactivity. Therefore, the neutron absorber sheets will be eliminated from the basket concept to reduce the DHC basket cost, simplify fabrication, and provide additional clearance for DHCs to facilitate loading operations.

DHC Disposal Borehole Configuration

For the DHC borehole disposal condition, the DHCs will be placed end-to-end inside the horizontal section of the boreholes, with parallel boreholes spaced at 100-feet apart. A bounding preliminary pre-closure criticality analysis was performed for this DHC borehole disposal configuration using the most reactive fuel assembly type (Westinghouse 17x17) and assuming in-leakage of the brine solution from the borehole into the DHC assembly.

A single DHC assembly, fully flooded with brine solution, is modeled with the surrounding buffer (brine), steel casing, cement, and soil. Brine solution is modeled inside the borehole and DHC.

The results of the preliminary criticality evaluation of the DHC borehole disposal configuration show that the system reactivity is much lower than the regulatory limit, with k_{eff} +2σ = 0.9245. As expected, these results demonstrate that the DHC borehole disposal configuration is inherently subcritical, even with fresh fuel, fully-flooded, and no neutron absorbers in the DHC assembly.

CONCLUSION

The preliminary design study evaluated a DHC for structural, thermal, shielding and criticality aspects. Changes to the design to incorporate improvements were made based on the analysis. The updated DHC design provides a generic design that meets expected requirements for storage, transportation and disposal while being small enough in diameter to facilitate disposal in a borehole.

REFERENCES

[1] EPRI report number 1018722 “Cost Estimate for an Away-From-Reactor Generic Interim Storage Facility (GISF) for Spent Nuclear Fuel”, May 2009.

[2] U.S. Nuclear Regulatory Commission, 10 CFR Part 72, “Licensing Requirements for the Independent Storage of Spent Nuclear Fuel, High-Level Radioactive Waste, and Reactor-Related Greater Than Class C Waste”, Current Revision.

[3] U.S. Nuclear Regulatory Commission, 10 CFR Part 71, "Packaging and Transportation of Radioactive Material", Current Revision.

[4] U.S. Nuclear Regulatory Commission, 10 CFR Part 63, "Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada", Current Revision.

[5] American Society of Mechanical Engineers Boiler and Pressure Vessel Code, Section III, *Rules for Construction of Nuclear Power Plant Components*, Division 1, Subsection NB, *Class 1 Components*, 2013 Edition.

[6] American Society of Mechanical Engineers Boiler and Pressure Vessel Code, Section III, *Rules for Construction of Nuclear Facility Components*, Appendices, Nonmandatory Appendix F, *Rules for Evaluation of Service Loadings with Level D Service Limits*, 2013 Edition.