Progress on Canisters for Radioactive Waste Transport, Storage and Disposal in Boreholes – 23528

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ABSTRACT

Safe disposal of high-level waste and spent nuclear fuel remains a key objective to global energy portfolio health, with many countries keen on developing solutions over the next decade. Of these proactive countries, many are taking an interest in Deep Isolation for its use of directional drilling technology that would emplace nuclear waste in canisters deep underground in vertical, deviated, or horizontal boreholes. The Deep Isolation borehole solution offers a safe, modular solution where waste can be emplaced on- or near-site, thus reducing risk and cost of waste transportation. Lastly, a standardized canister design allows for process and cost efficiencies for disposal solutions of any size.

Deep Isolation has spent the past several years collaborating with NAC International (NAC) on a drillhole canister (DHC) designed for the deep geological disposal of pressurized water reactor (PWR) fuel assemblies in a borehole. During the 2022 Waste Management Symposium, Deep Isolation and NAC presented the DHC preliminary design, demonstrating confidence in the structural, thermal, shielding, and criticality safety analyses for loaded DHCs in storage, transportation, and disposal configurations.

Over the past year, significant progress has been made to enhance DHC system safety, lifting and handling operations, manufacturability, and economic viability. Deep Isolation commissioned the Nuclear Advanced Manufacturing Research Centre (NAMRC) to conduct a design for manufacture review and NAC updated the DHC design based on this review and continued development. Additional collaboration with partners to review lifting and handling operations, along with planned emplacement and retrieval processes, resulted in changes to the DHC lift adapter, improving safety and reliability.

The results of the NAMRC design for manufacture review provided valuable insights into the manufacturing process that NAC factored into DHC design changes, resulting in significant savings for Deep Isolation and its customers per deep borehole repository project while simplifying canister manufacturing using standardized dimensions and manufacturing practices. These changes are not expected to impact the canister loading capacity, safety basis, or diameter of the borehole needed for waste disposal.

A collaborative investigation with Deep Isolation partners was performed in the past year regarding the use of various potential emplacement rigs commonly used in the oil and gas industry. While Deep Isolation's 2019 demonstration employed a wireline for the emplacement of a sealed source-size canister, simulating a Department of Energy – Hanford Site cesium or strontium capsule, in a borehole, the use of coiled tubing has since been explored to provide additional functionality, including increased emplacement and retrieval forces for the larger and heavier PWR disposal canisters.

The investigation into the use of coiled tubing also resulted in an opportunity to improve upon the planned interface of the canister via a lift adapter with existing drilling technologies. The lift adapter will

be installed atop the canister prior to facilitating disposal operations. The previous bolt-on design has been replaced with a lift adapter that is both easy to assemble and compatible with generic lifting and handling equipment. Fabrication of a mockup canister based on the updated PWR canister design is underway, with delivery expected in early 2023. Upon receipt, Deep Isolation is planning for functional testing of the redesigned lift adapter interface to support continued use of the PWR canister.

INTRODUCTION

The safe disposal of high-level waste and spent nuclear fuel remains a key challenge to achieving a sustainable global energy portfolio, with many countries keen on developing solutions over the next decade. Of these proactive countries, many are taking an interest in Deep Isolation for its use of directional drilling technology that would emplace nuclear waste in drillhole canisters (DHCs) deep underground in either a vertical, deviated, or horizontal orientation. The Deep Isolation borehole approach offers a safe, modular solution where waste can be emplaced on- or near-site, thus reducing risk and cost of waste transportation. Lastly, a standardized canister design allows for process and cost efficiencies for disposal.

DISCUSSION

While the baseline horizontal borehole assumes a 1 km vertical access hole gradually transitioning to a 1.5 km horizontal section for waste emplacement, actual disposal borehole parameters may vary based on specific geology, waste form, and stakeholder requirements. An Electric Power Research Institute report on borehole disposal [1] and a technology readiness assessment completed by Deep Isolation [2] discuss the concept of operations in greater detail.

DHC Baseline Analysis

Each DHC accommodates a single pressurized water reactor (PWR) fuel assembly, and several canisters may fit into a variety of storage and transportation casks designed by Deep Isolation's partner, NAC International (NAC). NAC has developed the engineering design of a DHC for storage, transportation, and disposal of nuclear waste and has conducted preliminary structural, thermal, shielding, and criticality safety evaluations for each mode as discussed at Waste Management Symposium 2022 [3]. The preliminary evaluations provide reasonable assurance that the DHC design will satisfy regulatory requirements for storage (US 10 CFR Part 72 [4] and equivalent international regulations) and transportation (US 10 CFR Part 71 [5] and equivalent international regulations). While no regulations in the United States exist for borehole disposal, NAC used the Yucca Mountain candidate repository framework (US 10 CFR Part 63 [6] and equivalent international regulations) for guidance and will conduct additional analyses as design and regulations mature.

Structural Summary: Analyses were conducted in accordance with Subsection NB [7] and Appendix F [8] of the American Society of Mechanical Engineers' boiler and pressure vessel code. All DHC shell configurations can withstand at least 165% of the anticipated hydrostatic pressure load and 143% of the anticipated lithostatic pressure load without collapsing, in accordance with the applicable allowable stress design criteria of ASME Subsection NB for normal (Service Level A) and accident (Service Level D) conditions, respectively. The DHC vertical lift analysis demonstrates that the applicable allowable stress design criteria are satisfied. A stuck DHC retrieval analysis showed that the bolt on lifting adapter could withstand a pulling load of 26.7 kN (~6000 lb), which is significantly less than the load limit for the DHC closure weld (200 kN or ~45000 lb). Thus, a more robust lifting adapter design could increase the maximum pulling load to increase chances of stuck canister retrieval. Additionally, the DHC design was evaluated for damage following a 1 meter end drop, 1 meter side drop, and 1 meter side puncture drop. Lastly, the DHC design was evaluated for damage following a free drop into a horizontal borehole. Assuming a 3.0 km vertical section, the free drop analysis concluded the DHC would attain a maximum velocity of 4.1 m/s before stopping between 389 m and 417 m into the curved section (range based on different friction coefficients) with localized stresses at the top and bottom of the DHC. All structural analysis results demonstrate that the initial design concept satisfies the applicable design criteria.

Thermal Summary: Up to 19 DHCs can safely be transported in an NAC-designed MAGNATRAN shipping container without exceeding the 23 kW rating, but a personnel safety barrier is required per 10 CFR Part 71.43 [5] since the outer surface temperature could exceed 85°C. For disposal at a 1 km depth, analysis showed that the DHC design is in temperature compliance with worst-case conditions.

Shielding Summary: Shielding of the DHC transfer cask and DHC transport configuration were analyzed and demonstrated acceptability to regulatory standards. The DHC transfer cask is shown to have acceptably low surface dose rates for transportation when an additional 4-5 cm of steel-equivalent shielding is added to the cylindrical sides of the cask. With a 2 m range dose rate of 0.07 mSv/hr (7 mrem/hr), the DHC transport configuration satisfies the dose rate limits of 10 CFR Part 71 [5] for exclusive-use shipments.

Criticality Safety Summary: Both DHC transport and disposal configurations were analyzed for criticality safety in limiting conditions and demonstrated k_{eff} sufficiently below the regulatory threshold of 0.95 to assure sub-criticality.

Canister Overview

The drawing of the preliminary DHC design [9] considered in the preliminary analysis is shown below in Figure 1. This preliminary DHC design consists of a thick-walled cylindrical shell and a bottom plate with a rounded corner and a field-installed shield lid on the top. Within, the DHC shell is separated from a fuel assembly by four side inserts, which provide both structural and thermal support. Atop the shield lid sits a closure ring, which serves as a redundant confinement boundary consistent with Nuclear Regulatory Commission guidelines. A lift adapter is bolted atop the closure ring prior to disposal at a borehole repository. The lift adapter consists of a central lifting and an outer collar (e.g., threaded pipe end) for contact and guidance. Changes to this design are discussed below.

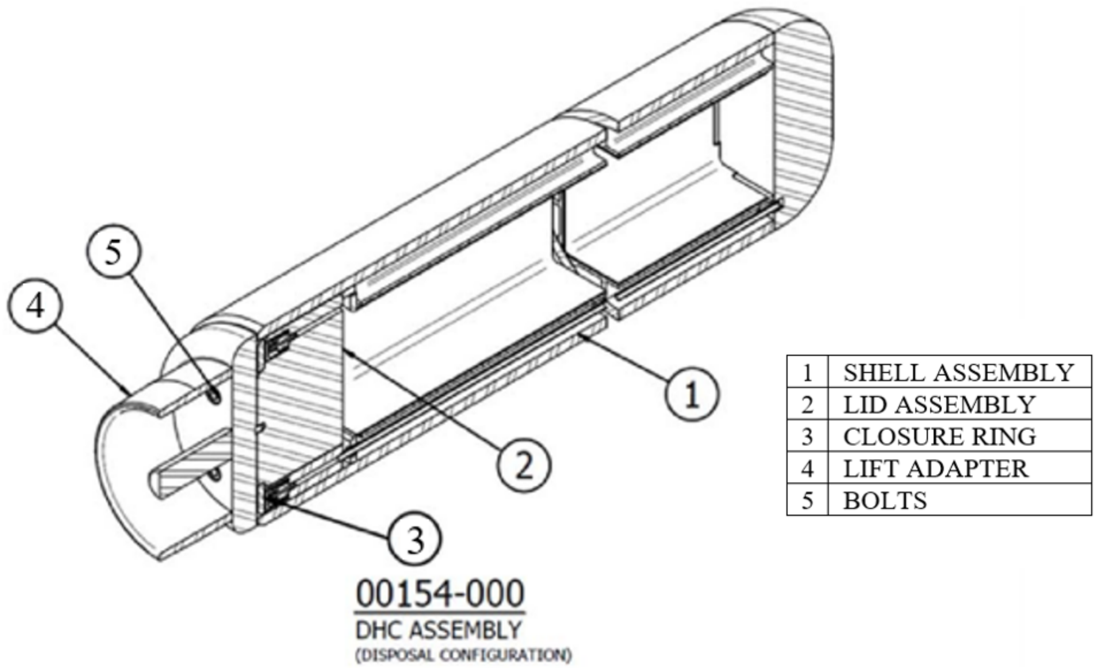

Fig. 1. Drillhole Canister Preliminary Design (Disposal Configuration, Rev. B).

Manufacturability Improvements

The latest iteration of the DHC designs for disposal configuration [10] and storage/transportation configuration [11] are shown below in Figures 2 and 3, respectively. A manufacturability review conducted by the Nuclear Advanced Manufacturing Research Centre (NAMRC) [12] prompted NAC to incorporate improvements to the borehole canister design, focusing on material dimensions and processing compliant with commercial standards, where practicable. This emphasis will ultimately save Deep Isolation and its customers millions of dollars per deep borehole repository project while simplifying canister manufacturing using standardized dimensions and manufacturing practices without impacting the canister loading capacity, safety basis, or borehole construction requirements. The most notable changes to the DHC design shown in Figures 2 and 3 are discussed below.

Bottom Plate Modifications

The bottom plate thickness was reduced from 12.06 cm (4.75 in) to 5.08 cm (2.0 in), while maintaining a large corner radius to facilitate borehole insertion operations. The reduced thickness of the bottom plate partially compensates for the increased thickness of the shield lid and reduces the total shell length by approximately 5.8 cm (2.3 in) to provide additional axial clearance for a basket structure used for transportation. The new bottom plate design reduces fabrication costs and simplifies manufacturing while providing a larger DHC bottom end contact area for greater stability in an upright configuration. In addition, several different bottom plate-to-shell weld configuration alternatives have been added to allow for different manufacturing methods and provide alternatives that allow non-destructive examination (NDE) of the seam weld from the shell exterior. NDE of the bottom plate-to-shell seam weld was identified in the NAMRC manufacturability review as a significant challenge due to the small diameter and long cavity of the DHC, and although it is possible to develop fixturing to perform inspection activities from the inside of the shell, alternate joint configurations were recommended. These alternatives include locating/centralizing features and integral backing to facilitate assembly and welding. All bottom plate-to-shell weld configurations require full volumetric weld examination by radiographic testing (RT) or ultrasonic testing (UT) in accordance with the applicable requirements of ASME Subsection NB.

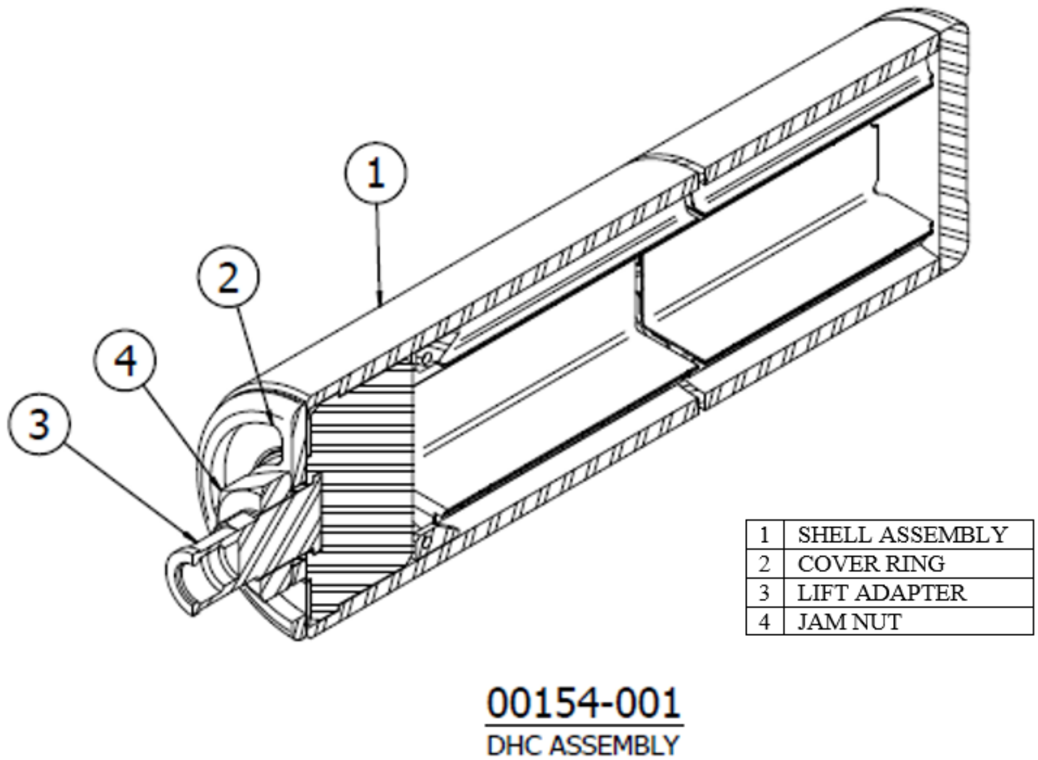

Fig. 2. Drillhole Canister Current Design (Disposal Configuration, Rev. D).

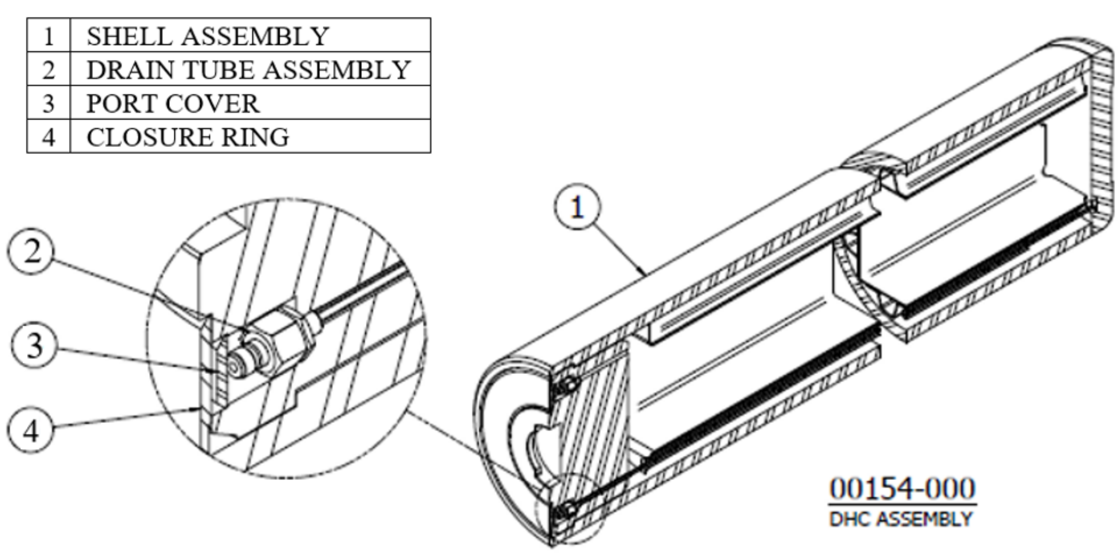

Fig. 3. Drillhole Canister Current Design (Storage/Transportation Configuration, Rev. A).

Shell Modifications

The ID of the shell was increased by 0.64 cm (0.25 in) to provide additional diametral clearance between the shell and basket to account for recommended manufacturing tolerances. To avoid significantly increasing the DHC size and associated impacts on the borehole design, the maximum shell thickness was reduced from 3.49 cm (1.375 in) to 3.18 cm (1.25 in) based on refinements to the structural analysis. In addition, a machined pocket was also added at the top end of the shell to support the shield lid, as discussed below.

Closure Lid Modifications

The closure lid modifications include the addition of a keyhole lifting interface, a shoulder (i.e., stepped outer diameter), and a larger chamfer on the bottom edge. The small counterbore hole in the top end of the shield lid was replaced with a larger and deeper keyhole feature to facilitate storage and transport lifting operations and provide an anchor point for the lifting adapter used for disposal. To maintain shielding performance the thickness of the shield lid was increased slightly to compensate for the increased depth of the keyhole. The outer profile of the shield lid was modified to include a larger diameter shoulder at the top end. The shoulder fits within the top pocket of the shell and is supported axially by the shell to avoid direct shear loading of the closure weld under external pressure loads. The chamfer on the bottom (leading) edge of the closure lid was increased to 1.27 cm (0.50 in) × 45° to facilitate remote insertion of the closure lid into the top of the shell in a spent fuel pool.

The NAMRC study also placed an emphasis on features or setups that will promote first-time quality on closure welds connecting the end plates to canister shells, saving time and resources while also improving reliability.

In conjunction with the NAMRC manufacturability review, NAC added an alternative keyhole tungsten inert gas (K-TIG) closure weld configuration to the DHC design. K-TIG is a low cost, high speed, deep penetration, and high-quality weld option. Unlike traditional canister closure groove welds that cannot be volumetrically examined and must be examined using progressive PT, the K-TIG closure weld configuration can be examined using UT methods. Future work is planned to perform weld qualification trials for the K-TIG closure weld configuration to determine the essential welding parameters, verify the weld quality, and demonstrate UT inspection methods.

Lift Adapter Modifications

Following a visit to the SLB Kellyville Training Center in Kellyville, Oklahoma, in May 2022, Deep Isolation began further investigations to support the use of coiled tubing equipment for emplacement of loaded DHCs into a borehole repository. Coiled tubing rigs, whose use in the oil and gas industry is standard, allow for high loading capabilities with additional features such as fiber optic cameras for visual confirmation throughout the canister disposal process. As a result of this visit, NAC modified the DHC lifting adapter design to engage with these standard coiled tubing connections profiles.

The previous lift adapter design consisted of a center lifting post and outer collar, both with threads for connecting to the coiled tubing. The new lift adapter (seen in Figure 2), which utilizes standard profiles to interface with existing pressure-actuated lifting equipment (GS connector) used by the oil and gas industry, thereby eliminating the need to rotate the connector to attach to the lift adapter, is inserted into the keyhole on the top end of the DHC shield lid and rotated 90-degrees. A cover ring is then placed over the adapter with two tabs inserted into the keyhole slots and a jam nut is threaded onto the lift adapter to seat and secure the cover ring on the closure lid and prevent the lift adapter from disengaging from the

DHC. The design allows for easy and quick installation of the lift adapter on the DHC for accelerated operations and reduced occupational exposure.

Demonstration of the DHC lifting interface is planned for late February 2023. This demonstration – involving no radioactive material – will involve lifting and maneuvering of a mockup DHC with a prototypic lifting adapter, weight (to simulate a DHC loaded with a PWR fuel assembly), and exterior dimensions. Specific tasks of the demonstration include transfer of the mockup inside of a transfer cask or cradle in a vertical orientation, attachment to the mockup lift adapter with standard oil and gas industry lifting equipment, vertical lifts of the mockup, and simulation of borehole emplacement. Deep Isolation anticipates that the testing will demonstrate suitable lifting adapter engagement with rig equipment and preliminary rig handling data for future emplacement operations. Deep Isolation and NAC have conducted an initial walkthrough and will be on-site for mockup canister receipt and handling.

Future Considerations

While NAC has already incorporated many DHC design changes based on the NAMRC Design or Manufacture report, additional design changes will likely be required or desired for the final design and regulatory approval. Additional features and design enhancements will be considered in parallel with other dimensional changes permissible within the design safety basis. Furthermore, NAC will continue to consider the cost-benefit of advanced manufacturing techniques of the canister shell and bottom plate, along with lessons learned from future demonstration program activities. Lastly, NAC will continue to monitor supply chain and vendor limitations and adjust the design accordingly.

The current DHC design is a safe, manufacturable concept capable of receiving, storing, transporting, and disposing of spent nuclear fuel in a deep horizontal borehole. The deep borehole disposal system design is based on initial assumptions on requirements constrained by regulations, retrievability, drilling feasibility and costs, manufacturing capabilities, material accessibility, and many other parameters. Although not expected to occur, changes to the canister design (or material) might occur if the regulatory requirements for retrieval are explicitly specified for very long periods (>100 years) or if very deep disposal (>4 km) is deemed necessary at a future repository site. Furthermore, the canister has been designed specifically for structural loads and drop scenarios associated with the horizontal disposal configuration. Additional design work, such as the development and emplacement of axial bridge plugs in the borehole or modifications to the top and bottom of the canister, may be required to support the use of the canister in a vertical disposal configuration.

As part of a three-year ARPA-E ONWARDS program that initiated in July 2022, Deep Isolation and NAC are also developing and prototyping a "universal canister" for various advanced reactor waste forms. This project which will further assess the economic trade-offs between using different borehole diameters, configurations, and canister diameters in the broader context of minimizing waste volumes and disposal costs. The DHC design and prototyping effort has a significant head start compared to the universal canister and is thus anticipated to reach market availability sooner. As the sensitivities of different parameters affecting the borehole disposal system are better understood, Deep Isolation and NAC will revisit the costs and benefits of modifying the Universal or DHC designs as part of the complete portfolio of near-term and long-term products developed by Deep Isolation.

CONCLUSIONS

During the 2022 Waste Management Symposium, Deep Isolation and NAC presented the preliminary design of the borehole disposal canister, demonstrating confidence in the structural, thermal, shielding, and criticality safety analyses for loaded canisters in storage, transportation, and disposal configurations. Since then, the DHC design has been refined for manufacturability, cost, compatibility with commercial lifting equipment, and quality assurance. These changes are not expected to impact the canister loading capacity, safety basis, or diameter of the borehole needed for waste disposal. Further design changes may occur based on feedback from demonstration evolutions and value engineering considerations.

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