Innovations in Canister Design could offer improved cost-effectiveness and Flexibility in Nuclear Waste Disposal Systems

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INTRODUCTION

As nuclear energy experiences a resurgence of interest around the world, to meet net zero targets and achieve greater energy security, innovations in nuclear waste solutions are in turn becoming a more urgent priority.

That is particularly the case in the European Union thanks to the new taxonomy rules for environmentally sustainable economic activities, which require nuclear power plant developers to have a waste disposal plan in place by 2050 as they seek to deploy new facilities.

While there has been progress toward establishing mined repositories in several countries for the disposal of spent nuclear fuel, high-level waste, and other highly radioactive materials, disposal in deep boreholes is an alternative or complementary approach that has been considered and evaluated for more than a decade.

This disposal method uses directional drilling techniques and proposes emplacing disposal canisters in either a vertical, slanted, or horizontal (or nearly horizontal) orientation in boreholes far deeper underground than in a mined geologic repository. **Fig. 1** shows the alternative borehole orientations. Geologic media such as sedimentary, igneous, or metamorphic host rocks that have remained isolated from the environment for hundreds of thousands or millions of years are under consideration as the preferred location for borehole disposal.

This concept has the potential to provide a more economical disposal solution for high-level waste and spent nuclear fuel from existing reactors as well as advanced reactors, small modular reactors, and for countries with smaller waste inventories, but it could be even more effective to package that waste – when removed from a spent fuel pool – directly into a "disposal ready" canister that would also be designed to fit into a borehole. Furthermore, a standardized canister designed for borehole disposal presents an opportunity for greater system efficiencies throughout the nuclear power life cycle, while preserving options for other disposal methods such as mined geologic repositories.

Boreholes for disposal will be customized for the specific geology, waste form and stakeholder requirements. This concept leverages mature technologies that are widely used in the oil and gas industry and is one that Deep Isolation has integrated and enhanced with patented innovations.

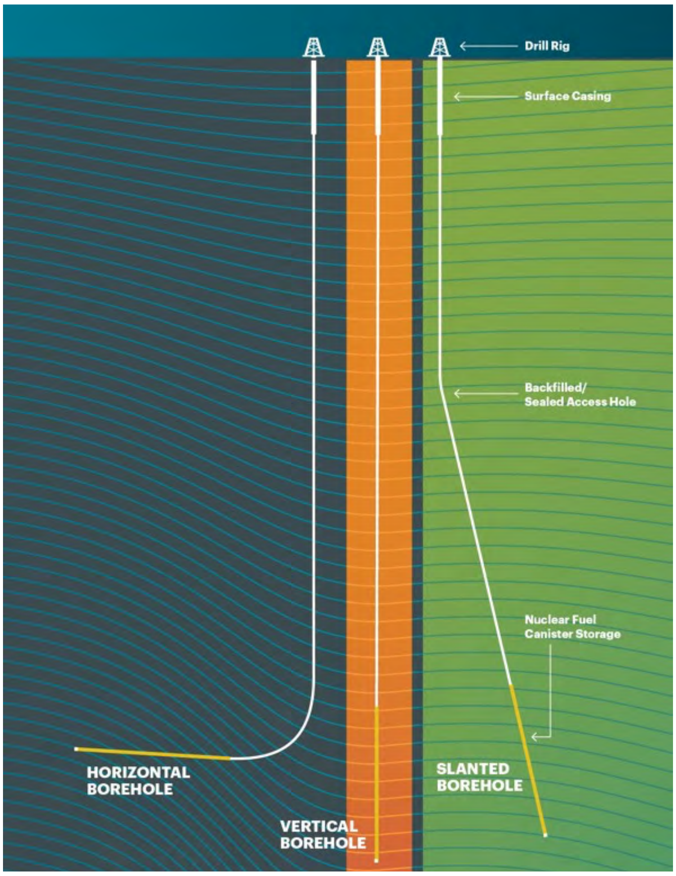

Fig. 1:
Alternative borehole orientations.

Fig. 2 below illustrates the horizontal borehole disposal concept. The directional drilling shown in this figure is a highly developed technology used in over 70,000 oil and gas wells in the United States and Canada.

Deep Isolation and NAC International Universal Canister Designs

During the past two years, Deep Isolation, in partnership with NAC International Inc. (NAC), further advanced the engineering design of canisters for storage, transportation and disposal of spent fuel assemblies from pressurized water reactors (PWRs). These canister designs potentially eliminate the need for repackaging spent fuel for disposal, leaving open many nuclear waste management options for the lifecycle of the waste. Deep Isolation started this canister design process by developing a functional requirements specification for disposal of spent nuclear fuel in a deep horizontal borehole. NAC used those requirements to develop the canister designs. The canister designs considered a generic repository design with a vertical access hole that gradually transitions to a 1,500-meter horizontal section in which the waste canisters would be emplaced at total vertical depths ranging from 1,500 to 3,000 meters. Designs with different shell thicknesses were developed for the deeper disposal depths to ensure structural integrity. The canisters were designed to accommodate a single intact PWR fuel assembly, and different design configurations were developed with varying internal cavity lengths sized to accommodate the vast majority (90 %+) of PWR spent nuclear fuel generated in the United States and Europe. The canister would be fabricated with high-strength, corrosion-resistant steel alloy materials (Duplex stainless steel was assumed as the canister material for this design effort) to ensure integrity during emplacement as well as during any required retrieval.

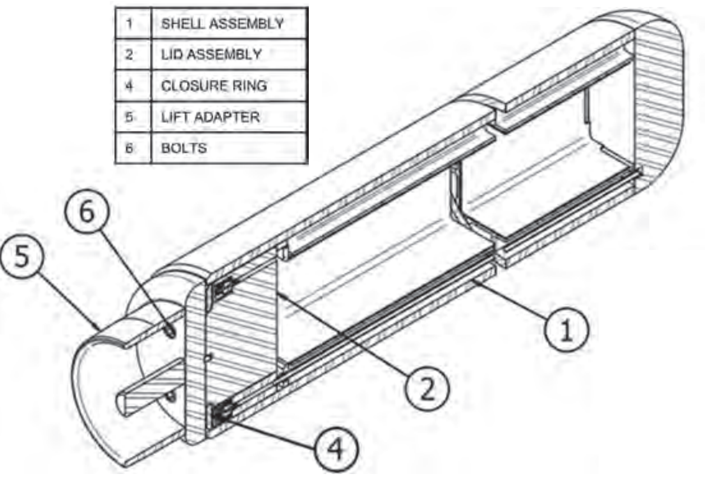

Fig. 3:
This illustration depicts the canister design.

As shown in **Fig. 3**, the canister, which is part of an overall engineered barrier system for storage, transport, and borehole disposal, consists of a canister shell assembly, an internal support 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 backfill the canister cavity with inert helium gas. A lift adapter is bolted to the top end of the canister to provide a lifting interface for handling at the borehole repository surface facility. The lift fixture would be used only in the disposal configuration to assist with emplacement into (and if necessary for retrieval out of)

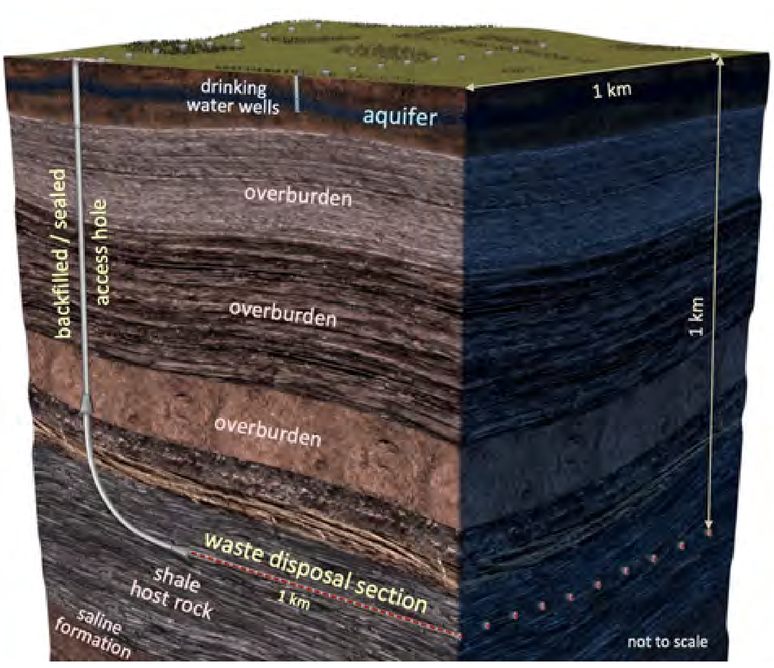

Fig. 2:
Horizontal borehole disposal concept

the borehole. The canister internals consist of a fuel tube and four side inserts that bridge the gap between the fuel tube and shell, providing both structural support and heat transfer capability required to meet current United States Nuclear Regulatory Commission (NRC) regulations.

Preliminary structural, thermal, shielding, and criticality safety evaluations were performed for design-limiting conditions to develop canister designs sufficient to satisfy established regulatory requirements for storage and transportation and anticipated regulatory requirements for disposal. The analyses were performed assuming up to nineteen canisters stored within an existing licensed NAC MAGNASTOR® concrete storage cask or loaded into NAC's MAGNATRAN® transportation cask. The preliminary safety analyses were performed to satisfy established and anticipated regulatory requirements, as follows:

- **Storage:** United States Title 10 Code of Federal Regulations Part 72, "Licensing Requirements for the Independent Storage of Spent Nuclear Fuel, High-Level Radioactive Waste, and Reactor-Related Greater Than Class C Waste" and the equivalent International Atomic Energy Agency regulations

- **Transportation:** United States Title 10 Code of Federal Regulations Part 71, "Packaging and Transportation of Radioactive Material" and the equivalent International Atomic Energy Agency regulations

- **Disposal:** United States Title 10 Code of Federal Regulations Part 63, "Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada" and the equivalent International Atomic Energy Agency regulations (for pre-closure operations only)

It is recognized that the United States' disposal regulation, Title 10 Code of Federal Regulations Part 63, was established specifically for the proposed candidate repository site at Yucca Mountain, but it was used for this design effort as representing the most recent disposal regulatory framework from the United States NRC. In the paragraphs that follow, a summary of the analyses performed by NAC is presented:

Structural Evaluation

The structural evaluation of the preliminary canister designs included: (1) buckling analyses of the canister shell under repository hydrostatic and lithostatic loading, (2) stress analyses of the canister for repository handling conditions, including a vertical lift and retrieval of a stuck canister using the lift adapter attached to the top of the canister, and (3) dynamic analyses of the canister for a range of postulated drop events at the borehole repository, including free drops at the surface facility and a free drop into the borehole. The buckling evaluation demonstrates that canister shell will withstand hydrostatic and lithostatic pressure loading in the borehole and provide the required factors of safety against buckling instability. The repository handling evaluation demonstrates that the canister handling features satisfy the applicable allowable stress design criteria for normal handling conditions and off-normal stuck canister retrieval conditions. For an inadvertent drop of a canister, evaluations were performed for a one-meter free drop onto an unyielding horizontal surface, a one-meter side drop onto a six-inch diameter steel puncture bar, and a free drop into a 3,000 meter deep brine-filled borehole; in the latter scenario, the analysis found that the canister would stop prior to exiting the curved section of the borehole, due to hydrostatic resistance of the fluid in the borehole, thus assuring such a drop would not impact the canisters already emplaced in the horizontal section of the borehole.

Thermal Evaluation

The thermal evaluation for transportation conditions, which is based on an array of 19 canisters in a MAGNATRAN® transportation cask, assuming each canister has a heat load of 1.21 kilowatts, demonstrates compliance with applicable temperature limits. The disposal thermal evaluation, which models an array of canisters and radiation and conduction heat transfer from the fuel assemblies to the canister, engineered barrier system, and host rock, demonstrates compliance with all applicable temperature limits.

Shielding Evaluation

The shielding evaluation was based on a single Westinghouse 17x17 PWR fuel assembly inside the canister with representative source terms that are typical for fuel assemblies discharged in the last decade. For example, the following assumptions were used: 4.3 weight percent U-235 initial enrichment, 55 gigawatt-days per metric ton uranium burnup, and 7-year cool time in a spent fuel pool. The primary concern is the radiological dose above the canister during closure operations: a peak dose of 1.2 millisieverts per hour (0.12 Rem per hour) was calculated and this is sufficiently low to comply with occupational radiation exposure limits during canister loading operations. Surface dose rates were also calculated during transportation as well as for transfer cask operations, and all regulatory limits were met.

Criticality Evaluation

The criticality analysis demonstrated that no neutron absorbing materials are needed to comply with transportation criticality requirements. For disposal, it was found that an infinite array of parallel boreholes spaced 100-feet apart and containing canisters loaded with a PWR fuel assembly is inherently subcritical, even with fresh fuel and no neutron absorbers assumed in the canister.

Summary of Design Analyses

In summary, the preliminary design study evaluated the canister for structural, thermal, shielding, and criticality aspects. The canister met all established regulatory requirements for storage and transportation and anticipated regulatory requirements for disposal. Importantly, this study provides a generic design that meets expected requirements for storage, transportation, and disposal (pre-closure operations) while being small enough in diameter to facilitate disposal in a borehole.

Next steps for advancing deep borehole disposal

Deep Isolation, in conjunction with NAC, has partnered with the United Kingdom's Nuclear Advanced Manufacturing Research Centre (NAMRC) to complete an initial design-for-manufacture review. This review led to some evolution in the design features of the canister to improve the fabrication process, as shown in **Fig. 4** in its storage configuration.

With the initial borehole canister design in hand, Deep Isolation plans to leverage this work to further advance deep borehole disposal. There is consensus in the international community that a beneficial next step is to perform a full-scale demonstration of the technology. Deep Isolation conducted a study in 2021 to analyze international stakeholder views across 18 countries in the Americas, Europe, and the Asia-Pacific region about deep borehole repositories for nuclear waste disposal. The results show that those surveyed agree overwhelmingly that the ideal next step in the development of borehole disposal technology is an end-to-end technology demonstration.

In 2019, Deep Isolation completed a successful small-scale demonstration, in which a small disposal canister (with no waste inside) was emplaced in and later retrieved from a pre-existing horizontal drillhole. Deep Isolation is committed to building on this effort by working with the international community to launch the planning process for a long-term collaborative borehole demonstration program. Working with industry partners and government research

Fig. 4: The canister in its storage configuration.

institutions, Deep Isolation intends to assemble an independent, science-driven non-profit task force of experts and interested stakeholders to oversee the program. Once launched, it will be the first ever public-private partnership devoted to researching how deep boreholes can be used to safely dispose of spent nuclear fuel and other types of high-level radioactive waste. The goal of the project is to advance the technology readiness levels of deep borehole disposal in a progressive, cost-effective manner, accelerating the preparation for global deployment as a licensed disposal technology.

As a first step in this demonstration program, Deep Isolation is moving forward with the fabrication of a full-size prototype of a disposal canister, based on the jointly developed designs with NAC discussed above, and plan to demonstrate the functionality of the physical interface between the canister and a drill rig and the ability to lift the canister using standard oil and gas industry drilling equipment.

As part of this demonstration program, Deep Isolation also plans to continue its collaboration with NAMRC, working with the Center to develop manufactured prototypes for full scale field and laboratory testing, with the goal of elevating the borehole canister design to a minimum of Technology Readiness Level 7 to assure its readiness for commissioning within a borehole repository.

CONCLUSION

Based on preliminary analyses by Deep Isolation, the cost of disposal for smaller waste inventories in a properly sited horizontal borehole disposal system has the potential to be significantly less than the cost of a mined geologic repository. Other factors must be considered, but work done to date on the post-closure safety case and technology indicate that nuclear waste can be safely disposed using borehole disposal repositories while offering cost savings when compared to mined geologic repositories. In addition, with no workers underground in a deep borehole repository, compared to a mined geologic repository, the pre-closure safety case from both an industrial safety and radiation safety perspective could potentially be much improved.

This new, first-of-a-kind disposal canister has been specifically designed and evaluated for use in the transport, storage, and disposal of commercial spent nuclear fuel in deep boreholes. It has the potential to become an integral component of a technically viable, cost-efficient, and safe deep borehole solution to the long-standing problem of the disposal of spent nuclear fuel and other high-level nuclear waste.

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Chris Parker is Deep Isolation's Global Head of Business Development, and Managing Director of its subsidiary for Europe and the Middle East (Deep Isolation EMEA Limited). He works with multiple countries investigating the suitability of deep borehole disposal of nuclear waste. This includes most recently working with Estonia, which has contracted with Deep Isolation to study disposal of waste for a proposed advanced reactor small modular reactor, and also leading a review of borehole disposal for five countries within the ERDO Association: Croatia, Denmark, Netherlands, Norway and Slovenia. Parker also led a survey of international opinions on deep borehole repositories. Formerly a civil servant reporting to the British Prime Minister on the digital transformation of the UK's economy and public services, Parker has more than 30 years of experience in stakeholder engagement, governance and partnership development for innovative solutions.

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Jesse Sloane, Deep Isolation's Head of Engineering, is a former U.S. Naval Officer who worked with the Naval Nuclear Propulsion Program, including the management of transportation and storage-related tasks for the Navy's spent fuel inventory.
He has led risk assessments related to nuclear fuel fabrication facilities and transportation operations of nuclear waste for large-scale nuclear companies.
His role at Deep Isolation includes the management of the company's U.S. federal grant awards, which focus on the disposal of pyroprocessing waste streams and the development of a universal disposal canister system for advanced reactor waste forms.

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Mark Frei, Senior Project Manager for Deep Isolation, has more than 45 years of experience in the nuclear energy industry, including nuclear weapons-related legacy environmental cleanup and nuclear waste disposal. After serving as an engineer for the U.S. Department of Energy (DOE) on advanced nuclear reactor projects, he served as Head of Engineering on DOE's Yucca Mountain mined geologic repository project. He then headed up the project team to take the Waste Isolation Pilot Plant – the United State's geologic repository for defense-generated intermediate level waste – from a construction complete status to an operational status, addressing regulatory, safety, environmental, legislative, and technical issues. He later served as Deputy Assistant Secretary in the DOE managing critical components of the environmental cleanup program, as well as serving as Manager of the Idaho Operations Office – overseeing the Idaho National Laboratory and related environmental remediation. After retiring from the U.S. government, he was the Project Operations Manager at the Hanford Site's Waste Treatment & Immobilization Plant for Bechtel National Inc., and is now consulting for nuclear waste cleanup industry contractors, including Deep Isolation. At Deep Isolation Mark managed the completion of the deep borehole canister design performed by its partner, NAC International, and is serving as the project management lead on the program to demonstrate the deep borehole disposal technology.