Progress on the Development of the Universal Canister System for Advanced Reactor Waste Forms – 25254

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ABSTRACT

Progress in the development of advanced nuclear reactors must be paralleled with the ability to safely manage the back end of the fuel cycle to support the deployment of advanced nuclear power. With support from the US Department of Energy's Advanced Research Projects Agency – Energy, Deep Isolation is leading a project to develop a Universal Canister System as a fully integrated waste management approach for the safe storage, transport, and disposal of advanced reactor waste streams. Project UPWARDS: *Universal Performance Criteria and Canister for Advanced Reactor Waste Form Acceptance in Borehole and Mined Repositories Considering Design Safety* is nearing completion, and when finished will deliver a preliminary canister design – replete with a functional prototype canister available for future demonstration and field-testing – and associated generic waste acceptance criteria. This pairing of canister design and waste acceptance criteria will allow end-users to confirm compatibility with various waste streams across dry cask storage, transport, and final disposition in either deep boreholes or mined repositories.

Deep Isolation introduced the Universal Canister System at the 2024 Waste Management Symposia, presenting an overview of Project UPWARDS – a collaboration between Deep Isolation, NAC International, Inc., University of California Berkeley, and Lawrence Berkeley National Laboratory. This paper provides an update of the technical work conducted since the project was introduced last year, including advanced reactor waste form characterization and performance modeling, canister fabrication, and integration of work streams to develop waste acceptance criteria.

Through extensive literature review and industry research, University of California Berkeley identified lanthanide borosilicate glass, tri-structural isotropic (TRISO) spent fuel (pebbles, compacts, and full prismatic assemblies), and intact halide salts as ideal candidates for further investigation. Although the level of knowledge for some of the safety-relevant parameters has been well documented, experimental investigations are being performed to improve current assessments of parameters such as activation energy of lanthanide borosilicate glass, waste degradation rate of the outer silicon carbide layer of TRISO fuels based on temperature and pH effects, and the near-saturation condition behavior of intact halide salts to consider whether retardation mechanisms may be needed. These experiments will establish lower and upper bounds for a suite of parameters the project team has determined to be potentially relevant to repository safety performance. Once complete, these data will supplement those which were collected through previous studies and will allow Deep Isolation and Lawrence Berkeley National Laboratory to finalize source terms and complete safety and performance assessments of advanced reactor waste forms

in horizontal borehole, vertical borehole, and conventional mined repository systems. These modeling efforts will allow for the establishment of an acceptable performance envelope for the variable parameter sets and will in turn inform the development of waste acceptance criteria for each of the investigated advanced reactor waste forms.

In parallel with the experimentation and modeling, NAC International, Inc. has completed the development of a preliminary design for the Universal Canister System. Structural, thermal, shielding, and criticality analyses of the most limiting configurations of the Universal Canister System in storage, transport, and disposal were completed and iterated upon, aligning on an optimized design configuration. Prototype fabrication was completed in November 2024. Similar prototype fabrication was also recently completed on Deep Isolation's drillhole canister for pressurized water reactor spent fuel assemblies. Those fabrication efforts were compared during a Technical Workshop in October 2024 to review lessons learned and align on best practices needed to support large-scale manufacturing and commercial deployment of the Universal Canister System.

Once complete, Project UPWARDS will deliver a first-of-a-kind fully integrated waste management system, enabling the safe storage, transport, and disposal (in both mined and deep borehole repositories) of advanced reactor waste streams. Additional efforts are underway to apply this integrated approach on an international scale. In collaboration with the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA), Deep Isolation and the Project UPWARDS team are participating in the planning of the Joint Project on Waste Integration for Small and Advanced Reactor Designs (WISARD), which will begin in early 2025. The Universal Canister System has already been presented as a well-developed example of an integrated waste management system that can address the needs of both open and closed nuclear fuel cycles across storage, transport, and disposal.

INTRODUCTION

More than 20 countries attending the 2023 Conference of the Parties to the U.N. Framework Convention on Climate Change (COP28) committed to a tripling of nuclear energy generation by 2050 [1]. This desire was reaffirmed in a 2024 pledge by the US government to add 200 GW of net new nuclear energy capacity by 2050, with 35 GW of new capacity by 2035 [2]. While the global nuclear industry is now investing in the development of advanced reactor concepts with a goal of achieving clean, safe, efficient nuclear energy, there has been little development in the technology needed to manage the waste streams from these novel designs. With grant funding support from the U.S. Department of Energy's (DOE) Advanced Research Projects Agency – Energy (ARPA-E), Deep Isolation is leading a project to do just that: design and fabricate a unique solution that provides for the safe storage, transport, and disposal of waste streams from advanced reactors. In collaboration with NAC International, Inc. (NAC), University of California Berkeley (UCB), and Lawrence Berkeley National Laboratory (LBNL), this three-year project – Universal Performance Criteria and Canister for Advanced Reactor Waste Form Acceptance in Borehole and Mined Repositories Considering Design Safety (UPWARDS) – will deliver a first-of-its-kind Universal Canister System (UCS) with associated generic waste acceptance criteria (WAC) for a variety of advanced reactor waste forms, while also ensuring compatibility with storage, transport, and disposal in both a conventional mined repository and deep borehole repositories.

In March 2024, Deep Isolation presented an introduction to Project UPWARDS at the 2024 Waste Management Symposia [3]. The project scope was outlined, consisting of four parallel work streams to characterize advanced reactor waste forms, design and manufacture a UCS prototype, assess the repository safety of the UCS loaded with these waste forms through the use of generic performance and assessment screening models, and develop generic WAC applicable across storage, transport, and disposal. These iterative and interdependent work efforts are now nearing completion, with final project deliverables anticipated in July 2025.

DISCUSSION

Waste Form Development and Characterization

Initial research led by UCB identified three waste forms from advanced reactors and fuel cycles that are trending nearest to market implementation and are representative of other waste forms expected for advanced fuel cycles, and thus should be considered for further study as part of Project UPWARDS: vitrified waste streams, tri-structural isotropic (TRISO) fuels from high-temperature gas-cooled reactors, and frozen halide salts from molten salt reactors [4], [5], [6]. Results from UCB's initial literature review were documented in a manner which also identified knowledge gaps related to repository safety performance for the relevant waste forms [7]. Experimental programs were planned to collect additional data, allowing for a comprehensive set of waste form parameters to be used as part of the project's performance modeling scopes of work. These data are being used to delineate upper and lower bounds for these safety-relevant parameters within the source-term and safety and performance assessment screening models, while also providing unique reference data points.

Vitrified Waste

Early in the development of the UPWARDS project scope, stakeholders aligned on a need to investigate not just the acceptability of vitrified waste disposal in the UCS, but particularly the use of lanthanide borosilicate (LaBS) glass, offering the potential to increase waste loading density, and thereby realizing a reduction in waste volumes and repository footprints. UCB's initial research identified uncertainty in the degradation behavior of LaBS glass in a range of repository-relevant conditions [8]. To address that uncertainty, UCB devised and executed an experimental program to investigate the effect of temperature (believed to be the primary variable parameter affecting waste form degradation in the safety and performance assessment model), which evolves over time in a repository environment, on the waste form's degradation rate, and thus impacts the initial rate by which radionuclides are released into the geologic environment and migrate to the surface [9].

Using International Simple Glass 1 (ISG-1) and a small quantity of LaBS glass (AmCm2-19) obtained from the Pacific Northwest National Laboratory (PNNL), UCB crushed the glass samples using a tungsten carbide shatterbox (ring and puck mill), mechanically sieved the crushed samples, and cleaned them to remove any fines and obtain consistent particle sizes in the range of 75 to 150 μm (Figure 1). Accelerated leaching tests were then performed at temperatures ranging from 50°C to 250°C following the ASTM C1285.21 protocol. Elemental analysis of the leachate was performed using inductively coupled plasma optical emission spectroscopy (ICP-OES).

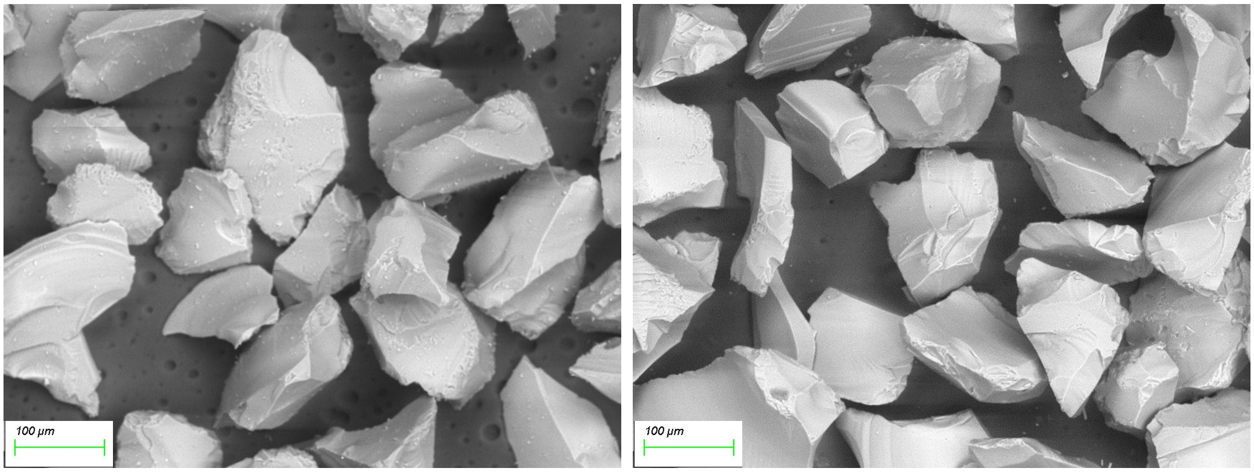

Figure 1: Scanning electron microscope (SEM) images of crushed and sieved (+200 -100 Mesh) ISG-1 glass before (left) and after (right) washing. Note that the unwashed sample contains significantly more fines adhered to each grain [9].

For the AmCm2-19 samples, the analysis showed leach rates for boron and silicon constituents two to three orders of magnitude greater than those rates for the remaining constituents. Because silicon tends to form secondary phases with many constituents of the glass, UCB concluded that the initial release rate for boron can be conservatively used to represent (and thus bound) the congruent dissolution of the entire glass waste form. At elevated temperatures, it was apparent that secondary effects such as mineral precipitation or the formation of a passivating gel layer may be occurring. This behavior is typically observed for alkali aluminoborosilicate glasses when the concentration of silicon, the primary constituent of the material, approaches saturation in the leachate. However, the concentration of silicon measured in these studies remained far from the saturation point. This suggests that other primary constituents of AmCm2-19 glass that are less soluble than silicon may drive its passivation, such as lanthanides that constitute ~50 wt% of the material [10]. These data will be made available in a future update of reference [7], as well as in planned peer reviewed publications.

TRISO

TRISO fuel is being used by several advanced reactor developers (e.g., Kairos Power and X-energy) due to its substantial safety benefits, where small TRISO particles consisting of uranium-based ceramic or alloy are encased within a graphite buffer and surrounded by an inner pyrolytic carbon, a structural silicon carbide (SiC), and an outer pyrolytic carbon layer. This highly durable fuel form is being pursued in a variety of configurations, including spherical pebbles, cylindrical compacts, and full prismatic assemblies.

UCB has developed an experimental program to investigate the dissolution of the impermeable SiC layer. Experiments are currently underway to investigate the effects of SiC purity, temperature, and pH as it relates to the degradation rate of the outer SiC layer. Prior studies in literature utilize a variety of SiC materials that range in purity (97-99.9995%), phase (i.e., alpha, beta) [11], and manufacturing process (i.e., chemical vapor deposition, Acheson, etc.) [12], [13], [14]. Performance assessment modeling of TRISO particles in deep geological repositories utilize these data under the assumption that durability data from each type of SiC is broadly applicable to the chemical vapor deposition (CVD) SiC layer of TRISO particles [15], [16], [17]. However, the validity of this assumption has not been directly assessed. Purity testing, comparing degradation of low-purity SiC (~97.5% pure) to CVD SiC (>99.9995% pure) has completed, showing that lower purity SiC degrades as much as five times faster than the representative high purity CVD SiC. These findings suggest that future studies should ideally be conducted with CVD SiC, and that historical data obtained with varying compositions of SiC likely represent pessimistic corrosion rates.

With the results of the purity tests now in hand, UCB is proceeding with CVD SiC for the remainder of their experimental program. Temperature and pH experiments are currently in progress, and the results of these experiments are forecasted to complete by year end 2024. Currently, the project team hypothesizes that a prolonged period of degradation may be assumed for the highly durable outer SiC layer, which can be approximated in the performance assessment screening model using an increased canister breach time followed by a conservative instantaneous release of the radionuclide inventory contained within the TRISO particles.

Intact halide salts

UCB identified stabilized salt waste from molten salt reactors as a third waste stream from advanced reactors worth consideration for compatibility with the UCS. Frozen halide salt in a sealed austenitic stainless steel canister would be placed inside the UCS canister. An experimentation program was devised to investigate the dissolution of intact halide salts in a variety of configurations to represent both uranium-bearing fuel salts and fission products. Solubility experiments were completed with samples of UCl_3/NaCl and $TbCl_3$/NaCl salts, with the resultant samples analyzed using inductively coupled plasma mass spectrometry (ICP-MS). Both kinds of salts could form fully aqueous, unsaturated solutions within a matter of minutes, suggesting that a conservative assumption of instantaneous dissolution and solubility-limited release from the salt waste form once the UCS has been breached is the most appropriate method for modeling repository performance. Since the kinetics of halide salt dissolution are essentially instantaneous, experiments focused on thermodynamics of halide salt dissolution. Measurements of the concentrations of Na^+, U^{3+}, and Tb^{3+} in saturated NaCl/UCl_3 and NaCl/$TbCl_3$ solutions were performed. For both systems, suppression of the dissolution of each salt by the other was observed, and the combined molar concentration of the halide salts could be calculated. The solubility studies were performed in four different aqueous solutions whose compositions were representative of various waters expected borehole environments.

Integrated Safety and Performance Assessment Screening Model

Disposal of advanced reactor waste forms in the UCS is being evaluated through numerical modeling to determine the effects of numerous safety-relevant parameters on radiological dose exposure to the public at the surface near a repository. In order to support the goal of true universality of the UCS, the project team aims to investigate a variety of configurations of waste form, canister design parameters, geologic environments, and repository concepts. Deep Isolation and LBNL previously aligned on development strategies for a modeling framework which could be applied to a range of waste forms and generic disposal pathways [3]. This framework, utilizing both source-term and repository performance models using TOUGHREACT and iTOUGH2 modeling tools [18], [19], has now been realized.

Preliminary safety and performance assessment screening models have been developed for a horizontal borehole repository, a vertical borehole repository, and a mined repository [20]. These screening models are simplified representations of the repository system that allow for the flexible, automatic adjustment of potentially safety-relevant factors of the repository layout, waste form, canister, geologic formation, and thermal-hydrogeologic conditions. The models will be used to delineate a performance envelope for these parameter sets, which will in turn be used to formulate generic WAC.

The advanced reactor waste forms being investigated in Project UPWARDS contain a large number and variety of radioisotopes that are harmful to the public. Emplacement in a deep geological repository, either in a mined repository or in a deep borehole, is intended to isolate these harmful radioisotopes such that only a subset of them, in much smaller quantities and concentrations and only after a long period of time, will reach the accessible environment. To account for that, a methodology was developed to down-select these safety-relevant radionuclides into a manageable subset based on their effect on peak radiological dose exposure.

With the models fully constructed, reference cases using a proxy radionuclide of ^{129}I were tested to ensure proper configuration of the models and their parameters. It was concluded that the models return reasonable predictions of repository performance, and that simulations for analysis of the multiple advanced reactor waste forms can commence. Simulations are now underway to determine the full performance envelope for each of the three categories of advanced reactor waste streams identified above: LaBS glass, TRISO fuel, and intact halide salts.

In parallel with this effort, source-term models were developed to study the release of radionuclides under the influence of near-field thermal, hydrological, and geochemical (THC) conditions [21]. The results of the source-term model analyses are intended to validate assumptions in the performance assessment screening models. Due to a large amount of uncertainty regarding the alteration of the waste forms over time in a repository environment, the interaction between repository system components, and the combined effect of these, difficulty exists in trying to parameterize and model – through numerical simulations – the release and transport of radionuclides. The source-term models, therefore, support the performance assessment screening models by providing the evolution of near-field geochemical conditions (e.g., pH, Eh, mineral phases, etc.), evaluating parameters related to formulating radionuclide release, and better understanding the various processes that control the migration of radionuclides in the near field. Ultimately, the source-term models help the safety and performance assessment screening models make informed model choices about the source term.

UCS Preliminary Design and Prototype Fabrication

NAC completed the preliminary design of the UCS in early 2024, analyzing limiting configurations of storage, transport, and disposal for structural, thermal, shielding, and criticality performance [22]. The design of the UCS incorporates universal features for loading, closure, lifting, and handling into the design of a family of canisters with varying diameters and shell thicknesses to accommodate the variety of advanced reactor waste forms and disposal configurations under consideration. Additionally, the UCS is designed to be compatible with NAC's existing Modular, Advanced Generation, Nuclear All-purpose Storage (MAGNASTOR®) and Modular, Advanced Generation, Nuclear All-purpose Transport (MAGNATRAN®) systems for storage and transport, respectively, and ultimately will support disposal in a deep borehole repository or be loaded into a larger waste package/overpack for disposal in a mined repository.

With a complete preliminary design, NAC solicited bids for fabrication of a prototype canister from a list of previously qualified vendors. The project team ultimately selected R-V Industries, Inc. (R-V), located in Honey Brook, Pennsylvania, as the UCS prototype fabrication vendor. Procurement of materials, weld trials, and ultimate fabrication occurred within a five-month span.

Fabrication efforts culminated in a Technical Workshop in October 2024, hosted by R-V and attended by project team members and the UPWARDS Technical Advisory Committee, comprised of representatives from industry and government organizations. With the recent completion of another prototype fabrication project for Deep Isolation's drillhole canister [23], team members discussed the prototype fabrication efforts, lessons learned, potential for scaling fabrication to larger quantities of canisters, and technologies that would enable precise and potentially lower cost canister fabrication at scale.

Workshop attendees also toured the R-V fabrication facility, viewing the near-complete UCS prototype, and having an opportunity to disassemble and reassemble the lift adapter assembly (Figure 2 and Figure 3). This tour provided insight into anticipated procedures, challenges, and environmental considerations once the UCS is deployed at scale. Following the workshop, final leak testing, load testing, and surface finishing were conducted on the prototype canister (Figure 4), and the final assembly was shipped to a Deep Isolation facility for future demonstration and testing.

Figure 2: UPWARDS project team and Technical Advisory Committee members with the UCS prototype canister at R-V Industries, Inc.

Figure 3. UCS Prototype, with lift adapter assembly fully disassembled (left), disassembled lift adapter assembly (top right), and fully assembled prototype canister (bottom right).

Figure 4. Completed UCS prototype.

Development of Waste Acceptance Criteria

A key deliverable of the UPWARDS project will be a set of generic WAC for the UCS to address not just disposal of advanced reactor waste streams, but also acceptability for storage and transport. Though much of the WAC will be developed in the final few months of the project, as waste form characterization experiments and safety and performance assessment modeling efforts conclude, Deep Isolation has already developed a framework for the generic WAC. Based upon a review of existing WAC and similar documents for remote-handled transuranic (RH-TRU) waste for the Waste Isolation Pilot Plant (WIPP) [24] and for vitrified waste from the Defense Waste Processing Facility (DWPF) [25], Deep Isolation has categorized the anticipated WAC for the UCS into five (5) key categories. The categories are summarized in Table 1 below, and were first reported in a June 2024 paper presented at the International Atomic Energy Agency (IAEA) [26].

Table 1. Waste Acceptance Criteria Categorization

Category	Criteria
Container Properties	Physical dimensions & weights Mechanical performance
Radiological Properties	Radiation effects (dose) Contamination control Decay heat Nuclear criticality
Physical Properties	Free liquids Compressed gases
Chemical Properties	Chemical durability Combustibility Gas generation Fire and explosion hazards Toxic/corrosive materials
Data Package Contents	Unique identification

Of the five categories listed above, radiological properties are expected to be the most limiting for waste streams loaded into the UCS. Common criteria can be blanketed across physical properties, chemical, properties, and data package contents consistent with other WAC documents. However, radiological properties will impose limits on canister loading, minimum cooling time requirements, and geometric spacing of UCS canisters (primarily in storage and transport configurations), and these limits may affect container properties (i.e., physical dimensions and weights). These radiological property criteria will be defined as the safety and performance modeling efforts near completion, and differences in limits across combinations will inform a set of pairing matrices being developed concurrent with the WAC. In total, these pairing matrices will be developed for combinations of three (3) canister classes/sizes, three (3) advanced reactor waste forms, three (3) applications (i.e., transport, storage, and disposal), and, within the disposal application, three (3) repository configurations (i.e., mined repository, vertical borehole, and horizontal borehole). The full set of WAC and associated pairing matrices are expected to be completed in July 2025.

The Economic Case for the UCS

The lifetime savings that a multi-purpose canister such as the UCS can deliver across the back end of the nuclear fuel cycle are significant. A separate paper presented by Deep Isolation at Waste Management Symposia 2025 [27] presents detailed analysis of the economic impact delivered by the UCS in two scenarios, both compared to a reference case based on traditional long-term dry storage followed by eventual repackaging for disposal. In one scenario, the UCS is initially used for long-term interim storage ahead of eventual disposal; in the other, spent fuel is encapsulated in the UCS as soon as possible after cooling and then disposed of immediately in deep boreholes. In the former case, the UCS delivers savings compared to the reference case of 37% for LWR spent fuel and 38% for TRISO spent fuel; in the latter case, the savings are 67% for LWR spent fuel and 64% for TRISO spent fuel.

OECD-NEA Joint Project WISARD

In 2023, the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA) contacted UPWARDS project team members about plans to investigate waste management for future reactor designs. Planning for this Joint Project, Waste Integration for Small and Advanced Reactor Designs (WISARD), began in earnest later that year. The WISARD project aims to explore how decisions at the front-end and design phases of reactor development will impact back-end management of the resultant waste streams. The project will focus on characterizing spent fuel and other waste streams, including those from treatment and recycling processes, storage, transport, and disposal, with cross-cutting integration planned throughout the duration of the project (Figure 5).

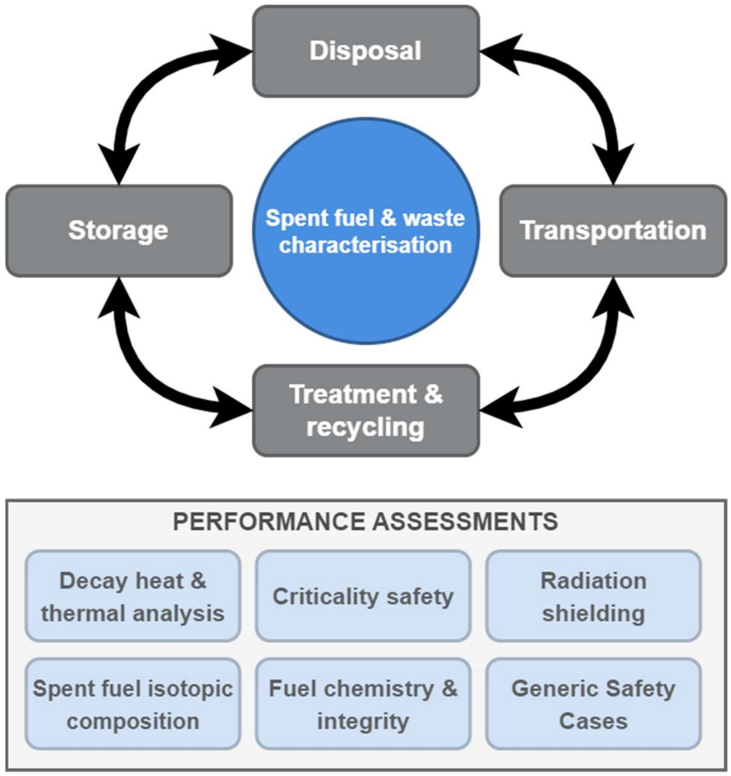

Figure 5. OECD-NEA Joint Project WISARD [28].

OECD-NEA hosted a kickoff meeting for the WISARD Joint Project in Paris in March 2024 [29], followed by a workshop in Orlando, Florida in May [30]. At those meetings, representatives from advanced reactor developers, waste management organizations, regulators, academia, and industry came together to discuss the project goals, tentative work scopes, and the management structure of the project.

With support from ARPA-E, Deep Isolation is leading efforts for the UPWARDS project team to assist OECD-NEA in the planning of the WISARD Joint Project, with an aim to ensure that the UCS is, at a minimum, used as a base case as an example of how a fully-integrated waste management strategy can be designed, analyzed, and eventually deployed to help manage the safe storage, transport, and ultimate disposal of waste streams from advanced reactors and fuel cycles. Stakeholders are currently aligning on the final work scopes for the three-year Joint Project, which is expected to kick off in 2025.

Market research across the nuclear industry conducted in 2024 [31] found that two of the top three priorities that industry stakeholders (particularly in the US) have for the WISARD Joint Project are closely related to deliverables from the UPWARDS project:

- Establishing greater certainty about the generic WAC that geologic facilities will apply when accepting small modular reactor (SMR) and advanced reactor spent fuel and high-level waste; and

- Establishing clear regulatory standards for multi-functional canisters able to manage storage, transport, and disposal of spent fuel and high-level waste from SMRs and advanced reactors.

Deep Isolation and its partners look forward to engaging with other stakeholders in the WISARD Joint Project to ensure that international collaboration on these priorities is informed by the ground-breaking work of the UPWARDS project.

CONCLUSION

The successful completion of the UPWARDS project will help ensure the safe management of the back end of the fuel cycle for advanced nuclear reactors and support the deployment of these advanced nuclear technologies. With the development of the Universal Canister System, reactor developers, end users, waste management organizations, regulators, and other stakeholders will have confidence that a fully integrated waste management strategy has been developed to ensure the safe storage, transport, and disposal of several of the waste forms stemming from the advanced nuclear industry.

With a completed preliminary design and prototype manufacturing efforts now complete, the remaining duration of this project will focus on defining the performance envelope of acceptability for waste streams loaded into the UCS, and the subsequent development of the associated WAC. Upon completion of Project UPWARDS in July 2025, waste generators from advanced reactors and fuel cycles will have a viable path to enable the safe storage, transport, and disposal of their waste streams through direct loading into the UCS, preventing the need to repackage the waste, even in the face of uncertainty for final disposition pathways.

ACRONYMS

ARPA-E	Advanced Research Projects Agency - Energy
COP28	Conference of the Parties to the U.N. Framework Convention on Climate Change
CVD	chemical vapor deposition
DOE	Department of Energy
DWPF	Defense Waste Processing Facility
IAEA	International Atomic Energy Agency
ICP-OES	inductively coupled plasma optical emission spectroscopy
ISG-1	International Simple Glass 1
LaBS	lanthanide borosilicate
LBNL	Lawrence Berkeley National Laboratory
NAC	NAC International, Inc.
NEA	Nuclear Energy Agency
OECD	Organisation for Economic Co-operation and Development

PNNL	Pacific Northwest National Laboratory
RH-TRU	remote-handled transuranic
R-V	R-V Industries, Inc.
SiC	silicon carbide
SMR	small modular reactor
THC	thermal, hydrological, and geochemical
TRISO	tri-structural isotropic
UCB	University of California, Berkeley
UCS	Universal Canister System
UPWARDS	Universal Performance Criteria and Canister for Advanced Reactor Waste Form Acceptance in Borehole and Mined Repositories Considering Design Safety
WAC	Waste Acceptance Criteria
WIPP	Waste Isolation Pilot Plant
WISARD	Waste Integration for Small and Advanced Reactor Designs

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