DEVELOPING WASTE ACCEPTANCE CRITERIA FOR ADVANCED REACTOR WASTE FORMS IN THE UNIVERSAL CANISTER SYSTEM

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Abstract

Deep Isolation is leading a project to address back-end considerations of advanced reactor waste by developing a Universal Canister System. Designed for the safe storage, transport, and disposal of advanced reactor waste streams, the Universal Canister System will eliminate any need for repackaging. Thus, once encapsulated, the waste will be safe, future-proofed, and ready for any option the waste owner may choose, including long-term storage, disposal in a mined geologic disposal facility, or disposal in a deep borehole repository. The project is completing the design effort based on well-established industry best practices, advanced reactor waste stream characterization efforts, and repository performance assessments for conventional mined and deep borehole repository applications. In addition to a design and prototype canister fabrication effort, the project will develop generic waste acceptance criteria for advanced reactor waste loaded into the canister, paired against a matrix of repository configurations. The paper will provide an update on the success of the project's canister design effort and elaborate on the work to develop advanced reactor waste acceptance criteria for waste streams loaded into the Universal Canister System. Once complete, the project will provide a disposal option for numerous advanced reactor waste streams before such advanced fuel cycle facilities and reactor designs have progressed to construction and commissioning for use. Furthermore, Universal Canister System design efforts include requirements for compatibility with existing licensed systems for transport and storage, eliminating the need for any repackaging efforts once waste streams are loaded and sealed within the waste canisters, and providing a truly universal solution for advanced fuel cycle and reactor waste stream disposal.

1. INTRODUCTION

Deep Isolation and its partners aim to provide an integrated waste management system for advanced reactor (AR) waste streams prior to their deployment across the globe through the development of a Universal Canister System (UCS) and associated Waste Acceptance Criteria (WAC) that will provide a cost-effective nuclear waste disposal option for a broad range of AR fuel forms and waste streams. Funded by a grant from the U.S. Department of Energy's Advanced Research Projects Agency – Energy (ARPA-E), the three-year project – Universal Performance Criteria and Canister for Advanced Reactor Waste Form Acceptance in Borehole and Mined Repositories Considering Design Safety (UPWARDS) – aims to provide a disposal solution that allows for direct loading of AR waste streams into waste canisters and the elimination of the need to repackage prior to disposal.

The UPWARDS project comprises the following four work streams:

(a) University of California Berkeley (UCB) is leading research efforts to characterize AR waste streams that are trending nearest to market implementation and those that are likely to utilize a direct path to disposal. To date, the project has identified vitrified waste, tri-structural isotropic (TRISO) fuels, and frozen halide salts from molten salt reactors as representative waste streams for consideration. [1], [2], [3]

(b) NAC International Inc. (NAC) has completed the preliminary design process for the canister. The design is based on a set of functional requirements and design specifications which consider the most limiting aspects of structural, thermal, criticality, and radiological shielding performance. The design effort will culminate with the fabrication of a UCS prototype by the end of the project.

(c) Deep Isolation and Lawrence Berkeley National Laboratory (LBNL) are partnering to assess the long-term performance safety of the UCS using source-term and repository models for a conventional mined repository, a vertical borehole repository, and a horizontal borehole repository.

(d) Deep Isolation will integrate the first three work stream efforts to develop generic WAC for waste streams loaded into the UCS, paired against a matrix of repository configurations.

A Technical Advisory Committee of experts in the nuclear industry has been assembled and meets with project team members regularly to advise on matters important to the project's success, in particular through a series of technical workshops. These workshops address some of the key challenges faced during the project, including regulatory uncertainties associated with deep borehole disposal, AR waste form characteristics, and manufacturing of the UCS.

Project UPWARDS will deliver a new canister design for AR waste streams and a set of generic WAC with universal compatibility across storage, transport, and ultimate disposal of spent nuclear fuel (SNF) and high-level waste (HLW). This integrated waste management system will allow for direct loading of waste into the UCS, eliminating the need for repackaging and reducing risks associated with extended radiological work, ultimately reducing disposal costs.

Deployment of the UCS in the future will involve the loading of waste streams into canisters following the constraints of the WAC. The canisters will then be stored, transported, and ultimately placed into a repository, whose construction, operation, and closure will have to be approved by a relevant regulating authority (e.g., U.S. Nuclear Regulatory Commission) based on a comprehensive safety analysis, including an assessment of the repository's long-term performance. Within the UPWARDS project, performance calculations will be executed first, assessing a wide range of generic conditions and assumptions (including those related to the waste form) to delineate the combinations of site characteristics and design parameters that likely yield a safe disposal pathway for AR waste stream. Based on this delineation of the solution space of the integrated waste management system, generic WAC will then be formulated.

2. DISCUSSION

2.1. Early project progress

In the first year and a half of the UPWARDS project, considerable progress has been made in understanding the availability of AR waste form data, completing the preliminary design of the UCS canister, and reviewing the U.S. regulatory landscape and international WAC.

2.1.1. Waste form research and characterization

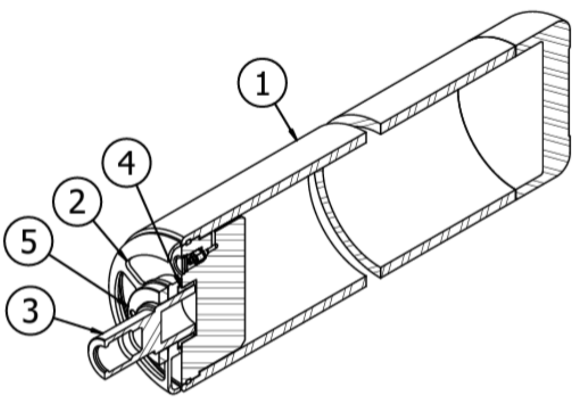
In order to ensure the UCS is designed to accommodate as many AR fuel types and waste forms as possible, UCB is leading efforts to research and characterize at least three representative waste forms nearest to market implementation, with a goal that data used to assess performance and safety will be bounding of the majority of waste forms likely to be seen with the deployment of ARs. Through extensive literature and process review, UCB has assessed the technological maturity, durability, thermal stability, radiation stability, waste loading density, and compatibility with canister materials for multiple potential waste forms and identified gaps in knowledge relevant to repository modeling. This assessment was supplemented with feedback from the UPWARDS Technical Advisory Committee during a workshop held at UCB.

Using borosilicate glass as a baseline from which to assess waste form knowledge completeness, UCB reviewed available data and information related to lanthanide borosilicate (LaBS) glass, TRISO particles, pebbles and compacts, and frozen halide salts. For the glass and salt waste forms, the material will be poured into and frozen in a secondary austenitic stainless-steel container that is then loaded into the UCS canister to avoid exceeding UCS canister material property thermal limits. The assessment found that the most notable gap in knowledge for LaBS glass is related to the waste degradation rate and how it will vary with temperature, pH, and pore fluid chemistry. More knowledge gaps were identified for TRISO waste forms and frozen halide salts, particularly regarding the mechanisms that govern their durability in repository-relevant conditions and guide the construction of predictive models, which will be used in safety assessments for repository licensing and the determination of site-specific WAC. These findings will be documented as a gap analysis in a report on AR waste form standards and specifications. Additional work will be performed by UCB to address these knowledge gaps, as discussed in Section 2.2.1 below.

2.1.2. Preliminary design of the Universal Canister System

NAC's work on the preliminary design of the UCS began with a review of applicable U.S. Nuclear Regulatory Commission (NRC) regulations regarding the storage [4], transport [5], and disposal [6], [7] of SNF and HLW. These regulations, along with information about the geologic, chemical, and radiological conditions anticipated in both mined and deep borehole repository environments, informed the development of a Functional Requirements Specification and a UCS Design Specification. The Functional Requirements Specification and UCS Design Specification in turn informed the canister material selection (duplex stainless steel 2205). Initial assumptions for UCS dimensions and the conceptual design were partially based on the drillhole canister (DHC) previously developed by NAC and Deep Isolation, which is designed to dispose of a single pressurized water reactor fuel assembly [8].

The UCS conceptual design (see *FIG. 1*) includes three canister classes, each with varying sizes to accommodate a broad range of AR waste streams, but with similar features for closure, lifting, and handling. The UCS consists of a thick-walled shell assembly, a closure lid welded after loading to provide shielding, and a lift adapter assembly field-installed at the repository used for surface handling, emplacement, and retrieval operations.



Item #	Description
1	UCS Assembly
2	Cap Plate
3	Lift Adapter
4	Key Plate
5	Jam Plate

FIG. 1. Universal Canister System (UCS) Preliminary Design

The UCS Preliminary Design Report documents the results of structural, thermal, criticality, and shielding analyses performed for what was determined to be the most limiting operational and credible accident conditions for storage, transport, and disposal [9]. The Design Report concludes that the UCS design complies with current regulatory requirements, as identified in the Functional Requirements Specification and UCS Design Specification, while also addressing what the UPWARDS project team determined to be potential limiting factors in future regulations. The design report also identified potential areas where additional analysis work may be performed and may result in changes to the UCS design, pending the results of other project work scopes.

2.1.3. Review of regulatory landscape and waste acceptance criteria

Deep Isolation performed a review of the current U.S. regulatory environment (both Nuclear Regulatory Commission and Environmental Protection Agency regulations), American Nuclear Society recommendations to update existing regulations, and international precedents related to HLW disposal efforts [10]. This review culminated in the identification of uncertainties and opportunities for innovation in regulations, as they relate to both mined and deep borehole repositories, while also identifying potential next steps to address these topics. The topics included reliance on engineered versus natural barrier systems, retrievability timing and logistics, repository configuration and design features, plug and backfill closure timing, reference dose rate to the public, assumed groundwater conditions for modeling, inadvertent human intrusion, and post-closure safeguards. The UPWARDS Technical Advisory Committee was consulted during a technical workshop on the regulatory landscape, particularly as it relates to deep borehole disposal. Their input was crucial to identifying the uncertainties in regulations, along with establishing recommendations for how the project (or future projects) should address those uncertainties.

The review included both U.S. (i.e., for vitrified waste and transuranic waste) and a variety of international (from Finland, France, Canada, and other European sources) WAC in order to develop a baseline for the identification of criteria and associated parameters relevant for the UCS [10]. These criteria and parameters may be generically applied or may be dependent upon the waste form, canister design, and/or repository configuration. In addition to those identified in the review, the Project team considered the following aspects as part of the development of the UPWARDS WAC: borehole conditions, credit for the UCS design, retrievability, and principles for the management of AR waste versus legacy waste.

2.2. Remaining project scope

2.2.1. Waste form characterization through experimentation

Using the information researched and documented in UCB's gap analysis report on AR waste forms, a series of experiments will be derived to fill in the knowledge gaps for LaBS glass, TRISO fuels, and intact halide salts. UCB will first identify the objectives for the experimentation phase, then develop a set of procedures and analytical methods. The intent is to derive a standard and common set of experiments that can be applied across the multiple waste forms being investigated to ensure consistency among the resulting data. Once the experimentation phase is complete, UCB's gap analysis report will be revised to incorporate the new data, resulting in a full set of documented parameters for LaBS glass, TRISO fuels, and intact halide salts that are important to repository performance. For the glass and intact halide salt waste forms, the potential role of a secondary container, as an engineered barrier, will be assessed. A secondary container could be useful 1) as a suitable vessel to pour high-temperature molten waste into prior to its cooling and solidification, and 2) as an additional barrier to halide-induced corrosion of the UCS canister prior to emplacement. Additionally, the experimental data will be compiled such that the relevant parameters can be shared with the full project team to support follow-on long-term safety calculations, as well as any canister design confirmatory analyses deemed appropriate.

2.2.2. Performance assessment modeling of the UCS

Long-term safety for the disposal of AR waste in the UCS will be assessed through the use of a framework using TOUGHREACT and iTOUGH2 modeling tools [11], [12]. Source-term models are in development for each of the three representative waste forms identified by UCB. Generic repository performance models will be developed for a conventional mined repository as well as deep borehole concepts using horizontal and vertical boreholes. This work builds off previous work performed by Deep Isolation and LBNL related to the performance of spent PWR fuel assemblies in deep boreholes [13], [14], [15], [16].

The project team identified a set of potentially safety-relevant features, events, and processes (FEPs), along with ranges for model input parameters. Because the specific waste characteristics will be unknown (until reactor-specific data is available), and only generic repositories will be evaluated (until a site-specific evaluation can be completed), generic screening models will be used to simulate the release of radionuclides from the UCS, factoring in relevant waste form degradation rates and release mechanisms, and the combined environment of the engineered barrier system and surrounding geosphere. The analyses will allow for quantification of the maximum exposure dose to an individual living near the repository. These calculations will be performed for a range of waste inventories, repository configurations, and host formations to determine a performance envelope that meets the requirements identified within the UCS Design Specification and remains below a typical peak dose standard of 10 mrem/year (0.1 mSv/year).

2.2.3. UCS prototype fabrication

NAC will engage with U.S. and international fabricators prior to the project team's selection of a qualified vendor to fabricate a UCS prototype canister based on expertise, schedule capabilities, ability to scale, and budget.

NAC already has a network of trusted and qualified fabricators based on their extensive work related to the transport and dry storage of spent nuclear fuel. Additionally, NAC is already aware of many fabrication lessons learned (e.g., welding and machining enhancements) as a result of an ongoing project between Deep Isolation, NAC, and the University of Sheffield, in which the latter's research center (Nuclear Advanced Manufacturing Research Center) has nearly completed fabrication of a prototype DHC for the disposal of spent PWR fuel assemblies. NAC and Deep Isolation anticipate key manufacturing challenges related to shell fabrication requirements to meet the UCS specifications (e.g., straightness, ovality, etc.), ensuring proper facilities to accommodate vertical handling and testing of components to simulate operational environments, and combatting weld/machining shrinkage of heated duplex stainless steel. In addition to incorporating lessons learned from the ongoing Sheffield project and conducting vendor outreach, NAC and Deep Isolation are planning a technical workshop with at least one qualified fabricator to discuss manufacturing strategies, future large-scale manufacturing capabilities, and an opportunity to assess fabricator facilities for UCS manufacturing suitability.

2.3. Development of Waste Acceptance Criteria

2.3.1. Integration of UPWARDS work streams

As shown in *FIG. 2* [17], the project's parallel work streams are interdependent and work together towards achieving the project goal to establish an integrated waste disposal solution for AR waste streams that meets both safety and economic considerations. Waste form attributes such as radiological, thermal, and mechanical loading have a direct impact on the canister design (e.g., thickness and material), and both waste form and canister details inform the source-term model essential to the safety performance assessments. The conclusions of modeling and safety work will identify areas of potential restrictions in waste loading, modifications of the canister design, choice of repository configuration, and ultimately repository suitability, all providing a basis for WAC. Using the initial iteration of the UCS preliminary design, a framework for the WAC will be developed by challenging the design with the additional information coming from the waste form research and safety analysis model results. Once complete, the UCS design and/or analyses may be subject to revision prior to development of final generic WAC.

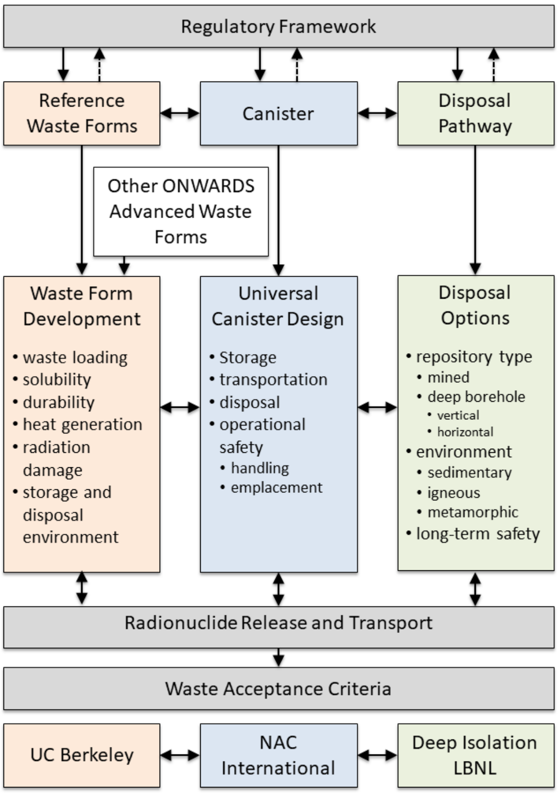


FIG. 2. An Integrated Waste Management System.

2.3.2. Categories of Waste Acceptance Criteria

The UPWARDS project team's review of U.S. and international WAC identified a framework for the development of a unique set of generic WAC for the UCS. The Project team considers WAC consistent with IAEA's qualitative acceptance criteria [18] to be ideal, but will divide these criteria into the five different categories consistent with the WAC for the Waste Isolation Pilot Plant for transuranic (TRU) material in Carlsbad, New Mexico [19]: (a) container properties, (b) radiological properties, (c) physical properties, (d) chemical properties, and (e) data package contents. The U.S. Department of Energy Waste Acceptance System Requirements document [20] also adheres to a similar framework for WAC. The criteria categorization planned for the UPWARDS project is shown in *Table 1*.

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

Container properties are a direct representation of the UCS design and, as such, have already been extensively analysed through the aforementioned UCS Preliminary Design report [9]. Physical dimensions and weights of both the canister and the cargo have been determined through the design process and informed initial structural evaluations of the loaded UCS. Mechanical performance criteria have been evaluated through structural analyses of limiting operational and off-normal conditions across all three canister sizes and all three waste form categories. The most limiting configurations demonstrate that the canister maintains containment/confinement through scenarios such as free drops down a borehole or onto an unyielding surface and stacking loads encountered in vertical borehole disposal configurations. As will be the case in subsequent categories, the canister itself may not be solely relied upon for certain scenarios. The UCS design is intended to be compatible with NAC's existing licensed transport and storage systems which already meet the requirements of 10 CFR Parts 71 [5] and 72 [4], respectively. Future work – beyond the scope of the UPWARDS project – will be required to design basket inserts to ensure such compatibility between the UCS and transport casks and storage containers. For the UPWARDS project, typical cask and basket parameters are assumed for relevant transportation and storage analyses, and any need for modification based on analysis results will be documented and incorporated into such designs when they are developed.

Radiological properties will dictate much of the canister system design and waste conditioning requirements. Radiation effects in the form of measured radiological dose exposure must be determined for each configuration to determine whether design modifications to the UCS are warranted, or if additional radiological controls (e.g., additional shielding) are necessary for dose rates to remain within regulatory limits during transport, storage, and disposal. Consistent with the planned criteria for structural performance in the *container properties* category, the UCS preliminary design analyses demonstrate that the containment boundary is maintained during all normal and off-normal conditions [9]. Therefore, the risk of radiological exposure due to a release of contaminants from the UCS is mitigated by the robust UCS design. Decay heat restrictions will dictate how soon after loading into a UCS a waste form may be placed into dry storage, transported, or disposed of in a repository. These decay heat considerations, based on the initial heat load at time of loading and the change in heat release over time, can be mitigated with time, cooling, and/or a requirement for reduced waste loading density. To determine appropriate decay heat limits, thermal performance analyses will be required to validate that external transport and dry storage cask surface temperatures meet regulatory limits during transport and dry storage, respectively, and that UCS external surface temperatures (a) do not reach the atmospheric boiling temperature of water (100ºC) at any time during emplacement operations; and (b) meet material property limits throughout the assumed maximum 50-year period for retrievability from a repository. Lastly, loaded canisters in all applicable configurations must demonstrate sufficient margin to criticality to ensure the contents remain subcritical during all normal and off-normal conditions. In the UCS Preliminary Design report [9], NAC analysed a variety of limiting configurations and determined adequate margins across nearly all possible scenarios.[1]

Physical properties generally refer to the state of matter of contents within a container. With the AR waste forms being considered in the UPWARDS project, it is assumed that the UCS canister will be devoid of free liquids and compressed gases. These metrics are generally achieved by processes assuring the waste is dry prior to loading (e.g., hot cell loading) while also ensuring gage pressure of any backfill gas (helium), if required, does not exceed limits of the licensing technical specification. Properties of gases formed by radiolysis or chemical decomposition over time will be addressed in the *chemical properties* category.

Chemical properties pertain to the chemical interactions within the waste form, between the waste form and the canister, between the canister and the external environment, and eventually the long-term waste form and the long-term disposal zone environment. Chemical durability is being evaluated by UCB and is essential to providing accurate isotopic and chemical data as a function of time in source-term and long-term safety models. Similarly, gas generation is being studied by UCB to ensure sufficient margin to UCS overpressurization, particularly for mined repositories (since the higher external pressure in a deep borehole may offset internal pressure increases and allows for higher internal pressures, though a need for such margin is not anticipated). Combustibility will be drastically reduced to the maximum extent practicable by minimizing conditions that would foster combustion (e.g., vacuum and helium backfill canister). Combustion events are unacceptable in transportation, storage, or disposal, as they would inhibit the reliability of the canister system in minimizing radiological exposure to the workforce and public. Fire hazards, explosion hazards, and toxic/corrosive materials are issues similar to combustibility in that they should be avoided entirely and will need to be reassessed if any assumptions on chemical composition or durability should change.

While the four categories discussed above provide a reasonable process for ensuring that a waste package is suitable for storage, transportation, and disposal, the *data package contents* category refers to the quality assurance and control measures necessary to ensure that material control and inspection processes were appropriately conducted and documented. This category, with criteria such as unique canister identification, requires rigorous documentation and verification of waste forms and attributes, and its proper development is incumbent on all parties seeking custody of waste from generation through ultimate disposal. The development of forms and procedures necessary to ensure data package compliance to satisfy this category is beyond the scope of the UPWARDS project.

Once all the appropriate categories and criteria have been established, acceptable parameter ranges will be determined. These acceptable ranges will be an integration of the results of UCB's AR waste form characterization work, NAC's preliminary design analyses for the UCS, and Deep Isolation's and LBNL's source-term and repository safety assessment modelling work.

2.3.3. Configuration applicability and pairing matrix

Upon formulation of these WAC for the UCS, each waste form will be evaluated against the criteria for each applicable configuration to develop a pairing matrix to determine acceptable configuration scenarios. An acceptable configuration entails: (a) at least one suitable UCS class (of the three envisioned); (b) acceptability for transportation; (c) acceptability for storage; and (d) acceptability in at least one repository configuration (mined repository, vertical borehole, or horizontal borehole) in at least one generic geology (sedimentary or granitic).

[1] The only configuration to not meet the criticality requirements was consolidated TRISO pebbles loaded into the largest UCS class. An array of 7 UCS canisters exceeded 10 CFR Part 71 criticality limits for the anticipated transport configuration. Future design phases of the UCS will address this scenario to ensure that all criticality requirements are met during all stages of transport, storage, and disposal.

Some pairings, such as vitrified waste in containers placed in the smallest UCS class canisters, may be inherently unapplicable due to an anticipated single binary metric (e.g., whether the waste fits in the canister). Other pairings may prove universally applicable. The remaining pairings may require optimization to balance attributes such as maximum waste loading, minimum cooling period, and repository configuration.

When finished, the pairing matrix will be accompanied by a roadmap to illustrate the process of designating a configuration suitable for both validation of waste forms studied within the UPWARDS project and as a framework for how to evaluate additional waste forms.

2.3.4. International application of the UCS and its waste acceptance criteria

In 2023, the Organisation for Economic Cooperation and Development – Nuclear Energy Agency (OECD-NEA) kicked off plans for a Joint Project on Waste Integration for Small and Advanced Reactor Designs (WISARD) [22]. The WISARD project aspires to create an integrated spent fuel and waste management strategy for small modular reactors, ARs, and advanced fuel cycles across transport, storage, and disposal, while also addressing waste treatment, reprocessing, and recycling. The WISARD project offers obvious synergies with the UPWARDS project, and both projects aim to define WAC that can be used for the widest possible set of spent fuels from ARs. Deep Isolation and OCEA-NEA are currently exploring opportunities for collaboration between projects, including use of the UCS and its WAC as a case study for how a waste disposal solution can be applied across storage, transport, reprocessing, and disposal prior to these ARs and fuel cycles beginning commercial operations.

3. CONCLUSION

In July 2025, Deep Isolation's UPWARDS project will deliver a first-of-a-kind canister, the Universal Canister System, specifically designed to accommodate the transport, storage, and disposal of AR waste streams. The canister and its associated WAC will be the first to address the long-term safety of AR waste streams in both mined and deep borehole disposal configurations. The development of the WAC marks the capstone of this ambitious project by integrating the analysis and design work of Deep Isolation, UCB, NAC, and LBNL to (a) characterize the anticipated cargo from a wide range of advanced fuel cycle technologies; (b) design a canister suitable for such cargo and compatible with existing transport and dry storage systems, while also supporting disposal in both traditional mined and novel deep borehole repositories; and (c) provide a framework for the long-term safety analysis of AR waste in a variety of repository configurations. While cargo- and site-specific long-term safety analyses will need to be performed as part of a repository license application to demonstrate safety, the analyses performed under the UPWARDS project aim to demonstrate an ability to model a variety of scenarios (e.g., nominal and some disruptive events) for disposal of AR waste through the robust design of the UCS and a set of WAC that can be ultimately tailored to each specific waste form and repository configuration.

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