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# Update on the United States Department of Energy's Used Fuel Disposition R&D Campaign

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*The United States Department of Energy (DOE) is conducting research and development (R&D) activities within the Used Fuel Disposition Campaign to support the implementation of the DOE's 2013 Strategy for the Management and Disposal of used Nuclear Fuel and High-Level Radioactive Waste. R&D activities focused on storage, transportation, and disposal of used nuclear fuel (UNF) and wastes generated by existing and future nuclear fuel cycles are ongoing at nine national laboratories. Additional relevant R&D is conducted at multiple universities through the DOE's Nuclear Energy University Program.*

*Within the storage and transportation areas, R&D continues to focus on technical gaps related to extended storage and subsequent transportation of UNF. Primary emphasis for FY15 is on experimental and analysis activities that support the DOE's full-scale cask performance demonstration project initiated at the North Anna Nuclear Power Plant in Virginia by the Electric Power Research Institute in collaboration with AREVA and Dominion Power. Within the disposal research area, current planning calls for a significant increase in R&D associated with evaluating the feasibility of deep borehole disposal of some waste forms, in addition to a continued emphasis on confirming the viability of generic mined disposal concepts in multiple geologic media. International collaborations that allow the U.S. program to benefit from experience and opportunities for research in other nations remain a high priority.*

## I. INTRODUCTION

The January 2013 U.S. Department of Energy (DOE) *Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste* identifies key goals and target dates associated with used nuclear fuel (UNF) and high-level radioactive waste (HLW) management. These goals provide a framework for setting priorities within the DOE Office of Nuclear Energy's Used Fuel Disposition (UFD) Campaign.

The goals summarized below are identified in the *DOE Strategy* document (DOE 2013), with the caveat that full execution of the plan requires enactment of revised legislative authority.

2021 Pilot interim storage facility opened and operating

2025 Consolidated interim storage facility (CISF) opened and operating

2026 Permanent repository site identified

2042 Repository site characterized; repository designed and licensed

2048 Repository constructed and operations commenced.

The UFD Campaign is conducting research and development (R&D) activities relevant to the storage, transportation, and permanent disposal of UNF and HLW that will support these strategic objectives.

## II. USED FUEL DISPOSITION CAMPAIGN OBJECTIVES

The Used Fuel Disposition Campaign has established near-term (5-yr) and medium-term (10-yr) objectives to meet the DOE's goals for used fuel and high-level waste management, building on research completed in these areas since the campaign was initiated in 2009.

***Near-Term (5-yr) UFD Objectives***

1. Provide technical expertise to inform policy regarding management of UNF and radioactive waste that would be generated under existing and potential future nuclear fuel cycles.
2. Develop additional support for the technical basis for extended long-term storage of UNF and high-level nuclear waste.
3. Develop additional support for the technical basis for retrievability and transportation of high burnup UNF.
4. Develop a comprehensive understanding of the current technical basis for disposal of UNF and high-level nuclear waste in a range of potential disposal environments.
5. Develop advanced computational models, with experimental validation as practical, for:

a. Evaluation of UNF performance under normal conditions of storage and transportation.

b. Evaluation of disposal system performance in a variety of generic disposal system concepts and environments.

***Medium-Term (10-yr) UFD Objectives***

1. Support the implementation of a full-scale, NRC-licensed confirmatory storage demonstration facility through significant collaboration with industry.
2. Support the implementation of integrated storage, transportation and disposal concepts.

## III. KEY TECHNICAL CHALLENGES

### *Storage and Transportation*

Used fuel from light-water reactors (LWRs) is currently being safely and securely stored in the U.S., primarily at the locations where it was generated. It is initially stored wet in used fuel pools, but as these pools fill to capacity the used fuel is transferred to dry canisters that are stored on-site at the nuclear power plant. UNF is also transferred from wet pools to dry storage systems when a nuclear power plant is decommissioned, and, at present, the used fuel remains at the former reactor site. HLW, including both liquid wastes from reprocessing of UNF and solid waste forms such as vitrified borosilicate glass generated from liquid wastes, is currently stored in the U.S. at facilities managed by the DOE Office of Environmental Management.

Neither wet nor dry storage systems offer a permanent solution for managing UNF or HLW. Rather, they are designed to be temporary, with plans for ultimate removal of the material and subsequent disposition (i.e., permanent disposal). Dry used fuel storage systems are typically licensed by the U.S. Nuclear Regulatory Commission (NRC) for a 40-year period, with the possibility of a 40-year license renewal allowing for up to 80 years of operations under current regulations. Over the next decade, these licenses will begin to expire. The UFD Campaign supports the development of the technical basis to judge the viability of extending the storage licenses to allow continued on-site storage.

Considerations relevant to the design of a storage R&D program from a longer-term strategic perspective include:

- *Storage Canister Integrity.* Extended storage will require verification that storage canisters retain their full integrity over longer periods than previously evaluated.
- *High Burnup UNF Storage.* The higher burnup UNF that is typical of current industry practice may require additional assessments to confirm its performance during extended storage.
- *Post-Storage UNF Integrity.* Additional support may be needed to demonstrate UNF integrity for transportation after long-term storage.
- *UNF Material Property Data.* Experiments to obtain used fuel cladding material property data are inherently expensive and complex, requiring careful prioritization and planning of experimental measurements.

R&D topics associated with the safe and secure transportation of UNF following extended storage include:

- *Cladding Integrity Investigations.* Data regarding the performance of high burnup fuels during transportation are currently limited. Experimental investigations will characterize the impact of burnup on the strength and ductility of fuel cladding and its performance during transport.
- *Over-the-Road Testing.* Gaps in the understanding of forces on UNF during transport will be investigated through road and rail tests on instrumented surrogate assemblies. This loading information, coupled with the cladding integrity investigations, will allow quantification of fuel response during transport.
- *Secure Transportation.* As planning continues for larger scale transportation campaigns, the security framework surrounding transportation will be evaluated in light of current rule-making that is advancing through the NRC.

The 5- and 10-year UFD goals for storage are structured to address these issues.

***Near-Term (5-yr) Storage & Transportation R&D Objectives***

1. Develop a sufficient understanding of how hydrides affect cladding integrity in high burnup UNF.

   a. Develop a predictive model of hydriding in nuclear fuel cladding that can address degradation phenomena not readily obtainable through experimentation. This model will be validated with experimental data where possible.

   b. Conduct experimentation and analysis to develop an increased understanding of pellet-to-pellet and pellet-to-clad interactions and the impact of the related stresses on hydride formation.

c. Perform experiments to develop a better understanding of the effects of temperature and pressure on the Ductile-to-Brittle Transition Temperature.

2. Characterize and develop an understanding of how corrosion and stress corrosion cracking affect the performance of stainless steel storage canisters.

   a. Understand the performance of the canister parent material and the closure weld material.

   b. Better characterize the on-site environmental conditions in both marine and inland locations.

   c. Understand residual stress and related stress corrosion cracking in typical dry storage canisters.

3. Characterize and understand how external loadings are transferred to UNF during normal conditions of transport. Develop a predictive model validated with experimental data.

   Work will be performed to determine if the stress induced by normal conditions of transport is greater or less than the maximum stress the material can withstand. This research includes instrumenting surrogate assemblies and subjecting them to the stresses and strains of normal conditions of transport, using both shaker tables and road/rail testing.

4. Complete analysis of assembly and cask thermal conditions during storage. Data will be collected during on-site environmental monitoring events and during the full-scale demonstration. These models will be used to predict hydride formation, corrosion rates, and other factors that will affect the integrity of the fuel and its packaging.

5. Support the full-scale *High Burnup Dry Storage Cask Research and Development Project* (EPRI 2014), initiated in 2013 as a collaboration between the DOE Office of Nuclear Energy and industry to collect data from a dry storage system containing high-burnup UNF.

   a. Collaborate with industry to identify sister rods, candidate fuel and support basket configuration analysis by 2017.

   b. Support identification of instrumentation for long-term monitoring by 2017.

   c. Identify separate effects test that align:

      i. Testing of sister rods to obtain time zero ($t_0$) data.

      ii. Characterization of fuel rods extracted from the dry storage canister (2027).

6. Support plans for facility upgrades by 2027 to handle the demonstration dry storage cask and to extract assemblies / fuel rods. Modification of an existing facility could require ~5 years, and would need to begin by 2022 to support 2027 evaluation of fuel from the dry cask demonstration

***Medium-Term (10-yr) Storage and Transportation R&D Objectives***

1. Develop an improved understanding of the effects of the vacuum drying process for used fuel. Fuel and cladding is exposed to its peak post-irradiation temperature during this process, causing it to be a critical time for many of the factors that affect fuel integrity. Aspects of interest include:

   a. Remaining moisture levels;

   b. Effect of drying on neutron poisons in the basket;

   c. Impact on hydride formation in the cladding;

   d. Effect on radiolysis (hydrogen production).

2. Support development of a dry transfer system that allows transfer from the current storage environment to interim storage.

   There are currently over 500 casks at Independent Spent Fuel Storage Installations (ISFSIs) that do not have a licensed transportation cask. Many of these sites do not have pools for cask handling, so a dry transfer system will be needed to transfer the contents to a transportation cask. A dry transfer system will also be necessary if an assembly and/or canister needs to be repackaged due to retrievability concerns.

3. Determine the impact of multiple drying cycles on fuel cladding hydride behavior.

   If fuel is repackaged due to transportation and storage needs or retrievability, some of that repackaging may occur in pools, resulting in multiple drying cycles.

***Disposal***

Safe disposal of radioactive waste is accomplished by isolating the waste from the human environment for sufficiently long time periods, as required by regulatory standards. Isolation is achieved through a combination of engineered and natural barriers (e.g., robust waste packages and very slow radionuclide transport through the surrounding rocks). Over the very long time periods necessary to isolate the wastes, the engineered barriers may degrade, allowing radionuclides still present in the waste to be released at a low rate into the natural system.

The natural system will act to delay the subsequent migration of radionuclides to the accessible environment and to reduce releases to levels below the limites established in regulatory standards, typically well below naturally occurring levels of background radiation. Understanding when radionuclides may begin to be released from the disposal system, the rate at which they may be released, and how they might migrate through the natural system are primary factors in demonstrating the safety of a disposal system concept.

Geologic disposal concepts are typically complex systems with physical and chemical couplings between the disposed waste, engineered barrier materials, and the natural system. The long-term radionuclide isolation capabilities and characteristics of a waste disposal environment are dependent on the details of the site and the form and contents of the wastes to be disposed. Disposal systems can be geographically large and the distance over which materials could potentially migrate can be long. In addition, because of the long time frames involved, precise predictions of repository performance are not possible, and uncertainty must be acknowledged in the decision-making process. Quantifying, propagating, and reducing this uncertainty through safety assessments have been and continue to be challenges in demonstrating the viability and safety of geologic disposal. Disposal R&D focuses on gathering sufficient data (laboratory and field) and developing computational models for evaluating and demonstrating long-term disposal system performance and safety.

The goals and objectives for disposal research are summarized below.

***Key Disposal Research Goals:***

A. Provide a sound technical basis for multiple disposal options in the U.S. for existing and reasonably projected future UNF from the existing commercial LWRs and the DOE managed UNF and HLW.

B. Capture and quantify the advantages and disadvantages of each generic disposal option using representative reference cases.

C. Develop science and engineering tools to support disposal concept implementation by 2026.

D. Provide the necessary technical information for a successful site-specific license application.

***Near-Term Disposal R&D Objectives (5-yr):***

1. Complete evaluation of the feasibility of direct disposal of dual-purpose canisters (DPCs).
2. Complete a Geographical Information System (GIS) database to support site screening and selection.
3. Develop an experimental and modeling basis for understanding the long-term performance of engineered materials, including waste form and waste packaging, clay buffers, and backfills at elevated temperatures.
4. Initiate a full-scale deep borehole field test that will provide basic data to evaluate feasibility of deep borehole disposal of HLW and DOE-managed UNF.
5. Develop an experimental and modeling basis for understanding the long-term performance of:
    a. Argillaceous host rock (clay-rich)
    b. Crystalline host rock
    c. Salt host rock, domal or bedded
    d. Deep boreholes
6. Develop system analysis tools to support generic technical site characterization, site screening, and prioritization of data needs.
7. Develop a process to capture and quantify realistic advantages and disadvantages of each disposal option. Develop reference cases for each disposal option.
8. Develop a process for generic technical characterization of volunteer and/or selected sites.
9. Leverage, and potentially partner with, current and future work conducted by international partners.

***Medium-Term Disposal R&D Objectives (10-yr):***

1. Provide technical input to advantages and disadvantages of specific volunteer sites. (Required timeframe: Must be complete by 2026 to support the 2013 *DOE Strategy*.)
2. Design and implement a site characterization program for one or more sites. (Required timeframe: ~2026 – mid-2030s)
3. Complete a full-scale deep borehole field test, including demonstration of waste canister emplacement using surrogate waste forms.
4. Establish generic or site-specific underground research laboratories to conduct research and demonstration tests.
5. Develop site-specific licensing basis for one or more sites. (Required timeframe: Complete by 2042)
6. Design and implement a specific performance confirmation program for each of one or more sites. This is an experimental program necessary to confirm the licensing basis, which must continue throughout

operation of the repository. (Required timeframe: ~2042 – 2048)

## IV. USED FUEL DISPOSITION CAMPAIGN ONGOING ACTIVITIES

### *Storage and Transportation Field Demonstration Activities*

Current activities include:

- Support the industry-led high burnup full-scale dry storage demonstration, specifically in the areas of fuel transfer, instrumentation and analysis.
- Develop the strategy for fuel pin receipt, characterization, sample allocation for the demonstration sister pins.
- Initiate readiness activities to prepare for receipt of sister fuel pins.
- Coordinate dry cask storage instrumentation development.
- Interface with DOE and industry to develop a dry transfer system.
- Coordinate with EPRI for storage canister in-service inspections.
- Conduct concrete degradation and stress corrosion cracking (SCC) detection, imaging and characterization studies.

### *Storage and Transportation Experimental Activities*

Current activities include:

- Establish process to receive irradiated UNF from utilities at a national laboratory for characterization and sample preparation.
- Design an appropriate small-scale test vessel for testing and evaluation of irradiated fuel in a hot cell.
- Characterize and evaluate cladding properties, e.g.:
    - Develop and test non-destructive examination techniques to characterize hydrides in fuel cladding. Irradiation and evaluation of non-hydrided and pre-hydrided cladding.
    - Conduct fuel bend tests on unirradiated, irradiated, non-hydrided, and pre-hydrided cladding samples to determine effects of each factor on cladding properties.
- Develop post-irradiation analysis tools and techniques for high burnup fuel examination (e.g., fission gas analyzer).
- Support development and implementation of direct disposal of dry storage canisters in a geologic repository.
- Evaluate dry storage canister performance through in-service inspections, examination of weld samples, corrosion testing, stress corrosion cracking, etc.

### *Storage and Transportation Engineering Analysess*

Current activities include:

- Address various technical gaps through model development to augment experimental work. Key technical gaps include: thermal profiles, stress profiles, drying issues, hydride reorientation and embrittlement in cladding, cladding creep, and annealing of radiation damage in cladding.
- Support the development of thermal profiles associated with in-situ dry storage systems, including analysis of canister thermal profiles to inform canister corrosion vulnerabilities. Conduct analyses to define fuel thermal characteristics to support assembly selection for the industry high burnup dry cask demonstration.
- Support the development of stress profiles for the evaluation of fuel performance subjected to storage and transportation mechanical loading environments.
- Initiate an Uncertainty Quantification (UQ) effort to complement the prioritization reflected in the technical data gap report. The UQ effort will focus on developing a methodology to provide guidance on what experimental data will have the greatest impact on meeting R&D objectives.

### *Transportation Activities*

Current activities include:

- Analyze shaker table test data for over-the-road normal conditions of truck transport.
- Conduct shaker table testing for normal conditions of rail transport.
- Collaborate with industry to ship an instrumented surrogate pressurized water reactor (PWR) assembly to conduct shaker table

tests using the vibration/shock response spectra obtained from the transport.

***Storage and Transportation Security Activities***

Current activities include:

- Assess the regulatory rule-making process and changes being considered in the physical protection and security requirements for storage and transportation.
- Assess the regulatory rule-making process and impact of potential changes in light of the need to de-inventory orphaned sites by transporting the used fuel to a consolidated storage facility.

***Disposal Research Host Rock-Specific Activities***

***Argillite*** *(clay-bearing host rock)*

Current activities include:

- Model development, including
    - Develop constitutive relationships for coupled processes.
    - Evaluate relevant physical and chemical processes for clay/shale disposal.
    - Develop thermodynamic databases and modeling approaches for chemical equilibria and sorption with insights from experimentally-based studies.
    - Develop process models to quantify the effects of chemical, electrochemical, and radiolysis reactions; physical mass transport processes; and environmental conditions on fuel matrix degradation, radionuclide release rates, and overpack performance.
- Conduct clay damage and discrete fracture studies.
- Establish a scientifically sound thermal limit on argillite host rock through high temperature laboratory tests.
- International collaboration:
    - Collaborate on testing at the Mont Terri Underground Research Laboratory in argillite in Switzerland.
    - Collaborate through DEvelopment of COupled models and their VALidation against EXperiments (DECOVALEX), an international cooperative research project on mathematical models of coupled thermal-hydrological-mechanical processing for safety analysis of radioactive waste repositories.

***Crystalline Rock***

Current activities include:

- Experimentally investigate structure-functionality relationships of radionuclide transport through and interaction with natural and engineered materials, with a focus on developing a new generation of buffer materials for nuclear waste isolation and establishing new thermal limits for the materials.
- Investigate the stability of intrinsic plutonium colloids in crystalline disposal environments.
- Develop models for fluid flow and radionuclide transport in fractured crystalline rocks and for thermal-hydrological-mechanical-chemical behaviors.
- Quantify the long-term weathering behavior of the used fuel matrix (as a waste form) in generic crystalline (granitic) disposal environments.
- International collaboration:
    - Collaborate on the Korean Atomic Energy Research Institute (KAERI) Underground Research Tunnel (KURT) testing.
    - Collaborate with multiple nations on the Colloid Formation and Migration and Full-Scale Engineered Barriers Experiment Dismantling projects at the Grimsel underground research laboratory in Switzerland.
    - Collaborate with the Swedish Nuclear Fuel and Waste Management Company (SKB) through the Groundwater Flow and Transport and Engineered Barrier Systems Task Forces.
    - Collaborate through DEvelopment of COupled models and their VALidation against EXperiments (DECOVALEX), an international cooperative research

project on mathematical models of coupled thermal-hydrological-mechanical processing for safety analysis of radioactive waste repositories.

***Salt***

Current activities include:

- Perform thermo-mechanical testing.
- Conduct brine migration studies:
  - Perform experiments at varying temperature and pressure conditions.
  - Develop constitutive models; benchmark models to test data.
- Investigate the potential for direct disposal of electrorefiner salt in a generic salt-based repository, with a focus on transportation criticality, primary container and overpack requirements, and salt / container chemical interactions.
- International collaboration with the German Federal Ministry of Education and Research [BMWi] and Clausthal University of Technology) on topics including safety case development, design of seals and plugs, benchmarking of thermal/hydrological/mechanical models, and possible applications of underground research laboratories.

***Disposal Research Engineered Material Performance Activities***

Current activities include evaluation of the impacts of radiolysis and associated locally oxidizing conditions on the degradation of uranium oxide fuel in reducing environments.

***Generic Disposal Systems Analysis***

Current activities include:

- Develop a source term conceptual model applicable to all generic disposal options.
- Integrate updated conceptual models of subsystem processes and couplings developed under other work packages; leverage existing computational capabilities.
- Develop and simulate reference cases for generic salt, argillite, and crystalline (granitic) disposal systems.
- Review and update the Disposal R&D Roadmap.

***Deep Borehole Disposal Research Activities***

Current activities include:

- Use the regional geology database to support site selection for the deep borehole field test.
- Develop reference designs for borehole disposal of small waste forms.
- Evaluate borehole sealing concepts for chemical, mineralogical and physical stability in the deep borehole environment.

Planned activities include initiation of a field demonstration test to evaluate the feasibility of the deep borehole disposal concept. Specific activities associated with the first year of a deep borehole field demonstration test using surrogate waste will include:

- Establishment of a project management structure.
- Preliminary characterization and evaluation of one or more candidate sites for a field test.
- Selection of a site for a field test, including land acquisition.
- Development of a conceptual design and requirements for borehole construction.
- Development of a conceptual design and requirements for disposal canisters and waste handling.
- Evaluation of regulatory and legal requirements, including obtaining necessary permits.
- Modeling to support site evaluation and test design.

***International Collaborations in Disposal R&D***

The UFD campaign conducts ongoing management activities to ensure the integration and coordination of UFD-supported activities among participating national laboratories and comparable programs outside the US. UFD management identifies international opportunities that complement ongoing campaign R&D and recommends collaborations to DOE that have the greatest potential for substantive technical advances. International collaborations implemented directly within the appropriate technical research areas are a beneficial and cost-effective strategy for advancing disposal science with regards to multiple disposal options and different geologic environments.

## V. CONCLUSIONS

Working under the direction of the DOE Office of Nuclear Energy, the UFDC is conducting a broad range of R&D activities at multiple U.S. National Laboratories to support the safe and secure storage, transportation, and permanent disposal of used nuclear fuel and high-level radioactive wastes derived from the existing and future nuclear fuel cycles. R&D activities focus on both near term goals, such as collaborating with industry to develop data that will support improved understanding of processes relevant to the extended storage of existing UNF, and long-term goals, such as supporting the future implementation of integrated storage, transportation, and disposal systems.

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