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US DOE Scientific-Technical R&D Work to Address Safety Assessments of Spent Nuclear Fuel Storage and Transportation

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ABSTRACT
As spent nuclear fuel (SNF) continues to accumulate in dry storage facilities around the United States, research is being funded by the Department of Energy (DOE) and conducted by the National Laboratories to address the scientific and technical challenges that concern the DOE and stakeholders. A Research and Development (R&D) Gap Analysis was published in 2012 and has been updated as needed to ensure that the challenges are being continually addressed. Specific focus areas include SNF mechanical integrity during extended storage, quantifying external loads on SNF during transportation and handling, and the potential occurrence and consequences of canister corrosion. The mission of this work is to enable integrated storage, transportation, and disposal of SNF and high-level wastes generated by existing and future nuclear fuel cycles. This paper focuses on the assessment of safety related to identified scientific and technical challenges and summarizes current research and conclusions and describes future research.

INTRODUCTION
Nuclear energy contributed 19% of US electrical generation in 2020 (US Energy Information Administration, 2021). The United States has an open fuel cycle, meaning after use in a nuclear reactor, spent fuel is destined for disposal; reprocessing of SNF does not occur. After uranium ore is mined, milled, converted, enriched, and fabricated into uranium oxide fuel pellets, it is then burned in a reactor. The *spent* nuclear fuel (SNF) is removed from the reactor and placed into a SNF pool adjacent to the reactor for storage while cooling. Most of the spent fuel pools in the United States are full, therefore, after approximately three to five years the SNF is sufficiently cooler and is moved from the pool and placed into a dry storage system to make room for additional fuel. Approximately 2200 metric tons of spent fuel are discharged every year from the spent fuel pools and placed into a dry storage system. If a US deep geologic repository is not operating by 2050, the US will have over ~136,000 metric tons of spent nuclear fuel in temporary storage at the nuclear plant sites. For the purposes of this paper, the back end of the nuclear fuel cycle starts when the fuel goes into dry storage.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

To understand the situation of the back end of the nuclear fuel cycle (BENFC) in the United States, it is helpful to understand the regulatory framework. In 1984 the United States Nuclear Regulatory Commission (NRC) issued the Waste Confidence Rule which is codified in 10 CFR 51.23. The purpose of the rule was to generically assess if the NRC had reasonable assurance that radioactive wastes *"can safely be disposed of, to determine when such a disposal or offsite storage will be available, and to determine whether radioactive waste can be safely stored on-site past the expiration of existing facility licenses until offsite disposal or storage is available."* This decision resulted in an Environmental Assessment and a Finding of No Significant Impact (FONSI) and the commission made five findings summarized as:

1. A mined geologic repository is technically feasible.
2. One or more repositories will be available by the year 2007 - 2009.
3. Radioactive waste and spent fuel will be managed in a safe manner until sufficient repository capacity is available.
4. Spent fuel generated in any reactor can be stored safely and without significant environmental impacts for at least 30 years beyond the expiration of that reactor's operating license at that reactor spent fuel storage basin or at either on-site or offsite Independent Spent Fuel Storage Sites (ISFSI), and
5. The commission finds reasonable assurance that safe independent on-site or off-site spent fuel storage will be made available if storage capacity is needed.

However, in 2010, licensing activities for the Yucca Mountain project were suspended and the Waste Confidence Rule was vacated.

In 2014, the NRC issued the Continued Storage Rule (https://www.govinfo.gov/content/pkg/FR-2014-09-19/pdf/2014-22215.pdf) (US Nuclear Regulatory Commission, 2014). This resulted in a generic environmental assessment which stated that radiological impacts would not exceed permissible levels over three time periods after the end of a reactor's license. The NRC assumed that there would be continued institutional control and that the NRC would continue to regulate spent fuel storage to protect public health, safety, and security. The NRC delineated three time periods in the Continued Storage Rule which are summarized as:

1. 60 years after the end of the reactor's license:
    - routine maintenance of pools and dry storage is required.
2. Up to 100 years after the end of the reactor's license:
    - routine maintenance is required
    - a one-time replacement of the ISFSI, spent fuel canisters and cask, is assumed and
    - construction and operation of a dry transfer system at each ISFSI is assumed.
3. The third time period is indefinite and assumes that the replacement activities would occur every 100 years.

As of December 2020, there was approximately 85,000 MTHM (metric tons heavy metal) of commercial SNF in storage in the United States. Approximately 38,000 MTHM is in dry storage at the reactor sites, in over 3300 canister/cask systems. The remainder is stored in the spent fuel pools.

The spent fuel is located at 76 different reactor sites in 35 different states. Some of these nuclear plants have shut down their power generation operations and the only fuel remaining on-site is in dry storage at an ISFSI with appropriate security. A list of shutdown reactors and dates is compiled by the US Energy Information Administration and can be viewed at https://www.eia.gov/nuclear/reactors/shutdown/.

The United States has over two dozen dry storage system designs, each of which contains the spent fuel within a metal enclosure (https://www.nrc.gov/waste/spent-fuel-storage/designs.html). Most are stainless steel canisters stored within a concrete overpack, some are thicker metal casks. Some canisters are stored horizontally while some are stored vertically; some are stored above ground and some below ground. While most SNF is stored in welded canisters, thick metal casks with bolted lids store bare SNF in specifically designed baskets. This diversity adds additional challenges to the management of SNF in the United States. All dry storage designs have one important similarity in that they are all passive cooling systems where the SNF decay heat is dissipated via both conduction and thermal radiation to the inner metal canister wall, where the heat is removed from the canister or cask external surface by conduction and natural convection of air across the outside of the canister. The outside air is never in contact with the SNF and the storage systems do not need any external power to store and cool the fuel. For the purpose of this paper, the terms “cask” and “canister” will be used interchangeably to describe these dry storage systems.

The United States Department of Energy (US DOE), Office of Nuclear Energy funds work at nine national laboratories to execute research and development (R&D) for the Spent Fuel and Waste Science and Technology (SFWST) Campaign. The SFWST Campaign mission is to identify alternatives and conduct scientific research and technology development to enable safe storage, transportation, and disposal of SNF and waste generated by existing and future nuclear fuel cycles. Recently, both the Storage and Transportation R&D program and the Disposal Research R&D program issued plans (Saltzstein et al., 2020; Sassani et al., 2020) that cover the primary objectives of the R&D work for an approximate five year period, depending on US federal government congressional funding levels.

To identify and address issues with SNF storage and transportation, the *Gap Analysis to Support Extended Storage of Used Nuclear Fuel* (Hanson B. , Alsaed, Enos, Meyer, & Sorenson, 2012) has been updated twice to ensure that the challenges of managing SNF indefinitely are identified and addressed (Hanson & Alsaed, Gap Analysis to Support Extended Storage and Transportation of Spent Nuclear Fuel: Five-Year Delta. SFWD-SFWST-2017-00005; PNNL-28711., 2019); (Teague, Saltzstein, Hanson, Sorenson, & Freeze, 2019). Specific R&D focus areas include:

- SNF mechanical integrity during extended storage,
- quantifying the external loads that spent nuclear fuel experiences during handling, storage, and transportation, and
- the potential occurrence and consequences of canister corrosion.

One goal of this work is to enable integrated storage, transportation, and disposal of SNF and waste generated by existing and future of nuclear fuel cycles.

In addition to the gap analysis, the Spent Nuclear Fuel Storage and Transportation R&D strategy identifies more specific testing to provide the data and technical bases to close the gaps identified in the gap analysis (Saltzstein, Hanson, & Freeze, 2020).

The gap reports and strategy document were used to address spent fuel behavior and integrity in light of longer than expected storage durations, higher fuel cycle loadings resulting in higher burnups, and transportation of potentially degraded SNF after extended storage. Potential gaps that were identified through these assessments include validation of spent fuel integrity during extended storage, canister integrity, and integrity of spent fuel during normal conditions of transport (NCT).

The remainder of this paper is a summary of the major projects and conclusions from the S&T R&D work to date.

SPENT NUCLEAR FUEL INTEGRITY

In 2017 the Electric Power Research Institute (EPRI) and the DOE collaborated to load an Orano TN-32B High Burnup Cask (also known as the Research Demonstration Cask) at the North Anna Nuclear Power Plant with thirty-two assemblies of high-burnup SNF. (See Figure 1) The purpose of this continuing project is to investigate the performance of high-burnup SNF (exceeding 45 gigawatt-days per metric ton of uranium) in dry storage and to benchmark thermal analysis codes and modeling to actual thermal data obtained from the demonstration cask. The Research Demonstration Cask was modified for this demonstration test by installing a thermocouple lance in the guide tube in seven of the fuel assemblies. This provides an accurate measurement of peak fuel cladding temperatures in seven different assemblies. Each lance has nine thermocouples positioned axially down the spent fuel assembly. The project started collecting temperature data during the drying process and is still collecting data daily, which is downloaded quarterly. The peak cladding temperature of 237°C was measured during the drying process. This value is well below the peak cladding temperature of 348°C originally estimated by industry in the licensing process ((Electric Power Research Institute), 2019) and significantly below the NRC guidance of 400°C (US Nuclear Regulatory Comission, 2003). The data from this demonstration has facilitated extensive thermal model validation, sensitivity analysis, and revealed many layers of parameter/model conservatisms which result in a large overprediction of peak cladding temperature using standard industry methods. (Fort, Richmond, JM, & Suffield, 2019)

Figure 1; Loaded TN-32 for the High Burnup Demo at North Anna NPP. The solar panel is powering the 63 thermocouples inside the canister. Photo Credit: North Anna NPP

Secondly in 2017, twenty-five fuel rods comprising three different claddings were removed from these or similar spent fuel assemblies at the North Anna Nuclear Power Station. These fuel rods are called "sibling pins" because they have the same design, similar power histories, and other similar characteristics to the fuel rods placed in the Research Demonstration Cask. These sibling pins are being tested per a negotiated test plan (Saltzstein, Billone, Hanson, & Scaglione, 2018) to document their post-irradiated mechanical integrity and these data provide baseline initial characteristics of those fuel rods being stored and monitored in the Research Demonstration Cask. Sibling pin testing is in progress in hot cells and glove boxes at Argonne National Laboratory, Oak Ridge National Laboratory, and Pacific Northwest National Laboratory. (See Figure 2) To date, experimental results have documented the internal rod pressures, gas communication, mechanical integrity of the sibling pins, and has indicated that the fuel rods are stronger and more ductile than predicted. Results also indicate residual water in the canister and work is ongoing to further quantify the residual water, calculate potential hydrogen buildup, and evaluate moisture in the dry storage systems. Work is continuing to quantify the mechanical integrity of the spent fuel rods and the quantities of particulates and respirable fractions released during fuel breakage. (Billone, TA, Chen, & Han, 2020) (Montgomery, 2020) (Hanson, et al., 2021). Additional hot cell testing at elevated temperatures is planned to obtain data for cladding that may experience higher drying temperatures that may cause radial hydride formation in the cladding.

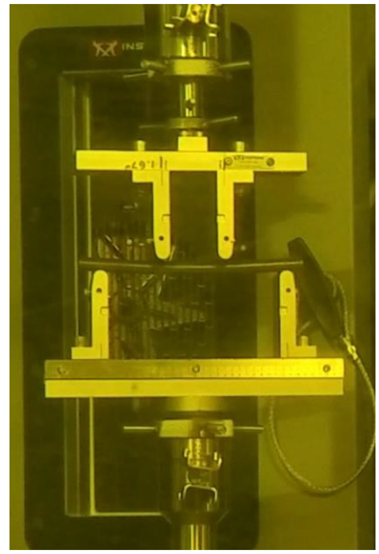

Figure 2: The load frame configured for a 4-point bend test of a sibling pin in a hot cell.

Research results to date suggest that dry cask storage systems have significantly lower heat loads than estimated in licensing calculations. These conditions have implications for expected cladding mechanical integrity, the timeline to de-inventory pools and to transport, initiation times for canister corrosion, and potentially the repository footprint needed for thermal management.

QUANTIFICATION OF EXTERNAL LOADS ON THE FUEL

Thirdly in 2017, DOE, Sandia National Laboratories, Pacific Northwest National Laboratory, Argonne National Laboratory, Equipos Nucleares Sociedad Anón (ENSA) from Spain, the Korean Nuclear Fuel Company (KEPCO), the Korea Atomic Energy Research Institute (KAERI), and Korea Nuclear Fuel (KNF), collaboratively performed a multi-modal transportation test using surrogate SNF. The purpose of this test was to quantify the strains and accelerations that the surrogate fuel experiences during NCT by heavy-haul truck, barge, ocean-going ship, and rail. (McConnell, 2017) A six-minute video summary of this test can be viewed at https://www.youtube.com/watch?v=wGKtgrozrGM. This

Figure 3: Surrogate assembly in basket before 30-cm drop onto unyielding target.

data is used to develop and validate models that can be used to extrapolate this experience to other transportation systems. During this test, strain gauges and accelerometers were placed directly on the surrogate fuel rods, the assembly hardware, the basket, the cask, the cradle, and the transportation platform. Analysis of the test concluded that, *"…no further analysis is necessary to demonstrate that SNF cladding will remain intact during shock and vibration loading conditions that occur during normal conditions of transportation (NCT)…"* and that *"…it is reasonable to conclude that the fatigue damage is approximately zero."* (Klymyshyn, et al., 2019) (Kalinina, 2018). The fuel integrity during the 30 cm drop, which falls under NCT (a routine handling incident), was investigated in the 30 cm drop test of the surrogate fuel assembly. (See Figure 3) The major conclusion that can be drawn from the 30cm drop test is that the fuel rods will maintain their integrity after being dropped 30 cm or less. (E. Kalinina, 2021). Note that 10 CFR 71.71 defines the appropriate package testing to demonstrate acceptable package performance under NCT conditions.

Further testing will focus on the effects of different seismic conditions on the integrity of the fuel.

CANISTER CORROSION

Because many of the 3000+ spent fuel canisters currently storing SNF around the United States are made of a material that is susceptible to corrosion, such as 304 or 316 stainless steel, the US DOE is evaluating the conditions and corrosion behavior of these materials. The DOE has documented through-wall tensile stress at the weld and heat affected zones of these canisters. In addition, canisters have a passive cooling design which allows dust and salts to deposit onto the surface of the stainless-steel canister. The DOE, EPRI, and the national laboratories are collaborating to understand the composition of the dust and brines deposited on the surface of the canister and how that dust and brine evolves over time to influence corrosion risk. Additional work is focused on understanding what factors inhibit or accelerate the corrosion process of stainless-steel canisters under realistic temperature, humidity, and salt loading conditions. This information is being used to identify technologies to mitigate or repair damage if corrosion is found.

Models are being developed, parameterized, and validated to help predict the timing, progression, and occurrence of canister corrosion. (See Figure 4) This work involves understanding what influences the incubation time before corrosion starts. Data are being collected to reduce model uncertainties regarding salt compositions, canister surface temperatures, relative humidity, and airflow. Once conditions supporting corrosion are achieved, corrosion pits begin to form in the metal. Experimental data reveals that pit size and shape is controlled by the temperature, humidity, surface roughness, salt load, and the stress field. (Schaller, 2020). Pits may eventually either stop growing (stifle), or if sufficient stresses are present, initiate a stress corrosion crack. Work evaluating canister corrosion consists of geochemical modeling and laboratory experiments to understand the environment on the surface of the canisters and the timing of corrosion, experimental evaluation of pit growth and pit sizes as a function of environmental parameters, pit-to-crack transition phenomena, and laboratory empirical measurements of stress corrosion cracking crack growth rates in different temperature, humidity, and salt environments. (MB Toloczko, 2020)

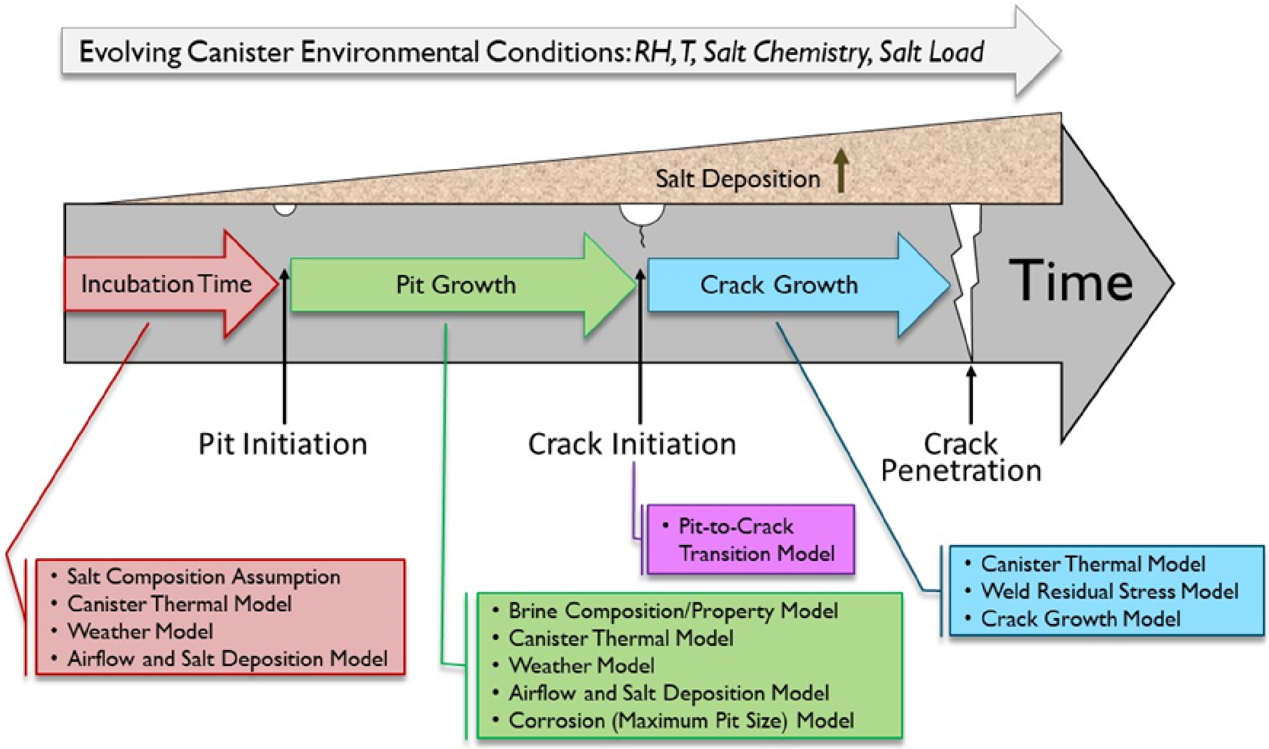

Figure 4: Probabilistic Stress Corrosion Cracking Model. Data is being generated at SNL, PNNL, SRNL, and numerous universities to populate and validate this model.

In addition to understanding the basic science behind atmospheric chloride-induced stress corrosion cracking, the program is also investigating different canister coatings that could prevent and/or remediate stress corrosion cracking. These coatings must withstand high temperatures and high radiation levels for many decades. Ideally, they should be able to be applied in a small annulus between the canister and the concrete storage overpack on a dusty surface and last decades. The current work involves investigating different coating classes and ascertaining their effectiveness for preventing long-term degradation, and for use as *in-situ* or *ex-situ* repair methods. (Knight, 2020)

DRY STORAGE CANISTER CRACK CONSEQUENCE

One area of synergy for all the work involving the mechanical properties of high burnup SNF, external loads, and stress corrosion cracking is the investigation of the consequence of a through-wall crack in a dry storage canister. Work is progressing to quantify the amount and size of spent fuel particles released from a failed fuel rod inside a dry storage canister and then released through a potential canister stress corrosion crack. Understanding the quantity and size of radioactive particles released from a canister-wall crack will help constrain the potential consequence and risk associated with a potential crack in a canister containing failed fuel. (Durbin, Lindgren, & Perales, 2020)

In addition to the research to look at current canister and fuel designs, the program is also looking into Accident Tolerant Fuels and advanced reactor designs that are in the development stage.

DIRECT DISPOSAL

The majority of the 3300 canister/cask systems currently in dry storage, and those projected for future dry storage, are dual-purpose canisters (DPCs) which are designed for storage and transportation but not for disposal. As spent nuclear fuel continues to accumulate in these DPCs, it is important to evaluate whether they can be directly disposed safely in a repository. As compared to repackaging the SNF for disposal, the direct disposal of SNF in DPCs has the potential to simplify disposal operations, minimize the number of transportation shipments, reduce occupational worker radiation dose, reduce waste quantities, and decrease the overall costs associated with geologic disposal.

DPCs tend to be large, heavy, and have a high thermal and radiological output. The possibility of direct disposal of SNF in DPCs includes options with or without modification to the DPCs. Studies of technical feasibility have focused on four aspects (Hardin, 2015):

1. operational and postclosure radiological safety,
2. engineering feasibility (e.g., handling and emplacement),
3. thermal management, and
4. postclosure criticality control.

Challenges associated with the first three aspects can be accomplished using currently available technologies and modeling approaches. R&D investigating approaches for postclosure criticality control is ongoing (Sandia National Laboratories, 2020) (Sandia National Laboratories, 2021).

SAFEGUARDS

The technical program described is focused on LWR reactor technology that is experiencing incremental changes in operational efficiencies and in defining the environmental conditions SNF is subjected to over extended periods of dry storage. Safeguarding of this material is licensed by the NRC under its current regulations, primarily 10CFR73. (US Code of Federal Regulations,).

The Department of Energy Office of Advanced Reactor Technologies (NE-4) is sponsoring programs to develop advanced reactors and fuel cycles (US Department of Energy, 2021). This work will necessarily involve an assessment of safeguards efficacy under current regulations. For example, several of the proposed advanced fuels will include HALEU (High Assay Low Enriched Uranium) as the source material for the nuclear fuel. This fuel can be enriched up to 20%. The manner in which this material is processed and fabricated into fresh fuel on the front end, and how it is managed on the backend will need to be carefully considered from a safeguards perspective.

The SFWST program is in communication with NE-4 and will collaborate when appropriate as technical issues develop. Since the NE-4 program has a longer R&D time horizon than the SFWST program, priorities for SFWST will remain focused on the LWR issues identified in the gap report.

CONCLUSIONS

Due to the suspension of licensing activities for the Yucca Mountain project, the United States' expanding inventory of SNF is being stored at numerous locations throughout the country for longer than the original design specifications of the spent nuclear fuel dry storage systems. Given the shift to longer storage periods, the DOE is working to identify potential gaps in understanding related to the longer storage duration and to develop solutions to mitigate/close those gaps. This work focuses on the mechanical integrity of the fuel, the thermal and chemical environment in which it resides, the external loads to which the fuel and storage and transportation system will be subjected, and the potential for stress corrosion cracking of the storage and transportation canisters. When necessary, mitigation technologies are being developed to ensure the fuel is stored and transported safely until a deep geologic repository is opened to permanently dispose of this fuel.

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This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

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