

SFWST Disposal Research R&D 5-Year Plan

Spent Fuel and Waste Disposition

***Prepared for
U.S. Department of Energy
Spent Fuel and Waste Science and
Technology***

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APPENDIX E
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SUMMARY

In the planning for FY2020 in the U.S. DOE NE-81 Spent Fuel and Waste Science and Technology (SFWST) Campaign, the DOE requested development of a plan for activities in the Disposal Research (DR) Research and Development (R&D) over a five (5)-year period. This report provides this plan for the SFWST Campaign DR R&D activities as a strategic guide to the work within the DR R&D technical areas (i.e., the control accounts), focusing on the highest priority technical thrusts. This 5-year plan will be a living document and is planned to be updated annually to provide for changes based on both SFWST Campaign objectives and funding levels (i.e., Program Direction). The annual update to this 5-year plan will address the DR R&D that has been completed, the additional knowledge gaps remaining, updates to the DR R&D priorities, and shifts in resources for the next stages of activities.

This document is structured with three main sections. Section 1 contains the background on evaluation and prioritization of the SFWST DR R&D technical work with a review of both the original Roadmap Report (2012) and the Reassessment of the Roadmap (Sevougian et al., 2019). In Section 2, the summary plan for R&D technical activities is provided for each of the SFWST DR R&D technical areas (note these correspond to the work breakdown structure control accounts for the DR R&D program for DOE NE-81). For each DR R&D technical area, the major technical thrust topics slated for the next five years are presented with discussions of the current/planned activities supporting those thrust topics. Those 5-year plans outline the general schedules for the thrust topics of each DR R&D technical area and provide the expected technical emphasis in two parts: the near-term (i.e., the more certain 1- to 2-year timeframe) and the longer term (less certain 3- to 5-year timeframe). The near-term emphasis can be viewed as a representation of the present DR R&D portfolio with modest modifications that reflect emerging priorities and funding levels. In contrast, the 3- to 5-year period represents a longer-term vision of where the SFWST Campaign DR R&D is heading provided there is no major change to the Program Direction. Section 3 provides an overview of high-level technical focus areas to cover the planned overarching priorities of the SFWST DR R&D work at a more strategic level for the next five (5) years. Some of those focus areas continue from prior R&D, whereas others have just started, and others have subparts that are yet to be initiated. This plan fulfills the Milestone M2SF-20SN010304045 in DR Work Package (WP) SF-20SN01030404 (GDSA - Framework Development – SNL).

The previous Used Fuel Disposition (UFD; from FY2011-FY2017) Campaign and the current SFWST Campaign disposal R&D programs have focused on the evaluation of the viability of mined repositories in three generic geologic media (salt, clay, and crystalline rock; e.g., Sevougian et al., 2019). The host lithologies were selected because they have been considered and analyzed as potential repository host rocks both in the U.S. and internationally for several decades (e.g., Faybishenko et al., 2016). The generic host rock types were identified at a broad level: salt includes both bedded and domal salt; clay was defined to include a broad range of fine-grained sedimentary rock types including shales, argillites, claystones, as well as soft clays; and crystalline rock may include a range of lithologies such as metamorphic gneisses, granite, and other igneous rock types. Recently generic unsaturated system mined repository concepts are also being analyzed, especially regarding their capabilities to effectively release heat via ventilation in open emplacement tunnels.

The above range of generic disposal systems evaluated thus far is not intended to represent a complete/comprehensive list of possible alternatives, and other options may also have the potential to provide safe long-term isolation. However, DOE and UFD/SFWST managers believe that R&D related to the evaluation of the selected generic media will be applicable to nearly any future program that relies on deep geologic disposal. The fundamental disposal R&D on these various generic geologic host rock systems will continue to be the cornerstone of the SFWST Disposal R&D program to support geologic repository disposal solutions in the U.S.

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The detailed portion of this five-year plan is given in Section 2 and provides an assessment for each of the DR R&D technical areas (TA) below. The ten TA covered below are:

- Argillite Disposal R&D
- Crystalline Disposal R&D
- Salt Disposal R&D
- Geologic Disposal Safety Assessment
- Direct Disposal of Dual-Purpose Canisters
- International Collaboration in Disposal Research
- Engineered Barrier System (EBS) R&D
- Online Waste Library (OWL) – Inventory and Waste Characterization
- Technical Support for Underground Research Laboratory Activities
- Knowledge Management

In this assessment, the plan for each DR R&D TA includes sections that:

- a. identify the primary thrust topics (these are the major technical priorities in each TA: ~2 to 4)
 - i. for the near-term (next 1- to 2-year period – i.e., our current DR R&D program)
 - ii. for the longer term 3- to 5-year period (i.e., where the DR R&D may go in the future if Program Direction remains the same)
- b. describe the activities in the TA that are addressing each of the thrust topics listed both for the program currently (i.e., near-term), and how that may change going forward to the longer-term. There is generally more detail available for the near-term, with the longer-term thrusts being discussed in comparison/contrast to the near-term thrusts.

In the next five years, the DR R&D will continue to focus on process model development and model implementation in GDSA Framework for different generic reference cases. At the end of the five years, it is anticipated that GDSA Framework and the reference cases will contain even more detailed representations of relevant improved process models, or surrogate models, and thus can be used for more diverse demonstrations of safety assessments, sensitivity analyses, and additional programmatic prioritization of targeted DR R&D activities in an even more robust manner than currently.

Beyond the core efforts to evaluate generic geologic systems for disposal behavior and constrain their key generic natural barrier capabilities with systematic integration of process-level understanding with system evolution of natural and engineered barriers, the SFWST Campaign DR R&D activities will maintain a further focus in the next five years on the following four areas: GDSA Capabilities Development and Demonstration; International Collaboration and Underground Research Laboratories; Engineered Barrier System Representations; and Evaluation of Potential Direct Disposal of Dual Purpose Canisters.

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ACRONYMS

BATS	Brine Test in Salt
BWR	Boiling Water Reactor
CI-D	Cement-Clay Interaction Test
DECOVALEX	DEvelopment of COupled models and their VALidation against Experiments
DHLW	DOE-managed High-Level Waste
DOE	Department of Energy
DOE EM	(DOE) Environmental Management
DOE NE	(DOE) Nuclear Energy
DPC	Dual Purpose Canister
DR	Disposal Research
DR-C	Diffusion in a Thermal Gradient Experiment
DSNF	DOE-managed Spent Nuclear Fuel
EBS	Engineered Barrier System
EBS-TF	Engineered Barrier System – Task Force
EDZ	Excavation Disturbed Zone
EM	(DOE) Environmental Management
FE	Full-scale Emplacement Experiment
FEBEX-DP	Full-scale Engineered Barrier EXperiment – Dismantling Project
FEP	Features, Events, or Processes
FY	Fiscal Year
GAST	Gas Permeable Seal Test
GDSA	Geologic Disposal Safety Assessment
GRS	Gesellschaft fuer Reaktorsicherheit
GT	Gas Transport Experiment
HLW	High-Level Waste
HOTBENT	High Temperature Effects (HOT) on BENTonite Buffers
HPC	High Performance Computing
IAEC	Israel Atomic Energy Commission
ISC	Important to the Safety Case
IWM	Integrated Waste Management
KM	Knowledge Management
LANL	Los Alamos National Laboratories

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LBNL	Lawrence Berkeley National Laboratories
LDT	Long-Term Diffusion Test
NE	(DOE) Nuclear Energy
N-TH	Neutronic-Thermal Hydraulic
NWTRB	Nuclear Waste Technical Review Board
OECD-NEA	Organisation for Economic Co-operation and Development - Nuclear Energy Agency
OWL	Online Waste Laboratory
PA	Performance Assessment
PFLOTRAN	Parallel FLOW and TRANsport
PWR	Pressurized Water Reactor
R&D	Research and Development
S&T	Storage and Transportation
SA	Sensitivity Analysis
SAL	State-of-the-art Level
SET	Bore Sealing Test
SFWST	Spent Fuel and Waste Science and Technology
SKB	Swedish Nuclear Fuel and Waste Management Co
SNF	Spent Nuclear Fuel
SNL	Sandia National Laboratories
SW-A	Large-scale Sandwich Experiment
TA	Technical Area
TCMH	Thermal-Chemical-Mechanical-Hydrologic
TDB	Thermodynamic Database
THM	Thermal-Hydrologic-Mechanical
THMC	Thermal-Chemical-Mechanical-Hydrologic
UFD	Used Fuel Disposition
UFDC	Used Fuel Disposition Campaign
UK	United Kingdom
URL	Underground Research Laboratory(ies)
US	United States
UQ	Uncertainty Quantification
WIPP	Waste Isolation Pilot Plant
WP	Work Package

SPENT FUEL AND WASTE DISPOSITION/SPENT FUEL AND WASTE SCIENCE AND TECHNOLOGY

1. INTRODUCTION

This five (5)-year plan for the Spent Fuel and Waste Science and Technology (SFWST) Campaign Disposal Research (DR) Research and Development (R&D) activities provides a strategic guide to the work within the DR R&D technical areas, focusing on the highest priority technical thrusts. This 5-year plan will be a living document and will be updated annually to provide for changes based on both SFWST Campaign objectives and funding levels (i.e., Program Direction). The annual update to this 5-year plan will address the DR R&D work that has been completed, the additional knowledge gaps remaining, updates to the DR R&D priorities, and shifts in resources for the next stages of activities. For each of the DR R&D technical areas, a review of the accomplishments completed during the previous year and the remaining gaps will be added to inform the updated priorities, technical thrusts, and major shifts in resource allocation for the updated 5-year plan discussions.

This document is structured with three main sections. Section 1 contains the background on evaluation and prioritization of the SFWST DR R&D technical work with a review of both the original Roadmap Report (2012) and the Reassessment of the Roadmap (Sevougian et al., 2019). In Section 2, the summary plan for R&D technical activities is provided for each of the SFWST DR R&D technical areas (note these correspond to the work breakdown structure control accounts for the DR R&D program for DOE NE-81). For each DR R&D technical area, the major technical thrust topics slated for the next five years are presented with discussions of the current/planned activities supporting those thrust topics. Those 5-year plans outline the general schedules for the thrust topics of each DR R&D technical area and provide the expected technical emphasis in two parts: the near-term (i.e., the more certain 1- to 2-year timeframe) and the longer term (less certain 3- to 5-year timeframe). The near-term emphasis can be viewed as a representation of the present DR R&D portfolio with modest modifications that reflect emerging priorities and funding levels. In contrast, the 3- to 5-year period represents a longer-term vision of where the SFWST Campaign DR R&D is heading provided there is no major change to the Program Direction. Section 3 provides an overview of high-level technical focus areas to cover the planned overarching priorities of the SFWST DR R&D work at a more strategic level for the next five (5) years. Some of those focus areas continue from prior R&D, whereas others have just started, and others have subparts that are yet to be initiated. This plan fulfills the Milestone M2SF-20SN010304045 in DR Work Package (WP) SF-20SN01030404 (GDSA - Framework Development – SNL).

1.1 Background

The Spent Fuel and Waste Science and Technology (SFWST) Campaign of the U.S. Department of Energy (DOE) Office of Nuclear Energy (NE), Office of Spent Fuel and Waste Disposition (SFWD) is conducting research and development (R&D) on deep geologic disposal of spent nuclear fuel (SNF) and high-level nuclear waste (HLW). The R&D addressing the disposal of SNF/HLW in the U.S. is currently generic (i.e., “non-site-specific”) in scope, following the suspension of the Yucca Mountain Repository Project in 2010. However, to prepare for the eventuality of a repository siting process, the former Used Fuel Disposition Campaign (UFDC) of DOE-NE (which was succeeded by the SFWST Campaign) formulated an R&D Roadmap (DOE 2012) outlining generic R&D activities and their priorities appropriate for developing a sound technical basis for multiple deep geologic disposal options in the U.S., increasing confidence in the robustness of generic disposal concepts, and developing the tools needed to support disposal concept implementation. Note that those priorities were established, in part, by how important the R&D would be for a potential (i.e., future) safety case developed for a future site. That 2012

UFDC Roadmap also identified the importance of re-evaluating priorities in future years as knowledge is gained from the DOE's ongoing R&D activities.

Since 2012, significant knowledge has been gained from these activities through R&D in the U.S. and via international collaborations, especially with countries that operate underground research laboratories (URLs). In 2019 an R&D Roadmap Update (Sevougian et al., 2019) was conducted to summarize the progress of ongoing generic disposal R&D activities relative to the Roadmap priorities, to identify gaps in the Campaign R&D, and to re-assesses R&D priorities and identify new activities of high priority, such as R&D on disposal of DPC (dual purpose canisters), which now contain a significant fraction of the Nation's commercial SNF activity.

As described in the 2012 UFDC Roadmap (DOE 2012), the UFDC defined and utilized a systematic, decision-analysis-based approach to develop and prioritize the R&D portfolio. The approach involved several steps, including the identification of potential "R&D issues" (information needs and knowledge gaps) and the prioritization of these R&D issues based on evaluation metrics (primarily their importance to a future post-closure safety case and the state of knowledge regarding the issue). Each identified R&D issue was derived from (actually, equated to) a FEP (Feature, Event, or Process) from the generic list of 208 FEPs considered as important to repository performance. A suite of 354 such R&D Issues was identified, which is greater than the original list of 208 FEPs, because each FEP may have a different importance to a potential safety case or a different state-of-the-art knowledge level depending on which of the three generic, host-rock concepts (argillite, crystalline, or salt) was being evaluated. Evaluation of the subsequent prioritization rankings of the 354 R&D Issues pinpointed an important set of broader cross-cutting R&D categories and a series of groupings of natural barrier system issues and engineered barrier system issues that were helpful for defining the future R&D program.

In the process of evaluating the R&D issues summarized in Appendix A of DOE (2012), UFDC scientists and engineers also identified several cross-cutting issues and R&D opportunities that do not correspond directly to individual issues in the UFDC Disposal R&D Roadmap Prioritization Information Matrix. However, they either cut across or integrate with several of the specific R&D issues and have therefore been defined as, and been considered part of, the UFDC R&D portfolio. These prioritized cross-cutting issues defined in the UFD Campaign Roadmap (DOE 2012) were used as the framework to develop the set of R&D activities within the UFD Campaign. The cross-cutting issues with their 2012 UFD Campaign Roadmap priorities are:

- HIGH: Design Concept Development
- HIGH: Disposal System Modeling
- LOW: Operations-Related Research and Technology Development
- MEDIUM: Knowledge Management
- MEDIUM: Site Screening and Selection Tools
- MEDIUM: Experimental and Analytical Techniques for Site Characterization
- MEDIUM: Underground Research Laboratories
- MEDIUM: R&D Capabilities Evaluation

The original 2012 UFDC Roadmap promised a re-evaluation of priorities in future years as knowledge was gained from ongoing activities in the U.S. and abroad (DOE 2012, Sec. 2.4). A full re-assessment of R&D priorities was initiated during fiscal year 2018. Sassani (2018) provided a high-level assessment of how well the R&D Campaign had addressed the cross-cutting issues priorities that the Roadmap summarized to drive the planning of the UFD/SFWST Campaign R&D activities at the SFW Annual Meeting. The full re-assessment culminated in a workshop of Campaign experts in early 2019, held at the University of Nevada in Las Vegas from January 15 to 17. In addition, a new document archive was

developed to organize and store the various reports generated by the disposal R&D work packages over the course of the UFD and SFWST Campaigns (Sevougian et al., 2019).

Though Sassani (2018) indicated the UFD/SFWST Campaign had made appropriate (relative to the priority assigned) progress in a number of the cross-cutting issues such as the high priority issues of *Design Concept Development* and *Disposal System Modeling*, it was also noted that the Campaign R&D progress seemed to fall short in the medium priority issues of *Knowledge Management* and *Experimental and Analytical Techniques for Site Characterization*. Additionally, further gaps were identified in the high priority FEP for waste package degradation and engineered barriers chemistry coupled processes, as well as for some additional medium priority FEP such as cladding degradation (Sassani, 2018; see highlights in backup materials). Those topical areas generally rely on more specific environmental conditions, so it was not surprising to see developmental lag in the generic R&D program for those.

1.2 Roadmap Reassessment Purpose and Results

The full re-assessment workshop results and analyses in Sevougian et al. (2019; Roadmap Reassessment) provide both a more extensive evaluation of the full range of R&D activities within the SFWST Campaign and a robust basis for planning the direction of the future Campaign work. The Roadmap reassessment captured the gaps noted here, as well as other gaps, many of which are related to the recently started evaluation of direct disposal of spent fuel stored in dual-purpose canisters related to the specific thermal and inventory characteristics of those DPC. The Roadmap Reassessment is summarized below with an overview of the results.

The objectives of the 2019 R&D Roadmap Update (Sevougian et al., 2019) included the following:

- 1) Recap the original 2012 Roadmap results and conclusions
- 2) Document the 2019 Roadmap Update Workshop approach, process, and evaluations
- 3) Summarize the status, progress, and priority of 2019 SFWST R&D Activities and their relation to the FEPs important to various host rocks and repository designs
- 4) Identify the generic R&D still needed to advance the state-of-the-art for important R&D Activities and associated FEPs
- 5) Identify important FEPs that have not been addressed adequately by Campaign R&D Activities (i.e., identify gaps)
- 6) Present a new document archive for UFD and SFWST milestone reports

Objectives 3 and 4 are primarily addressed in a series of appendices in Sevougian et al., (2019) that capture the wealth of consensus information compiled by SFWST Campaign experts during the three-day Roadmap Update Workshop. Regarding Objective 5, the update exercise identified a number of “gap” activities that represent future R&D necessary to adequately advance the state of the art of several high- and medium-priority FEPs. These gaps tended to be focused in the areas related to the engineered barriers, for example cladding and waste package degradation, as these investigations are more challenging for generic systems studies due to higher reliance on the details of chemical conditions in the system. Note that the details of the 2019 Roadmap systematic reevaluation process (summarized in Appendix A) were similar in many ways to that used in the 2012 Roadmap (DOE 2012), but with differences related to the progress that has been made within the Campaign.

In Sassani (2018) it was found that two high-priority areas that were not covered well included waste package degradation and cladding degradation investigations. It was also found in the full set of Gap activities identified in the full reassessment workshop that more work on these two specific R&D topics was a priority for crystalline, DPC activities, and EBS activities. The Roadmap reassessment identified other gaps in various areas (see summary in Appendix A; and Sevougian et al., 2019 Appendix I) covering flow and transport in natural systems, thermally coupled processes in the engineered barrier

system, re-wetting/re-saturation processes, DPC system modeling and criticality processes, coupled chemical systems and waste form degradation, and gas migration. Additionally, the need was identified for more active integration within the DR R&D areas, especially among the host-rock based process models and the GDSA models (for the generic geologic repository Reference Cases) with emphasis on the method for models being integrated into the GDSA Framework. Other integration needs include developing more connections with the SFWST Campaign Storage and Transportation R&D, and the need for further integration with other DOE-NE campaigns that provide data/models for waste form degradation. These considerations helped to define overarching areas of R&D focus (Section 3).

Similar to the cross-cutting issues defined in the UFDC Roadmap (DOE, 2012), the current SFWST Campaign DR R&D program will move forward with its own areas of focused R&D for the next five-year planning period. Some of these focus areas are the same as defined as in the UFD Roadmap (DOE 2012), for example the geologic disposal system assessment (GDSA) capabilities development and demonstration, which underpins quantitative analysis of the post-closure safety of generic repository systems. Other focus areas are derived based on new program direction for specific R&D (e.g., evaluation of direct disposal of DPC). These areas of R&D focus are strategic points for integration/synthesis of the R&D being executed across the DR R&D program. For example, the generic geologic systems being studied remain a core effort, though it is expected that the specific R&D thrust topics (discussed in Section 2 below) in each generic geologic system would likely evolve over time.

Beyond the core efforts to evaluate generic geologic systems for disposal behavior and constrain their key generic natural barrier capabilities with systematic integration of process-level understanding with system evolution of natural and engineered barriers, the SFWST Campaign DR R&D activities will maintain a further focus in the next five years on the following four areas: GDSA Capabilities Development and Demonstration; International Collaboration and Underground Research Laboratories; Engineered Barrier System Representations; and Evaluation of Potential Direct Disposal of Dual Purpose Canisters. These areas of technical focus were defined based on both the Roadmap Reassessment results (Sevougian et al., 2019), discussions among the DR technical managers and the National Technical Director, and input from the DOE NE leads. These four areas are discussed further in Section 3.

2. PLANS WITHIN THE SFWST CAMPAIGN DISPOSAL RESEARCH R&D TECHNICAL AREAS

The detailed portion of this five-year plan is given below and provides an assessment for each of the DR R&D technical areas below. The ten technical areas (TA) covered below are:

- Argillite Disposal R&D
- Crystalline Disposal R&D
- Salt Disposal R&D
- Geologic Disposal Safety Assessment
- Direct Disposal of Dual-Purpose Canisters
- International Collaboration in Disposal Research
- Engineered Barrier System (EBS) R&D
- Online Waste Library (OWL) – Inventory and Waste Characterization
- Technical Support for Underground Research Laboratory Activities
- Knowledge Management

In this assessment, the plan for each DR R&D TA includes sections that:

- a. identify the primary thrust topics (these are the major technical priorities in each TA: ~2 to 4)
 - i. for the near-term (next 1- to 2-year period – i.e., our current DR R&D program)
 - ii. for the longer term 3- to 5-year period (i.e., where the DR R&D may go in the future if Program Direction remains the same)
- b. describe the activities in the TA that are addressing each of the thrust topics listed both for the program currently (i.e., near-term), and how that may change going forward to the longer-term. There is generally more detail available for the near-term, with the longer-term thrusts being discussed in comparison/contrast to the near-term thrusts.

The ten technical areas addressed below cover virtually all the technical work being done within the SFWST Campaign DR R&D program. However, in a few cases, some technical R&D work has been executed within the management and integration area for the SFWST Campaign, either as single events requested by Program Direction, or as multi-year projects that span the entire technical arena. One very good example of this latter type is the development of the *Knowledge Management* repository (see Section 2.10) that started as a mechanism to capture tacit knowledge of senior experts within the program of Disposal Research, including those involved with licensing/certification processes from previous repository programs. This work is ongoing, is becoming more desired across the SFWST Campaign (as well as in other technical venues), and will likely grow further in the coming years, especially to expand to the S&T R&D program. In the sections below for the DR R&D TA, the details of the plans for some are longer because the TA contains more R&D activities to cover in that plan (e.g., GDSA, DPC, International) and some are shorter (e.g., the online waste library) because of the more limited scope. The annual update to this 5-year plan will address the DR R&D work that has been completed, the additional knowledge gaps remaining, updates to the DR R&D priorities, and shifts in resources for the next stages of activities. For each of the DR R&D technical areas, a review of the accomplishments completed during the previous year and the remaining gaps will be added to inform the updated priorities, technical thrusts, and major shifts in resource allocation for the updated 5-year plan discussions.

In the next five years, the DR R&D will continue to focus on process model development and model implementation in GDSA Framework for different generic reference cases. At the end of the five years, it is anticipated that GDSA Framework and the reference cases will contain even more detailed representations of relevant improved process models, or surrogate models, and thus can be used for more diverse demonstrations of safety assessments, sensitivity analyses, and additional programmatic

prioritization of targeted DR R&D activities in an even more robust manner than currently. (Note that the DR R&D TA covered here correspond to the control accounts within the work breakdown structure in the DOE PICS:NE management system, which contains details of the planned R&D activities.)

2.1 Argillite Disposal R&D

Integration across disposal R&D activities is important for the argillite scope of work because all argillite activities are related to engineered barrier system activities and most depend on data from international URL activities.

Near-Term Thrust Topics (Next 1- to 2-year period)

- a) Elucidation of the coupled thermal, hydrologic, mechanical, and chemical (THMC) processes affecting repository performance and
- b) Development of multi-fidelity approaches for integration of process models into the GDSA Framework

These thrust topics are current focus areas, which are planned to continue out over the next five years as well. Continuing work includes expanding the applicability of coupled process models to elevated temperatures and integration of DPC-relevant information related to thermal management. These models include calculations of the permeability and porosity evolution of the EBS in clay formations using continuum approaches. Other work includes support of in-package chemistry model development that incorporates first principles atomic (density functional theory – DFT) simulation work on U-bearing solids for retrieval of thermodynamic data at elevated temperatures. Also, the development of electrochemical modeling tools for UO_2 corrosion is included.

Simplifying the representations of THMC processes occurring from within the EBS out into the argillite host rock is also a longer-term thrust with the goal to get these representations to include only the most essential variables for ease of implementation in the GDSA models. In the shorter term, one option is to develop response surfaces for key parameters (e.g., for permeability, porosity, cation exchange capacity, swelling stress) as a function of other system variables such as temperature. Longer-term thrusts include the development of reduced order/simplified model outputs for the complex argillite process models.

Longer-Term Thrust Topics (Next 3- to 5-year period)

- a. Simplifying the representations of THMC processes occurring from within the EBS
- b. International collaborations with inputs on field testing and process understanding

Partnerships with current international programs will be nurtured and expanded in the coming years to create a collaboration bridge gaining advanced knowledge of nuclear waste disposal research from URL activities worldwide. Emphasis will be given to THM and HM modeling activities for heater test experiments at international URL's and other relevant activities (e.g., DECOVALEX- DEvelopment of COupled models and their VALidation against Experiments). Specific examples of these are the heater tests at the Honorobe URL site in Japan and HotBENT at the Grimsel test site in Switzerland. The Grimsel site has provided a large suite of barrier material samples (bentonite, cement, rock) for characterization and experimental studies of fluid-bentonite interactions. These activities will continue during the next five years. Additional international collaborations include continued modeling of heater test experiments at Mont Terri. Participation in the OECD-NEA thermodynamic database (TDB) project, particularly in the review of the ancillary thermodynamic data volume, is planned to take place as soon as within the next two years. Taken collectively, these international collaborations are intended to provide access to the necessary data needed to develop, test, calibrate, and validate coupled process models. Such data sets will allow for detailed assessment of process models to identify the key THMC variables that are the major ones and those that may not need to be explicitly included in EBS THMC models for GDSA.

2.2 Crystalline Disposal R&D

The crystalline R&D thrust area has a significant focus on opportunities to improve process understanding and process model representations of the processes of most import to repository performance. Buffer erosion is a good example of an instance in which a new mechanistic representation can be developed, building on work that has already been done in Europe. Hydrologic properties of the EDZ represent another opportunity for improved representation. Overall, modeling a repository in crystalline rocks involves more issues with high reliance on the engineered barrier system performance than other generic host-rock types because understanding the fracture transport in crystalline systems may be key to performance where the EBS has failed.

Near-Term Thrust Topics (Next 1- to 2-year period)

- a) Flow and transport in fractures, including matrix diffusion
- b) Improved representation of coupled THM processes affecting fracture transmissivity

A primary thrust is advanced capability development for generating discrete fracture networks (Hyman et al. 2015) in high performance-computing systems for use in the GDSA Framework. In the near-term, model capability development will support assessment of coupled THM processes affecting fracture transmissivity and use multi-fidelity approaches to evaluate the uncertainty introduced by the stochastic nature of fracture networks. This area will continue to focus on model capability demonstrations using actual field data obtained from international collaborations. Systematic investigations of the potential effects of fracture geometry and distribution on fracture connectivity and field-scale permeability will continue. Such work may feed long-term studies delineating site characterization and siting characteristics.

Longer-Term Thrust Topics (Next 3- to 5-year period)

- a. Performance of candidate buffer materials under a range of disposal conditions

The interaction between the crystalline host rock and the EBS has been an important research thrust in the crystalline area and will continue to be because of fast transport in the natural fracture systems. Engineered buffer materials in the EBS are an important component for waste isolation in a crystalline repository. This area is pursuing development of a new generation of buffer materials that can be tailored to disposal environments for effective waste isolation. This effort includes molecular modeling and experiments to constrain and parameterize radionuclide interactions with newly developed buffer materials or corrosion products of EBS components. The goal of this modeling effort is the development of a continuum model used to simulate fluid flow and transport in the EBS materials as they degrade. Such a model will be used to evaluate the efficacy of new buffer materials and EBS design options. International collaborations have been, and will continue to be, a significant aspect of the crystalline research area. These activities include continued participation in DECOVALEX (for validation models), as well as collating and analyzing data from international URL.

2.3 Salt Disposal R&D

Salt formations are an attractive host rock for deep geologic disposal of SNF and HLW because the high thermal conductivity of salt dissipates heat, while its low water content, porosity, and permeability inhibit radionuclide transport. In addition, salt experiences visco-plastic deformation and recrystallization: fractures will heal, disposal drifts will creep closed, and granular salt backfill in waste disposal drifts will consolidate until its properties are equivalent to those of intact salt.

The objective of the Salt technical area is to develop conceptual and numerical models describing the response of natural and engineered features in a salt repository to excavation of the repository and emplacement of heat-generating waste. This understanding is important to both operational and long-term safety of a salt repository. Salt deformation affects drift stability; brine migration may affect waste

package corrosion; and radionuclide transport may be affected by the evolution of the disturbed rock zone, granular salt backfill, and cement seals.

Primary R&D thrusts in the Salt technical area are 1) measuring the effect of heat-generating waste on brine availability and salt deformation (Brine Availability Test in Salt); 2) evolution of engineered barriers in salt; and 3) development of coupled process models and constitutive relationships. Activities are coordinated with the EBS, GDSA, and International technical areas, and address high priority topical areas identified in the 2019 Disposal Research R&D Roadmap Update, including high-temperature processes (i.e., temperature-dependent constitutive models), coupled process models in salt, and evolution of cement seals.

Near-Term Thrust Topics (Next 1- to 2-year period)

Effect of heat-generating waste

- The Brine Availability Test in Salt (BATS), in the nation's only current underground research laboratory (URL) associated with nuclear waste disposal, measures the effects of coupled physical and chemical processes associated with emplacement of heat-generating waste in a salt host rock. BATS comprises a series of tests centered around a central borehole containing equipment for water-vapor collection and brine sampling, and surrounded by smaller-diameter satellite boreholes instrumented to measure temperature, electrical resistivity, distributed strain, and acoustic emissions. Both gas and liquid tracer migration tests will be conducted between boreholes. A larger-diameter satellite borehole includes a Sorel and salt cement plugging/sealing test. Over the next 1 to 2 years, data will be collected over multiple heating and cooling cycles of several months. In parallel, similar data are being collected from an identical control borehole array that is not heated. Follow-on series of borehole heater tests will be designed using information gathered from the first two tests.

Evolution of engineered barriers in salt

- Studies of the evolution of engineered barriers in salt repositories include two primary areas of investigation: cement seals and granular salt backfill (see Model Development). Both are the focus of international collaborations, and cement seal evolution is a component of BATS.
- Data pertaining to mechanical and chemical salt/brine/cement interactions will be collected at the end of BATS via overcoring. Strain gauges, thermistors, and relative humidity gauges are being used to monitor the cement seals during heating in adjacent boreholes as part of BATS. A German collaborator (GRS) is conducting complementary poromechanical tests on similar cement, brine, and WIPP salt cores.

Model development

- The unique and extensive dataset collected at BATS positions the US as a leader in salt repository science. The Salt team is leading a four-year task for DECOVALEX2023, in which participants will develop models of the coupled thermal-hydro-mechanical processes associated with emplacement of heat-generating waste in salt and validate their models against data collected at the BATS. Modeling teams from 4 countries (US, Germany, UK & Netherlands) are participating.
- The US benefits from several ongoing collaborative projects that are part of a long-standing bilateral agreement with Germany. Objectives include: 1) improving thermal-hydro-mechanical models for granular salt consolidation through model validation, consolidation experiments, and analysis of microstructural features; 2) improving constitutive models for salt deformation,

including creep behavior at low stress, dependence of healing on temperature, and influence of inhomogeneities such as clay seams; and 3) designing geotechnical seals for drifts and shafts in a salt repository.

Longer-Term Thrust Topics (Next 3- to 5-year period)

Many of the activities in the Salt technical area have multi-year plans. The current phase of BATS *in situ* testing is expected to run through 2021, at least. Subsequent heated borehole tests, building on the lessons learned from the first phase of BATS, will be constructed in nearby boreholes, while monitoring in the unheated BATS array will continue. Once the initial heating and testing cycles are complete in the initial heated BATS array, a significant amount of laboratory work will focus on analyzing samples from overcores collected from the tracer and cement seal boreholes. Data interpretation and model development and validation will continue through 2023 under the DECOVALEX project. In the next 3 to 5 years, process models and constitutive relationships developed in this project and in the US/German joint projects will be integrated into GDSA Framework for use in demonstrations of generic safety assessments and other repository systems analyses. The US/German collaboration benefits both countries by making available lessons learned in mined facilities in salt; sharing samples and experimental data; and expanding the community of salt repository scientists. In the future, collaboration on some activities may expand to include other countries considering repositories in salt, such as the Netherlands and the United Kingdom.

2.4 Geologic Disposal Safety Assessment

The objective of the Geologic Disposal Safety Assessment (GDSA) technical area is to develop a state-of-the-art software framework for probabilistic post-closure performance assessment analyses of facilities for deep geologic disposal of nuclear waste. This unified software framework provides the US DOE with robust, sophisticated simulation and analysis tools that will support site selection, site characterization, and licensing for the nation's next deep geologic disposal facility. The GDSA technical area is the nexus for integration of concepts, models, and understanding developed in other SFWST disposal research technical areas. Leadership and participation in international collaborations promotes innovation, ensures a world-class standard of practice, and engages the next generation of scientists in this compelling problem of national interest.

GDSA Framework (<https://pa.sandia.gov>) is an open source software framework developed to leverage the US DOE's high-performance computing (HPC) resources. The availability of this unique computing capability enables appropriately detailed modeling of the coupled physical and chemical processes affecting repository evolution and radionuclide transport, implementation of model domains with geologic fidelity, forward simulation over the 10^4 - to 10^6 -year timescale typically required by regulation, and propagation of uncertainty over many realizations of the problem.

Open source software development makes the simulation and analysis tools within GDSA Framework freely available to regulators, stakeholders, and the scientific community at large, thus promoting collaboration, driving development, and importantly, enabling transparent decision-making in a regulatory environment.

Primary R&D thrusts in the GDSA technical area are 1) advanced simulation capability; 2) state-of-the-art uncertainty and sensitivity analysis methods; 3) traceable, user-friendly workflow; 4) repository systems analysis, including simulation of generic reference case repositories in argillite, crystalline, salt, and unsaturated host rocks; and 5) development of geologic models, including generic archetypes for different host rocks and an interactive web-based application for visualization of regional geology in the US.

Near-Term Thrust Topics (Next 1- to 2-year period)*Advanced simulation capability:*

- GDSA Framework integrates coupled physical and chemical process models and material-specific constitutive models in PFLOTRAN (Lichtner et al. 2019), a multiphase flow and reactive transport simulator. Near term advancements in capability will focus on high priority topical areas identified in the 2019 Disposal Research R&D Roadmap Update, including high temperature processes, coupled thermo-hydro-mechanical processes affecting buffer evolution, waste package degradation models, criticality, and coupled thermo-hydro-chemical processes affecting radionuclide transport. Multi-fidelity model implementation including mechanistic models derived from detailed process understanding, reduced order models, and machine learning emulators enhances computational efficiency and dovetails with integration of advanced uncertainty and sensitivity analysis methods.
- Other software development tasks will include implementation and testing of advanced solvers and physics-based convergence criteria to improve computational efficiency when solving the nonlinear systems of equations that arise in simulation of complex systems; development of open-source biosphere simulation software; and release of an open source version of Vorocrust (Abdelkader et al. 2020), an automated meshing tool for generating conforming meshes of complex engineered and geologic features.

Uncertainty and sensitivity analysis:

- Uncertainty and sensitivity analysis (UQ/SA) methods in GDSA Framework are primarily available through Dakota (Adams et al. 2020), an open source HPC interface for coupling physics simulations to both tried-and-true and cutting-edge methods of UQ/SA, optimization, and parameter estimation. In the next 1 to 2 years, GDSA will identify and demonstrate methods consistent with the current standard of practice that add value to deep geologic repository performance assessment (e.g., metamodeling, variance decomposition); prototype multi-fidelity UQ/SA methods in coordination with development of multi-fidelity simulation capability; and contribute to development of an international consensus on best practices for sensitivity analysis in the context of repository performance assessment.

Workflow:

- Transparent, traceable workflows increase stakeholder confidence and user-friendliness. In the next 1 to 2 years, three important workflows will be established: an open source framework (scripted in Python) that automates software (PFLOTRAN) verification testing; a workflow that streamlines data transfer from the geologic model to the meshing software and ultimately to the simulator; and an automated, traceable workflow for performing probabilistic uncertainty and sensitivity analyses.

Repository systems analysis:

- Reference cases describing generic repositories in argillite, salt, crystalline, and unsaturated host rocks provide a platform for integrating concepts, demonstrating capability, and driving development of simulation software and analysis methods. In the next 1 to 2 years, conceptual models and simulations that account for high temperature impacts (associated with direct disposal of DPCs) in generic argillite and unsaturated repositories will be advanced. Integration with the DPC technical area will also address the consequences of criticality for repository performance.

- International collaborations will focus on crystalline and salt concepts. The GDSA team is leading a 4-year task for DECOVALEX2023 in which performance assessment (PA) simulation and analysis methods applied to generic crystalline and salt reference cases will be compared. Ten teams from 7 countries are participating. A US/German joint project will finalize a report to be published by the international Nuclear Energy Agency that documents FEP in salt repositories; and a broader coalition of countries will initiate a collaborative effort to establish best practices for development of scenarios for evolution of salt repositories from FEP.

Geologic modeling:

- Geologic modeling involves two primary efforts: generation of representative 3-dimensional (3D) regional geology models that inform reference case concepts and simulations, and development of an interactive web-based application (<https://gis1.inl.gov/regionalgeology/>) for visualizing argillite, salt, and crystalline formations in the US. In the next 1 to 2 years, geologic models of a generic unsaturated alluvial basin and of regional argillite stratigraphy will be linked into the meshing workflow described above; and 3D subsurface visualization tools will be developed within the web application.

Longer-Term Thrust Topics (Next 3- to 5-year period)

The research thrusts in the GDSA technical area are generally on-going efforts. In future years, capability development will continue to address high-priority topical areas and integrate new process understanding acquired in other SFWST technical areas. Model development and implementation may include multi-fidelity approaches to simulation of coupled processes in salt, in-package chemistry, gas flow in the EBS, and physical and chemical evolution of cement seals. Reference case simulations will continue to evolve to incorporate new designs, concepts, and models developed in other technical areas. The DECOVALEX PA comparison will progress from reference case development and simulation to uncertainty propagation and sensitivity analysis. In general, simulation capability will move toward a more sophisticated representation of a larger set of features, events, and processes affecting repository performance; UQ/SA will incorporate best practices consistent with up-to-date standards of practice; and the geologic modeling and meshing workflow will flexibly incorporate refined representations of engineered and geologic features as appropriate.

Depending on program direction, the tools and expertise that reside in the GDSA technical area could be expanded for eventual use in site evaluation, selection, and eventual characterization. The DOE's HPC platform, PFLOTRAN's multi-physics simulation capability, and Dakota's cutting-edge analysis tools together enable sophisticated methods of inverse modeling and data assimilation that are well-suited to interpretation of large, complex datasets and development of material parameterizations that incorporate uncertainty and stochastic variability. Together, the GDSA, Argillite, Crystalline, Salt, and International technical areas can leverage international collaborations to access site characterization data, to develop expertise in site evaluation methodology, and to test technical approaches to data collection and interpretation.

2.5 Direct Disposal of Dual-Purpose Canisters

Commercial SNF is accumulating in dry storage at over 70 sites across the US in dual-purpose canisters (DPCs), which are designed for storage and transportation, but not disposal. DOE is investigating the technical feasibility of direct disposal of commercial SNF in DPCs, as an alternative to repackaging the commercial SNF into purpose-built disposal containers. Direct disposal of DPCs has the potential to simplify disposal operations, minimize the number of SNF shipments, reduce collective worker dose associated with repackaging, and significantly decrease the costs associated with geologic disposal.

The main technical challenges for disposal of SNF in DPCs are thermal management, handling and emplacement of large, heavy waste packages, and postclosure criticality control (Hardin et al. 2015). In

prior years, DOE has published reports addressing engineering challenges associated with the large size and weight of DPCs and thermal management of the large heat load. Potential higher peak temperature in generic repository systems is being addressed in thermally-couple processes in argillite, crystalline, salt, EBS, and GDSA technical areas. Current research addresses postclosure criticality control, because modern DPCs depend on aluminum-based materials for neutron absorption during storage and transportation, and those materials will degrade in a few decades when exposed to groundwater in a repository.

Specific research focus areas (see Figure 1) include: (1) direct disposal without modification (postclosure criticality consequence analysis, as-loaded reactivity margin analysis); (2) modification of already-loaded DPCs (with injectable filler materials for criticality control); and (3) modification of DPCs to be loaded in the future, or the fuel they contain (changing loading maps, adding disposal criticality control features, or basket redesign).

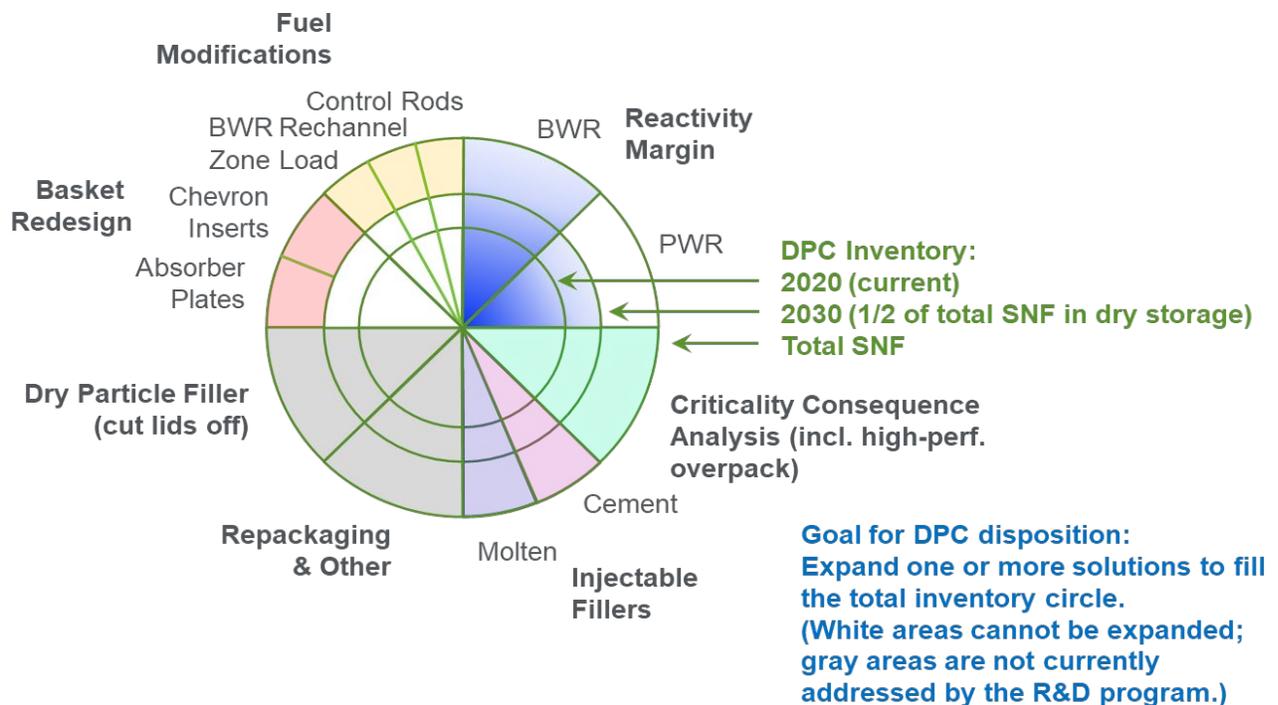


Figure 1. Overview of options to facilitate evaluation of feasibility of direct disposal of DPC. The pie slices represent research sub-topics within the four larger target quadrants of (clockwise from top left) changes to basket design, constraining reactivity margin, use of injectable fillers, and use of other methods involving opening the top of the DPC. The circumferential (i.e., circular) zones represent the DPC inventory that may be affected by the different methods. For example, the innermost ring reflects the current (2020) DPC inventory that cannot have their baskets redesigned (the upper left quadrant regions of this zone are shown as white).

Near-Term Thrust Topics (Next 1- to 2-year period)

Probabilistic Post-Closure DPC Criticality Consequence Analyses

The near-term focus of this thrust area is to evaluate the consequences of potential criticality events on overall repository performance to determine if the consequences are acceptably low, given a viable method for determining consequences. Consequence screening is a new approach, not fully constrained in an US or international repository R&D program to the degree planned here. This approach includes: developing a technical and regulatory strategy for low consequence analyses; developing a source term

representing effects from criticality events; using coupled process modeling input; and identifying appropriate criticality FEP, key parameters, and metrics.

Criticality scenario development with source term and near-field changes specific to different types of criticality events is needed to evaluate consequence screening. Contributing activities will couple nuclear dynamics (neutronics) and thermal hydraulics (N-TH coupling). Other activities will contribute effects from mechanical/hydrologic/chemical/radiolytic changes in fuel/basket/canister performance.

The near-term outcome is the development of generic models to represent repository performance with criticality events, and their preliminary implementation in a performance assessment (PA) model. These processes include fuel, basket and waste package degradation (e.g., cladding unzipping, UO₂ alteration/dissolution, basket corrosion and collapse, and canister/overpack breach evolution), interaction (heat, mass) with the near-field, and N-TH coupling.

This activity includes the following High Priority R&D Activities from the R&D Roadmap Update (Sevougian et al., 2019, Table 3-5):

(D-01) Probabilistic post-closure DPC criticality consequence analyses

(D-04) Coupled multi-physics simulation of DPC postclosure (chemical, mechanical, thermal-hydraulic) including processes external to the waste package

(D-05) Source term development with and without criticality

As-Loaded DPC Reactivity Margin Modeling

Recent analyses of reactivity for several hundred as-loaded DPCs, for a stylized degradation case representing loss of all neutron absorbing materials (complete removal and replacement by water) have shown that some of these DPCs have sufficiently low k_{eff} for direct disposal even in degraded condition, because of the basket design and the as-loaded fuel characteristics. The focus of this thrust area is to continue these types of as-loaded analyses to identify existing DPCs that are amenable to direct disposal (i.e., have zero/low probability of criticality in any disposal environment). This includes compilation of fuel characteristics (type, burnup profiles, etc.) and canister data (basket design, fuel loading schema, etc.) for all DPCs and analysis (and re-analysis) of reactivity for stylized degradation cases, and for disposal environments (e.g., natural groundwaters, chloride brines).

Canisters loaded today and in the future have less reactivity margin, caused by larger capacity and more compact basket design, with more advanced burnup credit analysis. Therefore, these analyses will focus on older DPCs, particularly ones loaded more than 10 years ago as they are more likely to have zero/low probability of criticality in any disposal environment.

DPC Injectable Filler Testing and Analysis

The near-term focus of this thrust area is to develop and demonstrate fillers that could be injected as liquids into existing DPCs, where they solidify, and displace or exclude ground water from breached waste packages in a repository, and preserve neutron absorbing materials to prevent criticality over the long-term. Fillers need to have desirable behavior (injectability, radiolysis, material interactions, leachability) and have long-term durability in the disposal environment. If successful, this approach could be used to treat all DPCs including those loaded without modifications. Several potentially effective filler materials are being considered including aqueous cement slurries, and molten metals, alloys, and low-temperature glasses.

The near-term investigations include initial mixing and handling of candidate filler materials, and demonstration of filler injection into small-scale representations of DPC fuel/basket geometries.

This activity includes the following High Priority R&D Activities from the R&D Roadmap Update (Sevougian et al., 2019, Table 3-5):

(D-03) DPC filler and neutron absorber degradation testing and analysis

Future DPC (Fuel/Basket) Modifications

The near-term focus of this thrust area is to identify potential modifications to future DPCs so they will remain subcritical in any repository setting. These include: a) loading schema with the possibility to blend fuel assemblies from fuel pools based on reactivity (PWR and BWR fuel); b) disposal control rods (PWR fuel); c) disposal control rods or rechanneling (BWR fuel); and d) replacement absorber plates (some, but not all BWR fuel baskets). DPC modification could be combined with other options, to treat different sets of DPCs and limit the overall probability of a criticality event.

Longer-Term Thrust Topics (Next 3- to 5-year period)

Probabilistic Post-Closure DPC Criticality Consequence Analyses

The longer-term focus of this thrust area is to develop a higher-fidelity, robust PA model that includes the integrated processes necessary to simulate the consequences of potential criticality events on overall repository performance. The integrated PA model would include a detailed source term representation (fuel, cladding, basket, and waste package physical and chemical evolution relevant to critical configurations), the effects of N-TH coupling, conditions external to waste packages (saturated and unsaturated repositories).

DPC Injectable Filler Testing and Analysis

The longer-term focus of this thrust area is the demonstration of the most promising filler materials and injection techniques at full- or near-full scale. This would also include large-scale representations of the geometries of the DPCs, baskets and other internals, and assemblies, and appropriate representation of the injection vent ports and filler tubes.

Future DPC (Fuel/Basket) Modifications

The longer-term focus of this thrust area is to further develop the most promising potential DPC fuel/basket modifications. This could include fabrications and/or demonstrations. An important consideration at this stage is the potential for DPC modifications to actually be implemented by vendors and/or utilities.

2.6 International Collaborations in Disposal Research

The SFWST Campaign has over the past few years established a balanced portfolio of international collaboration activities in disposal research, addressing relevant R&D challenges in fields like near-field perturbation, engineered barrier integrity, radionuclide transport, and integrated system analysis. These activities now form a central element of SFWST's disposal research, and significant advances have been made over the past few years across different host rock types and engineered barrier research challenges. International collaboration enables (1) leveraging a deep knowledge base in regards to alternative repository environments developed across the world, (2) utilizing international research facilities (such as underground research laboratory testing) not available in the U.S., and (3) sharing the cost of major research efforts such as full-scale in situ experiments or complex modeling efforts. SFWST currently has in place formal collaboration agreements with several international initiatives (DECOVALEX Project, Mont Terri Project, SKB Task Forces, HotBENT, FEBEX-DP) and various international partners. National lab scientists associated with the campaign are conducting a number of collaborative R&D activities that align with R&D priorities across most of the technical areas discussed in this section. In these collaborations, SFWST scientists contribute world class analyses, models, and data for both process understanding and system risk modeling and assessment (Birkholzer and Faybisenko, 2019).

A major focus of the international program are collaboration activities that provide access to and/or allow for participation in field experiments conducted in operating underground research laboratories in host rock environments not currently available in the U.S. Figure 2 gives a visual overview of activities

conducted to date, experiments in bold denote currently active international collaborations. The figure graphically illustrates the breadth and focus of SFWST’s international program. The research portfolio is equally distributed between engineered barrier, near-field and far-field focus, with an emphasis on argillite and crystalline host rock.

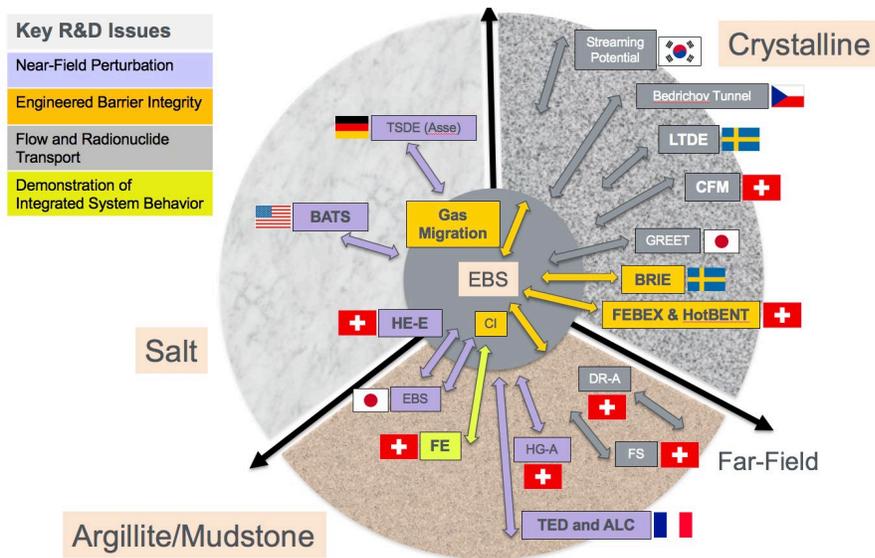


Figure 2. High-level overview of the major international experiments conducted in different countries that SFWST researchers have participated in since 2012. Experiments in bold denote currently active collaborations. See Table ES-1 in Birkholzer and Faybishenko (2019) for more information on each experiment.

Overall, the focus on international collaboration allows close integration with the international waste management R&D community in terms of best practices, new science advances, state of the art simulation tools, new monitoring and performance confirmation approaches, lessons learned, etc. The joint R&D with international researchers, the worldwide sharing of knowledge and experience, and the direct access to relevant data/experiments from a variety of underground research laboratories and host rocks provides an improved understanding of the current technical basis for disposal in a range of potential host rock environments. Comparison with experimental data allows for testing and validating predictive computational models for evaluation of disposal system performance in a variety of generic disposal system concepts. Comparison of model results with other international modeling groups, using their own simulation tools and conceptual understanding, enhances confidence in the robustness of predictive models used for performance assessment. The possibility of linking model differences to particular choices in conceptual model setup provides guidance into “best” modeling choices and understanding the effect of model uncertainty.

Near-Term Thrust Topics (Next 1- to 2-year period)

Continue participation within international R&D in underground research laboratories for a range of geologic systems

The current international research portfolio, which spans across several technical areas including Engineered Barrier System R&D, Argillite Disposal R&D, Crystalline Disposal R&D, Salt Disposal R&D, and Geologic Disposal Safety Assessment, has been re-evaluated and re-prioritized in 2019 as part of a broad activity-based priority assessment across the campaign (Sevougian et al., 2019). We expect that this revised portfolio will remain largely intact over the next two years. The current key activities either

involve long-term in situ experiments that will continue for years to come (e.g., the full-scale FE Heater Test at Mont Terri, the recent fracture network modeling task related to the SKB Task Forces), or they are multi-year collaborations that have just been initiated based on the revised 2019 roadmap (e.g., the HotBENT experiment at Grimsel Test Site, or the new collaborative tasks defined in the DECOVALEX 2023 Project).

Continue assessment of new international opportunities

Ongoing evaluation of existing and emerging opportunities for international collaboration is a key responsibility of the International Collaborations technical area. We will continue to review, assess, and develop such opportunities in close integration with international partners, will evaluate technical merit and alignment with the current and planned work scope within SFWST work packages, and make revisions to the portfolio of international R&D activities as appropriate. Examples of possible new activities might include:

- Additional joint field experiments addressing gas transport in engineered and natural barriers (e.g., participation in the Gas Transport, GT experiment at Mont Terri to better understand gas transport in clay host rock; joining the modeling/analysis team for the Gas Permeable Seal Test, GAST, at Grimsel Test Site)
- Additional diffusion studies for engineered and natural barriers (e.g., the Cement-Clay Interaction Test, CI-D at Mont Terri which characterizes diffusion through 10 year old rock-bentonite-cement interface; the upcoming Diffusion in a Thermal Gradient Experiment, DR-C which evaluates diffusion in argillites under a thermal gradient; and the Long-Term Diffusion Experiment, which is ongoing at Grimsel Test Site)
- Adding tunnel, shaft and borehole sealing elements as a priority theme for engineered barriers research (e.g., the upcoming Large-scale Sandwich Experiment, SW-A, which tests a promising layered technology for shaft seals; the upcoming Borehole Sealing Test, SET)

Pursue a more active role in conducting experimental work in international underground research laboratories

The SFWST campaign will evaluate whether its international collaboration focus should move from a mostly participatory role in ongoing in situ experiments conducted by other nations to a more active role in conducting its own experimental program in international URLs. The advantage of active planning is that the experimental focus and design can be better tailored to the campaign needs. Recently, SFWST played a leading role in establishing a broad international partnership to conduct the HotBENT in situ heater test, which addresses research needs related to the performance of clay buffers and near-field rock at temperature from 150°C to 200°C. Campaign scientists played a key role in the test design and predictive modeling, and with the start of the heating phase in late 2020 will be involved for years in monitoring and analysis activities for years. More such active collaborations can be considered in the future.

Contribute to integration and confidence building for Generic Disposal System Analysis

The international research activities, with their focus on modeling and comparative analysis for complex in situ experiments, ultimately lead to better predictive models and thus directly contribute to confidence building for post-closure performance assessments (PA) models. In the SFWST campaign, the work packages for international collaboration, for generic research on EBS and host-rock specific topics, and for GDSA need to be well integrated to make optimal use of improved process models leading to better safety assessments models. Confidence in PA models can also be enhanced by comparing PA methods to international standards, or by benchmarking PA studies against international data sets. Under leadership of SFWST scientists, the new PA/UQ/SA benchmarking task in DECOVALEX 2023 compares PA methodologies across multiple international disposal programs.

Longer-Term Thrust Topics (Next 3- to 5-year period)

International collaboration will continue to be a central element of SFWST Campaign's disposal R&D over the next five years and beyond. And as research priorities change and new opportunities for collaboration present themselves, the international research portfolio will be re-prioritized as appropriate. Many of the two-year themes discussed above will continue to drive the campaign planning. In addition, depending on the direction of the campaign and the progress made, international collaboration could be expanded to in several ways to serve other objectives. Below are two examples:

Develop best practices and technologies for site selection and characterization

The current campaign focus in disposal research is to (1) provide a sound technical basis for multiple disposal options in the U.S., (2) assess suitability and geographic distribution of host rock types, (3) increase confidence in the robustness of generic disposal concepts, and (4) develop the science and engineering tools needed to support disposal concept implementation. As the campaign evolves, a suitable goal for international collaboration may be to support site characterization for site screening and site selection, via engagement with countries that currently go through such efforts. At a minimum, such international collaboration would involve close observation and information exchanges, to gain a better understanding of best practices for different host rocks. Or the campaign could be actively embedded in ongoing international site characterization efforts, for example, via joint development and testing of surface- and borehole-based characterization tools.

Utilize international activities for training/education of junior staff

International collaboration has provided extremely valuable data sets from underground testing that are not only relevant to the SFWST's campaign R&D objectives but also provide for complex scientific challenges of high interest to young researchers. The campaign could make a dedicated effort to use international collaboration activities as an opportunity to recruit and train early-career scientists to become the next-generation workforce for disposal research in the U.S.

2.7 Engineered Barrier System (EBS) R&D

EBS R&D activities support all three of the generic host-rock types (argillite, crystalline, salt) with the specific EBS characteristic differing depending on the host-rock system. Because of this, EBS research activities address a wide range of topics on design materials and barrier performance. In addition, consideration of direct disposal of DPC expands the consideration of higher temperature conditions and chemical effects from potential additional DPC filler materials within the EBS environment. Because of all these aspects, EBS research thrusts are aimed at assessing the feasibility, applicability, evolution, and performance of EBS concepts in a given generic geologic medium and a particular waste inventory.

Near-Term Thrust Topics (Next 1- to 2-year period)

- a) Analysis of thermal, mechanical, and chemical processes that will influence performance of EBS designs for each host media
- b) Understanding of bentonite buffer drying and re-saturation processes (i.e., thermal-hydrologic behavior)

Advancing models of multiphase transport and its effects on buffer/backfill and response to varying thermal and mechanical conditions in the repository drift is being used to evaluate radionuclide transport in the EBS. Modeling and experimental activities are underway to assess performance of EBS components in the disposal environment, including buffer/backfill, waste package materials, waste forms (including SNF), and shaft and drift seal materials longevity and chemical effects.

Improved understanding of the effects of this dry-out on the resultant clay pore matrices, and on fluid permeability, is being pursued. Restoration or healing of pore matrices upon re-saturation (when the repository has cooled down) also is a target of improved understanding. Experiments and modeling will

be conducted to elucidate these phenomena in such a way that the results can help to improve confidence in predictions of buffer permeability evolution under more realistic repository conditions.

Longer-Term Thrust Topics (Next 3- to 5-year period)

- a) International collaboration and URL studies for EBS performance and design materials (e.g., cement)

International partnerships will continue to be developed and enhanced for both barrier performance understanding and constraints on materials evolution and chemical effects in the EBS. These international activities include participation in the Engineered Barriers System Task Force (EBS-TF - an international consortium that works collaboratively to study issues most critical to EBS Design and Performance). Participation in the EBS-TF, and DECOVALEX provides the latest international advances in EBS design and performance, but more importantly gives access to test data and samples from underground field tests of EBS performance. Additionally, this activity will provide a forum for further integration between EBS research activities undertaken at LANL, LBNL, and SNL. Collaborations will continue with German EBS researchers, focusing on EBS-related aspects of design and evaluation of a generic salt repository. This will include investigations into drift and shaft seal evolution, which evaluates crushed salt reconsolidation and cementitious materials performance. Over the next five years, a new partnership with JAEA researchers at the Honorobe URL in Japan will be developed, aimed at gaining better understanding of the interactions between cementitious EBS materials and the host rock. Collaboration with investigators from IAEC (Israel Atomic Energy Commission) will continue investigating modeling tools/approaches for understanding leaching of cementitious materials in repository conditions.

2.8 Online Waste Library (OWL) – Inventory, and Waste Characterization

The scope of the inventory and waste form characterization work in this area covers DSNF and DHLW, with the current intent to dispose of these in a deep geologic repository. It is recognized that the DHLW includes wastes that may be dispositioned in the future with a waste classification different than HLW (which would perhaps entail a different disposal pathway). In this work, the theoretical geologic repository for wastes, including DSNF and DHLW, is a deep mined geologic repository. The purpose of the work directly on the OWL is to provide the inventory data on DSNF and DHLW for safety assessment analyses of generic repositories for these wastes and their waste forms. Additional work on specific waste form characteristics includes assessing the inventory data and ensuring information exists for disposal relevant radionuclides, as well as evaluating the waste form degradation behavior of waste forms for implementation of waste form degradation models in the GDSA Framework

Near-Term Thrust Topics (Next 1- to 2-year period)

- a) Provide Change Control and Release Control processes for OWL
- b) Develop Glass Waste Degradation Expertise

The primary thrust for the OWL in the short-term is the production of both the OWL Change Control Process documentation and the Version Release Process documentation. Once finalized, these processes will cover all aspects of changing OWL content and/or structure, as well as the process and schedule for releasing a new version, both with full documentation tracing generated. Short-term activities will also include the continued updating of the listing and inventory data for DOE-managed HLW and SNF radioactive wastes that are potential candidates for deep geologic disposal. These data include those assessed in the previous disposal options evaluation work, and any newly identified additional wastes and/or waste forms. Additionally, updates for waste form characteristics and degradation models for a selected subset of DOE managed HLW and SNF will continue. As part of cross-campaign integration, assessment of the existing data and conceptual models for Stage III (accelerated, “resumptive”

degradation) rates for HLW glass is being conducted such that expertise exists in preparation to critically evaluate (and help implement) a model of HLW glass degradation that includes Stage III effects at a process level as delivered from another (NE-4) campaign.

Longer-Term Thrust Topics (Next 3- to 5-year period)

- a) Maintain OWL Inventory Content
- b) Consider Additional Interface Capabilities for the GDSA Framework

Maintaining the data sets within the OWL (inventory content) for any changes/updates, and adding additional inventory data sets, as needed for GDSA, is part of the longer-term thrusts for this technical area. In addition, OWL capability expansion activities are also possible over the next five years. Longer-term activities would include construction of the next stage development of the OWL to add capabilities for generating turn-key inventory output for safety assessment simulations. The OWL could also be augmented to include data sets for available radioactive waste “vessels”, for example cans/canisters/packages. Such additional data tables would include dimensional characteristics (inner and outer), masses, material properties, certification for usage, indication for which wastes/waste forms these are meant to enclose, as appropriate, etc. These data sets would be incorporated in much the same manner as the data for the wastes/waste forms. OWL capabilities could be developed to facilitate a more active integration with the GDSA Framework (e.g., generation of “as packaged inventory” from user-selected waste forms and vessels, and disposal date) for disposal analyses, and potentially with other codes for transportation/storage systems assessment.

2.9 Technical Support for Underground Research Laboratory Activities

The DOE has a shutdown underground research laboratory (URL) that will be leveraged to support R&D pertaining to generic disposal concepts, especially disposal concepts for unsaturated zone repositories. The URL has not been actively operated for an extended period of time (approximately 10 years) and all offsite electrical utility power has been disconnected remote from the location.

The URL technical area has two operational objectives and two R&D thrusts at this early stage of resuming operations. Operational objectives are to re-establish lighting and communications within the URL, and to develop planning and facility access protocols. The R&D thrusts are passive monitoring of atmospheric conditions in the underground, and measurement of cosmic ray background radiation (including muon detection). Both of these R&D activities serve as vehicles for achieving the second operational objective (develop planning and facility access protocols).

Near-Term Thrust Topics (Next 1- to 2-year period)

Operational

With the re-establishment of electric power and communications from the URL to outside locations, work can proceed by researchers in a safe and productive manner. In the next 1 to 2 years, operational activities will include installation and refurbishment of underground electrical, lighting, and communications equipment, and connection to surface power sources.

Underground activities will include cleaning of existing mine power centers; procurement and installation of approximately 6,500' of bare copper grounding/bonding conductor; refurbishment of approximately 100 subsurface light fixtures; procurement and installation of several hundred feet of low voltage and medium voltage portable power cables; and reconnection of 50 communication units.

Surface activities will include connecting two legacy diesel generators to the legacy underground power system through newly procured medium voltage unit substations. Two new earth ground points will be installed.

Passive monitoring

Passive monitoring instruments will be installed in the URL to quantify the impact of natural ventilation on in-drift conditions in an unsaturated zone URL. The test plan addresses planning and facility access protocols and proposes installing at least two instrument clusters to continuously measure barometric pressure, temperature, and air flow. In addition, one or more continuous gas stream analyzers will be installed to measure partial pressure of H₂O (humidity) and CO₂.

Cosmic radiation

Muons, negatively charged particles with 200 times the mass of electrons, are created when cosmic rays hit particles in the Earth's atmosphere, and can pass through hundreds of meters of solid material. The recent availability of portable detectors has enabled characterization of dense objects and subsurface features using muons. In the next 1 to 2 years, a muon detector as well as instruments for detection of other cosmic radiation (e.g. gammas, neutrons) will be installed in the URL for preliminary data collection. Long-term objectives are to develop non-destructive subsurface characterization methods using muon imaging, and to inform the design of sensitive physics experiments (e.g., rare-event searches) that require shielding from cosmic radiation. A test plan is under development now that will, together with the passive monitoring test plan, address planning and access protocols.

Longer-Term Thrust Topics (Next 3- to 5-year period)

Long-term data collection is planned for both the passive monitoring and cosmic radiation detection activities. In both cases, outcomes may include characterization of subsurface heterogeneity, development of geologic or hydrogeologic models, and implementation of additional related experiments.

Measurements of cosmic ray background as a function of depth in the URL could serve as an important input in designing future experiments to develop this technology for site characterization and safeguards and security applications.

When power, lighting, and communications are restored and planning and access protocols are in place, other opportunities to leverage the URL for generic R&D are expected to arise.

2.10 Knowledge Management

The primary goal of the Knowledge Management activity is to establish a Knowledge Management (KM) program covering the Nuclear Energy Fuel Cycle (NEFC) that is initially focused on relevance/benefit to the SFWST Campaign DR R&D program, with intent to expand coverage to the entire back end of the fuel cycle activities. The loss of senior staff members, who are not only leaders and mentors but also seasoned subject matter experts in nuclear waste management (NWM), necessitates an intentional approach to ensure a more efficient and rigorous approach to capturing, cataloging, archiving, and transferring institutional NWM tacit knowledge to the influx of new staff. This KM activity has been collecting, organizing, and cataloging such knowledge while developing the tools to archive, transfer, and use this tacit knowledge from our colleagues nearing the end of their professional careers. Capturing and managing this knowledge avoids the costs and risks of recreating already known methodologies once again (or worse in multiple instances) and mitigates the potential complete loss of that tacit experience base. There is also work underway to design current work processes into database workflows to capture knowledge and information as it is created by current NWM staff. As such, the KM activity cross cuts all the DR R&D areas (and ultimately S&T R&D and beyond), focusing on the larger technical and programmatic aspects of NWM projects.

The KM activity convened focus groups to understand the current state of KM implementation, the most beneficial ways to gather knowledge and the myriad of methods to communicate the knowledge to program staff working in NWM. The focus groups covered technical staff at SNL ranging from junior to most-senior staff grouped by experience levels, as well as a management focus group. A key finding from the focus groups is to design a web-based platform as an interactive and living tool for accessing the tacit

knowledge captured. A KM workshop was held to cover primary NWM knowledge from primarily the U.S. radioactive waste disposal programs, with some coverage of the history and regulatory structure of storage and transportation projects, and an overview of the Congressional budgeting and authority structure. The workshop was audio/video recorded as part of the KM collection and was followed by *Information Deep Dives* in key technical areas underpinning the safety case for a repository program. All these knowledge sets have been included in the pilot KM Repository developed in SharePoint on the Sandia restricted (i.e., internal) network (SRN). These materials are kept in various formats (e.g., video presentations, transcripts of video), with referenced materials, linked files, and a discussion board for interaction amongst staff.

Near-Term Thrust Topics (Next 1- to 2-year period)

- a) Continued maintenance and development on KM Repository
- b) Expand topical coverage more fully for disposal programs and to the S&T KM topics

The primary thrust for KM in the short-term is to maintain and develop the KM Repository, adding more materials relevant to the tacit knowledge for disposal programs, more linked structures, and additional tools for using and transferring this knowledge amongst the current NWM staff. A large amount of data/tacit knowledge is already included in the KM Repository, but there are vast areas that are yet to be mined for relevant experience and linked to key documented resources in the DR arena. Beyond this, expansion of the tacit knowledge content of the KM Repository to the wealth of experience in storage and transportation projects would be the next natural step for this activity and flesh out the NWM coverage of the back end of the fuel cycle.

Longer-Term Thrust Topics (Next 3- to 5-year period)

- a) Expand KM Repository efficacy to larger portions of the nuclear energy fuel cycle community
- b) Consider developing training course(s)

Further development of KM Repository content and capabilities would continue in the long-term. Providing interface capabilities to larger portions of the SFWST Campaign staff, and beyond to all NE-8 staff, would be one focus in the longer-term for KM activities. Additionally, expanding the topical coverage in response to the wider user group would be another focus in the out years. Potential development of explicit training courses using the KM Repository for new/junior NWM staff would be considered in the longer-term as well.

3. SUMMARY OF SFWST DR R&D HIGH-LEVEL TECHNICAL FOCUS AREAS FOR 5 -YEAR PLANNING

The previous Used Fuel Disposition (UFD; from FY2011-FY2017) Campaign and the current SFWST Campaign disposal R&D programs have focused on the evaluation of the viability of mined repositories in three generic geologic media (salt, clay, and crystalline rock; e.g., Sevougian et al., 2019), and, in addition to these mined repository disposal concepts, the evaluation of very deep boreholes in generic crystalline basement rock (Arnold et al. 2012; NWTRB 2016)^a. The host lithologies were selected because they have been considered and analyzed as potential repository host rocks both in the U.S. and internationally for several decades (e.g., Faybishenko et al., 2016). The generic host rock types were identified at a broad level: salt includes both bedded and domal salt; clay was defined to include a broad range of fine-grained sedimentary rock types including shales, argillites, claystones, as well as soft clays; and crystalline rock may include a range of lithologies such as metamorphic gneisses, granite, and other igneous rock types. Recently generic unsaturated system mined repository concepts are also being analyzed, especially regarding their capabilities to effectively release heat via ventilation in open emplacement tunnels.

The above range of generic disposal systems evaluated thus far is not intended to represent a complete/comprehensive list of possible alternatives, and other options may also have the potential to provide safe long-term isolation. However, DOE and UFD/SFWST managers believe that R&D related to the evaluation of the selected generic media would likely be applicable to nearly any future program that relied on deep geologic disposal. The fundamental disposal R&D on these various generic geologic host rock systems will continue to be the cornerstone of the SFWST Disposal R&D program to support geologic repository disposal solutions in the U.S.

As has been the case throughout the SFWST Campaign DR R&D program, there exists a continual need to have active integration among the process-level generic geologic systems studies and the performance assessment modeling (i.e., GDSA modeling). For example, studies of direct disposal of DPC actively integrate the existing stored spent fuel as packaged with disposal studies where models of the engineered barriers and natural system are actively being modified to address conditions based on the DPC characteristics. Within the SFWST Campaign there are programs of R&D addressing topics on Storage and Transportation (S&T) of SNF (e.g., Teague et al., 2020), in addition to Disposal Research. Moving forward tighter integration between DR R&D and the relevant S&T R&D would better define waste inventory characteristics/conditions for disposal. This would also enhance consistency of process interfaces such as SNF and cladding characteristics for disposal, physical conditions, and degradation processes, canister conditions, life cycle parameters (thermal, dose) for commercial SNF (the largest inventory for disposal), and treatment/overpack needs for DPC disposal. Beyond this internal SFWST Campaign integration, potential new technology (e.g., accident tolerant fuels; probable advanced nuclear fuel cycle reactor fuels) may generate additional/new waste forms. Addressing new challenges would be facilitated by coordination with relevant efforts in other external waste management areas such as more active integration with the back-end-of-the-fuel-cycle management processes within the Integrated Waste Management (IWM) Campaign. Even beyond the direct NE-8 mission, potential additional changes to inventory/processes for existing waste forms within both DOE NE and DOE EM could facilitate addressing the growing need for robust R&D in the deep geologic disposal of radioactive wastes.

^a DOE Campaign R&D for this concept was discontinued in 2017.

Beyond the core efforts to evaluate generic geologic systems for disposal behavior and constrain their key generic natural barrier capabilities with systematic integration of process-level understanding with system evolution of natural and engineered barriers, the SFWST Campaign DR R&D activities will maintain a further focus in the next five years on the following four areas: GDSA Capabilities Development and Demonstration; International Collaboration and Underground Research Laboratories; Engineered Barrier System Representations; and Evaluation of Potential Direct Disposal of Dual Purpose Canisters (DPC).

A. GDSA Capabilities Development and Demonstration

This cross-cutting issue was covered well with the previous DR R&D that defined a number of reference cases for generic geologic disposal systems, and this overarching activity for developing and demonstrating safety assessments of such systems will remain central to repository science. The continued development and improvement of a world-class safety assessment capability relies on a seamless integration of complex process-level models for the generic geologic disposal systems and the engineered barrier systems (EBS). Within this focus area, efforts include expansion of high-fidelity modeling capability in both the near-field (i.e., source-term and EBS transport) and far-field (i.e., the natural barriers) portions of the system model, as well as integration of multi-fidelity model forms that adequately represent performance-affecting processes while maximizing computational efficiency. For complex coupled chemistry, development of a drift-based model that includes major chemical components reacting with materials over appropriate temperature ranges is also being pursued. Utilization of high-performance computing, advanced computational methods, and enhanced treatment of uncertainty quantification and sensitivity analyses will underpin the tools being expanded. Workflow automation, software verification, and accessibility of these tools for potential use in a regulatory environment is also a key area of development.

B. International Collaboration and Underground Research Laboratories

The Campaign's continued participation within the International R&D community, especially with continued participation at a number of underground research laboratories (URL) in a range of geologic systems is an essential aspect of the core effort to evaluate multiple generic concepts for deep geologic disposal systems. This allows SFWST DR R&D investigators to not only contribute world-class analyses, models, and data for both process-level science and system risk modeling and performance assessment, but also provides collaborative access to world-leading URL investigations in the field and peer review by the international scientific community. Such direct studies provide enhanced leveraging of diverse knowledge, models, process understanding, and data sets and facilitate development of robust technical bases within the DR R&D program for multiple generic geologic disposal concepts. Goals in this focus area include providing more highly integrated capabilities for analyzing generic repository systems in argillite, crystalline, and salt host rocks, with integrated EBS treatments and GDSA demonstration capabilities. Additionally, a recent effort has been started to apply SFWST R&D expertise in heated experiments in U.S.-based salt host rocks underground, and potentially (next fiscal year) in an unsaturated system tunnel.

C. Engineered Barrier System Representations

This focus area touches on each generic geologic system because there are a number of engineered barriers (e.g., the waste form including cladding, the waste package, canisters, and backfill) that are common to a number of disposal concepts. Additionally, the thermal aspects rooted in the waste form/waste package source term region affect the host rock depending on the timing of disposal and the layout of the repository. This cross-cutting issue was handled well for EBS Concepts in the DR R&D program for those existing systems being investigated around the world, but there were specific gaps related to both waste package (WP) degradation and cladding evolution/failure in the post-closure DR R&D activities identified. Developing, constraining, and implementing models for both waste package degradation and cladding evolution are major goals

in this focus area. Additionally, the evaluation of feasibility of direct disposal of DPC raise some technical issues to more prominent levels, such as thermal effects, including coupled processes, degradation rates of waste forms and other engineered barriers, and evolution of the EBS transport pathways and rates. Consideration of stage III rate processes in glass degradation, as well as potential new waste forms from either accident tolerant fuels or advanced reactor fuel cycle development will become more of a central emphasis. One goal here, as with International Collaboration, is to provide more highly integrated capabilities for analyzing generic repository systems in argillite, crystalline, and salt host rocks, with integrated EBS treatments and GDSA demonstration capabilities

D. Evaluation of Potential Direct Disposal of DPCs

This focus area is driven by the recent effort to evaluate the feasibility of directly disposing of the SNF in dry storage in dual purpose canisters. Direct disposal of DPCs has the potential for significant cost savings and, lower worker health and safety doses as compared to repackaging the SNF for disposal. Because DPCs tend to be massive both physically and thermally, they present further challenges for operations (e.g., handling) and thermal management. This latter aspect enhances the need to understand coupled thermal-chemical-mechanical-hydrologic (TCMH) processes in all disposal concepts. Additionally, criticality evaluations both prior to closure of a repository and in the post-closure system are an essential part of the considerations. Criticality evaluations include direct disposal without modification (e.g., postclosure criticality consequence analysis, as-loaded reactivity margin analysis) and with modification/mitigation. Mitigation approaches for potential post-closure criticality includes consideration of modifications of the DPC internals, including fillers of both metallic and cementitious compositions. These materials in the EBS add to the considerations of chemical evolution in the near-field environment that applies to waste form degradation, radionuclide release, and EBS transport analyses. Additionally, DPC overpacks specifically for post-closure corrosion performance would likely be needed in a number of disposal concepts considered. The DPC would be integral to the EBS so they connect with all near-field studies, and thermal input may affect the damaged zone around the EBS and further into the host rock in terms of mechanical changes. Such effects push the process-level investigations in all areas, as well as the range of conditions considered in GDSA models, to levels higher than previously addressed.

4. SUMMARY AND CONCLUSIONS

In the planning for FY2020 in the U.S. DOE NE-81 Spent Fuel and Waste Science and Technology Campaign, the DOE requested development of a plan for activities in the Disposal Research Research and Development program over a five (5)-year period. This report provides this plan for the SFWST Campaign DR R&D activities as a strategic guide to the work within the DR R&D technical areas (i.e., the control accounts), focusing on the highest priority technical thrusts. This 5-year plan will be a living document and is planned to be updated annually to provide for changes based on both SFWST Campaign objectives and funding levels (i.e., Program Direction). The annual update to this 5-year plan will address the DR R&D that has been completed in the prior year, the additional knowledge gaps remaining, updates to the DR R&D priorities, and shifts in resources for the next stages of activities.

The document is structured with three main sections. Section 1 contains the background on evaluation and prioritization of the SFWST DR R&D technical work with a review of both the original Roadmap Report (2012) and the Reassessment of the Roadmap (Sevougian et al., 2019). In Section 2, the summary plan for R&D technical activities is provided for each of the SFWST DR R&D technical areas (note these correspond to the work breakdown structure control accounts for the DR R&D program for DOE NE-81). For each DR R&D technical area, the major technical thrust topics slated for the next five years are presented with discussions of the current/planned activities supporting those thrust topics. Those 5-year plans outline the general schedules for the thrust topics of each DR R&D technical area and provide the expected technical emphasis in two parts: the near-term (i.e., the more certain 1- to 2-year timeframe) and the longer term (less certain 3- to 5-year timeframe). The near-term emphasis can be viewed as a representation of the present DR R&D portfolio with modest modifications that reflect emerging priorities and funding levels. In contrast, the 3- to 5-year period represents a longer-term vision of where the SFWST Campaign DR R&D is heading provided there is no major change to the Program Direction. Section 3 provides an overview of high-level technical focus areas to cover the planned overarching priorities of the SFWST DR R&D work at a more strategic level for the next five (5) years. Some of those focus areas continue from prior R&D, whereas others have just started, and others have subparts that are yet to be initiated. This plan fulfills the Milestone M2SF-20SN010304045 in DR Work Package (WP) SF-20SN01030404 (GDSA - Framework Development – SNL).

The previous Used Fuel Disposition (UFD; from FY2011-FY2017) Campaign and the current SFWST Campaign disposal R&D programs have focused on the evaluation of the viability of mined repositories in three generic geologic media (salt, clay, and crystalline rock; e.g., Sevougian et al., 2019). The host lithologies were selected because they have been considered and analyzed as potential repository host rocks both in the U.S. and internationally for several decades (e.g., Faybishenko et al., 2016). The generic host rock types were identified at a broad level: salt includes both bedded and domal salt; clay was defined to include a broad range of fine-grained sedimentary rock types including shales, argillites, claystones, as well as soft clays; and crystalline rock may include a range of lithologies such as metamorphic gneisses, granite, and other igneous rock types. Recently generic unsaturated system mined repository concepts are also being analyzed, especially regarding their capabilities to effectively release heat via ventilation in open emplacement tunnels.

The above range of generic disposal systems evaluated thus far is not intended to represent a complete/comprehensive list of possible alternatives, and other options may also have the potential to provide safe long-term isolation. However, DOE and UFD/SFWST managers believe that R&D related to the evaluation of the selected generic media will be applicable to nearly any future program that relies on deep geologic disposal. The fundamental disposal R&D on these various generic geologic host rock systems will continue to be the cornerstone of the SFWST Disposal R&D program to underpin geologic repository disposal solutions in the U.S.

The detailed portion of this five-year plan is given in Section 2 and provides an assessment for each of the DR R&D technical areas below. The ten TA covered below are:

- Argillite Disposal R&D
- Crystalline Disposal R&D
- Salt Disposal R&D
- Geologic Disposal Safety Assessment
- Direct Disposal of Dual-Purpose Canisters
- International Collaboration in Disposal Research
- Engineered Barrier System (EBS) R&D
- Online Waste Library (OWL) – Inventory and Waste Characterization
- Technical Support for Underground Research Laboratory Activities
- Knowledge Management

In this assessment, the plan for each DR R&D TA includes sections that:

- a. identify the primary thrust topics (these are the major technical priorities in each TA: ~2 to 4)
 - iii. for the near-term (next 1- to 2-year period – i.e., our current DR R&D program)
 - iv. for the longer term 3- to 5-year period (i.e., where the DR R&D may go in the future if Program Direction remains the same)
- b. describe the activities in the TA that are addressing each of the thrust topics listed both for the program currently (i.e., near-term), and how that may change going forward to the longer-term. There is generally more detail available for the near-term, with the longer-term thrusts being discussed in comparison/contrast to the near-term thrusts.

In the next five years, the DR R&D will continue to focus on process model development and model implementation in the GDSA Framework for different generic reference cases. At the end of the five years, it is anticipated that the GDSA Framework and the reference cases will contain even more detailed representations of relevant improved process models, or surrogate models, and thus can be used for more diverse demonstrations of safety assessments, sensitivity analyses, and additional programmatic prioritization of targeted DR R&D activities in an even more robust manner than currently.

As has been the case throughout the SFWST Campaign DR R&D program, there exists a continual need to have active integration among the process-level generic geologic systems studies and the performance assessment modeling (i.e., GDSA modeling). For example, studies of direct disposal of DPC actively integrate the existing stored spent fuel as packaged with disposal studies where models of the engineered barriers and natural system are actively being modified to address conditions based on the DPC characteristics. Moving forward, tighter integration between DR R&D and the relevant S&T R&D would better define waste inventory characteristics/conditions for disposal. This would also enhance consistency of process interfaces such as SNF and cladding characteristics for disposal, physical conditions, and degradation processes, canister conditions, life cycle parameters (thermal, dose) for commercial SNF (the largest inventory for disposal), and treatment/overpack needs for DPC disposal.

Beyond the core efforts to evaluate generic geologic systems for disposal behavior and constrain their key generic natural barrier capabilities with systematic integration of process-level understanding with system evolution of natural and engineered barriers, the SFWST Campaign DR R&D activities will maintain a further focus in the next five years on the following four areas: GDSA Capabilities Development and Demonstration; International Collaboration and Underground Research Laboratories; Engineered Barrier System Representations; and Evaluation of Potential Direct Disposal of Dual Purpose Canisters.

In addition to the internal prioritizations discussed above, there are integration areas within, and potentially external to, the SFWST Campaign that may influence future planning for Disposal R&D.

Within the SFWST Campaign there are programs of R&D addressing topics on Storage and Transportation of SNF (e.g., Teague et al., 2020), in addition to Disposal Research. Improved definition of the interfaces across these R&D programs (i.e., enhanced integration) should lead to more connected data sets on aspects of the expected condition of SNF cladding and storage canisters for disposal when they are to be transported to a repository in the future. Additional understanding of the processes affecting canisters and SNF in long-term storage conditions and during transport would provide further data on FEP for post-closure constraints on materials evolution in the disposal environment. External to the SFWST campaign there are integration areas with the Integrated Waste Management Campaign (DOE NE-82), which provides a degree of coherence with other DOE Offices (such as EM) that manage wastes that will ultimately be disposed in a deep geologic repository, and with external stakeholders including local government agencies and tribal nations. Within the DOE NE-4 offices, development of new waste forms, accident tolerant fuels, and advanced reactor fuel cycles with a variety of other fuel types and potential treated waste streams may also affect facets of future planned Disposal R&D.

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Appendix A – Roadmap Reassessment and Results Summary

The 2019 Roadmap Update (Sevougian et al., 2019) utilized a systematic process that was similar in many ways to that used in the UFD 2012 Roadmap (DOE 2012), but with important differences in both the definition of the “items” or “quanta” to be prioritized, and in the criteria and process used for prioritization. There were five basic steps in the 2019 process:

1. Identify a set of items to be evaluated (e.g., R&D activities, issues, or options, ...)
2. Identify criteria and associated metrics for assessing the set of items, such as:
 - a. Importance to the safety case (ISC) (e.g., in this context, important to the post-closure safety assessment or performance assessment (PA) calculations, to technical bases supporting conceptual and numerical model development, and/or to building confidence in design concepts and process understanding)
 - b. Potential to reduce key uncertainties, i.e., to advance the state-of-the-art level (SAL) or knowledge
 - c. Other factors
3. Evaluate each item (R&D Activity) against the metrics
4. Define a “utility function” (or ranking function) to combine the metric values and produce an overall ranking or score for each item (R&D Activity)
5. Compare rankings of the items (R&D Activities)

The goal was to identify R&D items that provide maximum value to DOE in terms of advancing the program’s ability to support future decisions regarding the siting, selection, design, licensing and construction of a geologic repository. For the 2019 R&D Roadmap Update, the SFWST Campaign decided to redefine the R&D items to be prioritized. Instead of using the FEPs list as the basis, the new items to be prioritized were based on ongoing and proposed R&D work scope activities (or tasks) being performed within the SFWST Campaign (i.e., R&D Activities). Additionally, the generic FEP list was used to both map the R&D Activities to the FEP, and to help identify “gap” activities where existing R&D Activities did not fully address a FEP. To ensure that the 2019 Roadmap Update addressed all the R&D Issues identified in the 2012 Roadmap, SFWST staff identified and correlated all the medium- and high-priority FEP from 2012 with the R&D Activities defined for 2019. In this way, the 2012 FEPs list also served as a completeness check on the R&D Activities list and facilitated gap identification.

As noted above, the R&D Activities were assessed from two different perspectives or criteria, and evaluation metrics were defined for these two criteria before the Workshop. Importance to the Safety Case (ISC) was scaled as High, Medium, or Low, with specific definitions of the three scale values being dependent on the importance of the R&D Activity relative to components of a future post-closure safety case. The State-of-the-Art Level (SAL) was assigned to one of five values based on the level of knowledge currently available and what yet needs to be obtained. These two metrics were combined in synthesis work after the Workshop to define a Priority Score: High, Medium-High, Medium, or Low for each R&D Activity.

Consensus on ISC and SAL metric values was obtained within “breakout” sessions comprised of about ten to fifteen experts each, using the provided metric scales, and with guidance by the session chair and the overall Workshop chair. There were six breakout sessions: there were three host-rock (Argillite, Crystalline, Salt) day-long, concurrent sessions; and half-day concurrent sessions on EBS, DPC, and International R&D Activities (cross-cutting sessions relative to the host-rock based sessions). The PA and Other R&D Activities did not have their own separate sessions but were included in the other six sessions. Post-workshop synthesis led to priorities set for the R&D Activities across the entire set of them.

Of the eight topical R&D Activity groupings mentioned above, the DPC R&D Activity group had, by far, the highest percentage of High-Priority Activities (about 70% of its total), primarily because of the recent

work to evaluate direct disposal of DPC in generic deep geologic repository concepts, which has led to a number of newly emerging issues that are being addressed by these R&D Activities.

A review of the High- and Medium-High-priority R&D Activities (Sevougian et al., 2019) has led to the identification of a set of “High Impact R&D Topics,” including:

- High Temperature Impacts
- Buffer and Seal Studies
- Coupled Processes (Salt)
- Gas Flow in the EBS
- Criticality
- Waste Package Degradation
- In-Package Chemistry
- Generic PA Models
- Radionuclide Transport

These High Impact R&D Topics provide a high-level snapshot of the current and future generic R&D focus. Sevougian et al. (2019) provide the detailed information on how these High Impact Topics relate to specific R&D Activities, as well as elucidating some integration issues involved in generic PA model development. The Gap activities identified included:

- Technical integration between R&D Activities is essential because of the complexity of developing comprehensive technical bases, advanced process modeling capability, and generic repository reference cases for PA demonstration
- The temporal framework (or timeline) for “Generic R&D Needed” appeared to vary a lot between breakout sessions and could improve in the future with more intensive inter-group calibration prior to, and at the beginning of, the Workshop
- “Calibration” on the assignment of ISC and SAL metric values is important to develop prior to, and at the beginning of, the Workshop
- Adding a metric for level of effort (LOE) for individual activities would be very useful
- Integration of DPC-relevant parameters into all modeling activities is needed

Although much has been accomplished since 2012 both through R&D in the U.S. Program and through international collaborations, especially with those countries that operate underground research laboratories (URLs), the 2019 R&D Roadmap reevaluation reflects the need for continuing R&D on many of the 2012 R&D Issues, plus some obvious new priorities, such as R&D on disposal of DPCs (dual purpose canisters), which now contain a significant fraction of the Nation’s spent fuel activity. This new 2019 R&D prioritization effort is closely tied to advancement of capabilities in the Campaign’s generic performance assessment simulation and analysis toolkit, GDSA Framework.