Overview of Salt Repository Research and Development for Spent Nuclear Fuel and High-level Nuclear Waste in the United States - 20307

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ABSTRACT

This paper summarizes the current US Department of Energy Office of Nuclear Energy's (DOE-NE) work towards developing and executing a research and development program that addresses both scientific and technical issues related to long-term disposal of spent nuclear fuel (SNF) and high-level waste (HLW) in a hypothetical bedded salt based geological repository. A primary goal of the program is to create a generic Geologic Disposal Safety Assessment (GDSA) Framework that can be used to help guide decisions on siting a possible future bedded salt repository. The generic GDSA work includes analysis of the impacts of heat generation caused by decay of short-lived radionuclides. We report progress in four primary areas. First, we discuss the development and recent modifications of a research and development roadmap. Second, we briefly describe an experimental approach to better understand thermal processes in salt. Third, we highlight collaborations with the international research community that leverage salt-based repository science around the world. Finally, we discuss how our findings are being used to aid in the development of a generic safety assessment for a bedded salt repository containing SNF and HLW.

INTRODUCTION

The US Department of Energy Office of Nuclear Energy (DOE-NE) is actively engaged in planning for the future of spent nuclear fuel (SNF) and high-level nuclear waste (HLW) through the Spent Fuel and Waste Disposition (SFWD) Campaign. The SFWD campaign includes aspects of processing, storage, transportation, and ultimately waste disposal. Within the SFWD, the Spent Fuel and Waste Science and Technology (SFWST) office is tasked with conducting research and development (R&D) related to the geological disposal of SNF and HLW [1]. A primary objective of the R&D is to develop a range of geological disposal options that will inform decision-makers on how to best manage SNF and HLW [2].

A major piece of the R&D work is the creation of a generic Geologic Disposal Safety Assessment (GDSA) Framework, which is a suite of models and software for evaluating the potential performance of a deep geologic repository for SNF and HLW. Four reference cases and associated models have been developed within GDSA Framework, corresponding to each of four host rock types (salt, crystalline, argillite, unsaturated alluvium) that are being investigated. The GDSA Framework is a probabilistic performance assessment (PA) toolkit that predicts long-term radionuclide transport behavior [3,4], as shown in Figure 1. The GDSA Framework relies on the PFLOTRAN multi-physics software (reactive flow and transport with heat) for domain simulation [5] and the Dakota statistical software package for sampling and uncertainty analysis [6]. The philosophy in GDSA design is to have less reliance on assumptions, simplifications, and model abstractions and include significant coupled (multi-physics) processes in three-dimensions [7].

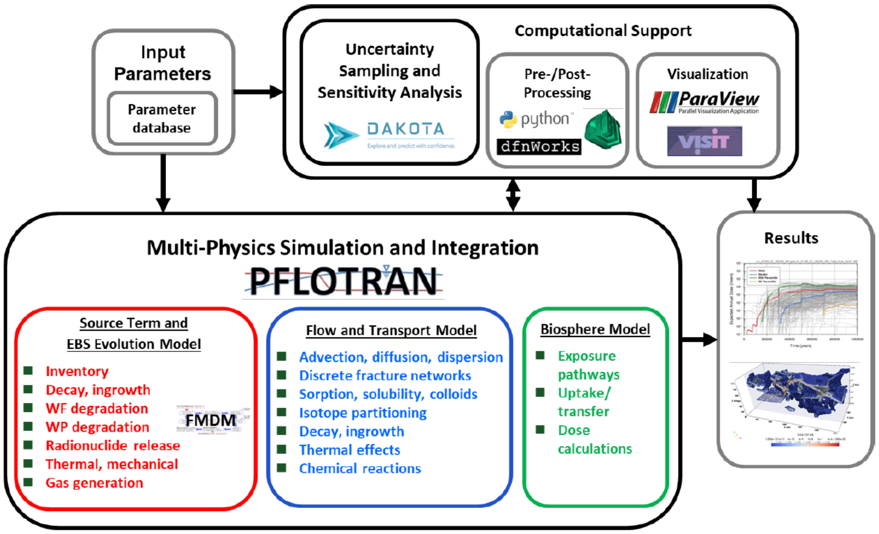

Figure 1. *GDSA Conceptual Diagram. From [4].*

Here we focus on the GDSA model and supporting process models for the generic bedded salt repository reference case and report on progress made since the generic repository R&D program was initiated in 2011 [2].

Although the basis for a long-term salt safety case for HLW and SNF is strong [8], US R&D programs continue [9,10,11] to reduce uncertainty, improve understanding of short-term complex processes, demonstrate operational concepts, confirm performance expectations, improve modeling capabilities, and improve stakeholder confidence in our predictions of future repository behavior [12].

To this end, three US National Laboratories (Sandia (SNL), Berkeley (LBNL), and Los Alamos (LANL)) have been working together for nearly 10 years to:

1) Develop a roadmap for generic salt repository R&D,
2) Conduct experiments and simulations to better quantify processes and ranges of parameters,
3) Develop international collaborations to leverage ongoing salt repository research around the world,
4) Provide input to a generic salt repository GDSA reference case.

In the following sections we develop each of these points and give examples of progress in the US generic salt repository program.

DEVELOPMENT OF A ROADMAP FOR GENERIC SALT REPOSITORY R&D

The R&D Roadmap for bedded salt host rock includes analysis and ranking of Features, Events, and Processes (FEPs) that are relevant to generic bedded salt repositories [13,14,15]. Originally published in 2012 [2], the R&D Roadmap for salt includes FEPs that are relevant to disposal in a hypersaline salt environment in the presence of heat generating HLW and SNF [9].

In January 2019 an update of the R&D Roadmap was performed to revisit R&D priorities. The 2019 R&D Roadmap Update summarizes the progress of ongoing generic disposal R&D activities, re-assesses previous R&D priority rankings, and identifies new activities of high priority [12,16].

Progress on several FEPs resulted in reduction of their R&D ranking. Knowledge gained during the campaign has also compelled the team to add R&D topics and FEPs that had originally not been called out.

Updates to Generic Salt R&D Priorities Related to GDSA integration

Within the salt R&D team, the focus in the workshop was to revise the Salt R&D Activity Table to reflect progress in the ongoing generic repository campaign. Nearly all salt tasks were modified in some manner. State-of-the-Art Levels (SAL) were reduced for several of the tasks (S-2, S-6, S-9, and S-10; Table 1) based on consensus that progress had been made in these areas. For example, S-9 was lowered from a SAL of 5 to a SAL of 3 because of advances made in the thermal-hydrological-mechanical-chemical (THMC) porous flow simulators FEHM [17], TOUGH/FLAC [18], and PFLOTRAN [19]. FEHM and TOUGH have well established capabilities from previous studies, while the newer, massively parallel simulator PFLOTRAN still requires further validation in some areas, with several salt specific constitutive models added for completeness. The recommendation from the workshop is to: “Perform code comparisons among PFLOTRAN, TOUGH, and FEHM on repository relevant simulations. Modeling will be calibrated on laboratory data and validated on field data.” S-10 (Drift re-saturation process in PA) was also lowered from a SAL of 5 to a SAL of 3 because drift re-saturation can be handled in the process-level simulation tools; however, this process is not currently in the GDSA salt repository reference case [3].

In addition to updating the SALs, the salt R&D team added three R&D tasks that the team agreed should be called out separately (S-11, S-12, and S-13). S-11 was added to acknowledge that further work is needed on the impacts of anhydrites, clays, and other non-salt components, especially in the presence of strong thermal gradients. These layers can be important because the permeability and porosity of bedded salt is such that non-salt layers may provide significant pathways or sources of brine [20], which can impact long-term performance. Further, non-salt layers have an impact on mechanical deformation. It was determined that it will be difficult to represent these layers in PA calculations because they are usually centimeter- to meter-scale heterogeneities. Integration of these layers into PA may require that a generic salt reference case include some effects of stylized non-salt layers. For the short-term, it was suggested that a process-modeling approach should be used to determine whether these features and their effects are important at repository time/length scales [21].

Table 1 2019 Salt R&D Tasks (Tasks and values in bold italics were modified from the 2012 analysis).

R&D Task #	R&D Task (or Activity) Name	2019 SAL Numerical Value**	2019 ISC Numerical Value
S-1	Salt Coupled THM processes, hydraulic properties from mechanical behavior ***(geomechanical)***	5	5
S-2	Salt Coupled THM processes, creep closure of excavations	***4***	5
S-3	Coupled THC ***advection and diffusion*** processes in Salt, ***multi-***phase flow processes and material properties in Salt	5	5
S-4	Coupled THC processes in Salt, Dissolution and precipitation of salt near heat sources ***(heat pipes)***	5	5
S-5	Borehole-based Field Testing in Salt	5	5
S-6	Laboratory Experiments to Validate Coupled Process models in Salt ***(in support of field test S-5)***	***3***	5
S-7	Brine ***Origin,*** Chemistry, and Composition in Salt ***(in support of field test S-5)***	4	5
S-8	Evolution of ***run-of-mine salt backfill***	4	5
S-9	Numerical modeling of dry-out in multiphase	***3***	3
S-10	***Drift re-saturation process in PA***	***3***	3
S-11	***THMC effects of anhydrites, clays, and other non-salt components***	***4***	***5***
S-12	***Laboratory testing and modeling of fluid inclusions***	***4***	***3***
S-13	***Acid gas generation, fate, and transport***	***5***	***3***

Salt R&D task S-12 was included to highlight ongoing work to understand the role of fluid inclusions in the short-term availability of brine. However fluid inclusion migration will be secondary to the long-term repository behavior. A process-modeling approach will be used to assess whether these features and their effects are important at repository time/length scales.

Salt R&D task S-13 was added because some laboratory conditions show hydrochloric acid formation from heating of WIPP salt above 150 °C [11] (Figure 2). Acid gas generation would impact long-term repository performance in a secondary way, however it was acknowledged that a process-modeling and laboratory experimental approach is required to determine the importance of these features and their effects.

Figure 2. Oven Corrosion after Heating WIPP salt from Clay Seam F.

CONDUCT EXPERIMENTS AND SIMULATIONS TO BETTER UNDERSTAND PROCESSES AND RANGES OF PARAMETERS

The experimental/simulation task was initiated in 2011 and built up from simple bench-top systems to more complex analyses including coupled THMC processes [11,22,23]. Analysis of existing data on brine production during heating of salt revealed R&D gaps [10,24]. In 2015, the US salt R&D team published a high-level test plan that laid out a phased approach for field testing, starting with heating in horizontal boreholes and ramping up to larger tests [11], which was based on a detailed R&D Study Plan for bedded salt [13,14]). The US salt R&D team is currently installing the first phase of this test plan, a thermal test (Brine Availability Test in Salt – BATS) at repository level in WIPP that is designed to provide data that our conceptual models and simulation tools can be tested against [22,25]. The BATS experiment is useful for (1) understanding the details brine distribution and migration, (2) assessing damage related to mining and disturbance, (3) confirming salt material properties, and (4) model validation. The test will also (5) provide ramp-up opportunities for testing new equipment and sensors in the field and develop modern best practices for in-situ experimentation to use during the larger tests in this staged testing plan.

Here, we show one example that demonstrates the need to use a radiative heat source to overcome poor connectivity in a stainless-steel block heater. Predictions made using FEHM [26,27] assumed perfect contact between the metal block heater and the rock salt in the borehole wall (Fig. 3). Data collected from Phase 1s of the BATS test showed that this assumption was not correct, and that the true connectivity was likely only occurring where the metal touched the salt, not where an air gap was present with poor thermal conductivity. Material properties used in the simulations are shown in Table 2. The simulations are performed on a 3-D mesh with high resolution (cm scale) spacing around the heated borehole.

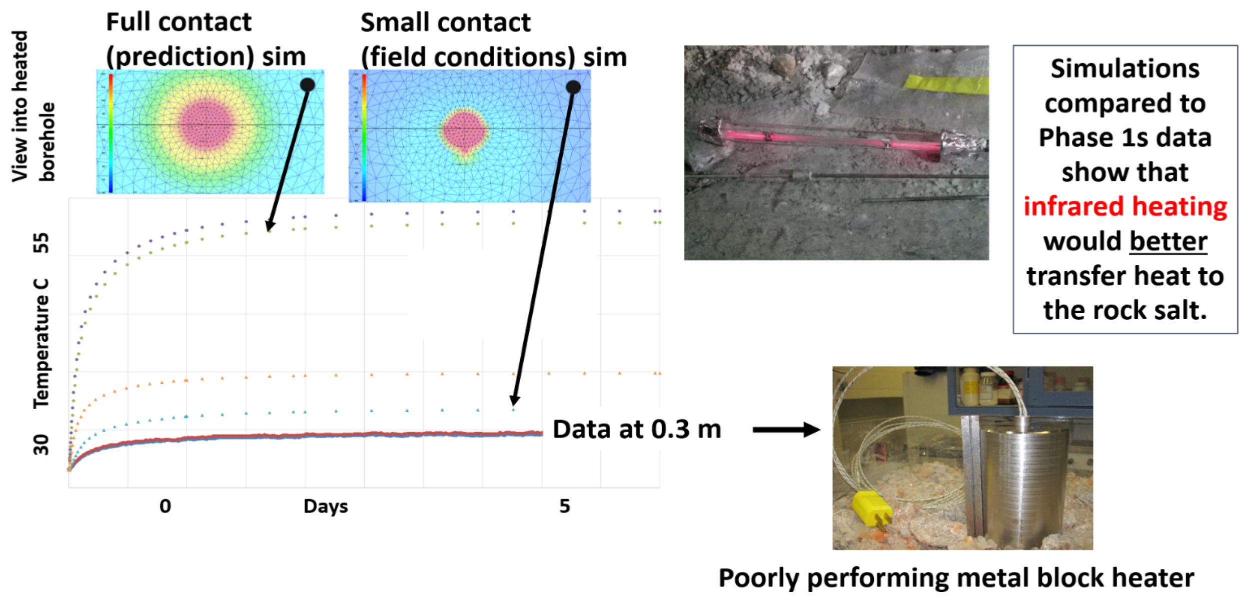

Figure 3. Experimental results led to the project switching from a poorly performing metal block heater to a more efficient infrared heater.

By introducing an infrared heater to the borehole, we were able to increase temperatures at a monitoring point located approximately 0.3 m from the heated borehole (Fig. 4).

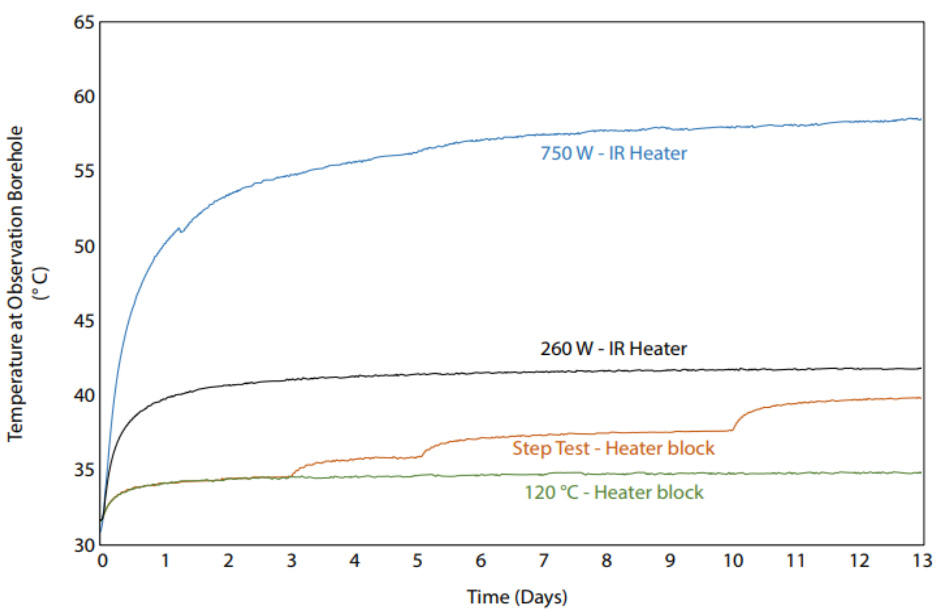

Figure 4. Temperatures observed at approximately 0.3 m away from the heated borehole in BATS Phase 1s.

Table 2: Material properties used in simulations.

Material	Porosity	Density (kg/m^3)	Thermal conductivity ($W/(m\cdot K)$)	Heat capacity ($J/(kg\cdot K)$)	Permeability (m^2)
Rock Salt	0.001	2170	Variable	931	1×10^{-20}
Air	-	1	0.06	1000	1×10^{-12}
Packer	0.9	300	1	500	1×10^{-26}
Heater	0.001	8000	15	1000	1×10^{-12}

DEVELOP INTERNATIONAL COLLABORATIONS TO LEVERAGE ONGOING SALT REPOSITORY RESEARCH AROUND THE WORLD

DOE-NE participates in numerous international collaborations spanning each of the three geologic disposal mediums [28] (Figure 5). During the life of the SFWST project, international collaborations between the three US national laboratories (SNL, LANL, and LBNL) and the international community have grown and strengthened. The US salt R&D team is involved in two international salt research working groups including the NEA Salt Club and the US/German Salt R&D Workshop. The US R&D team is also involved in several salt experimentation and benchmarking projects, two of which (KOMPASS and WEIMOS) are briefly summarized.

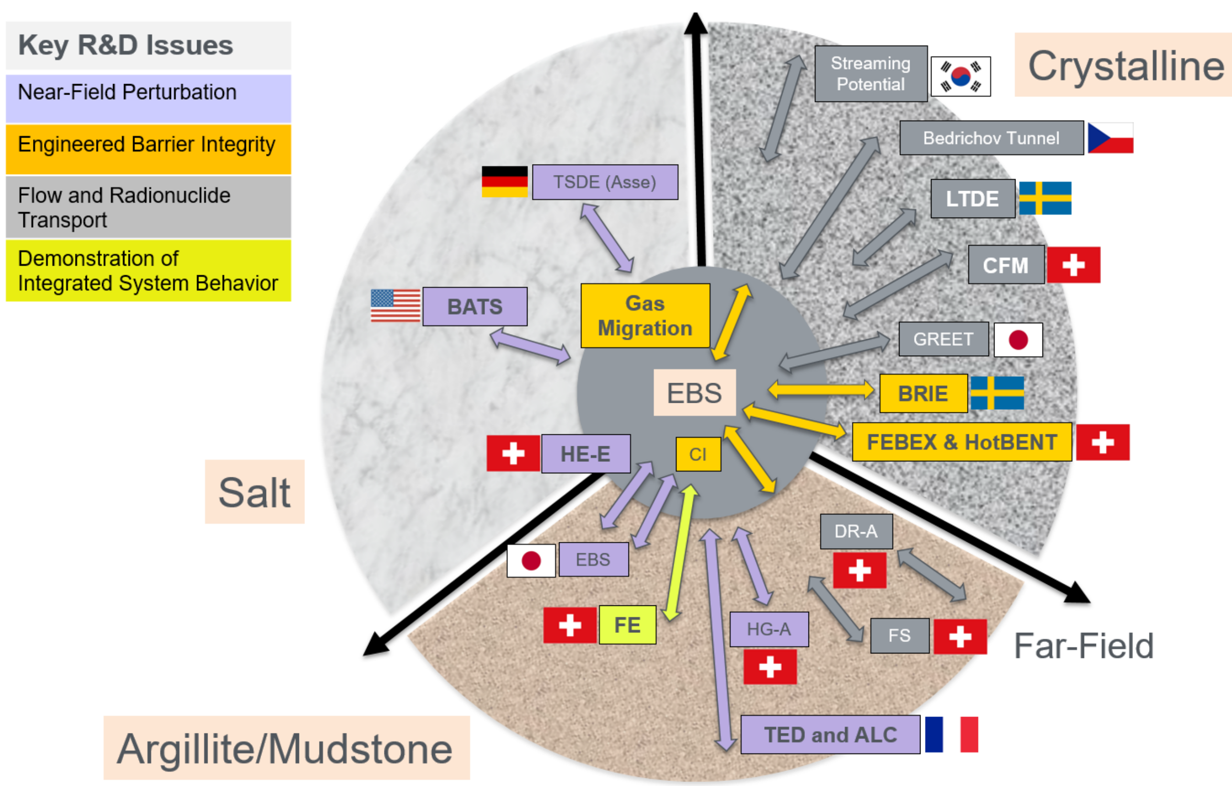

Figure 5. DOE-NE international portfolio. From [28].

International Collaboration: Salt Research Working Groups

Two major collaborative efforts funded by DOE-NE Salt International R&D are co-organization of, and participation in, both the US/German Workshop on Salt Repository Research, Design, and Operation and the Nuclear Energy Agency (NEA) Salt Club. NEA has developed an international FEPs database and continues to coordinate international efforts on SNF and HLW research [29]. The ninth meeting of the NEA Salt Club took place in Rapid City, South Dakota May 31, 2019. The tenth meeting of the US/German Workshop took place at South Dakota School of Mines May 28-29, 2019. These international collaborations are summarized in two reports [30,31].

Both of these endeavors aim to bring together researchers from the international community to discuss on-going R&D into salt-based geological storage of HLW and SNF. Annual meetings involve the exchange of information through presentations and discussion groups. Outcomes from these R&D working groups include increased cross-organizational sharing of data and ideas, faster recognition and inclusion of multiple organizations in salt experimentation and benchmarking projects, and increased ability to plan a coherent and efficient worldwide strategy for subsurface disposal of HLW and SNF.

Of particular interest and relevance to the US generic repository R&D effort, German partners recently completed an R&D project to develop a generic HLW repository concept in bedded salt (KOSINA), to complement the existing strong German case for domal salt. This project underlines the parallel nature of R&D between the two countries with ample opportunity for collaboration and knowledge sharing.

International Collaboration: Salt Experimentation and Benchmarking Projects

Here we discuss international collaborations on two R&D projects dealing with experimentation and benchmarking of numerical simulators for granular salt reconsolidation (KOMPASS) and geomechanical behavior of solid rock salt (WEIMOS).

KOMPASS is a collaboration between German and US researchers with a goal of improving consistency in laboratory testing procedures and development of thermo-hydro-mechanical (THM) constitutive models for crushed salt. The acronym KOMPASS, stands for "Compaction of Crushed Salt for Safe Enclosure". The KOMPASS partners include Bundesgesellshaft für Endlangerung Technology (BGE, Germany), Institute für Gebirgsmechanik (IfG GmbH, Germany), Technical University of Clausthal (Germany), Gesellschaft für Anglagen-und Reaktorsicherheit (GRS, Germany), Bundesanstalt für Geowissenschaften und Rohstoffe (BGR, Germany), and Sandia National Laboratories (USA) [30].

WEIMOS is a collaboration of German and US researchers working to improve thermomechanical modeling of salt repositories. The group aims to improve constitutive models for creep and healing of rock salt, including extensive laboratory test programs that provide data to calibrate simulations of the closure of underground openings such as drifts, boreholes, and shafts. The acronym WEIMOS stands for "Further Development and Qualification of the Rock Mechanical Modeling for the Final High-Level Waste Disposal in Rock Salt" [30]. WEIMOS partners include Hampel Consulting (Germany), Institute für Gebirgsmechanik (IfG GmbH, Germany), Leibniz University (Germany), Technical University of Braunschweig (Germany), Technical University of Clausthal (Germany), and Sandia National Laboratories (USA).

Finally, the DOE-NE Salt International R&D team has been invited to participate in the DECOVALEX (DEvelopment of COupled models and their VALidation against Experiments) project through sharing data from the BATS Phase 1 URL experiment. This new activity will allow US URL data to be shared with the international community and will lead to corroborative analyses with the potential to highlight benefits of using different modeling approaches to understand complex coupled processes.

PROVIDE INPUT TO A GENERIC SALT REPOSITORY GDSA REFERENCE CASE

The numerical simulation methods being developed through the R&D Roadmap Update [16] are being tested against data collected from experiments in both the US and the international salt R&D community to aid in creating a generic salt repository GDSA reference scenario. In the following two sections we discuss ideas developed after the 2019 R&D Roadmap Update for integrating processes-level simulation results into the generic GDSA reference case.

Permeability Evolution of Run of Mine Salt

Blanco-Martin et al. [32] present simulations using the THMC model TOUGH/FLAC that show a prediction of the evolution of porosity and permeability in Run-of-Mine salt for up 100,000 years. This work is being used to help guide future choices for the timing of permeability changes in the GDSA salt reference case, where the computational overhead of a coupled THMC model is not feasible. For example, in Figure 6, the permeability at 1000 years is estimated to be on order of 1 x 10^{-15} m^2. The current salt reference case backfill for a deterministic simulation is assigned a porosity of 0.113 and a permeability of 10^{-18} m^2 [3]. For probabilistic simulations the salt reference case samples porosity values from a uniform uncertain distribution between 0.01 and 0.20. The differences in the simulated permeability as a function of porosity for salt backfill between the TOUGH/FLAC and PFLOTRAN models is one point that is being improved, since this parameterization could have significant impact on transport through the drifts, rooms, and halls during the first 1000+ years of the post-closure repository. Further improvements of constitutive models and quantification of uncertainty in THMC calculations are also needed to improve overall GDSA accuracy and efficiency.

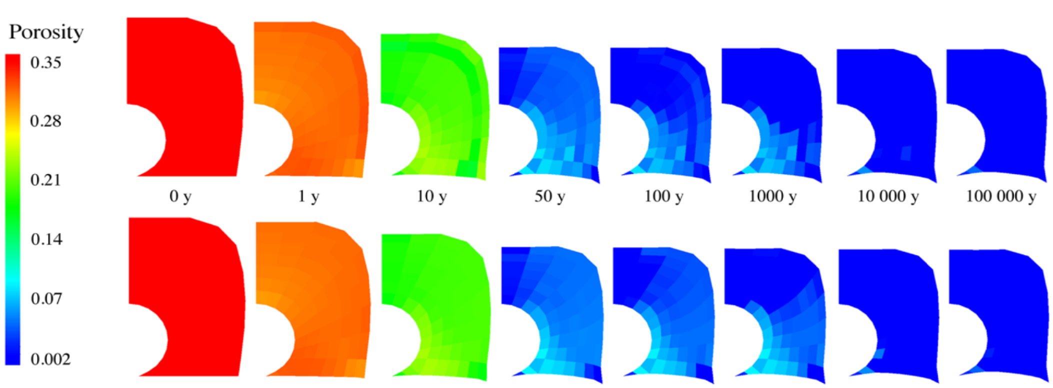

Figure 6. Porosity evolution for a generic salt repository: granular salt porosity at different dates during the post-closure phase. Top: case including halite solubility constraints; bottom: case neglecting halite solubility constraints [32].

Initial Run of Mine Salt Porosity

Johnson et al. [33] present simulations of a canister buried under WIPP Run of Mine (RoM) salt for nearly 9 months with 1000 W of heating (Fig. 7). Results from this analysis suggest that the initial porosity of the salt pile was close to 30%. The current salt reference case backfill is assumed to have an initial porosity of 35% [3]. The newly estimated initial RoM salt porosity can be used as input for both the TOUGH/FLAC and PFLOTRAN models. The new value is based on the thermal response of a large pile and is likely more robust than measurements taken on smaller samples, but both analyses do not include the largest aggregate found in typical run of mine salt (e.g., baseball size and larger).

Figure 7. Heater buried under a pile of WIPP Run of Mine salt [33].

CONCLUSIONS

Although much has been accomplished since 2012, through R&D in the U.S. and through international collaborations, the 2019 R&D Roadmap Update reflects the need for continuing R&D on many of the 2012 R&D issues, plus some new priorities. The new 2019 R&D prioritization effort is closely tied to the development of the DOE SFWST Campaign’s generic performance assessment model/software framework, GDSA (Geologic Disposal Safety Assessment) Framework, which results in much of the R&D being directly related to the supporting process models that feed the PA model and software. Given the importance of post-closure performance assessment in building confidence in the safety case, this path forward will lead to reductions in uncertainty in key components of the GDSA reference case and result in more robust predictions of future generic repository behavior [8].

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