LANL Contributions to Salt International Activities: 2020

Spent Fuel and Waste Disposition

Prepared for
US Department of Energy
Spent Fuel and Waste Science and Technology
Milestone M3SF-20LA010303042

Los Alamos National Laboratory
Eric Guiltinan, Michelle Bourret, Thom Rahn, Philip H. Stauffer

Sandia National Laboratories
Kristopher L. Kuhlman, Richard Jayne

Lawrence Berkeley National Laboratory
Jonny Rutqvist, Mengsu Hu

November 30, 2020
LA-UR-20-29681

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. SAND2020-13548 O

APPENDIX E

NFCSC DOCUMENT COVER SHEET [1]

Name/Title of Deliverable/Milestone/Revision No.	LANL Contributions fo Ssalt International Activities: 2020
Work Package Title and Number	Salt Disposal R&D SF - 20LA01030304
Work Package WBS Number	1.08.01.03.03
Responsible Work Package Manager	Phil Stauffer (Signature on file) (Name/Signature)

Date Submitted 11/30/20

Quality Rigor Level for Deliverable/Milestone[2]	☐ QRL-1 ☐ Nuclear Data	☐ QRL-2	☑ QRL-3	☐ QRL 4 Lab QA Program[3]

This deliverable was prepared in accordance with Los Alamos National Laboratory (LANL)
(Participant/National Laboratory Name)

QA program which meets the requirements of
☑ DOE Order 414.1 ☐ NQA-1 ☐ Other

This Deliverable was subjected to:

☑ Technical Review	☐ Peer Review
Technical Review (TR)	**Peer Review (PR)**
Review Documentation Provided	**Review Documentation Provided**
☐ Signed TR Report or,	☐ Signed PR Report or,
☐ Signed TR Concurrence Sheet or,	☐ Signed PR Concurrence Sheet or,
☑ Signature of TR Reviewer(s) below	☐ Signature of PR Reviewer(s) below
Name and Signature of Reviewers	**Name and Signature of Reviewers**
Hari Viswanathan (Signature on file)	

NOTE 1: *Appendix E should be filled out and submitted with each deliverable. Or, if the PICS: NE system permits, completely enter all applicable information in the PICS: NE Deliverable Form. The requirement is to ensure that all applicable information is entered either in the PICS: NE system or by using the NFCSC Document Cover Sheet.*

- *In some cases there may be a milestone where an item is being fabricated, maintenance is being performed on a facility, or a document is being issued through a formal document control process where it specifically calls out a formal review of the document. In these cases, documentation (e.g., inspection report, maintenance request, work planning package documentation or the documented review of the issued document through the document control process) of the completion of the activity, along with the Document Cover Sheet, is sufficient to demonstrate achieving the milestone.*

NOTE 2: *If QRL 1, 2, or 3 is not assigned, then the QRL 4 box must be checked, and the work is understood to be performed using laboratory QA requirements. This includes any deliverable developed in conformance with the respective National Laboratory / Participant, DOE or NNSA-approved QA Program.*

NOTE 3: *If the lab has an NQA-1 program and the work to be conducted requires an NQA-1 program, then the QRL-1 box must be checked in the work Package and on the Appendix E cover sheet and the work must be performed in accordance with the Lab's NQA-1 program. The QRL-4 box should not be checked.*

E-1

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

BATS	Brine Availability Test in Salt
DECOVALEX	DEvolpment of COupled models and their VALidation against EXperiments
DOE	Department of Energy
DOE-NE	DOE Office of Nuclear Energy
DRZ	disturbed rock zone
HLW	high level nuclear waste
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
SFWD	Spent Fuel & Waste Disposition
SFWST	Spent Fuel and Waste Science and Technology
SNL	Sandia National Laboratories
THMC	thermal, hydro, mechanical, chemically coupled
UK	United Kingdom
WIPP	Waste Isolation Pilot Plant (DOE-EM site)

This page is intentionally left blank.

2020 LANL INTERNATIONAL COLLABORATION ON SALT REPOSITORY RESEARCH

1. Introduction

The Spent Fuel and Waste Science and Technology (SFWST) Campaign of the U.S. Department of Energy (DOE) Office of Nuclear Energy (DOE-NE) is tasked with conducting research and development related to the geological disposal of spent nuclear fuel (SNF) and high-level nuclear waste (HLW).

As part of the Spent Fuel and Waste Disposition (SFWD) program within the SFWST, LANL, LBNL, and Sandia are supporting international collaboration. The objective is to share knowledge between the US SFWD program and foreign programs on technical issues related to disposal of heat generating radioactive waste in salt. This report focuses on contributions by LANL to the DOE-NE SFWD program in salt. The Sandia and LBNL authors are included because the international collaborations related to the Brine Availability Test in Salt (BATS) and DECOVALEX are inherently inter-lab, as well as international. That being said, these international collaborations focus on the contributions of LANL. Sandia also has an annual report on international collaboration (Kuhlman et al., 2020a). Both the Sandia and LANL international reports feed the LBNL international report (Rutqvist et al., 2020).

Since June, 2019 DOE-NE's international collaborations has included LANL participation in the 2020 Waste Management Symposia and the DECOVALEX international benchmarking collaboration. At the Waste Management Symposium, held in Phoenix, AZ, LANL presented three technical papers, two oral presentations, and a technical poster. In April 2020 the 2023 DECOVALEX benchmarking project began. LANL is participating in Task E along with international collaborators from the UK, Netherlands, and Germany. This collaboration has already yielded important model implementation improvements and will continue to benefit modeling of the Brine Availability Test in Salt (BATS) project moving forward. LANL is also participating in Task F-2, related to performance assessment in salt. LANL's participation in Task F-2 is primarily to participate in discussions of assumptions and risk drivers in site performance modeling and to gain insight into international perspectives on model integration into performance modeling. In addition to these activities LANL has begun to interface with the BenVaSim community. BenVaSim is an international collaboration run out of Germany designed to benchmark THMC codes for nuclear waste activities.

Typically LANL would participate in the US-German workshop and the Salt Club meetings. However these meetings were cancelled in 2020 due to COVID and we are making plans to participate in 2021. LANL attended the 2019 Rapid City S.D. US-German workshop and presented on the BATS testing.

In this report we present an overview of the collaborative work completed as part of the DECOVALEX project, the preliminary work completed for BenVaSim, as well as the talks and publications presented to the international audience of the 2020 Waste Management Symposium.

2. DECOVALEX

The DEvolpment of COupled models and their VALidation against EXperiments (DECOVALEX) is an international collaboration on benchmarking simulations against experimental data. DECOVALEX has a nearly global reach with teams from across Asia, North America, and Europe. Every four years the DECOVALEX community selects new experimental projects which form the basis of each DECOVALEX task for the following four years. In 2019 Phil Stauffer (LANL) and Kris Kuhlman (Sandia) participated in the final DECOVALEX 2019 meeting and made a pitch for the inclusion of the Brine Availability Test in Salt (BATS) experiments to be included in DECOVALEX 2023. The modeling of the BATS experiment is now Task E of DECOVALEX 2023 which began in April 2020. Task E includes teams from the Netherlands, UK, and Germany as well as a DOE-NE team comprised of LANL, Sandia, and LBNL Table 2-1.

Table 2-1. DECOVALEX participants in Task E

Team	Country	Modeling Tool	Type
BGR	Germany	OpenGeoSys V5	FE Multiphysics
COVRA	Netherlands	COMSOL	FE Multiphysics
GRS	Germany	CODE_BRIGHT	FE THMC
Quintessa	UK	QPAC	FV Multiphysics
DOE: LANL/LBNL/SNL	USA	FEHM/TOUGH-FLAC/PFLOTRAN	FV THM(M)C

Over the course of the next four years these teams will develop thermal, hydrological, mechanical, and chemically coupled (THMC) simulations of the brine and temperature response of salt formations to heat. These simulations will be validated to historical datasets from the Waste Isolation Pilot Plant (WIPP) as well as the ongoing BATS experiment. Task E is designed in four steps of increasing complexity through the inclusion of additional physical processes. Step 0, which began in April is the simplest, with simulations validated against historical brine flow measurements and the temperature response during Phase 1a of BATS. These simulations include only brine flow (H) or temperature response (T) and do not necessarily require coupling or the inclusion of the mechanical or chemical response. In this manner, the teams can build THMC experience together and have confidence in the accurate performance of each aspect of their simulations.

Phase 0 includes three simulations. The first two are simulations of boreholes drilled at WIPP as part of the Small-Scale Brine Inflow Experiments (Finley et al., 1992). The Small-Scale Brine Inflow Experiments was a collection of 17 boreholes which were installed and monitored for brine accumulation beginning in 1987. Two of the rooms which had boreholes installed were selected for simulation, Room L4 and Room D.

2.1 Room L4

The Room L4 experiment being simulated consisted of a single borehole, L4B01, which was drilled into map Unit 0 at WIPP (Figure 2-1) on May 16th, 1989. This was approximately two months after the excavation of the L4 room in March, 1989. L4B01 was 10 cm in diameter and 5.8 m in length upon completion. The borehole was sealed with a mechanical plug and periodically opened to allow accumulated brine to be removed by vacuum through a small-diameter tube. Water production from the borehole was reported for a little over two years (750 days) in Finley et al., 1992.

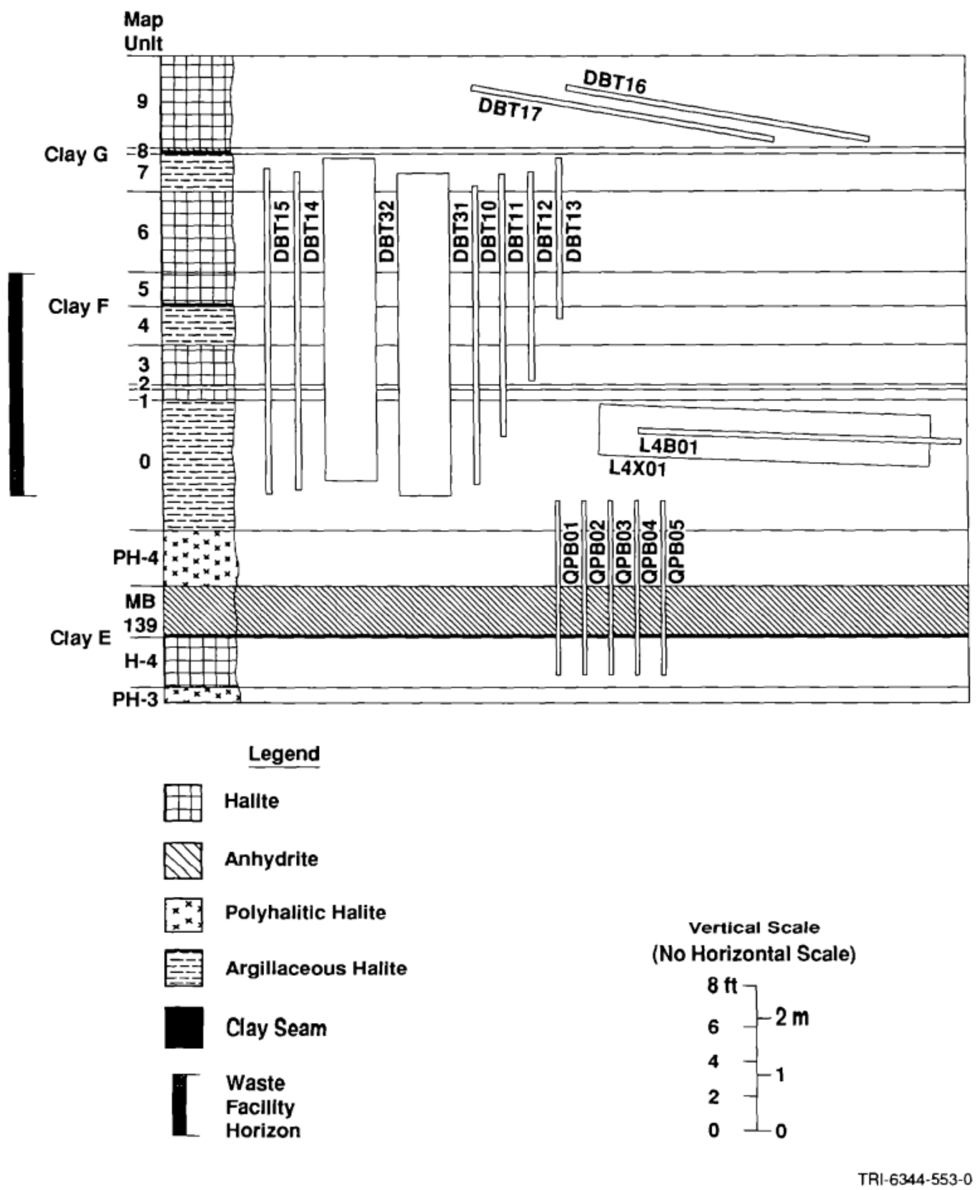

Figure 2-1. Location of the Room L4 and Room D boreholes within the lithologic strata of WIPP (Finley et al., 1992).

Modeling of the L4B01 experiment was completed by LANL and LBNL and the model development and results were presented at the annual DECOVALEX meeting in November, 2020. LANL's modeling approach utilized the porous medium flow simulator FEHM (Finite Element Heat and Mass transfer code; Zyvoloski et al., 2012; https://fehm.lanl.gov) and a 2D axially symmetric geometric mesh. The model domain was 5 × 12 m with 6,426 nodes with the L4B01 borehole placed in the geometric center. The L4B01 borehole was installed completely within map Unit 0 which is an argillaceous halite. For the purposes of this modeling we assumed map Unit 0 is homogeneous with a permeability of 1.2×10^{-22} m^2. The background formation pressure was set to 12 MPa and an atmospheric pressure and zero saturation boundary condition was used to represent the drift. At the back and far edge of the model a 12 MPa pressure and fully saturation boundary condition was used to represent the conditions at WIPP away from the mine (Figure 2-2). After 60 days the borehole was added to the model and dry air is circulated within the borehole to pick up and remove any water vapor. A 5 cm disturbed rock zone (DRZ) with a permeability of 5.0×10^{-18} m^2 was included around the borehole to represent the increased permeability due to drilling. This modeling approach is similar in concept to that used to model the BATS shakedown experiment (BATS Phase 1s) which was presented in Guiltinan et al., 2020a.

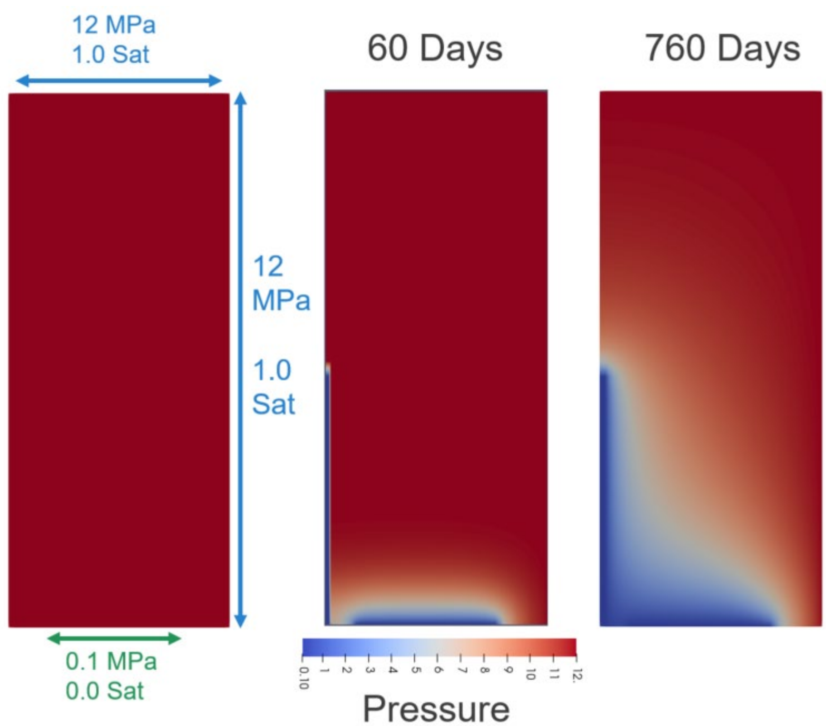

Figure 2-2. Boundary conditions and pressure distribution through time for the L4B01 borehole.

LBNL's modeling approach utilized the TOUGH simulation code (Transport Of Unsaturated Groundwater and Heat; Blanco-Martin et al., 2018, Rutqvist, 2017; http://tough.lbl.gov) and a 1D axially symmetric geometric mesh. LBNL used a background formation pressure of 12 MPa with a 12 MPa pressure and fully saturation boundary condition at the outer boundary. A permeability of 0.6×10^{-22} m^2 was used for the formation without the inclusion of a DRZ. The one dimension inflow rate was summed over the 5.6 m sealed borehole length. The model implements a 70% relative humidity within the borehole and removes water vapor as the relative humidity exceeds 70% (Figure 2-3).

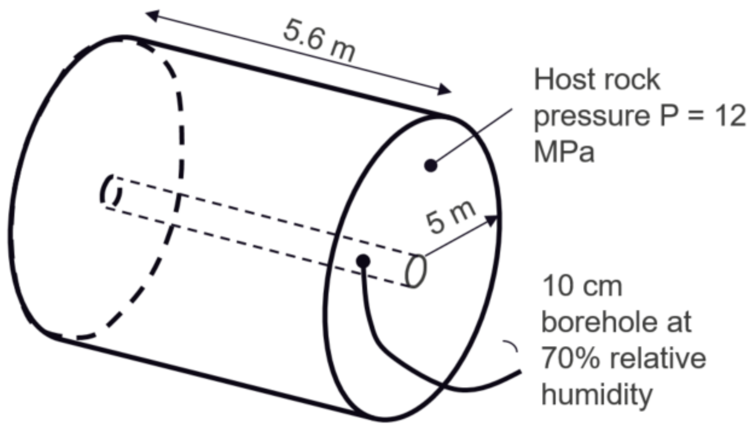

Figure 2-3. Boundary conditions model schematic of the LBNL model for L4B01.

The results of the two simulations are in close agreement despite the significant differences in model development (Figure 2-4). This provides an example of the benefit of DECOVALEX which allows different teams to observe the model development of each other, gain insights, and refine their approaches. Other modeling groups at DECOVALEX took similar, yet slightly different, approaches to this problem with each team being generally successful.

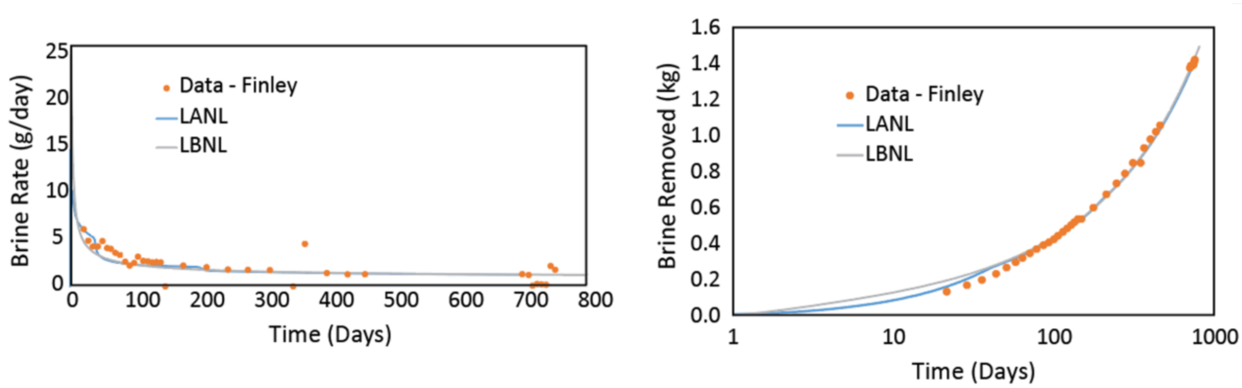

Figure 2-4. Comparison between the LANL and LBNL model results of the L4B01 brine inflow experiment.

2.2 Room D

Room D excavation was completed in March 1984 and the ten boreholes used for the small scale brine inflow experiments were drilled in September 1987. Room D was open for approximately 3.5 years before the boreholes were installed. Figure 2-1 shows the lithologic units crossed by each of the Room D wells (the "DBT" wells). For Task 0 of DECOVALEX the teams attempted to model the brine accumulation in wells DBT10, DBT11, DBT12, DBT13. The purpose of this task is to explore the effect of lithologic heterogeneity as well as the effect of closely spaced wells upon one another.

The modeling of Room D brine accumulation was completed by Sandia and LANL. Sandia used the TOUGH simulator and a 3 dimensional model which included the lithologic heterogeneity encountered by each of the four boreholes. The model is 40 m long, 5.6 m wide, and 10 m deep with uniform mesh spacing and includes 912,000 grid cells (Figure 2-5). The permeability and porosity of each lithologic unit is presented in Table 2-2.

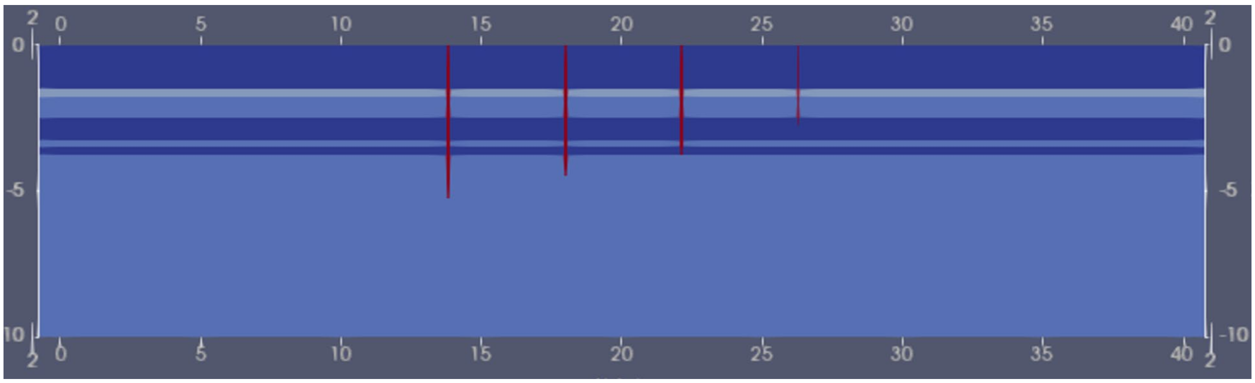

Figure 2-5. Sandia model of the Room D experiments. Layers represent the different lithologic units shown in Figure 2-1.

Table 2-2. Important lithology and hydraulic parameters for the Sandia Room D model.

Lithology	Permeability (m^2)	Porosity (-)
Halite (Dark Blue)	1×10^{-22}	0.001
Clay (Gray/Blue)	1×10^{-19}	0.15
Argillaceous Halite (Light Blue)	1×10^{-21}	0.001
Wells (Red)	1×10^{-12}	0.99

Sandia's model includes an initial pressure distribution development in a similar manner to the LANL L4B01 simulation. To represent the 3.5 years that the drift was open prior to the drilling of the Room D boreholes an atmospheric pressure boundary condition is applied to the top of the model and a 12 MPa background formation pressure is applied to the bottom (Figure 2-6). This simulation is run for 3.5 years of model time to arrive at an initial pressure distribution. The borehole are then inserted into the model and the brine accumulation is simulated. The final pressure distribution is shown in Figure 2-7.

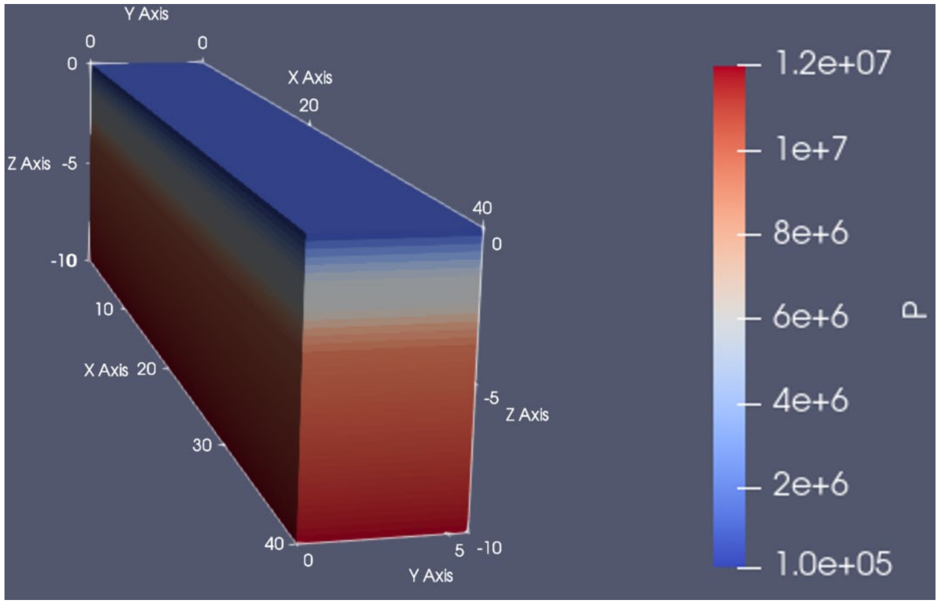

Figure 2-6. Oblique view of the Sandia Room D model and the development of the initial pressure distribution (Pa)

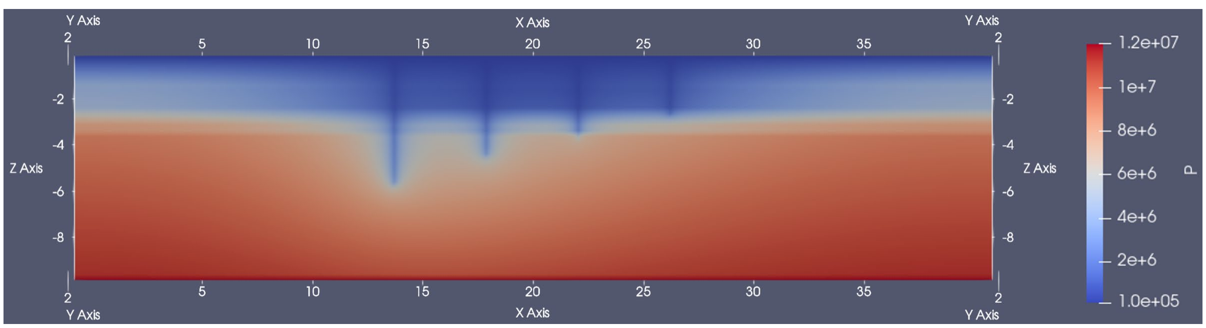

Figure 2-7. Two dimensional slice showing the final pressure distribution (Pa) after simulating the Room D brine accumulation experiment.

LANL's modeling of the Room D experiment was completed using FEHM and a three dimensional half-space symmetric orthogonal grid. The model was 40m long, 10m wide, and 30m deep with a total of 52,394 nodes with variable grid spacing that had an increased discretization around the wells. A schematic of the model is shown in Figure 2-8. An atmospheric pressure and zero saturation boundary condition was applied at the top and a 12 MPa formation pressure was applied at the bottom. An initial pressure and saturation distribution was developed in the same manner as the Sandia model. The permeability and porosity of each of the units is presented in Table 2-3.

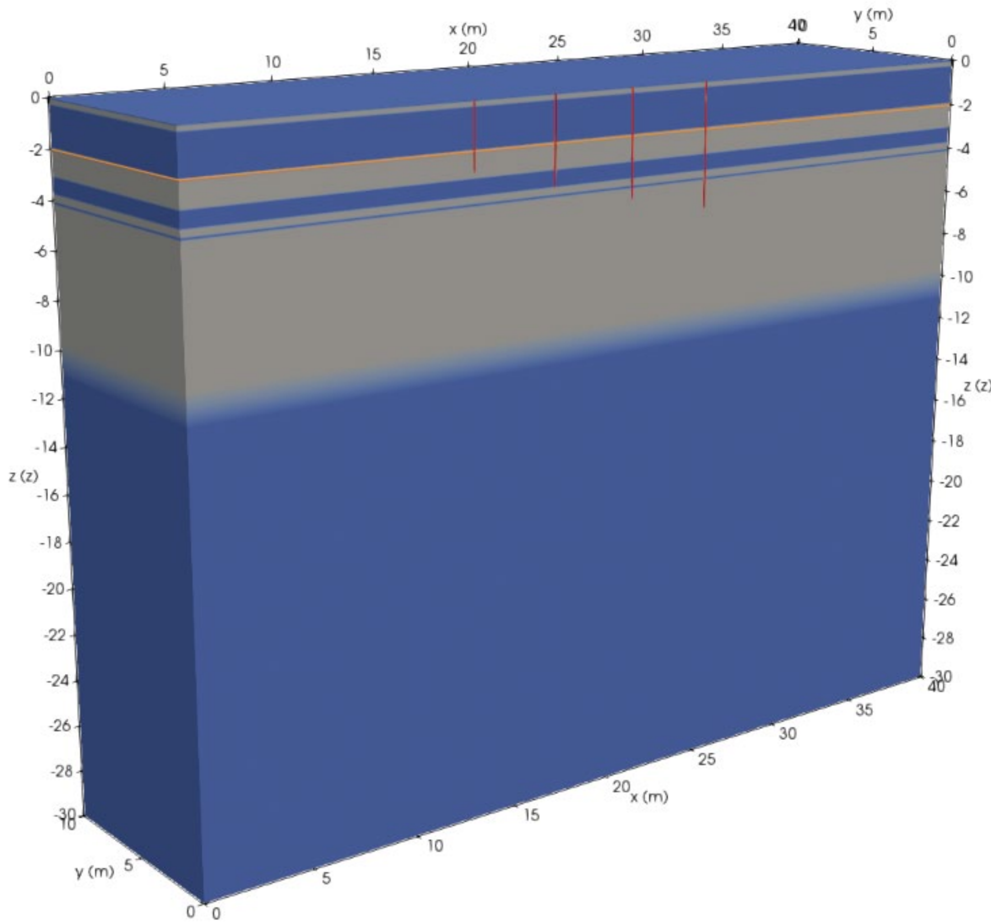

Figure 2-8. A conceptual diagram of the LANL Room D brine accumulation experiment. The model is symmetric about the $x = 0$ plane.

Table 2-3. Important lithology and hydrological parameters for the LANL Room D model.

Lithology	Permeability (m^2)	Porosity (-)
Halite (Blue)	1×10^{-22}	0.001
Clay (Orange)	1×10^{-17}	0.001
Argillaceous Halite (Brown)	1×10^{-19}	0.001
Wells (Red)	1×10^{-12}	0.999

The results of the LANL and Sandia models are shown for DBT10 and DBT12 in Figure 2-9. Both models do a decent job at approximating the brine accumulation field data however room for improvement exists. In the late time the brine accumulation increases but this was ignored by both models. These models are still under further development and parameters will be refined before the next DECOVALEX meeting.

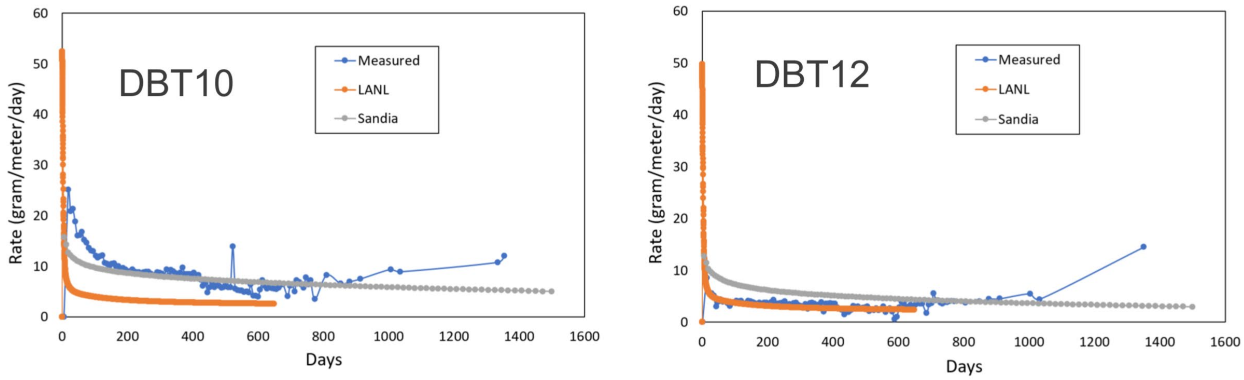

Figure 2-9. A comparison between LANL and Sandia's results of brine accumulation in DBT10 and DBT12.

2.3 BATS Phase 1a Temperature

The third modeling task for DECOVALEX was the temperature response to Phase 1a of the BATS experiment. The Phase 1 experimental plan is presented in SNL (2020) and includes experiments conducted on two borehole arrays located in the N-940 drift at WIPP. An as-built description of the Phase 1 experiment and detailed description of the instrumentation and data acquired is discussed Kuhlman et al., (2020b). A diagram of array is presented in Figure 2-10.

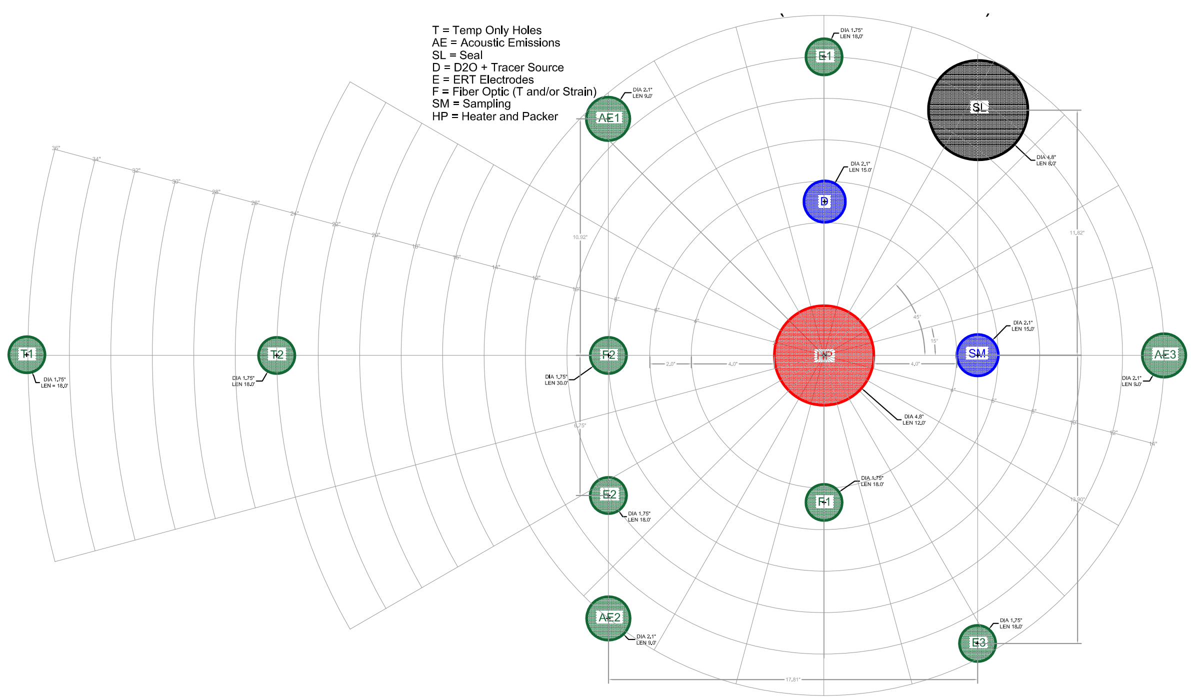

Figure 2-10. Borehole layout plan for the BATS test array.

Heating for Phase 1a was provided by a 750 W infrared heater isolated behind an inflatable packer along with a borehole closure gage. Temperature sensors were located in most of the boreholes including 16 thermocouples in each of the temperature boreholes (T1 and T2). For a complete review of all the data collected during BATS Phase 1a please see Kuhlman et al., (2020b). For DECOVALEX each team was tasked with modeling the temperature response of five thermocouples which were chosen to represent different distances from the heater and depths with in the formation. The thermocouples were: HE1TC2, HT2TC8, HT1TC8, HF2TC4, and HT1TC16.

The LBNL model used the TOUGH simulator and a 2D axially symmetric model centered around a 60 cm long heater source (Figure 2-11). For each of these models the primary controlling parameters are the thermal conductivity of the salt formation and the applied heater boundary condition. LBNL implemented a temperature dependent thermal conductivity function from the Bamabus project as well as the full applied heater wattage during the experiment Figure 2-12

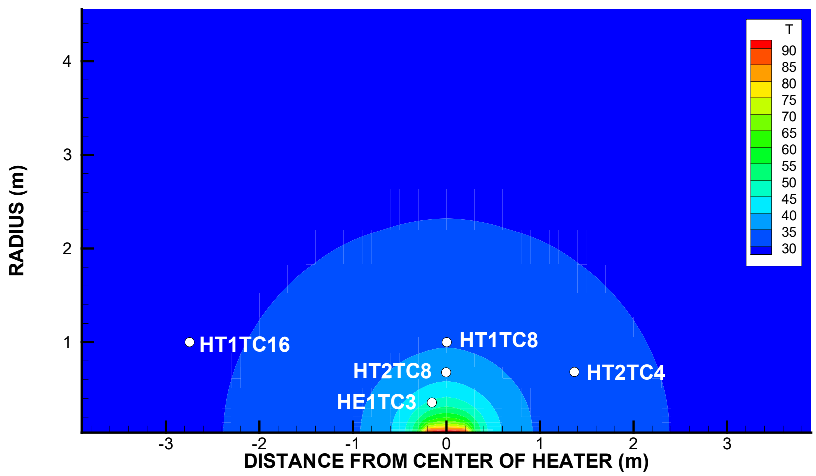

Figure 2-11. LBNL Model of the BATS Phase 1a experiment. The model is 2D axially symmetric and centered around a 60 cm long heater source.

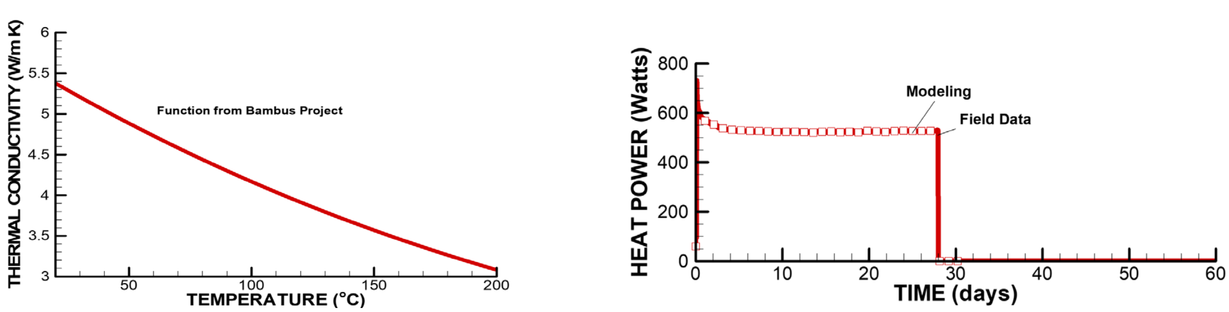

Figure 2-12. LBNL thermal conductivity model (left), and applied wattage boundary condition (right).

The Sandia model utilized a 1D radially symmetric model with the TOUGH simulation code. The model included a dual continuum approach with a fractured DRZ extending 1.25 m away from the borehole. The thermal conductivity of the salt was a constant 5.75 W/m °C but the presence of the fractures, which have very low thermal conductivity, lowers the overall thermal conductivity in the fractured region. Sandia used the full wattage applied to the heater for the heater boundary condition.

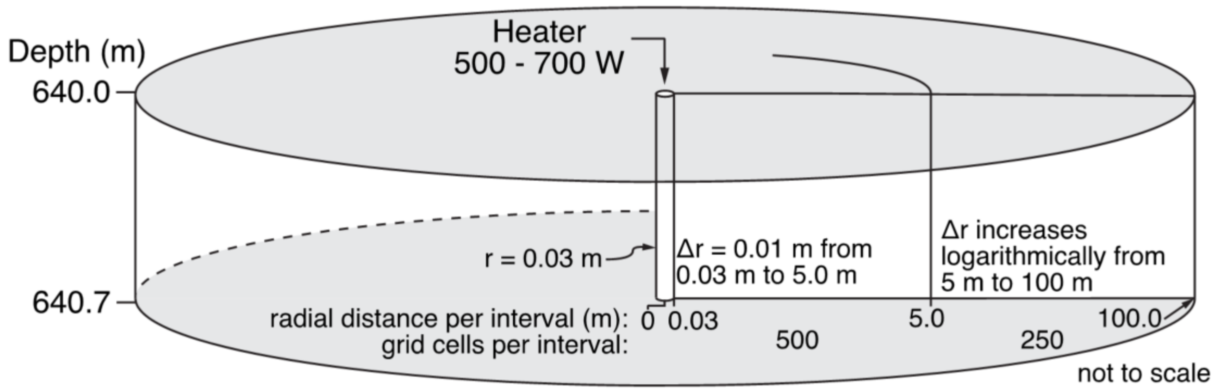

Figure 2-13. Sandia conceptual model of the BATS 1a temperature response for DECOVALEX

The LANL model used a similar approach to the LBNL model with a 2D axially symmetric model implemented in FEHM. However, for the thermal conductivity of the intact salt LANL fit the temperature dependent thermal conductivity model (Johnson et al., 2019; Munson et al., 1990) given by

$$\lambda_{IS} = \lambda_{IS,300}\left(\frac{300}{T}\right)^{\gamma_1} \tag{2-1}$$

where γ_1 is 1.14 and $\lambda_{IS,300}$ is 4.85 (W/m*K) to the thermal conductivity measurements completed by Sandia on the salt core from the BATS experiment (Figure 2-14; Kuhlman et al., 2020b) By using a lower thermal conductivity model than LBNL this meant LANL needed to reduce the heater wattage to compensate for the decreased heat dissipation given by higher thermal conductivities. Therefore, LANL implemented a heater boundary condition with a 15% loss factor. This loss factor could be explained due to the dry Nitrogen circulation removing heat and inefficiencies in the heater.

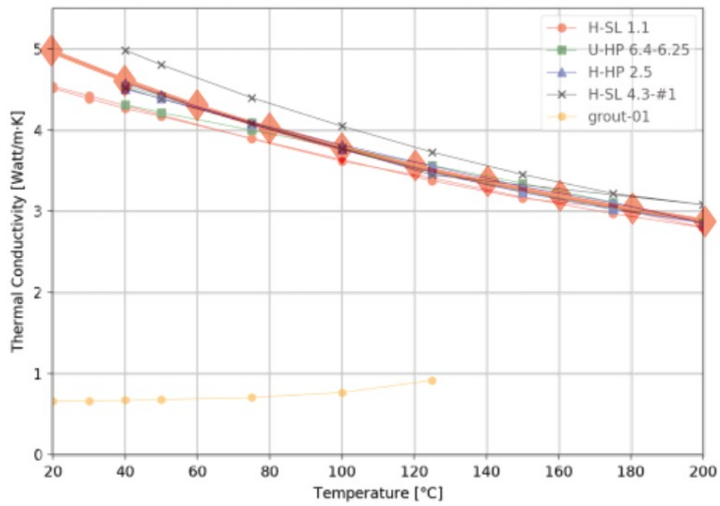

Figure 2-14. Thermal conductivity model fit (red diamonds) overlain on the lab thermal conductivity measurements made on the samples by Sandia. Modified from Kuhlman et al., (2020b).

Each of the three models performed well compared to the experimental data with only slight differences between them (Figure 2-15). The greatest difference is probably around the prediction of thermocouple HF2TC4. During the DECOVALEX meeting it was observed by the COVRA team that this thermocouple may have had its distance from the heater miscalculated which could explain some of the variation seen in this simulation. One technique employed by some of the other DECOVALEX teams was to move the thermocouples slightly within their boreholes to achieve a better fit. This can be justified because the exact position of the sensors within each borehole is slightly unknown. This is another technique which could be employed to correct the minor discrepancies in the observed vs predicted temperatures of these simulations.

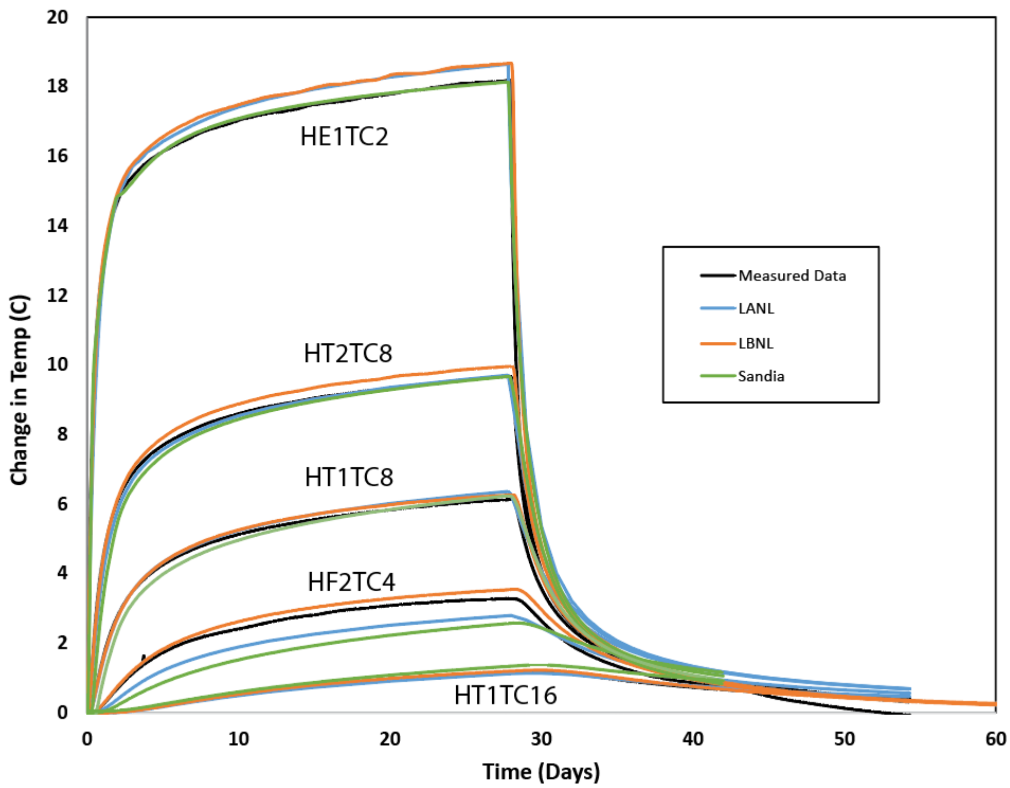

Figure 2-15. Comparison between the temperature predictions at 5 thermocouples of each model and the experimental BATS Phase 1a temperature data.

Overall, each team in DECOVALEX Task E (GRS, COVRA, BGR, Quntessa and DOE (LANL/LBNL/SNL)) used different approaches for modeling each of the three DECOVALEX experiments in Task 0. These different approaches included the use of 1D, 2D symmetric, and full 3D realizations of the various parameters. Different thermal conductivity, heater wattages, and thermocouple locations were used for the thermal modeling and different domain size, permeability, porosities, boundary conditions, and initial pressure and saturation distribution techniques were employed. For now the teams have chosen to not constrain themselves to a specific set of parameters or conditions but as the models increase in complexity to include more THMC processes the universe of modeling techniques will be constrained to those thought to be best within the Task E implementations.

3. BenVaSim

BenVaSim is an international collaboration on benchmarking THMC codes for radioactive waste disposal. Unlike DECOVALEX Task E, which is focused on benchmarking to experiments, BenVaSim is focused on benchmarking numerical simulators and new simulator couplings against one another. BenVaSim is run out of Clausthal University of Technology in Germany with six different teams. LBNL has been a partner in BenVaSim since its beginning in 2017. BenVaSim is currently in the first phase of four projected phases. Phase 1 is focused on the benchmarking of 1D simulations with analytical solutions. During last fiscal year LANL was in discussions with colleagues at GRS, a non-profit independent research organization focused on nuclear safety, about benchmarking FEHM through BenVaSim.

Our colleagues at GRS provided LANL with a BenVaSim benchmarking example which considers two-phase flow coupled with geomechanics. The example is a partially saturated salt column under compressive stress when a mix of air and water flows into it at a higher pore pressure and high saturation Figure 2-15. The high pore pressure decreases the effective stress and the column initially expands. Over time, the column begins to saturate and re-expand.

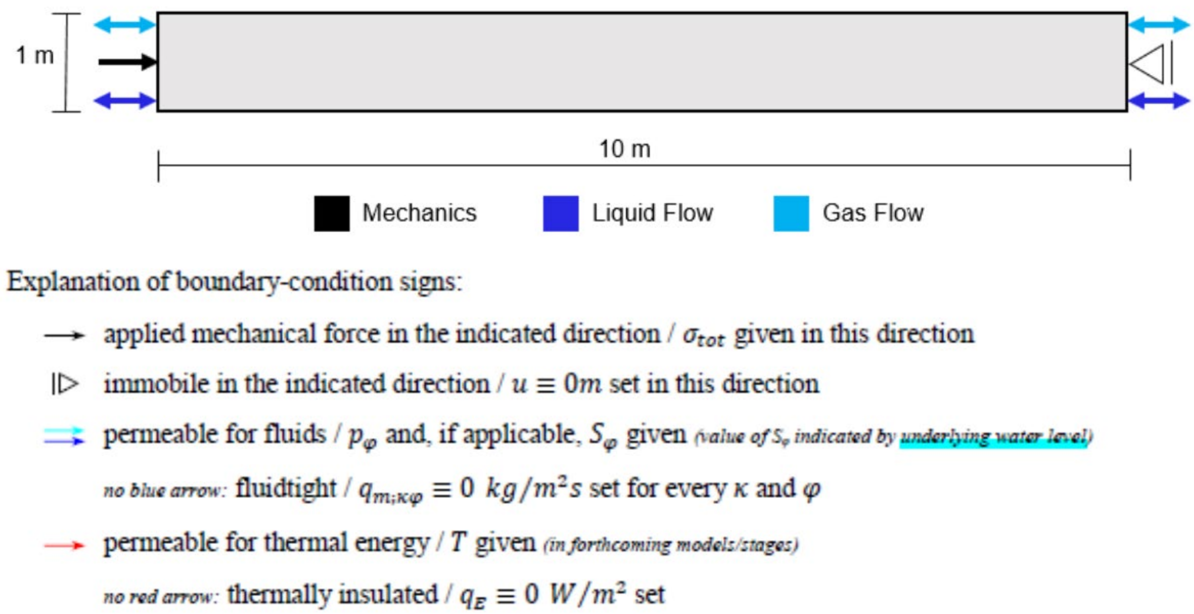

Figure 3-1. Model geometry and general boundary conditions applied to a salt column for BenVaSim

Plots comparing five different locations within the column are used for benchmarking purposes Figure 3-2 and the results of the FEHM simulation plotted against the expected results in Figure 3-3.

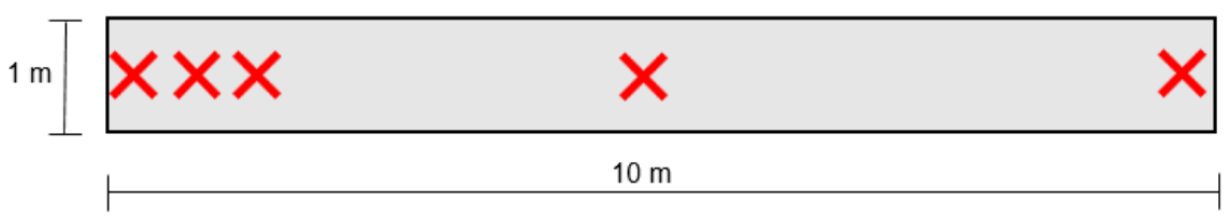

Figure 3-2. Histories of gas pore pressure, liquid saturation, and strain are benchmarked at each of the red X locations (0.25, 0.75, 1.25, 5, and 9.75m)

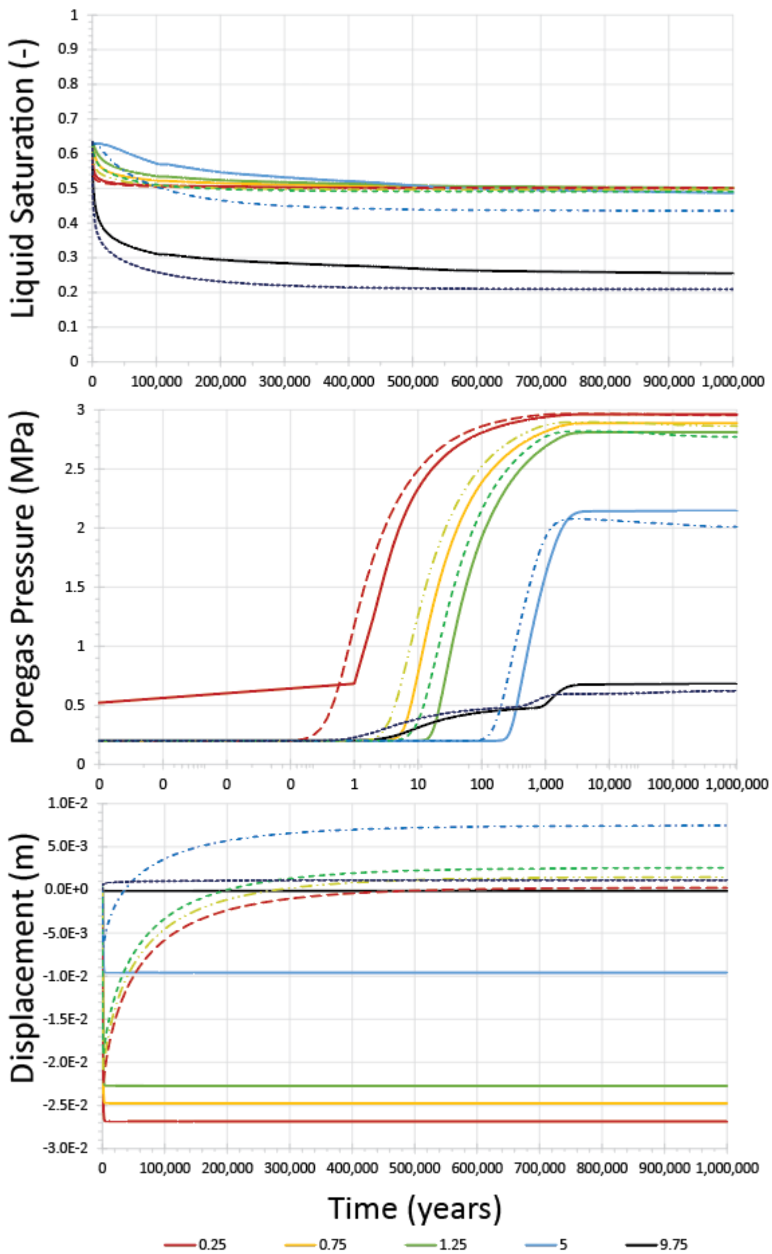

Figure 3-3. Comparison between FEHM and expected BenVaSim results for Model 1.4 – Scenario (Wb2). Solid lines are FEHM, dashed lines expected result.

The results show that the FEHM does a decent job at benchmarking to the expected gas pore pressure and liquid saturation in the salt core but is missing the re-expansion of the core after saturation. In order to accurately simulate this phenomena we are working to add saturation dependence to our strain calculation. We expect this to correct the displacement errors as well as narrow the differences between our saturation and gas pore pressure predictions. This is ongoing work which will continue under our international collaboration in fiscal year 2021.

4. Waste Management Symposium 2020

Here we provide abstracts from three presentations and associated peer-reviewed papers that LANL contributed to the 2020 WM Symposia, a meeting that has a strong international component. The WM2020 Symposium ran from March 8 through March 12, 2020 at the Phoenix Convention Center, Phoenix, AZ, USA.

4.1 WMS 2020 Paper 20307 - Salt Program Overview

This paper was designed to describe the current Salt R&D program in the US (Stauffer et al., 2020). This paper was a collaboration between the Salt R&D work package managers at LANL, SNL, and LBNL in addition to Dave Sevougian who provided review and input on the program. The presentation was given at 3:45 PM on Tuesday, March 12. The abstract of the paper is included below, while the paper can be found at the link following the abstract. The Los Alamos release number for this paper is LA-UR-19-28524.

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

Philip H. Stauffer*, Kristopher L. Kuhlman**, S. David Sevougian**, and Jonny Rutqvist***

*Computational Earth Science Group, Los Alamos National Laboratory
** Sandia National Laboratories
***Lawrence Berkeley National Laboratory

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.

https://sfwd.lanl.gov/_assets/documents/publications/FinalPaper_20307_1213124722.pdf

4.2 WMS 2020 Paper 20239 – THMC Simulations for BATS

This paper describes modeling of the BATS test data with contributions from LANL, SNL, and LBNL Guiltinan et al., 2020b). The presentation was given at 8:55 AM on Thursday, March 14. The abstract of the paper is included below, while the paper can be found at the link following the abstract. The Los Alamos release number for this paper is LA-UR-19-31638.

Brine Availability Test in Salt: Thermal-Hydrological-Mechanical-Chemical Simulations of a Heated Borehole in Salt - 20239

Eric J. Guiltinan*, Terry Miller*, Kris L. Kuhlman**, Jonny Rutqvist***, and Philip H. Stauffer*
*Computational Earth Sciences Group, Los Alamos National Laboratory
**Sandia National Laboratory
***Lawrence Berkeley National Laboratory

Abstract: The Brine Availability Test in Salt (BATS) is a collaboration between Los Alamos, Sandia, and Lawrence Berkeley National Laboratories that is being conducted to reduce the uncertainties associated with disposal of spent nuclear fuel (SNF) and high-level radioactive waste (HLW) in a hypothetical bedded salt repository. Bedded salt formations may be an acceptable host rock for disposal of nuclear waste due to salt's high thermal conductivity, extremely low permeability, and self-healing capability. In this paper, we report on the first round of the BATS project, a "shakedown test" known as Phase 1s, with an emphasis on the supporting numerical modeling. The experiment was conducted at the Waste Isolation Pilot Plant (WIPP) using previously drilled horizontal boreholes. The test included a heater borehole in which temperature, pressure, and moisture was monitored, and two nearby temperature monitoring boreholes . Numerical simulations that reflect the 36-year-long history of activity at the WIPP site are necessary to develop the appropriate initial conditions. Testing with different heater designs reveals that a 750 W radiative heater within a borehole can achieve the 120 °C borehole wall temperature goal.

https://sfwd.lanl.gov/_assets/documents/publications/20239.pdf

4.3 WMS 2020 Paper 20233 – Update on BATS Experiment Data

This paper describes data from the BATS test with contributions from LANL, SNL, and LBNL (Rahn et al., 2020). The poster was presented at 1:50-5:00 PM on Monday, March 9. The abstract of the paper is included below, while the paper can be found at the link following the abstract. The Los Alamos release number for this paper is LA-UR-19-31620.

Brine Availability Test in Salt, a Heated Borehole Experiment at the Waste Isolation Pilot Plant, New Mexico, USA

Thom Rahn*, Kris L. Kuhlman**, Hakim Boukhalfa*, Brian Dozier***, Doug Ware*, Shawn Otto***, Douglas Weaver***, Melissa Mills**, Courtney Herrick**, and Jonny Rutqvist****, Yuxin Wu****, Eric Guiltinan*****, Philip Stauffer*****
*Earth Systems Observations Group, Los Alamos National Laboratory
**Sandia National Laboratory
***ESH-Repository Science and Operations, Los Alamos National Lab
****Lawrence Berkeley National Laboratory
*****Computational Earth Sciences Group, Los Alamos National Laboratory

Abstract: The Brine Availability Test in Salt (BATS) is a collaboration between Los Alamos, Sandia, and Lawrence Berkeley National Laboratories formed to reduce the uncertainties associated with long-term disposal of spent nuclear fuel (SNF) in a hypothetical bedded salt repository. Bedded salt formations may be an ideal location for disposal of nuclear waste due to their high thermal conductivity, extremely low permeability, and self-healing capability. In this paper, we report on the first round of the BATS project with an emphasis on the supporting numerical modeling. The experiment was conducted at the Waste Isolation Pilot Plant (WIPP) and included heating previously drilled horizontal boreholes while monitoring nearby temperatures and water production to the borehole. We find due to the extremely low permeability of salt long term numerical simulations are necessary to develop the appropriate initial

conditions. Testing with different heater designs reveals that a 750 W radiative heater within a borehole can achieve temperatures expected from waste packages. In addition, the inclusion of a damaged rock zone plays an important role in the pressure and saturation distribution at the start of testing and the lower saturations within this zone may dissipate the thermal pressurization when compared to simulations that do not include a damaged rock zone.

https://sfwd.lanl.gov/_assets/documents/publications/20233final.pdf

5. Summary

This report summarizes the activities of LANL to foster international collaboration on salt repository research. Since June 2019 these activities have largely been centered on three activities: the DECOVALEX international benchmarking group, presentations to a largely international audience at the Waste Management Symposium, and preliminary participation in the BenVaSim THMC code benchmarking group. Participation in DECOVALEX, which is a group benchmarking THMC codes to experiments, has yielded important new ideas about model development for the BATS experiments at WIPP and will continue to be a significant benefit as the project is set to continue through 2023. While full participation in BenVaSim, the international group for benchmarking numerical simulation codes to each other, has not begun the preliminary modeling efforts have been beneficial and a source of new development efforts. In the next fiscal year LANL will continue these collaborative efforts and continue looking for other opportunities to engage with international colleagues in an effort to benefit salt repository research.

6. References

Guiltinan, E. J., K. L. Kuhlman, J. Rutqvist, M. Hu, H. Boukhalfa, M. Mills, S. Otto, D. J. Weaver, B. Dozier, and P. H. Stauffer, 2020a, Temperature response and brine availability to heated boreholes in bedded salt: *Vadose Zone Journal*, v. 19, p. e20019.

Guiltinan, E. J., T.A. Miller, K. Kuhlman, J. Rutqvist, P.H. Stauffer, 2020b, *Brine Availability Test in Salt: THMC Simulations of a Heated Borehole in Salt – 20239*, Waste Management Symposium, March 8-12, 2020, Phoenix AZ. LA-UR-19-31638.

Johnson, P. J., S. Otto, D. J. Weaver, B. Dozier, T. A. Miller, A. B. Jordan, N. G. Hayes-Rich, and P. H. Stauffer, 2019, Heat-generating nuclear waste in salt: Field testing and simulation: *Vadose Zone Journal*, v. 18, p. 1-14.

Kuhlman, K.L., M.M. Mills & E.N. Matteo, 2017. *Consensus on Intermediate Scale Salt Field Test Design*. SAND2017–3179R, Albuquerque, NM: Sandia National Laboratories.

Kuhlman, K.L., E.N. Matteo, M.M. Mills, R.S. Jayne, B. Reedlunn, S. Sobolik, J. Bean, E.R. Stein & M. Gross, (2020a). *International Collaborations on Radioactive Waste Disposal in Salt (FY20)*. SAND2020-7440R. Sandia National Laboratories.

Kuhlman, K., M. Mills, R. Jayne, E. Matteo, C. Herrick, M. Nemer, J. Heat, Y. Xiong, C. Choens, P. Stauffer, H. Boudkhalfa, E. Guiltinan, T. Rahn, D. Weaver, B. Dozer, S. Otto, J. Rutqvist, Y. Wu, M. Hu, S. Uhlemann, and J. Wang, 2020b, *FY20 Update on Brine Availability Test in Salt*, Albuquerque, NM, Sandia National Laboratories.

Munson, D., R. Jones, J. Ball, R. Clancy, D. Hoag, and S. Petney, 1990, *Overtest for Simulated Defense High-Level Waste (Room B): In situ data report (May 1984—February 1988): Waste Isolation Pilot Plant (WIPP) Thermal/Structural Interactions Program*, Sandia National Labs., Albuquerque, NM (USA).

Rahn, T., K. Kuhlman, H. Boukhalfa, B. Dozier, D. Ware, S. Otto, D. Weaver, M. Mills, C. Herrick, J. Rutqvist, Y. Wu, P.H. Stauffer, E. Guiltinan, 2020, *Brine Availability Test in Salt, a Heated Borehole Experiment at the Waste Isolation Pilot Plant, New Mexico, USA – 2023*, Waste Management Symposium, March 8-12, 2020, Phoenix AZ. LA-UR-19-31620.

Rutqvist, J., Y. Wu, M. Hu, S. Uhlemann, J. Wang, J. Birkholzer, Salt Coupled THMC Processes Research Activities at LBNL: FY20 Progress, Lawrence Berkeley National Laboratory, LBNL-2001350,

Sandia National Lab (SNL), 2020, *Project Plan: Salt in situ Heater Test*.

Stauffer, P.H., K. Kuhlman, S.D. Sevougian, and J. Rutqvist, 2020, *Overview of Salt Repository Research and Development for Spent Nuclear Fuel and High-level Nuclear Waste in the United States – 20307*, Waste Management Symposium, March 8-12, 2020, Phoenix AZ. LA-UR-19-31517.

Zyvoloski, G. A., B. A. Robinson, Z. V. Dash, S. Kelkar, H. S. Viswanathan, R. J. Pawar, P. H. Stauffer, T. A. Miller, and S. Chu, 2011, *Software users manual (UM) for the FEHM application version 3.1-3X*: Los Alamos National Laboratory, Los Alamos.