SAND2022-10213R

Salt International Collaborations FY22 Update

Spent Fuel and Waste Disposition

Prepared for
US Department of Energy
Spent Fuel and Waste Science and Technology

Kristopher L. Kuhlman, Edward N. Matteo,
Melissa M. Mills, Richard S. Jayne,
Benjamin Reedlunn, Steve Sobolik, James Bean
Sandia National Laboratories

July 29, 2022
M3SF-22SN010303063

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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.

Sandia National Laboratories

SUMMARY

This report summarizes the international collaborations conducted by Sandia funded by the US Department of Energy Office (DOE) of Nuclear Energy Spent Fuel and Waste Science & Technology (SFWST) as part of the Sandia National Laboratories Salt R&D and Salt International work packages. This report satisfies the level-three milestone M3SF-22SN010303063. Several stand-alone sections make up this summary report, each completed by the participants. The sections discuss international collaborations on geomechanical benchmarking exercises (WEIMOS), granular salt reconsolidation (KOMPASS), engineered barriers (RANGERS), numerical model comparison (DECOVALEX) and an NEA Salt Club working group on the development of scenarios as part of the performance assessment development process. Finally, we summarize events related to the US/German Workshop on Repository Research, Design and Operations.

The work summarized in this annual update has occurred during the COVID-19 pandemic, and little international or domestic travel has occurred. Most of the collaborations have been conducted via email or as virtual meetings, but a slow return to travel and in-person meetings has begun.

CONTENTS

ACRONYMS

BATS	brine availability test in salt
BGE	Bundesgesellschaft für Endlangerung
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe
COVID-19	coronavirus disease of 2019
DECOVALEX	Development of Coupled models and their Validation against Experiments
DGGT	Deutsche Gesellschaft für Geotechnik
DOE	Department of Energy
DOE-EM	DOE Office of Environmental Management
DOE-NE	DOE Office of Nuclear Energy
DRZ	disturbed rock zone
ELSA	Schachtverschlüsse für Endlager für hochaktive Abfälle
FEP	feature, event, process
FY	fiscal year (October to September)
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit
HLW	high-level waste
IfG	Institut für Gebirgsmechanik GmbH
IGSC	international group for the safety case
KOMPASS	Compaction of Crushed Salt for Safe Enclosure (English translation of German acronym)
NEA	Nuclear Energy Agency
OECD	Organisation for Economic Co-operation and Development
RANGERS	Entwicklung eines Leitfadens zur Auslegung und zum Nachweis von geo-technischen Barrieren für ein HAW Endlager in Salzformationen Design
R&D	Research and Development
SFWST	Spent Fuel and Waste Science & Technology
SNL	Sandia National Laboratories
US	United States
VSG	Vorläufige Sicherheitsanalyse Gorleben
WEIMOS	Weiterentwicklung und Qualifizierung der gebirgsmechanischen Modellierung für die HAW-Endlagerung im Steinsalz
WIPP	Waste Isolation Pilot Plant (DOE-EM site)

SALT INTERNATIONAL COLLABORATIONS FY21 UPDATE

This report is a summary of the international collaborations funded by the US Department of Energy Office of Nuclear Energy Spent Fuel and Waste Science & Technology (SFWST) as part of the Sandia National Laboratories Salt Research and Development (R&D) and Salt International work packages for fiscal year 2022 (FY22). Several stand-alone sections make up this summary report, each section completed by its participants. The sections discuss international collaborations on: geomechanical model benchmarking exercises (WEIMOS), granular salt reconsolidation (KOMPASS), engineered barriers (RANGERS), numerical model comparison of salt lab and field data (DECOVALEX), and a working group on the development of scenarios as part of the performance assessment development process.

Two primary collaborative efforts funded by Salt R&D and Salt International are the co-organization of, and participation in both the US/German Workshop on Salt Repository Research, Design, and the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA) Salt Club. These meetings were still virtual in early 2022 because of travel restrictions from the ongoing COVID-19 pandemic, but in-person meetings are planned later in this FY (e.g., September 2022). Despite the ongoing pandemic, our collaborative efforts with other countries have continued and perhaps strengthened, primarily relying on virtual meetings and email for collaboration. We slowly are resuming periodic in-person meetings with our international colleagues, but virtual meetings have shown their utility in allowing maintaining frequent contact between larger meetings which require more planning and travel.

Because each of the major sections of this report stands alone, each has its own references and conclusions. There is no overall summary or conclusions at the end.

1. International Collaboration through the RANGERS Project

SNL Authors: *Ed Matteo*, *Melissa Mills*, *Rick Jayne and Kris Kuhlman*

RANGERS is a collaborative project between Sandia National Laboratories and Bundesgesellschaft für Endlangerung (BGE) Technology (including Eric Simo, Phillip Herrold, and Andree Lommerzheim). After translating to English, the RANGERs acronym means "Design and Integrity Guideline for Engineered Barrier Systems for a HLW Repository in Salt". Geotechnical barriers for a repository in salt formations have already been the subject of numerous research projects. As part of the preliminary safety analysis for the Gorleben site (Vorläufige Sicherheitsanalyse Gorleben – VSG), a verification method for the integrity of sealing elements in a high-level waste (HLW) repository in domal salt formation was developed (Müller-Hoeppe, 2012). This made it possible to carry out a more detailed verification for a shaft closure. In the ELSA (Schachtverschlüsse für Endlager für hochaktive Abfälle) project, a design of shaft closures for HLW repositories was developed (Kudla, 2013). Further research projects such as those reported in Kudla (2009) and Sitz (1999) investigated different aspects of geotechnical closure systems. Recommendations for the planning and execution of geotechnical barriers were formulated in DGGT (2017) by the working group salt mechanics of the DGGT (Deutsche Gesellschaft für Geotechnik – the German Geotechnical Society).

Despite extensive knowledge and experience about geotechnical barriers in salt formations, there is no methodology for the design and verification of such structures for an HLW repository. BGE TEC and Sandia propose to develop jointly a Design and Integrity Guideline for Engineered Barrier Systems for an HLW Repository in Salt in the framework of a joint project between Germany and US. The project aims at developing a guideline for the planning and the design of geotechnical barriers in salt formations. This guideline will serve as a reference manual for the conceptualization of an HLW repository in Germany and the US. It will summarize the current state of art available in two reports and gives an outlook about the technologies which will impact the development of geotechnical barrier systems in the future.

The aim of the project is to develop a guideline for the design and verification of geotechnical barrier systems in repositories in salt formations that incorporates the existing knowledge and experience about geotechnical barriers of BGE and BGE Technology as well as of Sandia and of others. Recommendations for the design and verification of geotechnical barriers based on the state of the art in science and technology will be formulated and an overview of new concepts, building materials and technologies that will shape the state of the art of tomorrow will be given. Four sub-goals are formulated for this purpose:

1. Compilation of existing knowledge and experience for the design and construction of geotechnical barriers and compilation of new concepts and technologies about geotechnical barriers.
2. Development of a guideline based on the state of the art in science and technology for the design and verification of geotechnical barriers.
3. Preliminary design and verification of the geotechnical barrier system for selected repository systems based on the developed guideline.
4. Comparison of design results according to the new guideline with results of previous design and assessment.

The outcome of the project KOMPASS – another binational project between Germany and the US (see next section) – about the compaction of crushed salt as a key element of a sealing system in a salt HLW repository will be exploited in this project.

Overall, significant progress has been made in FY22 at SNL and BGE. Considerable work has been completed on compilation of existing data (i.e., state-of-the-art report). Because further work in RANGES depends on Performance Assessment (PA) and establishment of a Salt Reference Case, RANGERS has been participating in integration activities with DECOVALEX Task F and the NEA "Salt Scenarios" workshop (see later in this report). Salt Scenarios brings together researchers from the US, Germany, Netherlands, and the UK.

1.1 RANGERS FY22 Publications

In FY22, the RANGERS project produced a key report and a conference paper.

The State of the Art (SOTA) report was completed on engineered barriers, as a DOE-NE level-4 milestone report (M4SF-22SN010303065) in January 2022 (Simo et al., 2022). This SOTA report summarizes historical work and provides English-language summaries of several recent technical reports on engineered barriers in salt that were previously only available in German.

RANGERS presented in person at the Salt Mech X conference in Utrecht, Netherlands. This material also had a peer-reviewed conference paper associated with it (Simo et al., 2022). Conference papers are available as open-access publications from the journal website: https://doi.org/10.1201/9781003295808

The RANGERS project is finishing its third year, and the German participants at BGE TECH are seeking additional time and funding to continue the collaborative work begun during the COVID-19 pandemic for another fiscal year.

1.2 References

Simo, E., P. Herold, A. Keller, A. Lommerzheim, E.N. Matteo, T. Hadgu, R.S. Jayne, K.L. Kuhlman & M.M. Mills, 2022. *State of the Art and Science on Engineered Barriers in Salt Formations*, (117 p.) SAND2022-0204R. BGE TECHNOLOGY GmbH & Sandia National Laboratories. https://doi.org/10.2172/1855075

Simo, E., E.N. Matteo, K.L. Kuhlman, R.S. Jayne, P. León Vargas, P. Herold, A. Lommerzheim & A. Keller, 2022. *Design and Performance Assessment of Engineered Barrier Systems in a Salt Repository for HLW/SNF*. SAND2022-2624C, Salt Mech X proceedings.

2. International Collaboration through the KOMPASS Project

SNL Authors: *Melissa Mills, James Bean, and Ben Reedlunn*

Joint Project KOMPASS is a collaboration of German and American researchers seeking to improve thermo-hydro-mechanical models for crushed salt (i.e., run-of-mine or granular salt). Partners conduct experiments to understand crushed salt behavior and further develop, calibrate, and validate models for crushed salt. After translating to English, the acronym KOMPASS stands for "Compaction of Crushed Salt for Safe Enclosure". The KOMPASS partners are Bundesgesellshaft für Endlangerung Technology (BGE) (Peine, Germany), Institute für Gebirgsmechanik (IfG) (Leipzig, Germany), Technical University of Clausthal (TUC) (Clausthal, Germany), Gesellschaft für Anglagen-und Reaktorsicherheit (GRS) (Köln, Germany), Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) (Hannover, Germany), and Sandia National Laboratories (SNL).

The first phase of the KOMPASS project was completed in 2020, with a comprehensive final report produced (Czaikowski et al., 2020). During this phase, experimental techniques for consolidation were thoroughly evaluated to produce adequate pre-compacted and compacted samples under various conditions, which included characterizing sufficient reference material. A total of 34 different samples were produced, and several underwent microstructural investigations to document associated deformation mechanisms.

In addition to laboratory testing and analysis, model benchmarking initiatives revealed that while most models are capable of reproducing results, they still require a well-founded laboratory database to predict functional relationships to further characterize the THM-coupled compaction behavior of crushed salt. The various constitutive model approaches (i.e., C-WIPP, Heeman (BGR), Olivella/Gens (GRS), Callahan (Sandia)) were compared in the first phase to determine the main influencing factors or properties of each and identify specific lab tests needed for sufficient validation.

The second phase of the project (KOMPASS-II) officially began July 2021, with a partner kick-off meeting occurring in September 2021. Based on results from the first phase, a systematic test series is planned to further establish reproducible and predictable correlations between stress, duration of compaction, moisture states, and respective target porosity. Figure 1 shows the main factors contributing to the behavior of crushed salt and the type of experimental tests needed to improve predictions of those parameters. It is also desired to perform sensitivity analysis across all methods for measuring low porosity (<1% to 5%) and low permeability ($k < 10^{-19}$ m^2) of long-term compacted samples. Microstructural investigations will continue in the second phase with BGR, Utrecht, and SNL all studying the same or equivalent samples, so they can compare measurements of various relevant quantities, such as the grain size and subgrain size. On the modeling side, each partner plans to calibrate their model(s) against the tests on KOMPASS reference material, make model improvements as necessary, and use the resulting calibrated model(s) to simulate the closure of a drift backfilled with crushed salt. Each partner has already simulated the backfilled drift using their model calibration from KOMPASS phase 1. With each major model enhancement, the backfilled drift will be simulated again to quantify the impact of the enhancement.

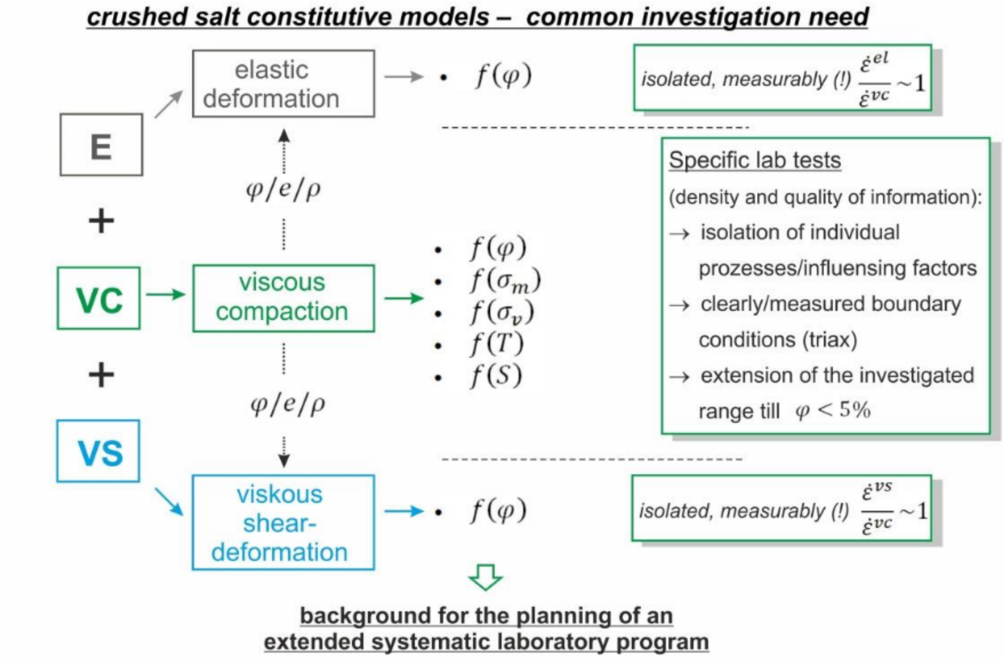

Figure 1. Schematic describing the factors contributing to crushed salt behavior and further laboratory tests needed to evaluate them (Czaikowski et al., 2020).

2.1 Preparation for Microstructural Investigations

During FY22, Sandia received nine pre-compacted samples of various parameters and testing types (i.e., triaxial, oedometric, and large or small scale) to prepare for and perform microstructural investigations. Table 1 gives details of each sample and their pre-compaction conditions. Samples are also shown in Figure 2. Final preparation of epoxy impregnated thin sections followed by observational work and image analysis are underway at the time of this report.

Table 1. Pre-compaction samples received from IfG and TUC with their respective test conditions and porosity values.

Partner	Sample	Test Type	Humidity	Temperature (°C)	Stress (MPa)	Duration of each stress step (days)	Initial porosity (%)	Final porosity (%)
IfG	684/OEDO1/TCC1	oedometric	dry	25	5	31.9	14.39	14.32
			dry	25	10	35.1	13.94	13.82
			dry	25	20	92	13.01	11.09
			dry	60	20	38	--	--
	684/OEDO1/TCC2	oedometric	dry	25	10	31.9	15.6	15.49
			dry	25	20	35.1	14.43	12.83
			dry	25	30	92	12.03	7.77
			dry	60	30	38	--	--
	684/OEDO1/TCC3	oedometric	dry	25	1	31.9	12.9	12.84
			dry	25	5	35.1	12.24	12.33
			dry	25	10	92	11.9	11.7
			dry	60	10	38	--	--
	684/OEDO1/TCC5	oedometric	wet (1%)	25	5	31.9	16	7.82
			wet (1%)	25	10	35.1	7.66	3.98
			wet (1%)	25	20	92	4.18	1.36
	684/OEDO1/TCC6	oedometric	wet (1%)	25	1	31.9	16.21	10.8
			wet (1%)	25	5	35.1	10.43	5.01
			wet (1%)	25	10	92	4.71	0.88
	684/OED01/Dry "Large cell"	oedometric	dry	25	1	7	33.75	28.92
			dry	25	5	7	25.03	22.03
			dry	25	10	7	20.13	17.86
			dry	25	20	7	14.81	12.36
TUC	14	Triaxial	wet (0.5%)	25	5	2	26	14
	15	Triaxial	wet (0.5%)	25	5	2	27	14
	21	Triaxial	wet (1%)	25	2	2	27	18


A.
KOMPASS
684/TCC1-oed-top
Up to 20MPa
60°C
dry
B.
KOMPASS
684/TCC2-oed-top
up to 30MPa
60°C
dry
C.
KOMPASS
684/TCC3-oed-top
Up to 10MPa
60°C
dry
D.
KOMPASS
684/TCC#5-oed-bottom
Up to 20MPa
60°C
wet
E.
KOMPASS
684/TCC6-oed-bottom
Up to 10MPa
60°C
wet
F.
G.
684/OEDO21 TROCKEN
UNTEN
HORIZONTAL
H.
KOM 21

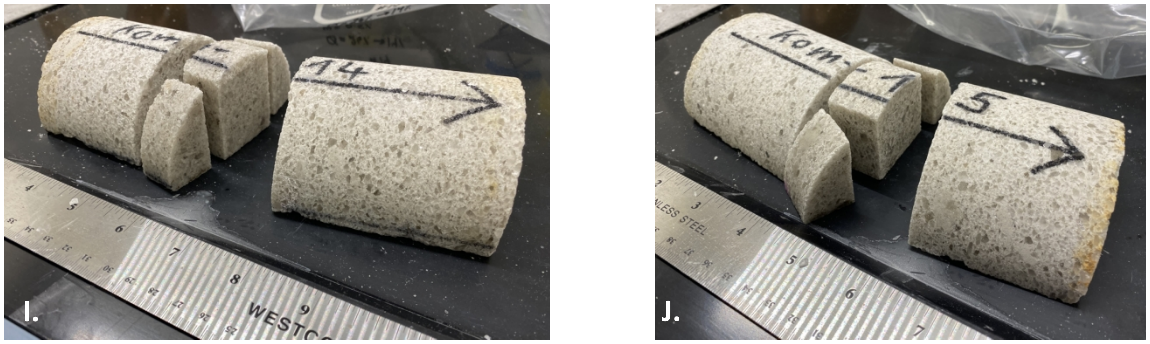

Figure 3. Reconsolidated granular salt samples from oedometric tests at IfG (a. through f.) and triaxial tests at TUC (g. through j.)

Throughout FY22, there has also been participation in several large KOMPASS-II meetings, as well as interim microstructure meetings between BGR, Utrecth University, and Sandia National Laboratories. The interim meetings are a smaller, less formal discussion about the ongoing microstructural investigations. A benchmarking activity was formed to determine qualitative investigations of deformation mechanisms and evaluate the observational techniques between each partner (i.e., software used, number of images, size of thin section). A subset of three micrographs were shared and a list of important microstructures were compiled, such as: number/size of grains, fractures, fluid inclusions, grain contacts, bent grains, subgrains, slip bands, recrystallized grains, and overgrowth features.

Several findings were made as an outcome of the benchmarking activity. First, there was variability in the total amount of time each partner spent analyzing each image and compiling results; a discussion was formed on how this could impact results. Evidently, some parameters could largely be impacted if there was not a large number present in the image (e.g., grain contacts, bent grains, and/or slip bands) and they were missed. Hence, it is important to understand the parameters that have the largest benefit to modeling endeavors, and ensure these types are concentrated on and accurately quantified. Another finding was determining how many imaged areas and/or thin sections would suffice to correctly draw conclusions about the overall sample results. It was concluded that at least two thin sections per sample should be investigated, assessing the whole thin section for larger deformation indicators (e.g., bent grains, inter- and intra-granular micro-cracks, and recrystallization), and more detailed, higher magnification images be thoroughly analyzed for fluid inclusion bands, grain contacts, and grain and subgrain sizes or areas. Finally, some indicators were found to be quantified more subjectively and interpreted differently amongst investigators. Therefore, for further collaboration, it was agreed that there should be a continuation of shared photomicrographs from partners, which could be discussed during interim microstructure meetings and form more refined conclusions.

2.2 Numerical Modeling

A Demonstrator model, developed by Ole Rabbel of IfG, was proposed to the KOMPASS-II partners. The model was designed to allow comparison of numerical simulations of the creep closure of an excavated room in salt that has been backfilled with crushed salt. During the first phase of the KOMPASS project, the partners generally used different constitutive models and calibrations to attempt to match several laboratory tests on crushed salt. Sandia National Laboratories used the crushed salt constitutive model developed by Callahan (1999) in phase 1. These constitutive models are being used to represent the mechanical behavior of the backfill in the Demonstrator model. Additionally, it was decided that all partners would use the same the constitutive model for the host rock. Thus, observed differences in simulated backfill compaction (porosity) would be primarily due to the constitutive models used to represent the backfill material.

The first step of the Demonstrator model was to simulate the closure of an empty room for a period of 10 to 15 years. These initial simulations were primarily used for the partners to identify errors in problem setup prior to introducing the crushed salt backfill into the problem. Two different constitutive models of power-law hardening were proposed for the host rock salt.

- Two-component model: this model includes two power law terms, one power-law term accounting for steady-state creep strains at low effective stresses (grain boundary pressure solution) and the second power-law term for steady-state creep strains at higher effective stress levels.
- One-component model: this model is based on the BGRa model parametrization (Hunsche and Schulze, 1994) and includes one power-law term for effective stresses but does not account for grain boundary pressure solution.

Figure 4 illustrates the added impact of the low stress term on the closure of an empty room. After 100 years the simulation with the low stress term (a) indicates the room would be almost closed while the room remains open when ignoring the low stress term in the BGRa model (b).

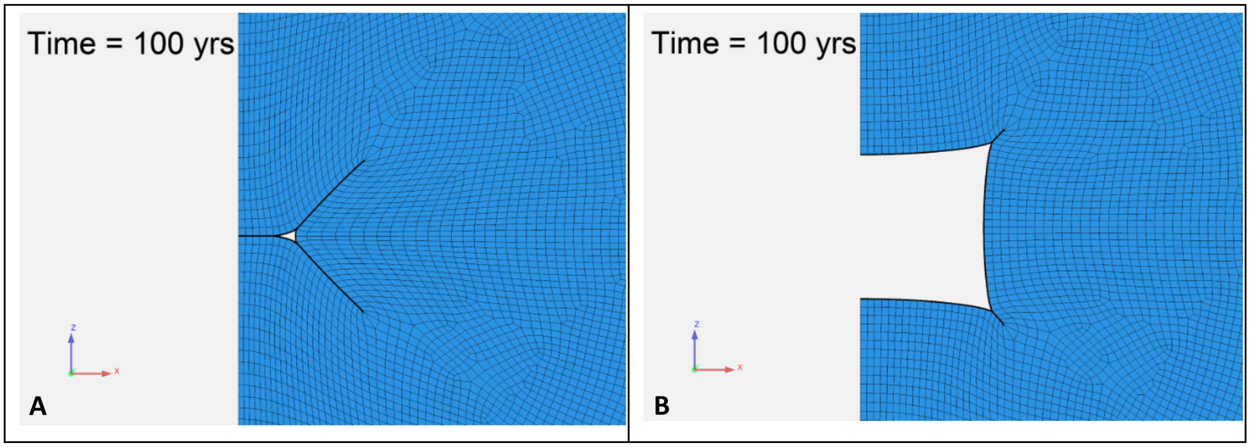

Figure 4. Comparison of empty room closure at 100 years for two different host rock constitutive models. A) two-component, B) one-component BGRa model

The simulations which included crushed salt backfill were performed out to a period of 500 years. A greater spread between all the models was found once the crushed salt backfill was introduced; further examination will be required. Figure 5 shows the average crushed salt backfill porosity when the two different host rock models were used in the SNL simulations. Also note that we examined the sensitivity of the numerical solution to the mesh resolution and found we had sufficiently accurate spatial discretization even with our coarsest mesh. Again, the two-component model produces a higher rate of room convergence leading to a greater rate of backfill porosity reduction.

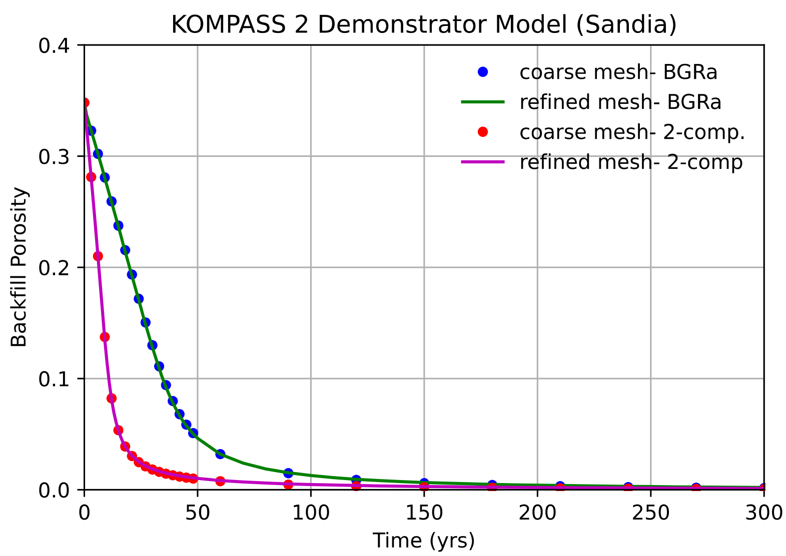

Figure 5. Backfill porosity histories for the two component and one component (BGRa) host rock models.

Further modeling work as part of KOMPASS will include:

- Determine if the current set of planned KOMPASS crushed salt experiments are sufficient to calibrate the Callahan model
- Calibrate the Callahan model against the KOMPASS crushed salt experiments
- Identify deficiencies in the Callahan model.
- Possibly develop a new model for crushed salt.

2.3 References

Callahan, G.D., *Crushed Salt Constitutive Model*, SAND98-2680, Sandia National Laboratories, Albuquerque, NM, February 1999.

Czaikowski, O., L. Friedenberg, K. Wieczorek, N. Müller-Hoeppe, C. Lerch, R. Eickemeier, B. Laurich, W. Liu, D. Stührenberg, K. Svensson, K. Zemke, C. Lüdelig, T. Popp, J. Bean, M. Mills, B. Reedlunn, U. Düsterloh, S. Lerche, J. Zhao, 2020. GRS-608: *KOMPASS- Compaction of crushed Salt for the Safe Containment*. Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH.

Hunsche, U., Schulze, O., 1994. *Das Kriechverhalten von Steinsalz*. Kali und Steinsalz 11 (8/9), 238–255.

3. International Collaboration through the Joint Project WEIMOS

SNL Authors: *Benjamin Reedlunn* and *Steve Sobolik*

Joint Project WEIMOS was a collaboration of German and American researchers seeking to improve thermomechanical modeling of salt repositories. The group primarily focused on improving constitutive models for rock salt, but the partners also undertook extensive laboratory test programs and refined methods for simulating the evolution of underground structures. The laboratory tests helped inform and calibrate the partners' constitutive models, which were then benchmarked against one another in relevant underground scenarios. After translating to English, the acronym WEIMOS stands for "Further Development and Qualification of the Rock Mechanical Modeling for the Final High -Level Waste Disposal in Rock Salt". The WEIMOS partners included Hampel Consulting (Mainz, Germany), Institute für Gebirgsmechanik (IfG) (Leipzig, Germany), Leibniz University (Hannover, Germany), Technical University of Braunschweig (TUBS) (Germany), Technical University of Clausthal (TUC) (Germany), and Sandia National Laboratories (SNL). WEIMOS effectively ended March 31st, 2022, but the partners continue to work on the final report, which should be released during September 2022.

Joint Project III, which preceded WEIMOS, helped identify the following work packages (WP) that together comprised WEIMOS:

1. Deformation behavior at small deviatoric stresses
2. Temperature and stress dependence of damage reduction and healing
3. Deformation behavior resulting from tensile stresses
4. Influence of inhomogeneities (layer boundaries, interfaces) on deformation
5. Virtual demonstrator

A short description of each work package is given below, followed by two other notes germane to Sandia's participation in WEIMOS and its predecessors.

3.1 (WP 1) Small Deviatoric Stresses

Salt creep at low deviatoric stresses (less than about 6 MPa) is typically the dominant cause of long-term room closure in salt repositories, but it is difficult to accurately measure low stress steady-state creep strain rates. The measurements are very challenging because the axial strain rates are small, sensitive to small temperature and humidity fluctuations, and can be convolved with volumetric consolidation/dilation strain rates.

Despite the challenges, the IfG developed a test procedure to accurately measure the steady-state strain rate at low stresses. The procedure first involves a long hydrostatic consolidation phase (>100 days) at an elevated temperature (>100 °C). Next, a non-zero, yet low, equivalent shear stress is applied and held constant while the temperature is decreased in a stepwise fashion over a year or more. The high temperatures cause the sample to accrue more creep strain and ostensibly reach the steady-state microstructure more quickly. Once the temperature is once again close to room temperature, the equivalent shear stress is returned to zero to confirm the volumetric strain rate is virtually zero. Finally, the non-zero equivalent shear stress is reapplied to confirm the same axial strain rate is observed. This process was successfully applied to a Waste Isolation Pilot Plant (WIPP) salt sample at 4 MPa (Lüdeling et al. (2022)), and further low stress tests are near completion. The full suite of test results should be published soon.

3.2 (WP 2) Damage Reduction and Healing

Healing of cracks in salt is important for the long-term safety case because cracks in the disturbed rock zone (DRZ), as well as broken pieces of rubble that fall into a room, can serve as flow pathways for radionuclides.

Although TUC's preliminary healing tests produced inconclusive results, new high precision equipment combined with innovative testing procedures produced clean sets of results on Asse salt samples (Wolters et al., 2022). As expected, increasing the mean compressive stress caused damage induced dilation to reduce, and increasing the compressive stress normal to microcrack planes reduced dilation more than increasing the compressive stress perpendicular to microcrack planes. Unexpectedly, dilation reduced substantially faster in one sample with 10 MPa equivalent shear stress and 14.3 MPa mean stress than another sample with 1 MPa equivalent shear stress and the same 14.3 MPa mean stress. Perhaps a higher stress difference causes more creep at the rough microcrack surfaces, thereby accommodating healing, but further experiments are needed to confirm. Additional experimental results, including results on WIPP salt, can be found in Lux et al. (2022). Each partner, besides Sandia, used the set of successful experiments to improve their constitutive model.

3.3 (WP 3) Tensile Stresses

Cracks due to tensile stress can play important roles in creation of the DRZ and subsequent roof fall events, yet limited data exists on tensile failure.

As discussed in previous updates, the IfG and TUC performed some of the first tensile test studies on WIPP and Asse salt. The cylindrical samples were first damaged (dilated) to different degrees in a triaxial compression cell, and then tensile tested along the cylinder axis to determine the tensile strength. The tensile strengths exhibited a large degree of scatter and did not appear to directly depend on the amount of damage for a given confining pressure. The lack of trends may have been caused by orientation of the microcracks induced during the triaxial compression phase. Triaxial compression under low confining pressures causes microcracks that open perpendicular to the subsequent tensile stress axis. Thus, the primary finding is future studies of the tensile strength's dependence on microcracking should attempt to create microcracks that are parallel to the subsequent tensile stress.

3.4 (WP 4) Layer Boundaries

The mechanical behavior of clay seams between layers of salt can substantially affect room closure rates and roof falls, yet experimental data on clay seam behavior does not exist in the literature.

During 2018 through 2020, Sandia sub-contracted RESPEC to perform a series of direct shear tests on natural clay seams extracted from a mine near the WIPP site and artificially manufactured clay seams. The natural clay seam cohesion strength and friction coefficient were nearly the same as pure salt without any interfaces because salt crystals spanned much of the clay seam interface (Sobolik, 2019). The artificial clay seam cohesion strength and friction coefficient, on the other hand, were like a saturated, highly consolidated, clay (Sobolik et al., 2020). The behavior of actual clay seams from the WIPP is expected to be somewhere in-between these two bounding cases. In 2022, the clay seam friction coefficient was varied between the two bounding cases (upper bound 0.42, lower bound 0.0279) in simulations of waste compaction within WIPP disposal rooms. The friction coefficient affected disposal room porosity during the first 300 years of operation, after which all calculations asymptotically reached the same porosity, independent of the friction coefficient. A summary of all this work was published in Sobolik et al. (2022).

Efforts to obtain actual clay seams from the WIPP have been unsuccessful so far. Clay G is known to slide in the underground but extracting Clay G cores would require angled coring because Clay G is close to the drift ceiling on WIPP's upper horizon. Clay F is more easily accessible, but it is a less uniform and distinct layer and not known to slide in the underground. Despite these difficulties, Sandia will continue to investigate ways to capture WIPP clay seam core samples.

3.5 (WP 5) Virtual Demonstrator

The WEIMOS partners, other than Sandia, performed two demonstrations of the modeling capabilities developed in the other work packages (Hampel et al., 2022). One demonstration simulated unrestrained open drift closure for 30 years, introduced a sealing system, and simulated the subsequent 70 years. During the first 30 years, the material models predicted substantially different amounts of dilation around the drift during the open phase, and predicted healing times that ranged from roughly 5 to ~170 years during the seal compaction phase. An additional comparison of simulations with and without low stress creep showed the low stress creep caused dramatic differences in room closure, stresses, and dilatancy. The second demonstrator resembled the main drifts next to a seven-room waste emplacement panel at the WIPP. As with the first demonstrator, the predictions of stress, dilation, and tensile failure were qualitatively different. These demonstrations indicate that--despite the model improvements during WEIMOS--further research into tensile failures, damage, and healing is needed.

3.6 Revisions to the WIPP Geomechanical Model

Joint Project III helped Sandia identify several concerns with the legacy geomechanical model for WIPP room closure. During WEIMOS, Sandia resolved many of the concerns (Reedlunn et al., 2022) with helpful advice from the WEIMOS partners. Sandia currently plans to incorporate this new geomechanical model into a revised disposal room porosity model, which will be used in the WIPP performance assessment (Reedlunn, 2022c).

3.7 Sandia Constitutive Model Development

Sandia continued to develop a new constitutive model for rock salt that improves upon the Munson-Dawson model (Munson, 1997). Work over the past year covered the following items. (1) The model formulation was substantially simplified by removing the hardening associated pressure solution creep. (2) This new, simplified, formulation was incorporated into the framework of Rational Thermodynamics, which forced the model to conform to a certain organizational structure and ensured the model satisfied the second law of thermodynamics. (3) The numerical implementation was made more robust. (4) Three successively more sophisticated model calibrations were developed using experiments on WIPP salt performed by the IfG and TUC during Joint Project III. (5) The two more sophisticated calibrations were partially validated against an observation of the Bauschinger effect. These various updates were published in Reedlunn (2021, 2022a, 2022b) and should pave the way to add damage and healing to the model soon.

3.8 References

Hampel, A., C. Lüdeling, R.M. Günther, J.Q. Sun-Kurczinski, R. Wolters, U. Düsterloh, K.H. Lux, S. Yildirim, D. Zapf, S. Wacker, I. Epkenhans, J. Stahlmann & B. Reedlunn, 2022. "WEIMOS: Simulations of two geomechanical scenarios in rock salt resembling structures at WIPP." In: *Mechanical Behavior of Salt X,* Proceedings of the 10th Conference on the Mechanical Behavior of Salt, July 6-8, 2022, Utrecht, Netherlands. Editors: de Bresser, Drury, Fokker, Gazzani, Hangx, Niemeijer & Spiers. https://doi.org/10.1201/9781003295808

Lüdeling, C., R.M. Günther, A. Hampel, J.Q. Sun-Kurczinski, R. Wolters, U. Düsterloh, K.H. Lux, S. Yildirim, D. Zapf, S. Wacker, I. Epkenhans, J. Stahlmann & B. Reedlunn, 2022. "WEIMOS: Creep of Rock Salt at Low Deviatoric Stresses." In: *Mechanical Behavior of Salt X,* Proceedings of the 10th Conference on the Mechanical Behavior of Salt, July 6-8, 2022, Utrecht, Netherlands. Editors: de Bresser, Drury, Fokker, Gazzani, Hangx, Niemeijer & Spiers. https://doi.org/10.1201/9781003295808

Lux, K.H., R. Wolters, J.Q. Sun-Kurczinski & K Herchen, 2022. *Verbundprojekt: Weiterentwicklung und Qualifizierung der gebirgsmechanischen Modellierung für HAW- Endlagerung im Steinsalz*

(WEIMOS) (Teilprojekt E: TUC). Final report, BMWi-FKZ 02E11446, Lehrstuhl für Geomechanik und multiphysikalische Systeme, Technische Universität Clausthal, Clausthal-Zellerfeld.

Munson, D.E., 1997. Constitutive model of creep in rock salt applied to underground room closure. *International Journal of Rock Mechanics and Mining Sciences,* 34(2):233–247.

Reedlunn, B., 2021. *Status of a New Thermomechanical Constitutive Model for Rock Salt, November 2021*. Memorandum. SAND2021-14666 CTF, Albuquerque, NM: Sandia National Laboratories.

Reedlunn, B., 2022a. "A New Constitutive Model for Rock Salt Viscoplasticity: Formulation, Implementation, and Demonstrations". ARMA 22-0640, In: *Proceedings of the 56th US Rock Mechanics/Geomechanics Symposium*.

Reedlunn, B., 2022b. "A New Rock Salt Constitutive Model with Back Stress and Drag Stress Hardening", In: *Mechanical Behavior of Salt X,* Proceedings of the 10th Conference on the Mechanical Behavior of Salt, July 6-8, 2022, Utrecht, Netherlands. Editors: de Bresser, Drury, Fokker, Gazzani, Hangx, Niemeijer & Spiers. https://doi.org/10.1201/9781003295808

Reedlunn, B., 2022c. *Analysis Plan for Improvements to the Disposal Room Porosity Model.* AP-197 Rev. 0, Albuquerque, NM: Sandia National Laboratories.

Reedlunn, B., J.G. Argüello & F.D. Hansen, 2022. A Reinvestigation into Munson's Model for Room Closure in Bedded Rock Salt. *International Journal of Rock Mechanics and Mining Sciences, 151*(2022):105007.

Sobolik, S.R., S.A. Buchholz, E. Keffeler, S. Borglum & B. Reedlunn, 2019. "Shear Behavior of Bedded Salt Interfaces and Clay Seams". ARMA 19-040, In: *Proceedings of the 53rd US Rock Mechanics/Geomechanics Symposium*.

Sobolik, S.R., E. Keffeler, & S. Buchholz, 2020. *Shear Behavior of Artificial Clay Seams within Bedded Salt Structures*, Technical Report SAND2020-11959, Albuquerque, NM: Sandia National Laboratories. https://doi.org/10.2172/1718985

Sobolik, S.R., C. Vignes, S.A. Buchholz, E. Keffeler, & B. Reedlunn, 2022. "WEIMOS: Shear Behaviors of Bedded Salt Clay Seams and Their Impact on Disposal Room Porosity". In: *Mechanical Behavior of Salt X,* Proceedings of the 10th Conference on the Mechanical Behavior of Salt, July 6-8, 2022, Utrecht, Netherlands. Editors: de Bresser, Drury, Fokker, Gazzani, Hangx, Niemeijer & Spiers. https://doi.org/10.1201/9781003295808

Wolters, R., J.Q. Sun-Kurczinski, U. Düsterloh, K.H. Lux, R.M. Günther, C. Lüdeling, A. Hampel, S. Yildirim, D. Zapf, S. Wacker, I. Epkenhans, J. Stahlmann & B. Reedlunn, 2022. "WEIMOS: Laboratory investigation and numerical simulation of damage reduction in rock salt." In: *Mechanical Behavior of Salt X,* Proceedings of the 10th Conference on the Mechanical Behavior of Salt, July 6-8, 2022, Utrecht, Netherlands. Editors: de Bresser, Drury, Fokker, Gazzani, Hangx, Niemeijer & Spiers. https://doi.org/10.1201/9781003295808

4. NEA Salt Club: Salt Scenarios Study

SNL Authors: *Kris Kuhlman*

Personnel from SNL and from Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) continue to progress in their long-standing development of a comprehensive Features, Events and Processes (FEPs) catalogue and FEP database (Freeze et al., 2020) to the development of a generalized approach to scenario development for a high-level waste repository at a generic salt site. This work is being conducted for the Nuclear Energy Agency (NEA) Salt Club expert group, which is a sub-group under the NEA International Group for the Safety Case (IGSC).

Virtual Salt Scenarios working group meetings were held via MS-Teams on 5 October 2021, 18 January 2022, 31 March 2022 and 9 June 2022. The ongoing working group meetings had contributions from US, German, UK, and Dutch colleagues, and the group continues to progress on a NEA Salt Club report on scenario development, tentatively planned to be completed in FY23. A small group also has continued to meet approximately monthly to develop a journal manuscript on the topic.

The group will present its status at the in-person NEA Salt Club meeting in Braunschweig, Germany in September 2022.

4.1 Reference

Freeze, G., S.D. Sevougian, K. Kuhlman, M. Gross, J. Wolf, D. Buhmann, J. Bartol, C. Leigh & J. Mönig, 2020. *Generic FEPs Catalogue and Salt Knowledge Archive*, (151 p.) SAND2020-13186. Albuquerque, NM: Sandia National Laboratories. https://doi.org/10.2172/1815346

5. DECOVALEX 2023 – Tasks E

SNL Author: *Kris Kuhlman*

The Brine Availability Test in Salt (BATS) is a field test that is being implemented at the US Department of Energy's (DOE) Office of Environmental Management's (DOE-EM) Waste Isolation Pilot Plant (WIPP) and funded by the DOE Office of Nuclear Energy (DOE-NE) (Kuhlman et al., 2020; Kuhlman et al., 2021). This field test is Task E in the current round of DECOVALEX (DEvelopment of COupled models and their VALidation against Experiments) model benchmarking exercise. Although all the in-person semi-annual DECOVALEX meetings to date have been replaced with virtual meetings have allowed teams to continue make significant progress. The November 2022 meeting is planned to be in person in Albuquerque, NM.

The initial Task E specification (Kuhlman, 2020) laid out the initial plan for the numerical comparison between the modeling teams and both historical and recent field observations. The first half of the DECOVALEX-2023 project has now completed (Heavy vertical line in the middle of Table 2), and a midterm report has been prepared, for distribution among the DECOVALEX funding organizations (Kuhlman et al., 2022).

Table 2. High-level DECOVALEX Task E schedule

	Apr.	Nov.	Apr.	Nov.	Apr.	Nov.	Apr.	Nov.
	2020		2021		2022		2023	
Step 0								
Step 1								
Midterm Report → (Nov 2021)								
Step 2								
Step 3								
					Papers and Final Report → (Nov 2023)			

DECOVALEX Task F2 is a salt performance assessment benchmarking exercise, which is funded by the Generic Disposal Safety Assessment workpages. Despite their differences, there are still some synergies between the Task E and Task F2 modeling efforts.

5.1 References

Kuhlman, K., M. Mills, R. Jayne, E. Matteo, C. Herrick, M. Nemer, J. Heath, Y. Xiong, C. Choens, P. Stauffer, H. Boukhalfa, E. Guiltinan, T. Rahn, D. Weaver, B. Dozier, S. Otto, J. Rutqvist, Y. Wu, M. Hu, S. Uhlemann & J. Wang, 2020. *FY20 Update on Brine Availability Test in Salt*, (107 p.) SAND2020–9034R. Albuquerque, NM: Sandia National Laboratories. https://doi.org/10.2172/1657890

Kuhlman, K., M. Mills, R. Jayne, E. Matteo, C. Herrick, M. Nemer, J. Heath, Y. Xiong, C. Choens, M. Paul, P. Stauffer, H. Boukhalfa, E. Guiltinan, T. Rahn, D. Weaver, S. Otto, J. Davis, J. Rutqvist, Y. Wu, M. Hu, S. Uhlemann & J. Wang, 2020. *Brine Availability Test in Salt (BATS) FY21 Update.* SAND2021-10962R. Albuquerque, NM: Sandia National Laboratories. https://doi.org/10.2172/1821547

Kuhlman, K., 2020. *DECOVALEX-2023 Task E Specification Revision 0*, (35 p.) SAND2020–4289R. Albuquerque, NM: Sandia National Laboratories. https://doi.org/10.2172/1616375

Kuhlman, K.L., J. Bartol, S. Benbow, M. Bourret, O. Czaikowski, E. Guiltinan, K. Jantschik, R. Jayne, S. Norris, J. Rutqvist, H. Shao, P. Stauffer, H. Tounsi & C. Watson, (2022). *DECOVALEX-2023 Task E Interim Report*, SAND2022-6606O. Albuquerque, NM: Sandia National Laboratories.

6. US/German Workshop and NEA Salt Club

SNL Author: *Kris Kuhlman*

6.1 US/German Workshop

In late FY21 (after the preparation of last year's edition of this report), the final meeting of the 11th US/German Workshop on Salt Repository Research, Design and Operation was held online via MS-Teams (3-4 September 2021). The first day of the meeting had presentations on the topic of Engineered Barrier Systems, Materials, and Backfilling. The second day of the meeting had presentations on the topic of numerical modeling. The proceedings from the 11th US/German workshop (held virtually over four days) are being prepared at the time of this report's preparation. When complete, they will be published on the Sandia National Laboratories salt repository research webpage: https://www.sandia.gov/salt/us-german-workshop/

In FY22, the 12th US/German Workshop on Salt Repository Research, Design and Operation is being held in person in Braunschweig, Germany. This is the original planned location of the 2020 US/German Workshop, before the in-person meeting was cancelled due to the COVID-19 pandemic. The workshop will be co-hosted by Michael Bühler (PKTA), Jörg Melzer (PKTA), Philipp Herold (BGE TECH), and Kris Kuhlman (SNL). The 12th workshop was previously planned to be held in May 2022, but was delayed until 6-9 September 2022, due to ongoing international travel restrictions related to the COVID-19 pandemic.

6.2 NEA Salt Club

The 11th NEA Salt Club meeting was held 11-12 May via Zoom. The topical session was performance assessment (PA). The topical session included presentations on geochemistry aspects, scenario development, US PA modeling involved with RANGERS and DECOVALEX Task F, characterization of halite deposits in the UK, and Dutch PA modeling in DECOVALEX Task F.

6.3 FY22 Plans

The 12th US/German Workshop and 12th NEA Salt Club meetings are planned to be in-person in Braunschweig, Germany 6-9 September 2022 (NEA Salt Club the morning of 6 September; US/German workshop starting in the afternoon that same day). This was the planned location of the 2020 US/German Workshop, before it was canceled due to the COVID-19 pandemic.