SAND2024-09939R

# Salt International Collaborations FY24 Update

## Spent Fuel and Waste Disposition

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

*Melissa M. Mills, Kristopher L. Kuhlman,*
*Richard S. Jayne, Jibril B. Coulibaly,*
*Benjamin Reedlunn,*
*Sandia National Laboratories*

*July 31, 2024*

M3SF-24SN010303063

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 (DOE-NE) 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-24SN010303063. Several stand-alone sections make up this summary report, each completed by the participants. The sections discuss granular salt reconsolidation (KOMPASS/MEASURES), engineered barriers (RANGERS), numerical model comparison (DECOVALEX), an NEA Salt Club working group on the development of scenarios as part of the performance assessment development process, and progress on seal percolation experiments with German colleagues at Gesellschaft für Anlagen- und Reaktorsicherheit (GRS). Finally, we summarize events related to the US/German Workshop on Repository Research, Design and Operations.

# CONTENTS

# ACRONYMS

| | |
|---|---|
| BATS | brine availability test in salt |
| BGE | Bundesgesellschaft für Endlangerung |
| BGR | Bundesanstalt für Geowissenschaften und Rohstoffe |
| 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 |
| 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 |
| SNF | spent nuclear fuel |
| SNL | Sandia National Laboratories |
| US | United States |
| VSG | Vorläufige Sicherheitsanalyse Gorleben |
| WIPP | Waste Isolation Pilot Plant (DOE-EM site) |

# SALT INTERNATIONAL COLLABORATIONS FY24 UPDATE

This report summarizes international collaborations funded by DOE-NE 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 2024 (FY24). Several stand-alone sections make up this summary report, each section completed by its participants. The sections discuss international collaborations on granular salt reconsolidation (KOMPASS), engineered barriers (RANGERS), numerical model comparison of salt lab and field data (DECOVALEX), and an NEA Salt Club 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. 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 a HLW repository. BGE TEC and Sandia jointly propose to develop a Design and Integrity Guideline for Engineered Barrier Systems for a HLW Repository in Salt in the framework of a joint project between Germany and the 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 a 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 TEC 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 FY24 at SNL and BGE TEC. Considerable work has been completed on compilation of existing data (i.e., state-of-the-art report). Because further work in RANGERS depends on numerical modeling of the length and time scales appropriate for performance assessment 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). The Salt Scenarios work brings together researchers from the US, Germany, Netherlands, and the UK.

In FY24, the RANGERS continued work on the State of the Art (SOTA) #2.

Eric Simo (BGE TEC) and Kris Kuhlman (SNL) gave a set of three in-person presentations on the RANGERS project at the 14th US/German Workshop in Manchester, UK, titled:

- *RANGERS: Integrity Assessment of a Drift Sealing System*
- *RANGERS: Salt Repository Evolution at Multiple Scales*
- *RANGERS: Contribution to Process Understanding of Gas Transport in Salt*

The RANGERS project is finishing its fifth and final year (an extension to complete reporting).

The RANGERS project has been a worthwhile collaboration on the design, optimization, and modeling of the engineered aspects of repositories for radioactive waste disposal in salt. Bringing together BGE TEC expertise on mechanical modeling and Sandia's expertise on flow modeling over the last five years, we have improved our understanding of the problem, and developed key collaborations that will continue in future collaborative efforts (e.g., EURAD-2).

## 1.1 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 and MEASURES Projects

SNL Authors: *Jibril B. Coulibaly and Benjamin Reedlunn*

Joint Projects KOMPASS and MEASURES are collaborations of German, Dutch, American, and British 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. The KOMPASS project included two phases (KOMPASS-1 and KOMPASS-2), while MEASURES is a follow-up project. After translating to English, the acronym KOMPASS stands for "Compaction of Crushed Salt for Safe Enclosure," while MEASURES stands for "Multi-scale experimental and numerical analysis of crushed salt material used as engineered backfill for a nuclear waste repository in rock salt." The KOMPASS and MEASURES 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), Centrale Organisatie Voor Radioactief Afval (COVRA) (Nieuwdorp, The Netherlands), Utrecht University (UU) (Utrecht, The Netherlands), Sandia National Laboratories (SNL), and Nuclear Waste Services (NWS) (United Kingdom).

The two phases of the KOMPASS project were completed in 2020 and 2023, with two comprehensive final reports produced (Czaikowski et al., 2020, Friedenberg et al., 2024). During FY24, the former KOMPASS partners developed the proposal for the MEASURES project. This proposal retains the overall framework of the KOMPASS projects (compaction experiments, microstructural studies, and modeling), but narrows the focus to the following specific topics:

- Separating the sensitivity to mean stress, water content, and porosity
- Quantification of contributions from individual microstructural mechanisms
- Permeability measurements over a range of relevant porosities
- Calibration of constitutive models
- Quantification of uncertainties in laboratory as well as in numerical simulations

The proposal was submitted to the German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) in Winter 2024 and received an "A" rating from the review committee. Once the MEASURES budget proposal is fully approved, funding would begin no earlier than Fall 2024.

While helping to develop the MEASURES proposal, Sandia also began developing a new crushed salt constitutive model to potentially supersede the Callahan model (Callahan, 1999). The process of calibrating the Callahan model during the KOMPASS projects revealed several shortcomings (Coulibaly, 2023). The new model strives to resolve these shortcomings and preserve the good features of the Callahan model. In its present stage of development, the new pressure solution creep formulation includes several novel features:

1. A generalized grain geometry, allowing a consistent transition from porous to intact salt without *ad hoc* effective stress and porosity modifications
2. An anisotropic formulation, capable of capturing deformation history
3. A physico-chemical model of the influence of water content, providing an alternative to phenomenological approaches

This model is anticipated to provide a better description of crushed salt at low porosity. The model presently allows simulation of constant stress creep tests at low stress (i.e., when dislocation creep is expected to play a minor role). Under hydrostatic loading, reconsolidation from compressible crushed salt to incompressible intact salt has been demonstrated. Under triaxial compression loading, reversal of the direction of radial deformation at low porosity has also been demonstrated. Future work includes adding an elasticity formulation, adding a dislocation creep formulation, and implementing the model into Sierra/SolidMechanics (2023) to use the model in general 3-dimensional finite element analyses.

Laboratory experiments on the reconsolidation of granular salt are both critical to the design and implementation of a repository in salt and are notoriously difficult to conduct in a repeatable fashion. The KOMPASS and MEASURES projects aim to develop repeatable methodologies for laboratory testing and then simulate these experiments using numerical models. Sandia and DOE-NE's participation in these efforts has been quite worthwhile and a very effective collaboration; we are benefitting from and contributing to the world state-of-the-art in the understanding and simulation of granular salt reconsolidation.

## 2.1 References

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

Coulibaly, J.B., 2023. *An Assessment of Callahan's Crushed Salt Constitutive Model*, SAND2023-06049R, Sandia National Laboratories, Albuquerque, NM.

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.

Friedenberg, L., J. Bartol, J. Bean, S. Beese, H. de Bresser, J. B. Coulibaly, O. Czaikowski, U. Düsterloh R. Eickemeier, A.-K. Gartzke, S. Hangx, K. Jantschik, B. Laurich, C. Lerch, S. Lerche, W. Liu and C. Lüdeling, M. Mills, N. Müller-Hoeppe, B. van Oosterhout, T. Popp, O. Rabbel, M. Rahmig, B. Reedlunn, A. Rogalski, C. Rölke, N. Saruulbayar, C. J. Spiers, K. Svensson, J. Thiedau, and K. Zemke, 2024. GRS-751. SAND2024-00570R: *KOMPASS-II: Compaction of crushed Salt for the Safe Containment – Phase 2*. Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH.

Sierra/SolidMechanics, 2023. *Sierra/SolidMechanics 5.16 User's Guide*. 5.16.3. SAND2023- 08528. Sandia National Laboratories. Albuquerque, NM.

# 3. International Collaborations through DECOVALEX

SNL Authors: *Kris Kuhlmam and Rick Jayne*

The DECOVALEX (DEvelopment of COupled models and their VALidation against EXperiments) project objective is developing understanding and predictive simulation capabilities for coupled processes relevant to radioactive waste disposal in geologic formations. DECOVALEX has been ongoing since the first round started in 1992, with a recently completed phase (DECOVALEX-2023) being the eighth installment (2020-2023). DECOVALEX-2023 was divided into eight tasks (A through G, including F1 and F2). In FY24, DECOVALEX-2023 model benchmarking exercise ended with a meeting in Troyes, France (November 2023), and the 2024-2027 round of DECOVALEX began with a virtual workshop (April 2024). There were two tasks in DECOVALEX-2023 (both continuing into DECOVALEX-2027) that are relevant to salt:

- Task E – BATS
- Task F2 – Salt reference case

The following sub-sections summarize the activities in these tasks at a high level. DECOVALEX has in general been a rewarding collaboration, for those participating and those leading tasks. Sandia and DOE-NE have leveraged a large amount of work and expertise from repository science researchers around the world.

## 3.1 Task E: BATS

In the 2023 phase of DECOVALEX, Task E focused on understanding thermal, hydrological, and mechanical (THM) processes related to predicting brine migration in the excavation damaged zone around a heated excavation in salt. Salt is attractive as a disposal medium for radioactive waste because it is self-healing and is essentially impermeable and non-porous in the far field. Investigation of the short-term, near-field behavior is important for radioactive waste disposal because this early period strongly controls the amount of inflowing brine. Brine leads to corrosion of waste forms and waste packages, and possible dissolution of radionuclides with brine transport being a potential transport vector to the accessible environment. Task E involved comparison of models to both historical and recent data illustrating the impact of brine availability in bedded salt deposits under heated conditions associated with permanent disposal of heat-generating radioactive waste in a salt repository.

The Task was divided into steps, along with sub-steps. Step 0 included matching unheated brine inflow data from boreholes at the Waste Isolation Pilot Plant (WIPP) and matching temperature observations during a Brine Availability Test in Salt (BATS) heater test. Step 1 included validation of models against a thermo-poroelastic analytical solution, and two-phase flow around an excavation. Finally, Step 2 required all the individual components covered in steps 0 and 1 to come together to match observed brine inflow behavior during the same BATS heater test.

There were a range of approaches from the teams, from mechanistic to prescriptive. Teams participating in this task included those from Germany (BGR and GRS), the Netherlands (COVRA), the UK (Quintessa), and the US (LANL, LBNL, and SNL). Given the uncertainties in the problem, some teams used one- or two-dimensional models of the processes, while other teams included more geometrical complexity in three-dimensional models. Task E was a learning experience for the teams involved, and feedback from the modeling teams has led to changes in follow-on BATS experiments at WIPP. The primary Task E lessons learned were the impact of hydrologic initialization methods (wetting up vs. drying down), the difference between confined and unconfined thermal expansion, and the large changes in permeability associated with heating and cooling.

Task E has gradually built-up complexity to the THM BATS 1a test. Starting from single-process benchmarks in step 0 (T and H), adding coupled processes and two-phase flow in step 1 (THM and two-phase H). The Room D benchmark (step 0a) contained multiple boreholes and demonstrated the relative importance of lithologic heterogeneity (Figure 1 upper left). Heat conduction in the BATS array was the most straightforward step of the whole exercise (Figure 1 upper right). The McTigue (1990) benchmark (step 1a) demonstrated the importance of simulating the confined thermal expansion (both brine and salt) on pore pressure in heated salt formations (Figure 1 lower left). Finally, the variety of results from the multiphase modeling exercise (step 1d), despite its prescriptive nature, showed the simulators can produce a wide range of saturation, liquid pressure, and brine production estimates.

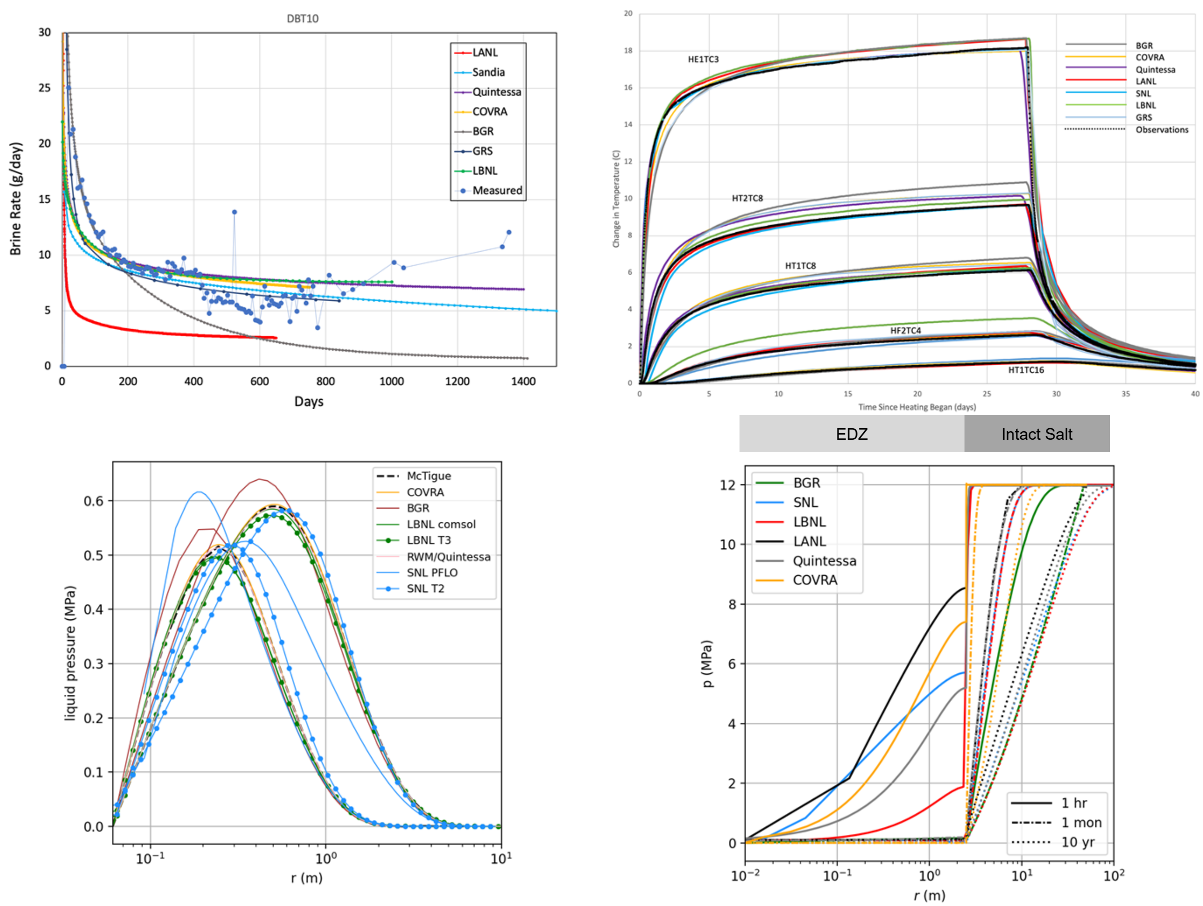


**Figure 1. DECOVALEX-2023 Task E key results from steps 0-1. Upper left: step 0a unheated brine migration. Upper right: BATS1 heat conduction. Lower left: step 1a McTigue benchmark comparison. Lower right: step 1b two-phase flow initialization.**

The multiphase comparison (step 1b) also challenged the default hydrological modeling assumption of a “drying down” system, despite not having an analytical solution or field data to benchmark against. The “wetting up” conceptualization was agreed to be more physically realistic, and this has significant impact on brine production simulations at early time; this is likely the most relevant detail from this task to performance assessment type simulations as well.

Step 2 of Task E focused on coupled processes observed in the BATS 1a heater test (Figure 2). Teams matched brine production during and after heating, which includes relevant coupled physics that were discussed independently in steps 0 and 1. The thermal response was simulated in step 0a, thermal expansion was simulated in step 1a, and the effects of two-phase flow were simulated in step 1b. Step 2 involved a combination of these individual steps already considered, along with the additional consideration of hydro-mechanical feedback (e.g., thermal expansion leading to closure of $\phi$ and reduction of k during heating, and subsequent reversal of this process during after-test cooling).

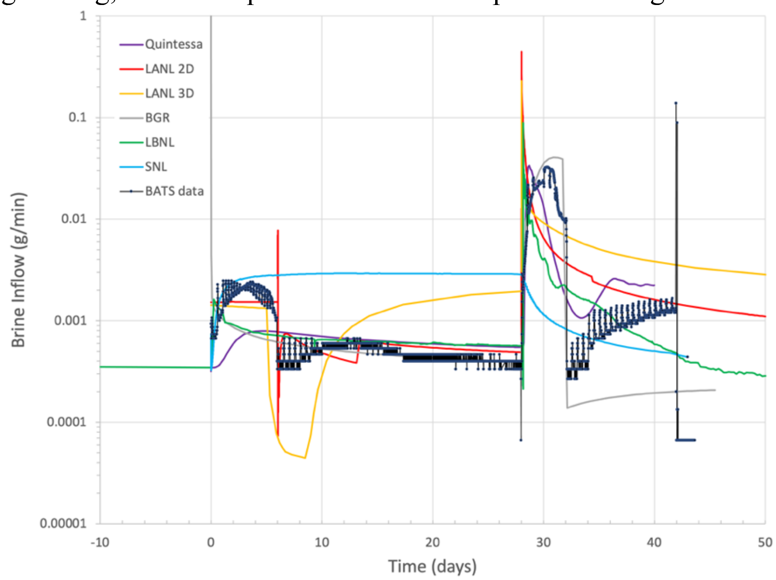


**Figure 2. Task E step 2: BATS 1a brine inflow results during heating.**

The complexity of the BATS 1a observations forced teams to pick which aspect of the data they thought were worth focusing on. Early data showed impacts from higher gas flowrates, and data gathered later during cooling showed extended brine production that did not follow an exponential decay. The complexities in the data, and the diversity of approaches shows there are different ways to represent the processes, but there were several common themes:

- Permeability is higher near the borehole/excavation, to represent effects of damage.
- Fluid pressure is highest at the end of heating, due to thermal pressurization.
- Permeability rises at the end of heating, which allows the higher pressures to dissipate.

In general, the Task E exercise led to an increased understanding of the complex processes expected to occur in the EDZ of a salt repository for disposal of heat-generating radioactive waste. In the longer term (tens to hundreds of years), it is expected the drift and the damage (i.e., porosity and permeability) of the EDZ will creep shut and the dynamic processes observed in BATS will be less important. Understanding these early-time and short-distance processes is important to quantify the initial conditions that performance assessment models will need, including the effects of model initialization and the amount of brine expected to flow into the drifts, as radionuclides dissolved in brine would typically be the primary release pathway. Understanding processes going on in the near field and short term are also important if any future repository design is to be optimized, for example maximum temperature in the damaged part of the host rock would impact spacing between waste packages or the length of any storage period required before disposal.

The organization of Task E tried to strike a balance between being prescriptive, which might result in more comparable outputs, and allowing complete freedom, which may better explore the possible space of modeling approaches as a group. The Task details and goals were significantly refined during the four years of DECOVALEX-2023. Discussions between the task lead and the teams were a critical part of the learning as a group (i.e., between the teams), as different approaches were attempted, modified, and sometimes dropped. The benefits from the Task E exercise extend beyond the improved conceptual understanding derived from modeling and the interactions between the teams, it also extends to the experiment design and execution.

Building on the success of Task E in DECOVALEX-2023, a new phase of DECOVALEX is underway, staring with a virtual meeting in April 2024. A new BATS task in this phase will expand on some of the things learned in the last phase, and allow other teams to come on board. The first in-person DECOVALEX-2027 meeting is planned to be in October 2024 in Berlin Germany, at BASE.

## 3.2 Task F2: Salt Reference Case

DECOVALEX Task F2 focused on the development and comparison of models, methods, and software that would be used for post-closure performance assessment (PA) of a salt repository. The primary objective of the task is a methodological development for PA, rather than model validation against experimental data. The reference case system used in this task incorporates data and measurements from relevant field sites and underground research laboratories, and associated features, events, and processes (LaForce et al., 2023). Task F2 was divided into three sub-tasks:

- Step S0: Deterministic Reference Case Creation
- Step S1: Benchmarks and Process Models
- Step S2: Deterministic Reference Case Model Comparisons

Task F2 included teams from Germany (BASE and GRS), the Netherlands (COVRA), the UK (Quintessa), and the US (DOE/SNL), which all contributed to the development of a domal salt reference scenario from the beginning of the Task F2 DECOVALEX-2023 phase. The scenario first considered a shaft seal failure at 1,000 years post-closure, where an influx of fluid was allowed to flow through the failed shaft from an overlying aquifer into the repository, and secondly, vitrified glass began dissolving upon emplacement along with an eventual simultaneous failure of spent nuclear fuel (SNF) waste packages at 500 years. To ensure consistency between modeling efforts of each team, the following stepwise process was used:

1. Model flow in the repository at variably saturated initial conditions
2. Add tracers, then radionuclide waste form release, mobilization, and transport
3. Include drift convergence by salt creep and backfill consolidation
4. Consider alternative scenarios

Each team used and compared different modeling approaches, assumptions, and quantities, which are explained in detail in La Force et al. (2023; 2024). Repository layouts for teams are shown in Figure 3. A few key approach differences include model dimensionality (i.e., 1D, 2D, or 3D), the process of how the repository fills (Richards' equation vs. single-phase Darcy's law), incorporation of solubility limits, and coupling salt compaction behavior. Some of the response comparisons were timing of shaft failure, heterogeneous shaft fill, geosphere brine inflow, multiphase flow variants, and changing initial water saturation of the repository.

The effects of incorporating salt compaction behavior (i.e., porosity changes) can be seen in the response of liquid saturation pressure within the SNF drift (Figure 4). Teams that incorporated creep closure saw an increase in liquid saturation early in the simulation, while it took much longer to increase saturation for the DOE-SNL team (which did not include creep closure of porosity). Figure 5 shows the results of tracer transport through the salt drift seal (into and out of). All models predicted an increasing rate of tracer transport into the seal, but at very low rates. The Quintessa model showed a small amount of tracer out of the seal, while the GRS model had the highest prediction within the 10,000-year simulation. All transport results at late time indicate a diffusion-dominated process. Overall, results showed that a shaft failure did not significantly control radionuclide or tracer transport; however, they did highlight the impact of including salt compaction models within the repository, which affect porosity reduction and resulting flow, and diffusive transport. Additional work is planned in DECOVALEX-2027 to better understand the most influential mechanisms for radionuclide transport (i.e. salt compaction model and diffusion).

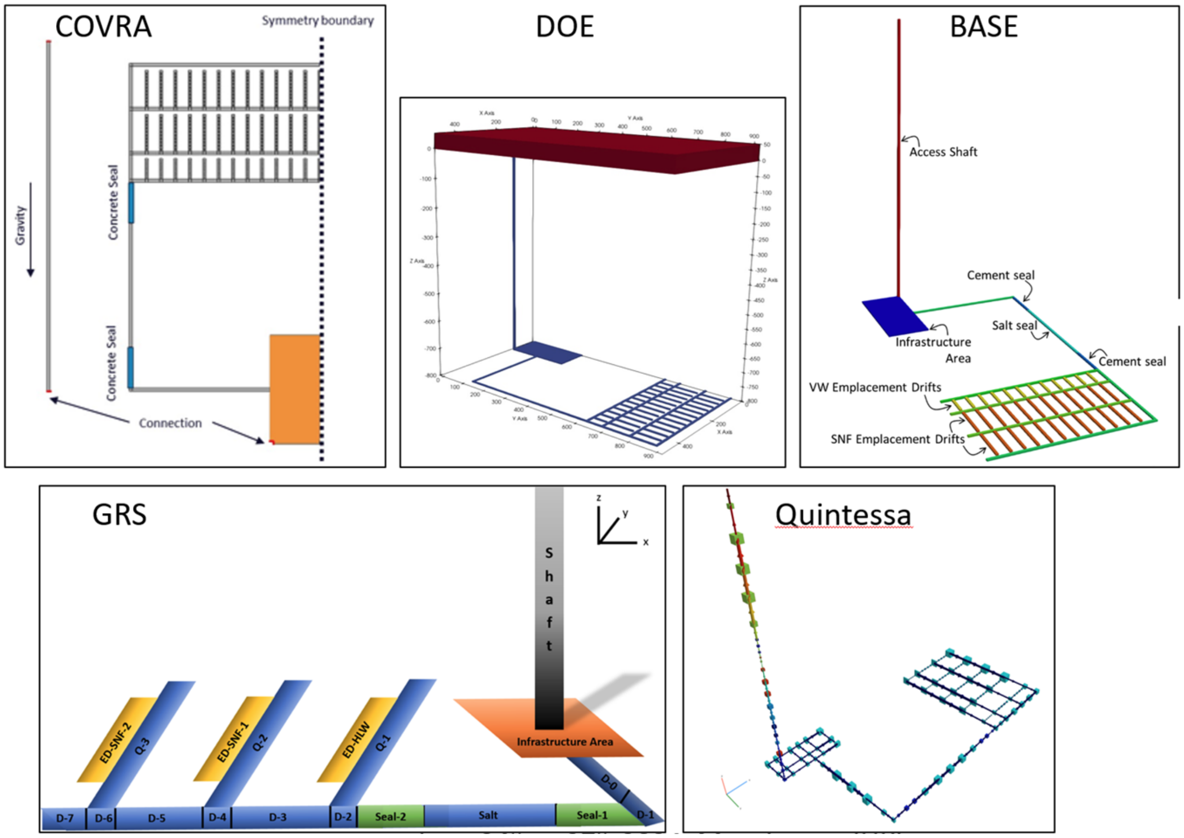


**Figure 3: Model representations of repository layout for each team in Task F2.**

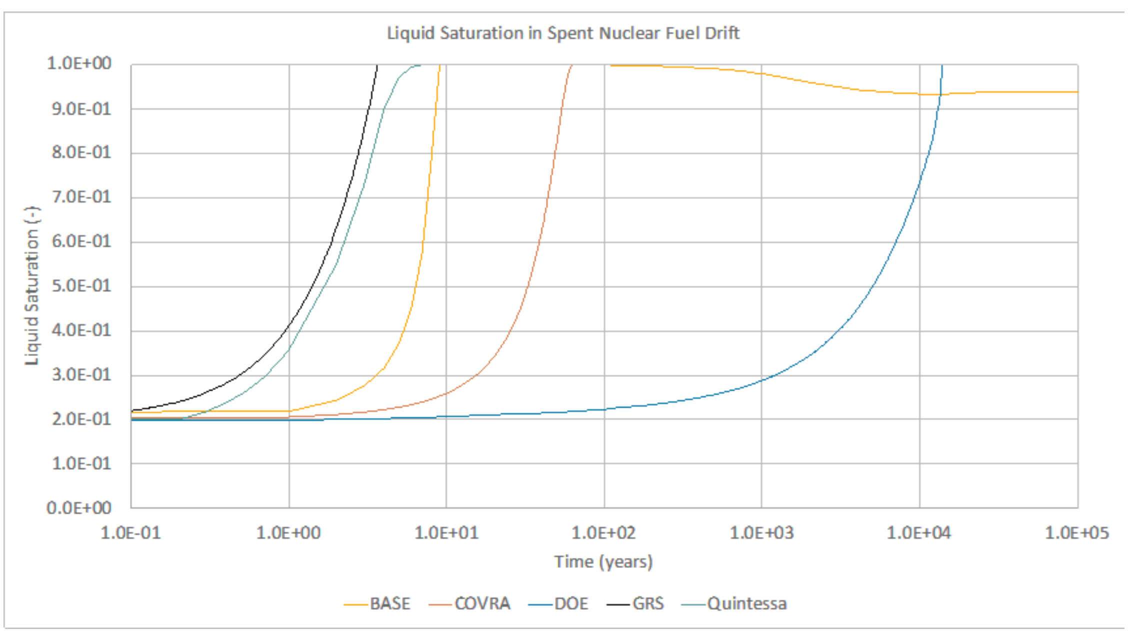

**Figure 4: Liquid saturation through time in the SNF drift for models considering closure (BASE, COVRA, GRS, Quintessa) and a model that does not incorporate closure (DOE-SNL).**


**Figure 5: Solute transport into (top) the drift seal from the waste area and out of (bottom) the salt drift seal towards the shaft.**

Given the outcomes of Task F2 in DECOVALEX-2023, the DOE-SNL team will continue to participate and lead a continuation of this task as Task PA in DECOVALEX-2027. The objectives of Task PA will be accomplished through expanding the analyses of the DECOVALEX-2023 results completed by the participating teams in their PA frameworks, including: (1) benchmark and process models (e.g., diffusion and salt creep); (2) deterministic simulation(s) of the entire PA model for defined reference scenario(s);

(3) probabilistic simulations of the entire PA model; and (4) uncertainty quantification (UQ) and sensitivity analysis (SA) methods/results for probabilistic simulations of defined reference scenario(s).

## 3.3 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, 2021. *Brine Availability Test in Salt (BATS) FY21 Update.* SAND2021-10962R. Albuquerque, NM: Sandia National Laboratories. https://doi.org/10.2172/1821547

Kuhlman, K., M. Mills, R. Jayne, E. Matteo, C. Herrick, M. Nemer, Y. Xiong, C. Choens, M. Paul, C. Downs, D. Fontes, B. Kernen, P. Stauffer, H. Boukhalfa, E. Guiltinan, T. Rahn, S. Otto, J. Davis, M. Carrasco Jr., J. Mata, J. Rutqvist, Y. Wu, H. Tounsi, M. Hu, S. Uhlemann & J. Wang, 2022a. *Brine Availability Test in Salt (BATS) FY22 Update*, 82 p., SAND2022-12142R. Albuquerque, NM: Sandia National Laboratories.

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, 2022b. *DECOVALEX-2023 Task E Interim Report*, SAND2022-6606O. Albuquerque, NM: Sandia National Laboratories.

LaForce, T., et al. 2024. FY24 GDSA Report (in progress)

LaForce, T., Bartol, J., Becker, D., Benbow, S., Bond, A., Dietl, C., Frank, T., Jayne, R., Kock, I., Magri, F., Nicholas, J., Pekala, M., Stauffer, P., Stein, E., Stone, J., and Wolf, J. 2023. *DECOVALEX-2023 Task F2-Salt Final Report*. Berkeley, CA: Lawrence Berkeley National Laboratories.

# 4. International Collaborative Percolation Experiments with GRS

In 2019, a collaborative effort began with colleagues at GRS to perform brine and gas percolation experiments of salt cement seals in conjunction with the BATS-1 experiment and task for DECOVALEX-2023 (Kuhlman, 2020). GRS performed similar experiments on German salt cement seals during the Full-Scale Demonstration of Plugs and Seals (DOPAS) project within EURAD-1, with LAVA-2 and LASA-EDZ as subprojects (Jantschik et al., 2018). The frame and pressure cell setup at GRS is unique and able to perform THMC experiments, including brine percolation. Due to unforeseen delays from COVID-19, personnel changes at GRS, and occupied equipment for other experiments, these tests were delayed several years; however, discussions on setup and sample types continued during meetings of the US/German Workshop. The proposed tests include coupled HMC flow tests at 25°C using simulated WIPP brine, coupled THM flow tests at 60°C, and HM flow tests at elevated pressures.

In FY23, SNL sent GRS several WIPP DRZ cores and lab-made salt concrete cores to obtain baseline permeability data. For a salt concrete core (Figure 6), a drop in permeability from $7.7 \times 10^{-18}$ m$^2$ to $5.5 \times 10^{-18}$ m$^2$ was observed at 1 MPa confining pressure after 90 days, which decreased to $4.7 \times 10^{-19}$ m$^2$ after increasing the confining pressure to 10 MPa. In FY24, SNL gently sub-cored and prepared additional hollow salt cylinders from WIPP DRZ core. These were then used to create salt cement samples for two scenarios: in-situ cured (like field emplacement) and ex-situ cured cement (similar to BATS installation and DOPAS experiments) (Figure 7). Samples were sent to GRS mid-FY24, where testing is anticipated to begin in FY25.

This collaborative effort continues to benefit both parties, since GRS is conducting tests on WIPP salt and cementitious plugs relevant to DOE-NE work, and SNL is providing samples to GRS that they would not otherwise have easy access to.

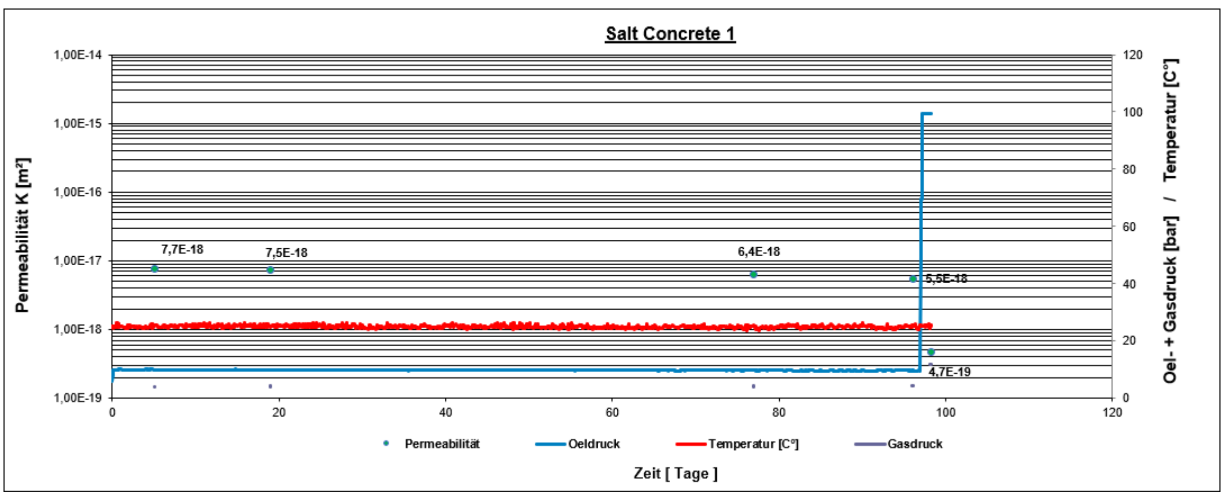


**Figure 6: Permeability results over time from GRS of salt concrete sample.**

**Figure 7: Types of salt core and salt concrete samples sent to GRS in FY24 (in-situ cured left, ex-situ cured right).**

## 4.1 References

Jantschik, K., J. Kulenkampff, & H. Moog, 2018. *Investigation of the Flow Along the Contact Seam between Salt Cement and Rock Salt*, in: The Mechanical Behaviour of Salt IX. Hannover, Germany.

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

# 5. International Collaborations through NEA Salt Club

SNL Authors: *Kris Kuhlman*

Personnel from SNL and Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) continue to lead and progress a long-standing development of a comprehensive Features, Events and Processes (FEPs) catalogue and FEP database (Freeze et al., 2020). This work is extended through 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).

The Salt Scenarios working group continues to progress on a NEA Salt Club report on scenario development, planned to be completed in FY24. A small group also completed a journal manuscript on the topic of scenario development, with a more general focus than salt (Kuhlman et al., 2024).

The group presented its status at the in-person NEA Salt Club meeting and the US/German Workshop on Salt Repository Research, Design & Operation in Manchester, UK in June 2024. This collaborative effort has brought together experts on FEPs and scenario development from Germany, the UK, Sandia and the Netherlands. The process of preparing the manuscript brought out the similarities and differences in the different programs, which are often due to regulatory differences. Understanding these differences is important when seeking to transfer lessons-learned through experience in international programs to the U.S. disposal program.

## 5.1 References

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

Kuhlman, K.L., J. Bartol, A. Carter, A. Lommerzheim & J. Wolf, 2024. Scenario development for safety assessment in deep geologic disposal of high-level radioactive waste and spent nuclear fuel: A review, *Risk Analysis*:1-15. https://doi.org/10.1111/risa.14276

# 6. International Collaboration through US/German Workshop

SNL Authors: *Melissa Mills and Kris Kuhlman*

The US/German Workshop on Salt Repository Research, Design & Operation is a multi-national annual meeting on repository science in salt, that has often met jointly with the NEA Salt Club plenary meeting. The proceedings from past US/German workshops are published on the Sandia National Laboratories salt repository research webpage: https://www.sandia.gov/salt/us-german-workshop/

**Table 1. US/German Workshop Venues**

| # | Dates | Location | Salt Club? |
|---|---|---|---|
| 1 | 25-27 May 2010 | Mississippi State Univ, Canton, USA | |
| 2 | 9-10 Nov. 2011 | Hotel Schönau, Peine, Germany | |
| 3 | 8-11 Oct. 2012 | SNL, Albuquerque, USA | |
| 4 | 17-18 Sep. 2013 | Hollywood Media Hotel, Berlin, Germany | ✓ |
| 5 | 8-10 Sep. 2014 | La Fonda Hotel, Santa Fe, USA | |
| 6 | 7-9 Sep. 2015 | Hotel Pullman Dresden Newa, Dresden, Germany | |
| 7 | 7-9 Sep. 2016 | Crystal City Embassy Suites, Washington DC, USA | ✓ |
| 8 | 5-7 Sep. 2017 | COVRA, Middelburg, The Netherlands | ✓ |
| 9 | 10-11 Sep. 2018 | BGR, Hannover, Germany | ✓ |
| 10 | 28-30 May 2019 | SD School of Mines, Rapid City, USA | ✓ |
| 11 | 2 Feb., 17 Jun., 8-9 Sep. 2021 | Virtual (MS-Teams) | |
| 12 | 6-8 Sep. 2022 | Hotel Steigenberger, Braunschweig, Germany | ✓ |
| 13 | 20-23 Jun. 2023 | Drury Plaza Hotel, Santa Fe, USA | ✓ |
| 14 | 25-28 Jun. 2024 | Manchester Piccadilly Hotel, Manchester, UK | ✓ |

In late FY24 ( 25-28 June 2024), the 14th US/German Workshop was held in Manchester, UK. The workshop was co-hosted by Michael Bühler (PKTA), Jörg Melzer (PKTA), Philipp Herold (BGE TECH), Simon Norris (NWS), Melissa Mills (SNL), and Kris Kuhlman (SNL).

Despite its name, the US/German workshop includes participants from several countries. The 14th US/German workshop included more than 60 in-person participants and multiple virtual participants from the following countries and organizations:

- Germany:
  - BASE (Bundesamt für die Sicherheit der nuklearen Entsorgung)
  - BGE (Bundesgesellschaft für Endlagerung) and BGE TECHNOLOGY
  - BGR (Bundesanstalt für Geowissenschaften und Rohstoffe)

- BMUV (Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbaraucherschutz)
- GRS (Gesellschaft für Anlagen- und Reaktorsicherheit)
- IfG (Institut für Gebirgsmechanik)
- KIT PTKA (Projektträger Karlsruhe Karlsruher Institut für Technologie)
- KIT-INE (Institut für Nukleare Entsorgung des Karlsruher Instituts für Technologie)
- TU Bergakademie Freiberg
- TU Clausthal
- Technische Universität Braunschweig

- United States:
  - Sandia National Laboratories
  - Los Alamos National Laboratory
  - Department of Energy Office of Nuclear Energy
  - Environmental Protection Agency
  - RESPEC,
- The United Kingdom:
  - Nuclear Waste Services
  - British Geological Survey
  - MCM Environmental Services
  - National Nuclear Laboratory
  - Quintessa, Ltd.
  - University of Liverpool
  - University of Manchester
- The Netherlands:
  - Centrale Organisatie Voor Radioactief Afval
- Australia:
  - Commonwealth Scientific and Industrial Research Organisation (virtual)
- International:
  - The International Atomic Energy Agency (virtual)

The topics included a status of national radioactive waste disposal programs, modeling results of various projects, approaches to safety case assessments, engineered barrier systems, and geochemistry. In addition, two parallel breakout discussion sessions were organized: one on the topic of creep tests under small deviatoric stresses, and the other on the future of the in-situ salt concrete ERAM experiment. Feedback from workshop attendees was highly positive, particularly from UK associations who enjoyed meeting and interacting with other repository scientists for the first time. The next US/German Workshop will be in Germany in October 2025.

The first few US/German Workshop on Salt Repository Research, Design & Operation were a key vehicle to bring back together repository scientists from the US and Germany, who had previously collaborated, until collaborative efforts had fallen to the wayside because of the focus on Yucca Mountain and Gorleben. With the shift to generic R&D to better understand fundamental processes in multiple geologies, the workshop allowed old collaborators to come back together, and create many new collaborations. In its 14th year, the workshop has moved past the researchers who started it, and now brings together early and mid-career researchers, and as was illustrated by the location in Manchester, it now brings together researchers from a wider range of countries than it originally did. Sandia and DOE-NE led efforts to continue the US/German workshop through the COVID-19 pandemic, and it has shown it can be a robust focal point for exchange of the state-of-the-art science, and we hope it continues this role for future collaborative efforts.