International Collaborations on Radioactive Waste Disposal in Salt

Spent Fuel and Waste Disposition

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SUMMARY

This report is a summary of the international collaboration and laboratory work 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 work package. This report satisfies milestone level-four milestone M4SF-19SN010303064. Several stand-alone sections make up this summary report, each completed by the participants. The first two sections discuss international collaborations on geomechanical benchmarking exercises (WEIMOS), granular salt reconsolidation (KOMPASS), engineered barriers (RANGERS), and documentation of Features, Events, and Processes (FEPs).

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
DRZ	disturbed rock zone
ELSA	Schachtverschlüsse für Endlager für hochaktive Abfälle
FEP	feature, event, process
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit
HLW	high-level waste
IfG	Institut für Gebirgsmechanik GmbH
KOSINA	Konzeptentwicklung für ein generisches Endlager für wärmeentwickelnde Abfälle in flach lagernden Salzschichten in Deutschland sowie Entwicklung und Überprüfung eines Sicherheits- und Nachweiskonzeptes
M-D	Munson-Dawson
NEA	Nuclear Energy Agency
RANGERS	Design and Integrity Guideline for Engineered Barrier Systems for a HLW Repository in Salt
R&D	Research and Development
SFWST	Spent Fuel and Waste Science & Technology
SNL	Sandia National Laboratories
THM	thermal-hydraulic-mechanical
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)

INTERNATIONAL COLLABORATIONS ON RADIOACTIVE WASTE DISPOSAL IN SALT

This report is a summary of the international collaboration 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 International work package. Several stand-alone sections make up this summary report, each section completed by different participants. The first two sections discuss international collaborations on geomechanical benchmarking exercises (WEIMOS) granular salt reconsolidation (KOMPASS), engineered barriers (RANGERS), and documentation of Features, Events, and Processes (FEPs).

Two of the primary collaborative efforts funded by Salt R&D are co-organization of, and participation in, both the US/German Workshop on Salt Repository Research, Design, and Operation and the NEA Salt Club. The ninth meeting of the NEA Salt Club took place in Rapid City, South Dakota May 31, 2019. The tenth meeting of the US/German workshop took place at South Dakota School of Mines May 28-29, 2019. These international collaborations will be summarized in detail in the upcoming proceedings, which will be a milestone completed in fiscal year 2019.

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

Authors: *Ed Matteo* (SNL) and *Eric Simo* (BGE Technologies)

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 as a whole. 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 (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).

BGE and BGE Technology have been developing and building drift seals in the Asse repository for more than ten years. 32 drift seals have been built and are already in routine operation. A real scale prototype sealing structure was built by the BGE in the Morsleben repository mine and is currently being scientifically investigated. BGE and BGE Technology therefore have a well-founded know-how in the field of geotechnical barriers.

Sandia National Laboratories has a long history in the design and testing of shaft and drift seals in bedded salt, including the design of geotechnical barriers at the Waste Isolation Pilot Plant (WIPP), as well as for barriers and seals in a generic HLW repository in a bedded salt host media (Christensen 1979; Stormont 1987; Wakeley 1994; Hansen 1999).

Despite extensive knowledge and experience about geotechnical barriers in salt formations, there is no guideline 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 USA, with the acronym RANGERS. 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 or the USA. It summarizes the state of the science and art available today in a single report 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:

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

The project is divided in 6 work packages. The outcome of the project KOMPASS – another binational project between Germany and USA – 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.

1.1 (WP 1) State of the Art in Science and Technology

- Extensive description of the state of the art in science and technology for sealing structures: drift seals construction in Asse mine, drift seal prototype at the Morsleben Repository, design and verification of shaft systems of the preliminary safety case of the Gorleben Repository (VSG), shaft seals work done for WIPP, closure concepts of Sandia, etc.
- Summary of all relevant findings for the design, construction and integrity verification of sealing structures
- This work package will also cover the international status of the design and construction of geotechnical barriers that deviate from the approaches currently being pursued in Germany and the USA. The research also covers new building materials such as polymer concretes, manufacturability and quality testing, in situ experiments as well as other concepts and technologies such as pre-stressing techniques or thermal elements for faster creep that are relevant for geotechnical barriers.

1.2 (WP 2) Basics and Requirements

- Evaluation and comparison of the regulatory requirements for the design and construction of sealing structures for salt mines and for repositories in Germany and the USA
- Determination of site- and repository-specific boundary conditions for the design of sealing structures using the example of repository concepts such as KOSINA and the WIPP.
- Compilation of relevant Features, Events and Processes (FEPs) and scenario developments for geotechnical barriers based on international and national FEP catalogues.
- Compilation of further basics and requirements from the findings of research projects and from practical experience.

1.3 (WP 3) Development of a Guideline Based on State-of-the-Art Science and Technology for Design and Verification of Geotechnical Barriers

- Compilation of all components and their functions required for the construction of sealing structures and recommendation for the selection of suitable building materials.
- Development of pre-dimensioning approaches for the design of sealing and shaft closures.
- Review of the technical demonstration concept developed in the scope of VSG for an HLW repository in Germany based on new insights from research projects such as KOSINA and ELSA, the final report of the German Commission for deep disposal of radioactive waste, the planned update of the safety requirements of the German Federal Ministry of the Environment and the characteristics of the different salt formation types.
- Development of a technical demonstration concept based on safety requirements and guidelines in the USA.
- Conversion of the FEPs into design loads and resistances as well as design situations according to country-specific guidelines for geotechnical structures.

- Derivation of an overall demonstration framework and the corresponding design situations for the shaft and drift sealing structures.
- Completion of the guideline

1.4 (WP 4) Preliminary Design and Verification of Geotechnical Barrier System

1.4.1 (WP 4.1) Preliminary Design and Verification of Geotechnical Barrier System for KOSINA Concept Based on the Developed Guideline

- Design and preliminary dimensioning of the drift sealing system for a repository concept from KOSINA as an iterative process
- Design and pre-dimensioning of shaft sealing system for a repository concept from KOSINA as an iterative process
- Assessment of the feasibility/constructability of the planned geotechnical barrier system
- Safety demonstration for the derived design situations
- Evaluation of the developed guideline based on the results of the demonstration

1.4.2 (WP 4.2) Preliminary Design and Verification of Geotechnical Barrier System for Generic Heat-Generating Waste Repository in Salt Based on the Developed Guideline

- Design and preliminary dimensioning of the drift sealing system for a generic salt host as an iterative process
- Design and pre-dimensioning of shaft sealing system for a generic salt host as an iterative process
- Assessment of the feasibility/constructability of the planned geotechnical barrier system
- Safety demonstration for the derived design situations
- Evaluation of the developed guideline based on the results of the demonstration

1.5 (WP 5) Comparison of Design Results According to New Guideline with Results of Previous Design and Assessment

In this work package, the applicants will compare the design and assessment analysis performed in WP 4 based on the developed guideline with other assessment and performance analyses carried out in previous projects such as VSG, ELSA, and WIPP, and current works for a generic salt repository site. Thus, the benefits and limitations of the guideline will be derived.

1.6 (WP 6) Documentation and Final Report

The outcomes of the project RANGERS will be documented in five reports:

- The first report about the state of the art in science and technology as well as an outlook for new concepts on the design of geotechnical barrier system of an HLW repository in salt rock will cover the work carried out in WP1.
- The elaboration of the guideline will be described in one report. This comprises the work done in WP 2 and WP 3.
- The prototypical design and verification of the geotechnical barrier system will be reported in two reports (WP 4): one for the German case based on a repository concept developed in the scope of

the KOSINA project and a second for the American case based on design concept from WIPP to be applied to a generic repository for heat-generating waste in a salt host.

- A synthesis report (WP 6) will close up the project with the main findings and summary and integrated in the comparison carried out in WP 5.

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2. International Collaboration through the KOMPASS Project

Authors: *Melissa Mills* (SNL) and *Ben Reedlunn* (SNL)

Joint Project KOMPASS is a collaboration of German and American researchers seeking to improve thermo-hydro-mechanical models for crushed salt. The project could be characterized as a Joint Project WEIMOS for crushed 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 (Peine, Germany), Institute für Gebirgsmechanik (Leipzig, Germany), Technical University of Clausthal (Germany), Gesellschaft für Anglagen-und Reaktorsicherheit (Köln, Germany), Bundesanstalt für Geowissenschaften und Rohstoffe (Hannover, Germany), and Sandia National Laboratories (Albuquerque, USA).

The project involves the following four work packages (WP's):

1. Benchmarking existing constitutive models
2. Thermal-hydraulic-mechanical (THM) characterization experiments
3. Analysis of microstructural mechanisms
4. Develop a sequel to the KOMPASS project

A short description of each work package is given below.

2.1 (WP 1) Benchmarking Existing Constitutive Models

The benchmarking work package involves both a literature review and quantitative comparisons against a specific experiment. The literature review of the various thermal, hydraulic, and mechanical models for crushed salt paid special attention to the coupling between the various processes and sub-processes. It was concluded that thermal models capture the experimental observations relatively well, but hydraulic and mechanical models have room for improvement, especially close to total compaction. The quantitative comparisons are to be against a well-controlled and documented crushed salt experiment named TK-31. Each partner is using a pre-existing calibration of their model to predict the measured deformations (principal strains, porosity changes) for the prescribed triaxial stress path in TK-31. Each partner then adjusts the model parameters to improve the comparison, and attempts to predict other validation experiments. Sandia has begun to simulate TK-31 using the Callahan model (Callahan, 1999).

2.2 (WP 2) Thermal-hydraulic-mechanical (THM) Characterization Experiments

This work package primarily aims to develop two sets of experimental techniques. The first technique seeks to efficiently pre-compact samples down to less than 10% porosity using in-situ loading conditions. To simulate the compaction of crushed salt by a closing drift, cylindrical crushed salt samples are being radially loaded while the axial deformation is constrained. The second technique endeavors to measure THM behavior of crushed salt samples down to 1% porosity. The partners are currently attempting to combine and optimize the advantages of existing techniques, such as porosimetry and cell oil volume balance.

2.3 (WP 3) Analysis of Microstructural Mechanisms

Sandia will study compacted crushed salt samples to determine what microstructural differences, if any, exist in order to guide the pre-compaction processes applied in WP 2. In a direct collaboration, microstructural investigations will be conducted at Sandia, as samples become available, to identify changes in structure and deformation mechanisms under various conditions. In July of fiscal year 2019, portions of three samples of pre-consolidated Sonderhausen salt were received at Sandia from Till Popp at

Institute für Gebirgsmechanik (IfG). The samples were compacted stepwise in a quasi-oedometer cell to a maximum axial load of 20 MPa. A fairly fine grain size of less than 5 mm was utilized. The initial half-cylinder dimensions were 100 mm in diameter and approximately 100 mm tall. Due to friction effects at the wall of the cell, the compaction varies along the sample axis from a porosity of 10% to 20% (bottom to top). The three sample conditions were as follows: room temperature for a duration of 5 days, 98 °C for one day, and 98 °C for 5 days (Figure 1).

Due to the fragility and variable porosity of pre-consolidated samples, the plan is to impregnate them with epoxy to further cut and create thin sections for analysis. Typical methods of single grain analysis with cleaving and etching will be attempted, but not guaranteed due to the small grain size of the samples. Thin sections will be examined under reflected light on an optical microscope and also a scanning electron microscope. Etching of surfaces will allow for subgrain size and free dislocation densities to be examined, along with grain boundaries. The investigation of the microstructure and the observation of any differences will optimize the approach used for pre-consolidation of future samples within the KOMPASS project.

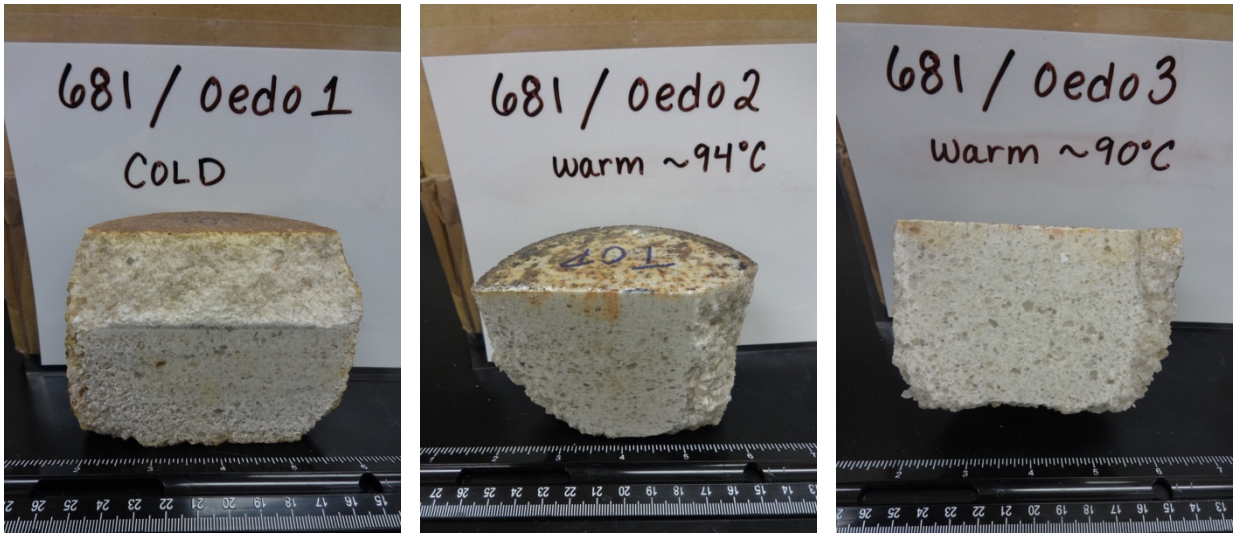

Figure 1. Samples recieved at Sandia from IfG for KOMPASS

2.4 (WP 4) Develop a Sequel to the KOMPASS Project

The KOMPASS project is only two years long and the existing knowledge deficits will not be resolved in this time. As such, the partners hope KOMPASS will be extended for several more years. This work package will take the results of work packages 1 through 3 to develop a methodical set of experiments for constitutive model calibration and validation

2.5 Reference

Callahan, GD. (1999) Crushed salt constitutive model. Tech. Report SAND98-2680. Sandia National Laboratories

3. International Collaboration through the Joint Project WEIMOS

Authors: *Benjamin Reedlunn* (SNL), *Steve Sobolik* (SNL), and *Melissa Mills* (SNL)

Joint Project WEIMOS is a collaboration of German and American researchers seeking to improve thermomechanical modeling of salt repositories. The group primarily focuses on improving constitutive models for rock salt, but the partners also undertake extensive laboratory test programs and refine methods for simulating the evolution of underground structures. Typically, the laboratory tests help inform and calibrate the partners' constitutive models, which are then benchmarked against underground experiments. 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 include Hampel Consulting (Mainz, Germany), Institute für Gebirgsmechanik (Leipzig, Germany), Leibniz University (Hannover, Germany), Technical University of Braunschweig (Germany), Technical University of Clausthal (Germany), and Sandia National Laboratories (Albuquerque, USA).

The three joint projects that preceded WEIMOS substantially improved the current state-of-the-art models and also helped identify the following work packages (WP) that together comprise 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.

3.1 (WP 1) Small Deviatoric Stresses

Salt creep is the driving force for room closure in salt repositories. The precursor to WEIMOS, Joint Project III, confirmed that salt undergoes a creep mechanism change between intermediate and low stresses. Low stress creep occurs below about 8 MPa equivalent deviatoric stress at 60 °C, but methods to accurately measure low stress creep at 20 to 30 °C, low stress creep's temperature dependence, and the underlying micromechanical mechanism behind low stress creep have not been established.

Creep strain measurement at low stress is very challenging. As such, Institute für Gebirgsmechanik (IfG) has created three new triaxial creep test rigs with high-resolution displacement measurement systems and vibration isolation. The rigs are located inside a chamber with tight control of humidity and temperature. Creep samples tested at intermediate stresses are typically isostatically reconsolidated for something between 1 and 10 days in order to heal microcracks associated with sample excavation and preparation. This reconsolidation phase was extended to 130 days for low stress creep experiments, yet the axial strain was still slightly changing after 100 days. Following reconsolidation, each sample will go through a series of creep phases at various stresses and temperatures to more quickly and accurately approach the true steady-state creep rate. Each test will require approximately 1 year.

The impact of low stress creep on room closure is striking. Sandia recently modified the Munson-Dawson model to include an assumed form for the creep mechanism at low stress. (The new model, including an improved numerical implementation, were documented in Reedlunn (2018a).) When the new model was calibrated against the Joint Project III data, the new low stress creep increased the predicted vertical closure rate of Room D at the WIPP by 2.7 times (Reedlunn, 2018b).

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, serve as flow pathways for radionuclides. Although shear-induced damage has been studied in the past, the influence of temperature and stress state on healing is not well understood. Accordingly, an experimental program is underway at Technical University at Clausthal to characterize these dependencies. They recently found that previous healing tests produced inconclusive results due to difficulties with precisely measuring the volume change. Future healing tests will be performed on new high-precision mechanical testing rigs.

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 very limited data exists on tensile failure. Due to initial funding limitations, the WEIMOS partners simply compared their predictions of tensile cracking in several structural simulations. Now that funding constraints have been eased, experiments are planned where samples will be pre-damaged to different degrees in a triaxial cell, followed by tensile testing to determine the tensile strength. These experiments will inform and calibrate the partners' constitutive models.

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. Consequently, Sandia sub-contracted RESPEC to perform a series of shear tests on clay seams, as well as salt/polyhalite and salt/anhydrite interfaces, extracted from a mine near the WIPP site. Surprisingly, the clay seam cohesion and friction angle were nearly the same as pure salt without any interfaces. Post-test inspection found salt crystals spanning much of the clay seam interface, which is not believed to be representative of clay seems from the WIPP (Sobolik, 2019). Efforts to extract actual WIPP clay seams are underway. In the meantime, preliminary tests on artificially manufactured clay seams measured a cohesion and friction angle roughly half that of pure salt. Once reliable experimental measurements have been collected the partners plan to develop constitutive models for the clay seam behavior.

3.5 (WP 5) Virtual Demonstrator

The WEIMOS partners are currently at work on a demonstration of the modeling capabilities developed in work packages 1 through 4. The demonstration involves a simulation of unrestrained open drift closure for 30 years, introduction of a sealing system, and continued simulation of the subsequent 70 years. A clay seam will intersect the drift. The closure of the open drift will exercise the low stress creep, tensile damage, and layer boundary capabilities, while the compaction of the seal will deactivate the damage evolution and activate the healing capability. Qualitative and quantitative comparisons to existing in-situ experiments will be attempted.

3.6 Further, Sandia Specific, Comments

Work packages 1 through 4 all involve experiments, and it would be of great benefit to the WIPP rock mechanics program if some experiments were performed on WIPP salt. Sandia is currently attempting to get core from WIPP to send to Germany, but WIPP's operational priorities may take precedence.

Sandia currently utilizes the Munson-Dawson (M-D) model for rock salt. The M-D model captures the temperature and stress dependence of creep along proportional stress paths, but does not include the evolution of damage or healing. It also fails to capture the mechanical response at moderate strain rates (10^{-6} to 10^{-4} 1/s) and along non-proportional stress paths. As such, Sandia is actively considering modifying the M-D model, as well as alternative constitutive models, such as the Aubertin model (Yahya et al, 2000). These model changes must be completed before Sandia can fully take part in Work Packages 2, 3, and 5.

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4. SaltFEP Catalog

Author: *Mike Gross (SNL)*

Personnel from SNL and from Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) have continued to collaborate on the development of a comprehensive Features, Events and Processes (FEPs) catalogue and FEP database for a high-level waste repository at a generic salt site. The salt FEP catalogue was developed using a matrix approach that classifies FEPs using a two-dimensional structure consisting of a Features/Components axis and a Processes/Events axis. The FEP catalog builds upon prior work at SNL and at GRS, and supports the Nuclear Energy Agency (NEA) Salt Club Mandate. The "SaltFEP" database archives information from the catalog and from other supporting documentation into a user-friendly format that is easy to search. The generic salt repository FEPs include consideration of relevant FEPs from a number of U.S., German, and international FEP lists and should be suitable for any repository program in bedded or domal salt formations.

During the past year, a number of changes were made to the salt FEP catalog, including an improved description of the thermal-mechanical and thermal-hydrological FEPs, the use of more generalized process descriptions that allow the FEP catalog to be extended to other types of geologic media, and a list of preliminary screening recommendations for processes at a generic salt site. These changes have been documented in a draft final report that is currently under review and scheduled for submission to the NEA by the end of 2019.

5. BATS as a task in DECOVALEX 2023

Author: *Kris Kuhlman* (SNL)

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) (Mills, et al., 2019). This field test has been proposed to be a task in the 2020-2023 round of DECOVALEX (DEvelopment of COupled models and their VALidation against Experiments; `www.decovalex.org`). The DOE national laboratories (Sandia, Los Alamos, and Lawrence Berkeley) participating in the test have tentatively committed to participating in the DECOVALEX task, as well as tentative agreement for international collaboration from COVRA, RWM, GRS, and possibly BGR.

If the BATS test is formally selected as a task in DECOVALEX 2023 (decision will be made at November, 2019 meeting), the project will begin in Spring 2020.

5.1 Reference

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