International Collaborations on Radioactive Waste Disposal in Salt (FY20)

Spent Fuel and Waste Disposition

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

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SUMMARY

This report is a summary of the international collaboration work conducted by Sandia and 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 milestone level-three milestone M3SF-20SN010303062. 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	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
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 (FY20)

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 R&D and Salt International work packages for fiscal year 2020 (FY20). 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 Nuclear Energy Agency (NEA) Salt Club. These meetings were postponed for one year (the May 2020 meeting in Braunschweig, Germany was moved to May 2021) as a consequence of travel restrictions from the COVID-19 pandemic. Other collaborative efforts have continued, relying on virtual meetings and email for collaboration. We hope to resume periodic in-person meetings with our German, Dutch, and British colleagues in the near future.

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*, *Kris Kuhlman*

RANGERS is a collaborative project between Sandia and BGE Technology (including Eric Simo and Andree Lommerzheim). After translating to English, the acronym is "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 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).

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 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 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 into six work packages. The outcome of the project KOMPASS – another binational project between Germany and the US – 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, much progress has been made this Fiscal Year in building the teams at SNL and BGE. With the teams assembled, considerable work has been completed in WP 1 and WP 2. Because the work in subsequent WP's (WP 3 through 6) will be dependent on Performance Assessment (PA) and establishment of a Salt Reference Case, RANGERS in participating in integration activities with "Salt

Scenarios" workshop in August of 2020. Salt Scenarios brings together researchers from the US, Germany, Netherlands, and the UK, who are interested in the PA-focused DECOLAEX 2023 Task F.

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

This State of the Art (SOTA) Report will include

- 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, Sandia closure concepts.
- 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 US. 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.

Progress on the SOTA Report has consisted of activities centered on updating previous reviews and reports of Seal Tests in Salt. Reviews are in progress to summarize field-scale tests in Germany and the US related to performance of shaft and drift seals. By creating a comprehensive review of prominent seal materials (e.g., cementitious materials, crushed salt, and asphalt), the SOTA will provide a firm basis for developing the Design Guidelines in WP 3, 4, and 5.

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 US
- 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.

Progress has also been made on developing a comprehensive perspective on the Basics and requirements. BGE has generated a seals-focused FEPs analysis that will be cross-checked against previous work on the US-German Salt FEPs Catalogue.

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 US.
- 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 Sandia and BGE 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

SNL Authors: *James Bean*, *Melissa Mills*, 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). The project could be characterized as analogous to the preceding Joint Project WEIMOS, but 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 (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 project involves the following four work packages (WPs):

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 comprehensive status report is currently under preparation (in English), but a short description of each work package is given below.

2.1 (WP 1) Benchmarking Existing Constitutive Models

The benchmarking work package involved 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 (i.e., low porosity). The quantitative comparisons were against three well-controlled triaxial stress compaction experiments on cylindrical samples of crushed salt, named TK-031, TK-033, and TUC-V2.

Each partner used a pre-existing calibration of their model to predict the measured deformations (principal strains, strain rates, porosity changes) for the prescribed triaxial stress paths in each compaction experiment. Sandia simulated the experiments using the Callahan model (Callahan, 1999). Both GRS and Sandia concluded that simulations of these experiments should not ignore the pre-compaction phase conducted prior to the experiment. Pre-compaction obviously reduces porosity, but the GRS and Sandia material models also predict hardening of the crushed salt during pre-compaction, and this hardening affects the subsequent triaxial compaction phase. Despite the improved predictions when including the pre-compaction phase, Sandia’s porosity reduction predictions are consistently too small following each applied compressive stress increase. Recalibration of the model would likely reduce this under-prediction.

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

This work package primarily strove to develop two sets of experimental techniques. The first technique sought to efficiently pre-compact samples with various moisture contents down to less than 10% porosity.

Pre-compaction duration, temperature, and applied stress were all varied, resulting in final porosities typically in the 14% to 17% range. The second technique endeavored to measure behavior of crushed salt samples down to 1% porosity using well controlled boundary conditions. Some details of several well controlled tests are reviewed below, as some tests were used for constitutive model validation in WP1.

The TK-031 and TK-033 samples were pre-compacted in an oedometer and then compacted in a triaxial cell. The oedometer pre-compaction applied a constant axial strain rate while constraining the radial strain to zero. One notable issue with an oedometer is the frictional forces between the crushed salt and the rigid oedometer walls can cause porosity gradients in a sample as it compresses axially. Triaxial cells, however, allow one to prescribe the axial and radial stresses, without substantial frictional forces. In TK-031 and TK-033, the triaxial cell applied nearly isotropic stress in multiple stages of increasing mean stress.

Test TUC-V2 was pre-compacted and compacted in a triaxial cell. In this case, the pre-compaction was performed with a constant lateral stress of 5 MPa while the axial strain was prescribed to be zero. These pre-compaction boundary conditions are representative of the compaction of a crushed salt backfill in a long drift (plane strain assumption) as the host salt converges inward. The oedometer friction problem is eliminated, but, after the pre-compaction phase, the sample must be trimmed to ensure that the sample is a cylinder with smooth exterior surfaces prior to using it in the subsequent compaction phase. During the compaction phase, intermittent deviatoric stress stages were imposed in the midst of each nearly isotropic stage.

A fourth test TUC-V3 used the same pre-compaction process as TUC-V2, but the triaxial stress phase was more complicated. In this case, the axial strain rate was specified, and the lateral pressure was continuously adjusted to maintain an axial to radial stress difference of 1 MPa. This test was not modeled in WP1, partly because simulation of TUC-V3 may require an iterative approach to satisfy the stress difference constraint, but it may be worth considering in the future.

2.3 (WP 3) Analysis of Microstructural Mechanisms

Sandia studied 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 were conducted at Sandia to identify changes in structure and deformation mechanisms under various conditions. Over the duration of the KOMPASS project, four pre-compacted Sonderhausen salt sub-samples were sent from Till Popp at Institute für Gebirgsmechanik (IfG), as shown in Table 1. The table lists the sample identification number, oedometer ring's inner diameter, sample temperature during pre-compaction, axial stress applied by the oedometer piston, pre-compaction duration, and final average relative porosity. The samples were compacted stepwise in a quasi-oedometer cell to a maximum axial load of 20 MPa with initial porosities between 31% and 36%. A predefined and optimized mixture of grain sizes less than 6 mm was utilized, where the average water content of the material was found to be around 0.1 wt-%. All four test specimens were pre-compacted under dry conditions.

Three samples, of equal initial density, were compacted in a small oedometer cell of 0.1 m diameter (Figure 1a.-c.) and one in a larger cell of 0.514 m diameter (Figure 1d.), noted as 'big compaction cell'. Rather than send the entire large cell sample, IfG sent Sandia two 100 mm diameter by roughly 25 mm thick cylindrical sub-samples. For the small oedometer samples, porosity decreases along the sample axis from bottom to top due to less force available for compaction from side friction of the sample cell wall.

To prepare thick-thin sections, specifically for reflected light analysis, the samples were prepared as follows. First, the small oedometer samples were cut into slabs lengthwise, using a low-damage Isomet saw with isopropanol as the cutting fluid. This was to maintain the variable porosity profile. Due to the overall length of the sample profile, two thick-thin sections were fabricated from each sample slab; top to middle and middle to bottom. After cutting adequately sized blocks for a standard thin section, they were each vacuum impregnated with a two-part epoxy with added rhodamine B dye for contrast. A semi-automatic grinder/polisher was used first with 600 grit SiC paper to create a parallel surface, followed by 1200 grit, both with alcohol-based lubricant. The polishing steps are outlined in Table 2, and also used an alcohol-based lubricant for each diamond suspension. After each polishing step, the thick-thin sections were cleaned in an ultrasonic bath of isopropanol. The large oedometer cell sub-sample thin sections were made similarly, however, profile orientation was not as meticulous due to the sizes of received samples.

Table 1: Test parameters for pre-compacted samples from oedometer experiments.

Sample ID	Oedometer Inner Diameter (m)	Temperature (ºC)	Axial Stress (MPa)	Duration (days)	Final Relative Porosity (%)
681/Oed 1	0.1	Ambient	20	5	14.8
681/Oed 2	0.1	94	20	1	10.5
681/Oed 3	0.1	94	20	5	10
Big Oed cell Dry (sub-sampled)	0.514	Ambient	20	28	13.6

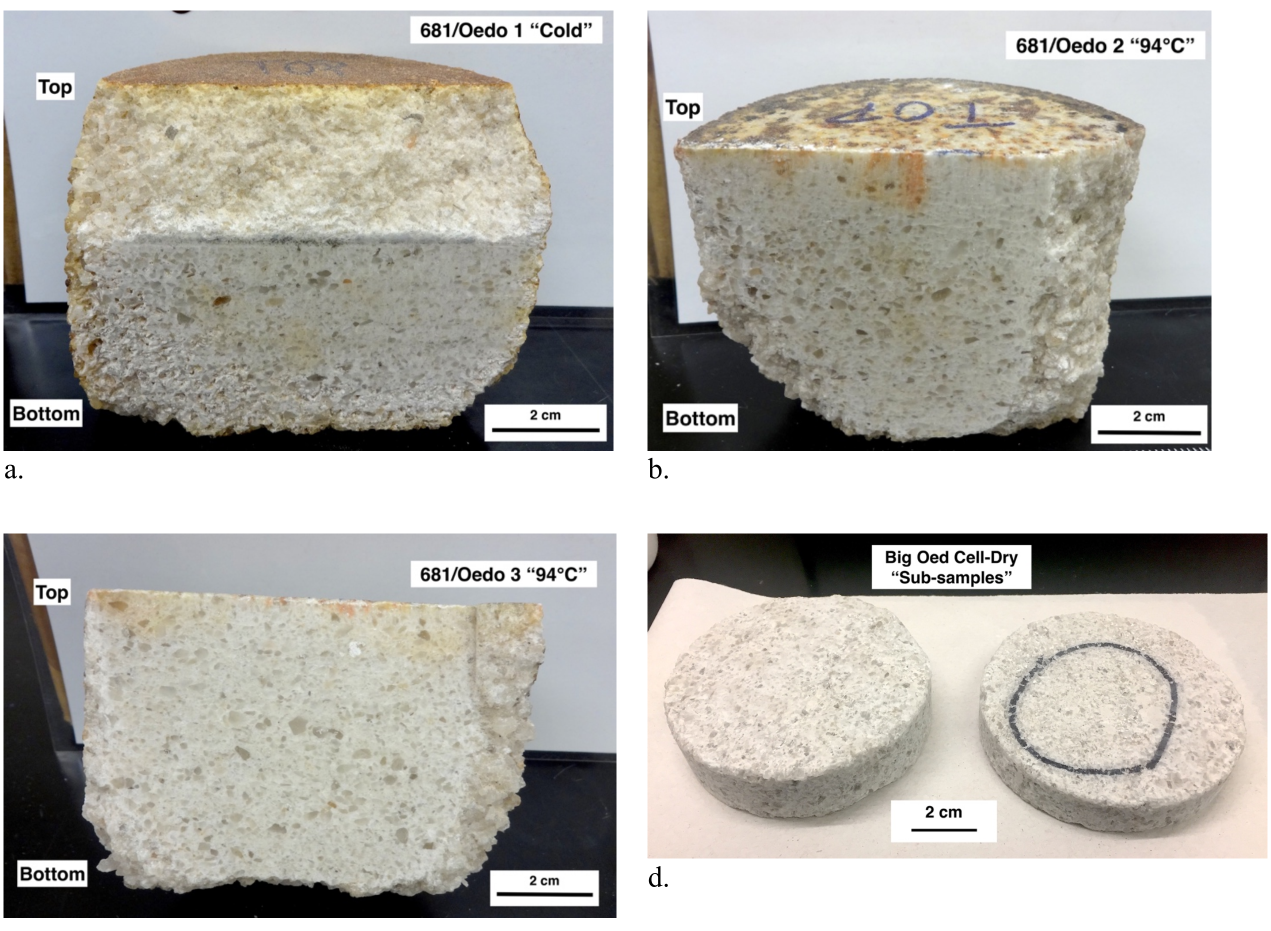


Figure 1: Oedometer test samples as received from IfG, prior to preparation of thick-thin sections.

Table 2: Polishing steps used for thick-thin section preparation.

Step	Surface and Suspension	Speed (RPM) Head/platen	Normal Force (N)	Time (min)
1	Non-woven pressed, 9 µm diamond	50/100	10	5
2	Soft woven synthetic, 3 µm diamond	50/100	10	10
3	Soft woven synthetic, ¼ µm diamond	30/50	5	5

After preparation, all thick-thin sections were examined under a Zeiss AxioScope 5 optical microscope, equipped with ZenCore imaging software, in both reflected and transmitted light. Reflected light was utilized to observe grain sizes, shapes, boundaries, and pore structures, while transmitted light was utilized to view fluid inclusion planes and bands with any attributable microcracks in the grain structure from deformation.

Figure 2 through 5 are the resulting photomicrographs for each respective sample. Each of the four samples experienced mechanical grain rearrangement and cataclastic grain deformation indicated by cracking across and through grains, as shown in Figure 2c.-f., Figure 3c.-d., Figure 4c.-d., and 5a.-c. and e, which can also be seen from areas of fluid inclusions forming linear patterns within grains. Contact points between grains, or at grain boundaries, mostly appear to be cohered together from reflected light images (Figure 2-Figure 4, a. & b.), instead of surrounded by smaller particles due to abrasion or grinding.

The effect of pre-compaction temperature can be seen by comparing the three smaller oedometer test samples. The two pre-compacted at 94º C exhibit areas of plastic deformation at grain boundaries, as displayed in Figure 3b. and Figure 4a.-b, which could indicate pressure solution redeposition or dislocation motion. The ambient temperature sample exhibits relatively little cohesion between grains in Figure 2a-b. This comparison is consistent with the 94º C samples' significantly lower relative porosity in Table 1.

Samples 681/Oed2 and 681/Oed3 were pre-compacted at 94º C and up to 20 MPa axial stress, yet for different durations. The 5 times longer pre-compaction of 681/Oed3 did not lead to any qualitative microstructural differences, which is consistent with the minor difference in final relative porosity between the two samples in Table 1. Although this result is encouraging, it may be useful to compare pre-compaction durations at ambient temperature, where dislocation motion and any pressure solution redeposition would occur more slowly.

Grains from the big oedometer sample, pre-compacted at ambient temperature over a long duration, experience a high degree of cracking and damage (5 a., b., and e.), as well as abrasion among grains (5d.). The subgrain structure from the large oedometer sample can be seen in 5f. showing a polygonal substructure.

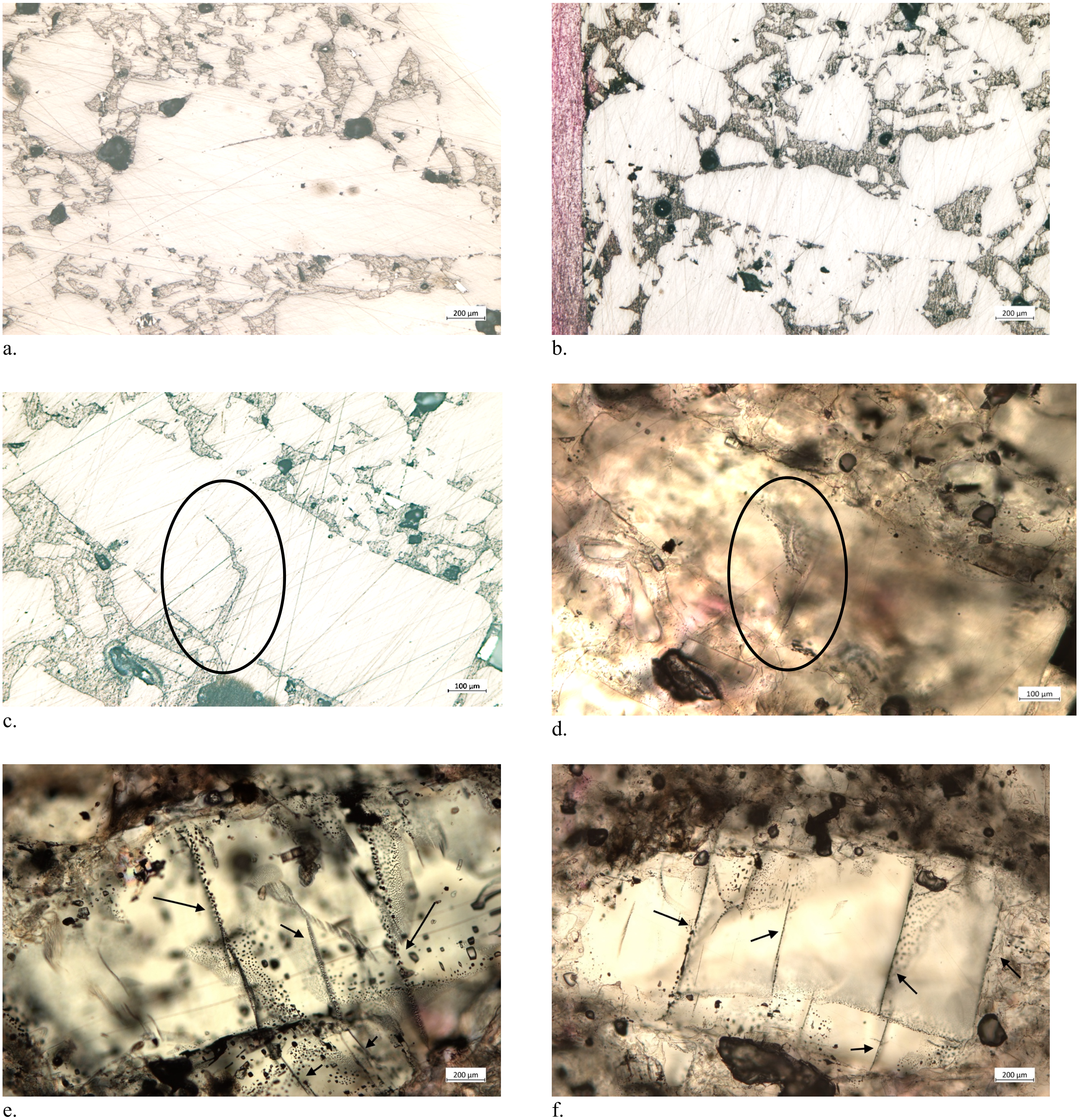
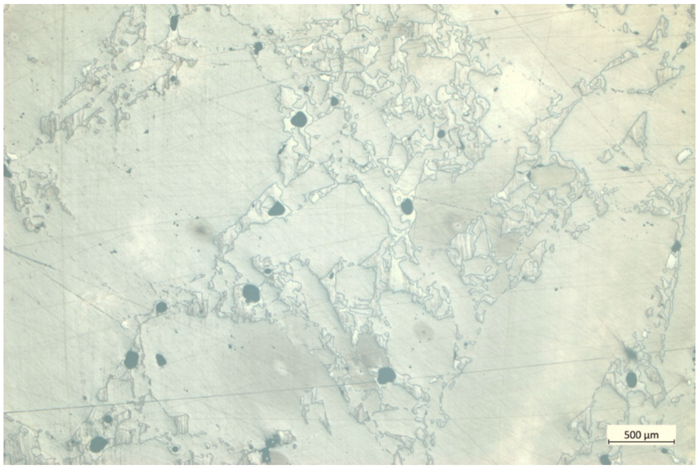
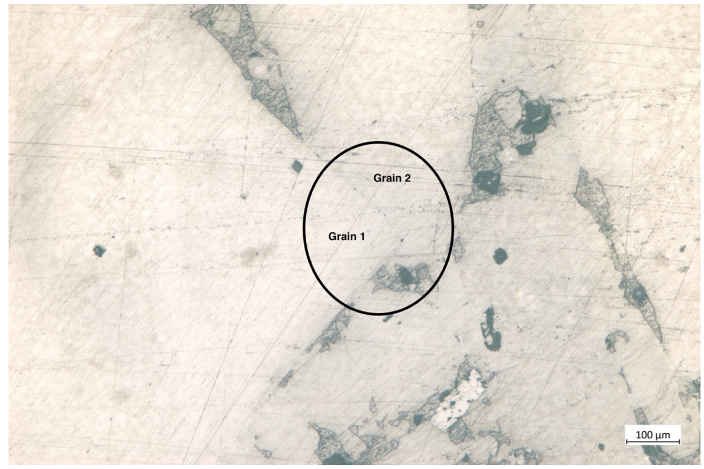


Figure 2: Sample 681/Oed1 a.& b. Low magnification photomicrographs to observe pore structure and grain shapes and sizes. c. Crack propagating through grain in reflected light. d. Same location as image c., in transmitted light, to observe fluid inclusions near crack. e.& f. Fluid inclusions in propagated micro-cracks (arrows) in transmitted light.



a.



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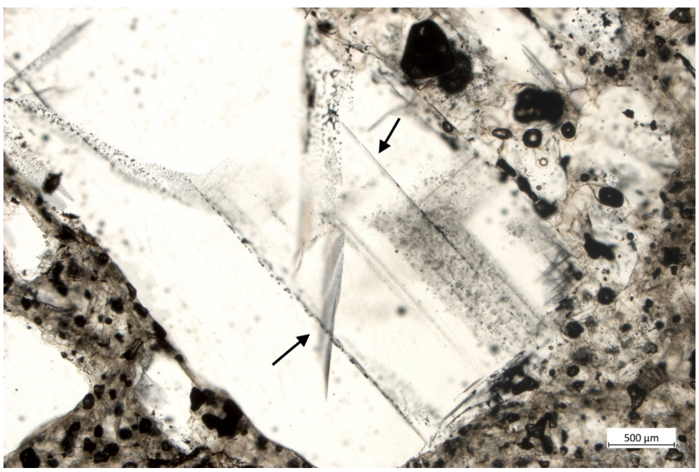
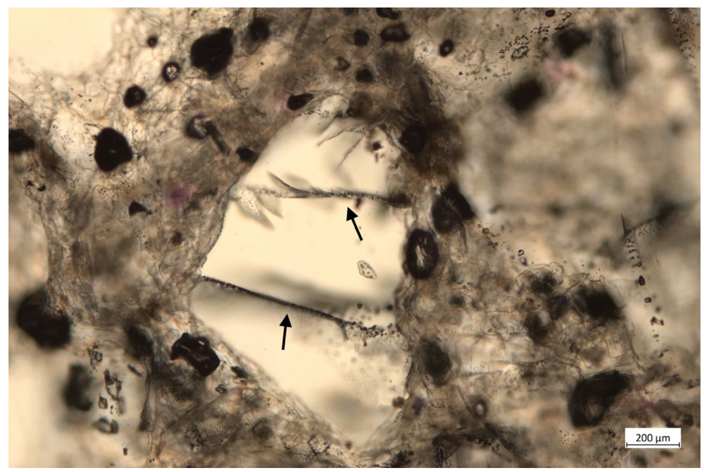
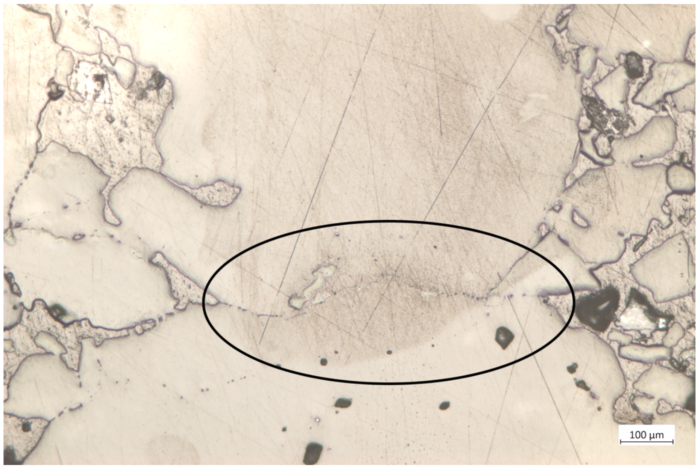


c.



d.

Figure 3: Sample 681/Oed2 a. Low magnification photomicrograph to observe pore structure and grain shapes and sizes. b. Plastic grain deformation at center. c. & d. Fluid inclusions in propagated micro-cracks (arrows) in transmitted light.



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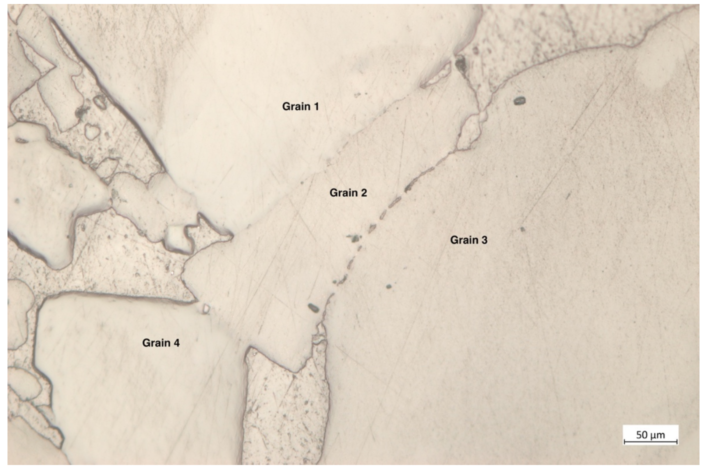

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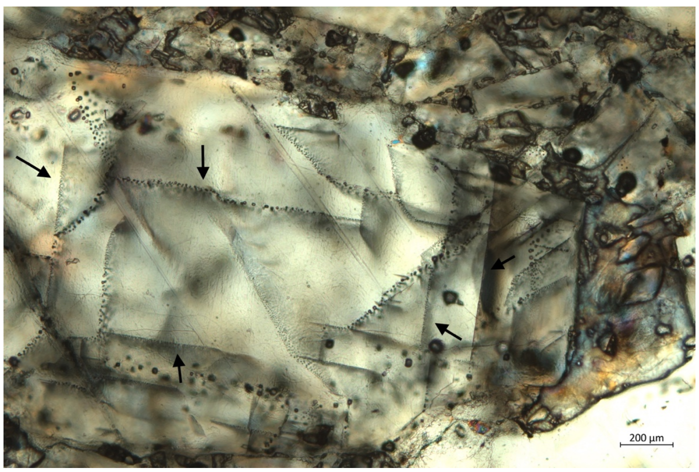

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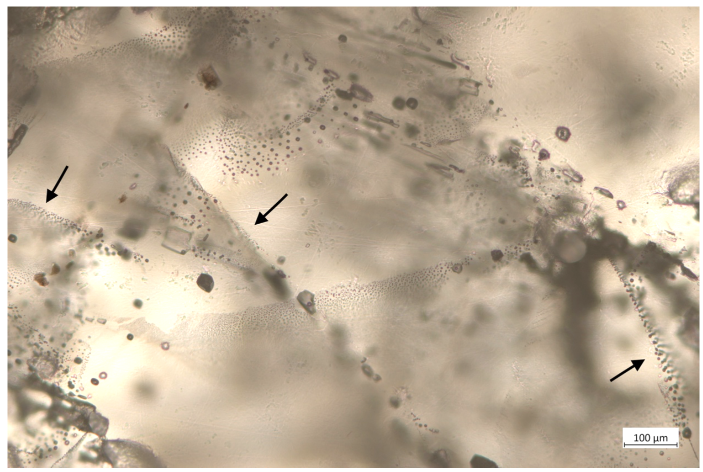

d.

Figure 4: Sample 681/Oed3 a. Low magnification photomicrograph to observe pore structure as well as grain boundary diffusional pressure mechanism b. Plastically-coupled pressure solution grain deformation at center (Grain 2). c.& d. Fluid inclusions in propagated micro-cracks (arrows) in transmitted light.

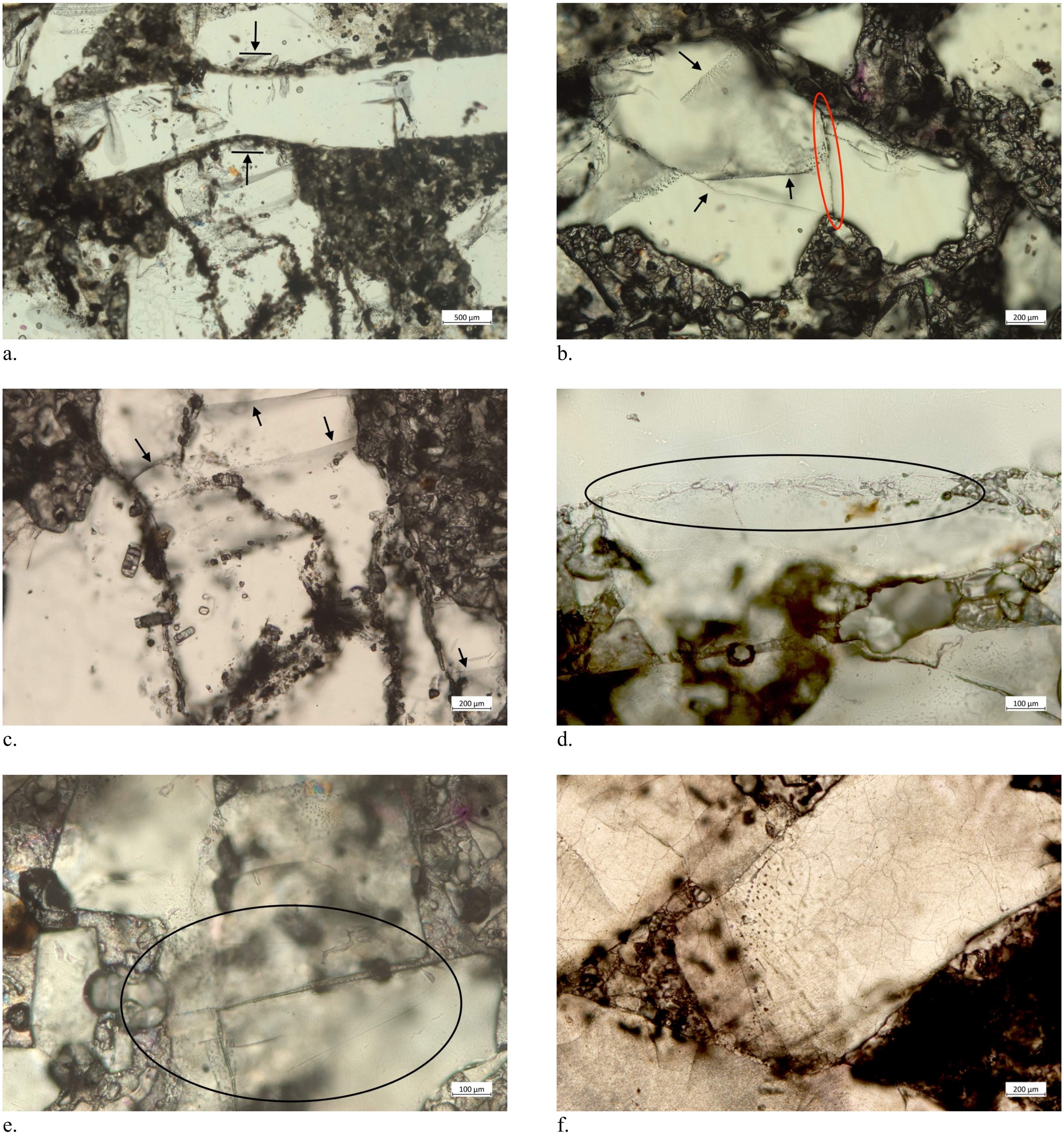

Figure 5: Big Oedometer Sample a. Impinged grain at center experiencing cataclastic deformation. b. Microcracks through grain, with transgranular crack at center (red circle). c. Microcracks (arrows) through grains in transmitted light. d. Mechanically abraded surface between grains. e. Large crack propagating through grain (center right going left) f. Polygonal subgrain structure ranging in sizes from 50 µm to 250 µm.

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

The KOMPASS project is only two years long and the existing knowledge deficits have not been fully resolved in this time. This work package took the results of work packages 1 through 3 and developed a comprehensive, methodical, set of experiments for constitutive model calibration and validation. These proposed experiments will quantify how crushed salt behavior depends on porosity, temperature, isotropic stress, deviatoric stress, stress Lode angle, strain rate, humidity content, and pre-compaction procedures. This experimental program will be pursued if the second phase of the KOMPASS project is funded. A period of 6 months or more will likely transpire between the first and second phase while the German government decides whether to fund the second phase.

2.5 Reference

Callahan, GD., 1999. *Crushed Salt Constitutive Model*. SAND98-2680. Sandia National Laboratories

3. International Collaboration through the Joint Project WEIMOS

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

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 (IfG) (Leipzig, Germany), Leibniz University (Hannover, Germany), Technical University of Braunschweig (TUBS) (Germany), Technical University of Clausthal (TUC) (Germany), and Sandia National Laboratories (SNL).

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, followed by two other notes germane to Sandia's participation in WEIMOS.

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 shear 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, the IfG 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. The IfG extended reconsolidation phase to 130 days for the low stress creep experiments, yet the axial strain still continued to slightly change after 100 days. This reconsolidation axial strain rate was small enough to be negligible compared to subsequent axial strain rates at equivalent shear stresses greater than 3 MPa, but non-negligible for smaller stresses. While the IfG investigates reconsolidation techniques that give negligible axial strain rate, they are running further tests to characterize the creep behavior at stresses greater than 3 MPa. Each test requires approximately 1 year.

In addition to characterizing the low stress creep behavior, Sandia has been trying to determine the micromechanical mechanism responsible for low stress creep. Such knowledge would inform constitutive modeling and focus WEIMOS's experimental efforts in the right regions. Efforts are underway to measure free dislocation density, sub-grain formation, and grain boundary deformation on IfG's creep tested WIPP salt samples using optical and scanning electron microscopy.

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 TUC to characterize these dependencies.

TUC found that preliminary healing tests produced inconclusive results due to difficulties with precisely measuring the small volume strain, which is usually on the order of 1%. The volume strain was measured using the displaced oil volume that provides the confining pressure. This measurement technique is sensitive to oil leaks, oil temperature changes, and the mechanical compliance of the oil containment system, which can also vary with temperature. More recent healing tests have been performed on new high-precision machines, each with their own oil supply system.

Using this new equipment, the TUC began most tests with a hydrostatic stress reconsolidation period, followed by damaging the sample by a known amount. The radial pressure was then raised to study repeatability, mean stress dependence, deviatoric stress dependence, and temperature dependence of healing. One test series varied the axial and radial stresses to hold the deviatoric stress fixed while varying the mean stress. This approach has the advantage of measuring damage-free creep, damage-induced creep, and healing all on the same sample, thereby avoiding the sample-to-sample variation that often plagues healing tests.

In the meantime, the WEIMOS partners are attempting to model the TUC tests. The concept of a dilatancy boundary, above which damage and volume strain develop, is universally accepted, but some models also include a healing boundary, below which damage and volume strain decrease. The damage and healing tests show, however, that volume strain accumulated during the damage phase begins to decrease upon any increase in confining pressure (or decrease in equivalent shear stress). This result suggests that a healing boundary may not be a useful construct. In addition, multiple modelers found that healing depends more strongly on confining pressure than equivalent shear stress, and they have begun parameterizing their models correspondingly.

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, the IfG has performed new experiments on 90×180 mm cylindrical WIPP salt samples.

The samples were first damaged (dilated) to different degrees in a triaxial compression cell, and then tensile tested to determine the tensile strength. The triaxial compression setup utilized confining pressures from 0.2 MPa to 5 MPa in order to generate volume strains ranging from 0.5% to 3%. Multiple confining pressures were utilized because small confining pressures produce microcrack surfaces whose normals are nearly perpendicular to the tensile testing axis, while larger confining pressures produce microcrack surfaces whose normals are closer to 45° to the tensile testing axis (an hourglass orientation). So far, the tensile strengths exhibit a large degree of scatter and do not appear to directly depend on the amount of volume strain for a given confining pressure.

Further investigations should hopefully resolve this measurement scatter issue. One possible remedy is to induce larger amounts of damage (volume strain) prior to tensile testing. If the microcracks remain too small during the damage phase, tensile failure may often occur at pre-existing defects in the sample instead of at intentionally grown microcracks. Another potential remedy is to test bigger samples. Small samples may or may not have a defect that leads to early tensile failure, while larger specimens have a more statistically representative number of pre-existing defects. Unfortunately, the IfG does not currently have sufficient WIPP core to conduct these follow-up studies, so Sandia is striving to send them more core.

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 interfaces with salt, including saly/clay, salt/polyhalite and salt/anhydrite interfaces, extracted from a mine near the WIPP site. Surprisingly, the clay/salt interface 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 seams from the WIPP (Sobolik, 2019). Efforts to extract actual WIPP clay seams are underway. In the meantime, a series of tests on artificially manufactured clay seams measured a significantly lower friction angle than that of pure salt, but with similar residual values for cohesion (Keffeler, 2020; Sobolik et al. (in preparation), 2020). These experiments will be used for two purposes; one, to prepare for tests on in situ samples with clay seams collected from the WIPP site; and two, the collected data will be used by the partners to develop constitutive models for the clay seam behavior.

3.5 (WP 5) Virtual Demonstrator

The WEIMOS partners are currently at work on demonstrations of the modeling capabilities developed in work packages 1 through 4. One 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. The closure of the open drift exercises the low stress creep and tensile damage, while the compaction of the seal deactivates the damage evolution and activate the healing capability. Simulations of this scenario are in progress. A second demonstrator scenario resembling the main access drifts at the WIPP site is also under consideration. The simulation domain would slice through all seven disposal rooms in a panel and the two nearest main access drifts that are parallel to the disposal rooms. The main drifts at WIPP likely see more damage than an isolated drift because the disposal room panels transfer the overburden load to the main drifts.

3.6 New WIPP Core

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. Over the past year, Sandia has coordinated with the Los Alamos WIPP Test Coordination Office, the Department of Energy Carlsbad Field Office, and Nuclear Waste Partnership to extract 16.5 m of 0.3 m diameter intact WIPP salt core. The core currently resides in Carlsbad and preparations are being made to ship it to Germany for testing. If shipment can occur soon, amidst COVID-19 restrictions, there may be time to do a number of experiments before the expected end of the WEIMOS project in September 2021.

3.7 Sandia Constitutive Model Development

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 damage-free mechanical response along non-proportional stress paths or at moderate strain rates (10^{-6} to 10^{-4} 1/s). The inability to capture damage-free moderate strain rate behavior is particularly problematic, as the degree of damage is usually inferred from the difference between the damaged and damage-free behavior. As such, Sandia is actively developing a new constitutive model, loosely based on the SUVIC model (Yahya et al., 2000). A preliminary calibration of this new model reasonably captured both damage-free creep tests with slow steady-state strain rates (10^{-11} to 10^{-8} 1/s) and moderate constant strain rate tests (10^{-6} to 10^{-4} 1/s). Future work will focus on adding damage and healing. These model changes must be completed before Sandia can fully take part in Work Packages 2, 3, and 5.

3.8 References

Keffelr, E., 2020. *Direct Shear Testing of Artificial Clay Seams*, DRAFT Technical Letter Memorandum RSI/TLM-191, RESPEC, Rapid City, South Dakota.

Sobolik, S.R., S.A. Buchholz, E. Keffeler, S. Borglum & B. Reedlunn, 2019. “Shear Behavior of Bedded Salt Interfaces and Clay Seams”. 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*, (in preparation), Sandia National Laboratories, Albuquerque, New Mexico.

Yahya, O.M.L., M. Aubertin & M.R. Julien, 2000. "A unified representation of the plasticity, creep and relaxation behavior of rocksalt”. In: *International Journal of Rock Mechanics and Mining Sciences,* 37(5):787-800.

4. SaltFEP Catalog and Salt Scenarios

SNL Authors: *Emily Stein* and *Mike Gross*

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 through a user-friendly website interface 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 SaltFEP catalog, including an improved description of the thermal-mechanical FEPs, the use of more generalized process descriptions that allow the FEP catalog to be extended to other types of geologic media, and creation of a crosswalk from the list of matrix FEPs to the NEA list of IFEPs (NEA 2019). The final report includes a new table of matrix FEPs that is fully consistent with the output from the SaltFEP database (www.saltfep.org) and includes a discussion of the differences between the matrix FEPs and the NEA IFEPs. A draft final report is currently under review and scheduled for submission to the NEA by the end of 2020.

An international virtual Salt Scenarios workshop in planned for August 2020. The workshop will have contributions from US, German, UK, and Dutch colleagues, to summarize the history of scenario development, and look to future approaches to the task. The scenarios workshop will coordinate with the development of a salt reference case as part of Task F of DECOVALEX 2023, and the discussion of FEPs and modeling associated with the RANGERS collaborative project.

4.1 Reference

NEA (Nuclear Energy Agency), 2019. *International Features, Events and Processes (IFEP) List for the Deep Geologic Disposal of Radioactive Waste, Version 3.0.* NEA/RWM/R(2019)1. Organisation for Economic Co-operation and Development (OECD), NEA, Paris, France.

5. BATS in DECOVALEX 2023 – Task 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) (Mills, et al., 2019). This field test has been accepted as a task in the 2023 round of DECOVALEX (DEvelopment of COupled models and their VALidation against Experiments). The preliminary test specification (Kuhlman, 2020a;b) was presented at the virtual DECOVALEX spring kickoff meeting (April 27-30, 2020).

The project formally began at the project wide DECOVALEX kickoff meeting in April 2020. Teams participating in Task E include: a US team consisting of the organizations conducting the BATS test (Sandia/Los Alamos/Lawrence Berkeley national laboratories), COVRA (Netherlands), RWM/Quintessa (UK), and GRS/BGR (Germany). The task has also held a Task-E specific kickoff meeting (Kuhlman, 2020c), which presented more detail about the requirements and steps involved in the first year of Task E (i.e., Step 0 in Table 3).

Table 3: High-level DECOVALEX Task E schedule (Kuhlman, 2020a)

	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)			

The first revision of Task E includes four steps:

- Step 0: Single-process H^1 and T benchmarks
- Step 1: TH1 benchmark & H^2M/H^2 unheated brine inflow test case
- Step 2: TH2M heated brine inflow test case
- Step 3: Alternatives (ERT/AE joint inversion, seals, TH^2MC, creep)

5.1 References

Kuhlman, K., 2020a. *DECOVALEX-2023 Task E Specification Revision 0*, (35 p.) SAND2020–4289R. Albuquerque, NM: Sandia National Laboratories (https://www.osti.gov/servlets/purl/1616375).

Kuhlman, K., 2020b. *DECOVALEX-2023 Task E (BATS) Specification*, (23 slides) SAND2020–4512PE. Albuquerque, NM: Sandia National Laboratories.

Kuhlman, K., 2020c. *DECOVALEX-2023 Task E (BATS) Kickoff,* (22 slides) SAND2020–5775 PE. Albuquerque, NM: Sandia National Laboratories.

Mills, M., K. Kuhlman, E. Matteo, C. Herrick, M. Nemer, J. Heath, Y. Xiong, C. Lopez, P. Stauffer, H. Boukhalfa, E. Guiltinan, T. Rahn, D. Weaver, B. Dozier, S. Otto, J. Rutqvist, Y. Wu, M. Hu & D. Crandall, 2019. *Salt Heater Test (FY19)*, (61 p.) SAND2019–10240R. Albuquerque, NM: Sandia National Laboratories.

APPENDIX E

NFCSC DOCUMENT COVER SHEET[1]

Name/Title of Deliverable/Milestone/Revision No. International Collaborations on Radioactive Waste Disposal in Salt (FY20)

Work Package Title and Number Salt International Collaborations – SNL

Work Package WBS Number SF-20SN01030306

Responsible Work Package Manager Kris Kuhlman (Name/Signature)

Date Submitted

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

This deliverable was prepared in accordance with Sandia National Laboratories *(Participant/National Laboratory Name)* QA program which meets the requirements of

☒ DOE Order 414.1 ☐ NQA-1 ☐ Other

This Deliverable was subjected to:

☒ Technical Review ☐ Peer Review

Technical Review (TR)

Review Documentation Provided

☐ Signed TR Report or,

☐ Signed TR Concurrence Sheet or,

or,

☒ Signature of TR Reviewer(s) below

below

Peer Review (PR)

Review Documentation Provided

☐ Signed PR Report or,

☐ Signed PR Concurrence Sheet

☐ Signature of PR Reviewer(s)

Name and Signature of Reviewers

HeeHo Park

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

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

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

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