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Ten-Year Review of US/German Collaboration in Salt Repository Research – Paper ID 20069

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ABSTRACT

A multinational collaboration on salt repository research, design and operation has enjoyed remarkable success since reinvigorating efforts in 2010. Nations now engaged in the shared salt repository research agenda include Germany, the United States, the United Kingdom, the Netherlands, and Poland. The scientific basis for safe and permanent disposal of nuclear waste in salt formations has been strengthened by annual workshops that recognize and address contemporary research, including breakout sessions to stimulate open discussion and focus planning for ongoing investigations. Collaboration not only identifies pertinent technical issues, but facilitates timely, expert, and cost-effective consideration. Contemporary workshops have been held annually since 2010 and are documented in yearly state-of-the-art Proceedings, which summarize content and conclusions. The Proceedings help preserve scientific understanding and provide timely source references. These workshops often produce valuable joint publications coordinated with the Nuclear Energy Agency and other suitable external forums for dissemination. Nuclear waste management programs face growing challenges, while permanent disposal in salt formations provides a robust, safe option for several nations. Workshop format and publications provide a cost-effective insurance against loss of scientific expertise and institutional memory. This paper summarizes ten US/German workshops since formal reinitiation, reexamines key technical issues, discusses the evolving research agenda, and highlights successes and challenges.

INTRODUCTION

Researchers and practitioners in Germany and the United States have shared expertise in salt science for many years, including halite-mineral mining, hydrocarbon storage, and long-term nuclear waste isolation. These relationships rejuvenated in 2010, when Germany emerged from a ten-year moratorium. Researchers (re)started the series of ***US/German Workshops on Salt Repository Research, Design, and Operation***, adopting a more formal approach. In 2011, a Memorandum of Understanding (MoU) between the US Department of Energy (DOE) offices of Environmental Management and Nuclear Energy and the German Federal Ministry of Economics and Technology (BMWi, now: Federal Ministry for Economic Affairs and Energy) officially sanctified the workshop relationship and broadly described its aspirations. On behalf of these two Ministries, Sandia National Laboratories, Albuquerque (New Mexico) and RESPEC, Rapid City (South Dakota) on the US side, BGE TECHNOLOGY GmbH (formerly: DBE TECHNOLOGY GmbH), Peine and PTKA (Project Management Agency Karlsruhe) within KIT (Karlsruhe Institute of Technology) on the German side together with assisting organizations have shared organization and publication of the annual workshops.

Favorable attributes for disposal in salt include zero permeability and self-healing, which combine to ensure materials placed within salt formations will remain entombed forever. Because salt has been conventionally-mined for mineral industries and solution-mined for storage caverns, vast hands-on knowledge exists for everyday salt mining operations. Repositories for chemo-toxic waste (Germany) and transuranic nuclear waste (US) have operated for many years. Disposal of heat-generating nuclear waste introduces new factors to the practical knowledge base and thus necessitates a rigorous research,

development and demonstration (RD&D) program. Joint international projects share financial burden and combine technical expertise to address pressing issues. In addition, nuclear waste disposal is fraught with highly debated societal issues, which further supports the need for international collaboration. Improved public perception can be derived from worldwide, transparent, and safety-oriented approaches. The US/German Workshops on Salt Repository Research, Design, and Operation also provide tangible preservation of knowledge and opportunity to develop requisite human capital for an extremely long-term life cycle.

The 10th workshop denotes a modern milestone in the sense of a significant event, yet a milestone also represents a new chapter and literally provides a measure of distance to a destination. Therefore, accomplishments of ten-years' work represent beginnings, that in their achievement illuminate the actual distance remaining. Brief summaries of each annual workshop are woefully insufficient to capture the amount of work and advancement of science undertaken and accomplished. Self-imposed emphases – pertaining to salt repository research, design, and operation – still embrace enormous breadth and depth. Principal themes of the ten most productive and important areas covered in the last ten years are:

- Constitutive modeling
- Laboratory testing
- Seal systems
- Materials, including reconsolidating salt and concretes
- Operational safety
- Natural analogues
- Features, events and processes
- Safety case
- Knowledge preservation
- Salt Club outreach

It's a matter of opinion which of these is singly most valuable or if they represent the 10 most important enterprises undertaken. Several other research topics were covered, including arising challenges or contemplation of special subjects. And, there are many abstract goals, such as promotion of interest, education, access, and outreach that are organic to the conduct of the work-shop. During assembly of these brief annual summaries, the bulleted items recur at the forefront of workshop content and their pursuit often spurred the next generation of investigations.

DISCUSSION

Repositories for nuclear waste, regardless of geologic medium, comprise a breadth of challenging issues. For the most part, this paper discusses technical aspects, but the specialized practitioners fully acknowledge that public acceptance and national policy often overwhelm scientific discourse. Collaborative research efforts have evolved considerably in ten years. Knowledge accumulates and state-of-the-art modeling improves analysis of operations, sealing, geomechanics, and a host of related detail, all aimed at reducing uncertainty. Knowledge also begets discovery. As science naturally advances, experimental methods mature and improve, test control and procedures become finer, fundamental mechanical processes unveil, modeling capabilities grow, and the overall discipline advances. Because the landscape of salt repository science is vast, collaborators streamlined and concentrated efforts to yield maximal impact and optimal resource utilization. Therefore, primary workshop focus shifted from year-to-year as emphasis changed and, in some cases, conclusions drawn. As recollected here, certain main themes pervade the workshop agenda – geomechanics, sealing systems and materials, performance assessment and the attendant features, events and processes rubric, licensing, operations and operational safety, underground research facilities, and attention to arising issues or related areas of interest.

The annual US/German workshops dedicated to salt repositories benefit from many sources, including federal and independent research groups, industry, national laboratories, and universities. Advances in understanding the mechanical behavior of salt were on full display at the 2018 Conference on the Mechanical Behavior of Salt held in Hannover [1]. The Solution Mining Research Institute has contributed significantly to salt research for many years. Laboratory proficiency and techniques are improving every day, computational capability has increased exponentially, and more-and-more full-scale mining experience often ties related research avenues together. Today, we remain actively engaged in basic salt research with better tools, deeper understanding, and accumulated experience.

A primary objective for producing Proceedings of each workshop is to sustain a track-record of ongoing collaboration and thereby provide continuity of long-term research, summarize and publish status as issues mature, and develop appropriate research by consensus in a workshop environment. The workshop Proceedings also provide a great resource for background material, photographs, and history of salt repository experience. Continuity of purpose has been established over recent years and the scientific breadth continues to call for teamwork. Themes and emphases arise progressively because advancing investigations, discussion, and new test results focus near-term research. A contemporary agenda has been documented periodically in external publications, in annual Proceedings, and is often integrated into requests to the German Federal Ministry for Economic Affairs and Energy and the US Department of Energy for financial support.

Workshop 2010

Changes and developments in US and German radwaste policy combined to stall repository progress. These circumstances were clear to leading organizations in both countries and gave rise to a new dedication for salt repository collaboration, with an added emphasis on sustainability. One impediment to nuclear waste disposal has been a lack of continuity of effort. A commitment to meet yearly and examine an agreed-to research agenda was conceived as an institutional blueprint for continuity.

The first workshop of the new era was hosted by Mississippi State University and held in Canton Mississippi [2]. At this formative stage, organizers decided to emphasize research, design, and operation of salt repositories and produce Proceedings of each workshop. Other research areas that could relate to salt repositories, such as potential for microbial activity and actinide solubility, already had dedicated collaboration. To help accommodate this overall breadth of scientific inquiry, workshop organizers further resolved to petition the Nuclear Energy Agency (NEA) for recognition and support for a Salt Club where a broader reach of ancillary issues might be adopted.

Workshop 2011

The 2nd workshop was held in Peine, Germany and embraced a more rigorous, formal agenda [3]. In part, collaborators desired to foster a "workshop" atmosphere – where vetting of issues was encouraged and vision toward resolution identified. Initial content of five sessions included: safety analyses, sealing concepts, backfilling, deformation and healing of rock salt, and natural analogues. The concept of a NEA-sponsored Salt Club was further advanced. Germany, the USA, Poland, the Netherlands, and the United Kingdom have salt formations that may be candidate hosts for deep geologic disposal.

Workshop 2012

The 3rd workshop was held in Albuquerque, New Mexico [5]. Three main salt repository topics were covered: the safety case, benchmark modeling, and reconsolidation of granular salt. A safety case or safety analysis involves long-term performance assessment. These discussions and recognition of transient national policy helped reveal terms of a collaborative research agenda, as exemplified by an overview of US ability to develop a safety case for bedded salt. The discussion of domal and bedded salt repositories was perceptive, serving as an example of how international collaboration can illuminate the most pressing

issues. Discussion of the safety case for different salt formations led to further testing and modeling research.

Several initiatives emerged. German salt modeling researchers and Sandia signed an agreement to participate in a US/German Joint Project (Comparison of Current Constitutive Models and Simulation Procedures on the Basis of Model Calculations of the Thermo-Mechanical Behavior and Healing of Rock Salt) to formulate a strategy for generic modeling of thermomechanical field-scale tests. Examination of extant data immediately identified the need for additional laboratory testing. Concomitantly, German researchers proposed that to fill this void in specific types of mechanical data, we needed to explore the possibility of undertaking testing of WIPP salt and to evaluate constitutive models for bedded salt.

Reconsolidation of granular salt was identified as a key technical issue for German repositories, WIPP panel closure options, and design and performance of salt repositories for heat-generating waste in the US. Based on these findings, a review paper was prepared by leading experts in this field and submitted as another joint report under the auspices of the NEA Salt Club [7], serving as an example of mutually-derived benefit for the advancement of salt repository science. Looking forward, this benchmark report illuminated remaining questions, including the ability to model permeability of reconsolidated salt at low porosity. Ensuing discussions and publications gave rise to additional collaboration in the study of granular salt consolidation.

The Salt Club proposal was officially acknowledged by NEA in spring 2012. Almost immediately, joint activity on natural analogues and a consolidated FEP-catalogue initiated. A successful international workshop on natural analogues was organized in Germany in September 2012 and the presentations published by NEA [4].

Workshop 2013

The 4th workshop was held in Berlin, Germany in September [8] and coordinated with the NEA Salt Club meeting. Over fifty salt repository research scientists from Europe and the US met to discuss selected aspects of the safety case for salt disposal of high-level waste, plugging and sealing, salt mechanics modeling and repository design. Addition discussion from the Salt Club group included geochemistry, microbiology, and hydrogeology. The FEPs database assembly continued with joint publications at appropriate venues [9].

Sealing capability is being demonstrated at full-scale, in a European project called DOPAS (Demonstration of Plugs and Seals) and in the first phase of a BMWi funded project called ELSA (Schachtverschlüsse für Endlager für hochradioaktive Abfälle; development of shaft seals for generic HLW repositories) shaft sealing concepts will be developed. Salt mechanics modeling engendered by the US/German Joint Project (Comparison of Current Constitutive Models and Simulation Procedures on the Basis of Model Calculations of the Thermo-Mechanical Behavior and Healing of Rock Salt) was officially extended to include two additional full-scale tests conducted at WIPP. Modeling was projected to compare isothermal Room D to heated Room B. These modeling studies identified a suite of laboratory testing to be conducted on WIPP bedded salt. Hundreds of tests addressing fundamental material behavior were identified at this time and set the stage for long-term collaboration on constitutive modeling.

At this juncture, Germany had issued its preliminary safety analysis for the Gorleben salt dome (Vorläufige Sicherheitsanalyse Gorleben, VSG [6]).

Workshop 2014

The 5th workshop was held in Santa Fe, New Mexico in September 2014 [10]. Forty-seven registered participants were equally divided between the United States and Germany, with one participant from The Netherlands. Following precedent, the agenda started to take shape at the close of the 4th Workshop, including facets of thermomechanical testing and modeling, plugging and sealing, and performance assessment. However, by far the most interest pertained to operational safety. An underground fire and radiological release in the month of February 2014 assigned operational safety a new sense of relevance and urgency. This is an example of how the workshops provide flexibility and means to address emerging issues. Operational safety was undertaken as a new topic.

Operational events at WIPP introduced unprecedented uncertainty with regards to mission and compromised other underground activities. One demonstration suggested for deployment at WIPP concerned early evolution of salt excavations. If planned appropriately, this mining demonstration could characterize host rock evolution before, during, and after excavation of test rooms. This work was proposed to tie together model prediction and confirmation of geophysical phenomena that are basic to the goals of the US/German salt workshops. Operational events at WIPP severely limited near-future possibilities.

Collaborators continued to compile an international FEPs catalogue pertaining to the safety case for disposal of heat-generating nuclear waste in salt. This effort was expected to be published under the aegis of the NEA Salt Club. For several reasons, a new effort to examine differences and similarities of bedded and domal salt was initiated, along with recognition and inclusion of pillow salt formations. In the following years (2015 - 2018) this led to the BMWi funded Joint Project KOSINA (Concept developments for a generic repository for heat-generating waste in bedded salt formations in Germany) [11], which is another example of arising issues ideally suited for international collaboration.

Workshop 2015

The 6th Workshop was held in Dresden, Germany in September 2015 [12]. Collaboration naturally continues between workshops and helps reveal future research directions. Remaining among previous research issues are the minimum stress criterion, granular salt properties at low porosities, constitutive model development, and other matters of mutual interest and pertinence to the salt safety case. The overall goal of the US/German Joint Project is to further develop tools for demonstrating safe, final disposal of heat-generating radioactive waste in salt formations. Tools in this context include constitutive models, numerical codes, and modeling procedures. Previous Joint Project activity evaluated proficiency against isothermal and thermal *in situ* test results. The most recent simulations of unheated Room D and heated Room B examine large-scale thermomechanical effects on closure. In concert, a large testing program on Salado Formation bedded salt has provided additional parameter quantification.

Large-scale demonstrations of concrete placement and performance provide important operational functions and closure contributions. Many drift seals made of salt-saturated concrete have been evaluated at full-scale using specialty concretes with cement or MgO as the binding agent and brine saturated with NaCl or $MgCl_2$. Investigations of pilot drift seals encompassed the primary elements of drift seals: construction materials, the excavation damage zone, and the contact zone.

tcCollaboration on characterization of bedded, pillow and domal salt formations as applied to disposal of heat-generating nuclear waste was continued. Heretofore, the US concentrated on bedded salt, while similar efforts in Germany emphasized geologic domal salt. In the year 2015, each nation was once again considering possible repository choices, which presents a need and an opportunity to compare repository-relevant differentiating characteristics of various salt formations.

Events in February 2014 at WIPP sharpened the focus on operational safety. One means to mitigate level of risk is to minimize exposure during operations. Knowledge gained regarding salt reconsolidation coupled with analogue examples, support a concept of modular design, sequential licensing, certification, and closure in large-scale salt repositories. Part of the optimism regarding modular-build-and-close derives from acceptance by the Environmental Protection Agency of the premise that crushed salt panel closures will return to a physical state comparable to native salt.

Priorities for underground testing, if possible, were also discussed in a breakout session. The basis for salt repository science and engineering has benefited from several full-scale field experiments. At this time, there is no defined test that must be conducted before a safety case can be prepared for salt disposal of heat-generating nuclear waste. Nonetheless, if an underground facility were to become available, the salt repository community can define high-value test priorities. Based on break-out sessions of this workshop, the consensus for highest priority field testing included large-scale consolidation and drift-seal demonstration.

Workshop 2016

The 7th workshop was held in Washington, DC September 2016, with over fifty participants [13]. The line-up of issues had a familiar ring: safety case, operational safety, geomechanics, and plugging and sealing. A new and sensational issue of percolation was added and addressed in a breakout session.

Comparisons between German and US approaches to establishing robustness in the safety case were made. A connection between operational and long-term safety was again discussed in terms of WIPP recovery. Engineered safety was at the forefront of concerns, and safety-by-design principles were identified that can add robustness and minimize risk exposure during operations [14].

Collaboration in geomechanics includes laboratory and field testing, constitutive model development and comparisons, benchmarking calculations, case study experiences, and analogues. All these topics have been discussed in terms of salt repositories over the last few years. However, new WIPP test results are coming in and modelers are fine-tuning approaches including creep of salt at low deviatoric stress states. The US/German Joint Project () ended and a new subsequent US/German Joint Project called WEIMOS (Further development and qualification of the rock mechanical modelling for the final HLW disposal in rock salt) was started.

Historic seal experiences in Germany were summarized for the most common seal materials. Construction practices and performance measures provided assurance that large-scale, high-performance seals of readily available materials can be constructed in salt formations. Performance measures include strength, permeability, chemical stability and healing of the damage zone. Reconsolidation of granular rock was not rejoined at this meeting but will be taken up subsequently in newly defined research programs.

A new issue called deformation-assisted fluid percolation in salt was raised in the technical literature. Its presentation into the literature claimed that salt formations are permeable, which challenges a long-held fundamental tenet of salt disposal. Several experts contributed to open discussion in the breakout sessions, pointing out limitations of the published experiments as well as selective interpretation of the recently published results. However, workshop participants were not able to state definitively that deformation-assisted enhancements in percolation should not be anticipated in salt repository host rocks. Debate was expected to continue.

Workshop 2017

The 8th workshop was hosted by Centrale Organisatie Voor Radioactief Afval (COVRA), at their headquarters near the operating storage facility in Middelburg, The Netherlands September 2017 [15].

Fifty-five registered participants efficiently conducted the technical program at COVRA's premises, an excellent venue to present, discuss, and advance the basis for disposal of radioactive waste in salt formations.

The international collaboration is productive and successful and continues to identify prominent salt research that either emerges as the science and research agendas develop or continues to mature from existing, ongoing partnerships. This is mirrored and documented by annual Proceedings, updated mutual research agendas, and advancement of salt repository science across a forefront of issues.

Research themes frequently interrelate or feed information between and among activities. As an example, constitutive modeling efforts have been examining apparent underprediction of creep deformation at low deviatoric stress. In terms of modeling WIPP Rooms B and D, this apparent effect would apply to a large portion of the finite-element grid space. Until recently, there were no experiments with precise instrumentation and absolute control over state variables at the low strain rates of interest. The experimental door was opened by Bérest and coworkers [16], [17] and similar investigations now constitute significant emphasis in our collaborative research.

A dedicated project called KOSINA [11] was launched in the summer of 2015. Bedded salt was not considered previously to host a high-level-waste repository in Germany. The project foci include development of generic geologic models, including derivation of model parameters, development of a safety demonstration concept, development of technical repository designs for four different emplacement alternatives, analysis of geomechanical integrity, evaluation of operational safety, as well as analysis of radiological consequences. At this time, main achievements include four different repository designs, two per each generic geologic model (flat-bedded salt and salt pillow) based on thermomechanical calculations. Integrity of the geologic barriers could be demonstrated for all four repository designs, and the long-term predictions showed no radiological releases during the demonstration period of one million years.

Workshop 2018

The 9th workshop was held at the BGR in Hannover, Germany in concert with the international conference on the mechanical behavior of salt SaltMech IX, the NEA Salt Club meeting, and a regular meeting of the collaborators in the US/German Joint Project WEIMOS September 2018 [18]. More than 60 participants came from the US, Germany, the Netherlands, Poland, Switzerland and Austria. New test results and analyses of WIPP core, including shear strength of salt/clay and salt/anhydrite interfaces, were presented. The first results from microstructural investigations by optical and scanning electron microscopy on WEIMOS-relevant core samples tested in low deviatoric stress conditions were shown.

Germany completed several pilot applications of drift seals in the Asse and Morsleben sites. The results of which were publicly presented for the first time at the US-German Workshop. Batching, casting, and monitoring several concrete materials were successfully demonstrated. Monitoring included crack formation, gaps on the seal/salt interface, permeability, and porosity. Other drift seal strategies were outlined, including dynamic compaction of granular salt and a sealing system of cut salt bricks.

The KOSINA project was completed. It is a joint undertaking of the BGR, GRS, IfG and BGE TECHNOLOGY funded by the BMWi. The contribution of the KOSINA collaborators to the workshop included results from generic geological modeling, technical repository concepts, a safety and demonstration concept, numerical simulations on barrier integrity, and an analysis of radiological consequences.

Workshop 2019

The 10th US/German Workshop on Salt Repository Research, Design, and Operation was hosted by RESPEC and the South Dakota School of Mines and Technology, both located in the Black Hills of South Dakota May 2019 [19]. Sixty-four registered participants represented Germany, the United States, the Netherlands and the United Kingdom. This year's themes included siting, modeling challenges, seal systems and materials, operational safety and special topics. Two major breakout sessions addressed test sample conditioning and natural closure of salt openings. When the new-generation US/German workshops were conceived, one goal was to identify challenging issues related to salt repository sciences and then conduct open discussions in special "breakout sessions". These timely breakout sessions achieve the workshop paradigm and provide in-depth dialogue on highly important salt repository considerations.

In many respects, general themes of these salt-repository workshops reflect advances in the scientific basis for nuclear waste disposal in salt formations and develop naturally because of unremitting attention due largely to the workshop commitment. Technical capabilities in the laboratory and in the field continue to improve in concert with accumulating experience. Because of the close cooperation between US and German scientists and engineers, mechanical deformation at the micro-scale can be interpreted at a large scale, which is fundamental to predictive modeling of salt repository evolution.

CONCLUSIONS

This collaboration has come a long way since reconvening the United States (US) and German salt repository collaboration in 2010. The ongoing cooperative effort of the United States and Germany is a vivid example of the benefits of international cooperation among peers for mutual advantage. The most obvious benefit has been optimization of scarce human resources. Workshop participants strive to advance the technical basis for disposal in salt formations and jointly publish accomplishments in the open literature. Indeed, one can simply search the web for salt repository information and all the Proceedings can accessed.

A vital outcome of the ten-year cooperation is knowledge preservation. The geologic repository life cycle stretches beyond a single lifetime and could easily exceed a century. Evidence in the US and Germany suggests that resolution of final disposition of nuclear waste has an uncertain future and repository projects in both countries have required much more time than initially anticipated. At the same time, widespread skepticism about nuclear power has, perhaps, rendered the waste management field uninviting for young scientists and engineers, further complicating knowledge preservation and transference. This series of workshops has provided a vehicle to stimulate early-career scientists in an imperative mission to remove nuclear waste from the biosphere.

Thus, the 10th anniversary milestone has arrived; a milestone indicating how far we have come, but not how far we have to go. As these collaborations move forward and deepen, with motivated leadership, and focused workshops, our nations will be ready to license, operate, and close a nuclear waste repository in salt.

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