Solution Mining and Salt Cavern Challenges, SMRI's Role and Research Focus

Session: Salt production

Keywords: brine cavern, cavern storage, cavern design, cavern research, energy storage, abandonment

Abstract

Solution Mining Research Institute, Inc., (SMRI) is a world-wide, non-profit, member-driven organization with chief role of providing specialized education, technical reference information, and current issue research to those in the solution mining and storage cavern industries. SMRI has for over 50 years been actively researching subjects of current and future interest to our members and the cavern industry. We are helping train and develop your future industry experts and managers.

SMRI technical conferences are held two times each year, one each in North America and Europe, where most SMRI member organizations are based and/or have operations. Each conference has a technical class, includes about 20 technical paper presentations, and provides field trip opportunities to see first-hand various mines, brine/salt production and storage facilities, or historic sites/features to learn how they have been operated and managed.

This paper will briefly describe 20 SMRI research projects completed since the 9th World Salt Symposium 2009 in Beijing, list SMRI's currently active research projects or ongoing programs, and discusses our focus on future cavern research on subjects of value to the industry. SMRI research projects and resulting research reports ("RR"s) are funded entirely by SMRI annual membership dues. Research contractors and host research facilities frequently provide critical access and/or services contributed to the projects at zero or reduced cost.

As a disclaimer, SMRI's RRs and technical papers do not necessarily state or reflect the views or opinions of SMRI, nor are products or services mentioned in the RRs or technical papers endorsed or recommended by SMRI.

jvoigt@solutionmining.org +1 570 585 9082

Introduction

Since SMRI's founding in 1965, we have completed 183 research projects of industry interest, presented about 1500 technical papers at over 80 SMRI conferences. SMRI has grown to about 1250 member individuals representing 150 dues-paying organizations, and with 1400 non-member individuals in our database. Starting in 2010, Government regulatory agencies in the salt cavern and storage cavern industries have been invited to join SMRI as non-voting members without dues payments required of all other member organizations. The objective of this new Class R membership, as overwhelmingly approved by the membership, was to allow regulators free access to all information in SMRI's online library, thought to be useful to the regulators for technical reference and training, and to encourage regulators to participate in SMRI conferences.

The two major objectives of SMRI remain as:

1) Education through our conferences, website, and online library to facilitate technical discussion and advancement and
2) Planning and performing research projects with potential to improve our industry.

SMRI's 8 member volunteer Research Committee, led by Research Coordinator Leo Van Sambeek, is charged with selecting research subjects, recommending research projects, as well as managing, monitoring progress, and adjusting as necessary each research project plans, plus editing drafts and approving each research report (RR) before SMRI accepts the completed RR. Each research report has an SMRI Project Sponsor, normally a Research Committee member at the start of the project, often an expert in the specific field, who essentially monitors the project activity for SMRI, and is the SMRI point person for the head of the research team. Research opportunities are always open to non-members as well as members, and the Research Committee encourages international teams of experts who combine their talent to work on a research project team. Differences have evolved over the years in North American and European cavern design, development, operations, abandonment, and regulations, so it often makes sense to have both regions represented on research teams submitting proposals.

Current Industry Issues

In the United States, the State of New Mexico Oil Conservation Division (OCD) in September 2017 was actively looking for design/build teams to submit suggestions and/or proposals to backfill the Carlsbad I&W brine well/salt cavern. Details are available on the NM OCD website. SMRI assisted by forwarding the OCD requests to SMRI's email list. SMRI concerns about the I&W site risk were sent to the Governor of New Mexico following our spring 2017 conference in Albuquerque. OCD presentations were made at the SMRI conference, followed by an SMRI field trip to the I&W site and other Carlsbad area salt cavern and potash mining sites.

In Europe, new well integrity regulations / standards for the oil and gas industry have been drafted. The DIN EN ISO 16530-1:2017 Well integrity, Part 1 covers: life cycle governance. DIN CEN ISO/TS 16530-2, Part 2 section will govern well integrity during the operational phase, and are still being refined as of this writing. These standards when coming into force will be also valid for the cavern industry.

The mining laws and related legal framework in several European countries have been tightened to make it easier to hold mining companies liable for damages to surface property, particularly those which are mine subsidence related.

Legal challenges were filed in both European and US court systems to dispute patent applications for hydrogen storage in salt caverns, (e.g. with a permeation barrier,) and the court findings will have ramifications for clean energy storage.

Summaries of Completed Research Projects Since Beijing World Salt 9

20 SMRI Research Reports have been completed since the Beijing 9th World Salt Symposium, on the following subjects. These RRs are available to SMRI members in our online library. Logged in non-members are free to search the library for words, titles, authors, etc., obtain lists of search results, but cannot view or download any documents. Non-members may purchase most technical papers by contacting SMRI. RRs over 1 year old may be purchased from SMRI by non-members for prices set as 0.5% of the research project cost.

RR2009-1_SMRI_Bannach, *Stassfurt Shallow Cavern Abandonment Field Test*, Andreas Bannach, RWE ESK, May 2009. [RR2009-1_SMRI_Bannach]

This field test of Stassurt shallow cavern abandonment, SMRI RR2009-1, was performed by: Andreas Bannach and Michael Klafki of ESK GmbH (RWE,) Freiberg, Germany.
The research objective was to compare SMRI's previous cavern sealing and abandonment, (CSA RR2003-3) research results with 2 actual sealed, abandoned caverns equipped for pressure monitoring, with cavern depths of about 400-500 m (1310-1640 ft.). Wellhead pressures were recorded at caverns S101 and S102 for 45 months.
Restating RR2009-1 results, the cavern salt / fluid temperature heat transfer did not appear to be significant, since temperature logs performed before and after the monitoring period were comparable. Salt dissolution from leaching after initial pressurization period (days or weeks,) did not affect the brine permeation process at equilibrium. Cavern closure and permeation rates at shut in equilibrium pressure were both very low. Rock mechanics modelling projections of changing salt stress state implies changing permeability, and is confirmed by this pressure testing. The final conclusion was that permeability of the salt at different cavern pressures can change by an order of magnitude, as SMRI prior research anticipated. "*The main objective of the test was to demonstrate that an equilibrium exists at a certain cavern fluid pressure at which the cavern closure is equal to the brine volume permeating the cavern wall, thus consequently, the cavern fluid pressure is no longer rising… In summary, the executed cavern abandonment field test at Stassfurt demonstrated that the expected equilibrium pressure will be reached at a level certainly lower than the lithostatic pressure at the cavern roof*".

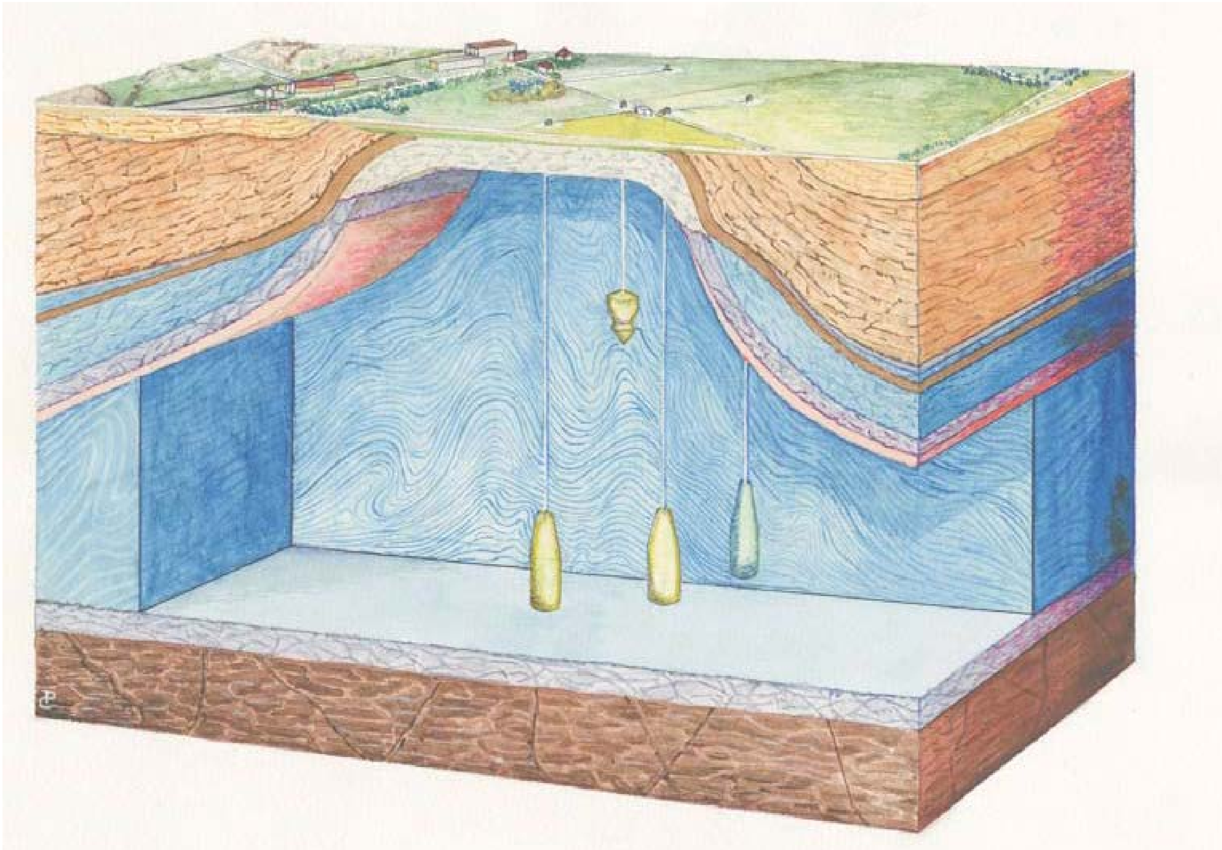

Figure 1: Geological cross section of Stassfurt salt deposit showing caverns
(from RR2009-1_SMRI_Bannach)

RR2009-2_SMRI_Nieland, *SALT-SUBSID Cavern Design Software Upgrade*, Joel Nieland, RESPEC, May 2009. [RR2009-2_SMRI_Nieland]

The research objective was to upgrade, as SMRI members requested, the SMRI's SALT-SUBSID software which was developed in 1991 by RESPEC for use in subsidence prediction above planned or existing, and either solution or underground salt mining. This project made specific improvements in SUBSID's cavern geometry model, added new capability for cavern growth for producing caverns, allows calculation of horizontal strains, can set cavern creep closure at depth dependent rate and cavern pressure, and added 2 additional possible subsidence models to calculate shape of subsidence area more accurately. These technical enhancements were accompanied by adding a graphical user interface (GUI) to run on the common PC Microsoft Windows platform. The GUI allows easier input and output options. Previous Fortran based maps were replaced by the GUI's modern GIS capability. RESPEC also prepared a new SALT-SUBSID user manual and taught optional user classes at 2 SMRI conferences. Computer requirements to run SALT-SUBSID are PC Windows based and are quite minimal by 2017 standards. SMRI members may use SALT-SUBSID at no cost as long as they maintain membership, and user support is included with the license. Non-members of SMRI may purchase a single user license for fee of $1,000.

RR2010-1_SMRI_Zander, *High Frequency Cycling of Gas Storage Caverns: Phase I: Development of Appropriate Lab Tests & Design Criteria,* part of High Frequency Cycling of Salt Storage Caverns (HFCSSC), Dirk Zander-Schiebenhöfer, KBB Underground Technologies GmbH, October 2010. [RR2010-1_SMRI_Zander]

Phase 1 of this research was started in 2009, for Development of Appropriate Lab Tests & Design Criteria. This research project was a preliminary study to define the specific research needs of the industry in the field of HFCSSC. To operate salt storage caverns in a faster cycle mode where operating pressure ranges fluctuate more often and over wider ranges than storage caverns have been used, how might this affect the cavern walls or require design modifications. The starting point was identified in this research report, and would require rock mechanics lab tests to cover colder operational limits than previously tested. This research report stated that the purpose of the next research phase should be determination of ultimate strength of rock salt at temperatures between 0 and 20°C (32 and 70°F) for comparison of predicted vs. measured values at cavern wall salt temperatures. This would extend the range of known rock salt properties down to the freezing point. Additional lab testing was recommended to determine creep response due to cycling of mechanical loads, including description of the creep response, by measuring stresses, creep strains and creep velocities, volumetric strain and damage parameters vs. time. SMRI's next HFCSSC research project to follow this recommendation would be RR2012-2_SMRI.

RR2011-1_SMRI_Brouard, *Salt-Cavern Abandonment Field Test at Carresse, Update of the SMRI Research Report 2006-1, Report #2*, Benoit Brouard, Brouard Consulting, October 2011. [RR2011-1_SMRI_Brouard]

This research report was to review recent data for cavern abandonment tests at Carresse, France which were monitored and studied by SMRI as reported in RR2006-1_SMRI_Brouard. According to the researchers, *"In 2006, TOTAL agreed with the mining authority to continue the monitoring of the 4 caverns prior to their final sealing. An agreement was found between Total and the SMRI, and* Total *provided the SMRI with pressure evolution data for the four shut-in caverns. After some time it became clear that brine pressure would not reach a maximum by 2008 but, rather, kept on increasing…" Five years later,* (after 2006) *"observation of the wellhead pressure evolution clearly confirmed that pressure build-up rate slowly decreased… However, the maximum which had been predicted to occur by February 2008 clearly did not take place. … Five years after the end of the 2004-2006 test, a discrepancy was observed between the actual and the predicted pressure evolutions."*

"…Computations proved that cavern temperature and pressure evolutions were not very sensitive to rock mass thermal diffusivity… Geothermal temperature was much more influential…", such that when *"…very precise predictions are under consideration, cavern brine temperature and geothermal temperature must be measured with an accuracy better than 0.1°C (as a 0.1°C underestimation of the gap between cavern temperature and geothermal temperature can lead to a 0.1 MPa underestimation in cavern maximum pressure)."*

RR2011-2_SMRI_ Duquesnoy, *Synthesis of Shallow Cavern Abandonment*, Antoine Duquesnoy, Well Engineering Partners (WEP) BV, March 2011. [RR2011-2_SMRI_Duquesnoy]

After SMRI completed a number of shallow cavern abandonment studies and field tests, including at least 5 related RRs, the SMRI Research Committee decided to have WEP review all shallow cavern abandonment research results, re-interpret data, and summarize the results. Focusing on caverns less than 1000m, or 3280 feet, deep, this research effort concentrated on aspects of long-term post mining stability, public safety, and environmental protection. After a review of the data and reports, the researchers mentioned that the RR2006-3_SMRI_Cavern Well Abandonment Guidelines by KBB-UT is a basic starting point, with 5 main phases. Duquesnoy's RR2011-2 then draws 5 conclusions for shallow caverns:

1) If the cavern is at or near thermal equilibrium, the long-term cavern pressure will be well below lithostatic.

2) Brine will slowly and gradually escape by permeation from the cavern, with some examples given.

3) The field tests support the concept of the 5 phases described in RR2011-2_SMRI.

4) Any rapid cavern pressure build up will require computer modelling to compare dissolution, transient salt creep, and brine permeation.

5) Typical rock mechanics modelling can provide long term assessment to regulators before abandonment, unless temperature equilibrium has not been reached.

Importantly, 7 additional, specific recommendations by Duquesnoy are included for consideration when appropriate for given cavern conditions.

RR2011-3_SMRI_ Païdoussis, *Study of Casing Pipe Vibration in Solution-mined Caverns*, Michael Païdoussis, McGill University, December 2010, [RR2011-3-SMRI_Païdoussis] and

RR2014-1_SMRI_ Païdoussis, *Cavern Tubing Flow Induced Vibration Theory and Lab Tests*, Michael Païdoussis, McGill University, October 2014. [RR2014-1_SMRI_ Païdoussis]

These 2 research projects, or phases, began with the help of Joe Ratigan, in effort to learn more about failures of commonly used hanging pipe in caverns, and eventually how various types of pipe failures might be prevented by avoiding excessive liquid and gas velocity or optimizing piping arrangements in caverns. The process began with discussions with Michael Païdoussis of McGill University in Montreal. Previous attempts by the storage cavern industry were unable to explain the pipe failures, although belief from field experience was that pipe velocities and injection rates must have an effect on pipe vibration and failure. There were many unknowns, and McGill's starting point was tubing flow induced vibration theory, followed by lab tests. Païdoussis managed the grad students who performed the research at McGill.

The first project, RR2011-3, involved both theoretical and lab testing of thin-walled pipe, and required design and building of experimental testing apparatus in the lab. The testing apparatus was capable of testing various pipe and flow schemes for vibration testing, and used high speed video and other instrumentation to analyze the vibration and record data. Pipe buckling and flutter were two common failure means observed, and Païdoussis set out to learn "…*whether the addition of a counter-current flow in the annulus vis-à-vis the flow in the pipe is beneficial or not. … in order to draw reliable conclusions for use in salt cavern applications, many more experiments are needed, to explore more widely the dynamics; for example, with different pipes, and then to compare the results in terms of dimensionless flow velocities and frequencies…"*

Phase 2 research was reported in RR2014-1_SMRI_ Païdoussis, using "*simple lab experiments to decide on injection/retrieval strategies which would increase the trouble-free operation, and prolong the lifespan, of brine strings.… The Phase II McGill research project is the first research program that has possibly identified the most critical flow configuration for flow induced tubular damage in solution-mined caverns. This flow configuration is encountered in liquid and gas storage caverns and cavern development and brine mining caverns and is therefore of interest to the whole of the cavern industry."*

2012-1_SMRI_Zander-Schiebenhöfer, *Deformation of Cemented Casings - Case Studies, Analysis, and Pressure De-rating Procedure*, Dirk Zander-Schiebenhöfer, KBB Underground Technologies GmbH (KBB-UT), May 2012. [RR2012-1_SMRI_Zander_Schiebenhöfer]

Cemented casing is a fundamental of well and cavern integrity in the cavern business, yet there are occasional failures which cavern operators share great interest in preventing. In effort to learn best design and operational guidelines, SMRI contracted KBB UT to undertake research on the subject. KBB UT's research started with a detailed questionnaire sent to cavern operators, to provide information/data about their experiences with casing and failures, which could improve understanding and lead to better casing designs. Types of deformation were noted, along with possible causes and theory, influences such as geology and rock mechanics, and possibility of developing casing de-rating methodology was investigated. Computer simulations were extensively used in this project. The guidelines developed by KBB UT do not fit every possible condition, but provide a good method or design framework to minimize cemented casing problems in the future.

RR2012-2_SMRI_Mellegard, *High Frequency Cavern Cycling – Phase 2: Cyclical Loading Effects on the Dilation and Creep Properties of Salt*, Kirby Mellegard, RESPEC, July 2012, and

RR2013-2_SMRI_Mellegard, *High Frequency Cavern Cycling—Phase 2-B: Extensional Cyclic Fatigue Testing of Salt*, Kirby Mellegard, RESPEC, October 2013, and

RR2017-3_SMRI_Buchholz, *Cyclic Thermal Loading Creep Tests*, Stuart Buchholz, RESPEC, August 2017.

These separate RRs were performed by RESPEC in 3 phases, investigating cavern design methodology for SMRI's ongoing High Frequency Cycling of Salt Storage Caverns (HFCSSC) research program into effects of faster pressure cycling and lower temperatures of storage caverns.

RR2012-2_SMRI_Mellegard, *High Frequency Cavern Cycling – Phase 2: Cyclical Loading Effects on the Dilation and Creep Properties of Salt*, Kirby Mellegard, RESPEC, July 2012. [RR2012-2_SMRI_Mellegard]

This research involved lab testing of salt cores at RESPEC's lab in South Dakota, and verifying results at Clausthal University of Technology (TUC) under direction of Uwe Düsterloh, in Germany. Cyclic loading tests were performed on salt core from the same salt dome, with high mean stress for a period of 30 days, then low mean stress for another 30 days as dilation was monitored ultrasonically. Results showed that dilation occurred only at the lower mean stress as expected, and "…*the creep deformation from cyclic loading did not appear to be significantly different than that from conventional static loading."*

RR2013-2_SMRI_ Mellegard, *High Frequency Cavern Cycling—Phase 2-B: Extensional Cyclic Fatigue Testing of Salt,* Kirby Mellegard, RESPEC, October 2013. [RR2013-2_SMRI_Mellegard]

This phase of SMRI's HFCSSC research program involved the similar lab test protocol as the previous RR 2012-2 except that "…*two additional cyclic loading triaxial extension tests* (were) *performed to assess what* effect *the intermediate principal stress may have on the cyclic loading behavior."* Mellegard's conclusion was that "*Cyclic loading was investigated for both extension and compression, and the results indicate that cyclic loading does not make the salt more prone to dilation than static loading conditions. A disclaimer to this conclusion is that the scope of testing was limited."* The researchers as a result recommended additional testing using different salt types and varying loading.

RR2017-3_SMRI_Buchholz, *Cyclic Thermal Loading Creep Tests,* Stuart Buchholz, RESPEC, August 2017. [RR2017-3_SMRI_Buchholz]

This research was intended to learn how strain and dilation of salt pillars is dependent on rapid temperature cycling, (characteristic of faster storage cavern withdrawal and injection rates) and took place in the same 2 labs of RESPEC and TUC in this research series. SMRI Project Sponsor Peter Jordan noted that "*When the effects of temperature cycling are isolated from the effects of differential thermal expansion and contraction because of temperature gradients, no measureable effect of temperature cycling on creep or dilational behavior was noted."*

RR2012-3_SMRI_Pereira, *Common Practices – Gas Cavern Site Characterization, Design, Construction, Maintenance, and Operation*, José Pereira, Sabine Storage & Operations, October 2013. [RR2012-3_SMRI_Pereira]

This is an excellent general and specific reference for common practices for gas storage caverns which applies to most caverns, from design through abandonment phases. Following are Pereira's major sections of this RR: Site Characterization and Selection Criteria, Drilling, Open-Hole Logging, Cementation Practices, Coring, Core Evaluation and Testing Options, Well Casing and Wellhead Design Practices, Solution Mining, Gas Completion and Dewatering, Geomechanical Cavern and Well Field Design Considerations, Well and Cavern Testing Practices, Well and Cavern Maintenance, and Basic Concepts for Abandonment. Included is a useful review of Gas Storage Well and Cavern Regulations in different countries, results of an industry survey completed as part of this research enable comparison of industry practices. While a long process to complete this project, the result is of great value to all cavern operators.

RR2013-1_SMRI_Brouard, *Analysis of Moss Bluff Cavern #1 Blowout Data*, Benoit Brouard, Brouard Consulting, November 2013. [RR2012-1_SMRI_Brouard]

Cavern data from a 2004 gas cavern blow out and fire at Moss Bluff, Texas was made available to SMRI for research purposes by Spectra Energy Transmission and their staff. SMRI prepared a request for proposals (RFP) and selected Brouard Consulting from 4 proposals received in response. Brouard's tasks specified in the RFP were to (1) use the available pre-incident data to evaluate the pressure and temperature evolutions during depressurization and compare fit with available incident data; calculate/describe the depressurization scenario and provide the theoretical background applied. (2) Use obtained pressure and temperature data in thermo-mechanical computations to evaluate the geomechanical consequences in Cavern MB #1; confirm the results with available post-incident data. (3) Describe the reliability/performance of the industry's available tools/models to predict the consequences of such a gas depressurization scenario. Provide a discussion of the comparison of the actual results versus model predictions.

This research was based on computer simulations using LOCAS finite element software for thermo-hydro-mechanical analysis, and SPECTROM-32 and SPECTROM-41 software for thermomechanical stress simulation. The cavern well underwent a Mechanical Integrity Test (MIT) after the blowout, and the casing and casing shoe were found perfectly tight. Detailed analyses were made for effects of low pressure and cold temperatures (caused by the blowout) on the salt wall's stresses, dilation, and convergence rates. While estimates were made for tensile stresses and microfracture/dilatant zone of the cavern wall using the simulation programs, refilling the cavern with water after the incident must have dissolved most of any such zone. The researchers found insufficient measurement data to estimate the change in cavern volume for comparison with the model predictions.

RR2015-1_SMRI_ Schlichtenmayer, *Renewable Energy Storage in Salt Caverns - A Comparison of Thermodynamics and Permeability between Natural Gas, Air and Hydrogen*, Maurice Schlichtenmayer, ESK/RWE, July 2015. [RR2015-1_SMRI_Schlichtenmayer]

ESK/RWE was contracted to investigate differences in the thermodynamic behavior and the permeability of rock salt for natural gas, hydrogen and compressed air. The results were expected to be important to future clean energy use of salt caverns for compressed air and/or hydrogen storage. The most important finding was that "*practically no difference in the permeability of rock salt for natural gas, hydrogen, and air could be observed. Any difference in the permeation rates of the gases through a portion of rock salt (given that there are permeation paths existing) results only from their different viscosities. Thus, rock salt can be expected to be suited as geological barrier for hydrogen and compressed air as it has been verified for natural gas for several decades. … The project has, therefore, significantly improved the competitiveness of salt cavern storage technologies in the field of renewable energy management."*

RR2015-2_SMRI_Ratigan, *Deep Cavern Abandonment Field Tests in Deep Caverns*, Phase 2, Joe Ratigan, Enterprise Products, February 2016. [RR2015-2_SMRI_Ratigan]

This was a rather long project to investigate cavern sealing and abandonment (CS&A). Joe Ratigan was the project champion, who, along with SMRI Project Sponsor Steve Bauer, and Mark Thompson of Enterprise persevered through unexpected interruptions beyond researchers' control to conclude the research. Four deep (over 1000 m or 3280 ft. below surface) caverns of Enterprise Products operation at Mont Belvieu / Barbers Hill salt dome, Texas, were monitored for 5 *years* to investigate possible cavern abandonment considerations. Cavern temperatures and pressures were monitored after the cavern wells were shut in. The maximum cavern pressure allowed in Texas was 0.8 of lithostatic, so cavern pressure during the abandonment test period was limited. The system was modelled and analyzed as part of the research. In this location, caverns nearest to the edge of the salt dome had higher permeation rates than the caverns with thicker salt walls. There were several conclusions drawn, the first was that the pressure increase was caused mainly by salt creep closure of the shut in caverns.

Other practical lessons were learned and documented, important to CS&A plans for any salt dome deep cavern.

RR2016-1_SMRI_Hevin, *Perform a Thermo-mechanical Test in a Salt Mine, as part of SMRI's High Frequency Cycling of Salt Storage Caverns (HFCSSC) Research Program*, Grégoire Hévin, Storengy, December 2016. [RR2016-1_SMRI_Hevin]

This research project was significant for a number of reasons, one of which was the Storengy team of 4 additional organizations working on this underground salt mine field test and research effort. The project was designed to look at geomechanical effects of cold temperatures on salt at the cavern or mine wall, a *suitable* underground salt mine test site was arranged with Salins at their Varangeville mine in France. The RR describes in detail the testing arrangements, such as acoustic monitoring, thermal and digital imaging, and examination of the salt floor test area cooled salt. Rapid cooling was used in phases, while ultrasonic and strain measurements were taken, and computer simulations were part of the analysis of temperature induced fracturing. Results verified that cracking of the salt does result from low temperature cycles used, and found that some of the cracks close when the temperature goes back up. As repeated cooling cycles were tested, the numbers of new fractures actually decreased, and fracture depth did not increase. Fracturing characteristics were consistent with the rock mechanics model computed stresses. Results of the RR will help design of safe caverns for future HFCSSC use, as well as point to future research ideas.

RR2017-1_SMRI_Berest, *Very Slow Creep Tests As a Basis for Cavern Stability Analysis*, Pierre Bérest, Ecole Polytechnique, January 2017. [RR2017-1_SMRI_Berest]

SMRI had another large and geographically diverse project team working on this research, led by Pierre Bérest, to experiment with the salt creep law in a range of small deviatoric stress that has been little studied previously. As the second recent SMRI research project that used instrumentation in a well-suited section of an underground, operating salt mine, the Altaussee Mine of Salinen Austria was selected by this excellent research team. This project involved setting up precise, multistep creep tests at an isolated mine location with almost no air temperature variation. *Carefully* characterized salt core samples from 3 different salt deposits were tested for 2 year duration at unusually low applied loads in the range of about 0.1 to 1.0 MPa (14.5 – 145 psi). Challenges of underground lab testing were overcome, and conclusions were reached that: 1) In these low stress creep tests, that transient creep was longer than generally considered. 2) Steady-state strain rates at low stress range are 7-8 orders of magnitude faster than projected from high stress tests. 3) The exponent of the power law, under low stress, is different from the high stress value. Additional testing in a slightly higher stress range was recommended by the research team, and was approved in fall 2017 by SMRI members to continue phase 2 of this research.

RR2017-2_SMRI_ Réveillère, *Past Salt Cavern Incidents Database, Part 1: Leakage, Overfilling and Blow-out*, Arnaud Réveillère, Geostock February 2017. [RR2017-2_SMRI_Réveillère]

Researchers from 7 organizations in 5 countries, led by Geostock, assembled publically available information about 3 specific types of salt cavern incidents, as was intended for phase 1 of eventually 2 SMRI RRs. Introductory comments by this SMRI Project Sponsor Yvan

Charnavel nicely describe this RR: "*The database provides our industry an additional tool to efficiently analyze and learn from past incidents to avoid repeating in the future. The database provides basic (publically available) information on each incident, but more importantly, highlights the geological and/or technical origin of the problem. Such highlights immediately focus on the lessons learned and the practical steps our industry has taken to avoid similar incidents.*
Phase I of this project addresses below-ground incidents/failures exclusively (including well-head) for storage in salt caverns, and intentionally focuses on just three "operational" domains: (1) leakage, (2) overfilling, and (3) blow-out.
An international and multi-disciplinary team went on massive data processing effort to end up with 21 incidents or case studies*. The present report is the culmination of their work. Each case is presented, described, explained, and analyzed with enough details to illustrate root causes and/or indications that can benefit the salt cavern community. The report benefits anyone tasked to scrutinize an underground storage, either existing or proposed, from safety point of view."*

RR2017-4_SMRI_Wille, *Salt Caverns and Salt Dome Boundaries*, Sven Wille, DEEP Underground Engineering GmbH, October 2017. [RR2017-4_SMRI_Wille]

How far should caverns or mines stay from the salt dome edge? The answer depends on the quality of the geological information known, particularly about the salt edge, and exploration methods used. The research team evaluated the range of geological conditions, exploration methods available, potential problems, and steps to take to rationally make these decisions. The RR has sections on geological characterization of salt dome, (with background information of possible conditions); exploration methods for salt dome boundary mapping, (mainly drilling and geophysics); geomechanical assessment to *evaluate* stability of planned or existing caverns or mining; regulatory requirements (varying by countries and US states); monitoring considerations and methods; and finishes with conclusions and excellent suggestions for possible future research. Wille's conclusion is that "*The most accurate delineation of the salt dome boundary, however, will be generated by integrating all available sub-surface data from wells drilled in and around the salt dome, formation evaluation with wireline logging data, seismic data sets, borehole seismic data sets, radar data, sonar survey results from mined caverns and any other available dataset with spatial reference into one 3D model. …This geological mapping and knowledge is critical when performing a geomechanical assessment of a cavern located near the salt dome boundary."*

RR2017-5_SMRI_Horvath, Update of SMRI's Compilation of Worldwide Salt Deposits and Salt Cavern Fields, Péter Horváth, KBB Underground Technologies GmbH (KBB UT), September 2017. [RR2017-5_SMRI_Horvath]

SMRI RRs were first completed as references for world salt deposits; bedded salt was RR2006-2, domal salt was RR2007-1, and were two of the most requested SMRI RRs ever. This new, combined domal and bedded salt RR includes added new detail on salt deposits and more extensive information on existing salt caverns. Information was added from questionnaires completed by many SMRI members, and input assistance from individuals in specific salt regions. This RR was presented *during* SMRI's Fall 2017 Münster conference, but was not yet in final version ready for the library. This new, more comprehensive Compilation includes GIS compatible maps and data, and various xls lists of salt deposits and cavern sites. As other SMRI RRs, the report will be available to members online, and will be available to non-members for purchase starting approximately in late 2018. SMRI Project Sponsor Markus Stöwer stated that *"This updated report will lead the SMRI members through the next decade and has the potential to trigger project development in new regions, to give substantial data input into strategic decisions and to act as foundation for optimizing existing supply structures."*

Active Research Projects

SMRI's 5 Active Research Projects, as of November 2017 follow, with brief description and objectives.

U2014-2 *Hanging String Dynamics and Vibration, Phase III*, cooperative project with PRCI, McGill University, Montreal. SMRI and McGill are continuing this research series, with this phase 3 underway in late 2017. *Phases* 3 and 4 are notably cooperative research with equal participation/funding by the Pipeline Research Council International (PRCI) and SMRI, with McGill's Michael Païdoussis continuing to guide the actual research. SMRI Project Sponsor Joe Ratigan reported that the experimental apparatus has been upgraded, and phase 3 experiments and model development are expected to be completed in early 2018.

U2017-03 *Additional Characterization of Hanging String Dynamics and compilation of results – Phase IV*, cooperative project of PRCI and SMRI, McGill University. Phase 4 was approved by SMRI members in September 2017, with research work to start in 2018. Phase 4 will conclude a series of flow configuration experiments and application of the theoretical modeling already developed to "real life" cavern well configurations and geometries. Finally, a software package for cavern operators to use to avoid pipe flutter and buckling failures is being developed.

U2017-01 *Thermal Expansion Coefficient and Modulus Measurements on Damaged Salt*, RESPEC, is phase IIC of High Frequency Cycling of Salt Storage Caverns (HFCSSC). This phase of rock mechanics research will advance SMRI's HFCSSC ongoing research series and was approved by SMRI members in April 2017. The project consists of lab testing by heated uniaxial and triaxial core tests to compare the thermal expansion coefficient of damaged versus undamaged salt. Results from this project are expected to allow more precise prediction of thermal induced stresses for fast cycling caverns.

RFP2017-01 *Collection and Distribution of Standard-Salt Cores*, RESPEC. SMRI was informed that a large stock of Avery Island salt core acquired by RESPEC in the 1980s during field work for the US Office of Nuclear Waste Isolation (ONWI) was running low, SMRI recognized the value of having sufficient salt core available for future research. An RFP was issued and the only proposal received in response was approved for RESPEC. The project will allow collection by drilling of Avery Island underground salt mine core, stable transport and storage of the core, and distribution of core as approved by SMRI for future research. The project was approved by the members September 2017.

U2017-*02 Very Slow Creep Tests as a Basis for Cavern Stability Analysis.*
This research proposal was received from Ecole Polytechnique, with their 7 subcontractor team in place, and was approved by the SMRI members in April 2017 (see also RR2017-

1_SMRI_Berest in the completed RR section above, for a brief description of the additional rock mechanics data this will provide for improved cavern design accuracy).

Future Research Subjects, ideas for new projects – Let us hear from you!

Projects solicited by RFP or presently under consideration:

RFP2017-02 "Update Compilation of Physical, Chemical, and Mineralogical Properties to Salt Rock Strength and Deformation Characteristics", RFP was issued August 2017 with proposals due in December 2017.

U2017-04 "Acquisition of Flow Induced Vibration Data", Williams Mid-Continent Fractionation & Storage LLC (Williams) and Ratigan Engineering. Collection of industrial field data for vibrating hanging strings under a variety of configurations and flow rates. Hanging pipe strings are known to vibrate, proposal is in review process.

Database of Past Cavern Incidents, phase 2 is anticipated.

SMRI and our Research Committee are always looking for possible future research topics of interest to our members and the industry, of which several general subjects of particular value are:

- Cavern/well abandonment
- Integrity of caverns and cavern wells
- Geological characterization needs and exploration advances

Conclusion

SMRI is unique as an industry organization, having evolved from a small technical group trying to solve solution mining challenges, to a larger cavern community that brings together people focused on intertwined subjects of solution mining and cavern storage. At our conferences, each attendee finds, in addition to technical paper presentations, numerous informal opportunities to meet other delegates and learn elementary concepts or discuss highly technical aspects of all phases of the cavern industry. SMRI research subjects, (as outlined in this paper,) such as clean energy storage, cavern design and monitoring, cavern abandonment, salt deposit exploration, and others will continue to help the industry improve. The world's solution mining experts and their organizations on are found on SMRI's membership rolls, and always welcome you. SMRI is a working, efficient, technical organization that can help optimize your cavern programs and reduce risk.

Reference Numbers and List

RR2009-1_SMRI_Bannach, *Stassfurt Shallow Cavern Abandonment Field Test*, Andreas Bannach, ESK RWE, May 2009.

RR2009-2_SMRI_Nieland, *SALT-SUBSID Cavern Design Software Upgrade*, Joel Nieland, RESPEC, May 2009.

RR2010-1_SMRI_Zander, *High Frequency Cycling of Gas Storage Caverns: Phase I: Development of Appropriate Lab Tests & Design Criteria,* part of High Frequency Cycling of Salt Storage Caverns (HFCSSC), Dirk Zander-Schiebenhöfer, KBB Underground Technologies GmbH, October 2010.

RR2011-1_SMRI_Brouard, *Salt-Cavern Abandonment Field Test at Carresse, Update of the SMRI Research Report 2006-1, Report #2*, Benoit Brouard, Brouard Consulting, October 2011.

RR2011-2_SMRI_ Duquesnoy, *Synthesis of Shallow Cavern Abandonment*, Antoine Duquesnoy, Well Engineering Partners (WEP) BV, March 2011.

RR2011-3_SMRI_ Païdoussis, *Study of Casing Pipe Vibration in Solution-mined Caverns*, Michael Païdoussis, McGill University, December 2010.

RR2014-1_SMRI_ Païdoussis, *Cavern Tubing Flow Induced Vibration Theory and Lab Tests*, Michael Païdoussis, McGill University, October 2014.

RR2012-1_SMRI_Zander-Schiebenhöfer, *Deformation of Cemented Casings - Case Studies, Analysis, and Pressure De-rating Procedure*, Dirk Zander-Schiebenhöfer, KBB Underground Technologies GmbH (KBB-UT), May 2012.

RR2012-2_SMRI_Mellegard, *High Frequency Cavern Cycling – Phase 2: Cyclical Loading Effects on the Dilation and Creep Properties of Salt*, Kirby Mellegard, RESPEC, July 2012.

RR2013-2_SMRI_ Mellegard, *High Frequency Cavern Cycling—Phase 2-B: Extensional Cyclic Fatigue Testing of Salt,* Kirby Mellegard, RESPEC, October 2013.

RR2017-3_SMRI_Buchholz, *Cyclic Thermal Loading Creep Tests,* Stuart Buchholz, RESPEC, August 2017.

RR2012-3_SMRI_Pereira, *Common Practices – Gas Cavern Site Characterization, Design, Construction, Maintenance, and Operation*, José Pereira, Sabine Storage & Operations, October 2013.

RR2013-1_SMRI_Brouard, *Analysis of Moss Bluff Cavern #1 Blowout Data*, Benoit Brouard, Brouard Consulting, November 2013.

RR2015-1_SMRI_ Schlichtenmayer, *Renewable Energy Storage in Salt Caverns - A Comparison of Thermodynamics and Permeability between Natural Gas, Air and Hydrogen*, Maurice Schlichtenmayer, ESK/RWE, July 2015.

RR2015-2_SMRI_Ratigan, *Deep Cavern Abandonment Field Tests in Deep Caverns*, Phase 2, Joe Ratigan, Enterprise Products, February 2016.

RR2016-1_SMRI_Hevin, *Perform a Thermo-mechanical Test in a Salt Mine, as part of SMRI's High Frequency Cycling of Salt Storage Caverns (HFCSSC) Research Program*, Grégoire Hévin, Storengy, December 2016.

RR2017-1_SMRI_Berest, *Very Slow Creep Tests As a Basis for Cavern Stability Analysis*, Pierre Bérest, Ecole Polytechnique, January 2017.

RR2017-2_SMRI_ Réveillère, *Past Salt Cavern Incidents Database, Part 1: Leakage, Overfilling and Blow-out*, Arnaud Réveillère, Geostock February 2017.

RR2017-4_SMRI_Wille, *Salt Caverns and Salt Dome Boundaries*, Sven Wille, DEEP Underground Engineering GmbH, October 2017.

RR2017-5_SMRI_Horvath, Update of SMRI's Compilation of Worldwide Salt Deposits and Salt Cavern Fields, Péter Horváth, KBB Underground Technologies GmbH (KBB UT), September 2017.