TECHNICAL CHALLENGES FOR SOLUTION MINING AND SALT CAVERN STORAGE TO MEET FUTURE ENERGY AND MINERALS DEMAND, AND SOLUTION MINING RESEARCH INSTITUTE'S (SMRI) ROLE

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1. INTRODUCTION

Salt deposits are numerous and found in most regions of the world. The best salt deposits for both salt production and cavern storage tend to be either the thickest bedded salt deposits or salt domes. Without getting into the geology, salt domes are formed as bedded salt is deeply buried and compacted by sediment. The less dense salt rises toward the surface to form massive plugs which can be several miles in diameter by 10 miles deep. Those familiar with U.S. Gulf Coast oil and gas geology know that the Gulf region has over 500 salt domes, many of which have produced oil and gas from traps on the flanks of the domes. Both bedded salt and salt domes are of quiet but great economic importance worldwide, supplying salt as basic feedstock to many chemical production facilities, winter road deicing, water treatment, and food processing. Figure 1 shows bedded and domal salt deposits in France.

KEY WORDS

solution mining, cavern storage, gas storage, energy storage, salt cavern, research

THE BASICS OF SOLUTION MINING AND CAVERN STORAGE

It is possible to mine salt from rock salt deposits using either underground mining or solution mining methods. Local geology, economics, and salt demand influence the choice of which mining method is used. Underground conventional mining is more capital intensive and can provide greater production capacity, but also exposes salt miners to the hazards of being underground (even if salt mines tend to be quite safe compared to other types of mines). Solution mining uses one or more drilled wells to inject fresh water, which dissolves salt in a controlled manner and produces saturated brine. The brine may be piped directly to chemical plants or recrystallized to produce high purity 'evaporated' salt, which we know as table salt. The solution mining and salt recrystallization process produces a much finer crystal size, higher-purity salt than underground mining does, but energy cost per ton for recrystallized is

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FIGURE 1. Salt deposits, salt mining, and cavern storage operations in France. (SMRI Research Report 2006-2)

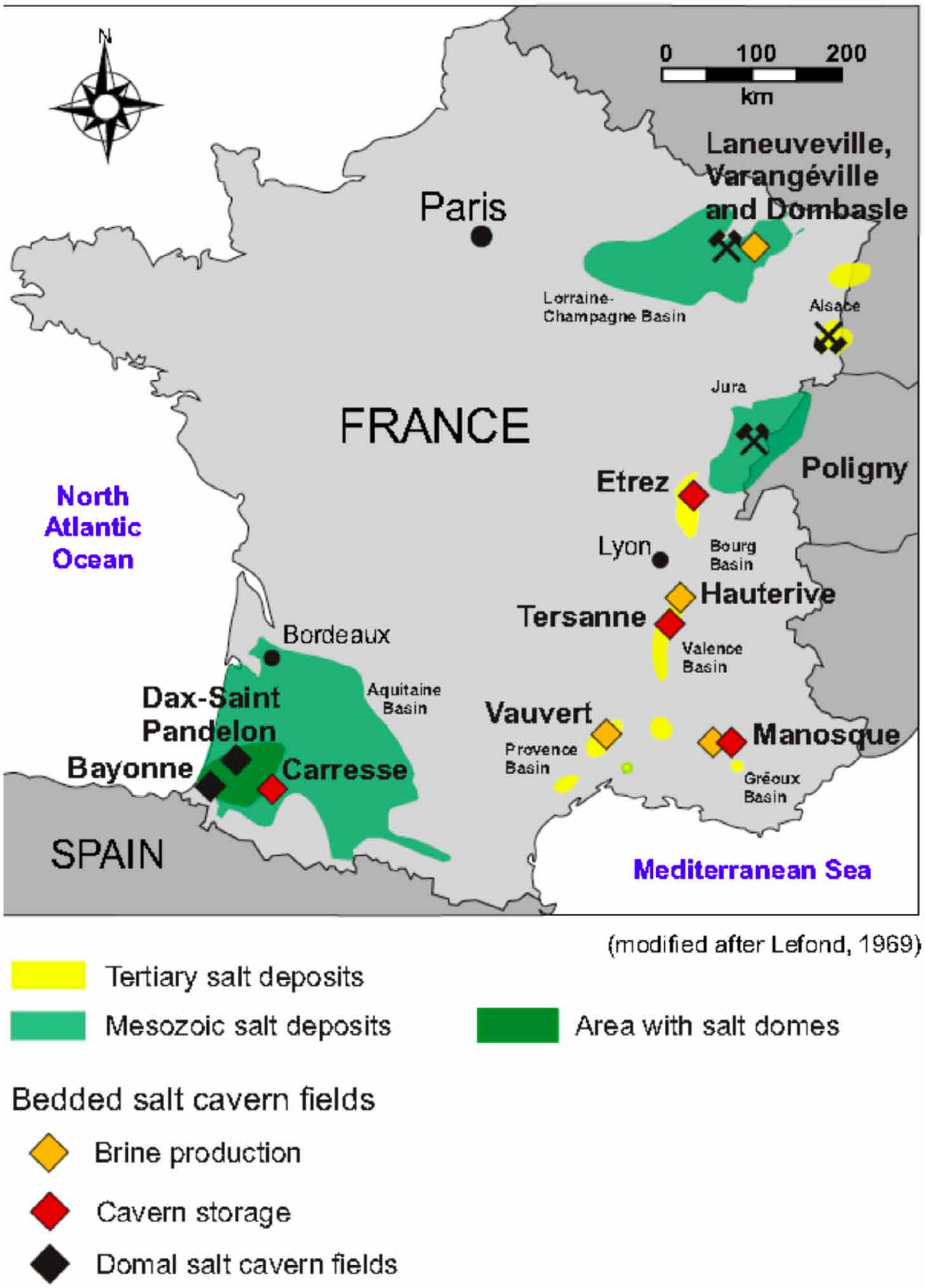


Fig. 6.1.5-1
Salt deposits of France

FIGURE 2. (Courtesy of KBB Underground Technologies GmbH.)

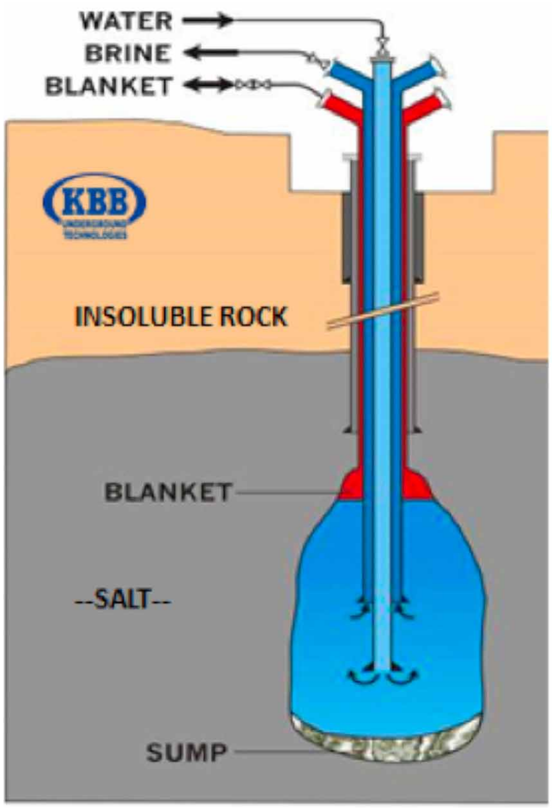
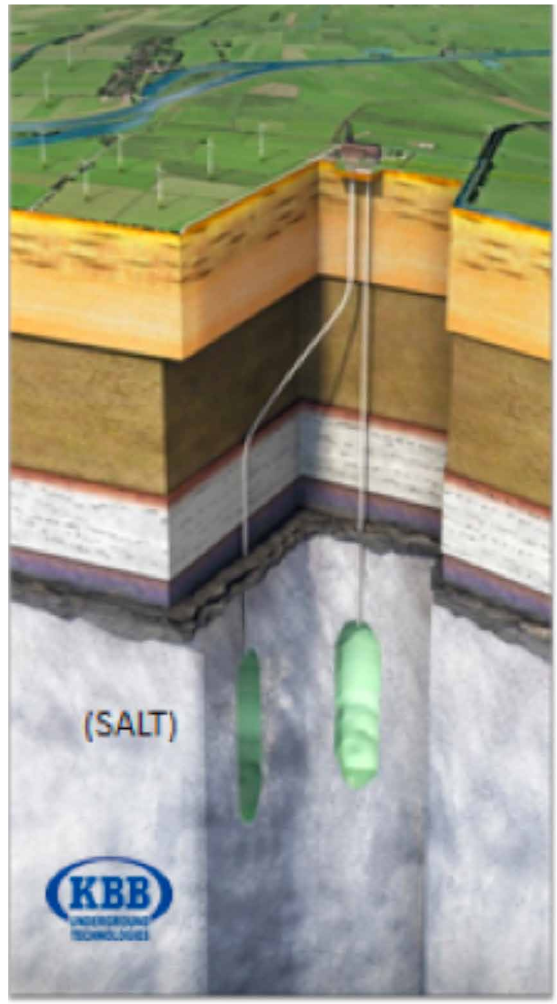


FIGURE 3. (Courtesy of KBB Underground Technologies GmbH.)



much higher. Figure 2 shows the concept of a solution mining well and cavern created by salt dissolution, while the denser saturated brine is pumped to surface.

Solution mining is not a new practice, having begun thousands of years ago in China by dissolving underground salt with fresh water through the use of bamboo drill pipe. Theprocess has evolved into a specialized industry to solution mine water-soluble minerals such as trona and potash, in addition to rock salt. Over the last twenty years, empty salt caverns resulting from solution mining have in some cases become far more valuable than the salt recovered, as caverns are commonly used for storage of natural gas and crude oil, in addition to other hydrocarbons, and in some cases, for waste storage. Salt caverns are well suited for storage because salt does not become dissolved into or degrade the products stored. Storage cavern industry growth has been reflected in Solution Mining Research Institute's (SMRI) growing membership as gas storage interest and investment has taken off. Storage caverns dissolved out from salt formations provide a secure and accepted method of storing natural gas, without some of the risk of constructing equivalent surface storage. Gas has also been stored successfully underground in depleted gas reservoirs, but salt caverns have a higher output rate to meet demand spikes expected during the coldest winter months. Another common example of salt cavern storage is for crude oil storage by various countries to provide an emergency source of crude oil in the event of disrupted crude oil supply from the largest oil exporters, many of which are located in the more politically volatile regions of the world. The U.S. Strategic Petroleum Reserve is one such example, storing large quantities of crude oil in salt dome caverns, ready to be piped to refineries in case of a national emergency. Figure 3 shows a 3-D illustration of salt caverns developed by drilled wells (the left cavern shown is accessed by directional drilling to limit surface footprint required).

2. SMRI: THE ORGANIZATION

There are other papers available describing the Solution Mining Research Institute, Inc.'s (SMRI) history, and a summary with references is available on SMRI's website at http://www.solutionmining.org/index.php?id=6. SMRI is a 48-year-old non-profit industry organization. SMRI's purposes are performing research to support the solution mining and storage cavern industry, acting as technical source, and offering networking opportunities and training for our members and others interested in the industry. SMRI is supported by member dues and our members include: mineral production corporations; universities; service companies; engineering, geophysics, and geology consulting firms; equipment vendors; government regulatory agencies; gas storage and pipeline companies; and waste storage companies. Membership is open to organizations only, and information can be found at http://www.solutionmining.org/index.php?id=8. Our organization is led by volunteer members who serve on SMRI's Executive Committee and our research program is geared to focus our resources on those industry aspects most important to our members. SMRI has a track record of committing research resources to help the industry achieve the highest possible environmental and safety standards. In 2010, SMRI members authorized a new membership class designed to get our technical information and resources into the hands of budget-strapped government regulators so they have free access to up-to-date technical information, even if they cannot afford to attend our tech conferences. SMRI Research projects are approved for the purposes of solving challenges, improving industry processes, and offering tools and information to members and industry for achieving better results. When appropriate, SMRI has utilized partnerships with other associations and multi-country research teams to maximize the impact of our research funds to investigate, solve problems, and provide technical information of timely importance to our members.

3. BAYOU CORNE, ASSUMPTION PARISH, LOUISIANA USA: SINKHOLE INCIDENT AND IMPACT ON PEOPLE, THE ENVIRONMENT, AND SALT CAVERN REGULATIONS

On August 3, 2012, residents of Bayou Corne noticed a diesel fuel odor and a sinkhole was discovered in a swamp area south of highway 70. Trees in the approximately 200 feet × 200 feet area collapsed and the surface appeared like a mud slurry. The Louisiana State Department of Natural Resources (LA DNR) identified a Texas Brine OXY GEISMAR #3 well/salt cavern as a potential cause. LA DNR issued an emergency order to Texas Brine to evaluate cavern integrity and remediate. LA DNR also issued orders to operators of pipelines near the sinkhole to empty and shut in. A Crosstex pipeline experienced deflection. Three days later, LA DNR issued a Declaration of Emergency, and on August 9, 2013, Assumption Parish emergency personnel were going door to door notifying the residents of about 150 homes that they were in a "Mandatory Evacuation Area." By July 2013, about half of Bayou Corne's residents were still out of their houses because the risk of methane gas leakage through an aquifer into residences cannot be ruled out. Texas Brine has started offering "buy out" of those residents wishing to re-locate.

Months before the surface sinkhole was discovered, there were reports of seismic tremors and gas bubbling in the area, such that the U.S. Geological Survey (USGS) was asked by Assumption Parish government officials to provide assistance determining the locations and probable cause(s) for this seismic activity. USGS began monitoring and immediately detected seismic activity, however, no probable cause could be detected. More detailed seismic and microseismic monitoring is now underway.

An extensive investigation is being conducted both by Texas Brine and by CB&I. (Previously The Shaw Group, CB&I is the main contractor for the LA DNR.) This project has generated a tremendous amount of information and data, far too much to be summarized adequately in this article. The following two websites are recommended for obtaining both background details and current information:

LA DNR: http://dnr.louisiana.gov/index.cfm?md=pagebuilder&tmp=home&pid=939&pnid=0&nid=172

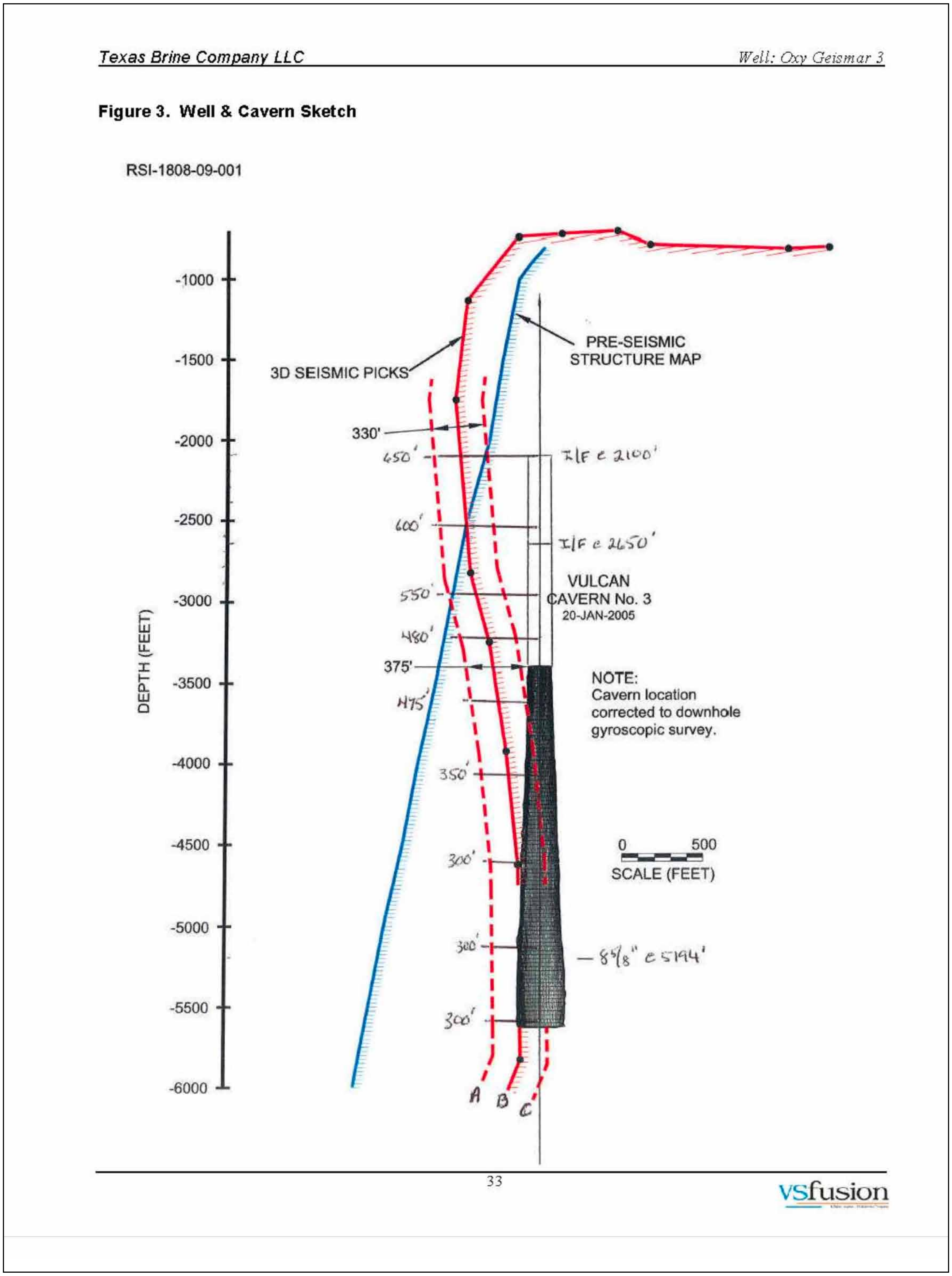
Assumption Parish, LA: http://assumptionla.wordpress.com

The Napoleonville salt dome is located in south Louisiana, between Baton Rouge and Morgan City. Salt domes are common structures in south Louisiana and the Napoleonville dome is not out of the ordinary, geologically speaking. The salt dome is not evident from the flat, marshy, surface topography. The salt is overlain by about 300 feet of anhydrite caprock and the shallowest salt is about 700 feet below the surface. There are seven different operators of 53 salt caverns on this dome. Most caverns, as Texas Brine's OXY #3, were strictly for brine production, while 20 others are permitted as storage caverns. Cavern volumes are wide-ranging, from about 1 million bbls to as much as 47 million bbls.

Texas Brine began development of the cavern in 1982. According to a sonar survey in 2007, the top of the cavern was about 3384 feet (1031 m), the base of the cavern was about 5600 feet (1707m), and the cavern diameter was a maximum of over 200 feet (61 m). The cavern was completed before 2011, when it was plugged and abandoned. A seismic VSP survey was run in September 2010 which indicated there was a salt overhang on the side of the dome near OXY#3 cavern, and the edge of salt was likely closer to the cavern than designed. Figure 4 is from a survey report filed by Texas Brine with the LA DNR. On the Well and Cavern Sketch, the blue line "Pre-Seismic Structure Map" shows the previous interpretation of the edge of salt relative to the Oxy#3 cavern and the red line shows the 2010 interpreted VSP processed edge of salt. Some doubt could be raised about the 2010 interpretation because at the cavern depth of 5000 to 5500 feet, the edge of salt solid red line B as shown is essentially on the cavern wall, a situation that in reality is extremely unlikely without immediate cavern failure. If the most optimistic 2010 interpretation (dashed red line A) is correct, the resulting slight salt overhang places the edge of salt close enough to the cavern wall that the salt wall may not be thick enough to ensure cavern structural or hydrological integrity.

As investigations continue by Texas Brine, and for the State of Louisiana by CB&I, the technical issues of how the cavern failure occurred, estimated versus actual subsidence, the source pathway, and how to mitigate the methane and hydrocarbons previously trapped along the flank of the salt dome will become clearer. The most uncomfortable fact for the solution mining community is that many residents of the beautiful Bayou Corne community are still

FIGURE 4. Vertical Seismic Profile.

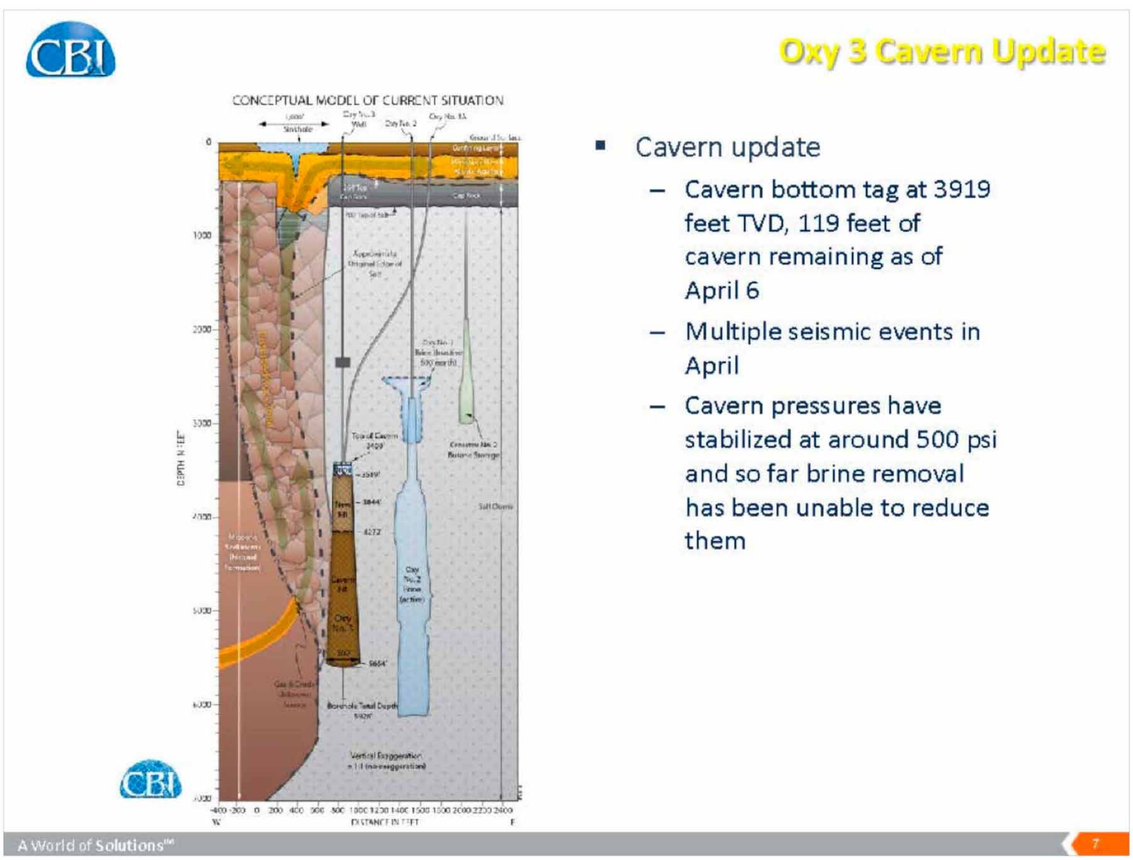


waiting to hear an "all clear" to return to their homes less than a half mile from the sinkhole area. Texas Brine quickly built and continues to maintain a berm around the still widening sinkhole area to contain brine and oil contaminants from moving off site. A focus of the investigation and remedial work is the methane gas bubbling from the surface in a wide area, including parts of Bayou Corne. Experts believe that when the cavern's salt wall failed, the sediments adjacent to the salt dome immediately began moving into the cavern, eventually leading upward to the surface collapse. Also, naturally occurring oil and gas deposits were located along the flank of the dome, and when containing sediments were disturbed by the sinkhole material slumping/flowing into the cavern, it created a new escape path for the oil and gas to begin to move upward. Some of the upward moving gas found least resistance pathways into the Mississippi River Area Aquifer (MRAA) that extends for miles laterally across the delta sediments. Methane then moved from the MRAA upward through weak points in the overlying clay layers, bubbling out of the ground or water surface, some alarmingly in residents' yards. Many relief wells have been drilled to drain off the methane before it spreads through the MRAA, but the size of the source and the time it will take to drain off the methane are still unknown.

Figure 5 shows a May 1, 2013, CB&I interpretation of the salt dome, OXY#3 cavern, the sinkhole, and the "disturbed Rock Zone" (DRZ) as presented by LA DNR, during a briefing.

The question facing the solution mining and storage cavern industry is "how can we assure neighbors that our operations are safe and not at risk of similar failures?" The LA DNR

FIGURE 5.



has already, in direct response to the Bayou Corne sinkhole, released a directive to all cavern operators in Louisiana that they must submit information showing the position of each cavern relative to the closest edge of salt. Many other regulatory agencies around the world have been watching the Bayou Corne story unfold, and it is certain that more government regulations will be enacted in hopes of preventing similar failures. Cavern designers have far better tools to analyze cavern structural design than 30 years ago, and advances in geophysical methods such as high resolution and 3-D seismic have been tremendous developments for imaging geology and salt deposits before a new cavern is developed or re-purposed. Our industry must recognize and respect our neighbors' fear of the unknown aspects of new projects, and anticipate that exaggerations by some opponents of cavern projects are sometimes rooted in misunderstanding of technical issues or controversial siting issues. The best way for industry to deal with neighbors is through an open information policy which allows any questions to be asked and answered honestly, and exchanges such as having 'open houses' to show residents presentations of how the design and operation processes work, while explaining that the integrity and safety of a project is critical to the company and shareholders' success just as much as the residents. In the information age, with the instant ability to post messages and news, it is impossible to control communications, so the credible reputation of the company and spokespeople become most important factors. Does the public have faith that a company will execute a project to their best capability so there is no risk of failure? A single, unforeseen project failure such as Bayou Corne can create a devastating financial and operating situation for the company, place the public's safety at risk, and consume massive government and company resources. No rational company would knowingly allow such an accident to take place, nor try to save money by neglecting the care of such operation.

4. RESOURCES SMRI PROVIDES TO THE INDUSTRY NICHE

Technical Conferences and Classes

SMRI typically has two conferences each year, a spring conference in North America, and a fall conference in Europe. The conferences follow a tested format that our members like, and which is designed to easily get to know other attendees by having open breakfast, coffee breaks, lunches, optional evening events, and optional field trips where conversations are easy to start. Professional contacts made during these informal conversations may prove to be quite valuable. One important task is to keep attendees informed about occasional important industry news events, such as the August 2012 Bayou Corne cavern failure, and making available both recognized experts and references to help members address such issues. Conference locations vary as we try to hold these events in locations that offer opportunities for good professional field trips, as well as other considerations: how many members and new potential members are in the region; travel access and reasonable cost for conference attendees; and solution mining cavern storage activity or potential in the region. We tend to have the best attendance in the U.S. Gulf coast Texas and Louisiana locations, in Germany, and at sites where we can get underground mine visits scheduled, so those locations are frequently in the schedule. The next conference will be in Avignon, France from 29 Sept to 2 October 2013. Up to date information on this conference is available at http://www.solutionmining.org/index.php?id=20. An optional technical class will be offered at Avignon, on the subject of "Salt Well Logging."

Future conferences are planned for Spring 2014 in San Antonio, Texas and Fall 2014 in Groningen, The Netherlands, where the tech class subjects will be "Subsidence and Sinkholes."

Website and Online Library

Our website, www.solutionmining.org, has taken on greater importance in keeping our members (over 1000 individuals working for member organizations) informed. Our routine communications are entirely by website and e-mail. SMRI maintains an online technical library for the use of our members. We have thousands of SMRI conference papers, all of SMRI's research reports, and every World Salt Symposium technical paper (for 1 through 9 Symposia). The library is fully word searchable and maintained by ArchivalWare/PTFS with adjustable search and browse capability. Members must be logged in to access the library documents, and non-members may perform searches and see a list of documents, but cannot access the documents unless they wish to purchase specific papers.

Software

SMRI offers 3 copyrighted software titles to members with their membership, 'SMRI SALGAS', 'SMRI TOOLBOX', and 'SMRI SALT_SUBSID' each were developed under contract for SMRI.

SMRI SALGAS for Windows is a proprietary program which simulates the dissolution of sodium chloride salt by water, optionally simulates the hydraulic properties and power requirements of the mining system, and optionally simulates the properties of a nitrogen pad used to protect the roof of the cavern from upward dissolving.

SMRI TOOLBOX for Windows makes several tools available to hydrocarbon storage operators and brine producers. This computer toolbox operates on a personal computer and contains tools such as: a calculator for static downhole pressure; a pressure-drop calculator; a calculator for static gas cavern-volume and working volume; a database for fluid (pure gas and liquid) properties and a properties calculator; a calculator for brine and natural gas properties; a tubings/casings database; a minimum allowable casing thickness calculator; units conversion; and a database of useful links.

SMRI SALT_SUBSID is a subsidence model used to evaluate surface subsidence over underground openings in salt, potash, and trona which can be used for predicting the future subsidence of a new or existing mining plan. The program can also predict casing string stresses and strains resulting from subsidence over solution wells. Time-dependent, creep closure induced, subsidence simulation can be performed on solution wells or dry mines.

5. SMRI RESEARCH: RECENT/CURRENT PROJECTS AND RESULTS:

(1) SMRI's Cavern Sealing and Abandonment Research Program

The SMRI and its member companies have long recognized the complex issues associated with high fluid pressures in solution-mined caverns, particularly the high pressures that may develop in sealed and abandoned caverns. SMRI responded to this need for more information by initiating a multi-project research program focused on addressing cavern sealing and abandonment (CS&A) of solution-mined cavern wells. The objectives of the SMRI program were to:

1. Determine the primary knowledge and technology gaps associated with cavern sealing

2. Execute research efforts to reduce the uncertainties and knowledge gaps
3. Develop guidelines for safe and acceptable cavern sealing and abandonment.

The program initially focused on an assessment of exactly what is known in the scientific and commercial communities regarding cavern sealing and abandonment. This initial effort resulted in a comprehensive bibliography of the understanding and practice of cavern sealing. Following completion of the bibliography, a series of Requests for Proposals (RFPs) were issued to pursue research in the key areas of uncertainty. Contracts were awarded to study (1) salt permeability under complex stress states, (2) hydraulic and mechanical integrity of the well casing shoe through bench-scale testing, and (3) geomechanical modelling of fluid/salt hydraulic and mechanical interaction in a sealed cavern.

Years of CS&A research has led to the development of some very important scientific and operational observations and conclusions:

- Salt permeability at brine pressures approaching the confining salt stresses is an extremely strong function of the difference between the salt total stress and the brine pore pressure. As this difference becomes small or slightly tensile, salt permeability increases significantly (i.e., many orders of magnitude).
- Bench-scale simulations of casing shoe configurations must reproduce the emplacement of cement while the salt is under pressure if the test is to reproduce the *in situ* condition.
- In the absence of brine thermal expansion, the vast majority of solution-mined salt caverns can be sealed and abandoned without concern for salt fracture generation or significant brine migration from the cavern.
- Prior to cavern sealing, the cavern should be kept open as long as possible and practical to ensure a stabilization of the brine temperature. Information from continuous well shut-in and bleed-off periods will contribute to the knowledge base necessary for safe and environmentally acceptable sealing.
- Casing shoe integrity tests should be performed prior to sealing to ensure this potential pathway has maintained integrity comparable to that required during the cavern operational history.
- Tall caverns and/or caverns that must be sealed before thermal equilibrium is approached require a case-by-case evaluation of sealing strategy.
- The most significant achievement of this still active research program has been the development of a salt cavern abandonment concept permitting the safe sealing of the vast majority of solution-mined salt caverns. This concept has been applied successfully in a series of SMRI–sponsored field tests on shallow caverns, and demonstration on deep caverns is in progress.

(2) SMRI's High Frequency Cycling of Salt Storage Caverns Research Program

Innovative uses of salt storage caverns in recent years include "High Performance Natural Gas Storage" (HPNGS) and "Compressed Air Energy Storage" (CAES). Compared to seasonal storage caverns, operating pressure conditions are here characterized by (1) higher injection/production rates and subsequently higher pressure variation rates, and (2) more intensive cycling, i.e., essentially more cycles over the anticipated operating lifetime. The SMRI recognizes that the design and operation of such salt storage caverns can require important refinements of the rock salt Constitutive Behaviour Laws as well as the Mechanical Stability Design

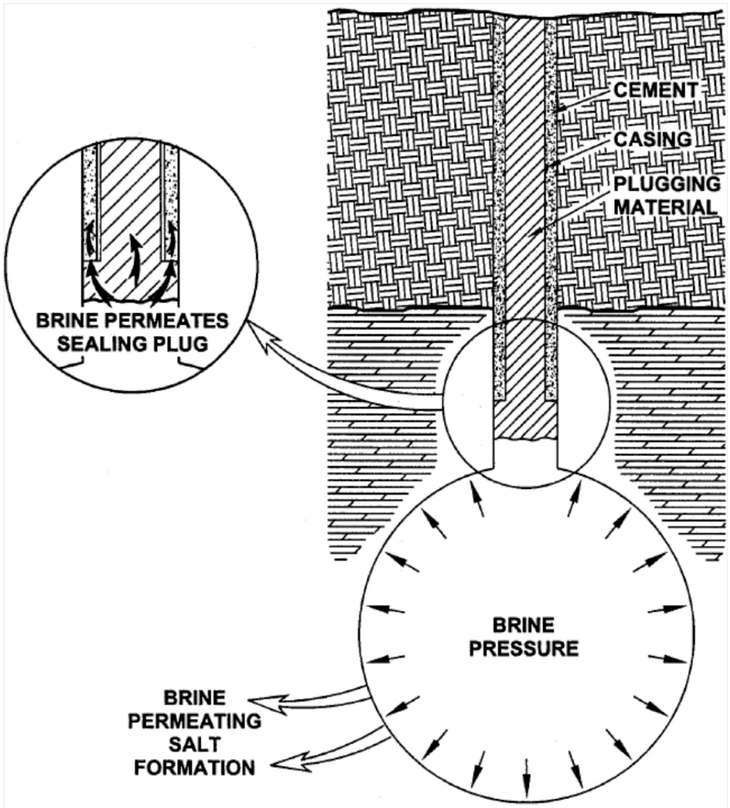
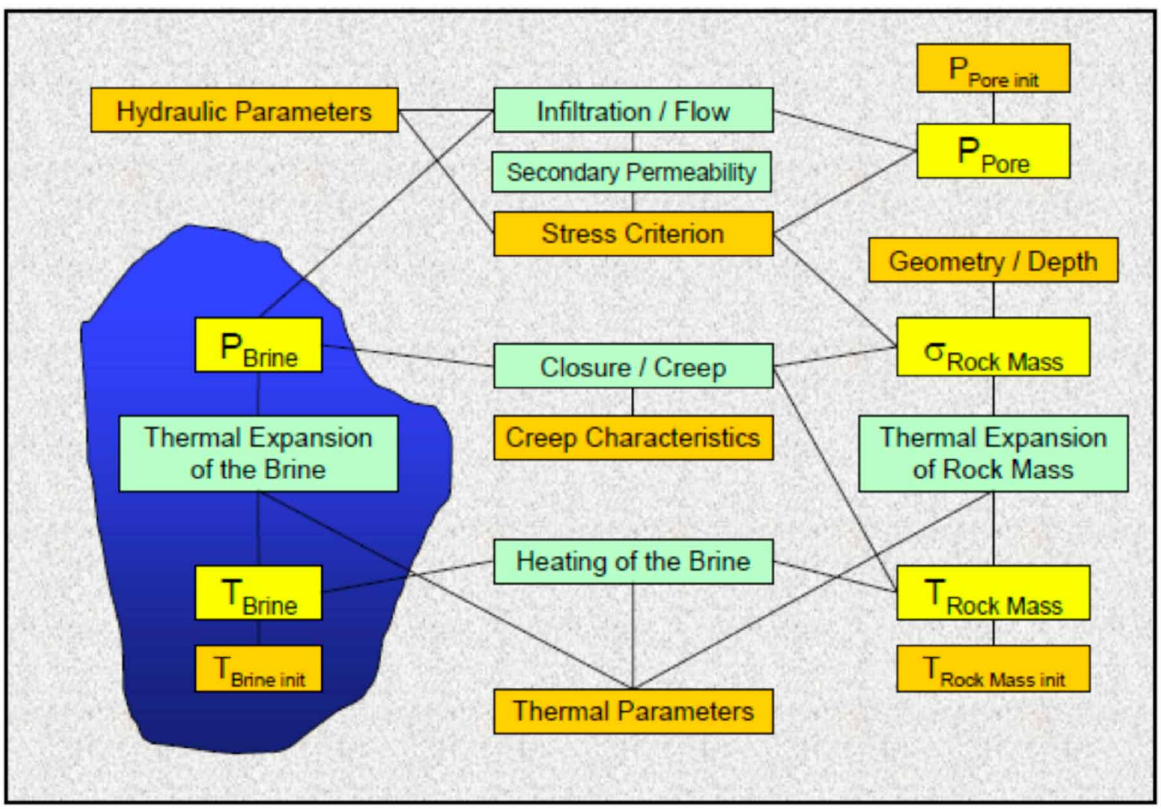


FIGURE 6. Schematic illustration of a sealed cavern in a salt formation.

FIGURE 7. Project flowchart for one SMRI cavern abandonment analysis.

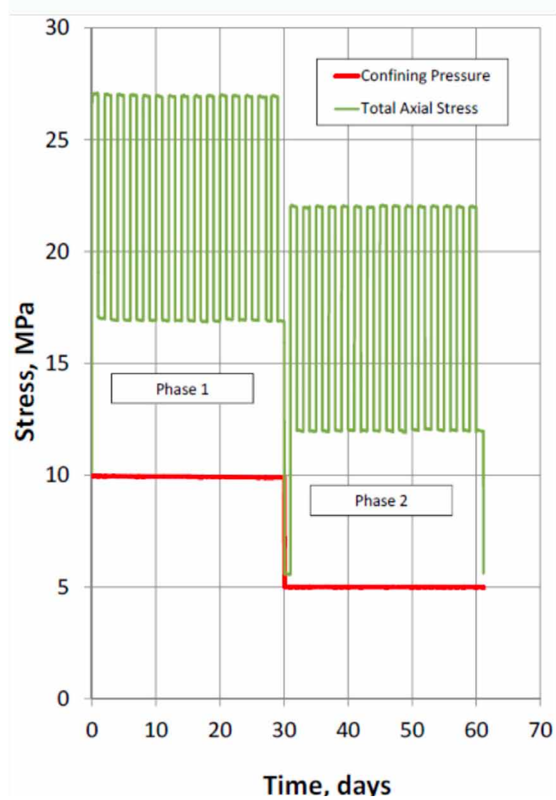


Criteria currently used by the industry for seasonal storage caverns. Due to the relatively more "aggressive" pressure scenarios, these adjustments need to consider: salt material fatigue; reduced average cavern pressure; thermally induced stresses; reduced transient creep periods; and specific field monitoring.

Consequently, the SMRI has initiated a step-by-step, multi-project research program focused on:

1. A preliminary study for a detailed definition of the research needs of the industry in the field of High Frequency Cycling of Salt Storage Caverns (HFCSSC).
2. Laboratory work and numerical computations performed on domal and bedded salt specimens to research rock salt fatigue behavior under representative operating conditions.
3. Laboratory work and numerical computations performed to research thermally-induced mechanical effects in *in situ* rock salt under representative operating conditions.
4. Development of adjustments, if applicable, to existing rock salt 'Constitutive Behaviour Laws', or proposal of new models, for *in situ* salt material under representative operating conditions.
5. Development of adjustments, if applicable, to existing cavern Mechanical Stability Design Criteria, or proposal of new criteria for *in situ* salt material under representative operating conditions.
6. Guidance on practical, effective measures for monitoring the mechanical stability of salt storage caverns under representative operating conditions.

FIGURE 8. Load path followed in one of SMRI's salt core cyclic loading tests.



Step 1 defined the following steps of the program. Step two is still active with the performance of both compressional and extensional cyclic loading tests on cylindrical specimens of domal salt. The tests were performed at a single temperature of 30°C, and replicate tests were performed by two different laboratories using similar test protocols but different test systems.

The most significant observations at this point in the research program is essentially that cyclic loading at non-dilational stress states are similar to static tests, and behavior predicted by an existing constitutive model for creep leads to the conclusion that cyclic loading is not significantly more hazardous than static loading.

FIGURE 9. SMRI obtained blow-out data from cavern MB#1, Moss Bluff, TX for research.

(3) Analysis of Moss Bluff, Texas, Cavern MB#1 Blow-out Data

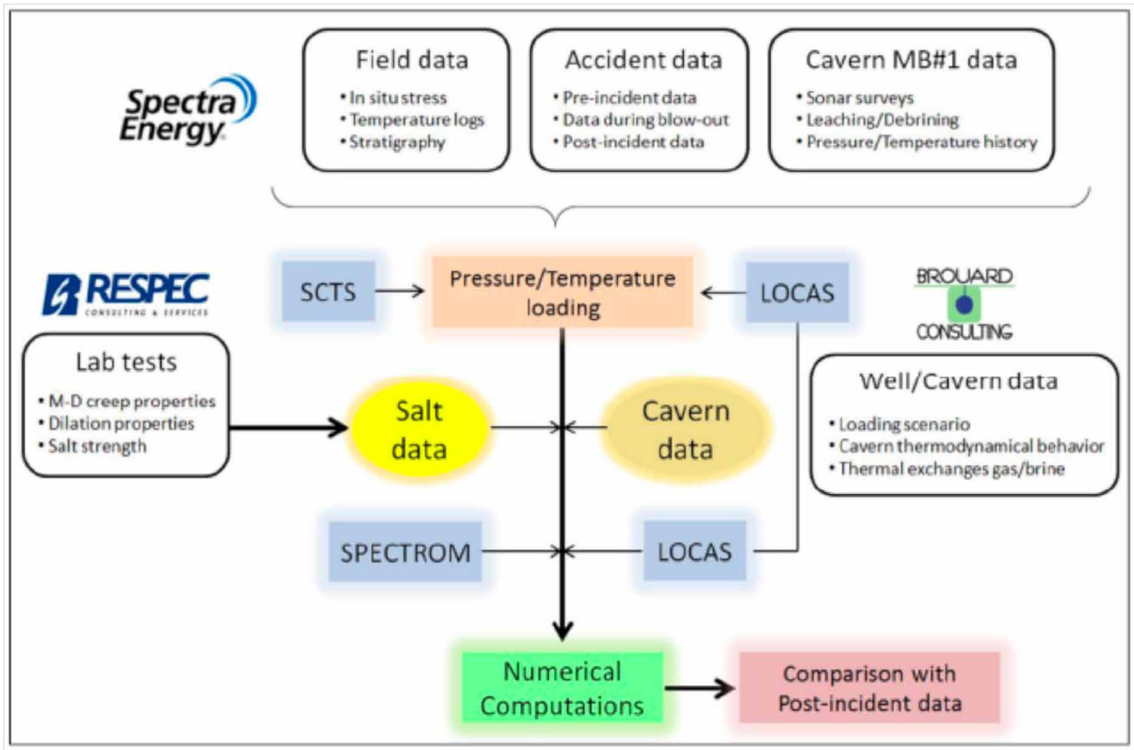
In August 2004, Cavern MB#1 at the Moss Bluff, Texas, natural gas storage facility, holding about 6 Bcf of gas under about 2000 psi well head pressure (WHP), was operating in de-brining mode. Suddenly gas was released through the de-brining string, and the wellhead assembly rapidly separated from the casings, allowing full flow from the 20-inch casing and the resulting fire shown in Figure 9. Five days later the fire self-extinguished after the cavern's gas was exhausted and WHP pressure was 0 psig. Cavern re-brining to stabilize the cavern began less than a month later, a nitrogen mechanical integrity test (MIT) was successfully performed about nine months later, and less than a year from start of the incident Moss Bluff Cavern #1 was restored to natural gas storage operation.

SMRI members recognized a unique opportunity for research on a gas storage cavern having encountered extreme cavern decompression conditions. Pre- and post-incident data were made available to SMRI for research by Spectra Energy, the facility operator that had acquired the site after the incident. SMRI funded a research project for the performance of studies addressing the following:

1. Use of the available pre-incident data to evaluate the pressure (P(t)) and temperature (T(t)) evolutions during the depressurization, then calculate/describe the depressurization scenario and provide the theoretical background applied,
2. Use the obtained P(t) and T(t) in thermo-mechanical computations to evaluate the geomechanical consequences in Cavern MB #1; confirm the results with available post-incident data,
3. Assess the reliability/performance of the industry's available tools/models to predict the consequences of such a gas depressurization scenario.

The principal results of this research effort were: (1) currently available software needs revision to complete simulations of a gas cavern blow-out and cavern wall response details subsequent to a gas cavern blow-out; (2) available pre- and post-blow-out data are unfortunately often insufficient for researchers to satisfactorily analyse blow-out incidents; (3) the importance of a choked-flow approach for the simulation of blow-out gas flow at the well-

FIGURE 10. Project flowchart for SMRI's cavern blow-out analyses research project.



head was demonstrated; (4) the two sets of separate simulations by separate research groups gave coherent results regarding cavern wall tensile and dilation zones and cavern closure rates, but the cavern re-watering leached out most of the potential damage, leaving no data usable as criteria.

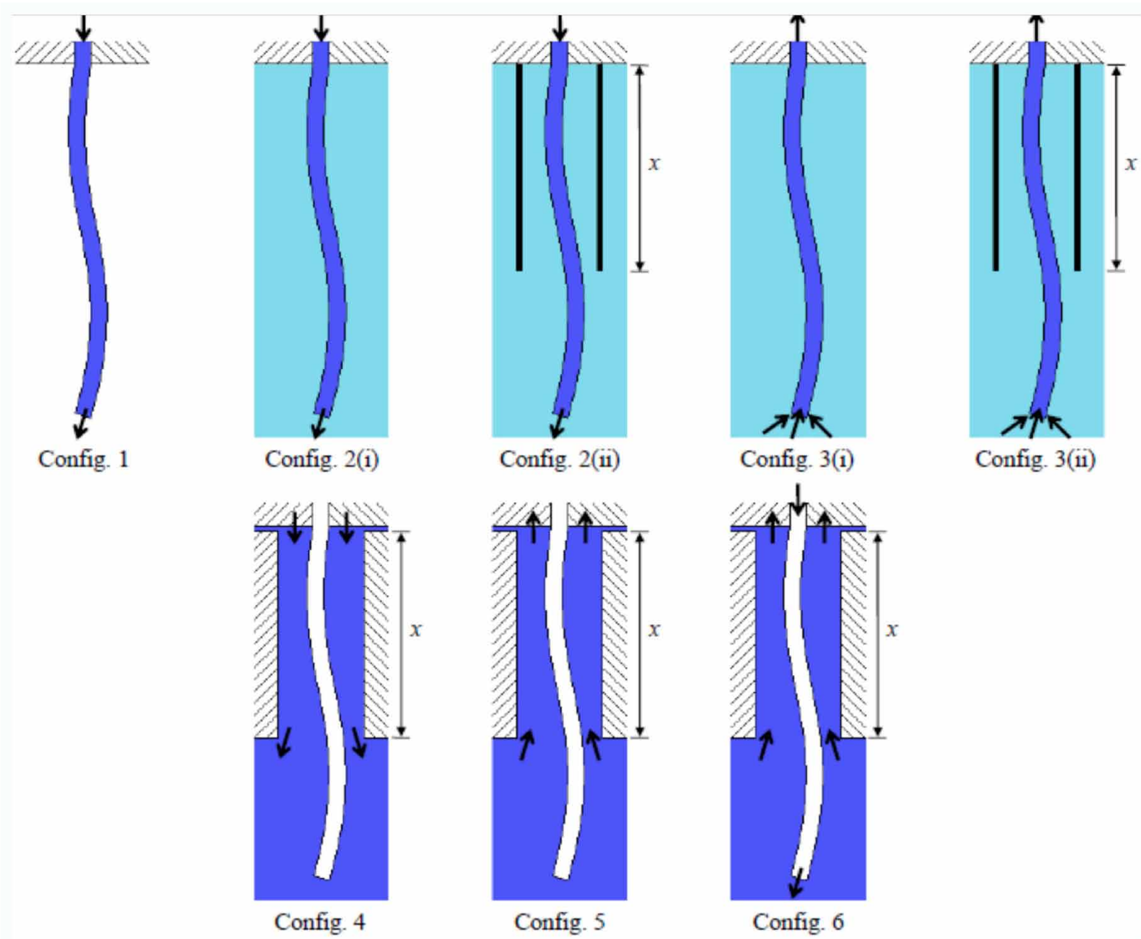
Research Proposal Management

The SMRI welcomes and encourages submittal of unsolicited proposals for research related to solution mining and underground storage in solution-mined caverns. Normally, SMRI's Research Committee prefers having more than one research proposal for a specific research effort, so issues an appropriate Request for Proposals (RFP). SMRI's Research Committee has a well-defined procedure for evaluating and rating research proposals received in response to RFPs. Each proposal is first evaluated by the Research Committee, which sends a recommendation for funding to the Executive Committee. A recommendation is made by the Executive Committee to the SMRI voting members, normally during business meetings, for required vote of project approval by the membership.

(1) Unsolicited Proposal: Flow-induced vibration of pipe or tubing in solution-mined caverns

Occasionally, research projects are approved without going through the RFP process. These projects are considered unsolicited even if SMRI puts a research team together for a specific purposes or opportunities. This research project is such an example. Figure 11 shows various pipe configurations modelled during this active project.

FIGURE 11. Cavern hanging pipe string configurations for SMRI laboratory testing program at McGill.



Fluid injection rates in hanging tubulars (or the annulus between the hanging tubular and the production casing) in solution-mined storage caverns are sometimes limited, without a strong scientific basis, to reduce or avoid flow-induced vibration that may lead to pipe buckling or structural failure. Such failures can have significant financial impacts; a gas cavern dewatering string failure replacement can cost upwards of $1 million (not including lost service). Cavern operators want to avoid hanging tubular failures, but still have an objective to maximize flow rates. A design tool that would allow the operator to determine the maximum allowable flow rate is highly desired. Similarly, new well completion technologies that allow higher maximum flow rates would be welcomed by the cavern storage industry.

Recently, the SMRI approved the complete funding of an unsolicited research proposal on this subject, and is underway at McGill University, Department of Mechanical Engineering, Montreal, Canada. The basic components of this multiyear research effort are:

1. Perform experimental lab and supporting theoretical work, using and developing further the existing knowledge toward gaining new understanding of the dynamics of brine pipe strings in solution-mined caverns.

2. Use the obtained insight for improved design and operation guidelines, with the goal of reducing pipe problems during solution mining, liquid hydrocarbon storage caverns, and natural gas cavern de-watering.

(2) New RFP: Determining a safe distance from salt caverns to a domal salt edge or salt limit.

This is a preview of a new request for research proposals the SMRI will be issuing in 2013.

Over time miners tend to develop the best parts of salt deposits first. As more caverns are developed within the boundaries of a given salt dome, the new caverns are sometimes placed closer to the flanks of the salt dome. The previously described cavern collapse and sinkhole formation in Bayou Corne, Louisiana, has highlighted the need to further examine the design and operation of these caverns located in close proximity to domal boundaries, and the need to better define and monitor the relationship between the cavern limits and the salt limits or dome flank. SMRI concurs that our industry must pursue efforts (1) to improve the quality of current mechanical stability assessments for salt caverns positioned near the edge of salt domes and to better define what criteria determine a safe distance between a salt cavern and the edge of a salt dome, and (2) to identify what methods are available for imaging and mapping the distance from the cavern boundaries to the edge of a salt dome, and what are the corresponding limits of accuracy for those methods. Thus, the potential maximum capacity of a cavern field could be more accurately assessed.

The SMRI Research Committee recognizes that this new project will require integrated research efforts in several fields to achieve the objectives of identification/development of adequate combined exploration techniques to define reliably salt dome geometry and boundaries, including improved characterization of the sediments surrounding the salt dome to allow better assessment of potential impact on cavern stability. There may be a need for adapted geomechanical assessment procedures or specialized/customized monitoring schemes, or other aspects such as exploration drilling yet to be considered. SMRI recognizes that this study will require a wide range of competences including geology, geomechanics, geophysics, logging, drilling, seismic measurements, solution mining, among others. Additionally, integration of existing knowledge and practices from different countries must be taken into account. SMRI's proposal evaluation may tend to favor research proposals from international research teams using experts in these related field competences.

(3) Direction of SMRI research: preparing for major energy market changes

The transition from fossil to renewable energies—mainly wind and solar (photovoltaic solar panels, or PV) power—will change the energy source, but electric power will still be the primary energy carrier. Wind and PV based power are weather and season dependent, not predictable or certain, and disconnected from demand. Before a major shift to wind and PV energy can be possible, there must be far more capacity for storing larger amounts of electrical energy via some method. Compressed air energy storage (CAES) is in use and proven using salt caverns, but new wind/PV hydrogen systems may be the logical choices to fill this need, unless tremendous advances in battery or some new technology take place.

We see man-made salt caverns as a key option for storing large amounts of compressed air and hydrogen, so this could be how SMRI and our members will become more involved in meeting world demand for cleaner energy.

In spring of 2013, SMRI released a public request for proposals ***2012-2 Renewable Energy Storage in Salt Caverns*** asking for research proposals in the field of CAES and hydrogen storage. As a result, several very promising proposals were submitted. The technical evaluation process for proposals received is now underway by SMRI's Research Committee, with decisions on funding expected in the near future. SMRI considers RFP 2012-2 to be open-ended, so we are willing to accept proposals at any time. For additional information, use the link to the RFP at http://www.solutionmining.org/index.php?id=22.

6. CHANGES IN ENERGY MARKETS AND SMRI MEMBERS' POTENTIALLY LARGER ROLES

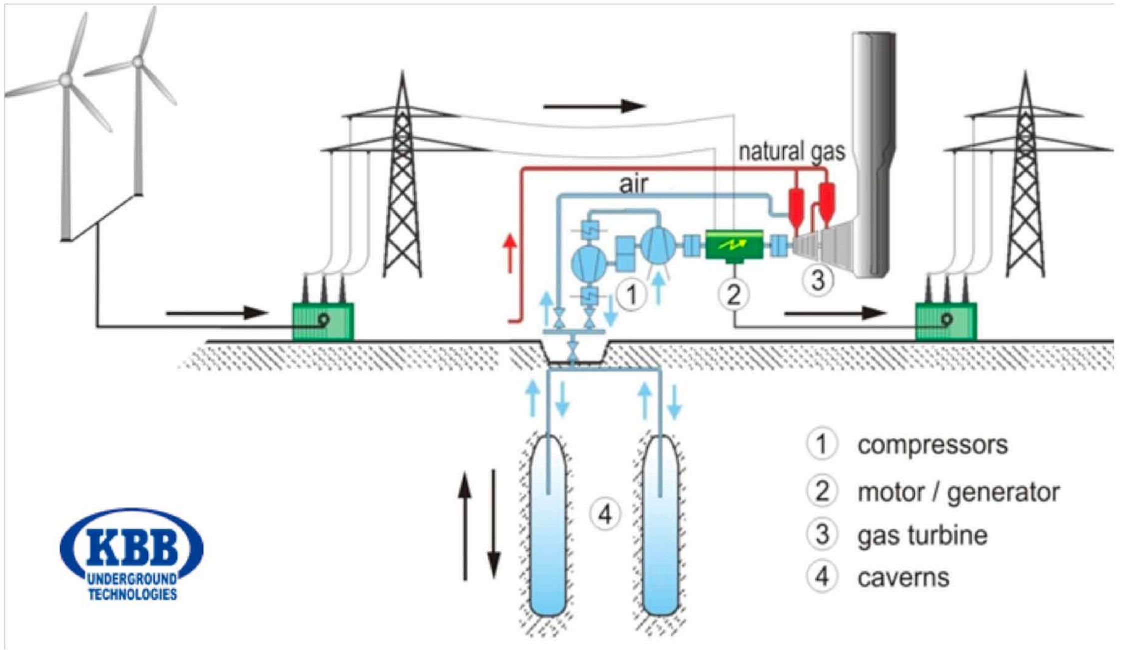
There is a strengthening global consensus that achieving climate protection targets through carbon dioxide reduction means that increasing use must be made of renewable energy sources—primarily wind and solar power. This may prove difficult for emerging economies such as China and India, but the main role must be played by highly industrialized countries such as Germany, France, and the United States.

A transition to wind power and solar energy will have considerable consequences for the energy market involving the following aspects:

- The previous fossil fuels, such as oil and gas, can be easily stored in huge volumes in underground salt caverns for subsequent use to generate electrical power in power plants precisely where and when needed.
- Wind and solar power can produce electrical power only during certain times or conditions. Storing electrical energy is much more difficult than storing oil and gas. As an example, the underground storages for natural gas currently available in Germany cover approximately 42 days of demand (corresponding to 200,000 GWh). The storage capacity for electrical energy on the other hand is less than 1 hour (corresponding to 0.04 GWh)! This mismatch highlights the enormous future demand for electrical energy storage.
- Storage of electrical energy at a large scale requires conversion to a different form of energy which can be stored more easily. The main storage technologies available for this purpose are pumped hydro power, compressed air energy storage (CAES), and wind-hydrogen storage systems.
- Today, road traffic depends almost exclusively on fuel in the form of liquid hydrocarbons gasoline and diesel fuel, but more motorized vehicles in the future will be powered by electrical energy in the form of battery or fuel cell vehicles.

Because the possibility of constructing new pumped hydro power plants around the world is limited, many energy experts agree that the storage of fluctuating renewable energies at an industrial scale would primarily involve large-scale underground storage in the form of CAES for shorter time periods, and for longer time periods in the form of wind or PV hydrogen systems. In the case of diabatic compressed air storage, excess power is used to inject compressed air into a cavern via a compressor (see Figure 12). The compressed air is stored in the cavern until a later point in time when electricity is required—the compressed air is then released to drive a turbine used to generate power. For the hydrogen option (see Figure 13), excess electricity is used to generate hydrogen by electrolysis—and the hydrogen may be stored in caverns.

FIGURE 12. Diabatic CAES CT power plant.



For various reasons, salt caverns are the most suitable option for the storage of compressed air and hydrogen. Salt caverns can withstand the associated flexible injection and withdrawal operations. Unlike rock in pore storages, (depleted reservoirs,) salt does not react with oxygen or hydrogen, and has already proven its tightness and integrity with respect to hydrogen in industrial practice.

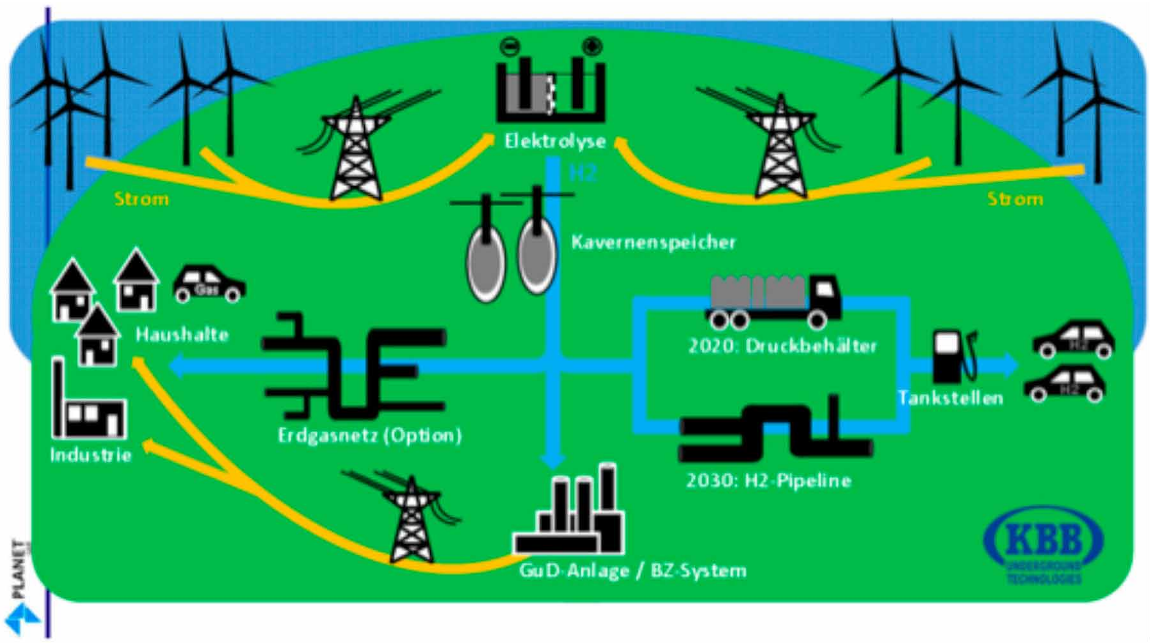
In recent years, intensive development work has been undertaken in Europe on so-called *adiabatic* CAES. Whereas in conventional *diabatic* CAES plants the heat generated when compressing the air is removed by coolers to the atmosphere, the heat is stored in the case of adiabatic CAES plants. Later, when power is required, the compressed air is then warmed up again using the stored heat before being fed into an expander/generator unit to generate electricity again. The advantages are no need for fossil fuel for heating the compressed air before entering the expansion turbine and a much higher efficiency.

A very recent development in Europe is the *power-to-gas concept.* This concerns the conversion of excess wind or PV power into hydrogen generated by electrolysis ("green" hydrogen). Hydrogen has a volumetric energy density exceeding that of compressed air by two orders of magnitude. Hydrogen is what makes it possible to store the huge volumes of energy required for the energy U-turn. Implementing this technology will mean that wind power or photovoltaic plants will no longer have to be switched off when production exceeds power demand for longer periods of time.

Hydrogen is imminently suitable for storage in salt caverns, as already demonstrated by several installations in the UK and the USA. Green hydrogen can be used in several ways:

- Direct use in the chemical industry for the operation of future fuel cell vehicles and the generation of electrical power in gas power plants

FIGURE 13. Wind/PV hydrogen scheme.



- Mixing the hydrogen with natural gas. This makes it possible to harness the enormous transport and storage resources incorporated in the natural gas infrastructure in the form of pipeline systems and underground storages. Research work is currently concentrating on how much hydrogen can be tolerated in the natural gas by the infrastructure components and even more by the various users.
- Methanation: because the amount of hydrogen that can be added directly to the natural gas system will probably be very limited in the long term, research is currently being carried out on the synthesis of green hydrogen with carbon dioxide to create "green" methane. This work is being undertaken in research labs and in demonstration projects. This technology has been around for many years in the form of the Sabatier process. The production of green methane will enable the existing natural gas infrastructure to be utilized without any restrictions.

An aspect shared by all of these three options is that hydrogen production is weather-dependent and thus completely unpredictable, meaning that these applications require the provision of reliable and essentially continuous volumes. This is where the cavern industry may fit nicely to provide the necessary storage capacities.

CONCLUSIONS

Solution mining and use of the resulting salt caverns for storage is a proven technology and a very effective way to use our limited natural resources. Whether salt deposits (and potential new storage caverns) are situated where they can benefit pipeline collection and distribution networks to support flexibility to serve the growing shale gas development regions remains to be seem. With the increased pressure to develop greener energy sources, and the requirements of greatly increased energy storage capacity to develop wind and solar power, we may see salt caverns playing a more significant role, beginning in Europe.