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Research Report RR2011-02

Synthesis of SMRI-sponsored shallow cavern Abandonment Tests

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1 Executive summary

During the period 1998-2009 the Solution Mining Research Institute (SMRI) has sponsored three abandonment field tests in shallow brine-filled caverns. The test caverns involved are Etrez Ez53, Carresse SPR2 and Stassfurt S101 and S102. The volumes of these caverns vary between 7500 m^3 and 13300 m^3. In 2009 SMRI recognized that enough evidence had been gathered for preparing a synthesis of these in-situ field tests in shallow caverns. Therefore, SMRI has issued Request for Proposal RFP 2009-1: Synthesis of SMRI sponsored shallow cavern abandonment tests. In this synthesis a cavern is called 'shallow', if its bottom is situated at a depth of less than 1000 m.

The shallow cavern field tests consisted of building cavern pressure to different levels and observing pressure development in time. In the 1990's SMRI already initiated a multi-project research program focusing on issues associated with cavern sealing and abandonment (CS&A). From those SMRI funded research efforts it had become evident that pressure evolution in a sealed cavern is influenced by five clearly identified processes, such as 1) salt creep, 2) brine thermal expansion, 3) brine micro-permeation, 4) brine leaks through the casing shoe or plugged casing and 5) extra salt dissolution. The five processes result in cavern volume or brine volume changes, which are related to brine pressure changes through cavern compressibility. This concept of five prime factors governing brine pressure evolution is supported and verified by the results from the shallow cavern field tests.

Additionally, some other (SMRI) publications have been reviewed on non-SMRI financed field experiences (Carresse SPR3, Bernburg and Stade-Süd) that could add wider understanding to the sealing and abandonment of shallow caverns.

The following **main conclusions** are drawn from the SMRI-financed tests and the additionally reviewed relevant publications:

1. The three SMRI-financed field tests in shallow caverns show that, if cavern thermal equilibrium is (almost) reached, the long-term brine equilibrium pressure in the shallow caverns is well below lithostatic (=geostatic) pressure. More evidence for this conclusion is found in additional tests, such as the Carresse SPR3 creep test and the Bernburg shallow cavern pressure build-up test.
2. The enclosed brine will slowly and gradually escape from the shallow caverns. For the small shallow caverns investigated, the calculated brine permeation varies between 0.6 and 1.4 m^3 per year. In the case of Stade-Süd larger shallow caverns have been abandoned, where also a brine permeation rate of some m^3/yr has been calculated, resulting in a brine penetration front reaching 10 m above cavern roof after 100 years.
3. The three SMRI-financed field tests have been executed in shallow small-volume caverns under laboratory-like conditions. Under these circumstances the validity of the SMRI concept of five factors governing pressure build-up has been shown. Furthermore, the results from the additionally reviewed tests in shallow caverns of Carresse and Bernburg are evidently supportive to the SMRI CS&A concept.
4. After any rapid cavern pressure build-up several transient phenomena are triggered. In that case application of (sophisticated) numerical models is needed to separately determine the effects of transient salt creep, brine permeation and additional salt dissolution on cavern pressure, because these are coupled processes.
5. Semi-analytical or 2D/3D-FEM numerical models are needed for predicting the combined long-term effects of salt creep, brine permeation and brine thermal expansion on cavern pressure development. In case of (almost) thermal equilibrium a

conventional rock mechanical evaluation, applying well-known creep laws (Norton-Hoff, LUBBY2) and Darcy's flow law, is adequate enough. This type of modeling provides the long-term safety assessment normally required by mining authorities before granting permission for permanent cavern abandonment (Stade-Süd case, where also surface subsidence prediction and monitoring were obligatory).

In case of shallow cavern sealing and abandonment the following **recommendations** are relevant. The recommendations 1 to 4 are directly based on the results from the SMRI sponsored field tests. Recommendation 6 is given for the sake of completeness and might be relevant in exceptional cases only. It is based on the author's experience on abandoning shallow caverns in thinly bedded salts in The Netherlands. It should, furthermore, be noted that recommendation 6 does not apply to the many caverns dealt with in this report. Recommendation 7 is based on the author's general experience on official applications to mining authorities for definitely abandoning brine-filled caverns in the Netherlands, Germany and France:

1. Before permanently sealing a (shallow) cavern, an abandonment test should be performed. The test should consist of a sufficiently long observation period, during which one must try to assess separately the four processes (process 5: additional salt dissolution can be disregarded as it is a transient phenomenon) that govern long-term cavern pressure build-up. If more than one cavern at a cavern site has to be permanently abandoned, it should be checked whether the abandonment test results can be generalized.
2. During any cavern abandonment test a brine leak detection system should be installed in order to distinguish between brine migration into the salt rock and brine leaks through the casing shoe and wellbore.
3. If a shallow brine-filled cavern is at thermal equilibrium with the surrounding rock, the cavern can, in principal, be sealed and safely abandoned without delay. The tightness of the well must be proven; leaks through the casing and casing shoe have to be excluded. Furthermore, pay attention to the author's recommendations 6 and 7. This might imply that conventional numerical modeling is still needed to determine the long-term effects of salt creep and brine permeation on cavern pressure. Usually, before granting permission for permanent cavern abandonment mining authorities require this type of modeling with respect to a long-term safety assessment.
4. If thermal equilibrium is not yet reached, wait before sealing the cavern until the gap ΔT (°C) between brine temperature and formation temperature is smaller than $\beta/\alpha.(P_{litho}- P_{brine}) \sim 0.01$ H, where: β/α is close to 1 ^{0}C/MPa, P_{litho} = lithostatic pressure (MPa) at depth H, P_{brine}= halmostatic pressure (MPa) at depth H, and H= casing shoe depth (m TV). The ratio β/α should be assessed for each specific cavern site. The temperature increase rate must be measured or computed. If after an observation period the gap ΔT is small enough, inject some extra brine in the cavern to obtain a brine pressure slightly higher than the anticipated/ calculated equilibrium pressure and seal the cavern. If the pressure rate is negative after some months, or less positive than expected from brine thermal expansion alone, and if the tightness of the well (casing and casing shoe) has been proven, the cavern can be safely abandoned without any risk for macro fractures or sudden, significant brine release into the salt roof and the overburden. In the case of large caverns the observation period after the extra brine injection, which causes a rapid cavern pressure increase, should preferably last about half a year. This longer time period is needed to ensure that transient phenomena, such as transient creep and additional salt dissolution that both cause a pressure decrease, have fainted away sufficiently and do not obscure the long-term pressure rate.

5. The SMRI Guidelines Manual (Research Project Report 2006-3) 'Cavern Well Abandonment Techniques' represents a sound basis upon which companies should develop their own CS&A procedure for specific caverns, including a rock mechanical long-term stability analysis and surface monitoring.
6. Exceptionally, thus irrelevant for the many caverns reviewed in this report, a shallow cavern situated in thinly bedded salts and having a wide roof span with only a thin or absent salt roof layer starts (after an unknown period of time) migrating upward. This type of migration is the result of progressive roof deterioration mainly caused by rock mechanical overload and by brine affecting the overburden rock. This migration process may eventually cause a subsidence trough or even a sinkhole at surface. This process could form a threat to public safety or contaminate drinkable-water producing sand(stone) layers above the cavern. Thus, in case of doubt on the long-term rock mechanical stability of the cavern roof, an inventory of the migrating potential of the cavern and related potential threats to the environment and third-party interests should be made before definitely sealing off the wellbore and abandoning the cavern. As long as the cavern is accessible effective mitigating measures can be taken such as filling the cavern with solid materials.
7. Mining authorities often require an answer to the following question before they decide to grant permission for permanent brine-filled cavern abandonment: 'which brine volumes will eventually migrate where and at which times from the rock salt into water/brine bearing aquifers'? Related to this question is the need for a detailed geological analysis to show the presence of containment and confinement horizons in the overburden that prohibit aquifer contamination by expelled cavern brine. It is recommended that efforts of the **SMRI research** should now focus on these aspects of brine migration and containment, and on the development of a general methodology to tackle this question.

2 Introduction

The Solution Mining Research Institute (SMRI) has long recognized the complex issues associated with the high pressures that may develop in sealed and abandoned brine-filled caverns in salt. In the 1990's SMRI initiated and sponsored a multi-project research program for cavern sealing and abandonment (CS&A). The principal objectives of the CS&A program are to enhance the understanding of the prevailing factors in the sealing and abandonment of brine-filled salt caverns, and to develop guidelines for a safe and publicly acceptable sealing and abandonment of these caverns. A potential long-term hazard in CS&A is the possible migration of cavern brine into the overlying formations, especially to potable water-bearing strata.

The evolution of cavern brine pressure after the well is plugged has been widely investigated and discussed with contributions from many SMRI members. From these SMRI funded research efforts it has become evident that pressure evolution in a sealed cavern is influenced by five clearly identified processes, such as 1) salt creep, 2) brine thermal expansion, 3) brine micro-permeation, 4) brine leaks through the casing shoe or plugged casing and 5) extra salt dissolution. The five processes result in cavern volume or brine volume changes, which are related to brine pressure changes through cavern compressibility.

During the Spring 2008 SMRI Business Meeting the need was expressed for a position paper summarizing the principal findings and recommendations of the ongoing CS&A program. Meanwhile, SMRI-sponsored abandonment tests on shallow caverns were completed on the sites of Etrez, Carresse and Stassfurt. In 2009 SMRI recognized that enough evidence had