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Abstract

Salt cavern leaching is a critical process in the development of underground storage facilities for natural gas. The process involves the injection of water into salt formations, which dissolves the salt and creates cavities or caverns. These caverns are then used for gas storage. The simulation of this process requires accurate modeling of fluid flow and salt dissolution dynamics. This study employs Cartesian grids for discretizing the domain and simulates the leaching process through multiple wells.

The simulation of complex processes is a critical tool for effective planning and monitoring. In intricate operations such as solution mining, simulations provide valuable insights into the effects of various geological, physical, and chemical parameters on outcomes. For the specific case of salt cavern leaching, two well-established software programs are commonly employed. These programs, however, are based on radial symmetry for their simulation grids, limiting their capability to simulate caverns with multiple wells. Additionally, integrating results from geological modeling tools into these programs is not straightforward.

This article outlines the fundamental principles of salt cavern leaching and introduces a newly developed simulation program designed to address these limitations. This program enables the simulation of leaching processes involving multiple wells and facilitates the incorporation of geological models. It builds upon methodologies derived from software used in the oil and gas industry for simulating fluid flow in complex reservoirs. The article also presents examples, including a history-matching case for cavern leaching, as well as scenarios involving heterogeneous geology and leaching operations with two and three wells.

Key words: leaching simulation, salt caverns, gas storage

Introduction

The first simulation program was developed by HIEBLINGER and KLEINITZ [6,7] in the early 1970's. In the 1980's the program SALGAS was developed by Thomas Eyermann and improved by SMRI [8].

There is mainly the software WinUBRO® being used for the simulation of the solution mining process. The WinUBRO software is widely spread in the salt cavern leaching industry and was developed by the Polish solution mining company CHEMKOP [2]. Other programs include PCL 5 from UGS [10], or alternatively, CFD applications such as COMSOL Multiphysics, as proposed by LING et al. [11], can be used for the leaching of horizontally oriented caverns.

These programs utilize a radial symmetry coordinate system for the simulation grid, which is effective for describing near-wellbore conditions but becomes increasingly inaccurate as the radius expands. However, accurately modeling solution mining processes often requires capturing variations in the geological, physical, and chemical properties of the salt body. For instance, heterogeneities such as layers with differing dissolution behaviors e.g., highly soluble evaporites or zones with significant insoluble content, can significantly influence the leaching process.

To address these complexities, it is advantageous to incorporate Cartesian grids from geological models or introduce geological features with distinct physical and chemical properties. Moreover, the radial coordinate system inherently limits the simulation of solution mining involving multiple wells, as it requires the well to be positioned at the center of the grid. This constraint makes it challenging to model scenarios with multiple wells accurately.

Program Development

To use Cartesian grids or even corner point grids and to simulate more than one well for leaching or complex geological situations, an existing program for simulation of gas storage was extended to the simulation of the leaching process LITTMANN [4,5]. Corner-point grids are grids in a Cartesian co-ordinate system, where the grid blocks are not regular cubes but follow geological features like faults, layers or anticlines.

The simulation utilizes a regular Cartesian grid, which is a common approach in reservoir simulation models. The grid is designed to represent the physical space of the salt formation, with each grid cell corresponding to a small volume of the reservoir. The Cartesian grid provides a structured and efficient way to solve the governing equations of fluid flow or heat transfer.

Multiple wells are modeled within the grid, representing the injection and production wells used in the leaching process. These wells are strategically placed to optimize the dissolution process and cavern development. The leaching process is simulated by injecting water into the salt formation, which dissolves the salt and creates cavities. The simulation tracks the evolution of the cavern geometry and the distribution of salt and water throughout the reservoir.

The input to the simulation is provided in a keyword-based format, similar to other black oil simulators. The parameters defining the reservoir properties, well configurations, and fluid properties are specified using keywords. These parameters include the dissolution rate of the salt formation, the injection rate of water, and the properties of the fluids involved in the leaching process.

The output of the simulation includes both printed summaries of key results, such as the volume of salt dissolved and the size of the caverns, as well as graphical representations of the cavern development over time. The results are generated in Eclipse binary format, which can be processed using Eclipse Office or exported to Excel for further analysis. Graphical plots and 3D visualizations are generated to illustrate the evolution of the cavern-geometry and the distribution of fluids within the reservoir.

Leaching Fundamentals

The leaching process is described by the dissolution rate of salt in water. It is given by the mass dissolved from an area of the salt body during a certain time. The dimension is $m/A/\Delta t$, where m is the mass, A the area and Δt the time. If the dissolution rate is related to the density of the mineral, it becomes the dimension of length per time. The units are cm/s or as used here mm/h. The dissolution rate depends on the concentration of the solvent (brine) as shown in *Figure 1*. The dissolution rate decreases linear with the salt concentration. The value at zero salt concentration is measured in laboratory experiments and depends strongly on the physical properties and on the chemical composition of the salts. The value used in *Figure 1* only represents a rough figure for the dissolution rate of almost pure halite.

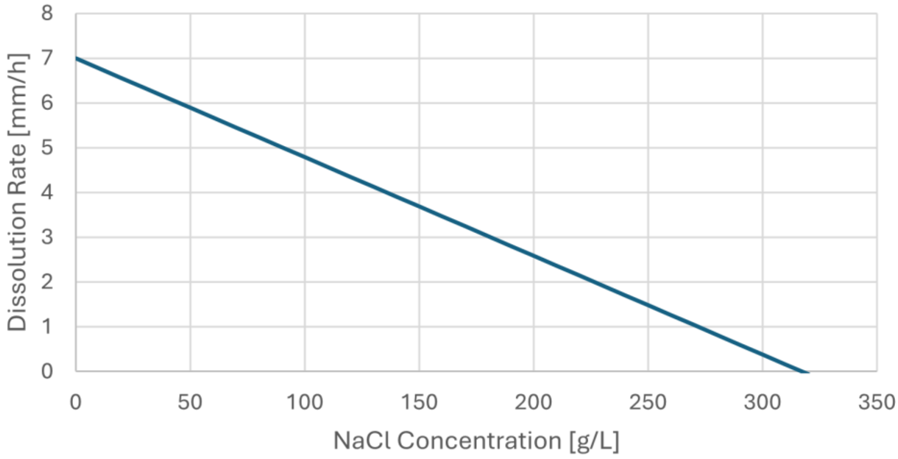

Figure 1: Idealized dependence of dissolution rate of pure halite on NaCl concentration of leaching brine(20 °C, maximum dissolution rate 7 mm/h, saturation 317.1 g/L).

The salt concentration in the leaching brine is governed by the freshwater injection rate and its interaction with the brine produced during the dissolution process. The mixing occurs in the zone located between the blanket and the lower pipe level as shown in *Figure 2*.

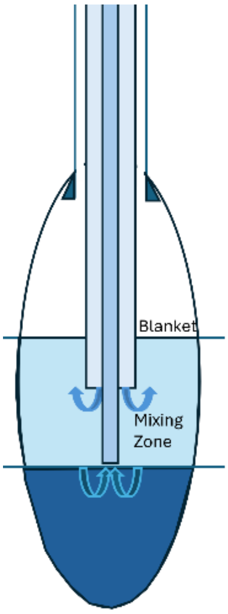

Figure 2: Mixing zone between freshwater and brine in the cavern during leaching (Schematic drawing).

The concept of the mixing zone ensures a homogeneous salt concentration in this part of the cavern, thereby influencing the overall salt dissolution process. However, the salt concentration may vary between the inner portion of the mixing zone and the cavern boundary. This variation is influenced by factors such as the radius of the cavern and the freshwater injection rate. Notably, during the initial stages of leaching, when the mixing volume is relatively small, and the freshwater injection rate is high in proportion to the cavern volume, a correction to the brine concentration becomes necessary.

This effective concentration is given in *Equation 1*

$$c_{eff} = c_{avg} \cdot \left| \frac{1 - {}^{R_0}/_{R}}{1 + {}^{q \cdot t}/_{V}} \right| \qquad \text{Equation 1}$$

where c_{eff} is the effective concentration for leaching, c_{avg} the average brine concentration in the mixing volume according to material balance, R_0 the inner radius or well radius and R the cavern radius, q is the freshwater rate and t the timestep size.

This process yields a concentration profile as depicted in *Figure 3*. The primary factor influencing the effective salt concentration, and consequently the leaching rate, is the distance between the cavern wall and the injection point, rather than the injection rate. The scale for the cavern radius is logarithmic, as illustrated in *Figure 4*. Mixing predominantly occurs in the vicinity of, and between, the inlet and outlet of the injection and the production pipes.

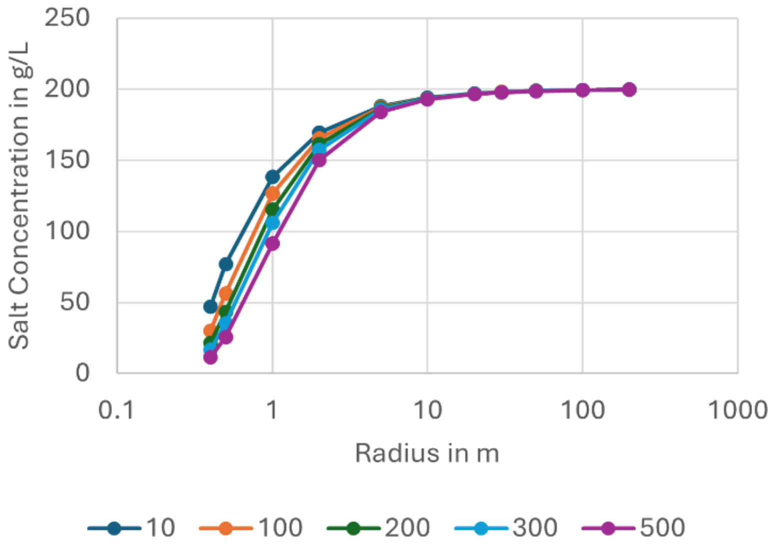

Figure 3: Radial concentration profile in the cavern with an average concentration of 200 g/L. Parameter fresh-water rate in m3/h – Scale for cavern radius is logarithmic.

The exact distribution of the salt concentration can be simulated by solving for the pressure distribution around the leaching strings. However, this approach has not yet been implemented in the current leaching simulation, as the previously described method yields satisfactory results, as demonstrated in the following section. Additionally, the widely utilized WinUBRO simulation program employs a uniform salt concentration during one time step, which has also been shown to produce accurate results.

An example for the simulated salt concentration distribution is given in *Figure 4* [HIEBLINGER, KLEINITZ 1972). It is obvious that there is almost no change in concentration at the cavern wall, where the salt dissolution process occurs. The most mixing is in the middle of the cavern between the injection and production pipe shoes. It is important to note that the cavern radius scale is represented logarithmically to visualize this effect.

Only a vertical concentration gradient due to gravity develops. This concentration gradient is app. 1 g/(L m). The gradient can be passed to the simulation as input parameter.

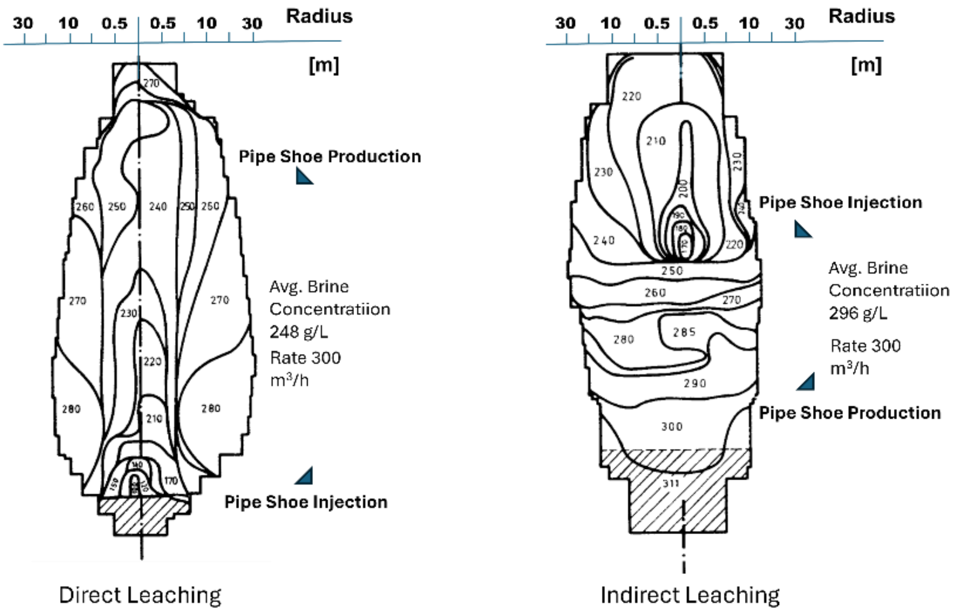

Figure 4: Salt concentration distribution during direct and indirect leaching [6,7] (after HIEBLINGER and KLEINITZ) Note: The scale for the cavern radius is logarithmic.

The dissolution rate also depends on temperature, pH, chemical composition of the salt, mineralogy, impurities etc.

The temperature and temperature gradient may vary depending on the geological situation and the specific location of the salt formation. The dissolution rates are usually measured at the laboratory conditions at 20 °C. These values must be adjusted to account for the temperature conditions within the leaching zone. The temperature and the gradient measured during leaching are not at the initial geological conditions, as there occurs a significant cooling during circulation of cold water. In the simulation program, the temperature within the leaching zone is kept as constant, and any variations are incorporated by adjusting the dissolution rate input accordingly.

The dissolution rates used in the simulations were therefore not constant values and slightly higher than the dissolution rates of pure halite. The dissolution rate of pure halite at 20°C is about 7 mm/h and the values matched in the simulations were in the range of 7 – 10 mm/h, considering higher temperature. The dissolution rate can be specified independently for each grid block, within the option to apply different dissolution rates in each direction. Further details regarding the statistical variation of the dissolution rate are discussed in the following section.

Leaching Grid

For the simulation the salt body is divided into grid blocks as shown in *Figure 5*

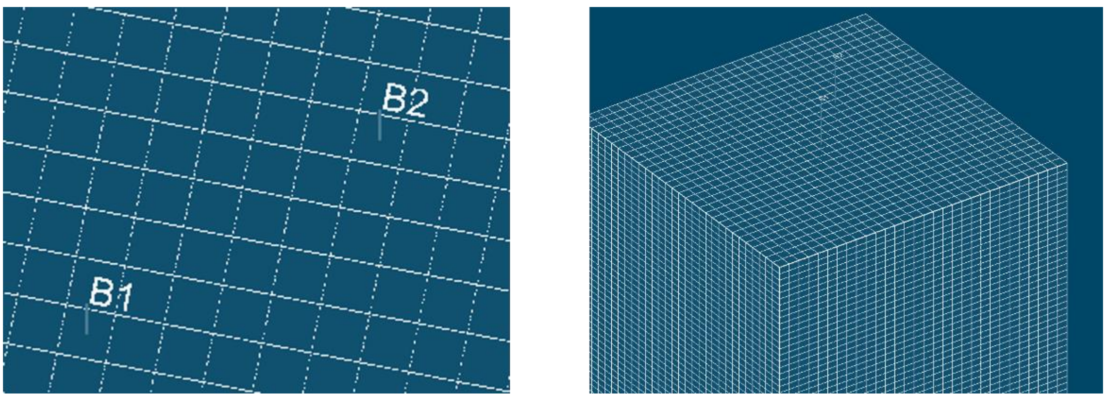

Figure 5: Grid blocks for the leaching simulation with 2 wells.

The amount and size of grid blocks can be chosen according to the simulation requirements. The grid shown in *Figure 5* has 30 blocks in horizontal direction and 200 blocks vertically. The block size is 4 m horizontal and 2.5 m vertical, which is equivalent to the normal vertical resolution of sonar measurements. This results in 180 000 grid blocks, which is a number that can be calculated on normal PCs in a reasonable time of 1 – 2 minutes for about 3 years of leaching.

Calculation Procedure

Within the horizontal grid blocks the distance leached is calculated and stored, so that accuracy of the simulation is sustained and only depends on the size of the time steps. The normal time-step size is 12 hours. In cases where, e.g. the size of the mixing zone is small as compared to the freshwater injection rate, smaller time steps are applied automatically.

In one time step the following calculations are made:

1. *Determine the grid blocks involved in the leaching process.*
    a. *These are the blocks between the blanket level and the lowest pipe level, which have already been leached partially or are adjacent to a fully leached block.*
2. *Calculate additional leached salt mass at current brine concentration.*
    a. *Determine the brine concentration in the block using the overall concentration from a material balance considering the position of the block according to equation 1 and the vertical concentration gradient.*
    b. *Calculate the leached volume according to the leaching rate of this block at the given concentration.*
3. *Calculate a new volume for mixing.*
4. *Calculate a new overall brine concentration.*
5. *Calculate sump level and leached volume.*

The simulation is a simple material balance, spatial variations of brine concentration is based on empirical correlations (Equation 1, Figure 3, 4).

The program code is designed with an object-oriented architecture, enabling the definition of multiple caverns as required. During the leaching process, once caverns merge, common volumes for the sump and mixing zones are systematically calculated.

The accuracy of the simulation is given by the vertical grid block size. Horizontally the leached distance is stored. An inaccuracy is only in the 3D visualization of the caverns, where only whole blocks can be displayed. Efforts are currently underway to implement an alternative visualization method to enhance accuracy.

Leaching Simulation – History Matching

History matching refers to the process of calibrating simulation parameters using empirical data derived from the leaching history of a cavern. The leaching parameters are adjusted in such a manner that the simulated results align with the observed historical data.

To calibrate the leaching parameters, input data for the simulation were derived from the leaching history. These input data primarily include the freshwater rate, followed by leaching parameters such as dissolution rate, brine concentration profile, insoluble content of the salt, and the bulking factor of the insoluble sediments in the sump.

The simulation results were then compared with the free cavern volume, as measured through Sonar Surveys or calculated from the mass of salt produced and the concentration of salt in the produced brine.

A history match for a specific cavern is presented in the figures below.

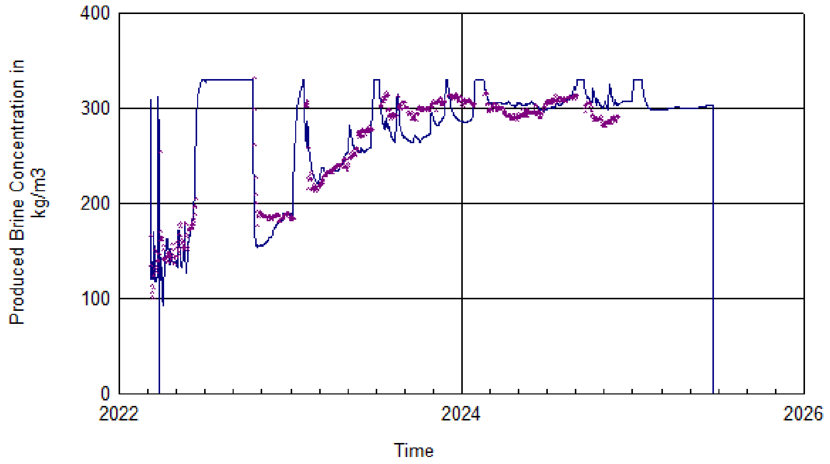

Figure 6: Salt concentration in produced brine (line: Simulation, dots: measured values)

In *Figure 6* the salt concentration as produced in the brine is plotted over the total leaching time and compared with measured values. The salt concentration is lower at the beginning and increases with the growing cavern volume. This development and the brine concentration itself are well matched in the simulation.

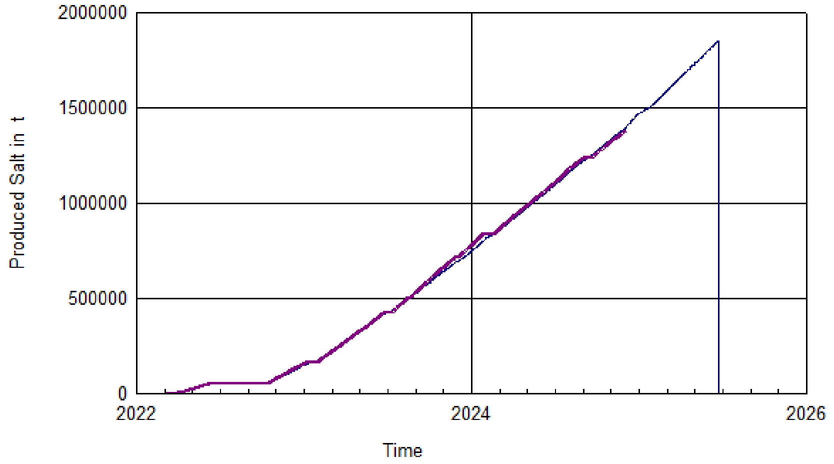

Figure 7: Produced salt mass (line: Simulation, dots: measured values)

Figure 7 shows the cumulative produced salt mass. This is also matched as well as the free cavern volume in *Figure 8*. This Figure also shows the free cavern volume measured in sonar surveys. The free cavern volume is the leached volume minus the sump volume.

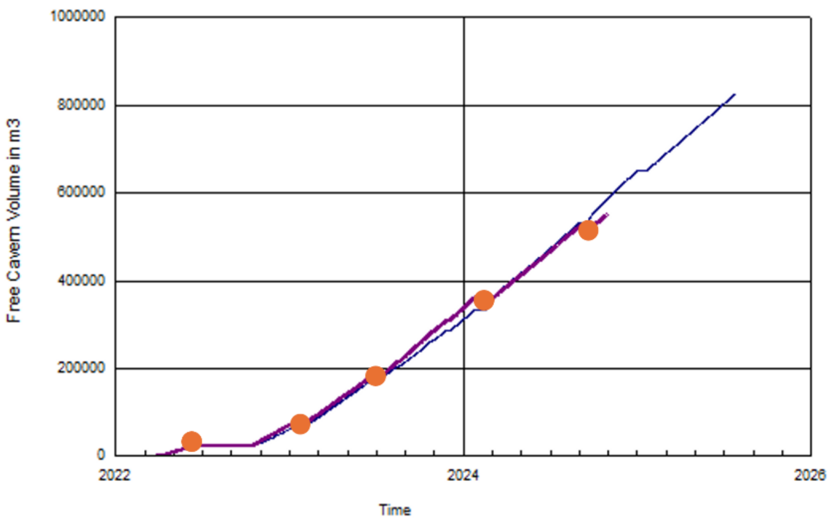

Figure 8: Free cavern volume (line: Simulation, dots: sonar and values analytically calculated from salt production

The shape of the cavern itself is shown in *Figure 9*. This form still shows the grid block contours and it is not smoothed, yet it accurately reflects the overall cavern shape. The different positions of the mixing volume, as well as the position of the leaching strings and the blanket, remain clearly visible.

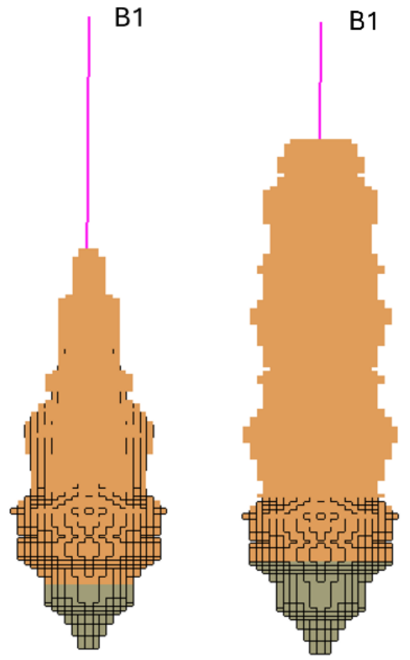

Figure 9: Simulated cavern (after 24 and 36 months) – free volume (yellow) and sump volume (grey)

Simulation of Leaching Caverns Using Two Wells

A standard leaching program was used to simulate a two well problem. In this context, a leaching program refers to a strategic plan detailing the timing and configuration of the leaching strings and the blanket, as well as the required freshwater injection rate to achieve a specific cavern volume and shape.

The freshwater injection occurred in both wells during the direct leaching process at the beginning. This approach continued until the two caverns merged. Subsequently injection was limited to one well, with production occurring from the other, resulting in a slightly asymmetric cavern development, as illustrated in *Figure 10*.

Figure 11 presents an example involving three wells, where all wells were actively engaged in leaching. This configuration resulted in the formation of a nearly spherical cavern, which contributes to enhanced mechanical stability.

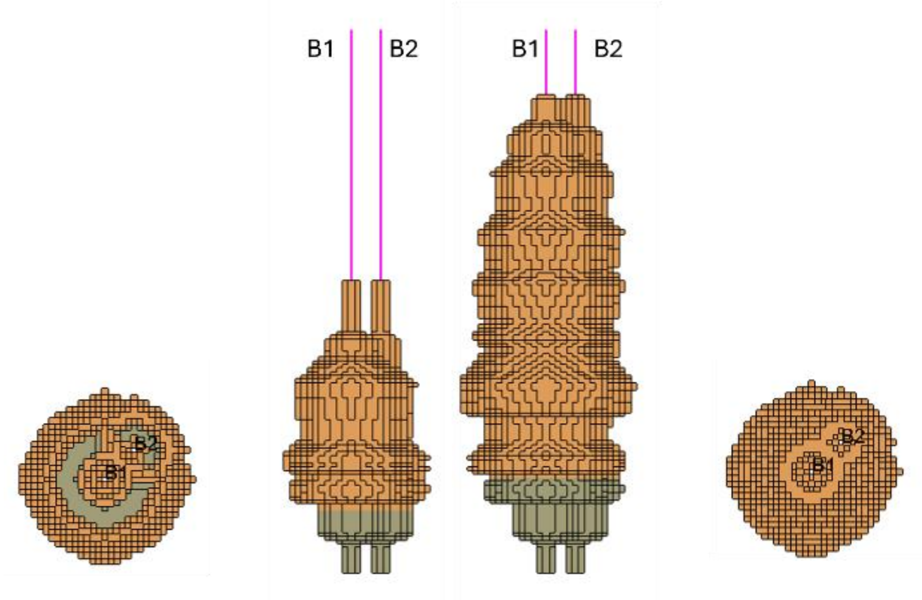

Figure 10: Cavern leached using two wells, B1 and B2.

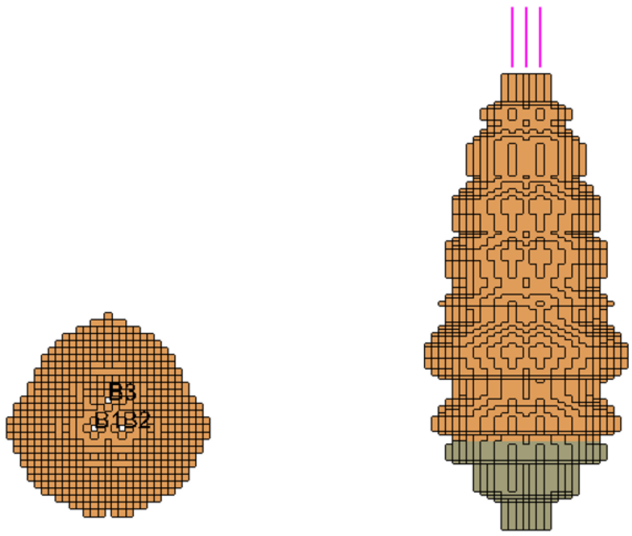

Figure 11: Cavern leaching with 3 wells.

Simulation of Leaching in a heterogeneous salt

Salt deposits are formed as sediments and are typically deposited as horizontal layers, as clearly shown in *Figure 12*. Over geological time periods, the pressure exerted by overburden sediments causes the salt to move upward, resulting in the formation of a salt dome. This process leads to the development of a structure, as depicted in Figure 13, where the originally horizontal salt layers are reoriented into a more vertical position.

Figure 12: Layering of a salt deposit. Evaporites in Zagros, Iran, Photo: Mohammad.Alinia.53/Instagram

Figure 13 represents a cross section through a salt dome, illustrating the positioning of potassium layers. In this cross section the positioning of potassium layers is shown and the mapping in this case is detailed as it was derived from an active salt mine. To get such data from an untouched salt dome is rather difficult, as wells are drilled perpendicular to strata, which does not capture the horizontal variations in the salt properties. These variations can, however, be obtained from wells located away from the salt dome that intersect the unfolded strata of the salt deposit. Such data can be used to construct the model of the folded salt dome. However, the focus of this article is not constructing such a model but rather on exploring the possibilities for simulating such scenarios.

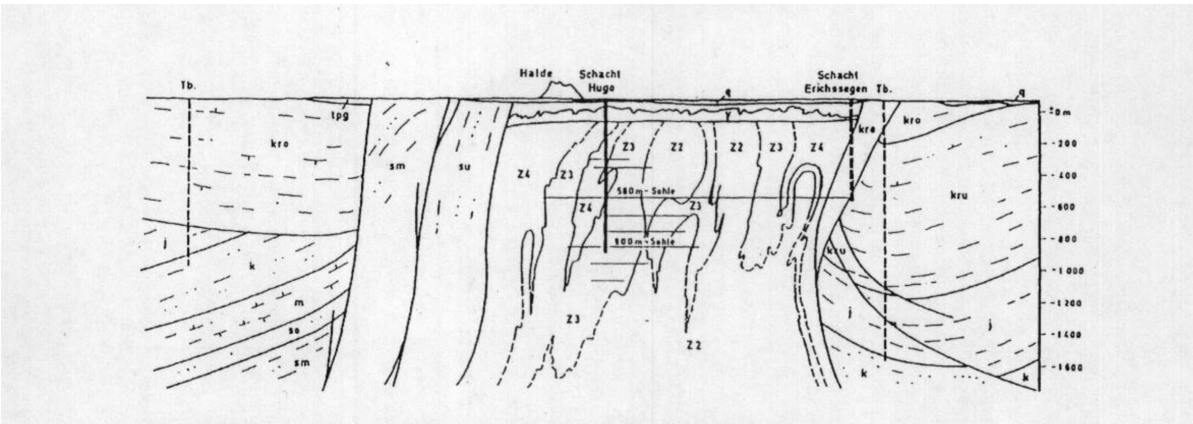

Figure 13: Cross section through a salt dome, showing the almost perpendicular

The dissolution rate of rock salt may vary in a broad range and for many reasons what is shown in *Figure 14*. The specific dissolution rate varies in this example for rock salt samples taken from different wells in a salt dome between 6.4 mm/h and 20.9 mm/h at a temperature of 20 °C.

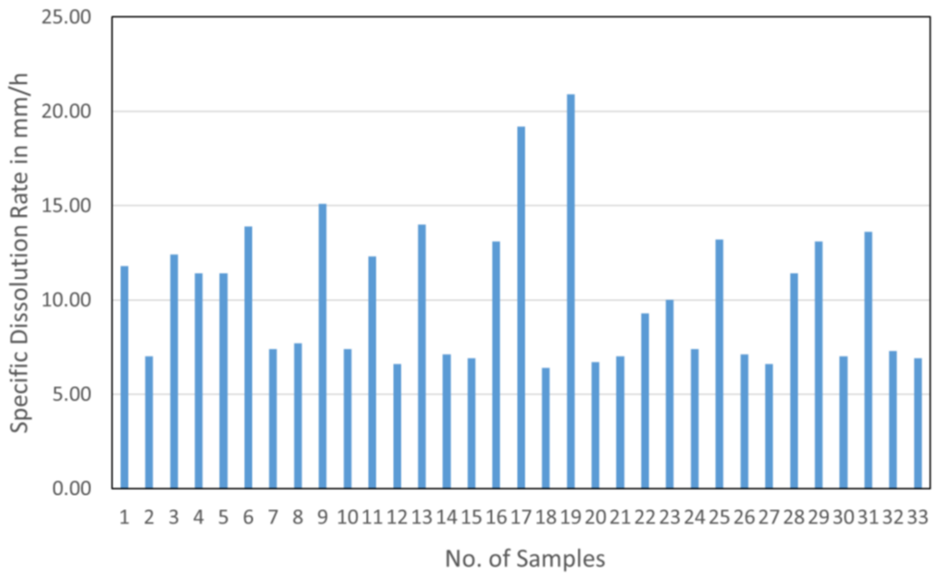

Figure 14: Specific dissolution rates of 33 samples at 20 °C from wells in a salt dome. (Minimum 6.4 mm/h, Maximum 20.9 mm/h, Average 10.26 mm/h. Ratio Max/Min = 3.3)

Two cases were analyzed to examine such a scenario. The first case involves a layer intersecting the well at an angle of 60° . The salt within this layer exhibits a significantly higher dissolution rate compared to the surrounding salt, leading to the formation of an expansive wing in the leached cavern, as shown in *Figure 15*. This figure illustrates the simulation grid, the resulting cavern shape, and the corresponding sonar survey image. A distinct pocket or "wing" develops upward within the cavern. At the bottom, the highly permeable layer remains largely unaffected by leaching due to the higher salt concentration, as reflected in the salt concentration distribution shown in Figure 4.

The concentration gradient was 1 g/L/m and the dissolution rate for the salt 6 mm/h and the high dissolution rate for the layer was 24 mm/h.

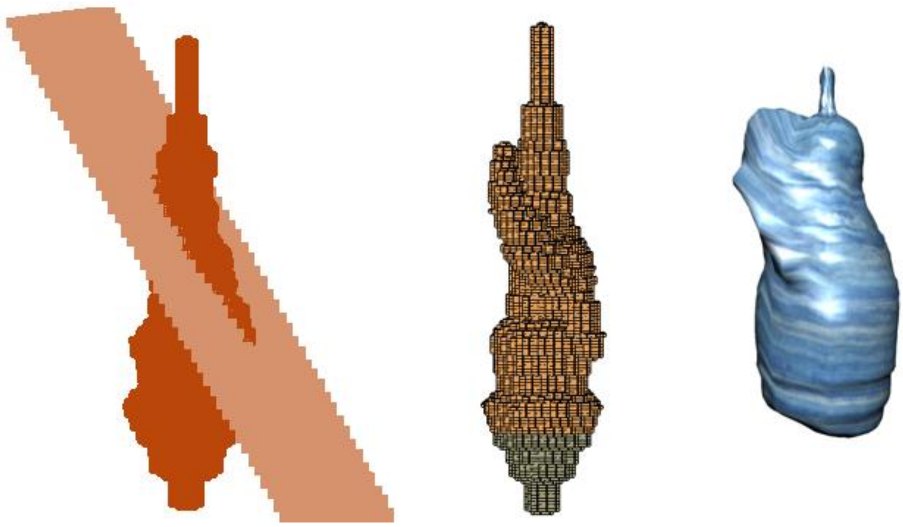

Figure 15: Cavern shape and pocket/wing development in a layer with high dissolution rate. Comparison with sonar measurement. (Sump in the simulation with darker color is not visible in the sonar)

In the second example it is assumed that a vertical layer with a higher dissolution rate is in the vicinity of a well bore in a salt having a lower dissolution rate. This leads to the development of an asymmetrically formed cavern. As comparison results of a sonar measurement of a similar cavern are given in *Figure 16*. The dissolution rate of the highly soluble salt was 2.2 times greater than that of the less soluble salt, which falls within the range of possible variations, as illustrated in Figure 14.

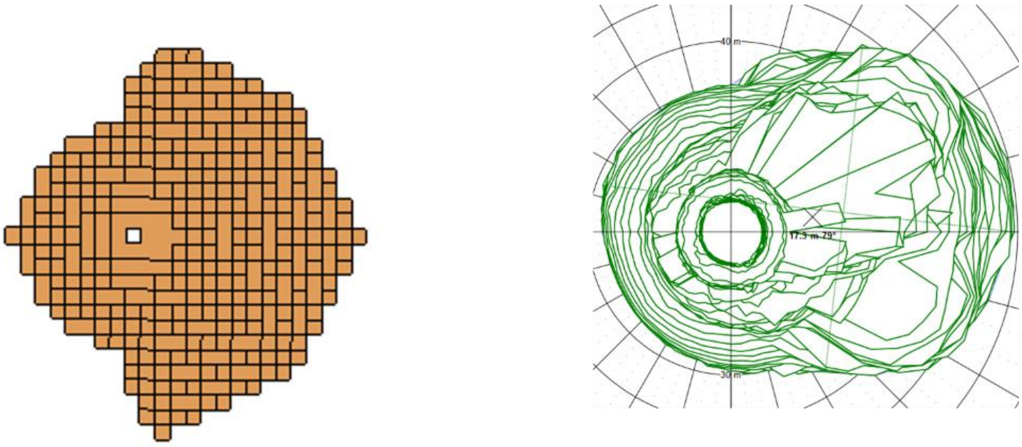

Figure 16: Simulation and sonar measurements of a cavern, having a perpendicular layer with a higher dissolvable salt (Factor 2.2) close to the well bore.

Program architecture

The grid that is used for the simulation is a regular Cartesian grid as used e.g. in the black oil simulator Eclipse® from Schlumberger. Also, corner point grids, as used in such simulations can be imported, which may be useful, if such grids come from a geological modelling program.

The input is keyword based similar as in black oil simulation programs. The output is obtained as a printout of the basic values but also a graphical output is generated. As the output is generated in Eclipse binary format a program like Eclipse Office can be used, but also the output to excel tables is possible and graphs can be generated from this output in Excel. The 3D visualization can also be generated for Eclipse compatible programs. Results from sonar surveys can be loaded for means of comparison.

Qualitative and Quantitative Comparison

The results of the simulation program were compared with those obtained from a simulation using WinUBRO. A representative leaching scenario was selected and run in both simulators. Standard leaching parameters were applied in WinUBRO, including a horizontal leaching rate of 12.986 mm/h and a vertical rate of 18.7 mm/h, with insoluble content set to zero. The leaching rate in our program was 10 mm/h, the vertical concentration gradient 0.5 g/L/m. The simulation results yielded a leached volume of 867 000 m^3 and 846 000 m^3 in bbox2, reflecting a discrepancy of approximately 2%.

The cavern geometries obtained from both simulations are compared in *Figure 17*. The leached volumes and resulting cavern shapes demonstrate strong agreement across both programs. Minor discrepancies are observed at the cavern neck and bottom; however, the variation in leached volume is negligible, given that standard parameters were uniformly applied in each case.

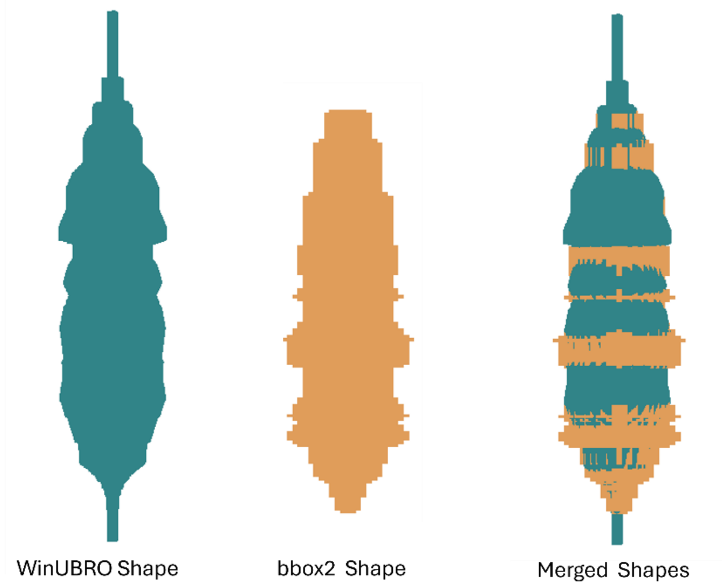

Figure 17: Comparison of cavern shapes. Exported WinUBRO cavern shape (Socon format) and cavern shape from this simulator.

Results and Discussion

The simulation results show the development of salt caverns over time, highlighting the effect of well placement, injection rates, and fluid properties on the leaching process. The results indicate that optimal well placement and controlled injection rates are crucial for efficient cavern development. The 3D visualizations provide a clear representation of the cavern geometry and the dissolution process, allowing for a better understanding of the dynamics of salt cavern leaching.

This case study demonstrates the effectiveness of using Cartesian grids and multiple wells in simulating the salt cavern leaching process. The simulation provides valuable insights into the factors that influence cavern development and gas storage capacity. The ability to visualize the cavern evolution in 3D and analyze the results using Excel or Eclipse-compatible programs enhances the understanding of the leaching process and supports decision-making in the design and operation of salt cavern storage facilities.

With respect to simulated free cavern volume, salt concentration in produced brine the obtained results are consistent with those from other comparable simulation programs.

While well hydraulics can be calculated within the simulation framework, they are beyond the scope of this paper

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