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FLOODING OF AN ABANDONED SALT MINE—MODELING TWO-PHASE FLOW IN COMPLEX MINE STRUCTURES

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ABSTRACT

The TOUGH module EOS7 has been used to model the conditions in a former salt mine during and after flooding. Of particular interest are the conditions in a small part of the mine where radioactive wastes are stored under an extremely low-permeability backfill. The salt rock between the waste emplacement cavern and the cavern underneath is disturbed and, therefore, has significant permeability. In our model, the structure of the relevant parts of the complex underground mine was simplified and then discretized with our own pre-processing software MAGICS to generate a 3D mesh consisting of about 18,000 hexahedrons.

The two-phase flow that occurs when a highly viscous and very dense flooding fluid is introduced into the mine was modeled successfully with the TOUGH module EOS7. Sensitivity analyses were performed to evaluate the influence of uncertain parameters. Post-processing and the 3D visualization of the results with TECPLOT have greatly enhanced our understanding of how the flooding fluid advances through the complex underground mine, and how air may be trapped in the process.

The modeling study has shown that the air trapped below the low-permeability backfill will most probably prevent the flooding fluid from coming into contact with the wastes. However, contact cannot be completely ruled out because of capillary effects.

BACKGROUND

An abandoned salt mine has been used to store low and intermediate level radioactive wastes for research purposes. The wastes have been emplaced in selected caverns that are part of a large network of caverns and connecting structures. The field task at hand is to close the mine, with the implementation of safety measures to meet given safety requirements.

As the salt formation creeps and the mine converges, it is necessary to backfill the open spaces with crushed salt with additives. In addition, the mine is to be flooded in a controlled manner, with a solution that is chemically nearly inert and of high density and viscosity. While the flooding is a safety measure, long-term processes may potentially cause the fluid to mobilize toxic substances of the wastes and transport them to where they may pose a risk.

PROBLEM DEFINITION

The overall objective of this study is to simulate, by numerical modeling, the two-phase flow in the mine, in order to predict the flooding of the waste emplacement caverns. Considering the many levels of the mine and its numerous caverns, one particular waste emplacement cavern—the MAW cavern—poses a special challenge. Because of its relative position, low-permeability backfill above and on the sides of the wastes, and hydraulic accessibility, it may not fully saturate, thereby influencing the possible mobilization of toxic substances from the wastes held in the cavern.

This paper presents work performed for the analysis of potential air entrapment in the MAW cavern. While the TOUGH module EOS7 was used to model the fluid flow, emphasis is placed on the pre- und post-processing methods and tools.

CONCEPTUAL AND 3D MODELS

For the model calculations presented here, it is sufficient to consider only part of the complex mine in detail, namely the MAW cavern and its vicinity (Figure 1).

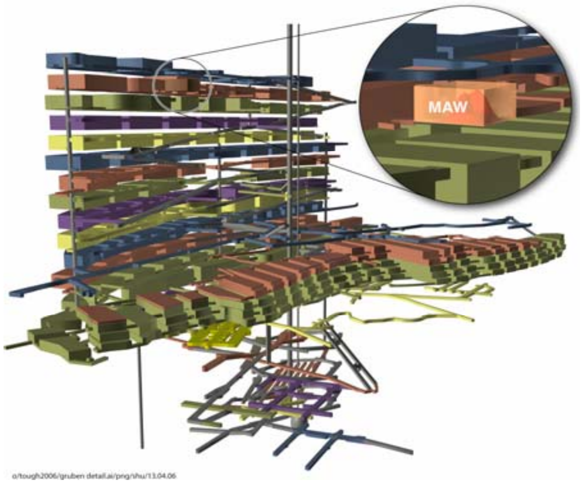


Figure 1. Schematic illustration of the underground mine, showing the location and relative size of the MAW cavern (after ALSA-C, 2005).

Most of the many mine levels (each with dozens of caverns) are of less interest. The relevant parts of the mine have been combined in one element of the model, referred to as the Southern Field. The Southern Field is captured as a boundary condition for the rising fluid level during the flooding phase, and for the growing pressure during the post-flooding phase (i.e., when the mine has been flooded and closed off.

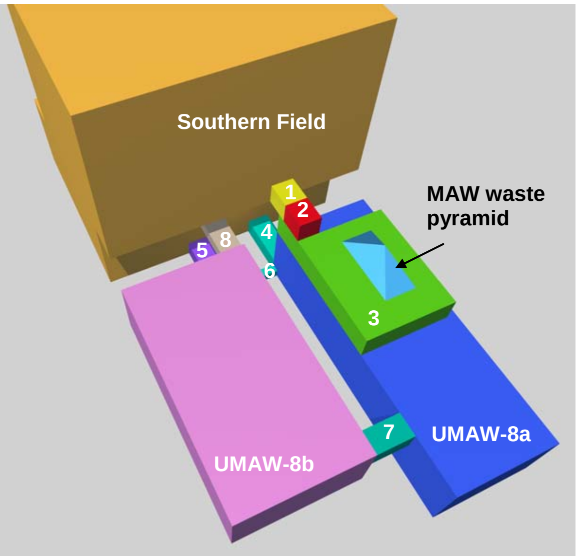


Figure 2. Structural model of part of the underground mine—caverns are named, connecting structures are numbered.

Elements of the Structural Model

Figure 2 is a schematic illustration of the part of the underground mine represented in the numerical model. The model consists of four caverns and eight connecting structures (drifts, galleries, and roof pillars, labeled with numbers in Figure 2).

Caverns

The Southern Field cavern has homogeneous properties and reflects the rise in the fluid level as special flooding fluid is introduced into the mine. In the model, it is connected to the two caverns UMAW-8a and UMAW-8b. Of the MAW cavern, only the pyramid-shaped waste pile is represented. The remainder of the MAW cavern will be backfilled with special concrete and is considered to be beyond the flow field of interest.

Connecting structures

The various connecting structures each have their own set of hydraulic properties. Most of them are filled with crushed salt. Others, namely connecting structure 8 and the top-most twin structure (structures 1 and 2) in Figure 2, are low-permeability concrete barriers intended to minimize fluid flow and potential contaminant transport. Included in the concrete-filled connecting structures are equivalent hydraulic properties of the adjacent excavation-disturbed salt rock.

Connecting structure 3 is the mechanically strained roof pillar between the MAW cavern (i.e., the waste pyramid) and the UMAW-8a cavern. The values assigned to essential parameters like pore volume, cross-sectional area, and height of the connecting structures honor the true conditions.

Features and Processes

Modeling fluid flow in the vicinity of the MAW waste pyramid requires consideration of the following features and processes:

- Only the Southern Field is flooded actively. As the fluid level rises in the Southern Field, the connecting drifts allow the flooding fluid to penetrate into the UMAW-8a and UMAW-8b caverns.
- The flooding fluid has a high viscosity of 8 mPa·s and a high density of 1,311 kg/m^3. The TOUGH module EOS7 is well suited to cope with these conditions. Local density variations resulting from chemical processes are neglected.
- Two-phase flow introduces relative permeabilities and capillary pressure functions.
- Of secondary importance is the solution of gas (air) in the solute according to Henry's law

The two-phase flow is simulated with relative permeabilities according to Corey's correlation and capillary-pressure relations according to the van Genuchten model. For all materials (crushed salt, salt roof pillar, concrete and excavation-disturbed zones around concrete barriers), the residual gas saturation, S_{gr}, is set to 0.16, the residual liquid saturation, S_{lr}, to 0.1. The van Genuchten parameter n in Equation (3) is assumed to be 1.5 for concrete and 2 for salt materials. The parameter p_0 in Equation (2) is defined such that for a water content of 80%, the capillary pressure p_{cap} corresponds approximately to the air entry pressure. The air entry pressure is approximated with Davies' correlation:

$$S^* = \frac{S_l - S_{lr}}{1 - S_{lr} - S_{gr}} \tag{1}$$

$$p_{cap} = \begin{cases} 0 & \text{for} \quad S_l \geq 1 - S_{gr} \\ -p_0 \cdot \left[\left(S^* \right)^{-\frac{1}{\lambda}} - 1 \right]^{1-\lambda} & \text{else} \end{cases} \tag{2}$$

with $\lambda = 1 - \dfrac{1}{n}$ (3)

whereby S_l is the liquid saturation [-]. The resulting relative permeabilities and capillary pressure functions are shown in Figure 3.

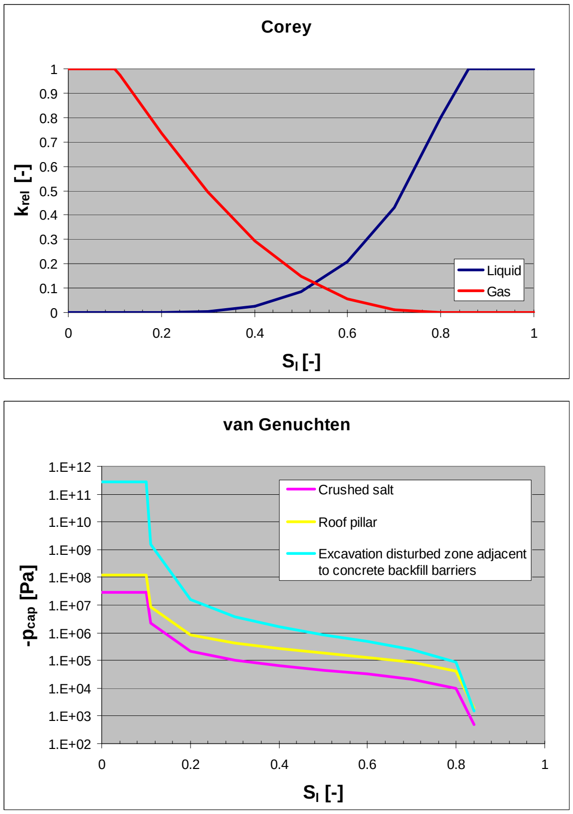


Figure 3. Relative permeabilities (top) and capillary-pressure functions (bottom).

The following processes do not need to be modeled explicitly with TOUGH:

- Compressibility of solids; i.e., only fluids are assumed to be compressible
- Convergence caused by salt creeping; i.e., this may be neglected for the time period of consideration
- Gas generation caused by corrosion and biodegradation of waste materials where in contact with water; i.e., this is only considered explicitly as a sensitivity test case (see below).

The transport of toxic substances, and in particular of radionuclides, is not of concern here. It is treated with due attention by specifically designed risk assessments and safety analyses, which are beyond the scope of this paper.

The boundary conditions used in the model runs are imposed on the system from outside:

- During the flooding phase, the rising fluid level in the Southern Field is controlled by the rate at which flooding fluid is pumped into the mine.
- For the post-flooding phase, i.e., after the flooding has been completed and the access shafts sealed, convergence taking place in all parts of the mine and, to a lesser extent, gas generation in the wastes are considered implicitly, through a pressure increase in the system.

The flooding rates were defined as part of the mine flooding concept. The rising fluid level is easily modeled with a virtual fluid source term at the bottom of the Southern Field.

The pressure increase over time for the postflooding phase was estimated in a separate study using different modeling codes (ALSA-C, 2005). In this study, the pressure increase is modeled by assigning a virtual gas source to the top of the mine.

PRE-PROCESSING

The caverns and connecting structures were discretized with MAGICS, an automatic mesh generation tool developed by Colenco. In all, the 3-D mesh comprises 18,000 cubic elements.

The MAGICS preprocessor can create 2-D quadrangular meshes and 3-D multilayer hexahedral meshes. These meshes can be either structured or unstructured; thus they can integrate complex geometrical constraints. Structured meshes are constructed on the basis of a 2-D multiblock geometry like the one used in this study. MAGICS allows the user to perform a custom discretization on those blocks to create “Scottish” mesh patterns. The connectivity between elements belonging to adjacent blocks is established automatically, and the resulting meshes are conform.

MAGICS meshes are generated with a modern graphical user interface (GUI) that facilitates geometry import and interactive geometry design (as well as user-friendly and fully interactive processing) to assign physical properties to the mesh elements. The resulting mesh can be exported as an ASCII file respecting the TOUGH2 input file format. MAGICS also exports the mesh’s coordinates into a file that is directly readable by the TECPLOT post-processing tool.

In the case presented here, the caverns and connecting structures of concern were discretized as a 3-D multilayer mesh composed of hexahedrons (Figure 4). This mesh is the result of some preliminary work: Most blocks were discretized with a “Scottish” mesh pattern to allow local mesh refinement, under the waste pyramid as well as in the UMAW-8a and UMAW-8b caverns, near the connecting structures where some fluid flow is expected to occur. Figure 5 shows the mesh in layers with a total of 57,402 elements. Some of the superfluous elements were removed and layers subdivided to obtain the 3-D mesh seen in Figure 4.

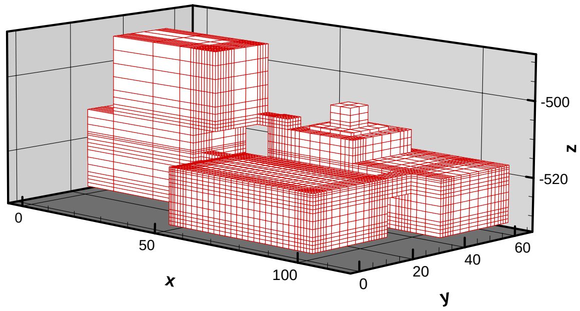


Figure 4. 3-D multilayer mesh composed of hexahedrons, based on the blocks of the structural model.

Figure 5. 2-D multiblock geometry representing the structural model in layers; discretization with a "Scottish" mesh pattern for local mesh refinement, an intermediate step before obtaining the 3-D multilayer mesh.

MAIN MODEL PARAMETERS

The Southern Field cavern that is used to simulate the rising fluid level in the underground mine is 40 m tall. Connecting structures 4 and 5 between the Southern Field and the large caverns UMAW-8a and UMAW-8b are backfilled with crushed salt. Their porosities are about 0.3 or 0.4 and, according to a porosity-permeability relation, their permeabilities are 3·× 10^{-12} m^{2} and 6·× 10^{-12} m^{2}. Connecting structures 6 and 7 between the two large caverns are also backfilled with crushed salt.

The bases of caverns UMAW-8a and UMAW-8b are 60 m× 27 m and 50 m× 28 m, respectively. Both are 16 m in height and are backfilled mostly with crushed salt. A 4 m wide segment in each cavern (closest to the Southern Field) is backfilled with concrete of porosity 0.13 and permeability 1·× 10^{-15} m^{2}.

Connecting structure 8 between the Southern Field and the top of the UMAW-8b cavern is also backfilled with low-permeability concrete. The roof pillar along the top of the UMAW-8a cavern, (i.e., connecting structure 3) has a thickness of 6 m, a porosity of 0.03, and a permeability of 1·× 10^{-15} m^{2}. The drift between the roof pillar and the Southern Field, i.e., twin connecting structure 1 and 2, consists of different kinds of concretes, including the surrounding excavation-disturbed zone. These are represented with a permeability of about 1·× 10^{-15} m^{2}.

The MAW waste pyramid has a volume of 463 m^{3}, a maximum height of 6.5 m and a porosity of about 0.3. The wastes are assumed to be quasi-homogeneous and to have properties similar to concrete.

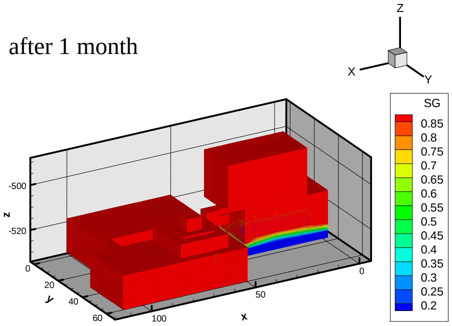
FLOODING THE SOUTHERN FIELD CAVERN

The flooding fluid's viscosity is about eight times higher than that of fresh water, and a density of 1,311 kg/m^{3}. It flows into the pore volume of the Southern Field in a controlled manner. According to the flooding concept, the flooding level reaches the roof of the Southern Field cavern after 259 days. In addition, the mine is subjected to a superposed air pressure of 1 MPa during the flooding phase. Note that the air remaining in backfill materials located below the flooding level is increasingly compressed.

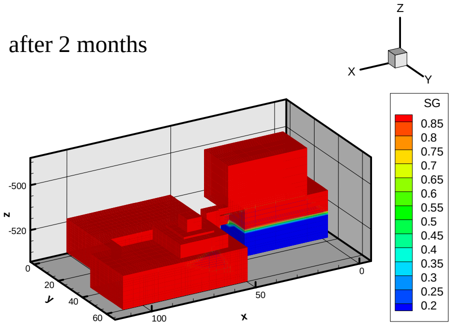
Figure 6 illustrates the calculated rising fluid level in the mine model in one-month intervals, beginning one month after flooding commences. In this figure, the Southern Field cavern is represented with reduced size, i.e., 1/20th the size of all other model components. Figure 6 indicates gas saturation: a residual gas saturation of 0.16 corresponds to complete fluid saturation (blue), whereas a gas saturation of 0.9 or higher corresponds to dry regions (red). The scale on the right-hand side is the same for all figures.

Because of its high viscosity, the flooding fluid reaches the lower-lying caverns UMAW-8a and UMAW-8b only after a delay. Even at the end of the flooding phase after 259 days, the fluid has not reached the far end of the UMAW-8b cavern, which is slightly farther away from the connecting drift than the far end of the UMAW-8a cavern. In the near end of the UMAW-8b cavern (i.e., underneath the MAW waste pyramid, the flooding reaches a level of about 4 to 6m. In other words, the upper 10 m in the UMAW-8b cavern remain dry. The gas pressure there reaches 1.2 MPa.

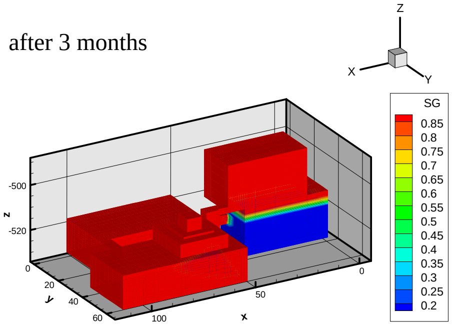
after 1 month



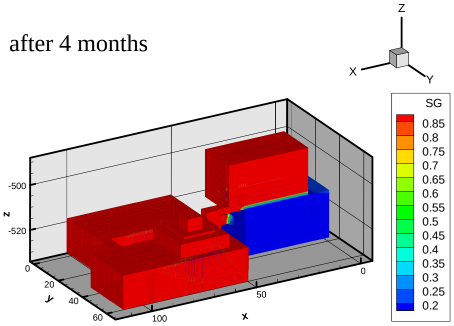
after 2 months



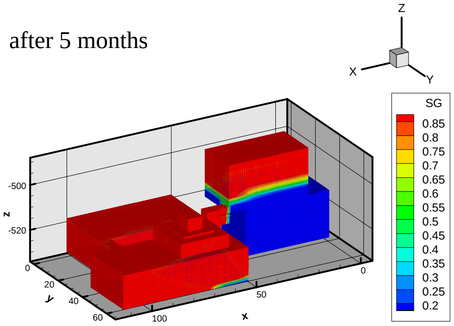
after 3 months



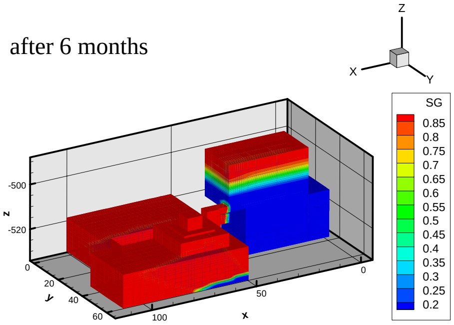
after 4 months



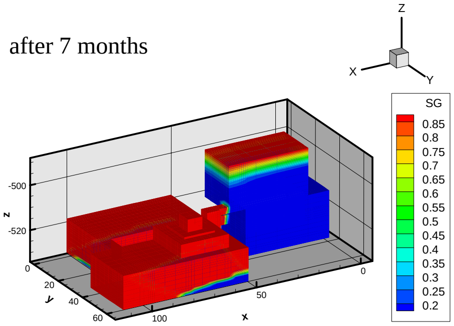
after 5 months



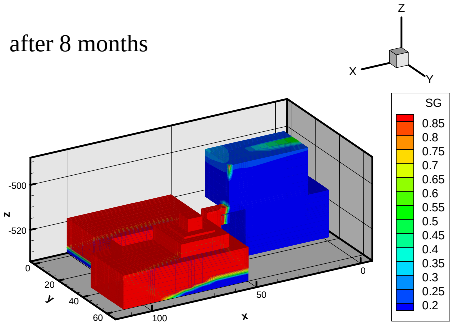
after 6 months



after 7 months



after 8 months



after 259 days

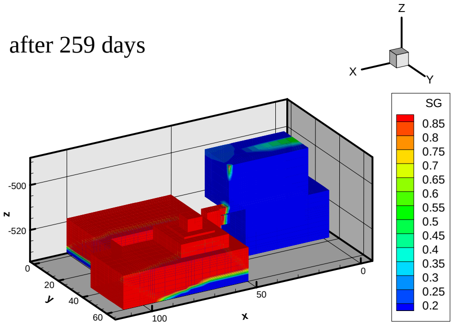


Figure 6. Flooding levels in 1-month intervals for 259 days after flooding commences; illustrated in terms of gas saturation. Graphs generated with TECPLOT.

RISING PRESSURE IN THE POST-FLOODING PHASE

Once the access shafts to the mine have been sealed, the pressure in the mine increases as a result of convergence and gas generation, because the stratigraphic formation on top of the salt structure provides resistance to flow. These processes have been studied with different models elsewhere (ALSA-C, 2005).

It was found that the pressure continues to increase for about 50 years after sealing. After that, the fluid pressure and the load capacity of the backfill materials retard the convergence rate. Therefore, only this 50-year period need be considered here. The expected pressure response up to its maximum is illustrated in Figure 7 (blue line). In TOUGH, this rise in pressure is simulated with a virtual gas source that is parameterized according to the increasing pressure.

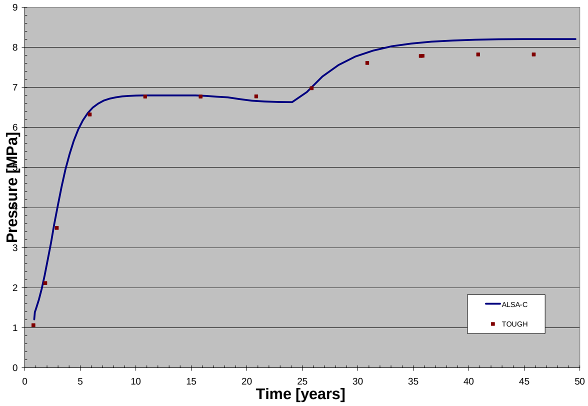


Figure 7. Pressure increase calculated in ALSA-C (2005) vs. pressure increase calculated with TOUGH using a virtual gas source

Looking at the UMAW-8a cavern under the waste pyramid (Figure 8), within the first year after sealing—or 1.8 years after the beginning of calculations—the initially sloped front of the advancing flooding fluid equalizes to a horizontal fluid level at about 8 m. The pressure increase in the mine causes further compression of the remaining air and, in addition, further flow of gas through the twin connecting structure 1/2 at the top of the UMAW-8a cavern into the Southern Field. (The flow of gas is indicated by a decrease in liquid saturation in the Southern Field directly above the twin connecting structure 1/2 in the period from 5 to 25 years.) These processes result in a further rise in fluid level within the UMAW-8a cavern. The cavern roof is reached after approximately 10 years.

After 25 years, the gas flow through the twin connecting structure ceases, because of liquid saturation in the drift. The fluid level continues to rise, albeit very slowly.

Already after a little over 5 years, the flooding fluid reaches the bottom of the roof pillar atop the UMAW-8a cavern (i.e., connecting structure 3). Capillary effects further enhance the liquid saturation, and after about 15 years, small amounts of fluid may reach the base of the waste pyramid. The calculations present this effect with a liquid saturation of about 30% along the base of the waste pyramid. The bottom 1 m of the pyramid contains 39% of the waste volume, packaged in barrels. The calculated capillary effects in and between the barrels are certainly overestimated, since the calculations are based on the assumption of quasi-homogeneous concrete. Still, it is not deemed impossible for the flooding fluid to penetrate the roof pillar in this short period of time.

RESULTS OF SENSITIVITY RUNS AND CONCLUSIONS

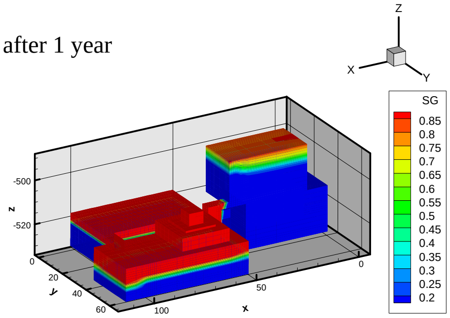
Several sensitivity scenarios were defined and calculated to enhance the comprehension of the main modeling results. The scenarios included:

- Higher permeability (by one order of magnitude) for the concrete backfill and adjacent excavation-disturbed zone in the connecting drifts
- Introduction of gaps along the tops of caverns UMAW-8a and UMAW-8b, i.e., less than complete concrete backfilling
- Variations in the flooding regime and the gas pressure
- Variation in the van Genuchten parameter n for two-phase flow
- Introduction of gas generation in the waste as it comes into contact with water

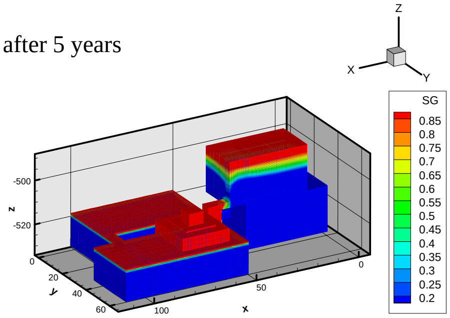
The main results presented above were confirmed by the sensitivity runs: The flooding fluid advances only very slowly into the lower lying caverns. After the shafts are sealed, the rising pressure causes a rise in fluid level. Eventually, the fluid reaches the roof pillar under the waste pyramid and may even penetrate it. The permeabilities of the materials considered are less crucial. That the wastes come into contact with flooding fluid as a result of capillary effects is highly uncertain. But the possibility cannot be ruled out altogether and must therefore be considered further in the safety analysis.

We feel that it is rather unusual to model the flooding of an underground mine with the TOUGH module EOS7. However, this study has proven its suitability for the complex geometric framework and physical processes we have encountered.

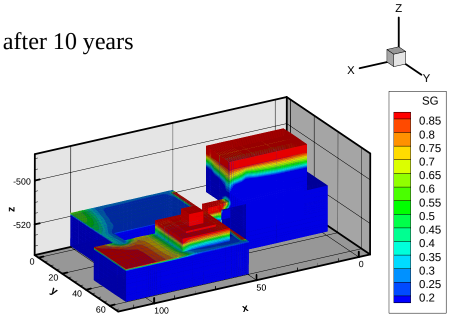
after 1 year



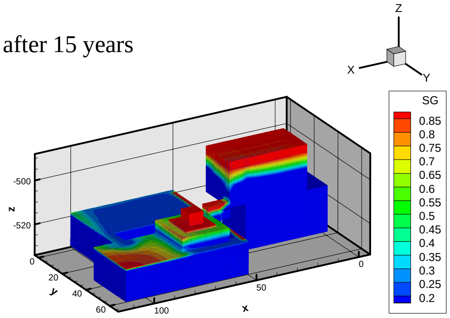
after 5 years



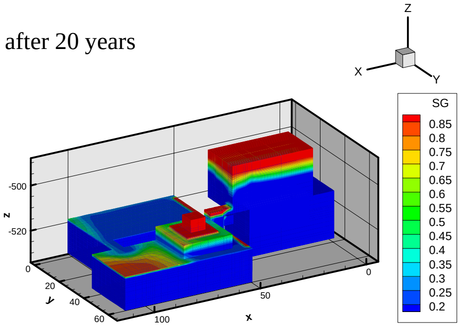
after 10 years



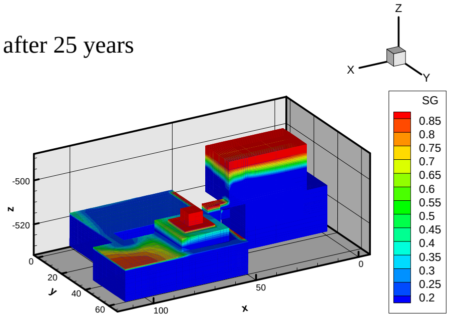
after 15 years



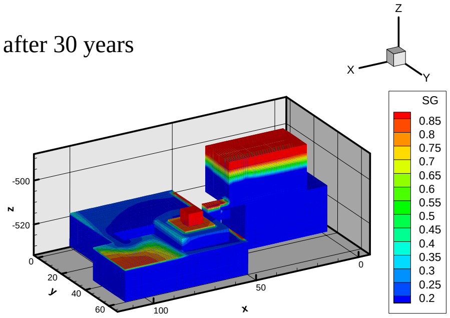
after 20 years



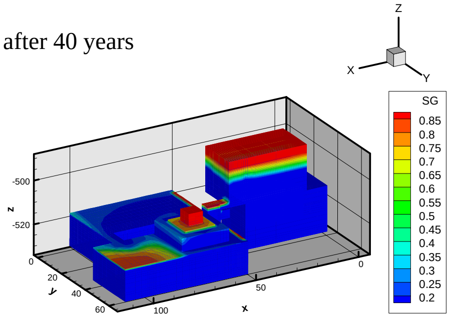
after 25 years



after 30 years



after 40 years



after 50 years

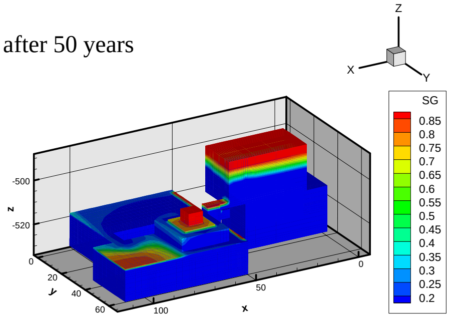


Figure 8. Rising level of the flooding fluid 1, 5, 10, 15, 20, 25, 30, 40, and 50 years after the access shafts to the mine have been sealed, illustrated in terms of gas saturation

ACKNOWLEDGMENT

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REFERENCE

ALSA-C, Fluid- und Radionuklidtransport am Standort Asse. NRG, Petten (NL); Colenco Power Engineering AG, Baden (CH); GRS, Braunschweig (D). Bericht ALSA-C-1.5B-NR145, July 27, 2005.