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Using LOCAS Software to Better Understand the Behavior of Salt Caverns

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USING LOCAS SOFTWARE TO BETTER UNDERSTAND THE BEHAVIOR OF SALT CAVERNS

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ABSTRACT

LOCAS is a semi-analytical and finite element code that provides 2D axisymmetric analysis of the short-term and long-term behavior of solution-mined caverns. Simulation of the non-linear and time-dependent mechanical behavior of salt caverns requires advanced constitutive models and accurate numerical computations. In addition, because many other phenomena are involved in the behavior of solution-mined caverns, special procedures are required to analyze thermal, chemical, and hydraulic phenomena. Although modeling a cavern is important in itself, many geotechnical engineering projects also involve modeling the well. One part of LOCAS includes the full modeling of the well and allows finite elements computation of the mechanical behavior of the cementation. LOCAS is equipped with special features that take into account the numerous aspects of the complex geotechnical structures of salt caverns. LOCAS can be helpful, for instance, in the issue of cavern abandonment, as illustrated in this paper.

Keywords: Cavern behavior, cavern abandonment, numerical computation, cementation.

INTRODUCTION

It is impossible to present all LOCAS features in a short paper. Here, we focus only on its main features with regard to solution-mined caverns. Originally, LOCAS was developed because it was very difficult to account for all phenomena involved in salt caverns using standard finite element codes. Several rock-salt codes had been designed for underground openings, but not for fluid-filled caverns. Most existing codes only focused on a few aspects of cavern behavior (mainly, mechanical or thermo-dynamic aspects)— but there was no code that that took into account all the phenomena and coupling effects necessary to simulate *in situ* measurements and long-term behavior. LOCAS is able to model all effects and to use, when possible, relevant data from *in situ* measurements rather than data fitted from laboratory tests. LOCAS is the result of years of theoretical studies, as well as many *in situ* tests performed by Brouard Consulting and Ecole Polytechnique.

INPUT FEATURES

❖ Cavern Geometry

LOCAS is a tool to analyze 2D axisymmetric caverns. A 2D finite element mesh is generated easily by using a mesher that is embedded in the software. Simple shapes (sphere or cylinder) can be selected, or a user-defined shape can be chosen. For user-defined shapes, a cavern profile can be defined point by point (Figure 1) or loaded automatically from an external file (sonar survey). Then, a mesh can be created easily in a few seconds. An example of a mesh is given on Figure 2. A rotating 3D view of the cavern is shown in the "3D Shape" tab (Figure 3).

LOCAS allows for fully automatic generation of unstructured finite element meshes with options for global and local mesh refinement. The mesh may contain thousands of triangular elements. A mesh database is embedded (Figure 4), and its possible to zoom in the mesh plot using the mouse (as in all other plots) and clicking on a node shows its number and location in the status bar.

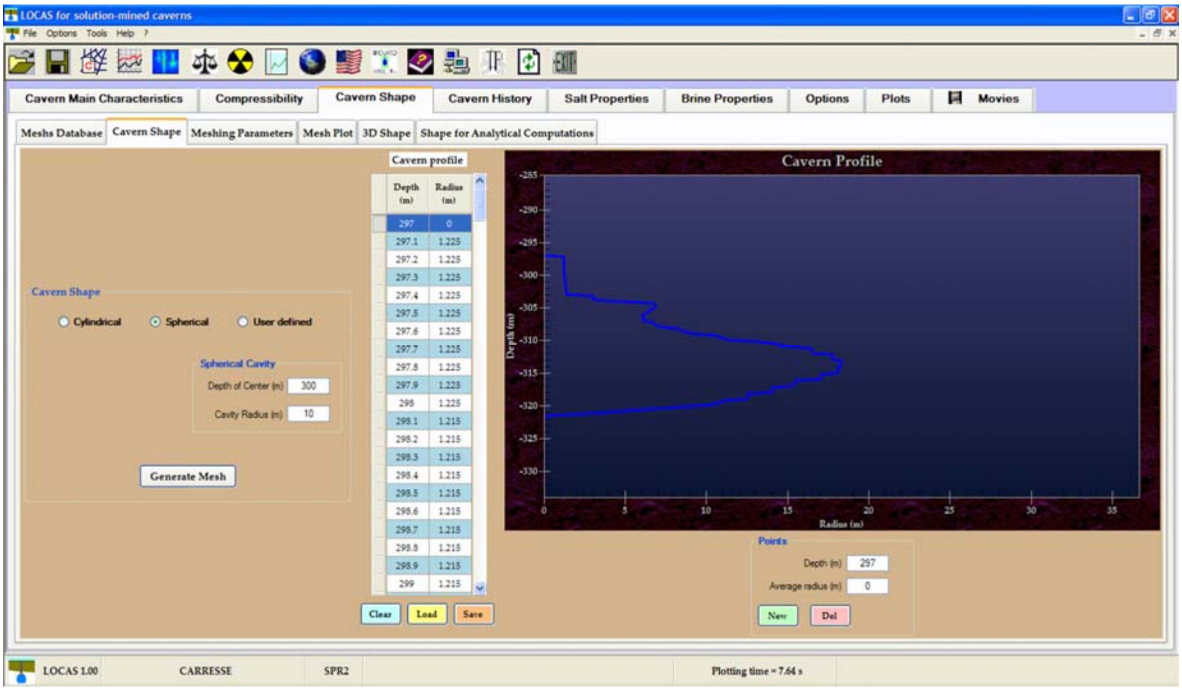

Figure 1 – The embedded mesher in LOCAS allows meshes to be generated for axisymmetric caverns.

The cavern profile provided in Figure 1 is that of the Carresse SPR2 cavern from the last sonar survey. An abandonment test supported by SMRI currently is being performed on this cavern (Brouard *et al*., 2006). Before being decommissioned, this cavern was used for LPG storage. Its shape if fairly axisymmetric; thus, the obtained mesh is realistic (Figure 2).

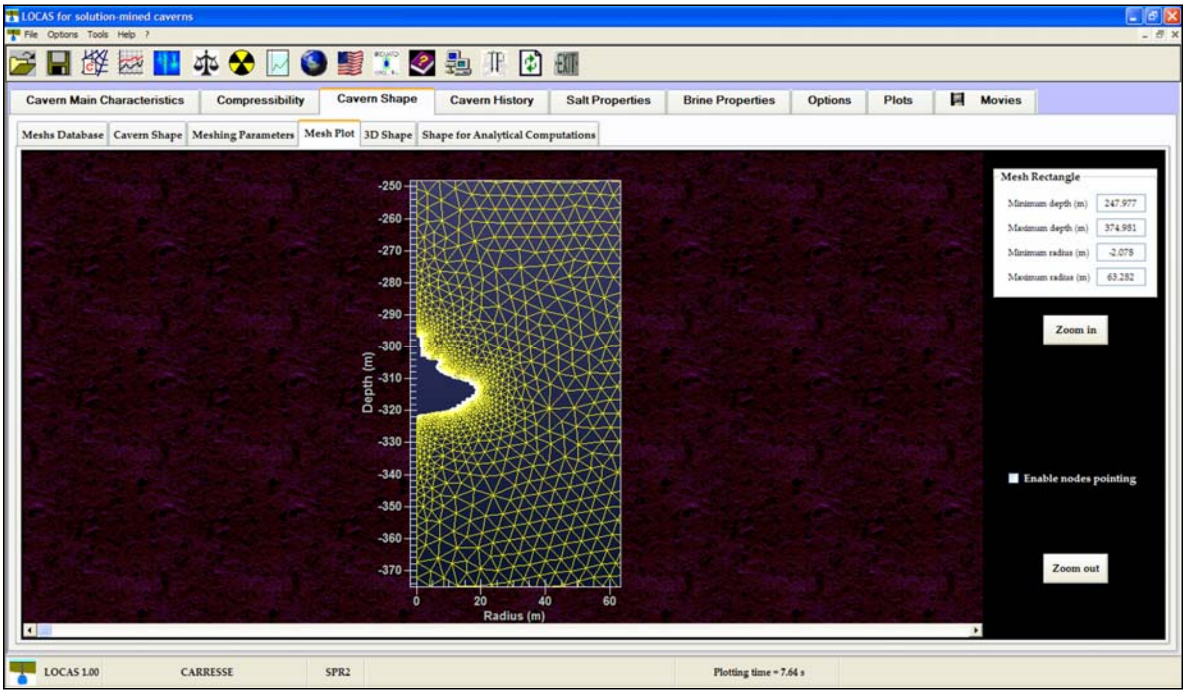

Figure 2 – Example of cavern mesh (In this case, the cavern profile was loaded from a sonar-survey file.)

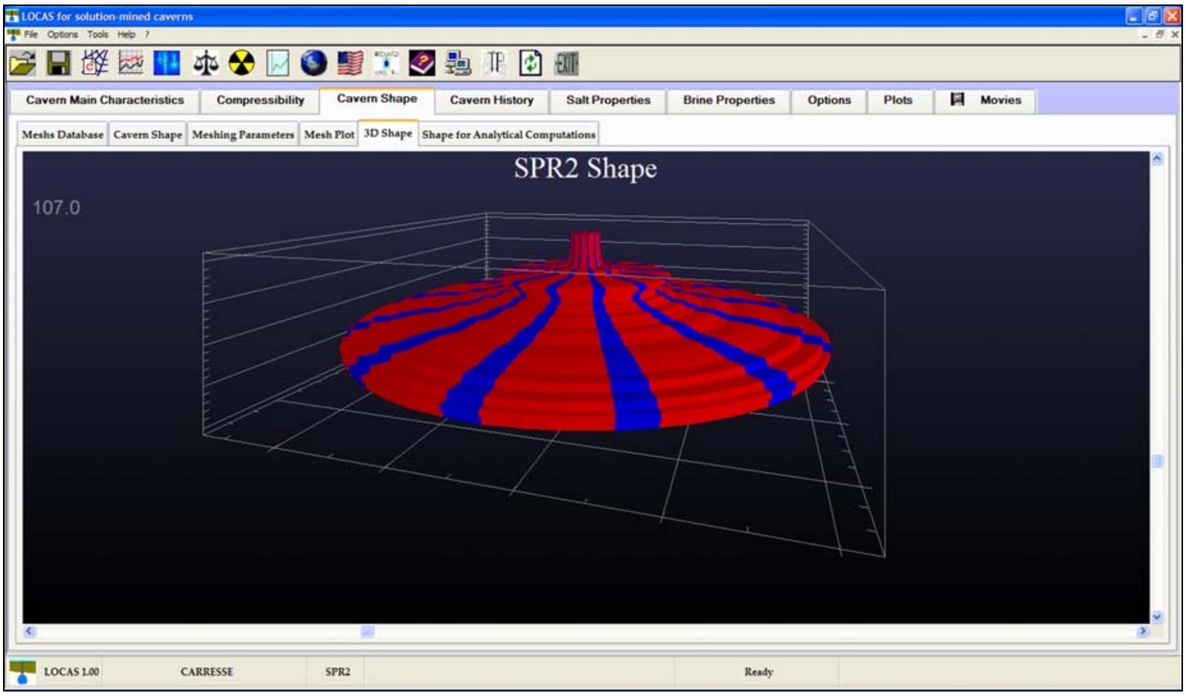

Figure 3 – Rotating 3D view of theSPR2 cavern.

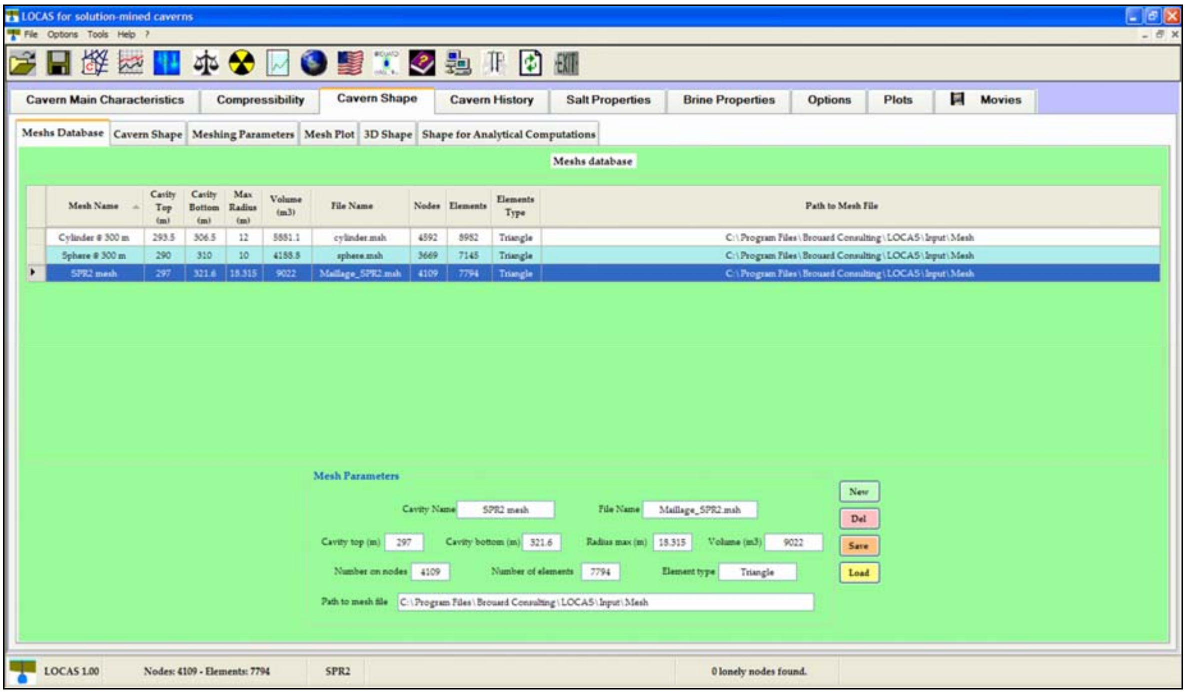

Figure 4 – A mesh database is embedded in LOCAS.

❖ Well Geometry

Because *in situ* measurements often are not performed directly in the cavity but, rather, in the well and/or at the wellhead, it is useful to model the well. Thus, part of the LOCAS code was designed for that purpose.

The "well part" of LOCAS includes several databases, including a "Strings" database, a "Rocks" database and a "Layers" database. The software allows full description of the well geometry and stratigraphy. The purpose of this paper is not to describe the capabilities of this part of the software; rather, to outline the cases for which modeling the well can be useful —for example, wellhead measurements (pressure variations, injection/withdrawal flows, etc.) often cannot be applied directly to a cavern.

Figure 5 shows the "Sections" database that can be created; Figure 6 shows an example of well architecture as displayed in LOCAS. A stratigraphic cross-section, including well casings, also can be displayed.

Central tubing pressure, annular pressure, atmospheric pressure and temperature as measured at the wellhead can be loaded with this part of the software. An embedded tool allows filtering of well-pressure variations due to atmospheric pressure and temperature. Atmospheric temperature variations have no effect on the cavern, and atmospheric pressure variations only have a reduced effect. When the cavern is closed and pressures recorded at the wellhead, LOCAS can calculate precisely the portion of atmospheric pressure variations that affect the cavern through the rock layers (approximately 40%).

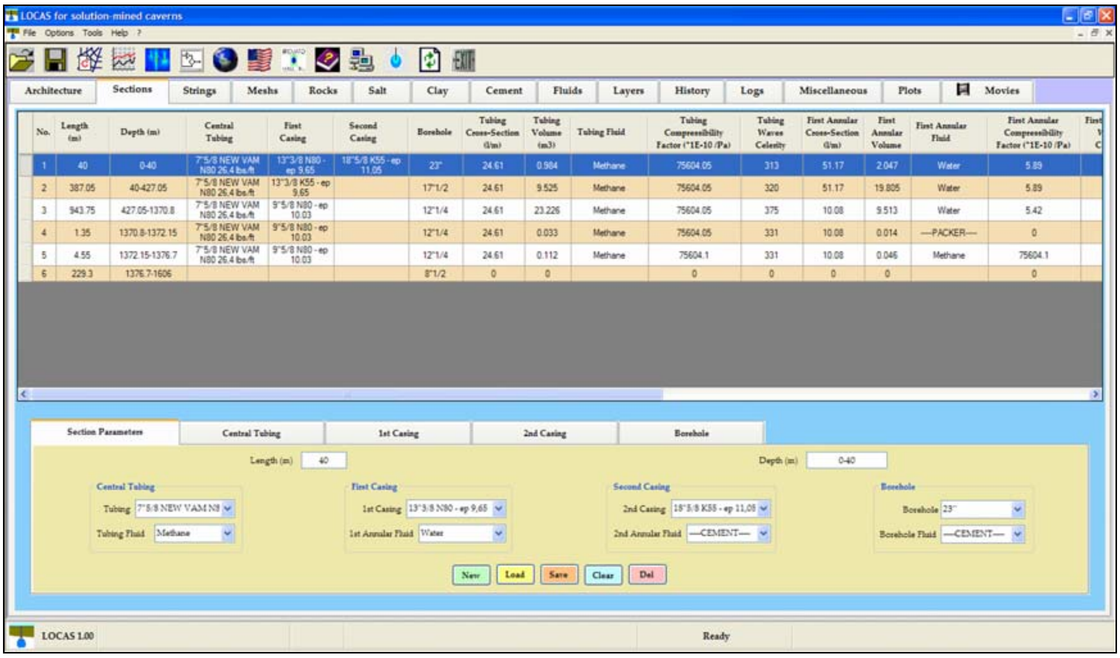

Figure 5 - The "Sections" database allows full description of the well geometry.

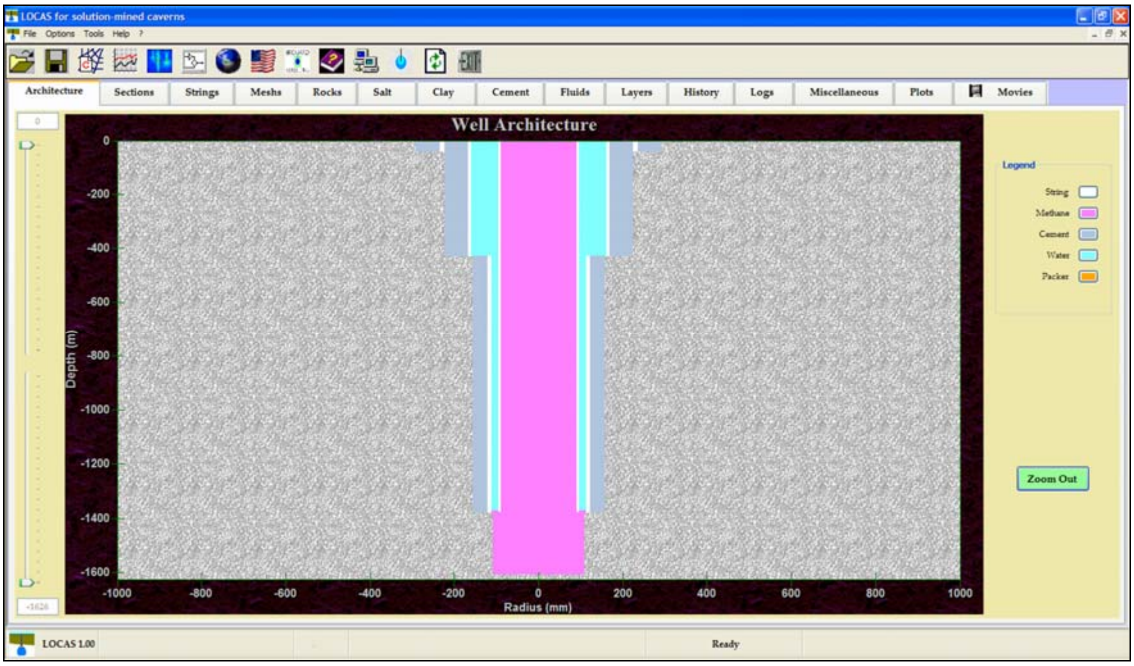

Figure 6 – Well architecture.

In the SPR2 abandonment test, because all measurements were performed at the wellhead, it was possible to use LOCAS to calculate the cavern pressure evolution during the test. The cavern pressure evolution then was used for finite elements computations — i.e., it was compared to the computed cavern evolution to fit model parameters.

CALCULATION FEATURES

❖ Phenomena that LOCAS takes into account

The following phenomena can be considered to compute cavern behavior:

- Primary (or transient) and stationary (or secondary) salt creep.
- Brine heating and thermal expansion.
- Brine micro-permeation assuming Darcy's law.
- Complementary dissolution/crystallization of salt.
- Adiabatic compression/decompression.
- Salt damage — i.e., the increase of salt permeability according to a criterion (choice between three criteria).

❖ Creep Laws

The following elasto-visco-plastic laws are implemented in LOCAS:

- Norton-Hoff.
- Lemaitre-Menzel-Schreiner.
- Munson-Dawson (modified to include "reverse" creep).
- Lubby2 (IUB).

Transient creep is implemented fully in LOCAS for Munson-Dawson and Lubby2 constitutive laws. Databases for "Creep Parameters" are embedded in the software (see Figure 7).

❖ Brine Properties

The complementary dissolution of salt can be computed; Figure 8 shows that all brine parameters needed for computation are given in the "Brine Properties" tab. The kinetics of complementary dissolution and crystallization are defined by two characteristics times.

❖ Brine Micro-Permeation

Hydraulic computations assume Darcy's law. In LOCAS, a hydromechanical coupling criterion can be selected for semi-analytical computation. Three criteria can be chosen (Figure 9).

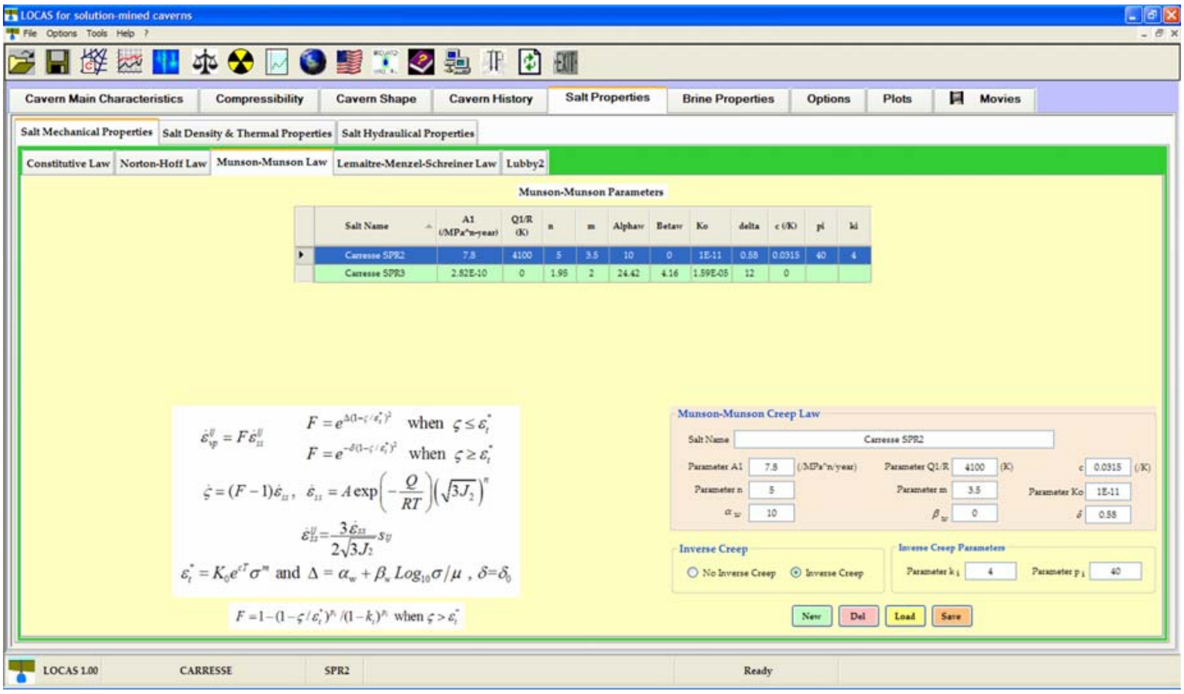

Figure 7 – The Munson-Dawson parameters database includes “reverse” creep.

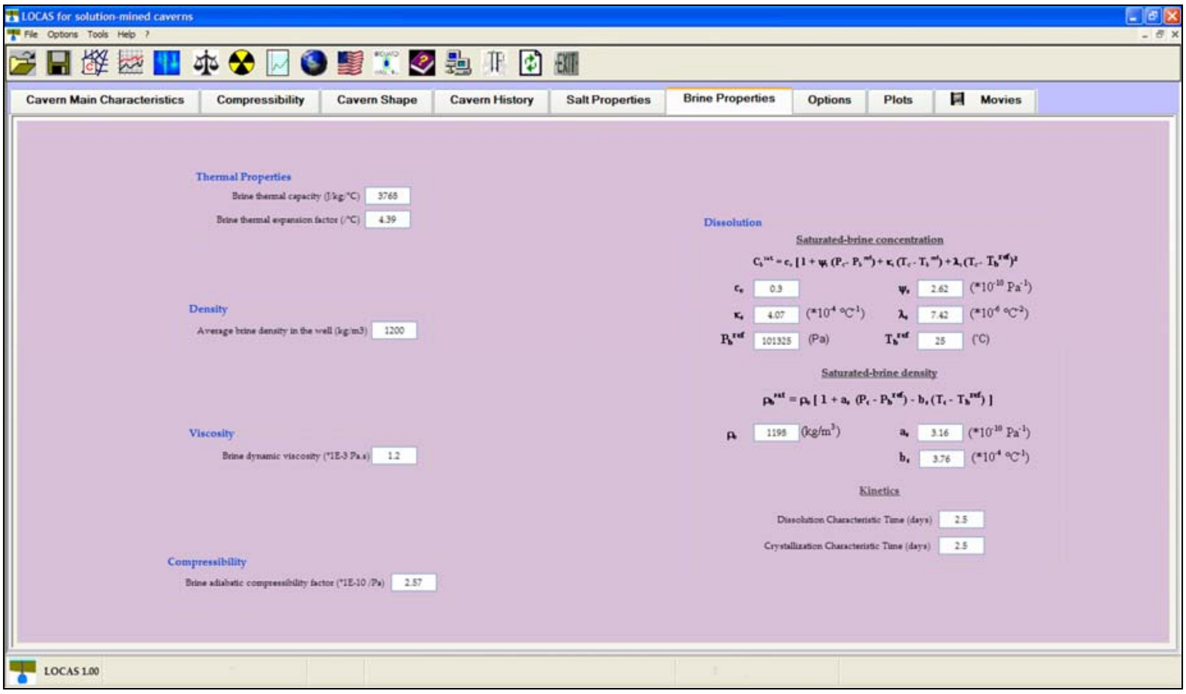

Figure 8 – Brine properties include complementary-dissolution parameters; kinetics of complementary dissolution and crystallization are defined by two characteristics times.

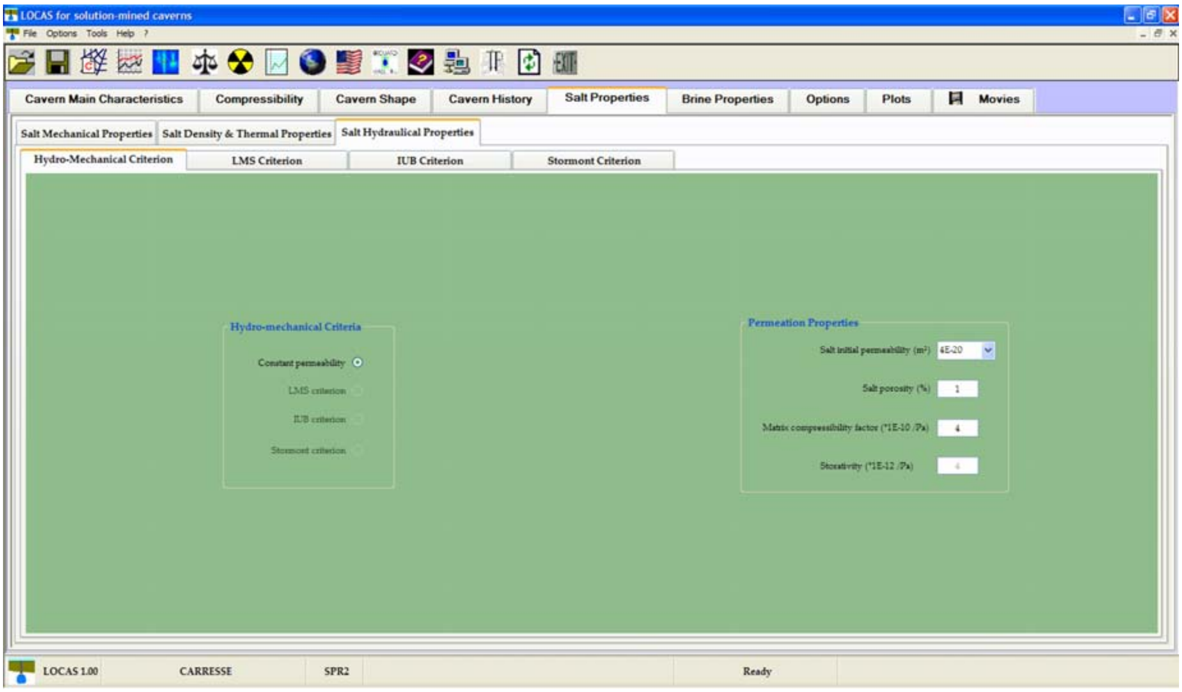

Figure 9 – For analytical computations, it's possible to select a hydro-mechanical criterion to simulate an increase of salt micro-permeability at high pressure.

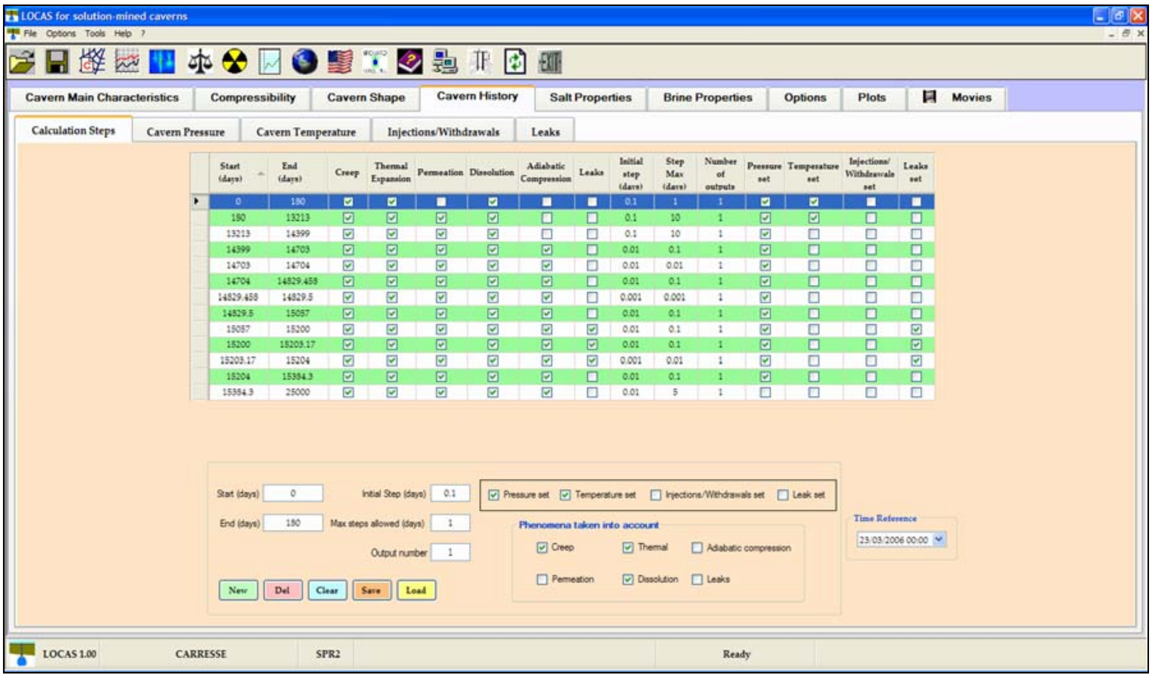

Figure 10 – Calculation steps are defined systematically by selecting the phenomena taken into account and optionally setting the cavern pressure and temperature.

❖ Calculation Steps

For each project, several calculation phases, called "steps", may be specified prior to calculation (Figure 10). For each calculation step, the phenomena listed above may be selected. In addition, cavern pressure and temperature may be set. If the cavern pressure or temperature is set during a step, the cavern history, as defined in the "Cavern Pressure" (Figure 11) or "Cavern Temperature" tabs, is assumed. On the other hand, if cavern pressure or temperature is not set, it is calculated.

These two possibilities allow, for example, stresses, flow due to thermal expansion or flow due to brine micro-permeation to be calculated using *in situ* measurements. When no data are available for cavern pressure and/or temperature, they are not set during the considered step, but they can be set if *in situ* pressure and/or temperature measurement has been performed. For all steps, several outputs are defined for use in post-processing.

LOCAS takes into account fluid injection and withdrawal as input data, as well as fluid leaks, which can be estimated, for example, during a Mechanical Integrity Test. It is also possible to simulate a casing leak by assuming the existence of a pressure threshold.

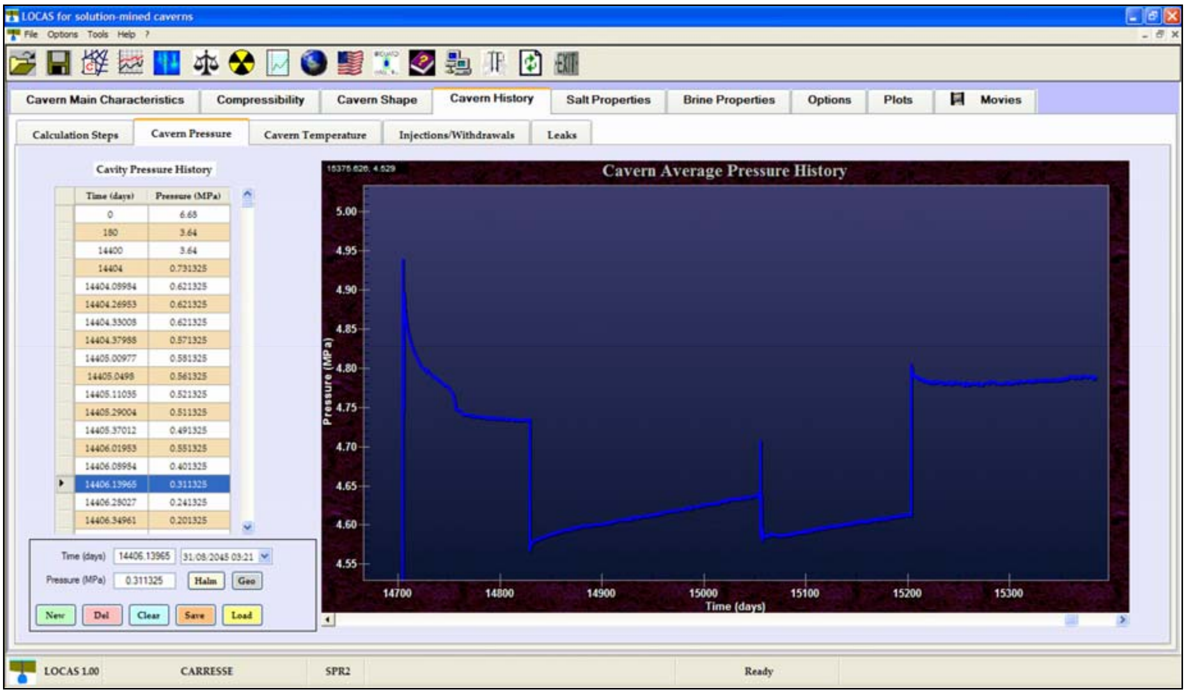

Figure 11 – Cavern pressure history may be set for computations; it can be loaded from an actual data file.

In the case of the Carresse abandonment test, wellhead pressures, flows and temperature measurements were loaded in the "Well" part of LOCAS; then, the cavern pressure evolution was calculated (as plotted on Figure 11). As a first step in a finite element code, it is useful to set the cavern pressure (boundary condition) to this "measured" cavern pressure evolution in order to fit some model parameters (see the following section). In the next step, the cavern pressure is not set; rather, it is calculated by the software through the coupling effect of compressibility and then compared to the measured pressure.

PARAMETER-FITTING FEATURES

One important feature of LOCAS is its ability to fit thermal, mechanical and hydraulic model parameters.

- It will be shown in the application example below how cavern temperature measurement can be fitted in order to simulate the thermal evolution of an idle cavern.
- If a compressibility measurement of the considered cavern has been performed, the elastic parameters of salt can be fitted automatically. Because cavern compressibility is always a key point in problems regarding the short- or long-term behavior of caverns, it is necessary to carefully assess that the ratio between cavern volume variation and cavern pressure variation taken into account by the numerical code is correct.
- LOCAS gives a unique opportunity to fit mechanical and hydraulic parameters from shut-in pressure test data. Once pressure measurement has been loaded in the software and a fitting period selected, fitting parameters can be chosen from among the various proposed constitutive laws (Figure 12).

Several optimization algorithms can be selected (various Nelder-Mead and Differential Evolution algorithms have been implemented). This feature allows fitting mechanical and hydraulic parameters for a given cavern. As these computations can be very long, especially when there is a long cavern history and many parameters are considered, LOCAS can be installed on a idle computer, or started from a idle Windows® account; it can send email on a regular basis, or only at the end of computations, to give information about the progression of the fitting.

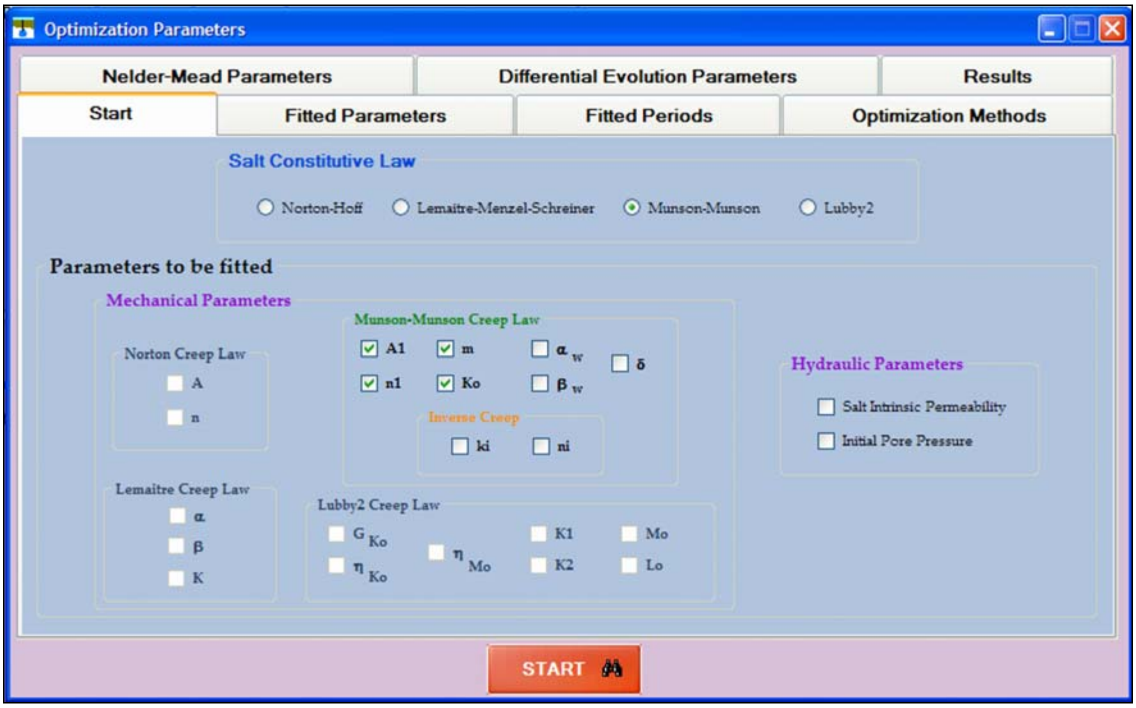

Figure 12 - Optimization window for selecting fitting parameters.

POST-PROCESSING FEATURES

The LOCAS post-processor has enhanced graphical features for displaying computational results. Values of displacement, stress, temperature, pore pressure, etc. can be plotted. All plots can be printed or sent as images to the Windows® clipboard to export them to other software.

- Many cavern parameters can be plotted as a function of time (pressure, temperature, flows, brine concentration, brine density).
- Contour plots can be plotted for all stresses, pore pressure, temperature, etc. (Figure 13)
- Movies can be created from contour plots (.avi format).
- Stress distributions (as a function of radial location) can be plotted.
- The subsidence bowl can be plotted simply (Figure 14) as a function of time by moving a track bar.

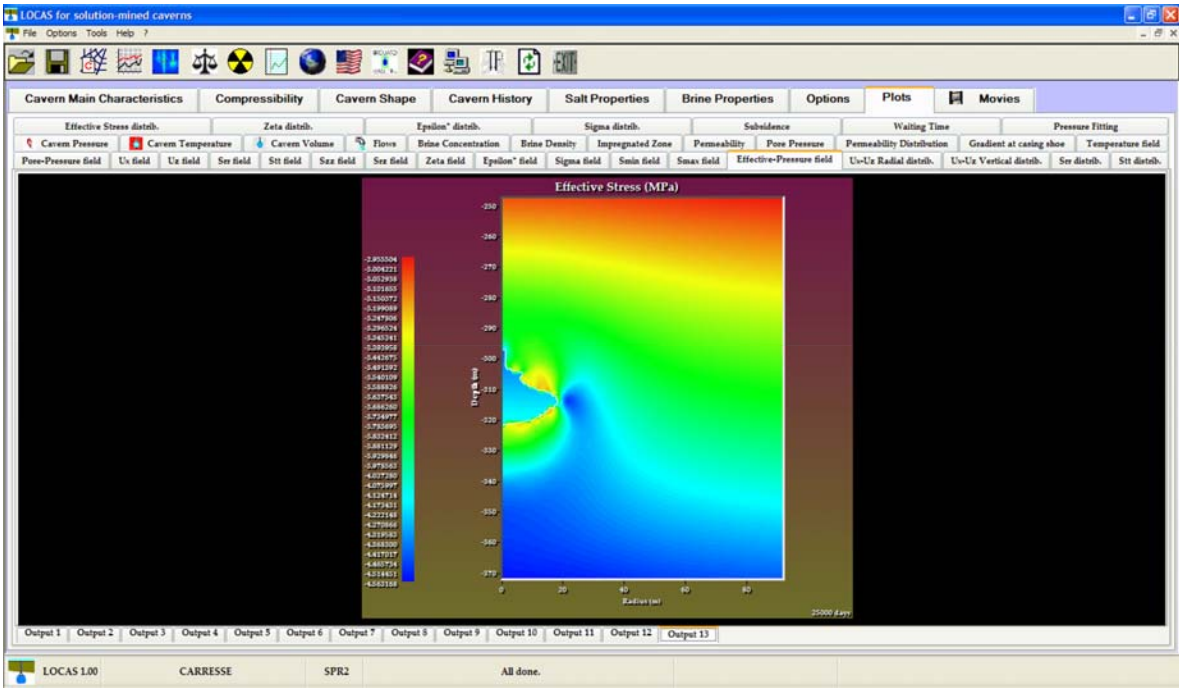

Figure 13 – Example of a long-term effective pressure contour plot.

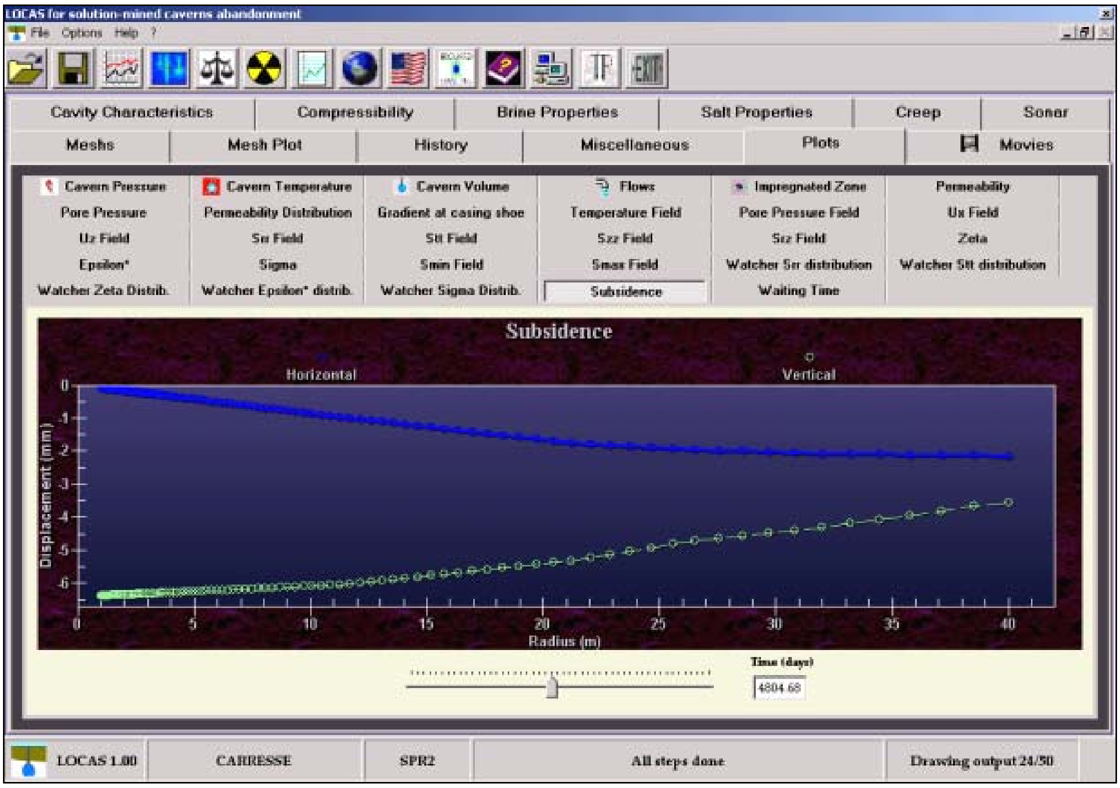

Figure 14 – Subsidence at ground level is plotted as a function radial location; a trackbar allows selection of the requested time.

EXAMPLE APPLICATION

In order to illustrate the possible use of LOCAS, we consider the problem of cavern abandonment.

Regarding the problem of cavern abandonment, the first problem to assess is the long-term evolution of brine temperature in the cavern. In most cases, after cavern abandonment is decided, a waiting period must be observed, as it is not possible to seal the cavern rapidly because brine thermal expansion is still active. Because the necessary waiting period is the most expensive phase to be considered in an abandonment project (Crotogino and Kepplinger, 2006), it is important to estimate as precisely as possible the duration of the waiting period.

If a cavern-temperature measurement taken prior to abandonment is available, LOCAS allows the temperature measurement to be fit by calculating a virtual cavern filling a few months before the measurement. This temperature fitting gives good confidence of the computed long-term evolution.

For the Carresse SPR2 cavern, a temperature measurement was performed in July 2002: the cavern temperature was equal to 18.35 °C and the temperature increase rate was 0.58 °C/year. LOCAS automatically computed that the cavern temperature since July 2002 could be simulated precisely if the cavern were virtually emptied on August 2000 (Figure 15).

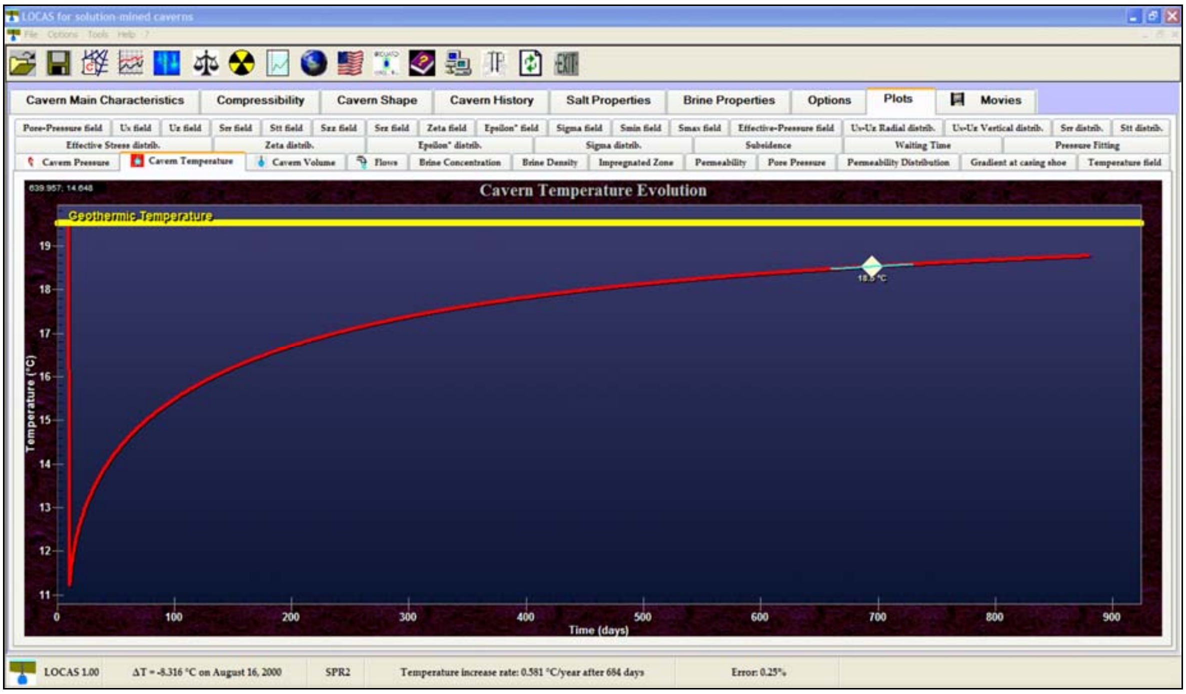

Figure 15 – SPR2 Cavern temperature model automatically fitted by LOCAS.

The former measurement shows that brine thermal expansion was still active in SPR2 cavern in July 2002. The SPR2 cavern is very small (9,000 m^3) and shallow (310 m or 1000 ft). In a larger and deeper cavern, if the cavern is sealed rapidly after the products are withdrawn, internal pressure in many cases will increase to geostatic pressure after several years.

LOCAS also allows calculation of the necessary waiting period (Crotogino and Kepplinger, 2006). During the waiting period, the wellhead is left opened or brine is withdrawn periodically. Figure 16 shows an example of occurrence of a fracture at the casing shoe as a function of the waiting time. If the waiting time is sufficient, no fracture will occur. In this example, the cavern volume is 300,000 m^3 (1,900,000 bbls) at an average depth of 1500 m (4900 ft); the initial cavern temperature is 30 °C, and the initial rate of temperature increase is 2 °C/year. The geothermal temperature at 1500 m is assumed to be 55 °C, and the salt micro-permeability is assumed to be 10^{-21} m^2.

It appears that this cavern must be kept opened for at least 26 years before being sealed (Figure 16). If the cavern is sealed just after 26 years, the cavern pressure will increase to geostatic pressure at the last casing shoe depth; then it will decrease to the final equilibrium pressure (13.5 MPa at cavern average depth).

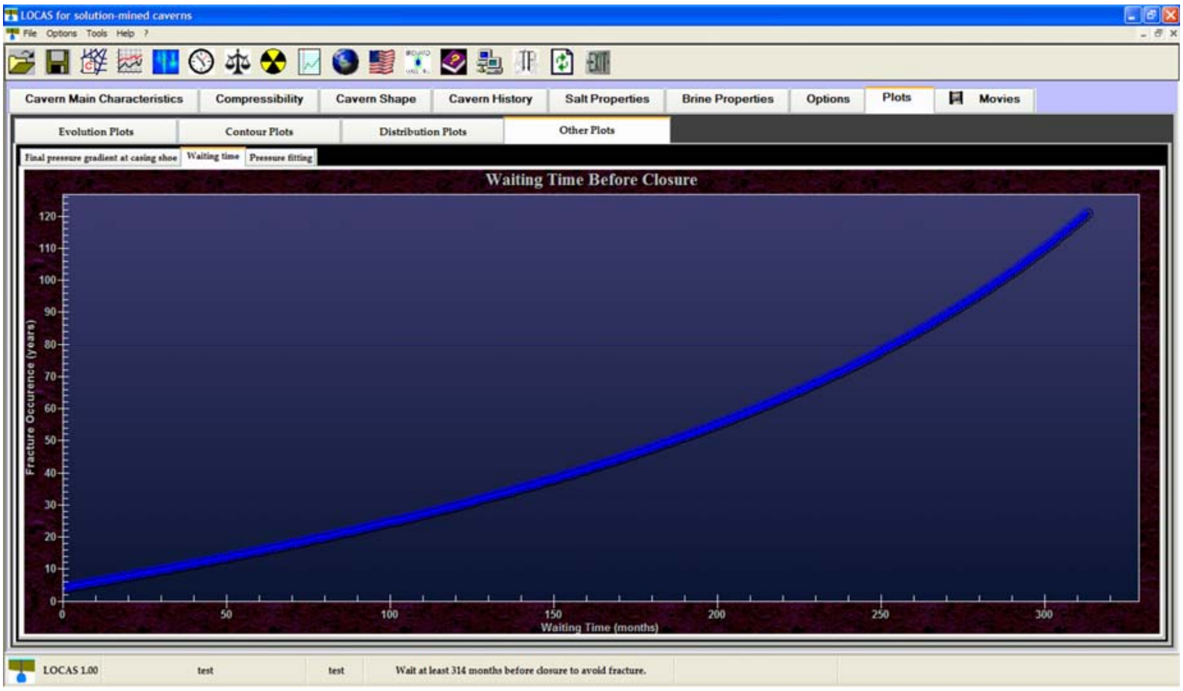

Figure 16 – Time of a fracture occurrence at the cavern roof plotted versus waiting time before cavern closure. (If the cavern is left open for 2 years (24 months) and then definitively sealed, cavern pressure will reach geostatic pressure at casing-shoe depth in approximately 8 years. In this example, this 300,000-m^3 cavern at a 1500-m depth must be kept opened for at least 314 months (26 years) before being shut in definitively.)

CONCLUSIONS

LOCAS works to understand and to predict the short- or long-term behavior of solution-mined caverns. Many phenomena can be taken into account, allowing the user to simulate and understand the behavior of the cavity. Numerous calculation and post-processing features allow computation of many cavern aspects, from short-term mechanical stability to long-term subsidence.

Minimal Hardware Requirements

- Optimized for 32 bits Pentium processors, 64 bits Itanium
- 500 MB of RAM, 1 GB recommended
- 128 MB Video, 256 MB recommended
- Free harddisk space 150 MB
- Screen resolution min. 1024x768
- Windows® NT 4.0; Windows® 2000; Windows® XP; Windows® Vista

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