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Technical Paper

LOSAC ©: A First Salt Cavern Abandonment Software

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LOSAC© : A first salt cavern abandonment software

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Abstract

Over recent years, considerable research effort, especially by the SMRI, has been invested on the subject of the long-term abandonment of salt caverns. At this point in time, the industry has still not clearly identified a universally accepted concept or approach to this major problem. One seemingly promising trend already identified is to consider the evolution of a saturated brine filled salt cavern with respect to the system's thermal (brine expansion), geomechanical (cavern closure by creep) and hydraulic (brine micro-permeation in the salt massif) characteristics. Gaz de France has applied such a concept in the development of a computer programme named LOSAC intended to evaluate the long-term evolution of its salt caverns in different abandonment scenarios.

LOSAC is financed by Gaz de France and developed with Brouard Consulting and LMS/Ecole polytechnique (France). This presentation proposes a short demonstration of the software with the aim of illustrating a practical application of this specific cavern abandonment concept in a very user-friendly computer program.

1. Introduction

Thousands of caverns have been leached out from deep salt formations. They are used for saturated brine production and/or hydrocarbons storage. They will be abandoned some day: the access well will be plugged with cement, isolating a large bubble of saturated brine. The later evolution of such a bubble raises serious concerns for environmental protection; salt creep and brine thermal expansion can lead to brine pressure build-up and rock-mass fracture, then brine seepage can lead to pollution of overlying water-bearing strata. Taking into account salt formation permeability leads to less pessimistic scenarios. LOSAC allows simulating brine pressure increase in a closed cavern taking into account all phenomena that play a role in this context.

2. Abandonment problem

2.1 General scenario

Most experts agree on the following general scenario. In most cases, prior to abandonment, the cavern will be filled with brine. Its initial pressure when the cavern is closed will result from the weight of a brine column filling the well from the surface to the cavern. Then a special steel plug will be set at casing seat and cement will be poured in the well, isolating a large ``bubble'' of fluid whose future evolution is the main concern of the present paper. After the cavern is closed and abandoned, cavern brine pressure will build up. Results of several so-called ``shut-in pressure tests'' clearly support this view (Bérest et al., 1979; You et al., 1994; Van Sambeek, 1990; Fokker, 1995; Bérest et al., 1998, Bérest et al., 2000a).

2.2 Final pressure in the cavity

The final value of cavern brine pressure is of utmost importance from the environmental protection point of view. In salt formation, the natural state of stress resulting from overburden weight is generally assumed to be isotropic. Several authors think that in many cases brine pressure will after some time reach a figure larger than geostatic pressure, then leading to hydrofracturing; brine will flow upward through fractures, to shallow water-bearing strata, leading to water pollution, cavern collapse and subsidence. Consequences will be more severe when the cavern contains wastes (Tomasko et al., 1997). This pessimistic scenario can be alleviated by taking into account salt permeability.

2.3 Three main phenomena

Three main physical mechanisms governing pressure build up are identified:

- a mechanical phenomenon : salt creep,
- a thermal phenomenon: brine thermal expansion,
- a hydraulical phenomenon: brine permeation.

2.3.1 Salt Creep

The role of cavern creep has been clearly identified, for instance by Langer et al. (1984), Wallner (1986), Cauberg et al. (1986), Van Sambeek (1990), Bérest (1990), Rolfs et al. (1996), Wallner and Paar (1997): salt mass creep leads to cavern shrinkage; cavern brine is offered smaller room and its pressure builds up in a sealed cavern. The process is slower when cavern pressure is high, and ultimately stops when cavern pressure is equal to geostatic.

2.3.2 Brine thermal expansion

Bérest et al. (1979) outlined the role played by brine thermal expansion: temperature distribution after cavern creation is out of equilibrium, brine is significantly cooler than salt mass; heat transfer from the salt mass leads to brine warming, thermal expansion and pressure build up. This idea has also been discussed by Hugout (1988), Ehgartner and Linn (1994), Bérest et al. (1995).

2.3.3 Brine permeation

For every standard engineering purpose, rock salt can be considered as an impermeable rock. The generally small permeability numbers resulting from laboratory tests are scattered, but they are suspect of being influenced by several biases (sampling, rock decompression, etc.)
Few in-situ tests are available; experiments performed at the WIPP site (Howarth et al., 1991) provide permeabilities as small as K=10^{-21} m² for undisturbed salt. A one-year-long test, performed in a well and supported by the SMRI (Durup, 1994), gave K=$6\cdot10^{-20}$ m². How small these numbers are is clearly demonstrated when one remembers that hydrogeology textbooks generally define an impermeable rock as a one whose permeability is smaller than K =10^{-17} m², a figure that exceeds the measured values described above by two orders of magnitude or more. It means that, when short-term use of salt caverns is considered, for instance, when hydrocarbons are stored, salt caverns can be considered extremely safe from the perspective of product confinement.

Bérest (1990) suggested that brine transfer to the salt formation through permeation--like phenomena is also to be taken into account in the abandonment problem. Cosenza and Ghoreychi (1996) proposed a set of equations governing pressure evolution in a sealed and abandoned cavern. Further contributions by Cosenza and Ghoreychi (1996), Bérest et al. (1997), Pfeifle et al. (1998) analyzed the role of this factor: even if exceedingly small in terms of yearly fluid flow, brine transfer can lead to significant pressure release.

However, the pioneering work of Fokker (1995) proved that a "secondary" permeability can be induced by high brine pressure in the cavern: tensile effective stresses at cavern wall provoke rock damage and a porosity/permeability increase. (Such a phenomenon must be distinguished from discrete fracture creation, which is the ultimate result of this damaging process.) Computations have proven that this permeability increase is probably large enough to allow significant brine outflow from the cavern (Ehgartner and Tidwell, 2000).

With regard to hydraulic fracturing in salt, Fokker's view has been confirmed by later SMRI-supported tests performed on hollow spherical samples (Bérest et al., 2000b and 2001a). Evaluations of these permeability tests (Stormont, 2001, Malinsky, 2001), and interpretation, based on this laboratory tests, of an earlier in-situ test (Hauck et al., 2001) allows to issue three different damaging criteria. These criteria give a quantitative relative relationship of permeability change and stress. Although still open to discussion, a stress-induced permeability increase can provide optimistic scenarios for the long-term behavior of a closed cavern in an impermeable salt formation: the rock mass self-adapts when high fluid pressures are involved to prevent fracturing. In-situ validations are still needed.

However, when very long-term behavior is considered, the general picture changes --- especially when considering the problem of pressure build-up in a closed cavern. Due to high cavern compressibility, even tiny losses of fluid can significantly lessen the effect of cavern creep and prevent cavern pressure from reaching high levels, or pressure can transiently reach high levels without major fracture creation (see Figure 10).

2.4 A very important parameter: cavern compressibility

Cavern pressure build-up rate $\dot{P}_c$ is a function of cavern volume change ΔV that is due to creep, brine thermal expansion, brine permeation and complementary dissolution:

$$\dot{P}_c = -\frac{\Delta V}{\beta V}$$

Where βV is cavern compressibility, this parameter can be quite easily measured in situ. The cavern compressibility can be also estimated, it depends on cavity shape, salt elastic parameters, brine compressibility and dissolution parameters (see Bérest et al., 1999). LOSAC automatically estimates βV when a related parameter is modified in the forms (see paragraph 3.5). If a compressibility measurement have been performed on the considered cavern, the actual value of βV can be put in the form called "Compressibility".

3. LOSAC – a program to simulate cavern abandonment

LOSAC can be used for processing a pressure build-up calculation, this goal requires relevant data be input. All inputs are made via user-friendly windows (see Figures 1 to 6). Users can select the international units system (m, °C, MPa, m^3 …) or a US units system (ft, °F, psi, MMbbls…). Default data are proposed to users, some parameters, as for instance cavern estimated compressibility or geothermal temperature at cavern average depth, are automatically calculated when some input data, for instance cavern depth or cavern volume, are modified. Nevertheless, LOSAC allows the user modifying all these –automatically--estimated data.

3.1. Phenomena taken into account in LOSAC

The following phenomena are considered in LOSAC for the calculations:

- Stationary (or secondary) salt creep assuming Norton-Hoff law.
- Brine heating and thermal expansion.
- Brine micro-permeation assuming Darcy's law.
- Variable cavern compressibility (function of brine pressure and temperature.)
- Complementary dissolution of salt.
- Salt damaging, i.e., increase of salt permeability according to a criterion (choice between three criteria: IUB, Stormont or LMS.)

3.2. Cavity Shape

LOSAC allows calculations using a simple shape for the considered cavity; the cavern volume must be the same as the real cavern. The available shapes are sphere, vertical cylinder, and horizontal cylinder. The choice of a simple axisymetrical shape is used to estimate the cavern compressibility and to perform semi-analytical calculations for the thermal, mechanical and hydraulical problems. The pear-shaped cavities can also be considered for the compressibility estimation. Most cavities used for storage of hydrocarbons exhibits a shape that is quite similar to these simple shapes. Calculations using the finite elements method (FEM) show a good agreement with LOSAC when the cavity shape is axisymetric and not too irregular.

The following properties and parameters are considered (Figure 1):

Cavern volume	Casing-shoe depth
Cavern height	Initial cavern compressibility
Cavern average diameter	Cavern average depth
Geothermic temperature at cavern average depth	Cavern shape

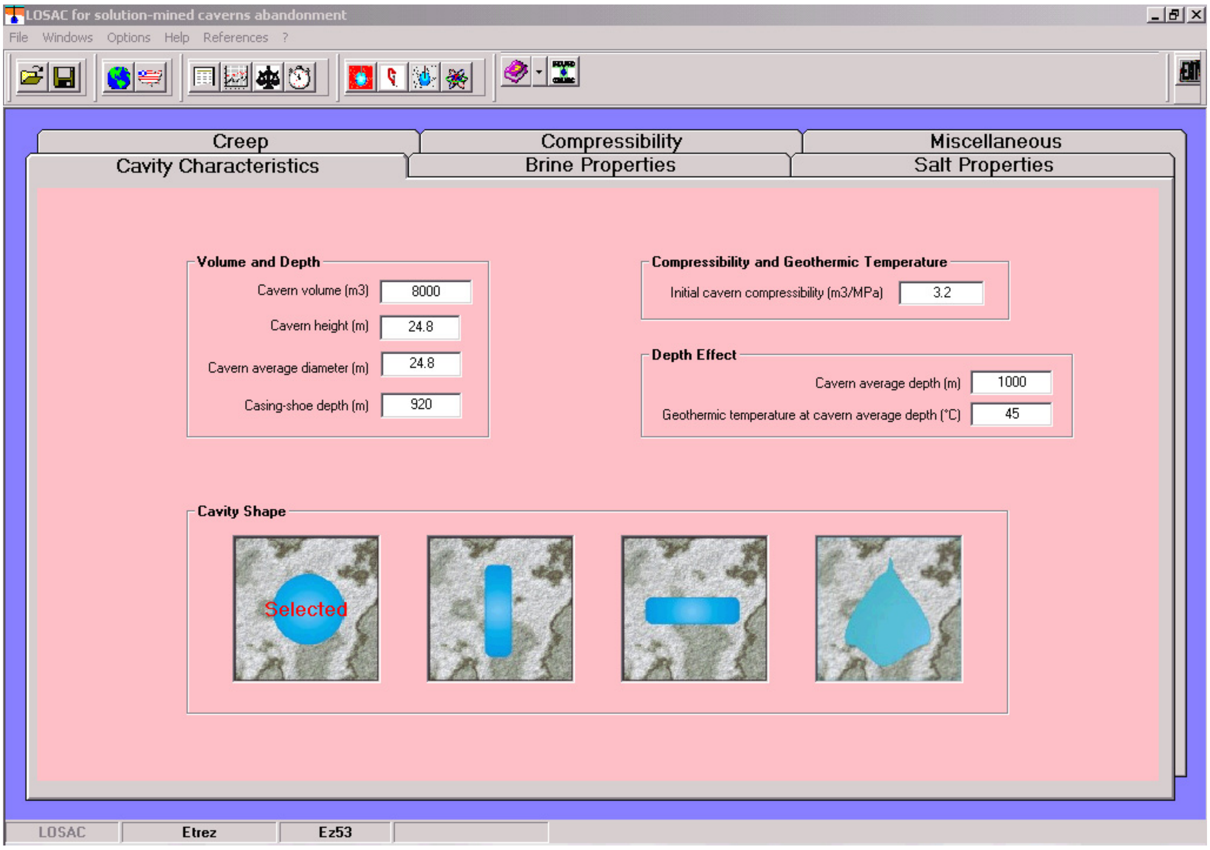


Figure 1 – Input window for cavity characteristics.

3.3. Brine Properties

The following brine properties are considered (Figure 2):

Brine thermal capacity	Average brine density in the well
Brine thermal expansion coefficient	Brine dynamic viscosity

Dissolution parameters are also considered, i.e., saturated-brine concentration C_b^{sat} (salt mass divided by brine mass) and saturated-brine density ρ_b^{sat} as a function of cavern average pressure P_c and cavern average temperature T_c.

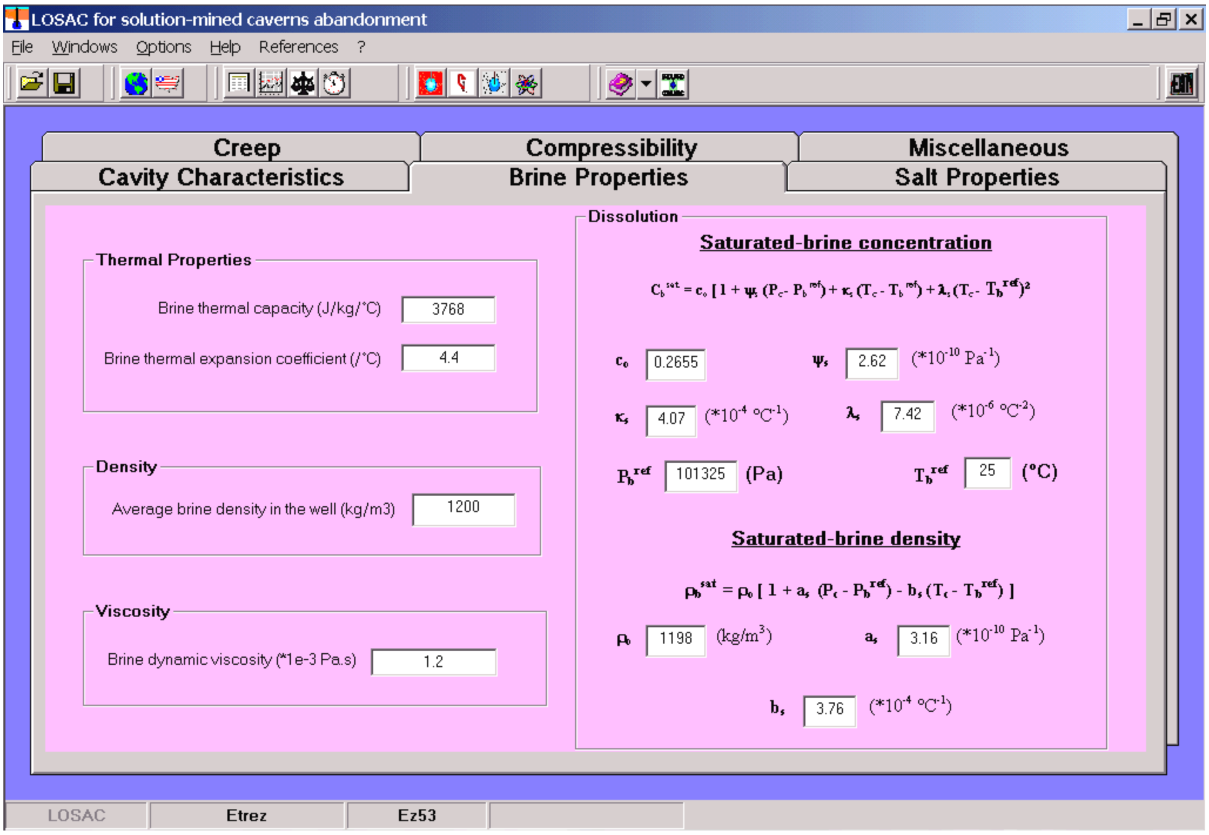


Figure 2 - Input window for brine properties.

3.3 Salt Properties

The following brine properties are considered (Figure 3):

Salt density	Salt initial permeability
Salt thermal capacity	Salt initial porosity
Salt thermal diffusivity	Salt matrix compressibility factor

In this window users choose to keep the salt permeability constant (default case) or to enable damaging by selecting a damage criterion (IUB, Stormont, or LMS criterion).

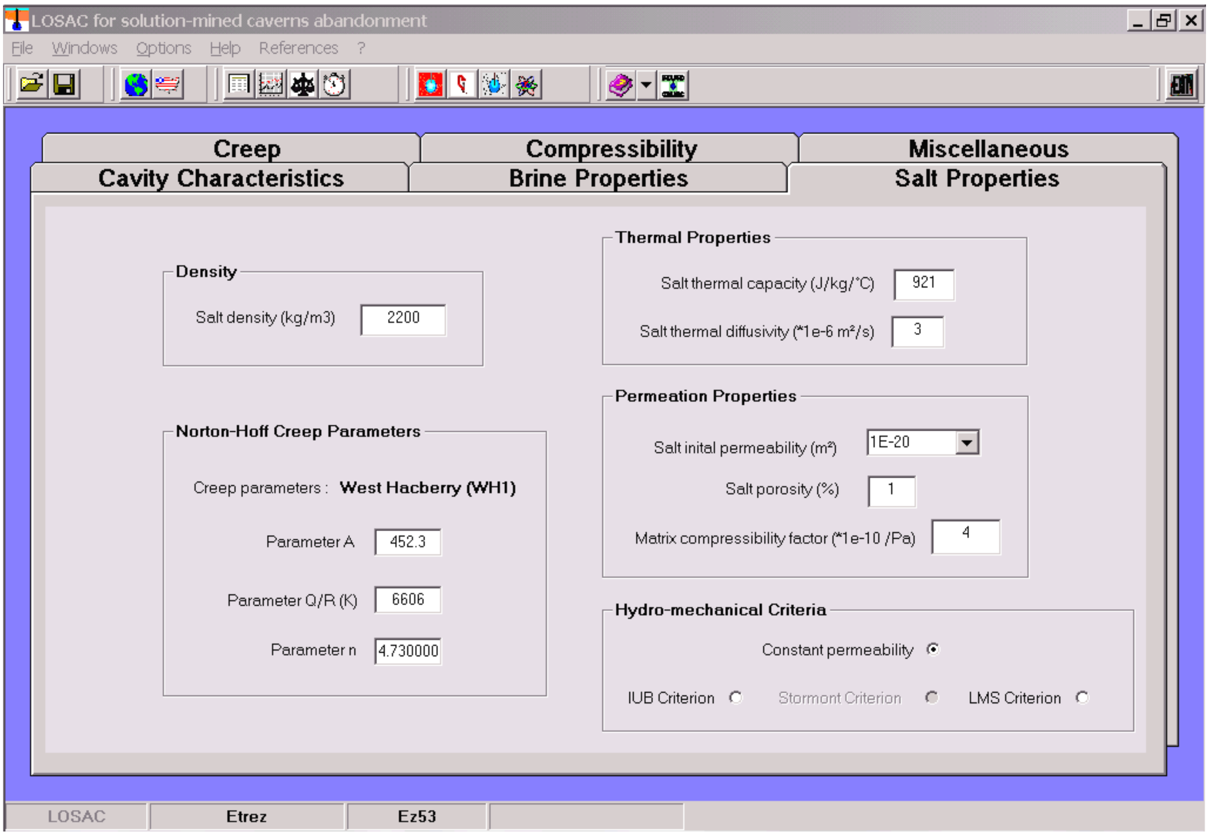


Figure 3 - Input window for salt properties.

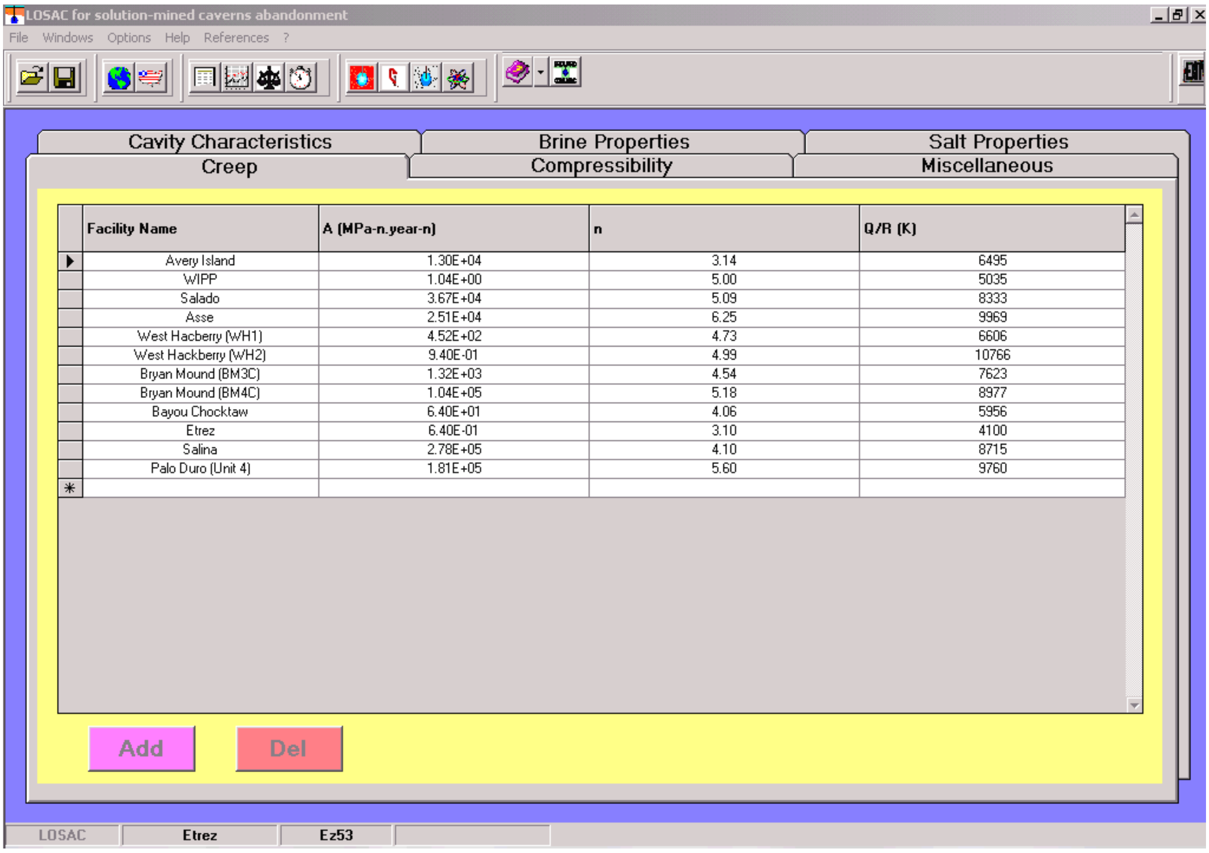
3.4 Creep Parameters

An internal database exists in LOSAC for managing the salt creep parameters (see Figure 4). The considered creep law for the long-term behavior of salt is the so-called "Norton-Hoff" law which requisites four parameters: *A*, *Q/R* and *n*

$$\dot{\varepsilon} = A \exp\left(-\frac{QR}{T}\right).\sigma^{n}$$

Where $\dot{\varepsilon}$ is the strain rate.

The proposed salts parameters come from papers dealing with long-term salt creep; a tentative classification of salts according to their creep properties can be found in Brouard and Bérest (1998). LOSAC allows choosing one of the proposed salts or introducing his own parameters in the database.



Facility Name	A (MPa-n.year-n)	n	Q/R (K)
Avery Island	1.30E+04	3.14	6495
WIPP	1.04E+00	5.00	5035
Salado	3.67E+04	5.09	8333
Asse	2.51E+04	6.25	9969
West Hacberry (WH1)	4.52E+02	4.73	6606
West Hackberry (WH2)	9.40E-01	4.99	10766
Bryan Mound (BM3C)	1.32E+03	4.54	7623
Bryan Mound (BM4C)	1.04E+05	5.18	8977
Bayou Chocktaw	6.40E+01	4.06	5956
Etrez	6.40E-01	3.10	4100
Salina	2.78E+05	4.10	8715
Palo Duro (Unit 4)	1.81E+05	5.60	9760

Figure 4 - Input window for creep parameters.

3.5 Cavern Compressibility

There are three inputs in this window (Figure 5):

Salt Young's modulus	Salt Poisson's ratio	Initial brine compressibility factor β_b

This window automatically displays results of cavern compressibility βV estimation according to input data, i.e., the value of the following parameters are displayed:

- Estimated rock-salt compressibility factor β_r
- Estimated cavern compressibility factor β
- Estimated cavern compressibility βV

Where V is cavern volume and $\beta = \beta_b + \beta_r$ (see Bérest et al., 1999).

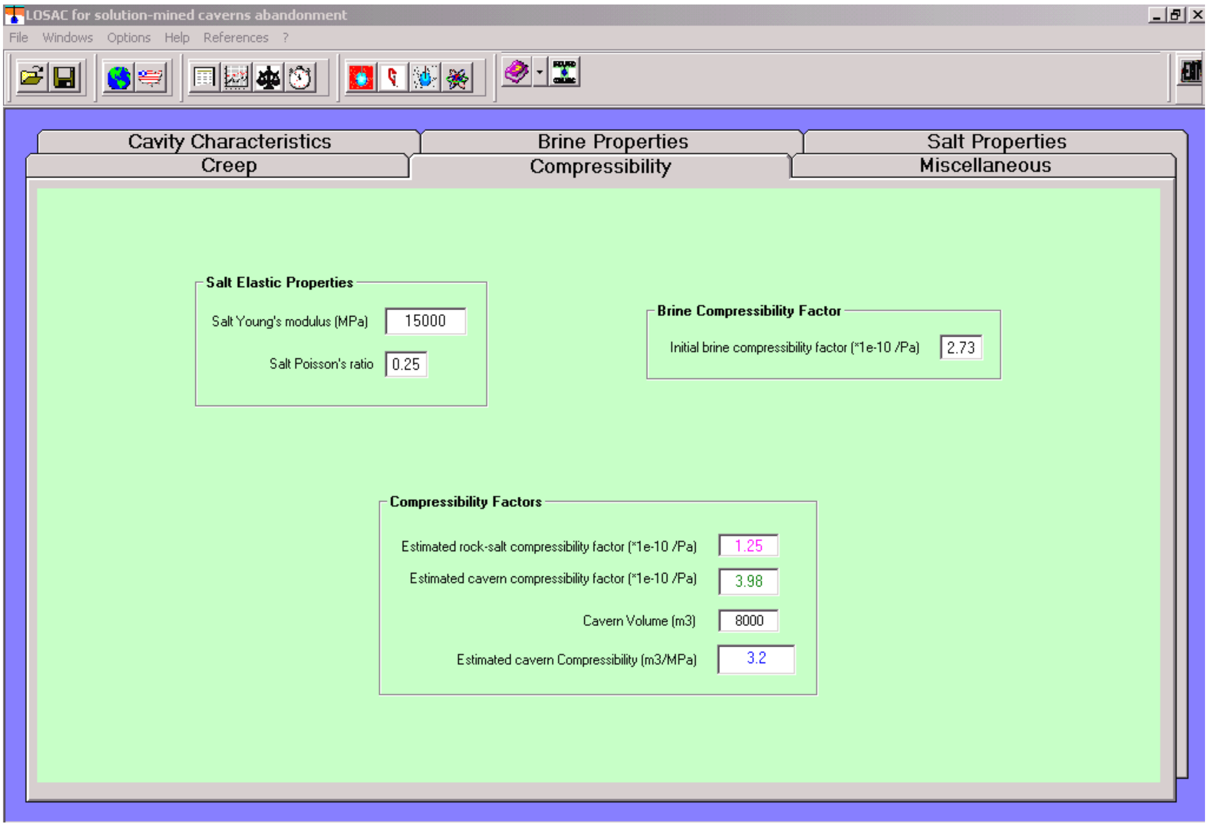


Figure 5 – Input/Output window for compressibilities.

3.6 Miscellaneous

This window (Figure 6) first displays some information about the cavity, i.e., cavity and facility names. The other important inputs here are for **initial** conditions:

Cavern average temperature	Well-head pressure	Waiting time before closure

This "waiting time" means that --for the simulations-- the cavern is left opened at wellhead during a certain time, during this period the pressure is kept constant in the cavern ("halmostatic pressure"), after that the wellhead is closed and the pressure is able to increase.

This window also displays the "limit time for plotting" which represents the maximum time for the calculation (for instance, calculation up to 50 years) and the paths to the data and results files.

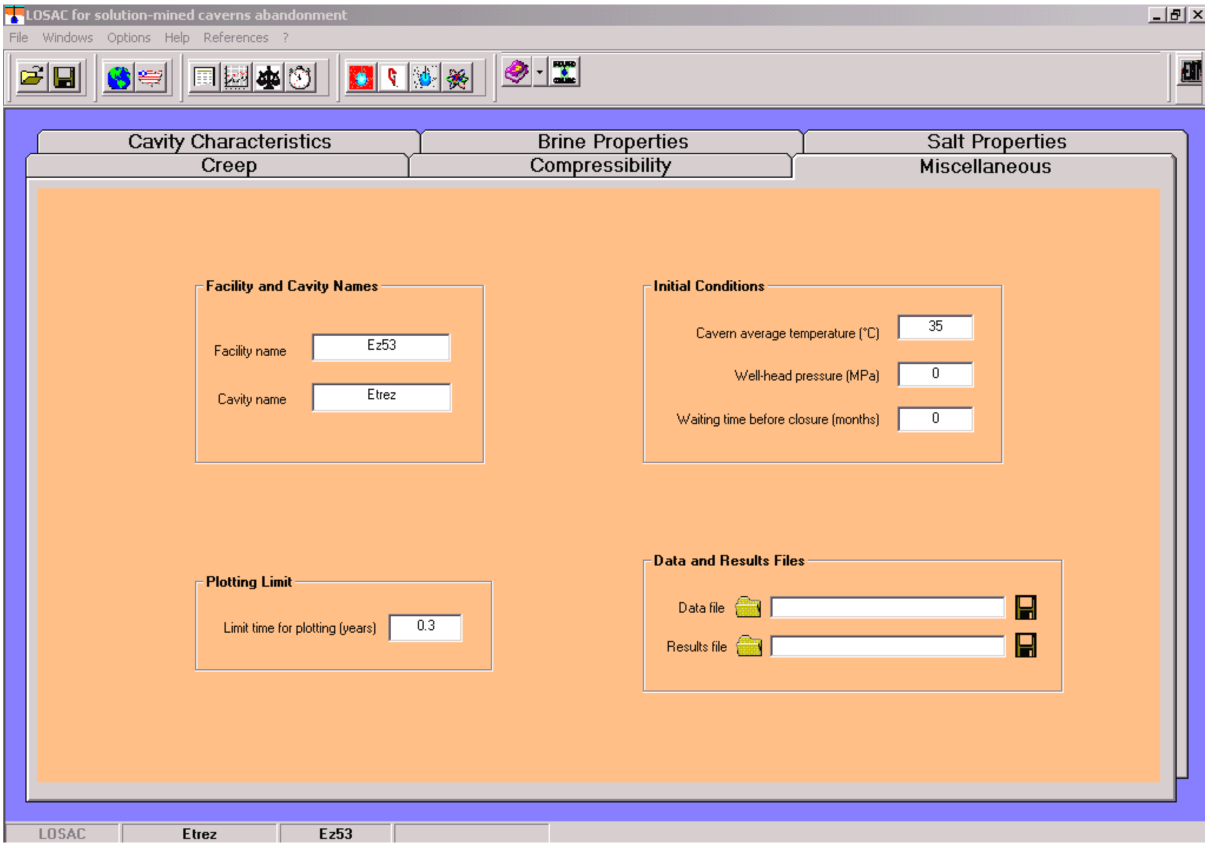


Figure 6 - Input window for miscellaneous.

All data inputs can be save in an external ASCII file and imported in LOSAC when necessary.

4. Hypothesis in LOSAC

- The thermal calculations in LOSAC are made assuming a uniform temperature in the cavity; we have made this hypothesis because of the existence of a natural convection due to the natural geothermal gradient in the salt mass (see Bérest et al., 2001b).
- The cavity is assumed to be plugged at wellhead; there is no cement plug in the well. This hypothesis does not change the results of the computations; it has been done in order to allow in-situ verifications of pressure build-up by easy measurements at ground level.
- The cavern is assumed to be filled with saturated brine; this brine is kept saturated during the calculations (complementary dissolution when pressure and temperature increase).

5. LOSAC outputs

5.1 Basic plots

When calculations are completed, LOSAC displays several plots:

- Wellhead pressure versus time (see Figure 7).
- Fluid temperature versus time (see Figure 8).
- Cavern volume versus time (see Figure 8).
- Impregnated zone versus times (see Figure 9).

Some examples of such plots are given on figure 7 to 9, the considered cavity is Ez53 from the Etrez facility (Gaz de France); an in situ test supported by the SMRI (Bérest et al., 2001b) allowed to verify these simulation results.

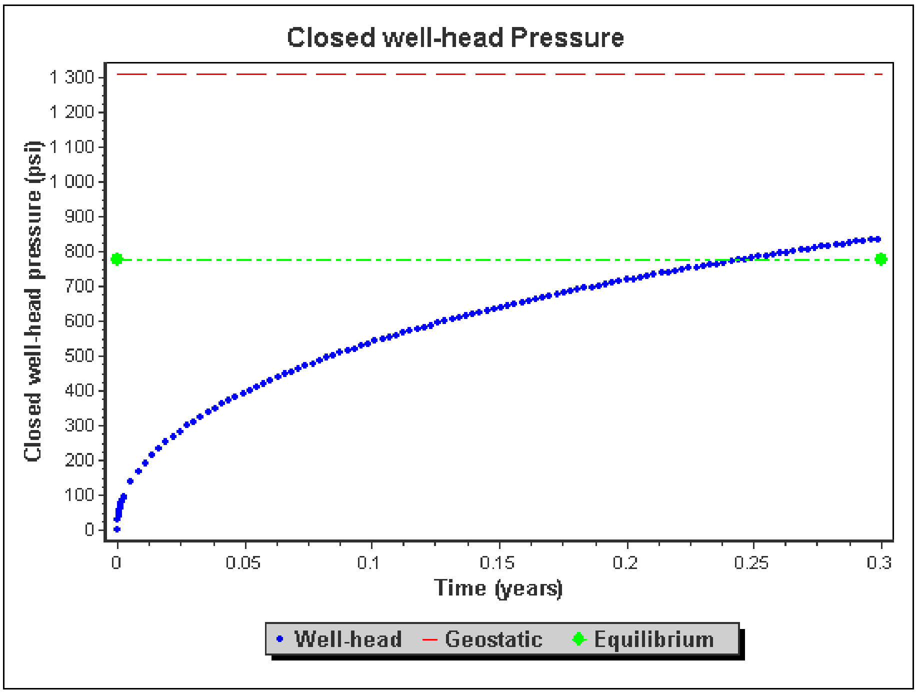


Figure 7 - Example of pressure build-up simulation.

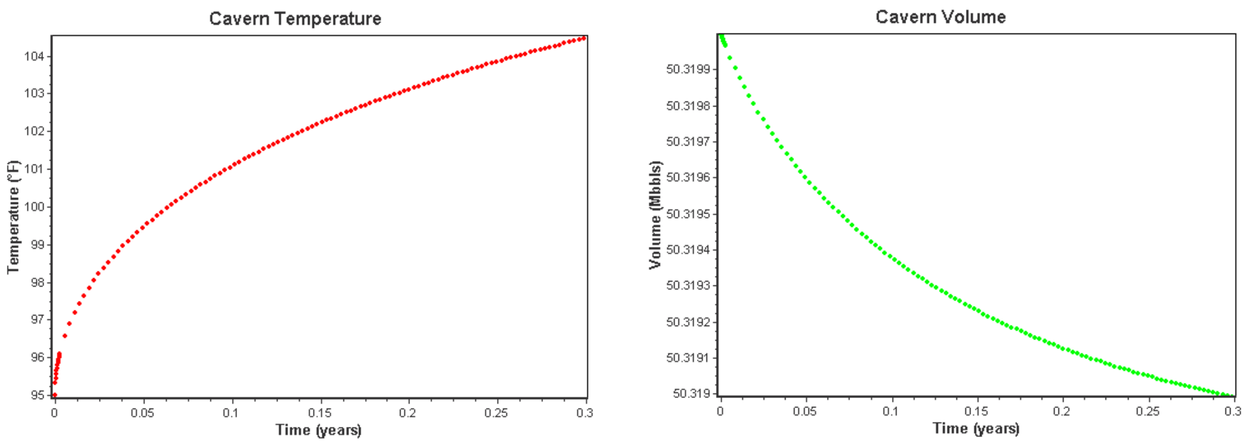


Figure 8 - Example of cavern temperature (left) and cavern volume (right) evolution.

The considered –constant-- salt permeability is K=10^{-20} m²; the so-called "impregnated zone" is defined as the zone where the brine has permeated assuming a uniform radial permeation. An example of the evolution of the impregnated zone is given on figure 9.

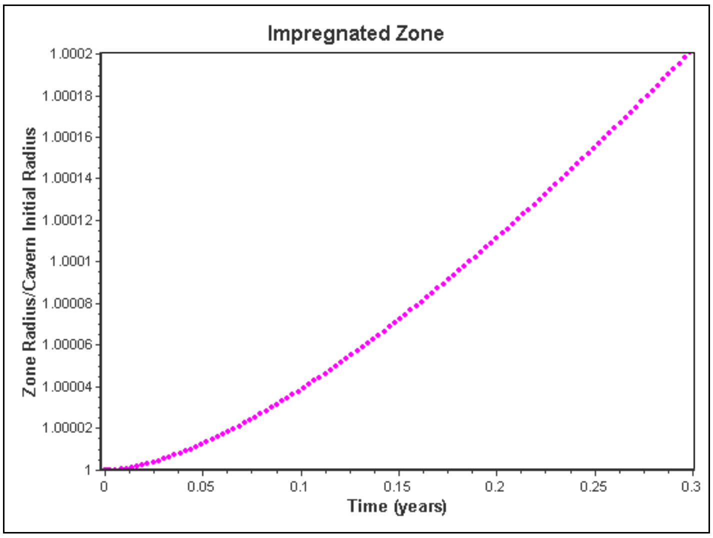


Figure 9 - Example of impregnated zone evolution.

5.2 Case of salt damaging

If some salt damaging occurred during the calculation (a damage criterion has been selected), then three other plots are displayed:

- Salt permeability distribution in the salt at the end of calculation as a function of radial position (see Figure 11).
- Pore pressure distribution in the salt at the end of calculation as a function of radial position (see Figure 12).
- Normalized permeability distribution in the salt at the end of calculation as a function of radial position (see Figure 13).

For the presented example, a V=50,000 m^3 cavity has been considered. The cavity is 1000 m deep; the brine initial temperature in the cavity is 15°C; the geothermic temperature at cavern average depth is 45°C. The waiting time before closure is 1 year, the figure 10 shows that during this waiting period the cavern pressure is kept constant (no pressure at wellhead). The LMS criterion for salt damaging has been selected. When brine pressure at casing-shoe depth becomes greater than the geostatic pressure at that depth, the calculation goes on, the salt permeability increases around the cavity wall as soon as the LMS criterion is checked (in this example, it is a few MPa below geostatic pressure at casing-shoe depth, i.e. just below "Geostatic" line on Figure 10.)

Figure 11 displays "salt equivalent permeability" versus time; this is a permeability that gives the same brine flow considering a uniform permeability in the salt around the cavity. This equivalent permeability decreases when cavity pressure begins to decrease; this is a kind of healing simulated by the damaging criterion.

Figure 12 and 13 display stationary pore pressure distribution and permeability distribution respectively as a function of radial position. Figure 13 shows that only a thin ring (less than 2 radii) around the cavern exhibits a increased permeability

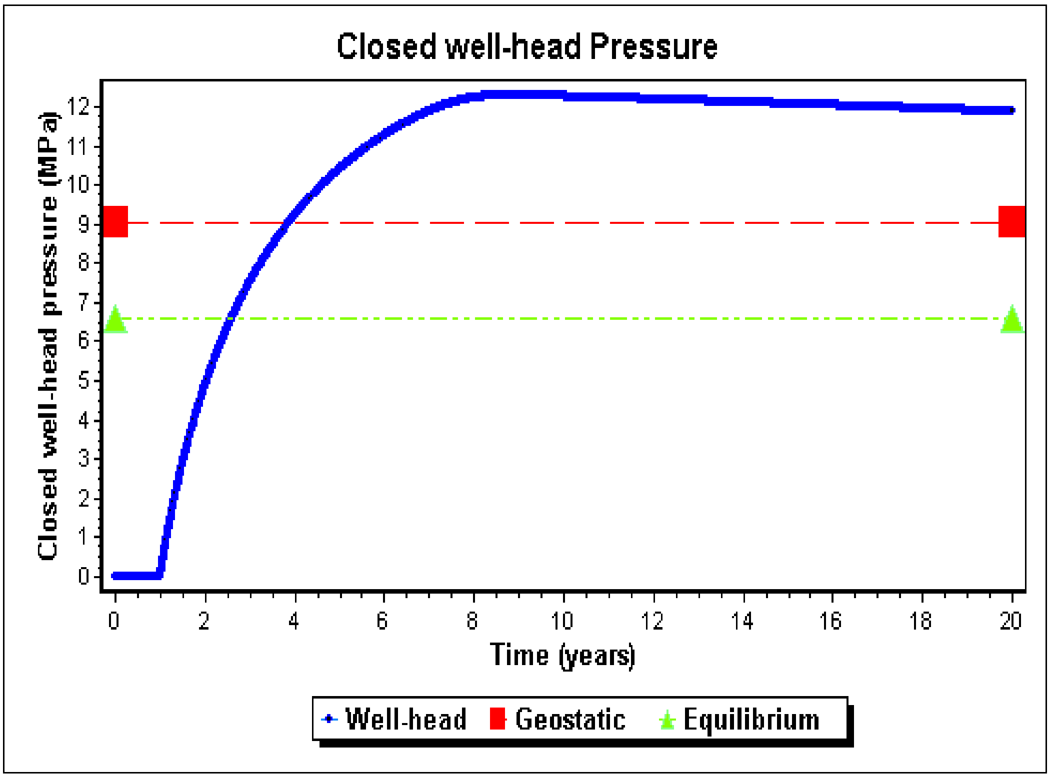


Figure 10 - Example of pressure build-up simulation with damage occurrence.

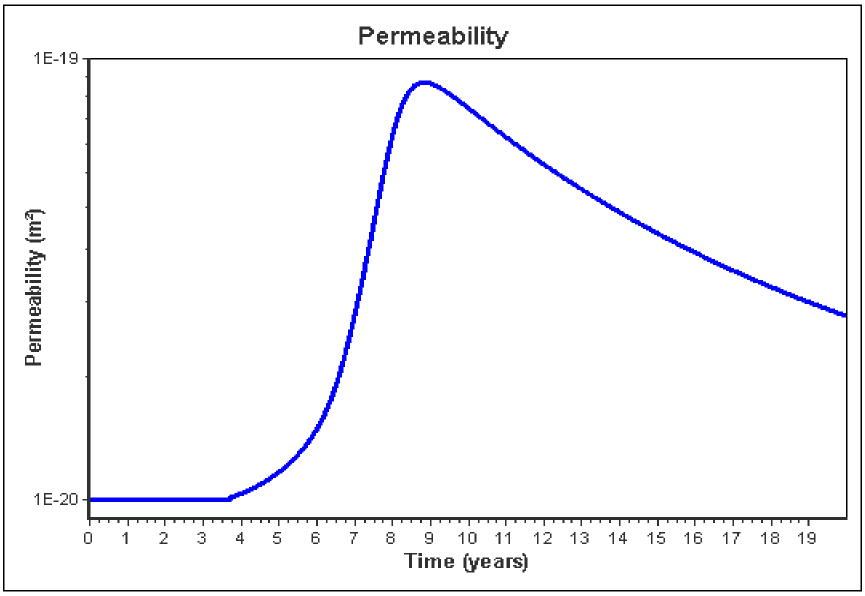


Figure 11 - Example of salt equivalent permeability evolution.

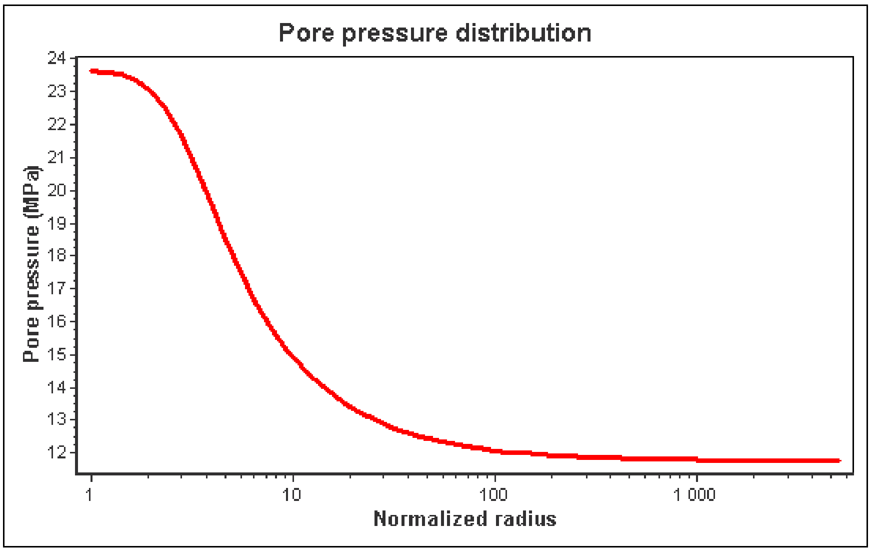


Figure 12 - Example of stationary radial pore pressure distribution in the salt.

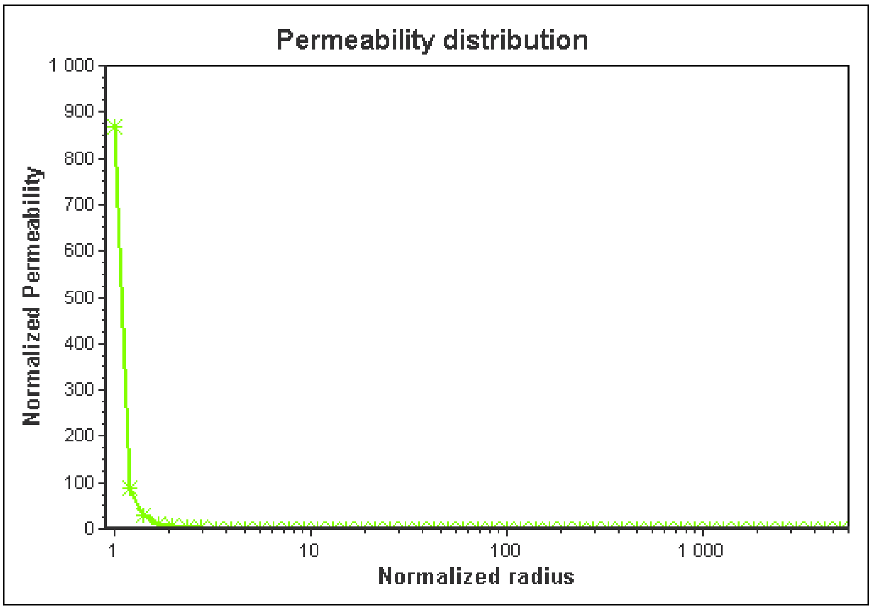


Figure 13 - Example of normalized permeability distribution as a function of radial position.

5.3 Calculation of the waiting time before closure

LOSAC allows calculating the necessary waiting time before well plug in order to avoid fracture creation, i.e. to avoid that brine pressure reaches --one day in the future-- geostatic pressure at casing-shoe depth.

5.4 Calculation of the equilibrium pressure

LOSAC is able to calculate and display the value of the equilibrium pressure, this is the final pressure at cavern average depth when brine micro-permeation exactly balances secondary creep.

5.5 Miscellaneous

All figures all full customizable (line style, line colors, background color, fonts, legend, title…) and can be directly printed. It is also possible to copy bitmap or metafile images (gif, jpg, bmp, tiff, png) to the Windows clipboard for direct pasting into reports.

All calculations results can be saved as ASCII output files that can be imported in MS Excel for instance.

Conclusions

- LOSAC is a very user-friendly program that is devoted to the calculation of pressure evolution in a closed cavern.
- LOSAC is able to calculate the waiting time before closure that allows avoiding future fracture due to pressure build up over geostatic pressure.
- LOSAC integrates the last knowledge about salt permeability and long-term behavior of solution-mined cavities.
- LOSAC has been successfully compared with calculations performed with a finite elements code assuming relatively simple shape.
- This software runs on conventional personal computers under Windows 95, 98, NT4, 2000, XP. LOSAC is available only in an English version and is capable to handle international and US units.
- The LOSAC software can be used without any additional need of other related software packages.

Contacts

For further information, trial version, prices, please contact Brouard Consulting, LOSAC@Brouard-Consulting.com, or visit LOSAC Web Site: http://www.Brouard-Consulting.com/LOSAC.htm

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