USING LOCAS SOFTWARE TO PREDICT THE LONG-TERM BEHAVIOR OF SALT CAVERNS

Technical Class

SMRI Fall Meeting - Leipzig, Germany

October 3, 2010

OUTLINE

- Introduction - LOCAS main features
- Example of application: cavern abandonment
- Conclusions

QUICK INTRODUCTION

WHAT IS LOCAS?

- A 2D axisymetrical Finite Element code
- A fully coupled Thermo-Hydro-Mechanical code
- A powerful –but user-friendly– Windows® software

WHAT IS IT FOR?

- Study of liquid-filled or gas-filled salt caverns
- Short-term and long-term behavior of caverns

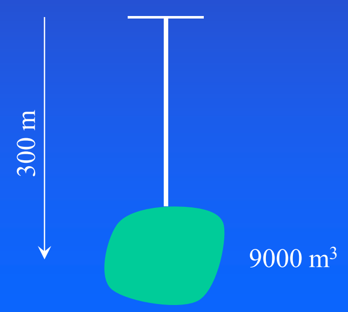
Examples of applications:

- Stability of cavern at min/max pressure, cycling
- Analysis of Mechanical Integrity Tests
- Abandonment of salt caverns

EXAMPLE OF APPLICATION

CAVERN ABANDONMENT

Carresse SPR2 cavern test supported by SMRI



KEY POINTS IN THE ANALYSIS OF AN ABANDONMENT TEST

- PRELIMINARY TASKS

Task 1: Calculate cavern pressure evolution during the test

Task 2: Calculate long-term cavern temperature evolution

Task 3: Assess casing/casing shoe leaks during the test

- DETERMINATION OF SALT PARAMETERS

  - Mechanical parameters
    - elasticity
    - secondary creep (Norton-Hoff)
  - Hydraulical parameters: salt permeability at cavern scale

- LONG-TERM FEM COMPUTATIONS → PREDICTIONS

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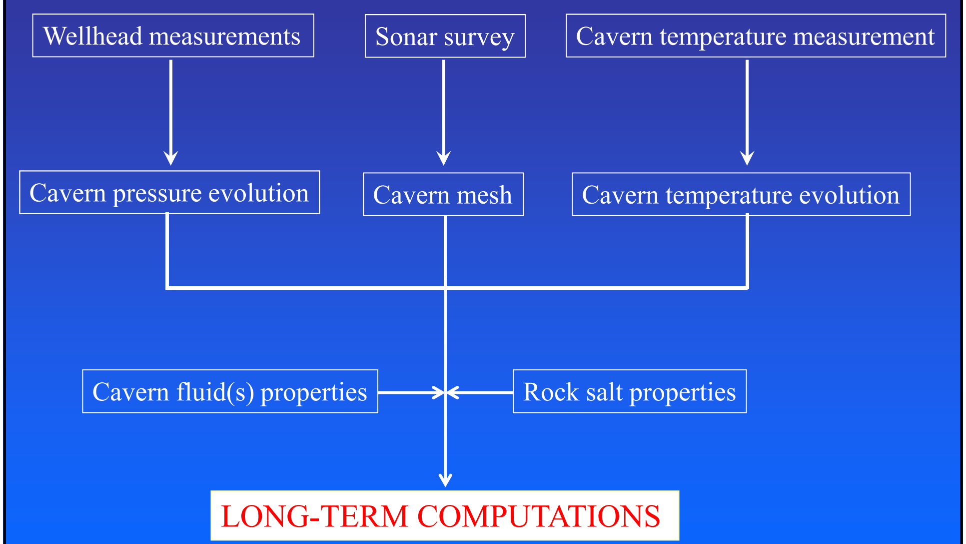
ANALYSIS OF A PRE-ABANDONMENT TEST



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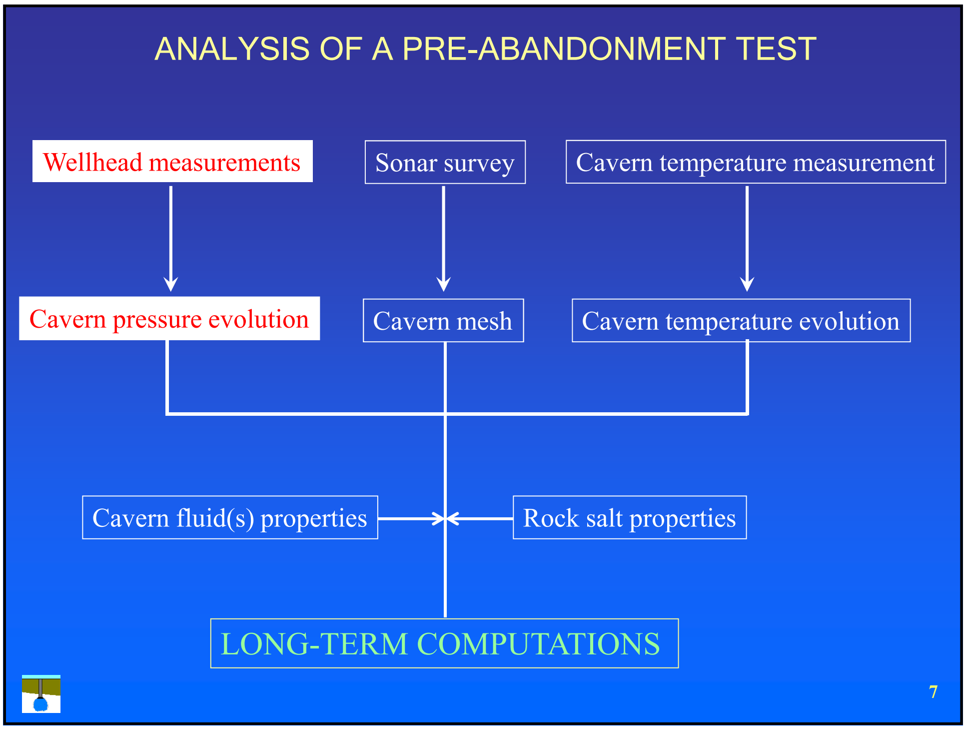
ANALYSIS OF A PRE-ABANDONMENT TEST
Wellhead measurements
Sonar survey
Cavern temperature measurement
Cavern pressure evolution
Cavern mesh
Cavern temperature evolution
Cavern fluid(s) properties
Rock salt properties
LONG-TERM COMPUTATIONS
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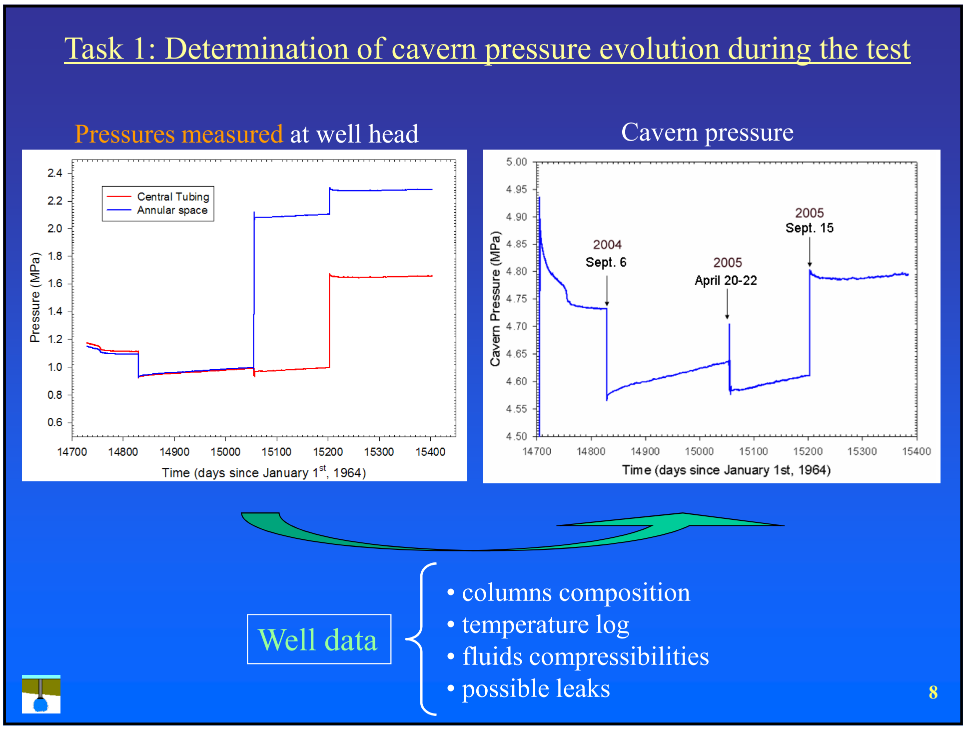
Task 1: Determination of cavern pressure evolution during the test
Pressures measured at well head
Central Tubing
Annular space
Pressure (MPa)
Time (days since January 1st, 1964)
Cavern pressure
Cavern Pressure (MPa)
2004
Sept. 6
2005
April 20-22
2005
Sept. 15
Time (days since January 1st, 1964)
Well data
• columns composition
• temperature log
• fluids compressibilities
• possible leaks
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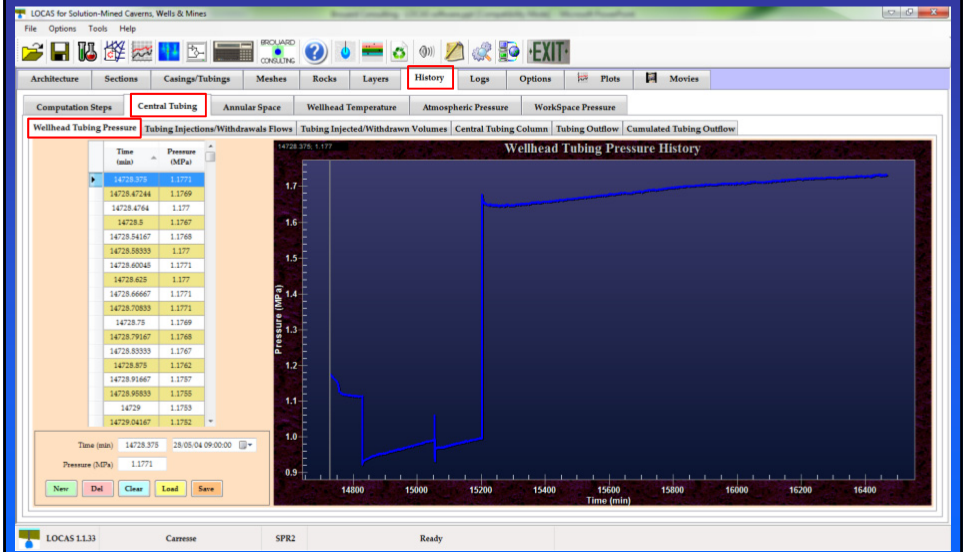
History of Wellhead Pressures



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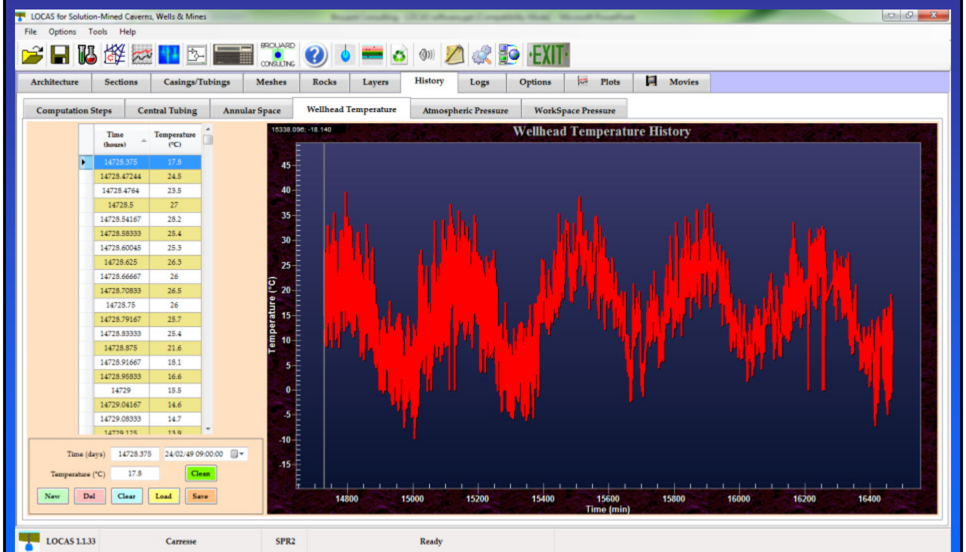
History of Ground Temperature



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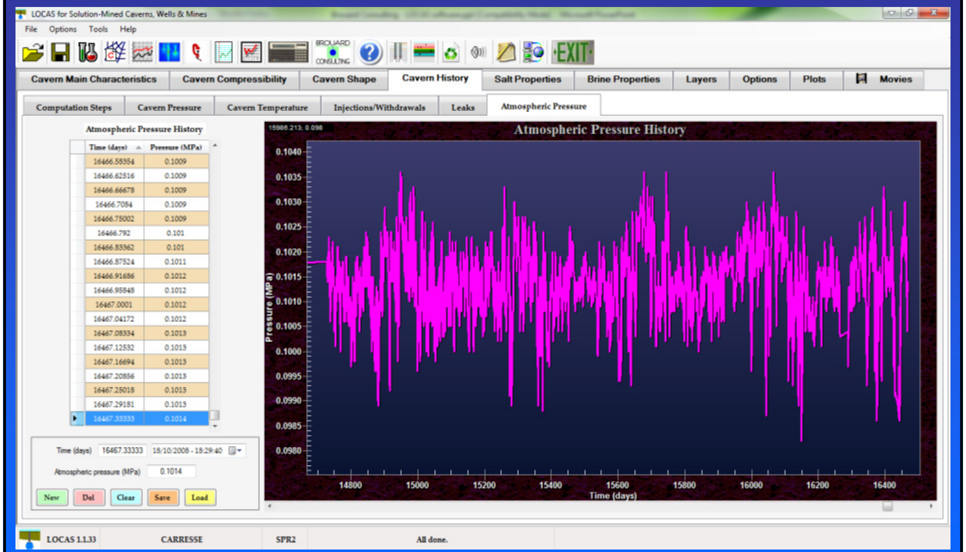
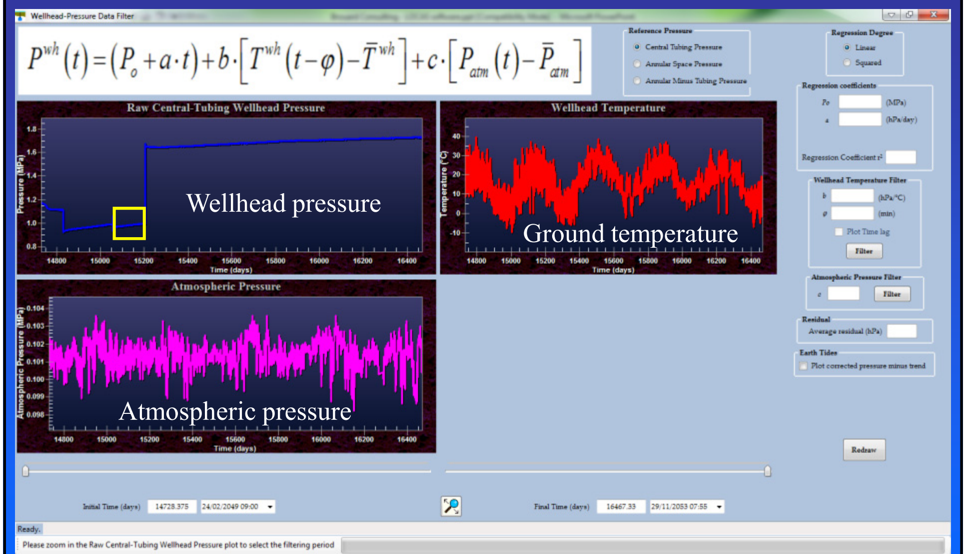
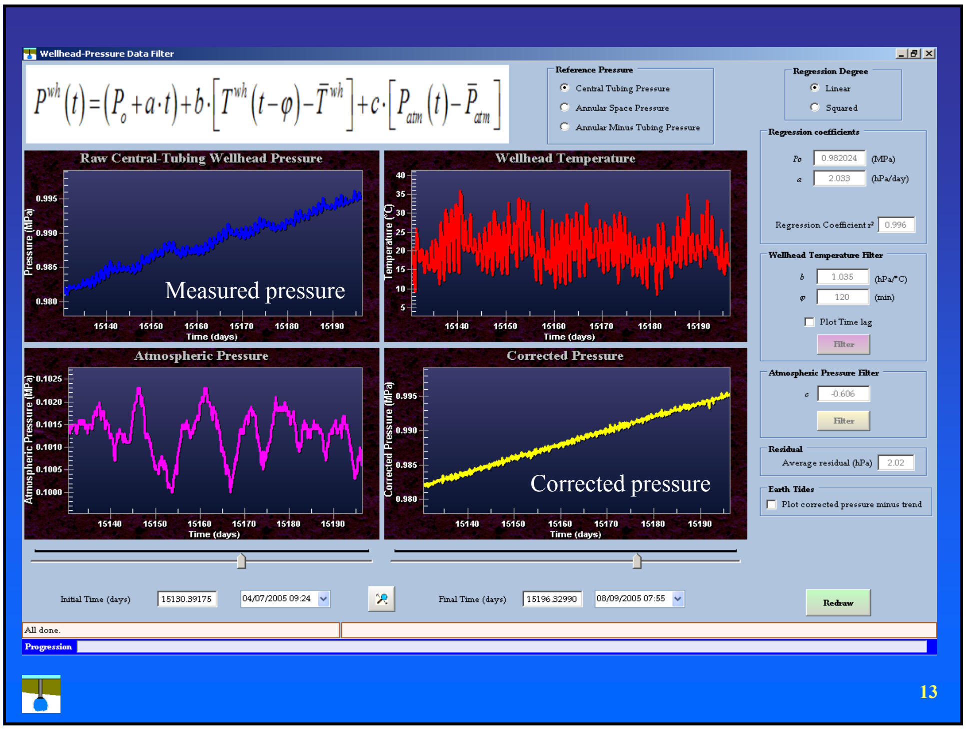
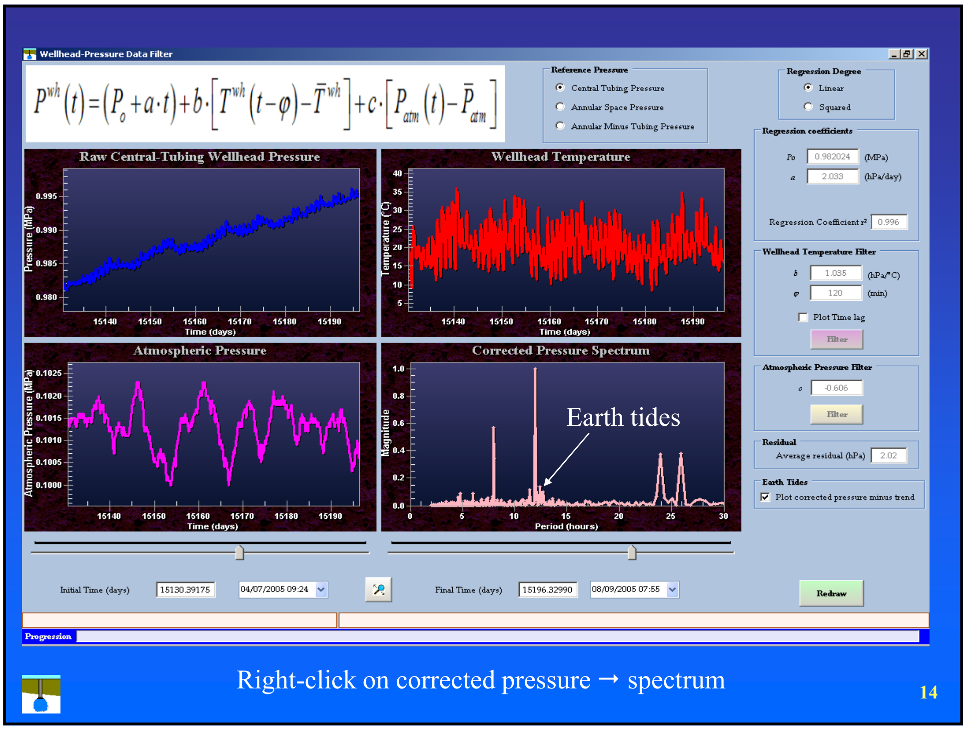
History of Atmospheric Pressure



A FILTERING TOOL IS EMBEDDED




Wellhead-Pressure Data Filter
Reference Pressure
Central Tubing Pressure
Annular Space Pressure
Annular Minus Tubing Pressure
Regression Degree
Linear
Squared
Regression coefficients
Raw Central-Tubing Wellhead Pressure
Measured pressure
Wellhead Temperature
Atmospheric Pressure
Corrected Pressure
Corrected pressure
Wellhead Temperature Filter
Atmospheric Pressure Filter
Residual
Earth Tides
Plot corrected pressure minus trend
Initial Time (days)
Final Time (days)
Redraw
All done.
Progression
13


Wellhead-Pressure Data Filter
Raw Central-Tubing Wellhead Pressure
Wellhead Temperature
Atmospheric Pressure
Corrected Pressure Spectrum
Earth tides
Period (hours)
Redraw
Progression
Right-click on corrected pressure → spectrum
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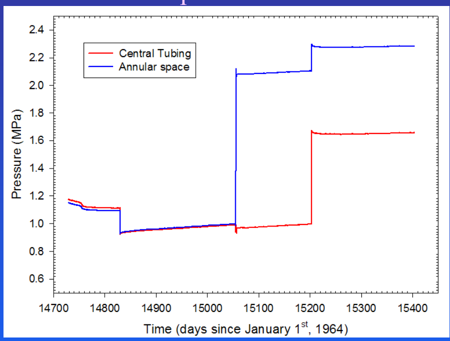
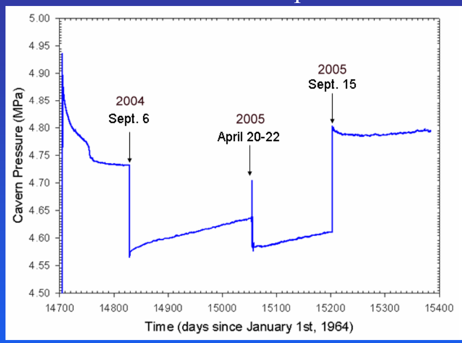
Task 1: Determination of cavern pressure evolution during the test

Corrected pressures at well head



Corrected cavern pressure



Well data

- columns composition
- temperature log
- fluids compressibilities
- possible leaks

Well Data in LOCAS

Strings database

Fluids database

Rocks database

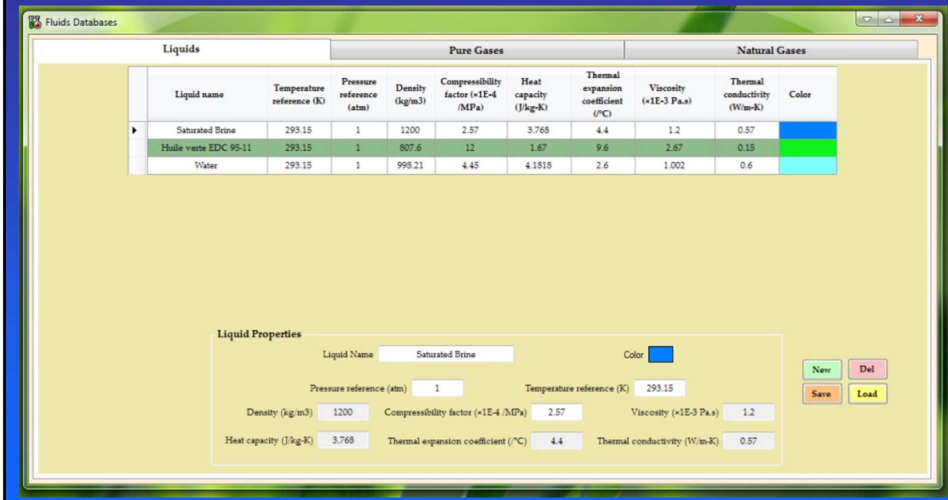
Layers database

Sections database

Stratigraphic cross-section view

Well architecture view

LIQUIDS DATABASE



Liquid name	Temperature reference (K)	Pressure reference (atm)	Density (kg/m3)	Compressibility factor (×1E-4 /MPa)	Heat capacity (J/kg-K)	Thermal expansion coefficient (/°C)	Viscosity (×1E-3 Pa.s)	Thermal conductivity (W/m-K)	Color
Saturated Brine	293.15	1	1200	2.57	3.768	4.4	1.2	0.57	
Huile verte EDC 95-11	293.15	1	807.6	12	1.67	9.6	2.67	0.15	
Water	293.15	1	998.21	4.45	4.1818	2.6	1.002	0.6	

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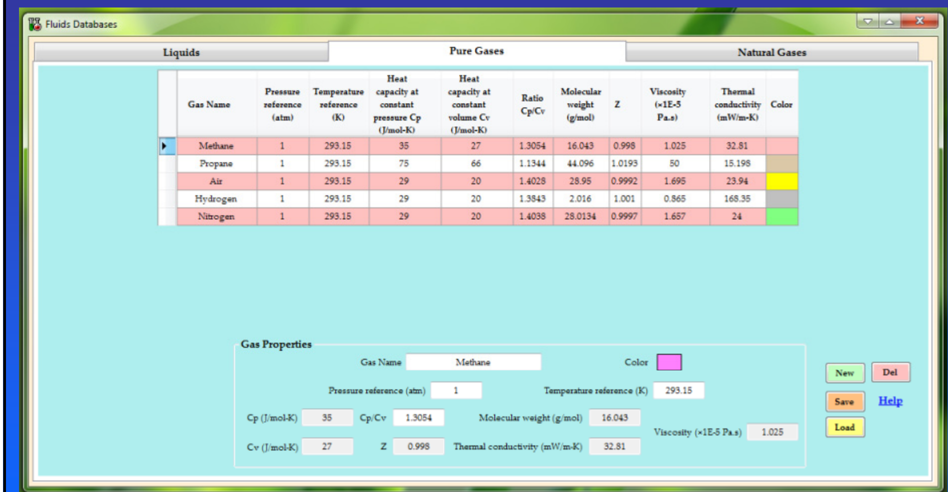
PURE GASE DATABASE



Gas Name	Pressure reference (atm)	Temperature reference (K)	Heat capacity at constant pressure Cp (J/mol-K)	Heat capacity at constant volume Cv (J/mol-K)	Ratio Cp/Cv	Molecular weight (g/mol)	Z	Viscosity (×1E-5 Pa.s)	Thermal conductivity (mW/m-K)	Color
Methane	1	293.15	35	27	1.3054	16.043	0.998	1.025	32.81	
Propane	1	293.15	75	66	1.1344	44.096	1.0193	50	15.198	
Air	1	293.15	29	20	1.4028	28.95	0.9992	1.695	23.94	
Hydrogen	1	293.15	29	20	1.3843	2.016	1.001	0.865	168.35	
Nitrogen	1	293.15	29	20	1.4038	28.0134	0.9997	1.657	24	

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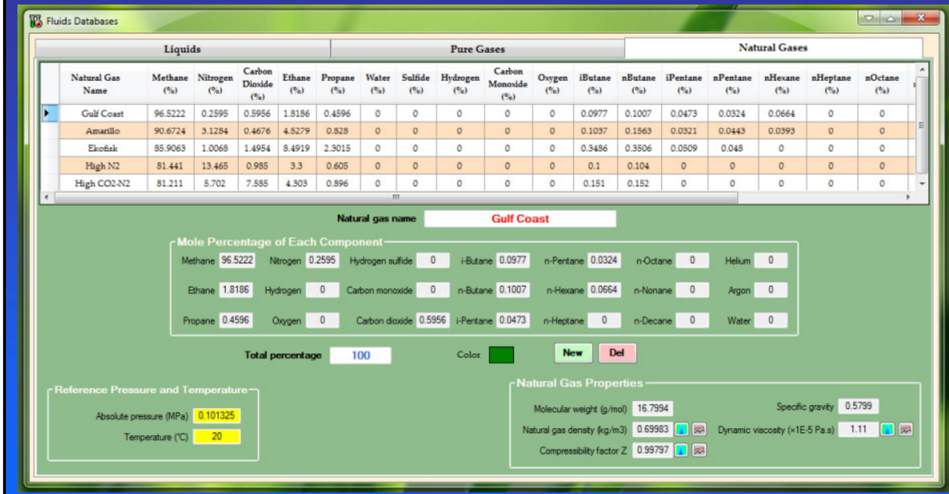
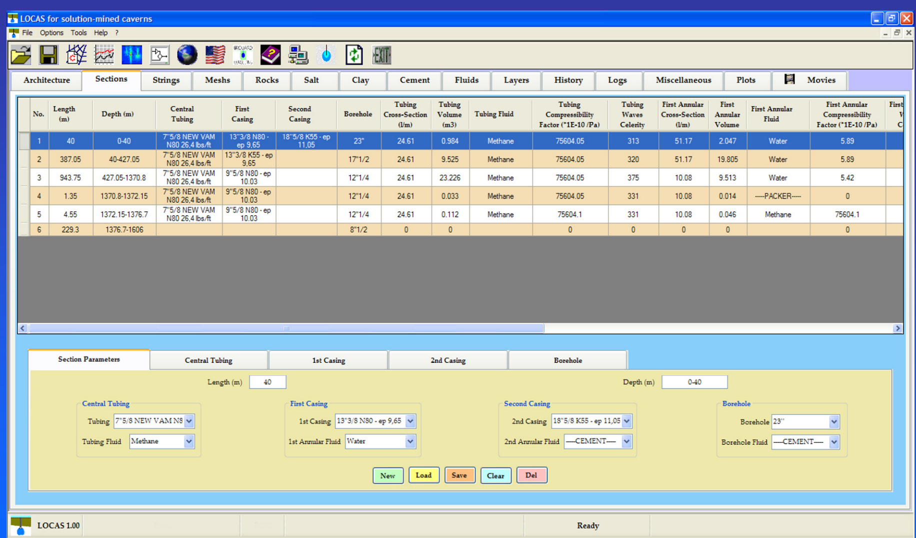
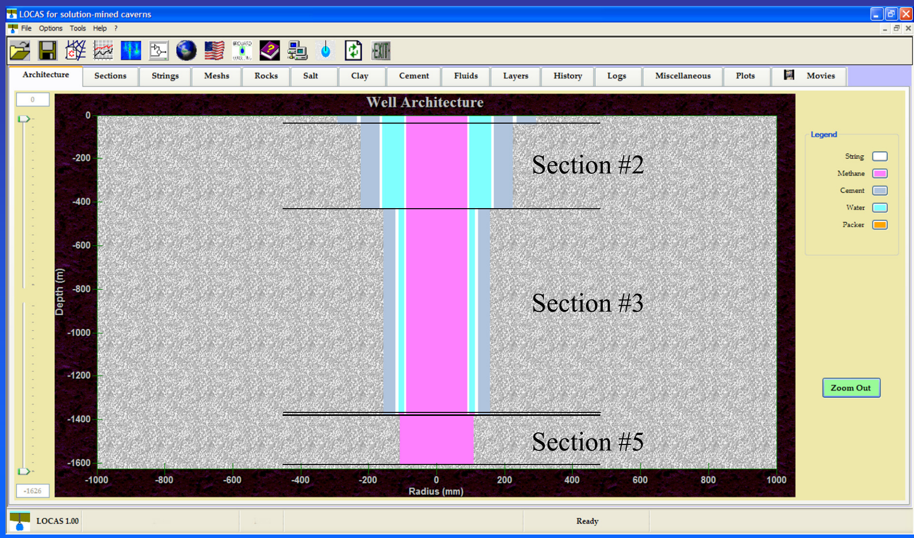
NATURAL GASES DATABASE



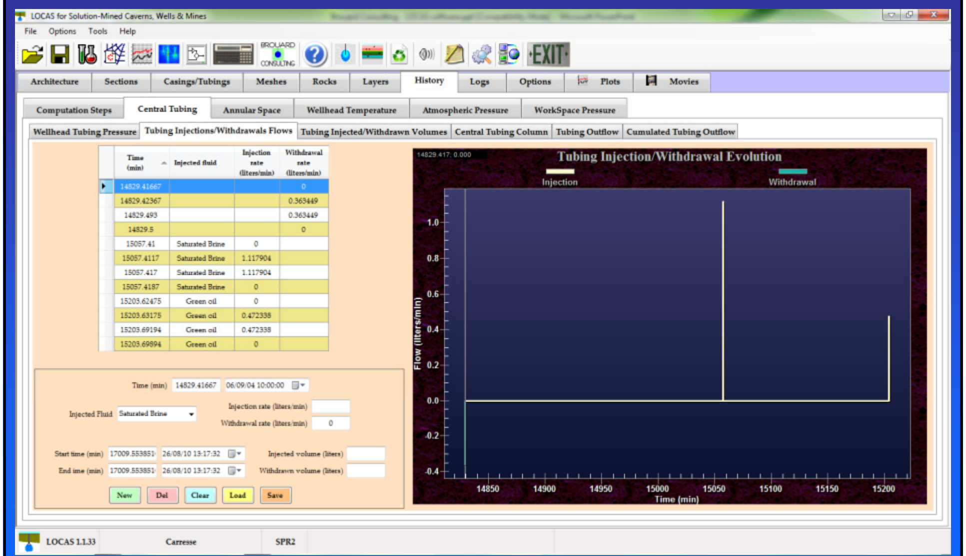
SECTIONS DATABASE



WELL ARCHITECTURE

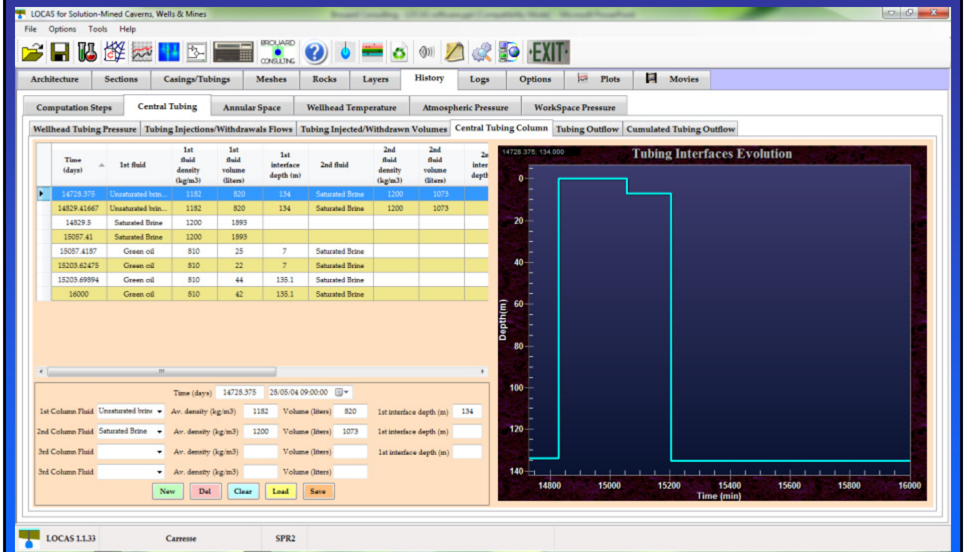


INJECTIONS/WITHDRAWALS DATABASE



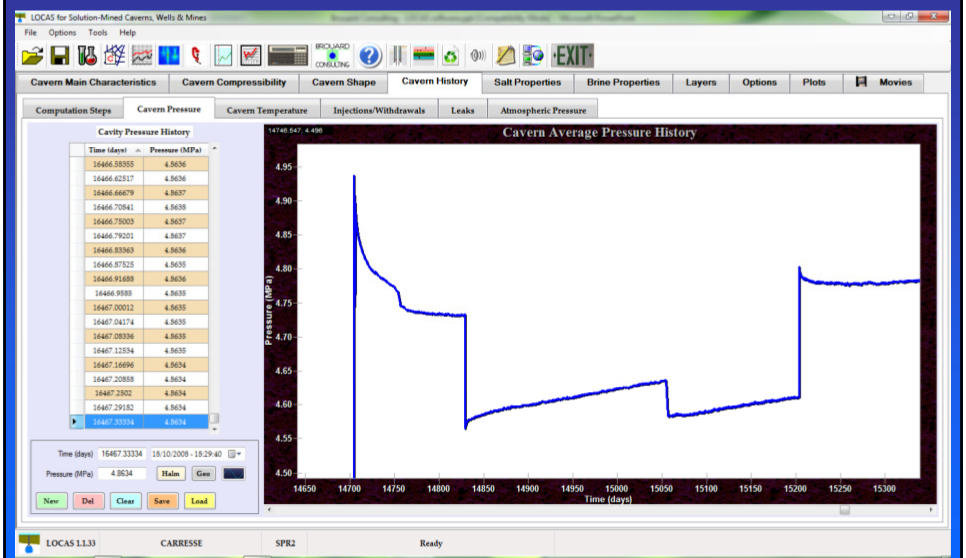
Data can be loaded from a flow measurement file

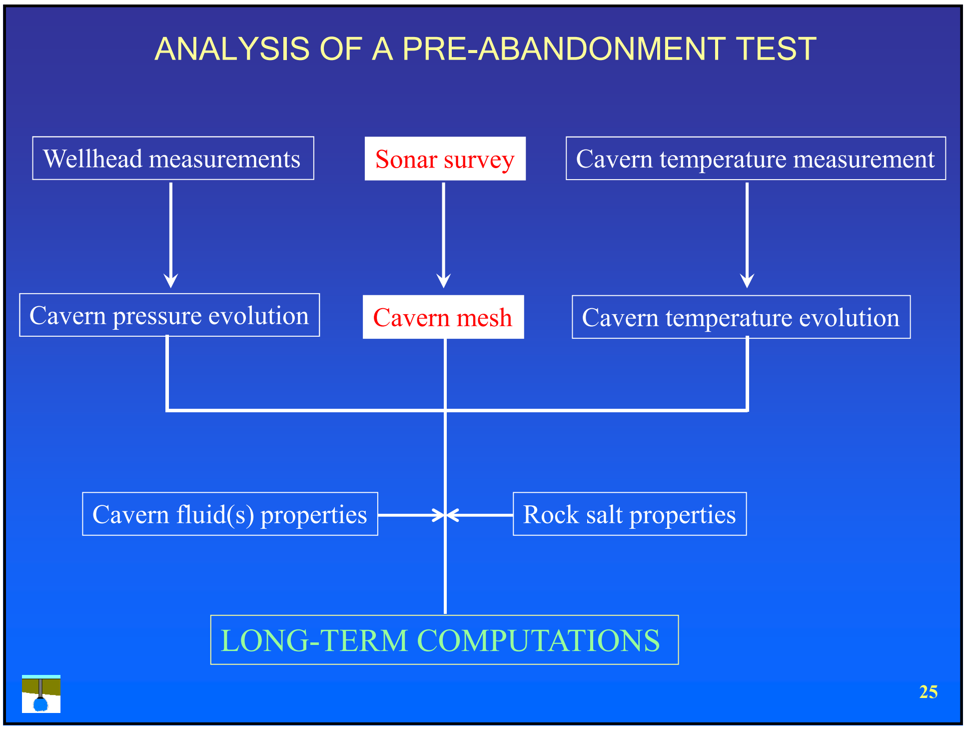
COLUMNS DATABASE



It's possible to have up to 4 different fluids in each column (3 interfaces)

HISTORY OF CAVERN PRESSURE

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Wellhead measurements
Sonar survey
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Cavern pressure evolution
Cavern mesh
Cavern temperature evolution
Cavern fluid(s) properties
Rock salt properties
LONG-TERM COMPUTATIONS
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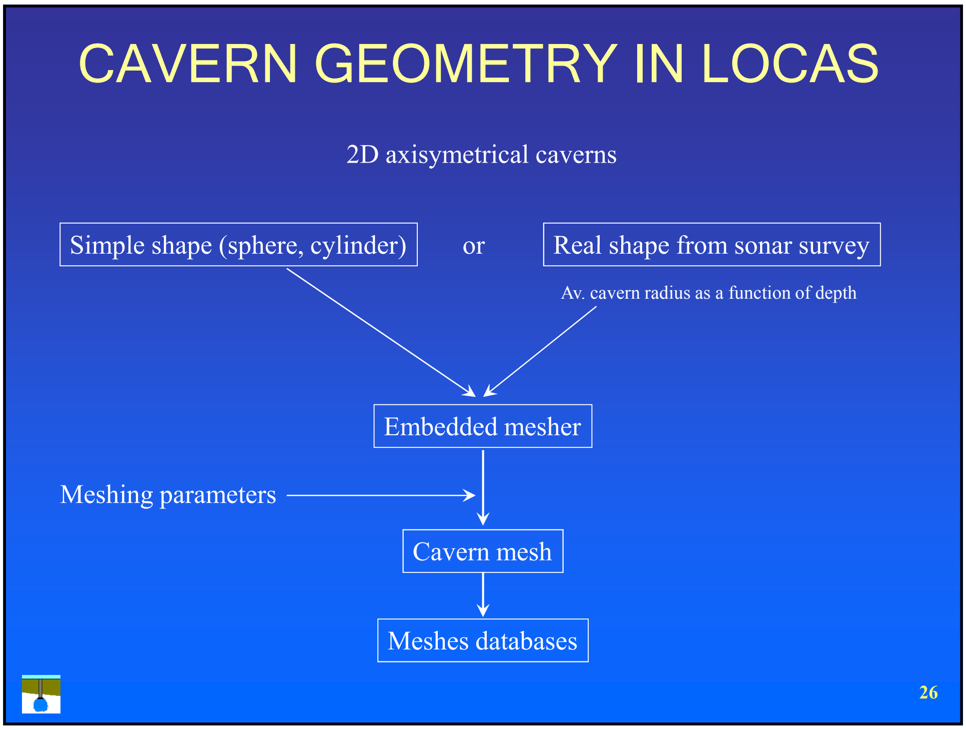
CAVERN GEOMETRY IN LOCAS
2D axisymetrical caverns
Simple shape (sphere, cylinder)
or
Real shape from sonar survey
Av. cavern radius as a function of depth
Embedded mesher
Meshing parameters
Cavern mesh
Meshes databases
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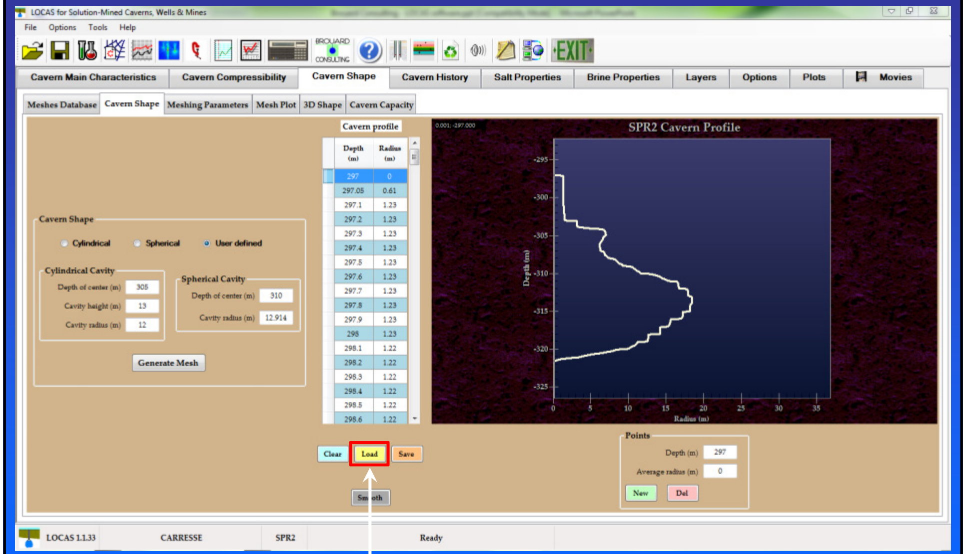
CAVERN PROFILE FROM SONAR SURVEY



Load file from sonar survey

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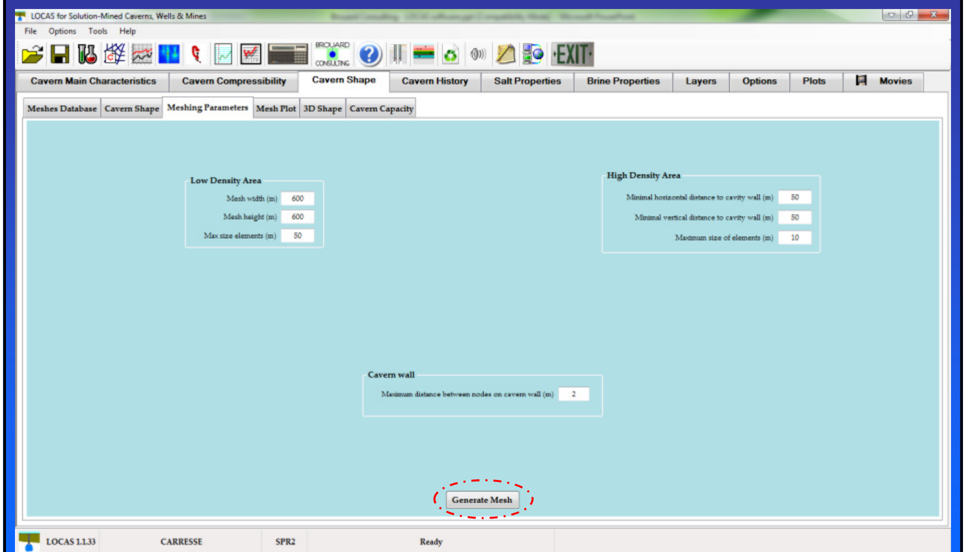
MESHING PARAMETERS



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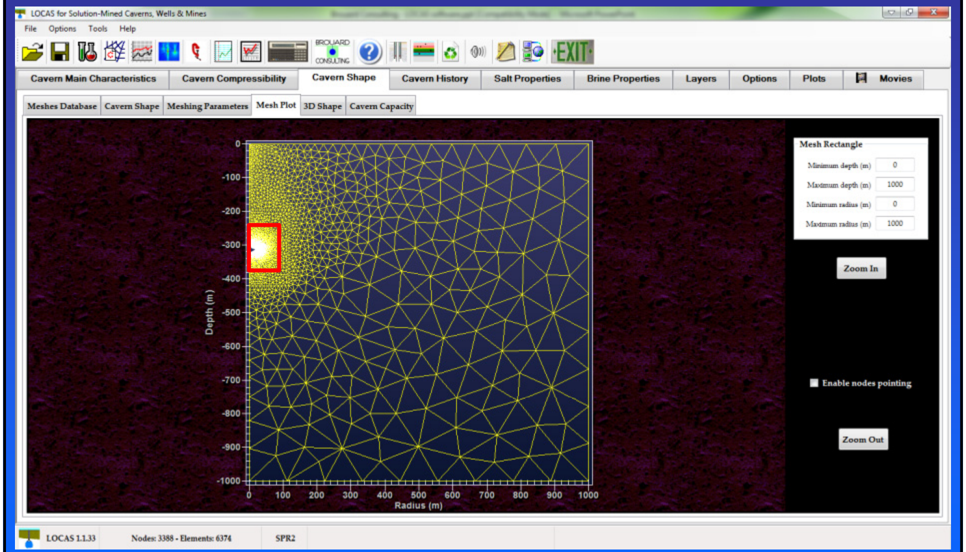
MESH VIEW



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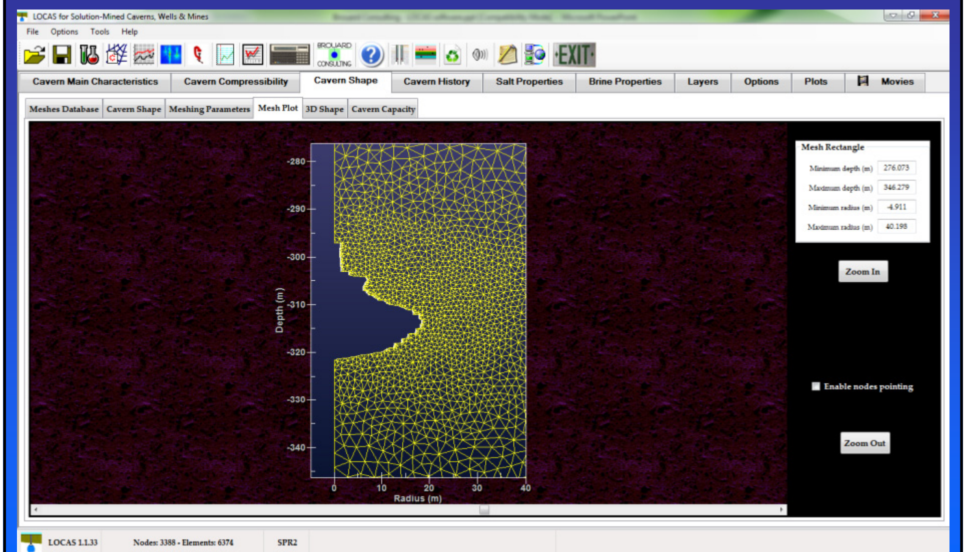

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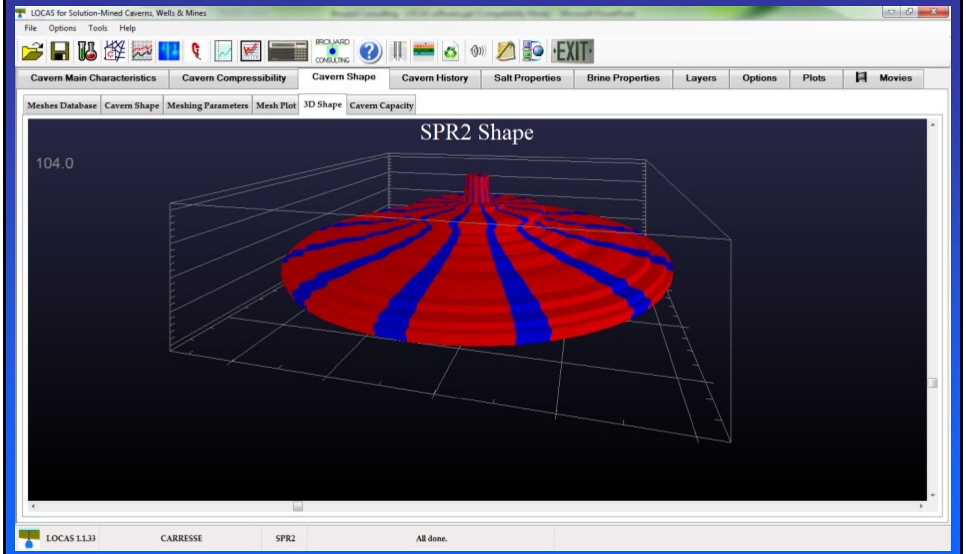
3D VIEW


LOCAS for Solution-Mined Caverns, Wells & Mines
File Options Tools Help
Cavern Main Characteristics
Cavern Compressibility
Cavern Shape
Cavern History
Salt Properties
Brine Properties
Layers
Options
Plots
Movies
Meshes Database
Cavern Shape
Meshing Parameters
Mesh Plot
3D Shape
Cavern Capacity
SPR2 Shape
104.0
LOCAS 1.1.33
CARRESSE
SPR2
All done.

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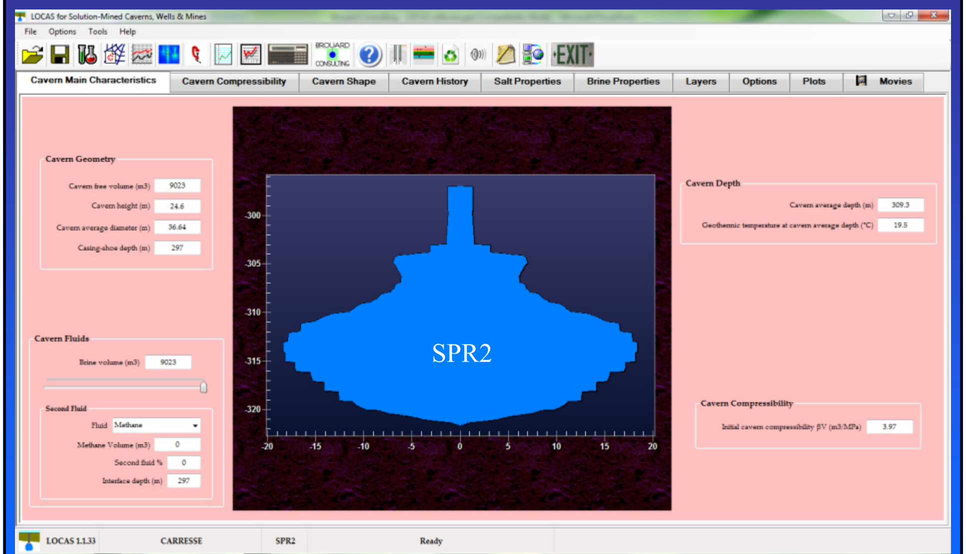
LOCAS for Solution-Mined Caverns, Wells & Mines
File Options Tools Help
Cavern Main Characteristics
Cavern Compressibility
Cavern Shape
Cavern History
Salt Properties
Brine Properties
Layers
Options
Plots
Movies
Cavern Geometry
Cavern free volume (m3) 9023
Cavern height (m) 24.6
Cavern average diameter (m) 36.64
Casing-shoe depth (m) 297
Cavern Fluids
Brine volume (m3) 9023
Second Fluid
Fluid Methane
Methane Volume (m3) 0
Second fluid % 0
Interface depth (m) 297
SPR2
Cavern Depth
Cavern average depth (m) 309.3
Geothermic temperature at cavern average depth (°C) 19.5
Cavern Compressibility
Initial cavern compressibility βV (m3/MPa) 3.97
LOCAS 1.1.33
CARRESSE
SPR2
Ready

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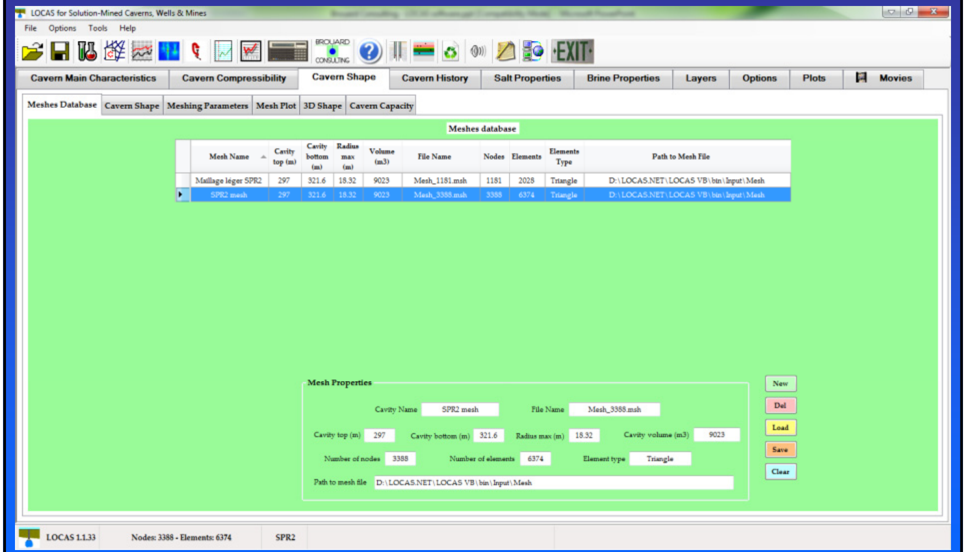
MESHES DATABASE



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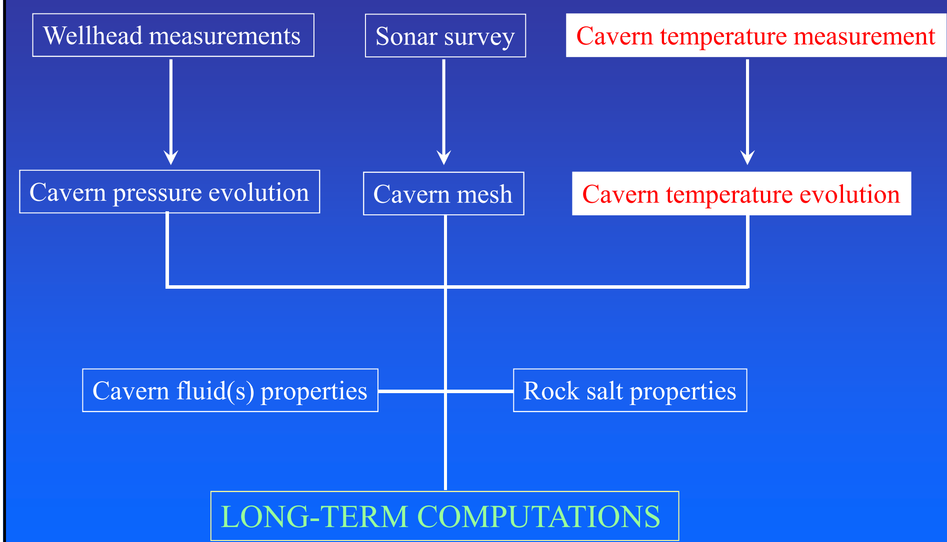
ANALYSIS OF A PRE-ABANDONMENT TEST



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<u>Task 2: Determination of long-term cavern temperature evolution</u>

- Determination of natural rock temperature T_∞
- Fitting of a cavern temperature measurement

Accurate prediction of
- brine temperature evolution
- brine thermal expansion

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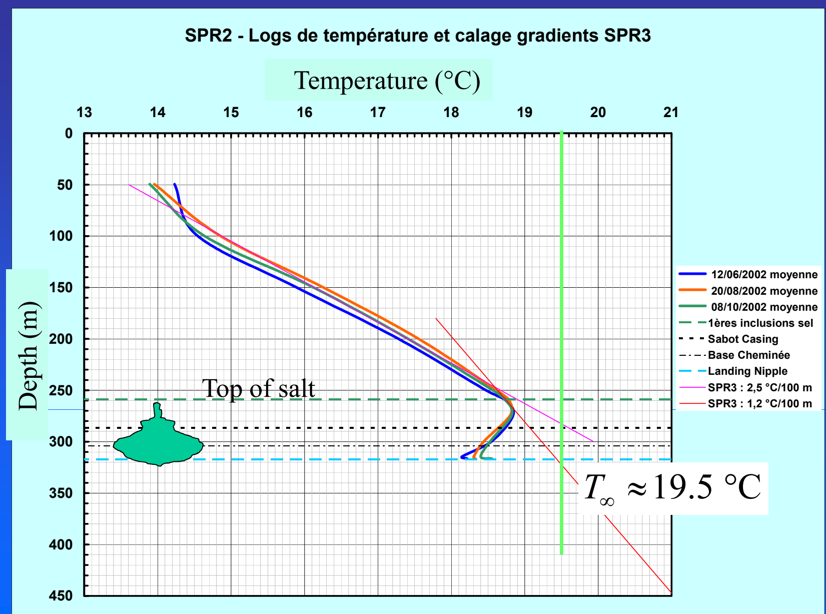
SPR2 Geothermal Temperature



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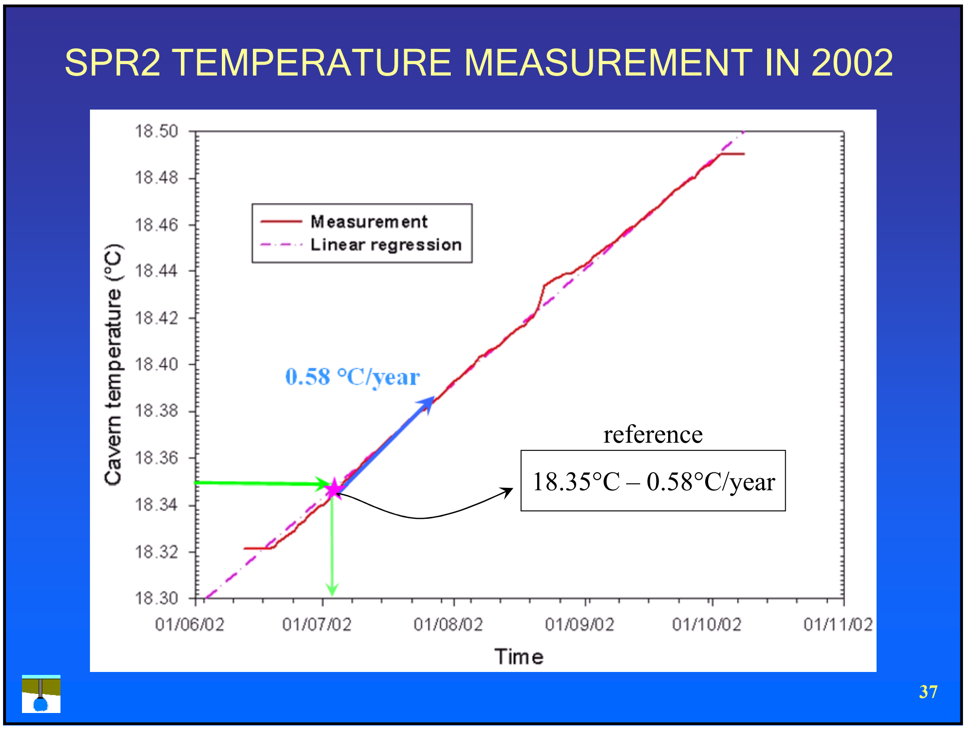
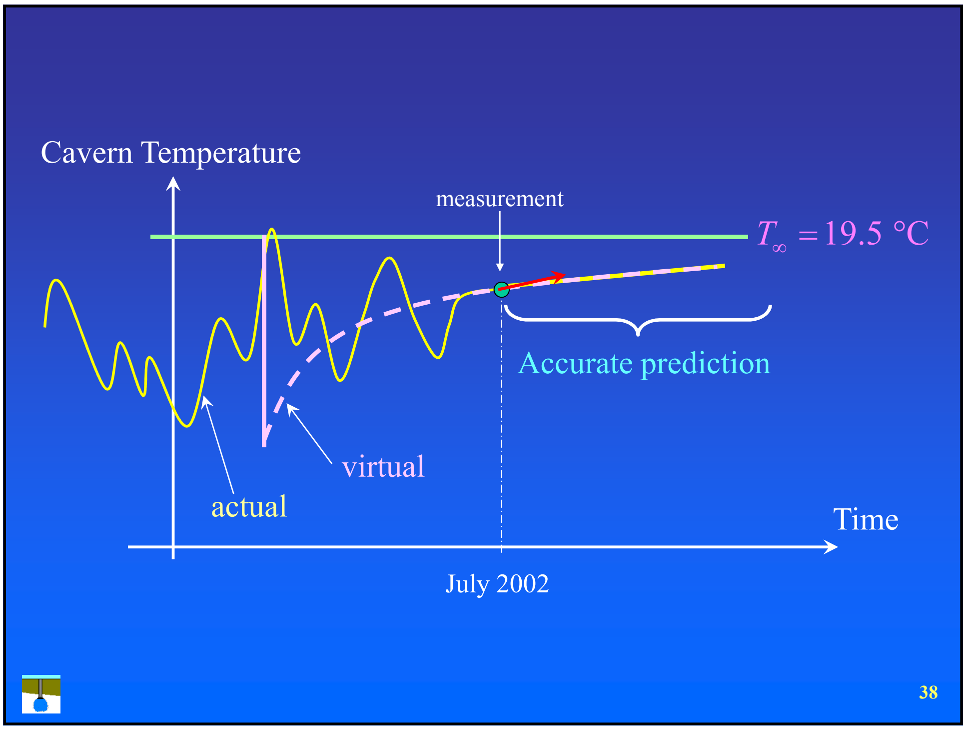


SPR2 TEMPERATURE MEASUREMENT IN 2002
Measurement
Linear regression
0.58 °C/year
reference
18.35°C – 0.58°C/year
Cavern temperature (°C)
18.50
18.48
18.46
18.44
18.42
18.40
18.38
18.36
18.34
18.32
18.30
01/06/02
01/07/02
01/08/02
01/09/02
01/10/02
01/11/02
Time
37



Cavern Temperature
measurement
T∞ = 19.5 °C
Accurate prediction
virtual
actual
Time
July 2002
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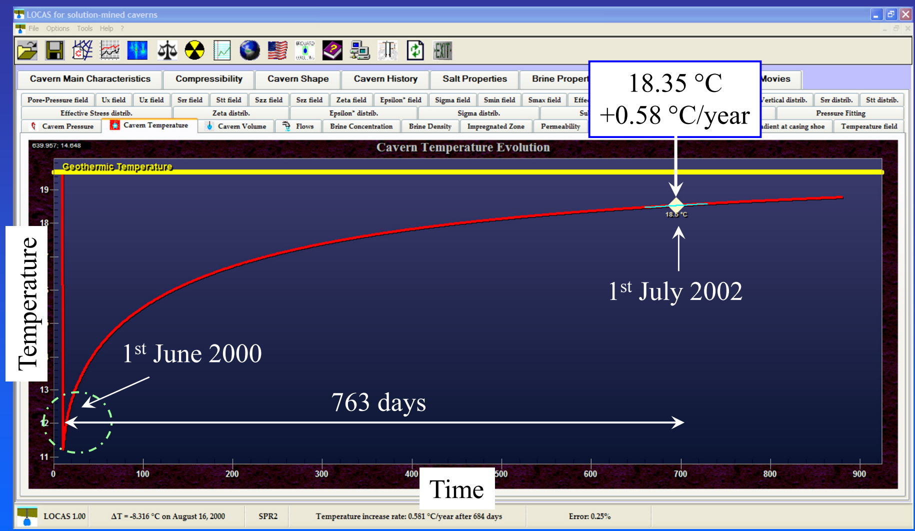
SPR2 CAVERN TEMPERATURE FITTING



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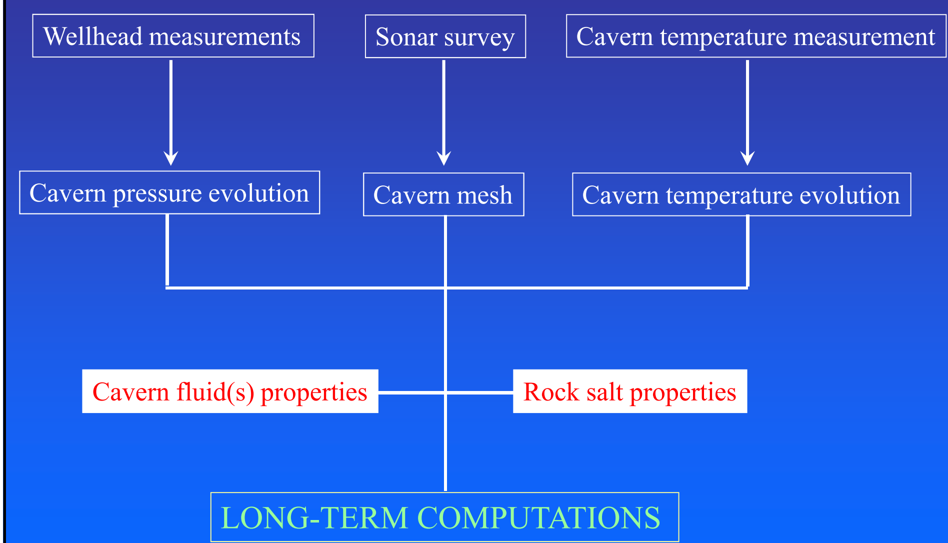
ANALYSIS OF A PRE-ABANDONMENT TEST



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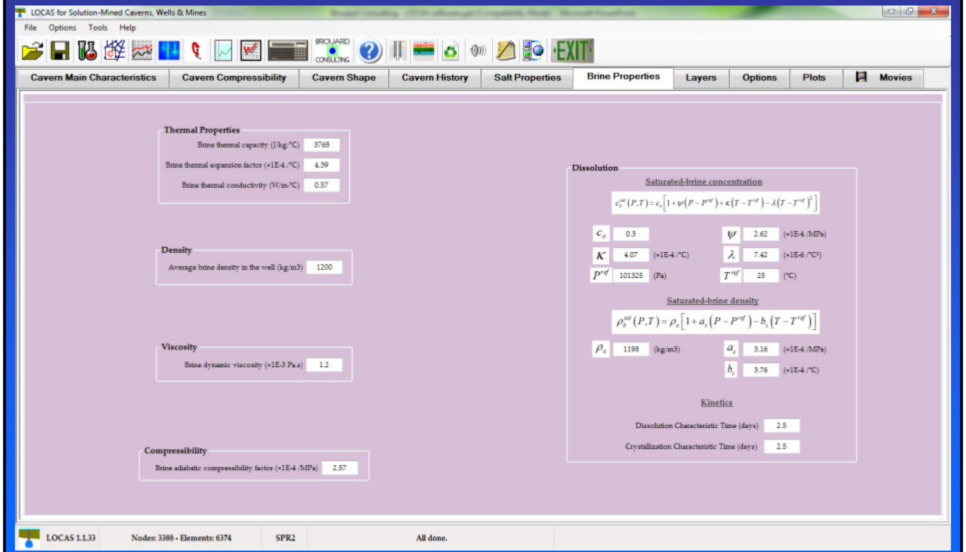
BRINE PROPERTIES



SALT PROPERTIES

- Mechanical properties
  - Elasticity
  - Creep: stationnary + transient

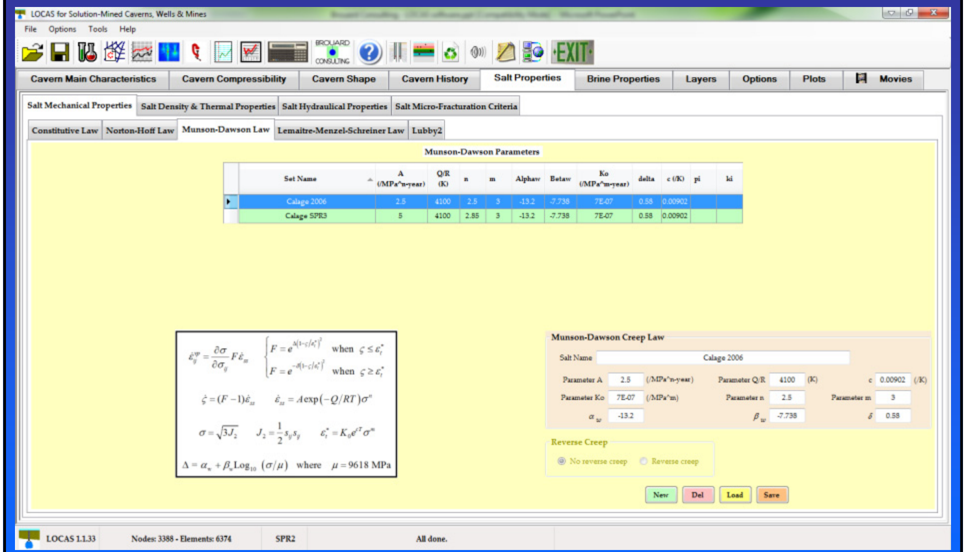
4 implemented creep laws

- Norton-Hoff
- Lemaitre-Menzel-Schreiner
- Munson-Dawson
- Lubby2

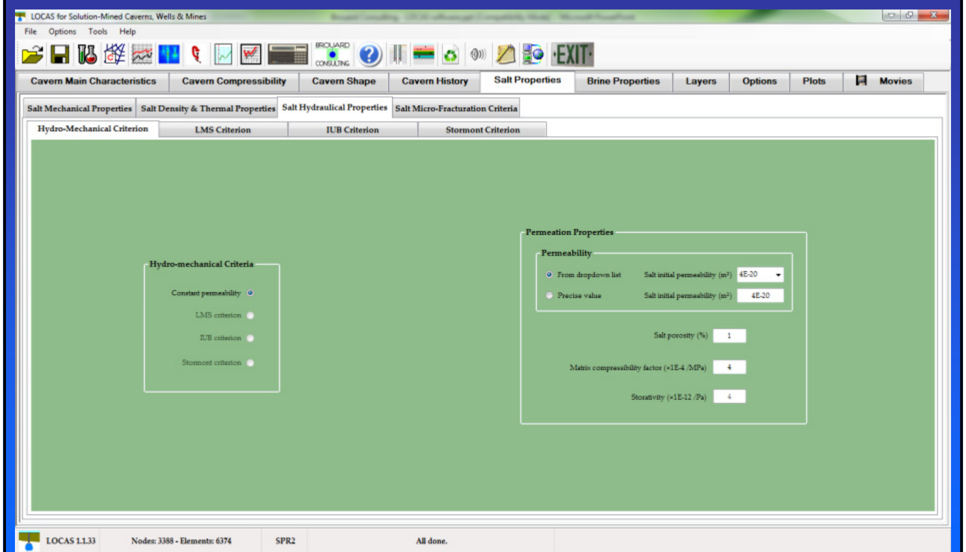
+ possibility of reverse creep using a modified Munson-Dawson law

- Thermal properties
- Hydraulical properties (micro-permeation)
- Chemical properties (dissolution/crystallization)

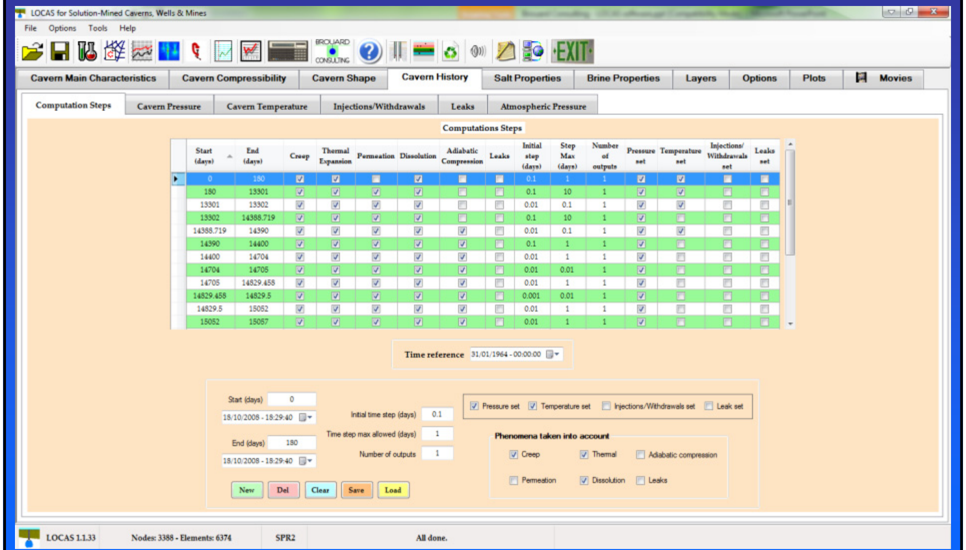
Munson-Dawson Database



Salt Micro-permeation Properties



Calculation Steps



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Phenomena that can be taken into account:

- Salt creep
- Cavern fluid heating/cooling
- Cavern fluid micro-permeation
- Salt complementary dissolution/crystallization
- Cavern fluid adiabatic compression/release

Coupled through cavern compressibility

Cavern pressure/temperature and casing leaks can be set or calculated

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Example of parameters back-calculation

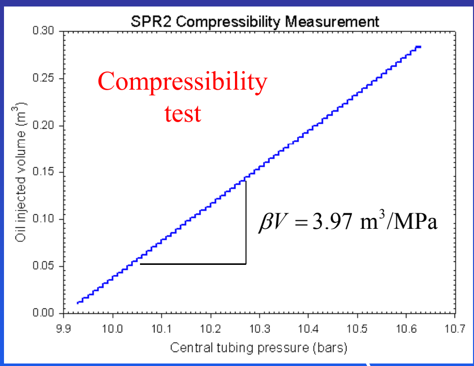
Salt parameters to be determined for long-term computations:

- Salt elastic parameters (E, ν)
- Salt creep parameters

  Stationnary creep: Norton-Hoff parameters $(A, n, Q/R)$

- Salt hydraulical parameters (K_{salt}^{hyd})

Back-calculation of Salt Elastic Parameters



$\nu = 0.25$ assumed

Finite Elements computation

$E \approx 16{,}500$ MPa

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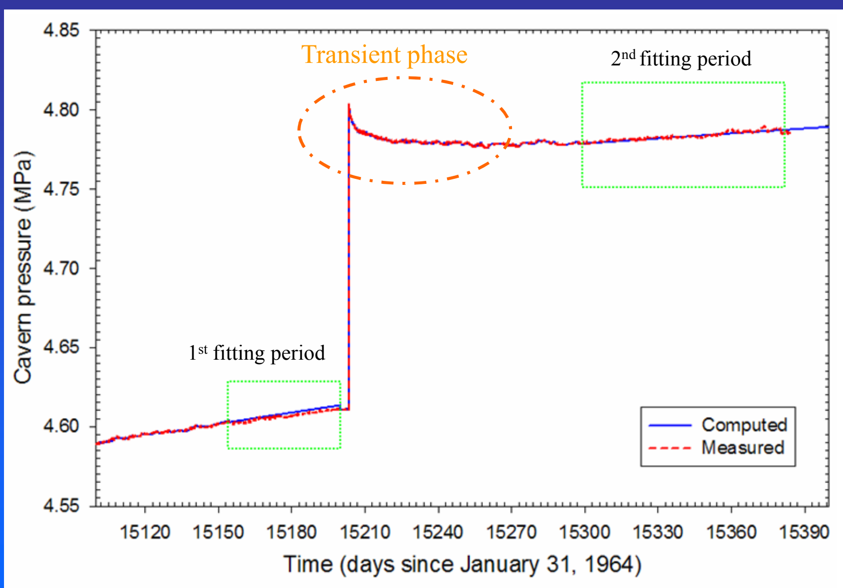
STATIONNARY PARAMETERS FITTED FOR TWO PERIODS



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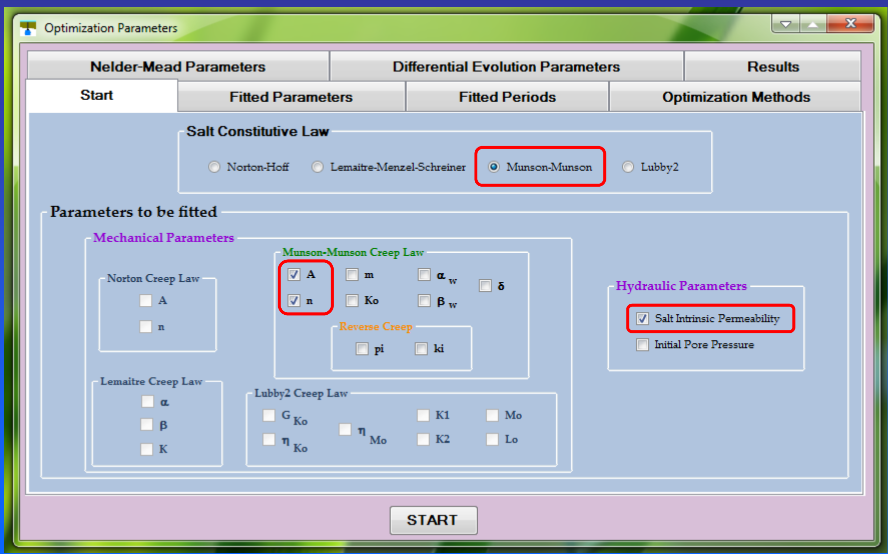
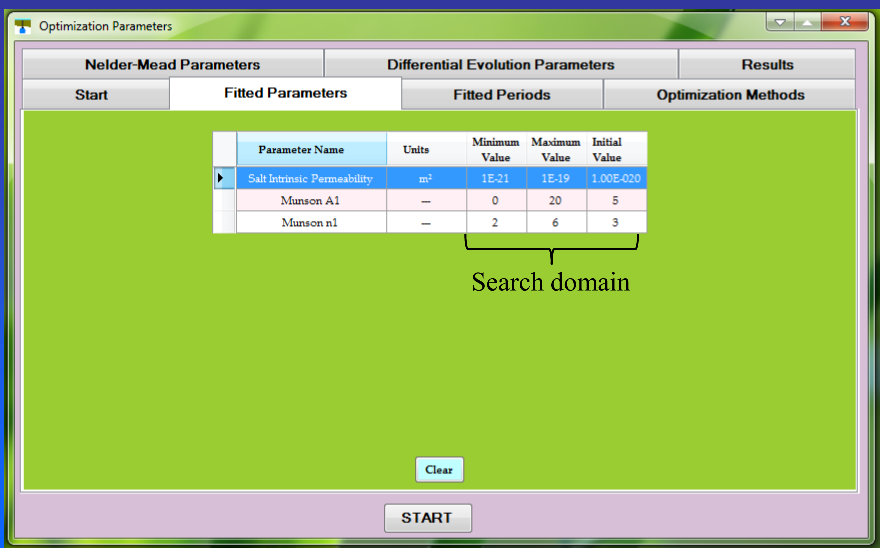
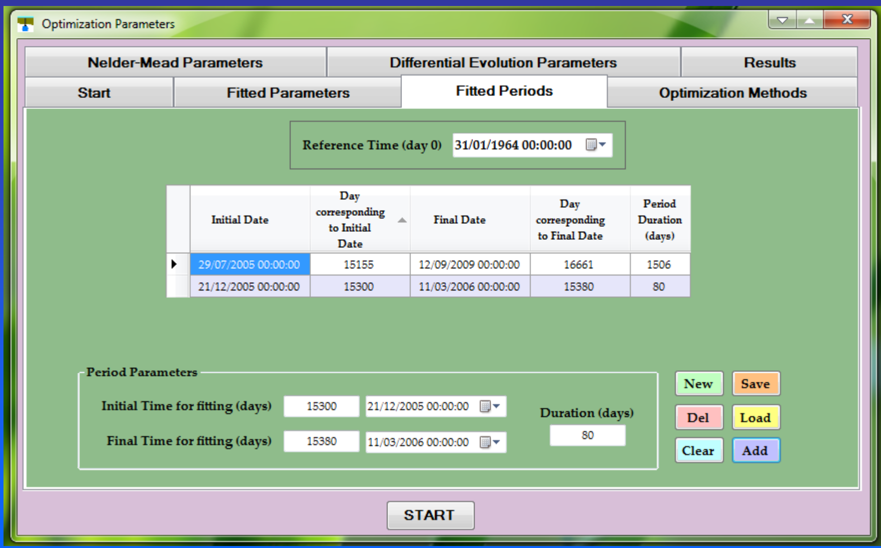
Selection of Parameters to be Fitted



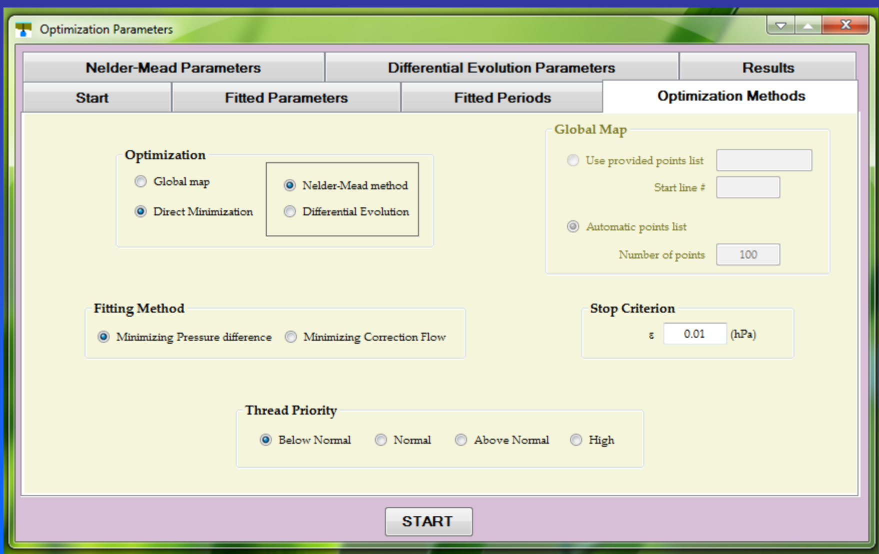
Parameters to be Fitted



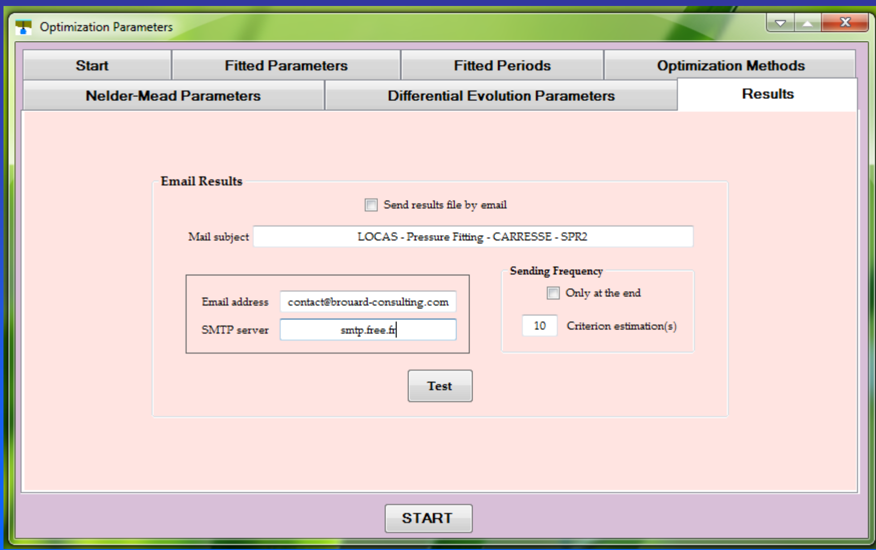
Selection of Fitted Periods

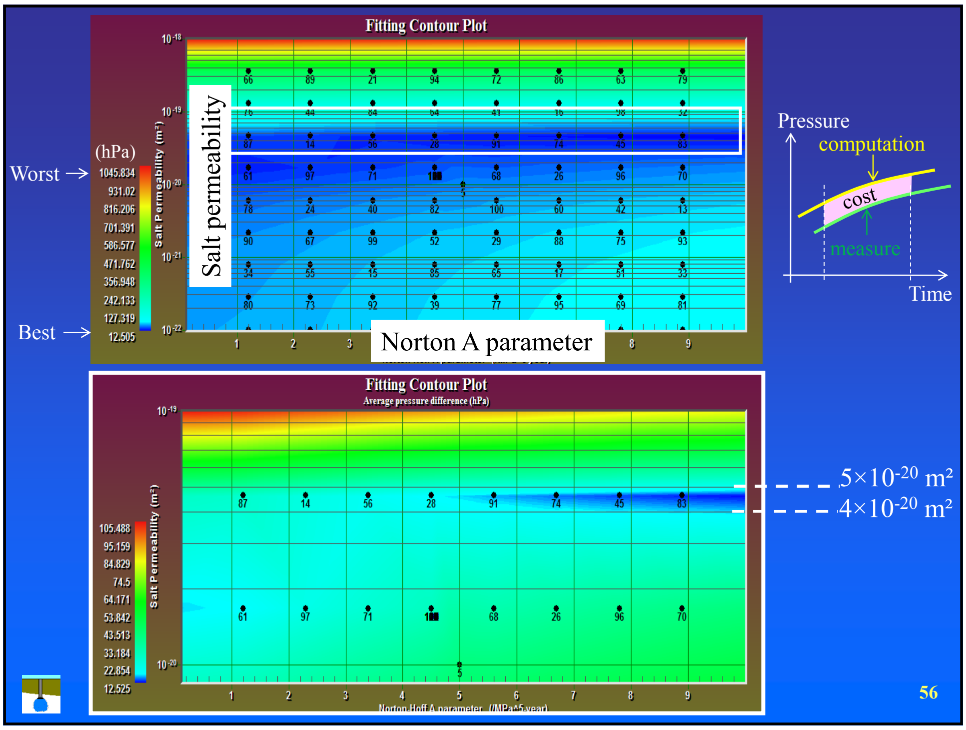


Selection of the Optimization Method

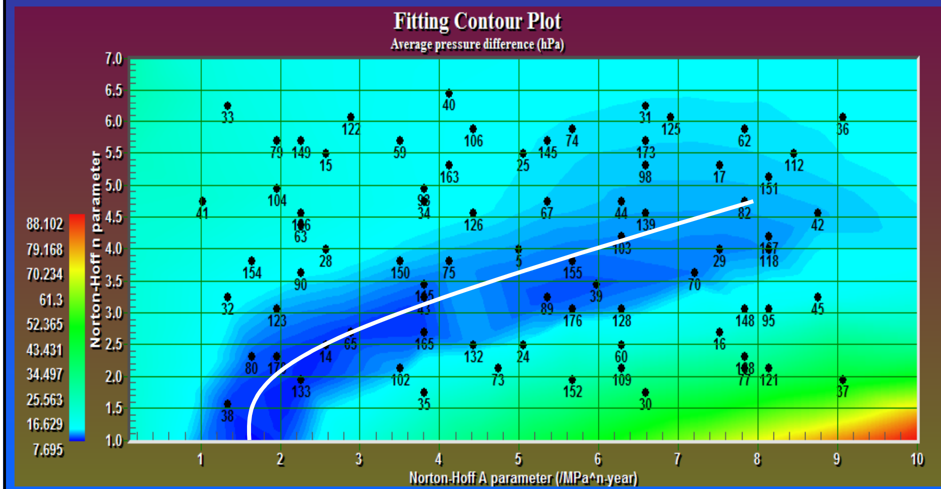


Fitting results can be emailed





INVESTIGATION OF FITTING SENSIBILITY



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SPR2 - FITTING MAIN RESULTS

Salt permeability: $K_{salt}^{hyd} \approx 3-4\times10^{-20}\ \mathrm{m}^2$

Salt stationnary creep: $\dot{\varepsilon} = A\exp\left(-\dfrac{Q}{RT}\right)\sigma^n$ (Norton-Hoff law)

2 possible sets of parameters

	A (/MPa^{-n}-year)	n	Q/R (K)
Set #1	2.5	2.5	4100
Set #2	7.8	5	4100

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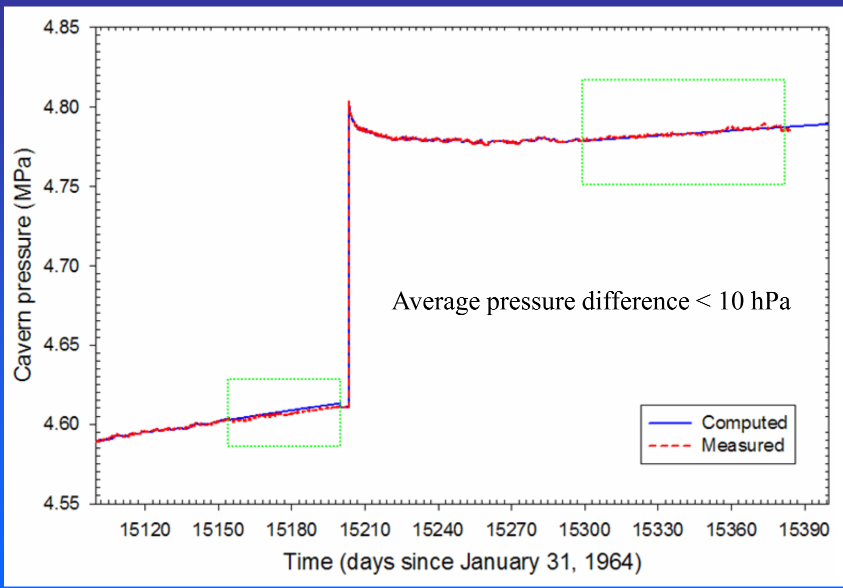
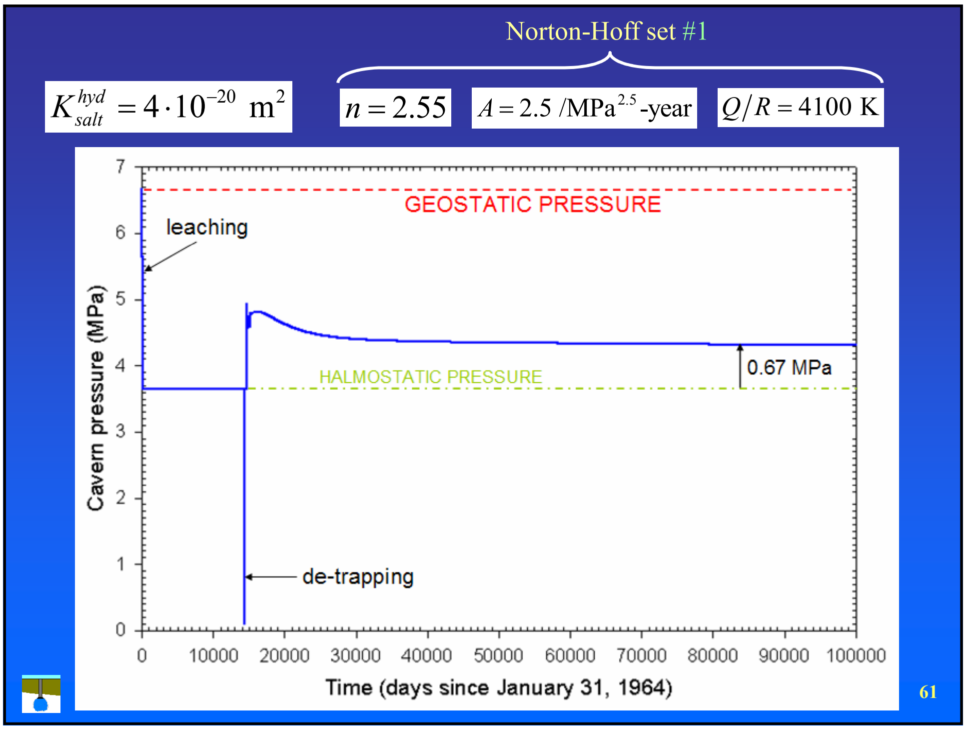
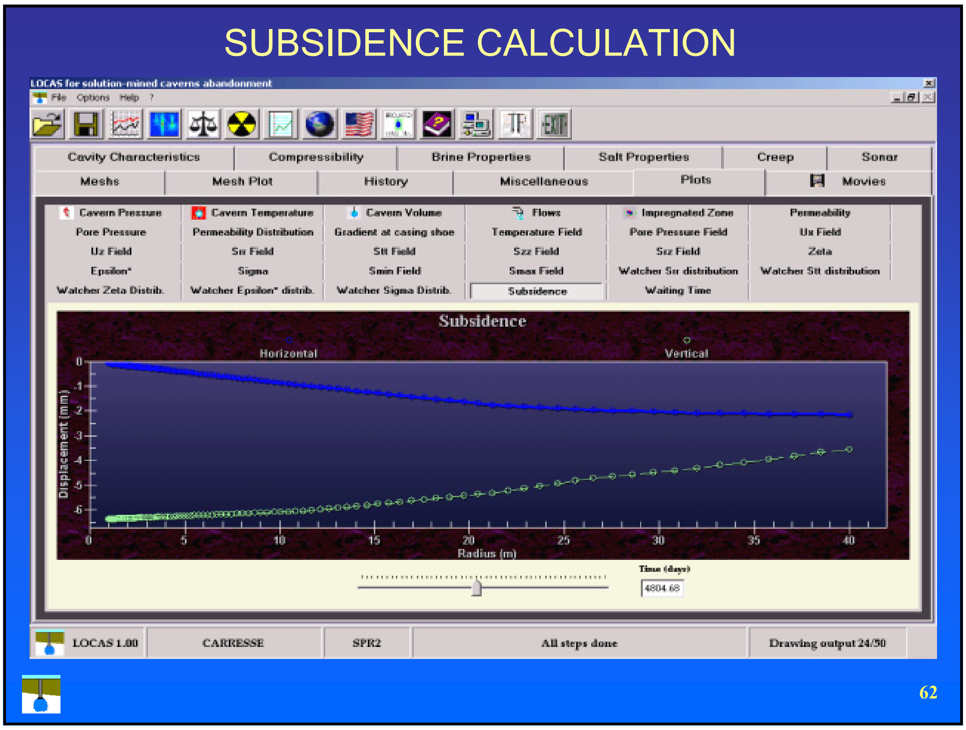
STATIONNARY PARAMETERS FITTED FOR TWO PERIODS



Long-term computation

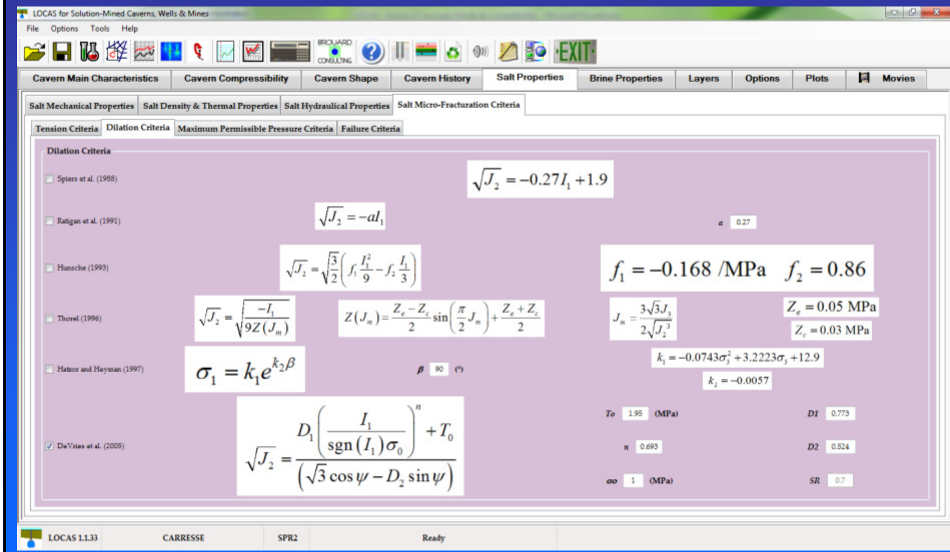


Norton-Hoff set #1
$K_{salt}^{hyd} = 4 \cdot 10^{-20}$ m^2
$n = 2.55$
$A = 2.5$ /MPa$^{2.5}$-year
$Q/R = 4100$ K
GEOSTATIC PRESSURE
leaching
HALMOSTATIC PRESSURE
0.67 MPa
de-trapping
Cavern pressure (MPa)
Time (days since January 31, 1964)
61

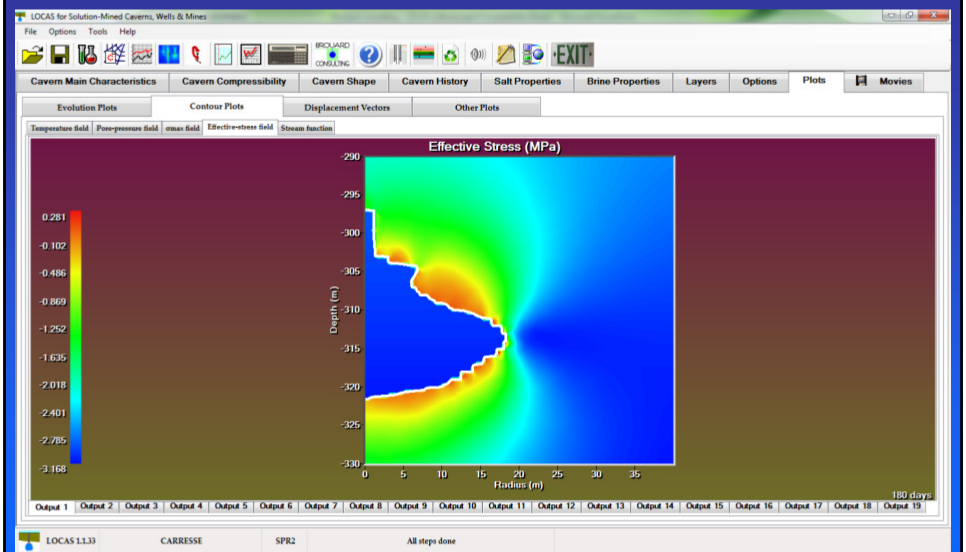


SUBSIDENCE CALCULATION
LOCAS for solution-mined caverns abandonment
Cavity Characteristics
Compressibility
Brine Properties
Salt Properties
Creep
Sonar
Meshs
Mesh Plot
History
Miscellaneous
Plots
Movies
Subsidence
Horizontal
Vertical
Displacement (mm)
Radius (m)
Time (days)
4804.68
LOCAS 1.00
CARRESSE
SPR2
All steps done
Drawing output 24/50
62

NO-TENSION CRITERIA, DILATION CRITERIA…



EXAMPLE OF CONTOUR PLOTS



It's also possible to create movies (.avi)

CONCLUSIONS

- Many features have been implemented in a software called *LOCAS*
- LOCAS can be helpful for various kinds of studies, as for instance:
  - ✓ pressure/temperature prediction including transient behavior
  - ✓ simulation of fast cycling loading - Natural gas, CAES
  - ✓ long-term simulations (abandonment, subsidence)
  - ✓ mechanical integrity tests (MITs) analysis
  - ✓ short-term stability (min./max. operating pressure)
  - ✓ mechanical/thermal/hydraulical parameters fitting from in situ tests

⟶ Prediction from data at cavern scale

CONCLUSIONS

- ➢ LOCAS supports all 32-bits Windows versions, Windows Seven included.
- ➢ 3D & 64 bits versions under development.
- ➢ LOCAS is not yet available for sale.

Interested people, please contact Benoit Brouard:

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