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 axisymmetrical 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

300 m

9000 m³
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)
  - Hydraulic parameters: salt permeability at cavern scale

- LONG-TERM FEM COMPUTATIONS → PREDICTIONS

ANALYSIS OF A PRE-ABANDONMENT TEST

Wellhead measurements → Cavern pressure evolution → Cavern fluid(s) properties → Rock salt properties
Sonar survey → Cavern mesh
Cavern temperature measurement → Cavern temperature evolution
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

Task 1: Determination of cavern pressure evolution during the test

Pressures measured at well head  Cavern pressure

Well data
- columns composition
- temperature log
- fluids compressibilities
- possible leaks
History of Atmospheric Pressure

A FILTERING TOOL IS EMBEDDED

\[ P^n(t) = (P_0 + a \cdot t) + b \cdot \left( T_{\text{ref}}(t) - T_{\text{avg}} \right) + c \cdot (P_{\text{atm}}(t) - P_{\text{atm}}) \]

Wellhead pressure

Ground temperature

Atmospheric pressure
Right-click on corrected pressure → spectrum
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

Rocks database

Layers database

Stratigraphic cross-section view

Strings database

Sections database

Well architecture view

Fluids database
### Liquids Database

<table>
<thead>
<tr>
<th>Liquid Name</th>
<th>Temperature Reference (K)</th>
<th>Pressure Reference (MPa)</th>
<th>Density (g/L)</th>
<th>Compressibility Factor (v)</th>
<th>Heat Capacity (J/kg.K)</th>
<th>Thermal Expansion Coefficient (K^-1)</th>
<th>Viscosity (mPa.s)</th>
<th>Thermal Conductivity (W/m.K)</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>298.15</td>
<td>1</td>
<td>1000</td>
<td>0.0</td>
<td>4.185</td>
<td>0.6</td>
<td>0.01</td>
<td>0.6</td>
<td>Green</td>
</tr>
<tr>
<td>Alcohol</td>
<td>298.15</td>
<td>1</td>
<td>0.8</td>
<td>0.0</td>
<td>2.4</td>
<td>0.4</td>
<td>0.01</td>
<td>0.4</td>
<td>Blue</td>
</tr>
</tbody>
</table>

**Liquid Properties**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Reference (MPa)</td>
<td>1</td>
</tr>
<tr>
<td>Temperature Reference (K)</td>
<td>298.15</td>
</tr>
<tr>
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</tr>
<tr>
<td>Thermal Expansion Coefficient (K^-1)</td>
<td>0.6</td>
</tr>
<tr>
<td>Viscosity (mPa.s)</td>
<td>0.01</td>
</tr>
<tr>
<td>Thermal Conductivity (W/m.K)</td>
<td>0.6</td>
</tr>
</tbody>
</table>

### Pure Gases Database

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>298.15</td>
<td>1</td>
<td>1.430</td>
<td>1.430</td>
<td>28</td>
<td>0.613</td>
<td>1.301</td>
<td>0.000</td>
<td>0.000</td>
<td>Green</td>
<td></td>
</tr>
<tr>
<td>Oxygen</td>
<td>298.15</td>
<td>1</td>
<td>1.508</td>
<td>1.508</td>
<td>32</td>
<td>0.608</td>
<td>1.406</td>
<td>0.000</td>
<td>0.000</td>
<td>Blue</td>
<td></td>
</tr>
</tbody>
</table>

**Gas Properties**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature Reference (K)</td>
<td>298.15</td>
</tr>
<tr>
<td>Pressure Reference (MPa)</td>
<td>1</td>
</tr>
<tr>
<td>Heat Capacity of Moist Gas (J/kg.K)</td>
<td>1.430</td>
</tr>
<tr>
<td>Heat Capacity of Dry Gas (J/kg.K)</td>
<td>1.430</td>
</tr>
<tr>
<td>Mol. Weight (g/mol)</td>
<td>28</td>
</tr>
<tr>
<td>Z</td>
<td>0.613</td>
</tr>
<tr>
<td>Mol. Volume (m^3/mol)</td>
<td>1.301</td>
</tr>
<tr>
<td>Cp (J/kg.K)</td>
<td>1.406</td>
</tr>
<tr>
<td>Cp (J/kg.K)</td>
<td>0.000</td>
</tr>
<tr>
<td>Thermal Conductivity (W/m.K)</td>
<td>0.000</td>
</tr>
</tbody>
</table>

**Gas Composition**

<table>
<thead>
<tr>
<th>Gas Name</th>
<th>Mol. Weight (g/mol)</th>
<th>Z</th>
<th>Mol. Volume (m^3/mol)</th>
<th>Cp (J/kg.K)</th>
<th>Cp (J/kg.K)</th>
<th>Thermal Conductivity (W/m.K)</th>
<th>Color</th>
</tr>
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<td>32</td>
<td>0.608</td>
<td>1.406</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>Blue</td>
</tr>
</tbody>
</table>

**Gas Properties**

- **Temperature Reference (K):** 298.15
- **Pressure Reference (MPa):** 1
- **Density (g/L):**
- **Compressibility Factor (v):**
- **Heat Capacity (J/kg.K):**
- **Thermal Expansion Coefficient (K^-1):**
- **Viscosity (mPa.s):**
- **Thermal Conductivity (W/m.K):**
WELL ARCHITECTURE

Section #2

Section #3

Section #5

INJECTIONS/WITHDRAWALS DATABASE

Data can be loaded from a flow measurement file
It’s possible to have up to 4 different fluids in each column (3 interfaces)
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

CAVERN GEOMETRY IN LOCAS

2D axisymmetrical 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
CAVERNS PROFILE FROM SONAR SURVEY

Load file from sonar survey

MESHING PARAMETERS
MESHES DATABASE

ANALYSIS OF A PRE-ABANDONMENT TEST

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LONG-TERM COMPUTATIONS
Task 2: Determination of long-term cavern temperature evolution

- Determination of natural rock temperature $T_{\infty}$
- Fitting of a cavern temperature measurement

Accurate prediction of brine temperature evolution and brine thermal expansion

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**SPR2 Geothermal Temperature**

![Graph showing geothermal temperature](chart.png)

**Temperature (°C)**

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>0</th>
<th>100</th>
<th>200</th>
<th>300</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15</td>
<td>16</td>
<td>17</td>
<td>18</td>
</tr>
<tr>
<td>SPR2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$T_{\infty} \approx 19.5 \, ^{\circ}C$
SPR2 TEMPERATURE MEASUREMENT IN 2002

Cavern Temperature measurement
Accurate prediction

T_{o} = 19.5 °C
SPR2 CAVERN TEMPERATURE FITTING

- Temperature: 18.35 °C
- Increase rate: +0.58 °C/year
- 1st July 2002
- 1st June 2000
- 763 days

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
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)
Calculation Steps

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
Example of parameters back-calculation

Salt parameters to be determined for long-term computations:

- Salt elastic parameters \((E, \nu)\)
- Salt creep parameters
  - Stationary creep: Norton-Hoff parameters \((A, n, Q/R)\)
- Salt hydraulic parameters \(K_{\text{hyd}}^{\text{salt}}\)
Back-calculation of Salt Elastic Parameters

\[ \nu = 0.25 \text{ assumed} \]

Finite Elements computation

\[ E \approx 16,500 \text{ MPa} \]

STATIONNARY PARAMETERS FITTED FOR TWO PERIODS

Transient phase

1st fitting period

2nd fitting period

Time (days since January 31, 1964)
Selection of Parameters to be Fitted

Parameters to be Fitted

Search domain
Selection of Fitted Periods

Selection of the Optimization Method
Fitting results can be emailed

Fitting Contour Plots

- Soil permeability
- Norton A parameter

Worst $\rightarrow$ Best

Pressure computation

- $5 \times 10^{-20} \text{ m}^2$
- $4 \times 10^{-20} \text{ m}^2$
INVESTIGATION OF FITTING SENSIBILITY

Salt permeability:

\[ K_{\text{salt}} \approx 3 \times 10^{-20} \text{ m}^2 \]

Salt stationary creep:

\[ \dot{\varepsilon} = A \exp \left( \frac{-Q}{RT} \right) \sigma^n \]  
(Norton-Hoff law)

2 possible sets of parameters

<table>
<thead>
<tr>
<th>Set</th>
<th>( A ) (MPa·year)</th>
<th>( n )</th>
<th>( Q/R ) (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>2.5</td>
<td>2.5</td>
<td>4100</td>
</tr>
<tr>
<td>#2</td>
<td>7.8</td>
<td>5</td>
<td>4100</td>
</tr>
</tbody>
</table>

SPR2 - FITTING MAIN RESULTS
STATIONNARY PARAMETERS FITTED FOR TWO PERIODS

Average pressure difference < 10 hPa

Long-term computation
**Norton-Hoff set #1**

\[ K_{\text{yield}}^{\text{hyd}} = 4 \cdot 10^{-20} \text{ m}^2 \]

\[ n = 2.55 \]

\[ A = 2.5 \text{ /MPa}^{2.5}\text{-year} \]

\[ Q/R = 4100 \text{ K} \]

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**SUBSIDENCE CALCULATION**

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**Geochemical Model**

Spatial relation of geochemical model.

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**Subsidence Calculation**

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**Subsidence**

Radial Subsidence vs. Time

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**Subsidence vs. Depth**

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**Subsidence vs. Temperature**

---

**Subsidence vs. Pressure**

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**Subsidence vs. Water Saturation**

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**Subsidence vs. Gas Saturation**

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**Subsidence vs. Oil Saturation**

---

**Subsidence vs. Salinity**

---

**Subsidence vs. Mineralogy**

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NO-TENSION CRITERIA, DILATION CRITERIA...

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:

contact@Brouard-Consulting.com