



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

Technical Class
SMRI Fall Meeting - Leipzig, Germany
October 3, 2010



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OUTLINE

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



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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

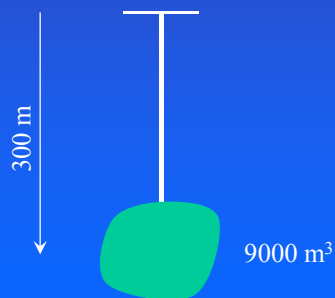


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EXAMPLE OF APPLICATION

CAVERN ABANDONMENT

Carresse SPR2 cavern test supported by SMRI



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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

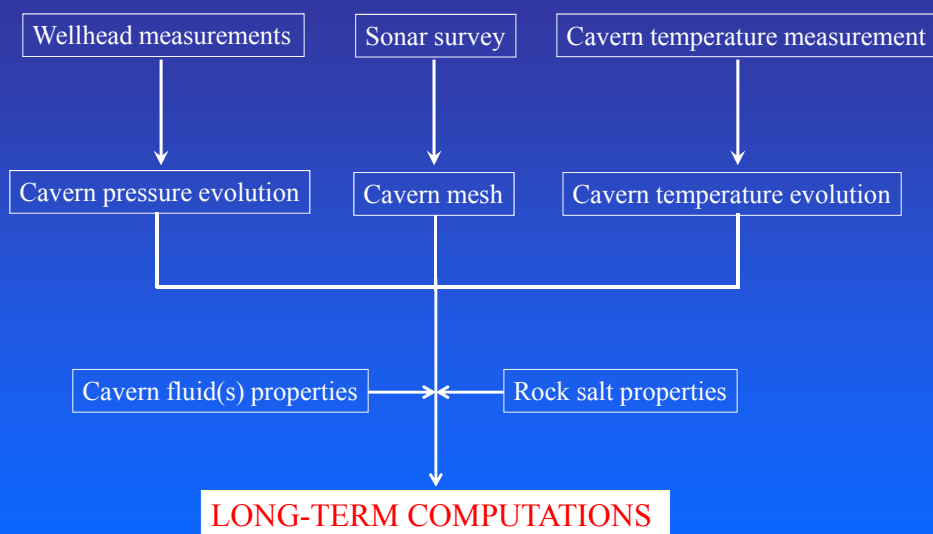
- Mechanical parameters
 - elasticity
 - secondary creep (Norton-Hoff)
- Hydraulical parameters: salt permeability at cavern scale

• LONG-TERM FEM COMPUTATIONS → PREDICTIONS



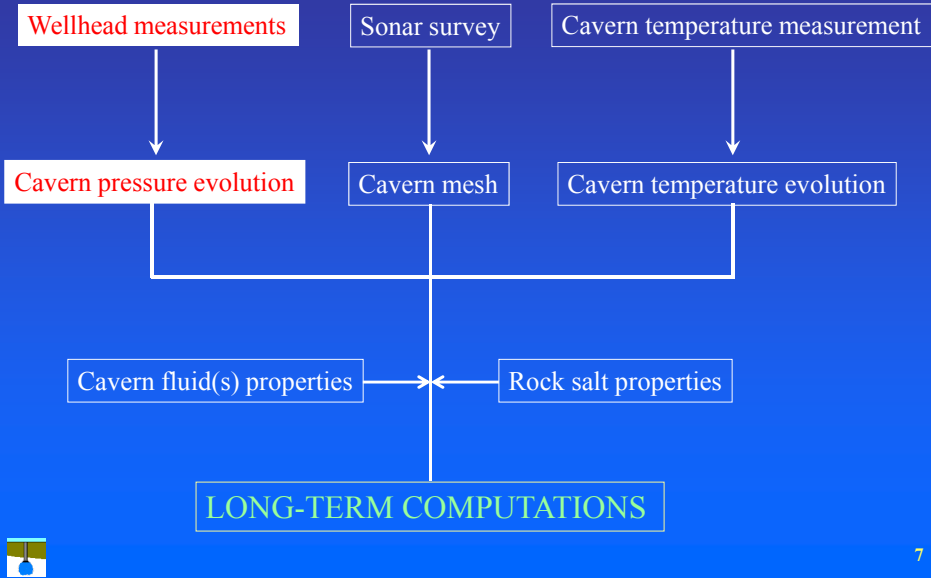
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ANALYSIS OF A PRE-ABANDONMENT TEST



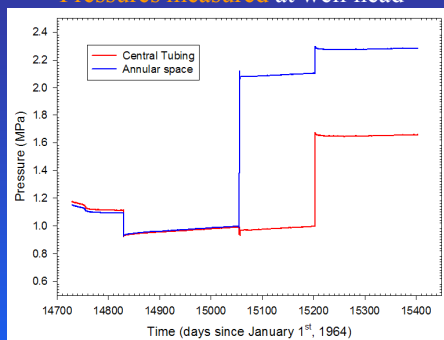
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ANALYSIS OF A PRE-ABANDONMENT TEST

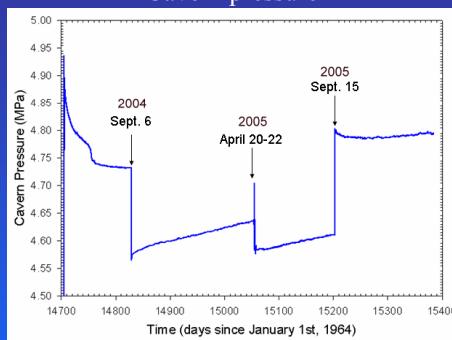


Task 1: Determination of cavern pressure evolution during the test

Pressures measured at well head



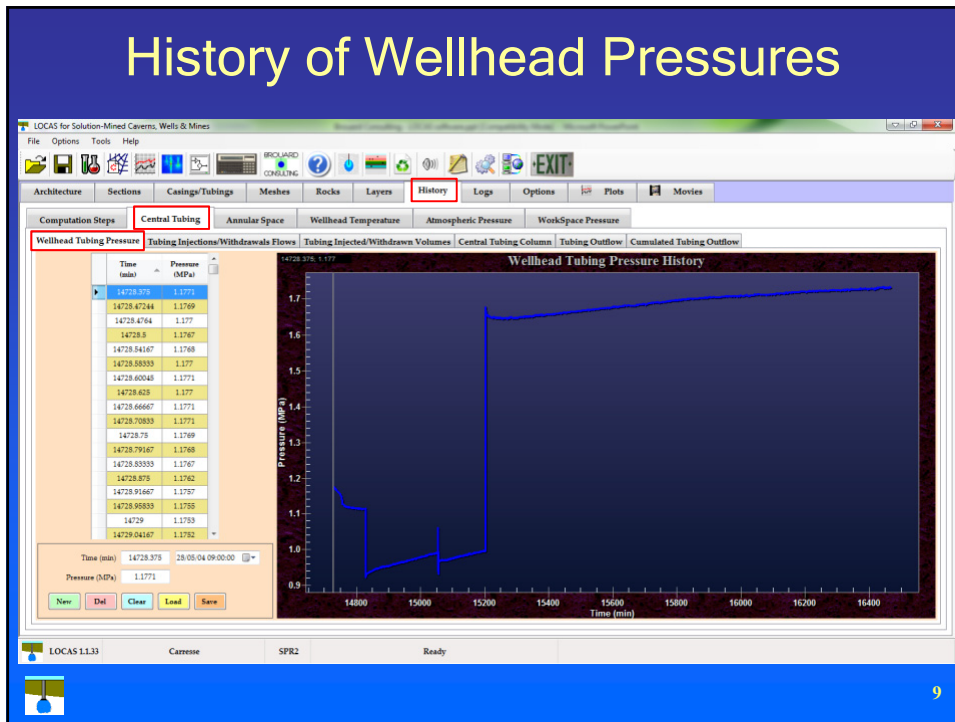
Cavern pressure



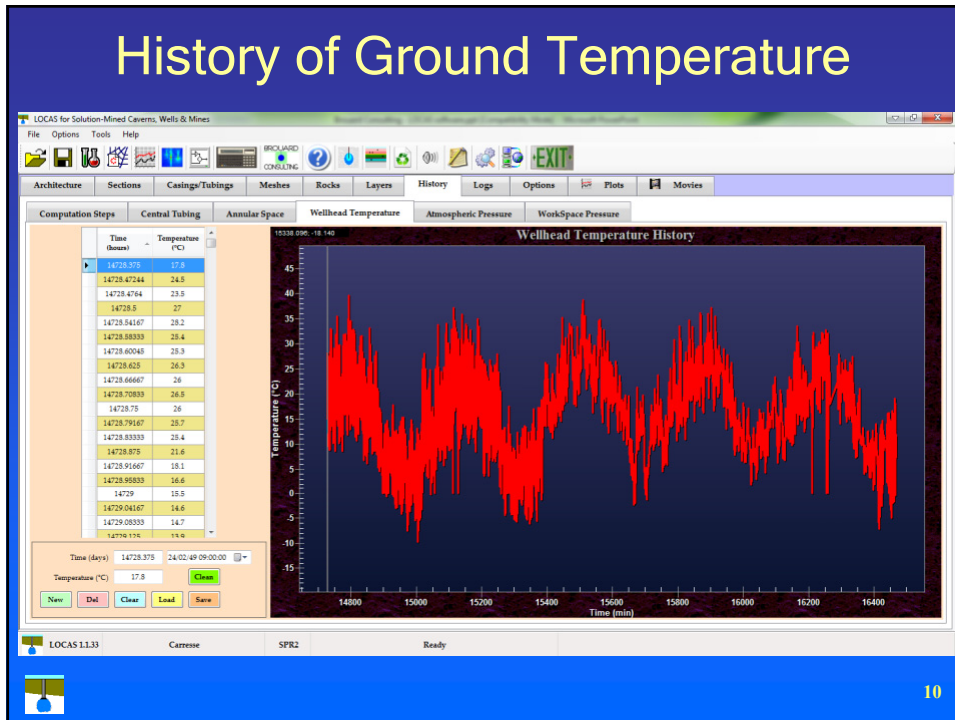
Well data

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

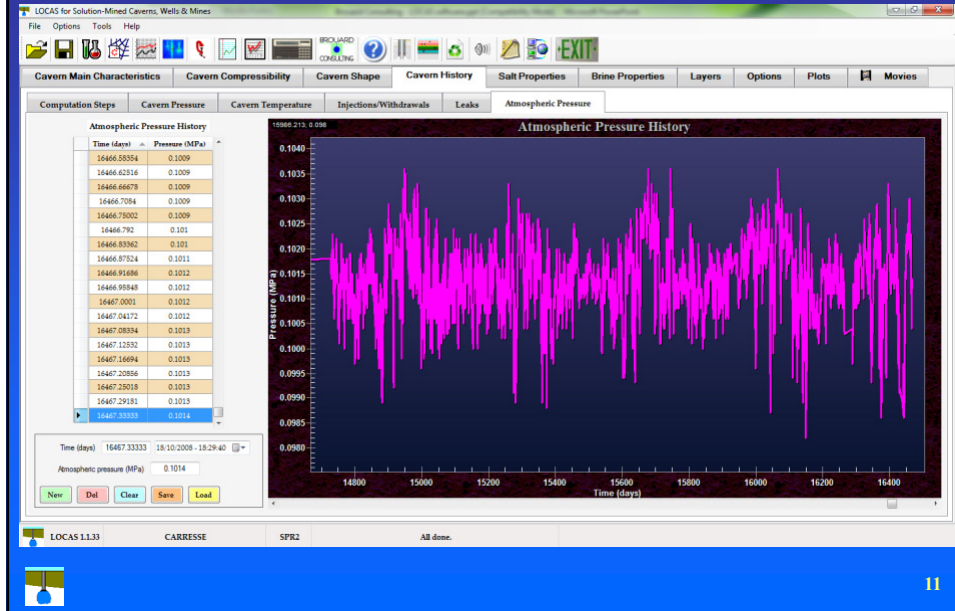
History of Wellhead Pressures



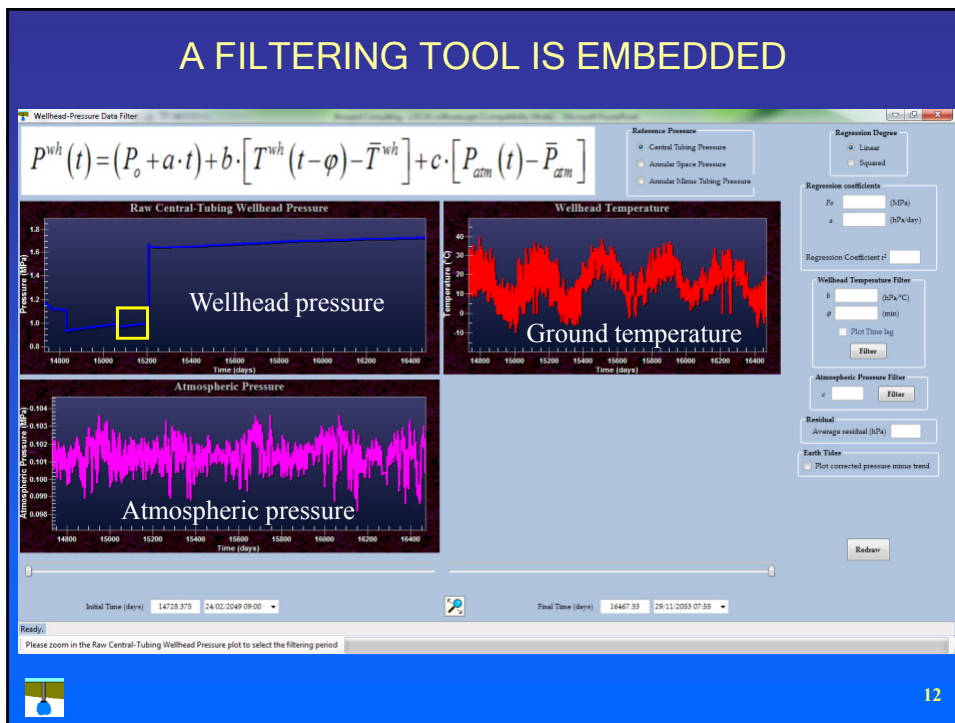
History of Ground Temperature

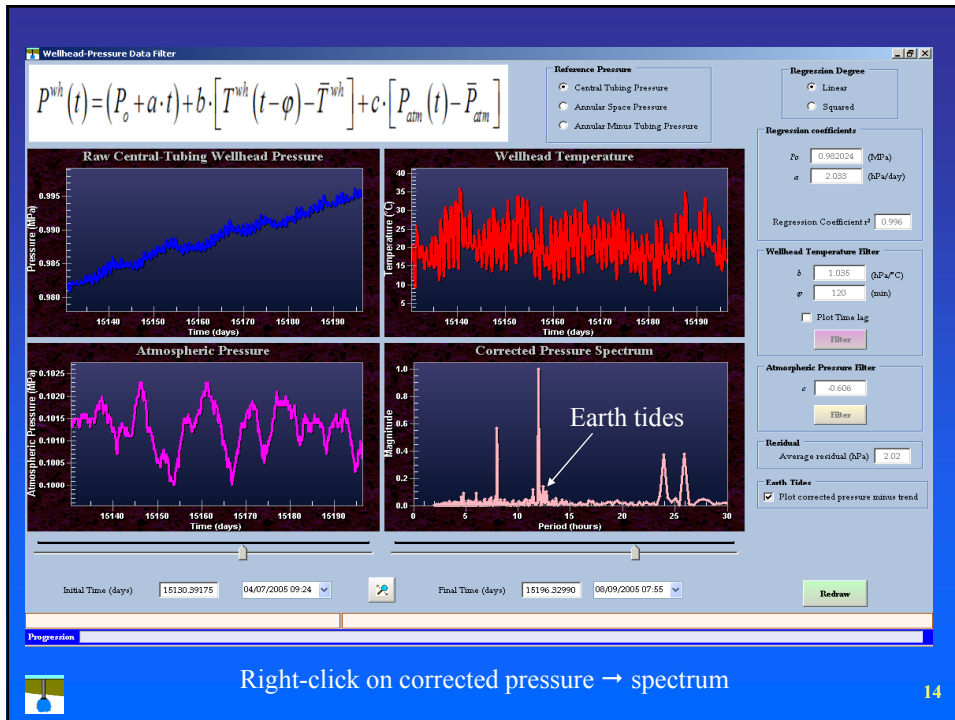
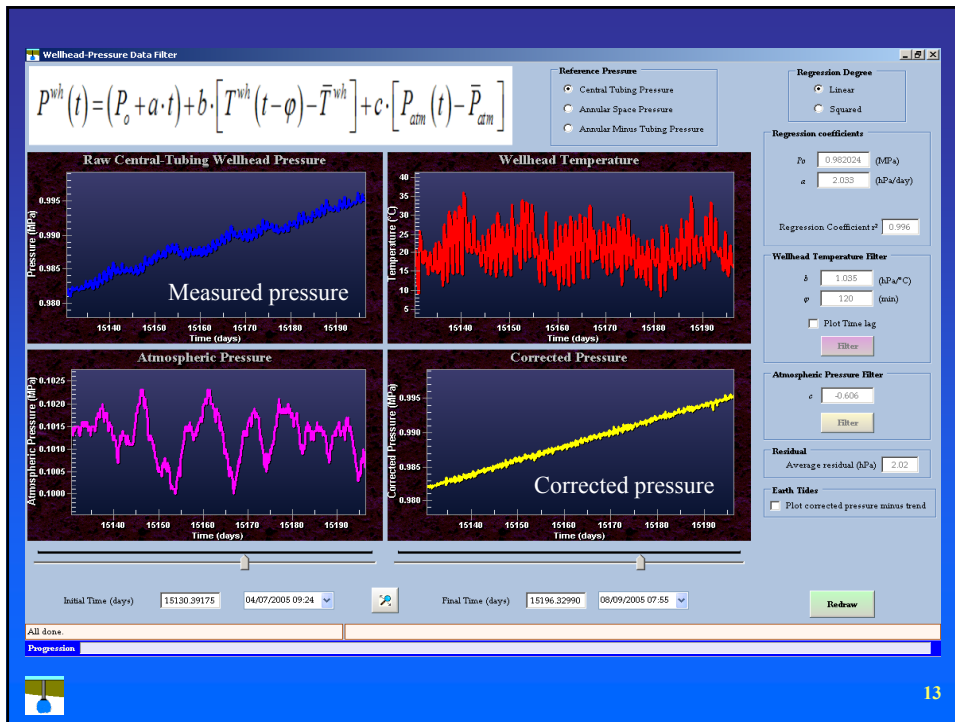


History of Atmospheric Pressure



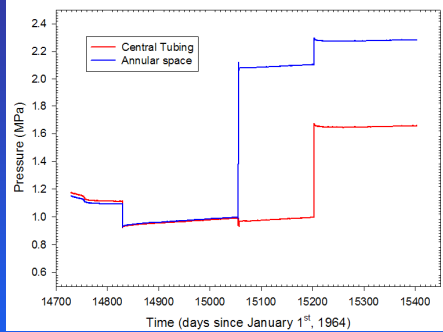
A FILTERING TOOL IS EMBEDDED



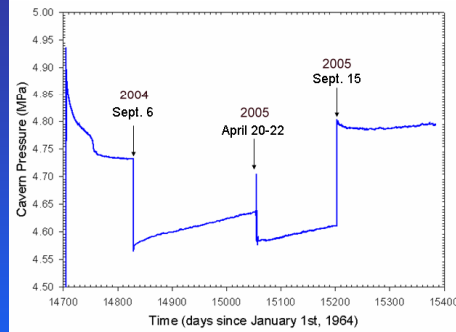


Task 1: Determination of cavern pressure evolution during the test

Corrected pressures at well head



Corrected cavern pressure



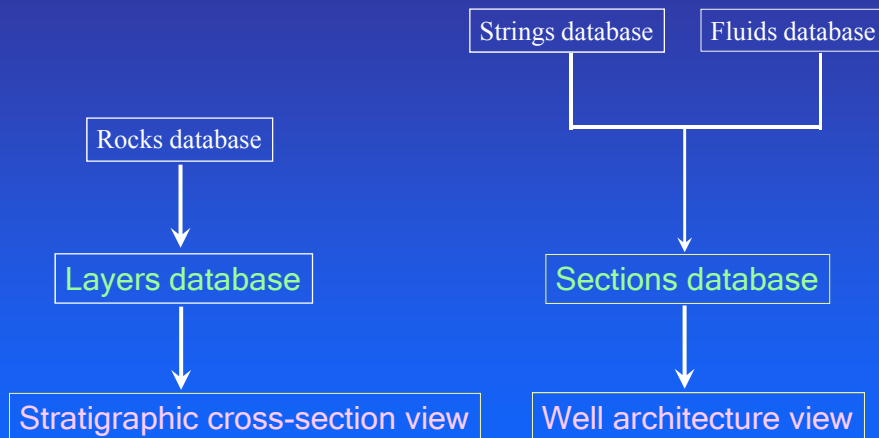
Well data

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



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Well Data in LOCAS






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
LIQUIDS DATABASE

Fluids Databases

Liquids Pure Gases Natural Gases

Liquid name	Temperature reference (K)	Pressure reference (atm)	Density (kg/m ³)	Compressibility factor (x1E-4 /MPa)	Heat capacity (J/kg-K)	Thermal expansion coefficient (°C)	Viscosity (x1E-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	4.1815	2.6	1.002	0.6	

Liquid Properties

Liquid Name: Saturated Brine Color: 

Pressure reference (atm): 1 Temperature reference (K): 293.15

Density (kg/m³): 1200 Compressibility factor (x1E-4 /MPa): 2.57 Viscosity (x1E-3 Pa.s): 1.2

Heat capacity (J/kg-K): 3.768 Thermal expansion coefficient (°C): 4.4 Thermal conductivity (W/m-K): 0.57






New Del Save Load

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PURE GASE DATABASE

Fluids Databases

Liquids Pure Gases Natural Gases

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 (x1E-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	15.195	
Air	1	293.15	29	20	1.4028	28.96	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	

Gas Properties

Gas Name: Methane Color: 

Pressure reference (atm): 1 Temperature reference (K): 293.15

Cp (J/mol-K): 35 Cp/Cv: 1.3054 Molecular weight (g/mol): 16.043 Viscosity (x1E-5 Pa.s): 1.025

Cv (J/mol-K): 27 Z: 0.998 Thermal conductivity (mW/m-K): 32.81

New Del Save Load Help

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NATURAL GASES DATABASE

Fluids Databases

Natural Gas Name	Liquids			Pure Gases							Natural Gases						
	Methane (%)	Nitrogen (%)	Carbon Dioxide (%)	Ethane (%)	Propane (%)	Water (%)	Sulfide (%)	Hydrogen (%)	Carbon Monoxide (%)	Oxygen (%)	i-Butane (%)	n-Butane (%)	i-Pentane (%)	n-Pentane (%)	n-Hexane (%)	n-Heptane (%)	n-Octane (%)
Gulf Coast	96.5222	0.2595	0.5956	1.8186	0.4596	0	0	0	0	0	0.0977	0.1007	0.0473	0.0324	0.0664	0	0
Amatillo	90.6/24	3.1284	0.40/6	4.52/9	0.52/8	0	0	0	0	0	0.103/	0.126/	0.0321	0.044/	0.029/	0	0
Ekofak	85.9063	1.0068	1.4954	8.4919	2.3015	0	0	0	0	0	0.3486	0.3506	0.0509	0.048	0	0	0
High N2	81.441	13.465	0.985	3.3	0.605	0	0	0	0	0	0.1	0.104	0	0	0	0	0
High CO2-N2	81.211	5.702	7.585	4.303	0.896	0	0	0	0	0	0.151	0.152	0	0	0	0	0

Natural gas name: **Gulf Coast**

Mole Percentage of Each Component:

Methane	96.5222	Nitrogen	0.2595	Hydrogen sulfide	0	i-Butane	0.0977	n-Pentane	0.0324	n-Octane	0	Helium	0
Ethane	1.8186	Hydrogen	0	Carbon monoxide	0	n-Butane	0.1007	n-Hexane	0.0664	n-Nonane	0	Argon	0
Propane	0.4596	Oxygen	0	Carbon dioxide	0.5956	i-Pentane	0.0473	n-Heptane	0	n-Decane	0	Water	0

Total percentage: 100 Color: ■ **New** **Del**

Reference Pressure and Temperature:

Absolute pressure (MPa): **0.101325**
 Temperature (°C): **20**

Natural Gas Properties:

Molecular weight (g/mol): 16.7994 Specific gravity: 0.5799
 Natural gas density (kg/m³): 0.69983 Dynamic viscosity (x1E-5 Pa.s): 1.11
 Compressibility factor Z: 0.99797

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SECTIONS DATABASE

LOCAS for solution-mined caverns

File Options Tools Help

Architecture Sections Strings Meshes Rocks Salt Clay Cement Fluids Layers History Logs Miscellaneous Plots Movies

No.	Length (m)	Depth (m)	Central Tubing	First Casing	Second Casing	Borehole	Tubing Cross-Section (in)	Tubing Volume (m ³)	Tubing Fluid	Tubing Compressibility Factor (*1E-10 (Pa))	Tubing Wave Velocity	First Annular Cross-Section (in)	First Annular Volume	First Annular Fluid	First Annular Compressibility Factor (*1E-10 (Pa))	First V C
1	40	0-40	7.5 8 NEW VAM N80 28.4 bar	13 3 8 N80 ep 9.65	15 3 8 K55 ep 11.05	23"	24.61	0.984	Methane	75604.05	313	51.17	2.047	Water	5.89	
2	387.05	40-427.05	7.5 8 NEW VAM N80 28.4 bar	13 3 8 K55 ep 9.65		171/2	24.61	9.525	Methane	75604.05	320	51.17	19.805	Water	5.89	
3	943.75	427.05-1370.8	7.5 8 NEW VAM N80 28.4 bar	9 5 8 N80 ep 10.03		12 1/4	24.61	23.226	Methane	75604.05	375	10.08	9.513	Water	5.42	
4	1.35	1370.8-1372.15	7.5 8 NEW VAM N80 28.4 bar	9 5 8 N80 ep 10.03		12 1/4	24.61	0.033	Methane	75604.05	331	10.08	0.014	—PACKER—	0	
5	4.55	1372.15-1376.7	7.5 8 NEW VAM N80 28.4 bar	9 5 8 N80 ep 10.03		12 1/4	24.61	0.112	Methane	75604.1	331	10.08	0.046	Methane	75604.1	
6	228.3	1376.7-1605				8 1/2	0	0		0	0	0	0		0	

Section Parameters

Central Tubing 1st Casing 2nd Casing Borehole

Length (m): 40 Depth (m): 0-40

Central Tubing: Tubing: 7.5 8 NEW VAM N80 28.4 bar, Tubing Fluid: Methane

1st Casing: 1st Casing: 13 3 8 N80 ep 9.65, 1st Annular Fluid: Water

2nd Casing: 2nd Casing: 15 3 8 K55 ep 11.05, 2nd Annular Fluid: —CEMENT—

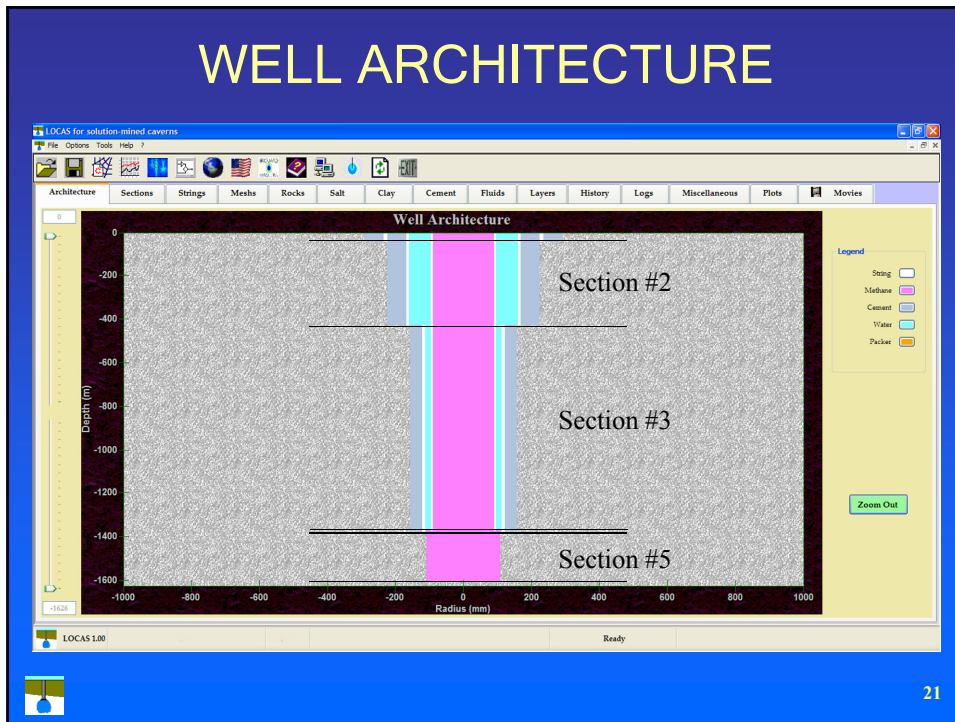
Borehole: Borehole: 23", Borehole Fluid: —CEMENT—

New **Load** **Save** **Clear** **Del**

LOCAS 1.00 Ready

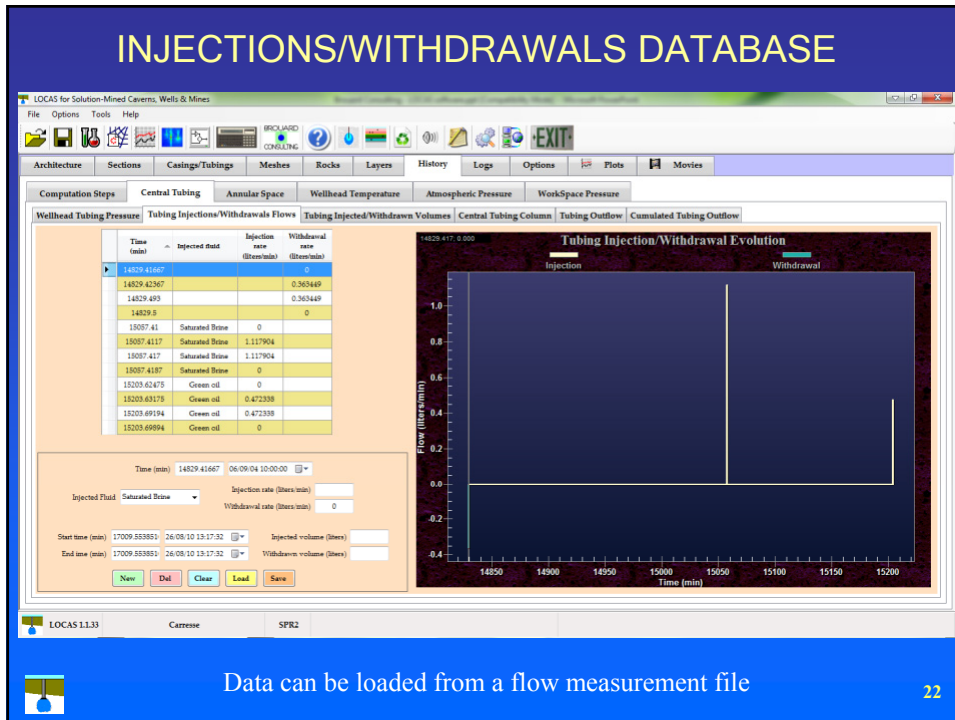
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WELL ARCHITECTURE



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INJECTIONS/WITHDRAWALS DATABASE



Data can be loaded from a flow measurement file

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COLUMNS DATABASE

The screenshot shows the LOCAS software interface with the 'Columns Database' window open. The window contains a table with the following data:

Time (days)	1st Fluid	1st Fluid density (kg/m ³)	1st Fluid volume (liters)	1st Interface depth (m)	2nd Fluid	2nd Fluid density (kg/m ³)	2nd Fluid volume (liters)	2nd Interface depth (m)
14728.375	Unsaturated Brine	1182	820	134	Saturated Brine	1200	1073	
14829.5	Saturated Brine	1200	1893					
15007.41	Saturated Brine	1200	1893					
15057.4187	Green oil	810	25	7	Saturated Brine			
15203.62473	Green oil	810	22	7	Saturated Brine			
15203.69894	Green oil	810	44	138.1	Saturated Brine			
16000	Green oil	810	42	135.1	Saturated Brine			

The 'Tubing Interfaces Evolution' graph shows depth (m) on the y-axis (0 to 140) and time (min) on the x-axis (14800 to 16000). The graph displays a step-like function representing the depth of fluid interfaces over time.

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

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HISTORY OF CAVERN PRESSURE

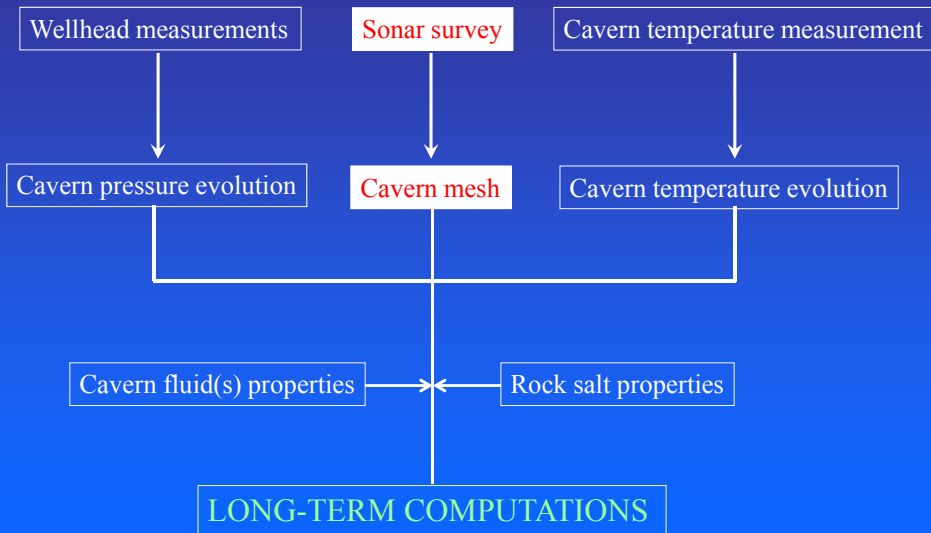
The screenshot shows the LOCAS software interface with the 'History of Cavern Pressure' window open. The window contains a table with the following data:

Time (days)	Pressure (MPa)
16466.53855	4.9636
16466.62317	4.9636
16466.66879	4.9637
16466.70941	4.9638
16466.75003	4.9637
16466.79201	4.9637
16466.83363	4.9636
16466.87525	4.9635
16466.91687	4.9636
16466.9585	4.9635
16467.00012	4.9635
16467.04174	4.9635
16467.08336	4.9635
16467.12594	4.9635
16467.16896	4.9634
16467.20858	4.9634
16467.2502	4.9634
16467.29182	4.9634
16467.33334	4.9634

The 'Cavern Average Pressure History' graph shows pressure (MPa) on the y-axis (4.50 to 4.95) and time (days) on the x-axis (14650 to 15300). The graph displays a step-like function representing the average cavern pressure over time.

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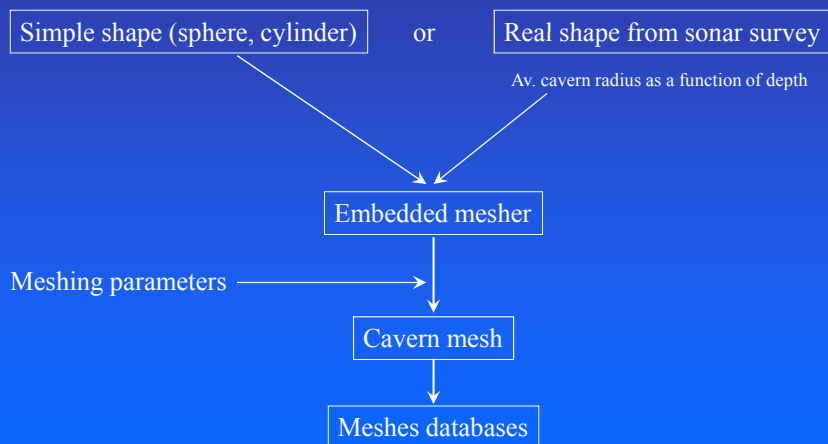
ANALYSIS OF A PRE-ABANDONMENT TEST



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CAVERN GEOMETRY IN LOCAS

2D axisymmetrical caverns



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CAVERN PROFILE FROM SONAR SURVEY

The screenshot shows the LOCAS software interface with the 'Cavern Shape' tab selected. The 'Cavern profile' table is as follows:

Depth (m)	Radius (m)
297.05	0.41
297.1	1.23
297.2	1.23
297.3	1.23
297.4	1.23
297.5	1.23
297.6	1.23
297.7	1.23
297.8	1.23
297.9	1.23
298	1.23
298.1	1.22
298.2	1.22
298.3	1.22
298.4	1.22
298.5	1.22
298.6	1.22

The 'SPR2 Cavern Profile' graph shows a cross-section of the cavern with depth on the y-axis (ranging from -297 to -325) and radius on the x-axis (ranging from 0 to 35). The 'Load' button is highlighted with a red box, and an arrow points to it from the text 'Load file from sonar survey'.

Load file from sonar survey

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MESHING PARAMETERS

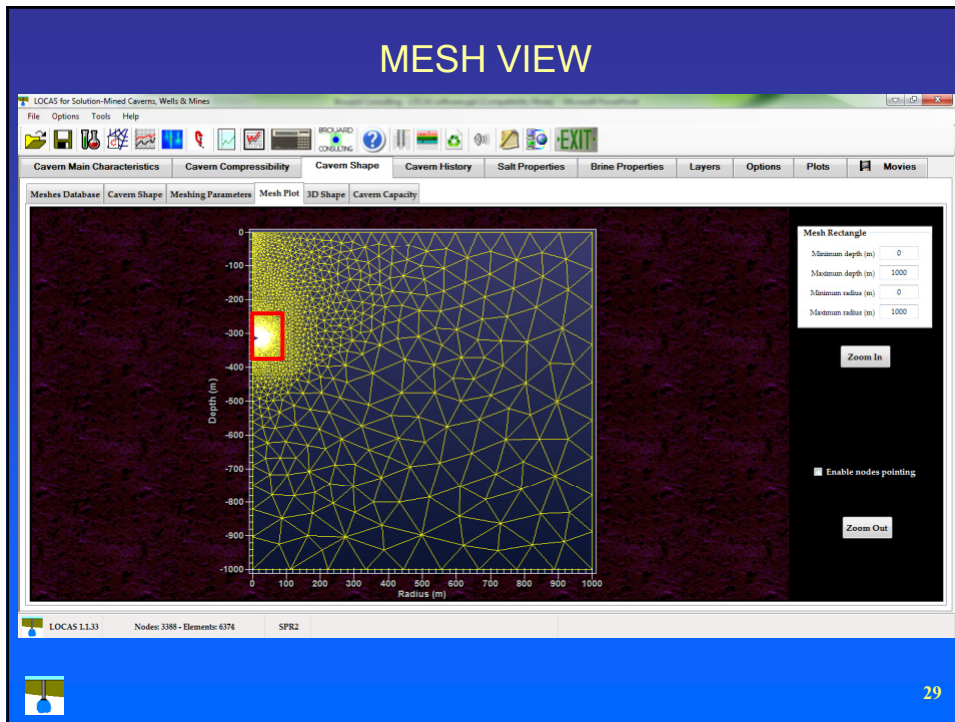
The screenshot shows the LOCAS software interface with the 'Meshing Parameters' tab selected. The settings are as follows:

- Low Density Area:**
 - Mesh width (m): 600
 - Mesh height (m): 600
 - Max size elements (m): 50
- High Density Area:**
 - Minimal horizontal distance to cavity wall (m): 50
 - Minimal vertical distance to cavity wall (m): 50
 - Maximum size of elements (m): 10
- Cavern wall:**
 - Maximum distance between nodes on cavern wall (m): 2

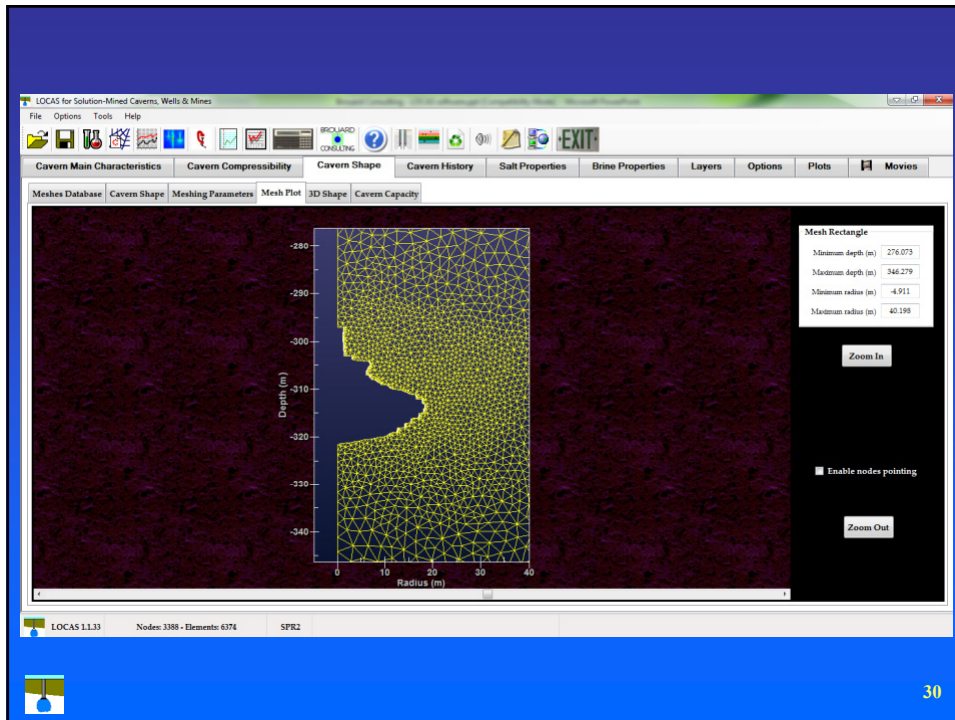
The 'Generate Mesh' button is circled in red.

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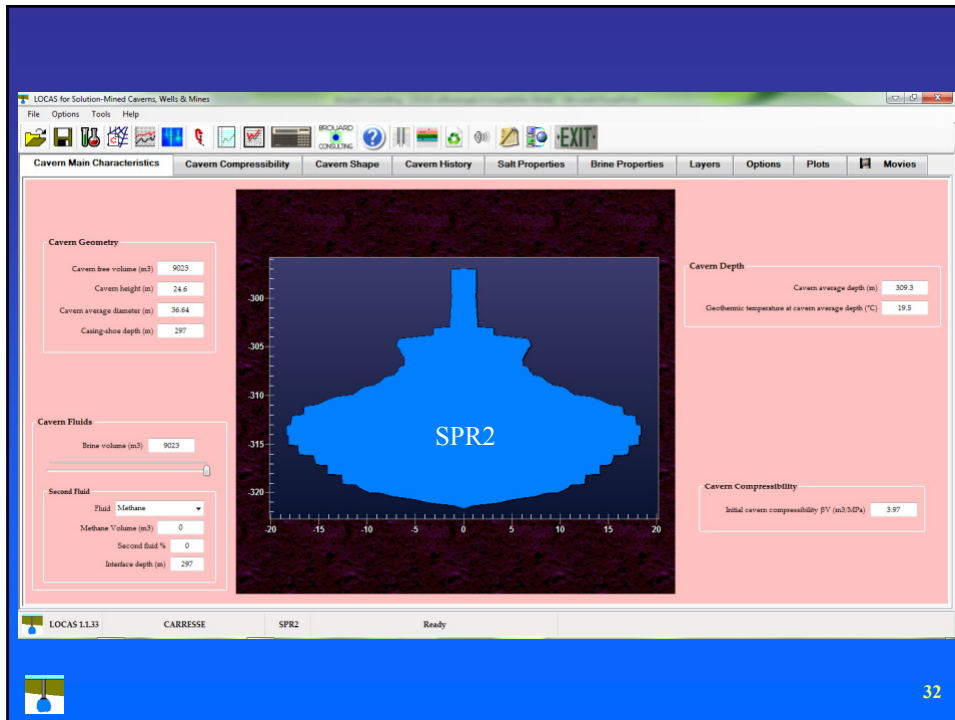
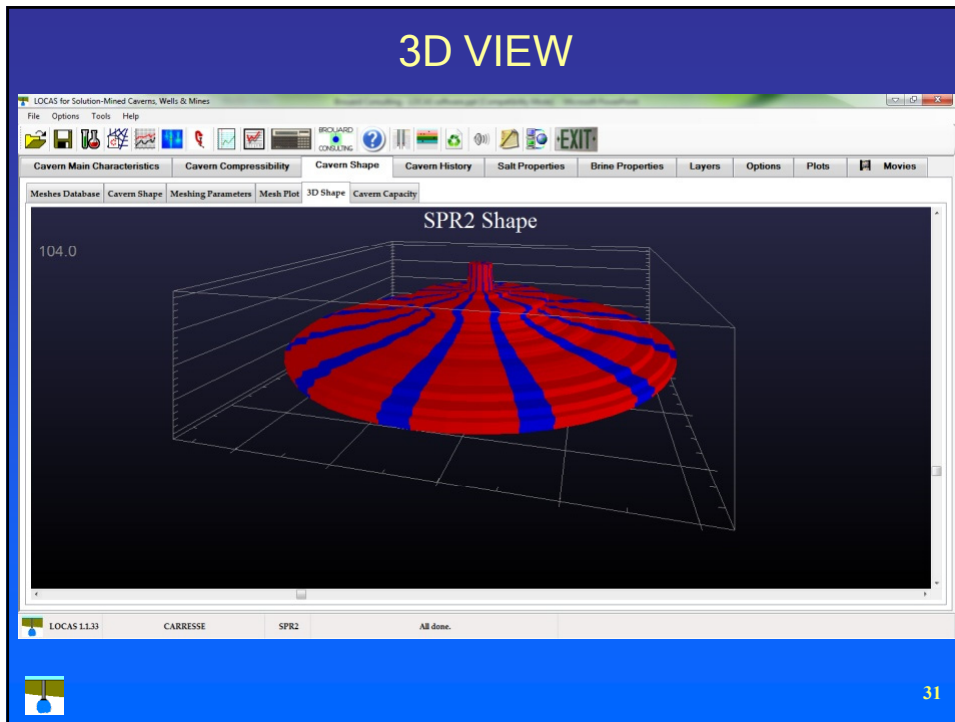
MESH VIEW



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MESHES DATABASE

The screenshot shows the LOCAS software interface with the 'Meshes Database' window open. The window contains a table with the following data:

Mesh Name	Cavity top (m)	Cavity bottom (m)	Radius max (m)	Volume (m ³)	File Name	Nodes	Elements	Elements Type	Path to Mesh File
Mallage léger SPR2	297	321.6	18.32	9023	Mesh_1181.msh	1181	2028	Triangle	D:\LOCAS.NET\LOCAS Y8\bin\input\Mesh
SPR2 mesh	297	321.6	18.32	9023	Mesh_3388.msh	3388	6374	Triangle	D:\LOCAS.NET\LOCAS Y8\bin\input\Mesh

Below the table is a 'Mesh Properties' dialog box with the following fields:

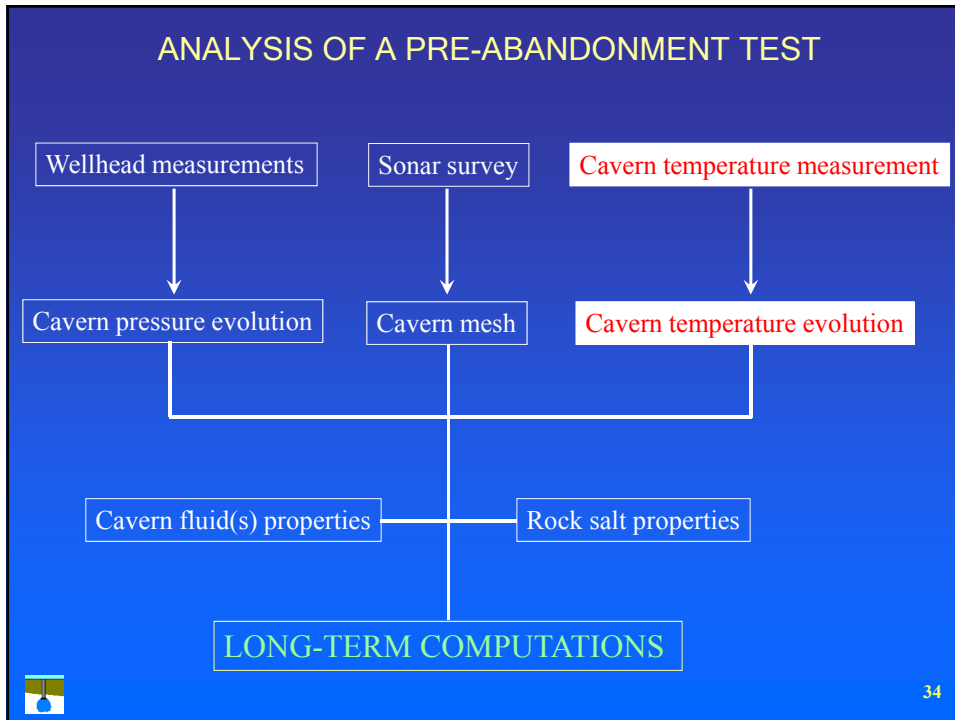
- Cavity Name: SPR2 mesh
- File Name: Mesh_3388.msh
- Cavity top (m): 297
- Cavity bottom (m): 321.6
- Radius max (m): 18.32
- Cavity volume (m³): 9023
- Number of nodes: 3388
- Number of elements: 6374
- Element type: Triangle
- Path to mesh file: D:\LOCAS.NET\LOCAS Y8\bin\input\Mesh

Buttons: New, Del, Load, Save, Clear.

LOCAS 1.1.33 Nodes: 3388 - Elements: 6374 SPR2

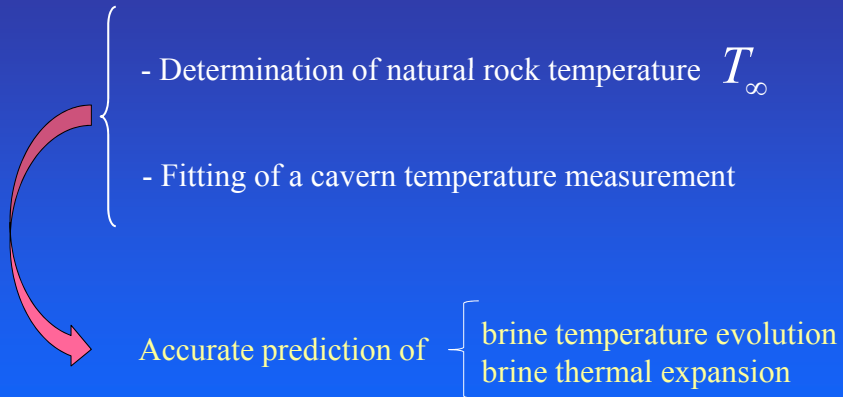
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ANALYSIS OF A PRE-ABANDONMENT TEST



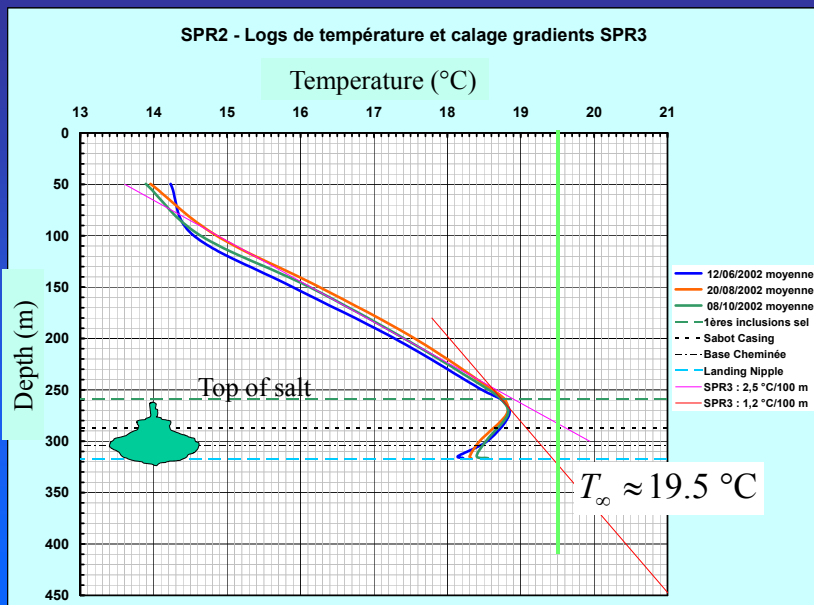
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Task 2: Determination of long-term cavern temperature evolution



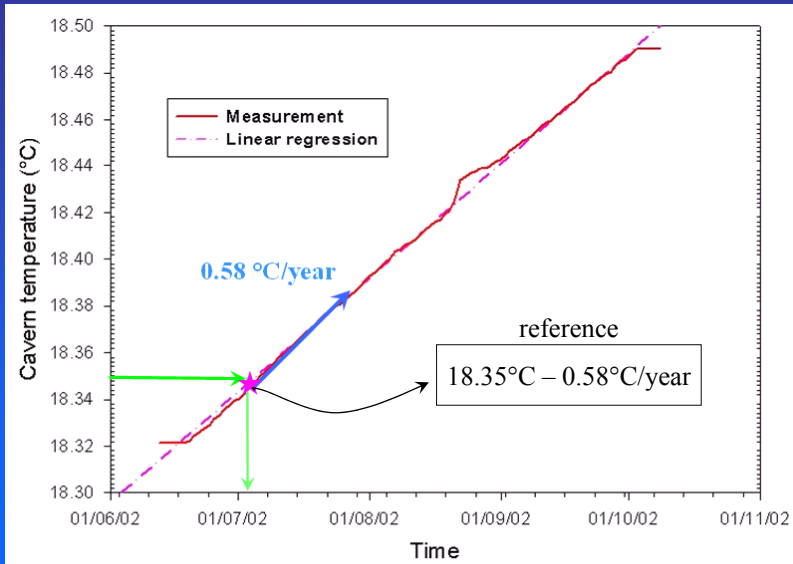
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SPR2 Geothermal Temperature



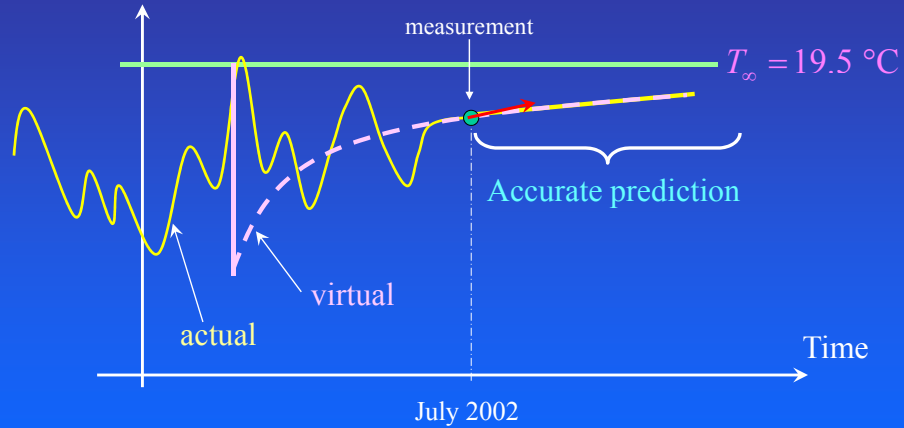
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SPR2 TEMPERATURE MEASUREMENT IN 2002



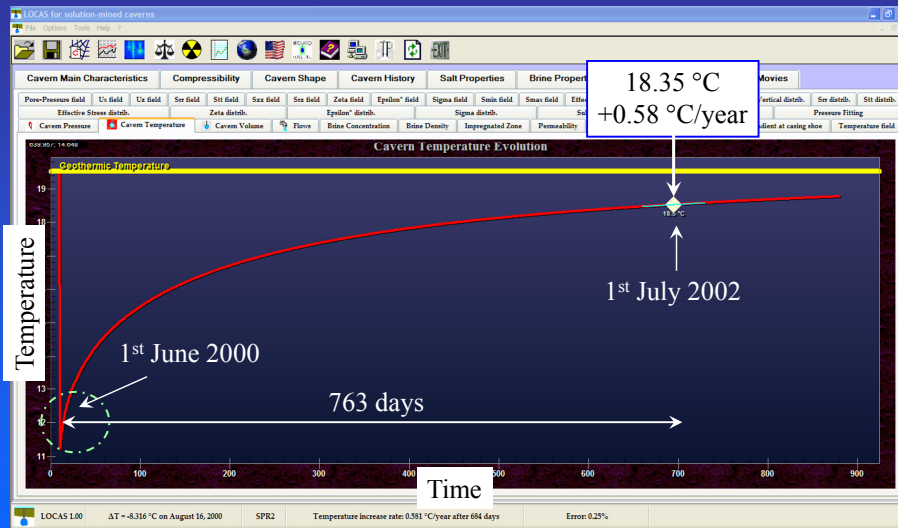
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Cavern Temperature



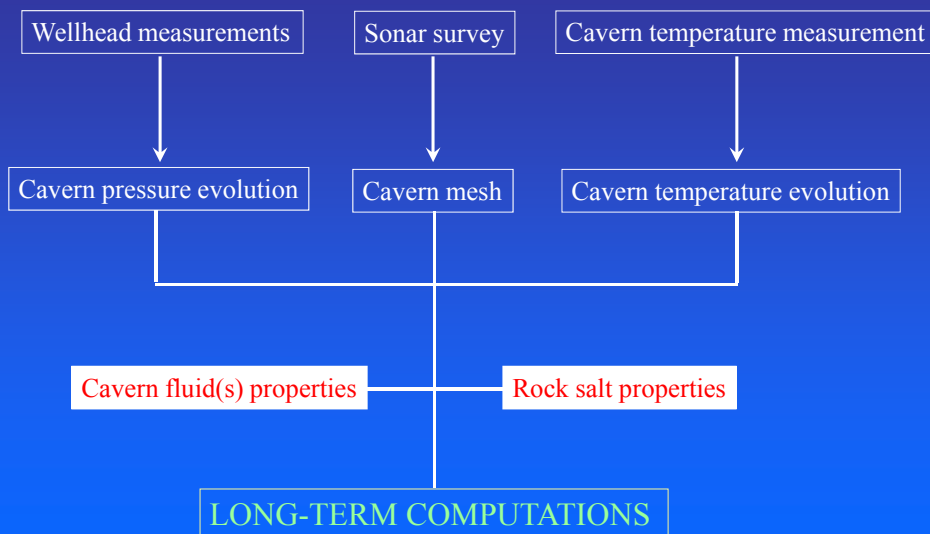
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SPR2 CAVERN TEMPERATURE FITTING



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ANALYSIS OF A PRE-ABANDONMENT TEST



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BRINE PROPERTIES

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SALT PROPERTIES

- Mechanical properties

- Elasticity
- Creep: stationary + 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
- Hydraulic properties (micro-permeation)
- Chemical properties (dissolution/crystallization)

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Munson-Dawson Database

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

Salt Mechanical Properties Salt Density & Thermal Properties Salt Hydraulical Properties Salt Micro-Fracturation Criteria

Constitutive Law Norton-Hoff Law Munson-Dawson Law Lemaitre-Menzel-Schreiner Law Libby2

Set Name	A (MPa ⁿ /year)	QR (K)	n	m	Alpha	Beta	Ka (MPa ⁿ /year)	delta	c (K)	psi	xi
Calage 2006	2.5	4100	2.5	3	-13.2	-7.738	75.07	0.58	0.00902		
Calage SPK3	3	4100	2.88	3	-13.2	-7.738	75.07	0.58	0.00902		

Munson-Dawson Creep Law

Salt Name: Calage 2006

Parameter A: 2.5 (MPaⁿ/year) Parameter QR: 4100 (K) c: 0.00902 (K)

Parameter Ka: 75.07 (MPaⁿ/year) Parameter n: 2.5 Parameter m: 3

alpha: -13.2 beta: -7.738 delta: 0.58

Reverse Creep: No reverse creep Reverse creep

New Del Load Save

LOCAS 1.1.33 Nodes: 3388 - Elements: 6374 SPR2 All done.

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Salt Micro-permeation Properties

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

Salt Mechanical Properties Salt Density & Thermal Properties Salt Hydraulical Properties Salt Micro-Fracturation Criteria

Hydro-Mechanical Criterion LMS Criterion ILB Criterion Stormont Criterion

Hydro-mechanical Criteria

- Constant permeability
- LMS criterion
- ILB criterion
- Stormont criterion

Permeation Properties

Permeability

- From dropdown list Salt initial permeability (m²): 4E-20
- Precise value Salt initial permeability (m²): 4E-20

Salt porosity (%): 1

Matrix compressibility factor (x1E-4 /MPa): 4

Stoastivity (x1E-02 /Pa): 4

LOCAS 1.1.33 Nodes: 3388 - Elements: 6374 SPR2 All done.

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Calculation Steps

The screenshot shows the 'LOCAS for Solution-Mined Caverns, Wells & Mines' software interface. The 'Computations Steps' table is the central focus, listing various simulation steps with their start and end dates and the physical phenomena to be modeled. Below the table, there are configuration options for time steps and which phenomena are taken into account.

Start (days)	End (days)	Creep	Thermal Expansion	Permeation	Dissolution	Adiabatic Compression	Leaks	Initial step (days)	Step Max (days)	Number of outputs	Pressure set	Temperature set	Injections/Withdrawals set	Leak set
0	180	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	0.1	1	1	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
180	13301	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	0.1	10	1	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
13301	13302	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	0.01	0.1	1	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
13302	14388.719	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	0.1	10	1	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
14388.719	14390	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	0.01	0.1	1	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
14390	14400	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	0.1	1	1	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
14400	14704	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	0.01	1	1	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
14704	14705	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	0.01	0.01	1	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
14705	14829.458	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	0.01	1	1	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
14829.458	14829.5	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	0.001	0.01	1	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
14829.5	15002	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	0.01	1	1	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
15002	15007	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	0.01	1	1	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>

Time reference: 31.01.1964 - 00:00:00

Start (days): 0
 18:10:2008 - 19:29:40
 End (days): 180
 18:10:2008 - 19:29:40

Initial time step (days): 0.1
 Time step max allowed (days): 1
 Number of outputs: 1

Phenomena taken into account:
 Creep Thermal Adiabatic compression
 Permeation Dissolution Leaks

LOCAS 1.1.33 Nodes: 3388 - Elements: 6374 SFR2 All done.

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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



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Salt parameters to be determined for long-term computations:

➤ Salt elastic parameters (E, ν)

➤ Salt creep parameters

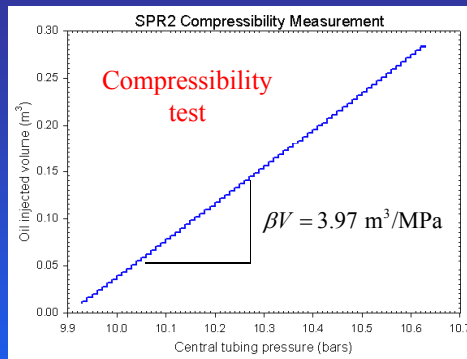
Stationnary creep: Norton-Hoff parameters $(A, n, Q/R)$

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



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Back-calculation of Salt Elastic Parameters



$\nu = 0.25$ assumed

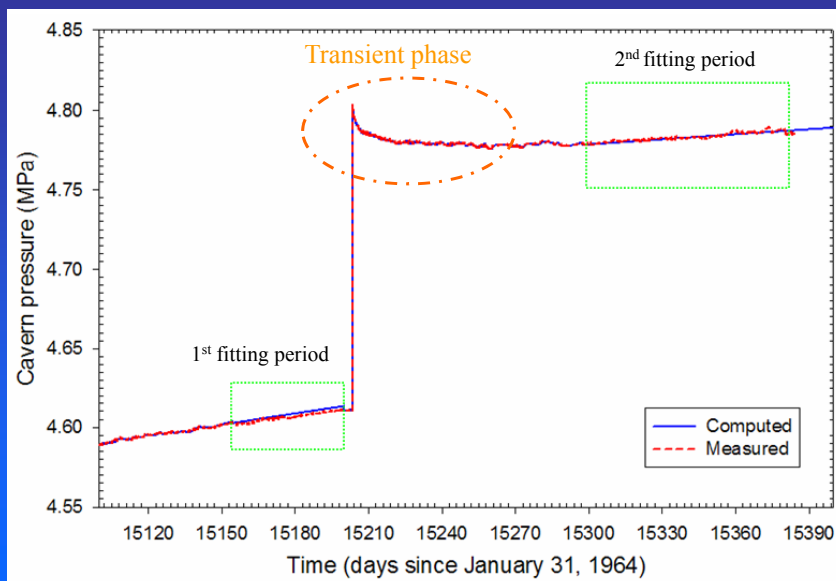
Finite Elements computation

$E \approx 16,500 \text{ MPa}$



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STATIONNARY PARAMETERS FITTED FOR TWO PERIODS



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Selection of Parameters to be Fitted

Optimization Parameters

Nelder-Mead Parameters Differential Evolution Parameters Results

Start Fitted Parameters Fitted Periods Optimization Methods

Salt Constitutive Law

Norton-Hoif Lemaitre-Menzel-Schreiner Munson-Munson Lubby2

Parameters to be fitted

Mechanical Parameters

Norton Creep Law

A n

Munson-Munson Creep Law

A m α_w δ

n Ko β_w

Reverse Creep

pi ki

Lemaitre Creep Law

α β K

Lubby2 Creep Law

G_Ko η Mo K1 K2 Lo

Hydraulic Parameters

Salt Intrinsic Permeability Initial Pore Pressure

START

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Parameters to be Fitted

Optimization Parameters

Nelder-Mead Parameters Differential Evolution Parameters Results

Start Fitted Parameters Fitted Periods Optimization Methods

Parameter Name	Units	Minimum Value	Maximum Value	Initial Value
Salt Intrinsic Permeability	m ²	1E-21	1E-19	1.00E-020
Munson A1	—	0	20	5
Munson n1	—	2	6	3

Search domain

Clear

START

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Selection of Fitted Periods

Reference Time (day 0) 31/01/1964 00:00:00

Initial Date	Day corresponding to Initial Date	Final Date	Day corresponding to Final Date	Period Duration (days)
29/07/2005 00:00:00	15155	12/09/2009 00:00:00	16661	1506
21/12/2005 00:00:00	15300	11/03/2006 00:00:00	15380	80

Period Parameters

Initial Time for fitting (days) 15300 21/12/2005 00:00:00

Final Time for fitting (days) 15380 11/03/2006 00:00:00

Duration (days) 80

Buttons: New, Save, Del, Load, Clear, Add

START

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Selection of the Optimization Method

Optimization

Global map Nelder-Mead method Differential Evolution

Direct Minimization

Fitting Method

Minimizing Pressure difference Minimizing Correction Flow

Global Map

Use provided points list Start line #

Automatic points list Number of points 100

Stop Criterion

ϵ 0.01 (hPa)

Thread Priority

Below Normal Normal Above Normal High

START

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Fitting results can be emailed

Optimization Parameters

Start Fitted Parameters Fitted Periods Optimization Methods

Nelder-Mead Parameters Differential Evolution Parameters Results

Email Results

Send results file by email

Mail subject: LOCAS - Pressure Fitting - CARRESSE - SPR2

Email address: contact@brouard-consulting.com

SMTP server: smtp.free.fr

Sending Frequency: Only at the end

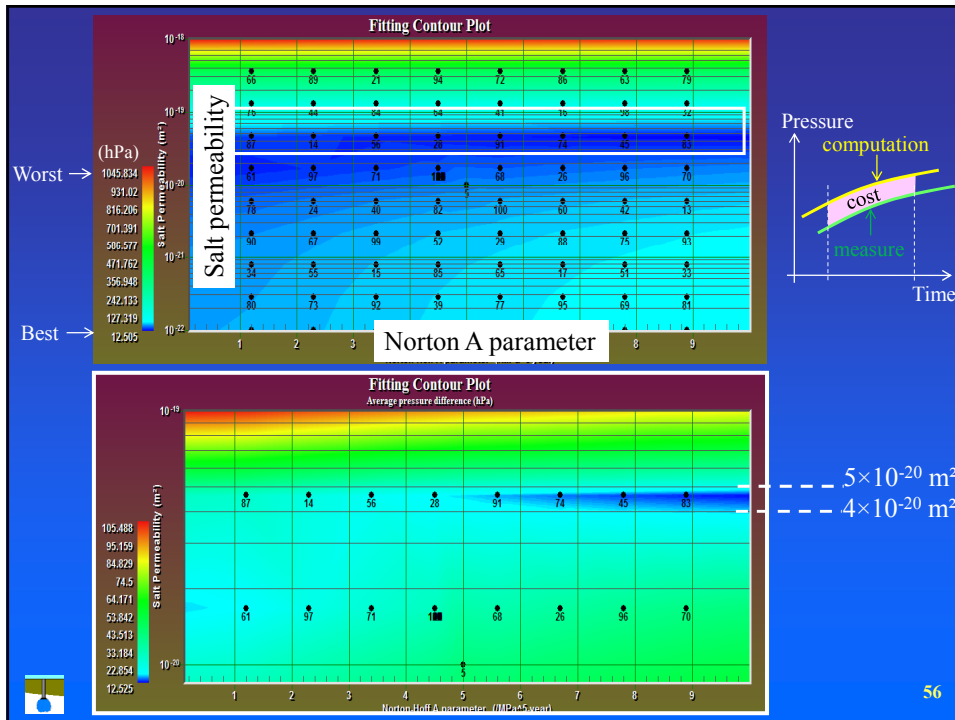
10 Criterion estimation(s)

Test

START

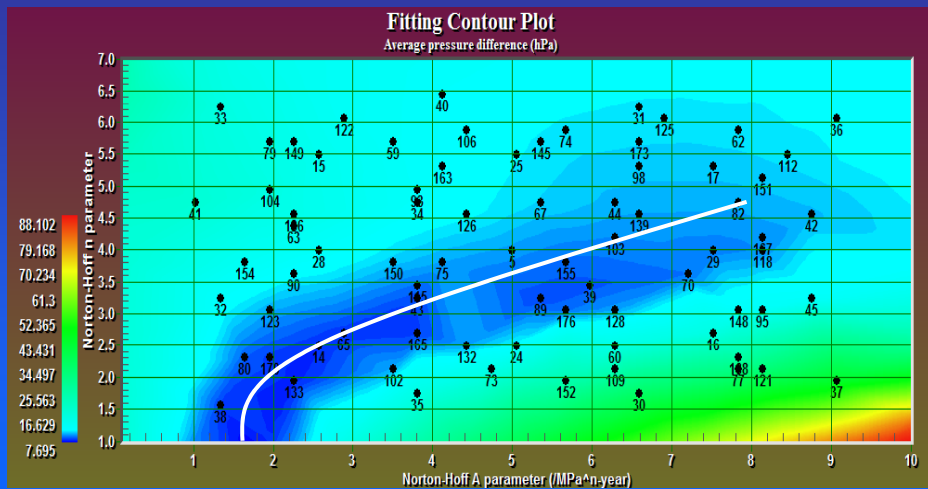


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INVESTIGATION OF FITTING SENSIBILITY



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SPR2 - FITTING MAIN RESULTS

Salt permeability: $K_{salt}^{hyd} \approx 3 - 4 \times 10^{-20} \text{ m}^2$

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

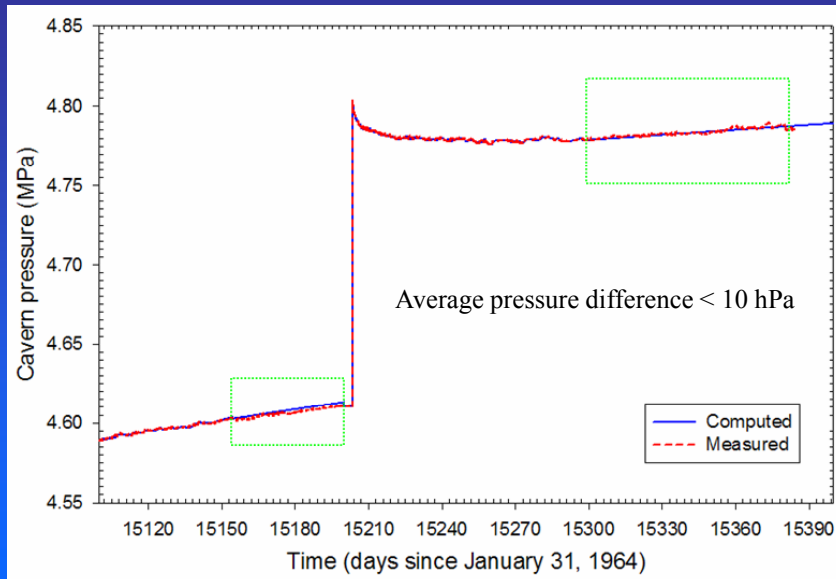
2 possible sets
of parameters

	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

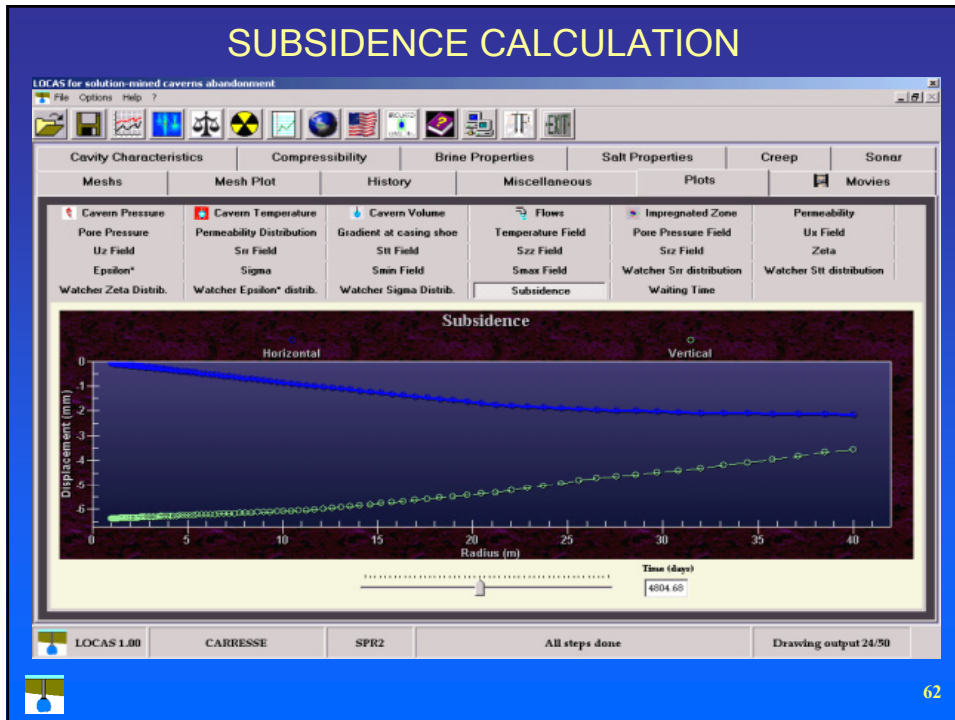
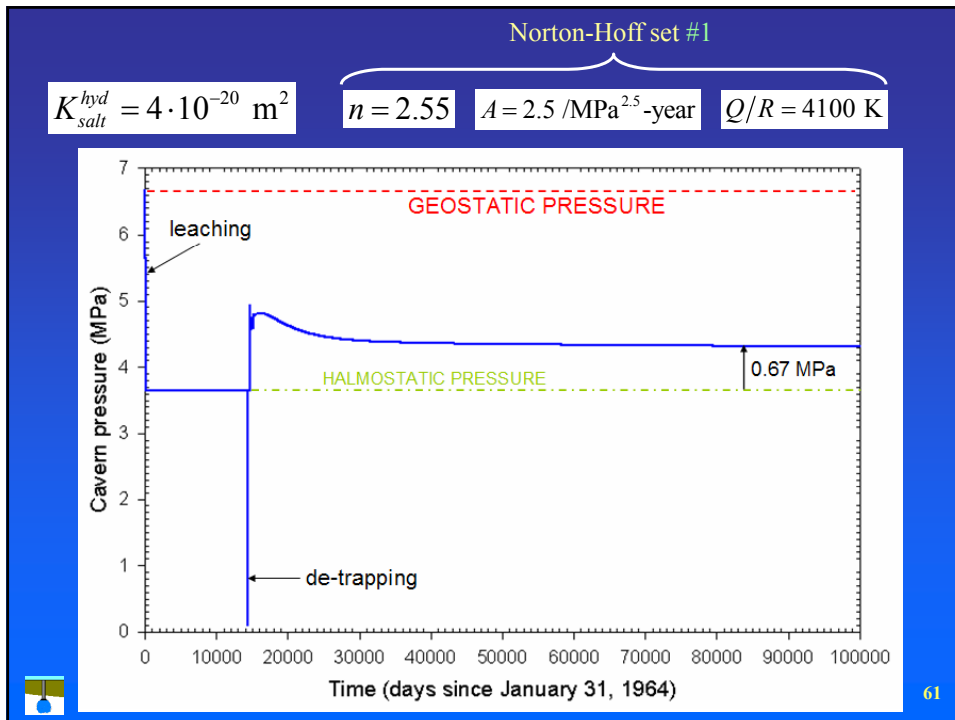


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Long-term computation



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NO-TENSION CRITERIA, DILATION CRITERIA...

The screenshot displays the 'Dilation Criteria' section of the LOCAS software. It includes several mathematical models for cavern stability, each with associated parameters:

- Spiers et al. (1988):** $\sqrt{J_2} = -0.27I_1 + 1.9$
- Ratgan et al. (1991):** $\sqrt{J_2} = -aI_1$ (with $a = 0.27$)
- Hanache (1993):** $\sqrt{J_2} = \frac{\sqrt{3}}{2} \left(f_1 \frac{I_1^2}{9} - f_2 \frac{I_1}{3} \right)$ (with $f_1 = -0.168 \text{ MPa}$, $f_2 = 0.86$)
- Thorel (1996):** $\sqrt{J_2} = \frac{\sqrt{-I_1}}{\sqrt{9Z(J_n)}}$ and $Z(J_n) = \frac{Z_c - Z_c \sin(\frac{\pi J_n}{2}) + Z_c + Z_c}{2}$ (with $Z_c = 0.05 \text{ MPa}$, $Z_c = 0.03 \text{ MPa}$)
- Hiscock and Hayman (1997):** $\sigma_1 = k_1 e^{k_2 \beta}$ (with $\beta = 90^\circ$, $k_1 = -0.0743\sigma_1^2 + 3.2223\sigma_1 + 12.9$, $k_2 = -0.0057$)
- DeVries et al. (2008):** $\sqrt{J_2} = \frac{D_1 \left(\frac{I_1}{\text{sgn}(I_1)\sigma_0} \right)^n + T_0}{\sqrt{3 \cos \psi - D_2 \sin \psi}}$

Additional parameters shown on the right include: $J_n = \frac{3\sqrt{3}J_2}{2\sqrt{J_2^3}}$, $T_0 = 1.95 \text{ (MPa)}$, $D_1 = 0.775$, $n = 0.693$, $D_2 = 0.524$, $\sigma_0 = 1 \text{ (MPa)}$, and $SR = 0.7$.

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EXAMPLE OF CONTOUR PLOTS

The screenshot shows a contour plot of 'Effective Stress (MPa)' within a cavern. The vertical axis represents 'Depth (m)' from 290 to -330, and the horizontal axis represents 'Radius (m)' from 0 to 35. A color scale on the left indicates stress values from 0.281 (red) to -3.168 (blue). The plot shows a cavern with a complex internal structure, and the stress distribution is highest (red/orange) near the cavern walls and lowest (blue) in the central regions.

Below the plot, there are 19 'Output' buttons. The status bar at the bottom indicates 'All steps done'.

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

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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



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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



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