NUMERICAL MODELS REPRESENTING THE TEST CAVERN EZ53 – PUBLIC SUMMARY

HYPSTER PROJECT

Deliverable D2.4

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1. PUBLIC SUMMARY

HyPSTER is the first EU-supported project aiming for large scale green hydrogen underground storage in salt caverns. The demonstration facility will be built at Etrez in France. The WP2.1 of Hypster project aims at proving the suitability of models to simulate the complex behaviour of hydrogen-filled salt caverns.

EZ53 was leached out in Spring 1982 from the upper layer of the Oligocene bedded salt formation at Etrez, Ain, France, where Storengy operates a natural gas storage. Because of changes in the gas market, it was decided to end cavern leaching at an early stage, before EZ53 reaches its planned final shape. For this reason, EZ53 has not been used for storage; it was available for testing (Figure 1). Among others, several outflow tests and a 12-year long abandonment test (supported by the SMRI) were performed (Hugout, 1984; Brouard, 1998; Bérest et al., 2001; Bérest et al., 2010; Bérest et al., 2011). They provided a fair picture of cavern creep closure, both transient (following an abrupt cavern pressure change) and steady state (after a long quiescent period).

Part 1 – CHARACTERISTICS AND HISTORY OF EZ53

The first part of the deliverable (Sections 4 to 11) describes the information gathered during these tests (Figure 1), which is used in the following parts to calibrate the parameters of the constitutive law.

Part 2 – CALIBRATION OF EZ53 PARAMETERS

The second part of the deliverable (Sections 12 to 13) is dedicated to the calibration of thermal and mechanical parameters which will be used for further computations The dedicated 2D version of LOCAS software allows computing the thermal and mechanical behavior of an axisymmetrical cavern (Figure 2). At the beginning of the computation, several parameters are poorly known. An optimization procedure (several thousands computations are performed, and the computation time is more than two weeks) allows refining the values of the parameters to reach the best fit against in situ data. In the case of the mechanical optimization, several constitutive laws are tested against the results of the (transient) Hugout's test and the 1995 outflow tests performed during a quieter period. For both performed tests, the calibration results show the best match with the Munson-Dawson creep law. For the other creep laws (Lubby2 and Lemaitre), the automatic calibration yielded a less accurate history matching. The Munson-Dawson constitutive law provides a very good fit and can be used confidently for further computations.

- ✓ The thermal parameters have been calibrated and the following values were found:

$$\begin{cases} T_\infty = 45\ °C & T_i = 27.1\ °C & Q_{geo} = 62.8\ \text{mW/m}^2 \\ C_{salt} = 886\ \text{J/kg-K} & k_{salt} = 2.01\times10^{-6}\ \text{m}^2\text{/s} & K_{salt} = 3.85\ \text{W/m-K} \end{cases}$$

- ✓ Numerical computations using LOCAS, taking into account the actual shape of the cavern, were performed assuming a Poisson's ratio $\nu = 0.25$ and the elastic modulus was back-calculated to be $E = 16{,}809$ MPa.

- ✓ The following set of parameters were fitted for the Munson-Dawson creep law:

$A = 0.311\ /\text{MPa}^n\text{-yr}$	$n = 3.498$	$Q/R = 4100$ K
$K_0 = 7.91\times10^{-7}\ /\text{MPa}^m$	$\alpha_w = 25.16$	$\beta_w = 4.447$
$m = 2.513$	$\delta = 0.341$	$c = 0.00902$ /K

- ✓ The following set of parameters were fitted for the Lubby2 creep law:

$GK_0 = 40,290$ MPa	$\eta K_0 = 879,007$ MPa.day	$\eta M_0 = 7.92 \times 10^{14}$ MPa.day	
$k_1 = -0.297$ /MPa	$k_2 = -0.233$ /MPa	$m_0 = -0.289$ /MPa	$l_0 = -0.05$ /K

- ✓ The following set of parameters were fitted for the Lemaitre creep law:

$\alpha = 0.259$	$\beta = 3.27$	$K = 1.059$ MPa

Part 3 – DERIVATION OF AN ANALYTICAL SOLUTION FOR A SPHERICAL CAVERN IN A VISCOPLASTIC MEDIUM SUBMITTED TO PRESSURE CHANGES

The third part of the deliverable (Section 14) provides a very different and complementary approach of the mechanical problem. It is dedicated to a semi-closed form solution of the problem of a cavity leached out from a salt formation and submitted to various loadings. An idealized spherical shape is adopted. This solution provides a less precise solution than the numerical solution obtained in the second part; its main advantage is to provide additional insight on some general features of the behavior of a cavern excavated in a viscoplastic medium: following a pressure change, a “geometrical” transient evolution of the cavern volume is observed even when the constitutive law includes no transient behavior; following a large pressure increase, geometrical reverse creep and onset of tensile effective stresses at cavern wall can be observed; in a cavern whose pressure is cycled, volume loss rate is faster than in a cavern in which the average cycle pressure is applied; it is not extremely sensitive to cycle period; it is much faster when a Munson-Dawson law (rather than a Norton-Hoff law) is adopted. The Marketos-Spiers law, which accounts for the effect of pressure solution creep at low deviatoric stresses (in addition to dislocation creep), predicts a higher volume loss rate when caverns are more shallow. A simple solution of the leaching problem (in which cavern radius is a function of time) can be found.

It is proved that Hugout’s test and later outflow tests can be correctly fitted against a Munson-Dawson’s law, a confirmation of the results obtained in the second part through a more sophisticated optimization procedure. The volume loss rate during the cyclic test to be performed in 2022-2023 in the EZ53 pilot cavern is predicted (Figure 3).

Part 4 –ALTERNATIVE PARAMETER SETS FOR EZ53 MODELLING WITH LUBBY2

Further modelling was performed for the Hugout’s test and the 1995 outflow test at cavern EZ53 using the Lubby2 consitutive law and the software FLAC3D, which is a three dimensional finite volume software for geotechnical analyses. The results of the previous numerical parameter calibration were used as a basis for a comparison of the software tools LOCAS and FLAC3D and an analytical approach was employed to vary the model parameters for further optimization of the match between measurements and modelling. By this approach the difference between measured and modelled outflow rates could be significantly reduced for the Lubby2 constitutive law. However, as the best match was achieved with a parameter set, that is at the edge of the usual parameter range in literature, further work seems advisable to confirm these parameters or to identify the best set within the literature range. Nevertheless, the modelling showed the potential of the Lubby2 law and that from the present data no clear prefence for a certain constitutive law can be proven. This conclusion may change in situations, where the operating conditions during the reference measurements span a wider range, or where corresponding data from laboratory tests are available.

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✓ An example Lubby2 parameter set with good agreement with the long-term outflow measurements:

Transient/Kelvin				Stationary/Maxwell		
G_k0	**Eta_k0**	**k1**	**k2**	**Eta_m0**	**m0**	**l0 _l_3**
[MPa]	[MPa.d]	[1/MPa]	[1/MPa]	[MPa.d]	[1/MPa]	[1/K]
5,67E+04	2,00E+06	-0,600	-0,300	2,80E+14	-0,115	-0,0500

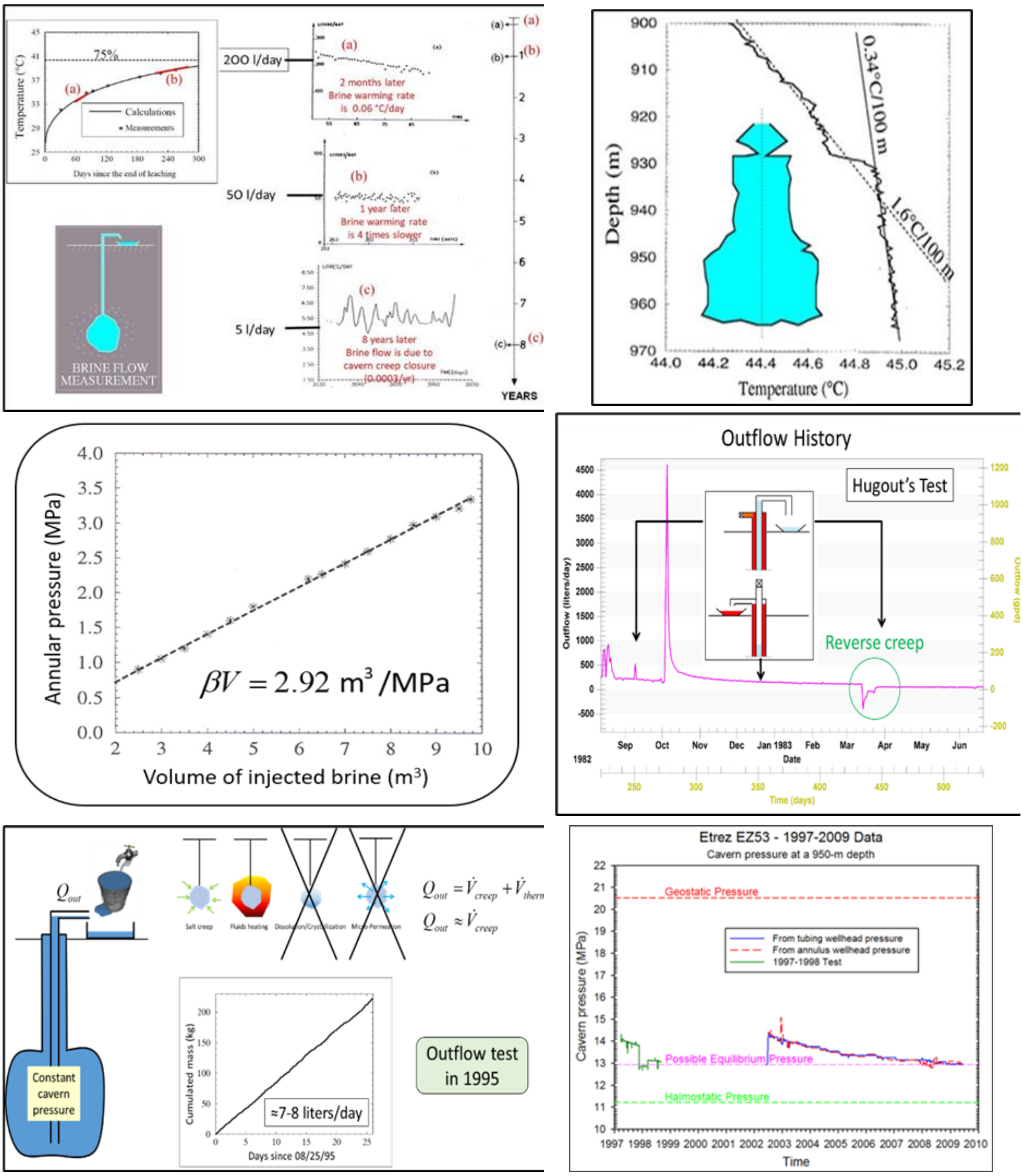

Figure 1. Six in situ tests performed in the EZ53 cavern. From top to bottom: Brine outflow tests performed after cavern creation; Temperature log; Cavern compressibility measurement; Hugout's test (transient mechanical behavior); Brine outflow test performed 13 years after cavern creation, Abandonment test.

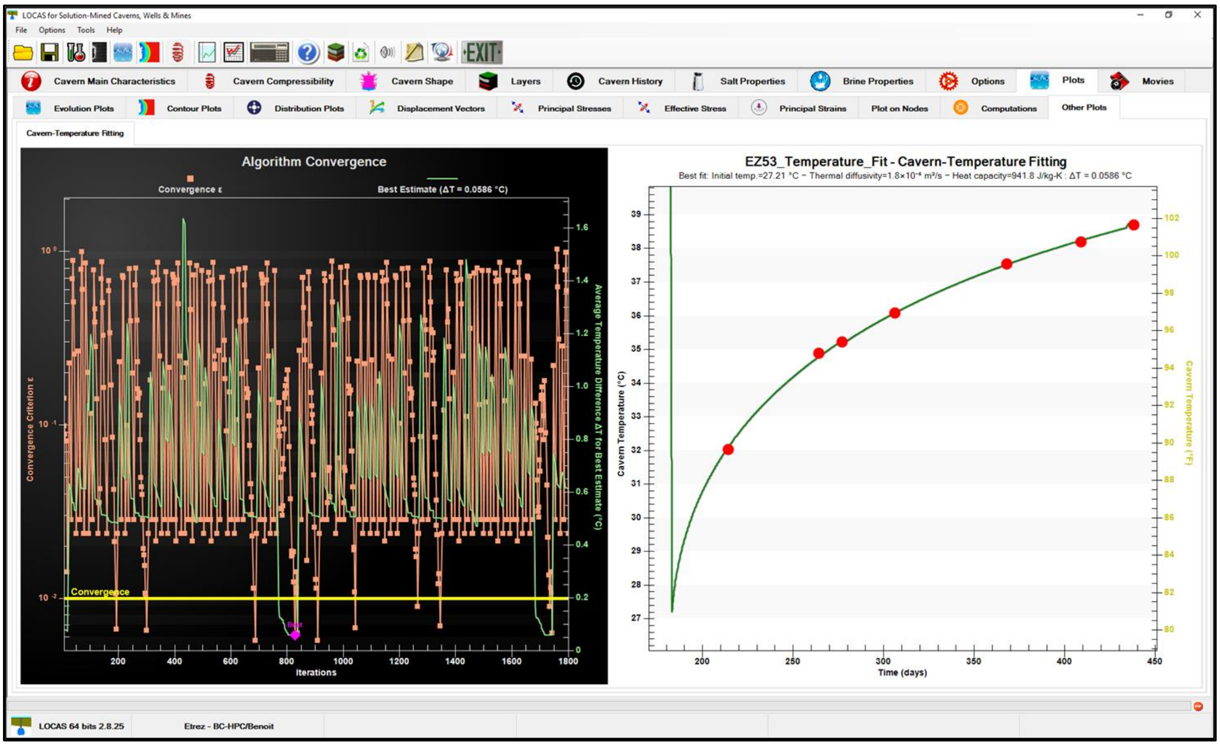

Figure 2. An example of an optimization procedure in which the best set of thermal parameters is searched for to fit measurements of cavern brine temperature. [LOCAS screenshot].

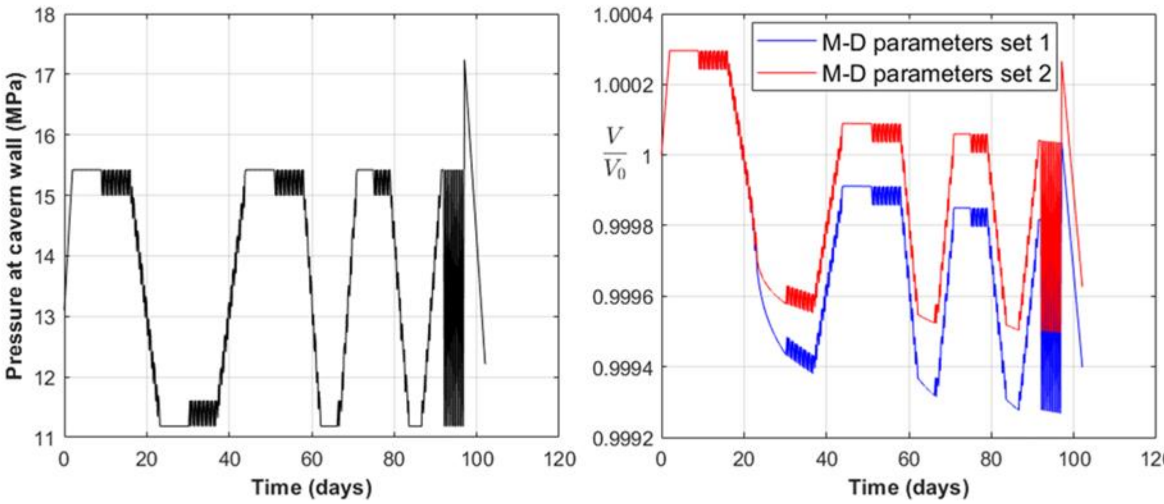

Figure 3. Modelling of the cyclic test to be performed on the EZ53 cavern: prescribed pressure at cavern wall (left), and volume change (right) computed using two different sets of parameters.

SYNTHESIS

Rock Mechanics studies for salt caverns generally consist of performing creep tests at the laboratory, adjusting the parameters of a creep law against tests data and performing numerical computations to predict the long term behavior of the caverns. There are possible flaws in this method. Results essentially depend on the choice of the creep law. This choice is based on the main features observed during tests which, in most cases, are a couple of months long (a two-month duration is typical) and during which, in most cases, the applied stress is kept constant. During such a period, sample behavior is transient: strain rate decreases more or less rapidly and it is difficult to infer from the strain rate observed at the end of the test what the strain rate will be one year or one decade later – the period of interest when predicting the behavior of a cavern. For this reason, the selection of the mathematical function which fits best the strain-vs-time observed curve is crucial (exponential, logarithmic, power law functions …). All these functions can provide a reasonably good fit against lab-test data, provided that the parameters of the fitting functions are correctly selected. However, when it comes to extrapolation to long periods of time, these functions will predict very different responses.

The methodology used for this deliverable is different. The results of a couple of creep tests performed several decades ago at Ecole Polytechnique and Ecole des Mines de Paris were available. However, the analysis performed by Armines/Ecole Polytechnique, Brouard Consulting and ESK mainly rely on in situ tests performed in the EZ53 cavern. More specifically, two tests were used. The first one, performed from days 93 to 253 (after end of EZ53 leaching), i.e., in 1982-1983, consisted of lowering abruptly cavern pressure from 114 bars (halmostatic pressure) to 80 bars, keeping this pressure constant during 160 days and measuring the fluid flowrate expelled from the cavern. This flowrate is deemed to be representative of cavern creep-closure rate, at least when account is taken of several other effects contributing to brine-outflow rate, the main such effect being brine slow warming and thermal expansion. The second test, performed in 1995, after a long period during which the cavern was kept quiescent (cavern pressure was halmostatic during this period), was also an outflow test: the wellhead was opened and the expelled flow rate was measured. This flowrate is deemed to be almost perfectly representative of the cavern creep-closure rate; secondary effects such as thermal expansion had almost exhausted themselves (thermal equilibrium has been reached in 1995), 13 years after cavern creation.

The two tests were selected as the first one put emphasis on cavern transient behavior following a cavern pressure drop, and the second one is more representative of cavern steady-state behavior – even if it was shown in Armines/Polytechnique contribution that, actually, steady-state creep closure rate in a salt cavern can be reached after a very long period – one century (or several decades) rather than one decade when cavern pressure is kept constant – because of the significance of the so-called "geometrical" transient behavior of a cavern: the slow redistribution of stresses in the rock mass.

Dozens of creep laws have been considered in the literature to describe the rheological behavior of salt. In many cases, it is assumed that the overall creep rate of a sample tested at the laboratory is the sum of a transient component (the "Kelvin" component) plus a steady state component (the "Maxwell" component). In fact, in this deliverable, four different constitutive laws are discussed: the Norton-Hoff law, the Munson-Dawson law, the Lubby2 law and the Lemaitre law. In simple terms, these laws can be characterized as a combination of non-linear Kelvin and Maxwell components (the relation between strain rate and stress – non-linear dashpot -, or between strain and stress – non-linear spring -, are non-linear). The Norton-Hoff law includes no transient ("Kelvin") component. Conversely, the Lemaitre law includes no steady-state ("Maxwell") component. The Munson-Dawson includes both components; however, the transient component is not standard in that loading and unloading are not treated in a symmetrical manner; "reverse" rheological creep is not described; when the transient component is not taken into account, the Munson-Dawson (M-D) law reduces to the Norton-Hoff (N-H) law. The Lubby2 law also includes both components. However, the non-linear relations between strain rate and stress – or between strain and stress – are of the exponential type - rather than power laws in the case of the Munson-Dawson law. This law allows describing rheological reverse creep. The parameters of these two laws were fitted against the results of many laboratory testing campaigns – in the US, for the M-D law; and in Germany and the Netherlands for the Lubby2 law.

Armines/Ecole Polytechnique considered the N-H and M-D laws. A FEM or Finite Volume numerical method is not used, but, rather, a semi-closed form solution is developed. An idealized spherical shape is considered; as such, an extremely accurate computation (of volume loss rate, for instance) is not accessible. However, the set of parameters of the M-D law which fit the results of the two tests described above are not extremely different from those calculated by Brouard Consulting. A systematic optimization was not tried, the parameters were suggested by Brouard Consulting. The main interest of this method is that, beyond the computation of the EZ53 tests, it provides generic results from which general lessons can be drawn: when N-H law is used, transient "geometrical" volume loss rate is observed, due to the slow redistribution of stresses in the rock mass, although this law does not include "rheological" transient creep. When cavern pressure is kept constant after a rapid pressure decrease, this "geometrical" transient behavior is active during one century; in the case of the M-D law, both "geometrical" and "rheological" transient behaviors are active; however, the rheological transient behavior exhausts itself after 5 years, typically. Geometrical reverse creep (originating in stress redistribution in the rock mass) is observed following a rapid and severe pressure increase in the cavern. The "cyclic" test which will be performed in 2023 in the EZ53 cavern was also modelled; it provides interesting results (when creep closure rate in considered, cycle amplitude plays a major role; the effect of cycle period is much less pronounced.) Volume loss rate was also computed when cavern growth during leaching is taken into account (a "moving boundary" problem), an effect which is not discussed in standard numerical computations.

Brouard-Consulting considered three constitutive laws: the Lemaitre law, the Munson-Dawson law and the "strain hardening" Lubby 2 law and used LOCAS, its commercial software dedicated to salt caverns behavior. LOCAS is a two and three dimensional finite element software for geotechnical analyses. LOCAS takes into account, in addition to creep closure, such phenomena as brine warming, additional dissolution/crystallization and permeation. The methodology adopted by Brouard Consulting includes an automatic optimization approach (several thousand runs were perfomed) which is likely to be the first of its kind performed in the case of a salt cavern. Both outflow tests are computed during each run (they are not computed separately). Lemaitre law provides a fairly good fit against the Hugout's test (and against laboratory tests performed at Ecole des Mines de Paris; however, computation of the 1995 outflow test underestimates by one order of magnitude the as-observed outflow rate. This was expected as this law, which provides relatively good results in the case of a pressure-cycled cavern, includes no steady-state (Maxwell) component. Munson-Dawson law provides a good calibration of the results of both tests. The 1995 flow rate is overestimated by a small amount. Lubby2 law provides poorer results (especially during the initial 15-day period following immediately the initial pressure drop, during which the actual flow rate is underestimated).

ESK also considered the "strain hardening" Lubby2 law and the FLAC3D commercial software was used. FLAC3D is a three dimensional finite volume software for geotechnical analyses. FLAC3D includes *engineering design, thermal and geothermal influences, and factor-of-safety prediction.* ESK observed that the automated calibration performed by Brouard Consulting, using the commercial LOCAS software together with the Lubby2 model, did not lead to a fully satisfactory result (when calibration of the parameters of this law against the two EZ53 tests is considered) and selected a different approach. 30 cases were modeled using sets of parameters obtained on other salt caverns site. Cavern evolution during the 800 first days after cavern creation was modeled. The latest period of the Hugout's test is correctly reproduced; the end of the Hugout's test is qualitatively well reproduced, as reverse rheological creep is observed, which is consistent with Armines/Ecole Polytechnique prediction. However, the initial response of the cavern (immediately after the pressure change) is less accurately described than what was obtained by Brouard Consulting using Lubby2. The 1995 outflow test was computed assuming that steady state was reached (the effects of the Hugout's test are assumed to have exhausted themselves), an assumption which is not fully correct when Armines/Ecole Polytechnique results are considered, but led to a satisfactory comparison with the results of the 1995 test. Generally speaking, the ESK set of parameters gives an important weight to the steady state component of the Lubby2 law (when compared with other sets of the literature).

As underlined by ESK,"the range of operating parameters during the historical tests at EZ53 was limited" (cavern pressure dropped from 11.4 MPa to 8 MPa, instead of 5-6 MPa when the expected operating conditions of an hydrogen storage are considered; in addition, Hugout's test was not cyclic; cyclic operating conditions might put an emphasis on the transient (Kelvin) component of the creep law.) and “a clearer preference for a certain creep law might result from tests during which a wider parameter range is covered”.

As a conclusion, discrepancies remain between the results provided by the different approaches; in addition, the range of cavern pressures applied during the two tests (and, maybe more important, the absence of a cyclic loading during these tests) are not fully representative of the operating conditions in a hydrogen cavern. However, this approach constitutes a remarkable (and not frequent) attempt to base the calibration of a constitutive law on the actual behavior of a salt cavern – rather than on the data resulting from laboratory tests only. Further in situ tests performed in the frame of the Hypster project may provide an opportunity to fine-tune this calibration, especially when transient behavior is considered. For instance, rheological reverse creep may prove to play a significant role during cyclic tests. Generally speaking, this first attempt, performed by three different teams, is fully representative of the innovative Hypster approach of the calibration problem.

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