THE ETREZ ABANDONMENT FIELD TESTS

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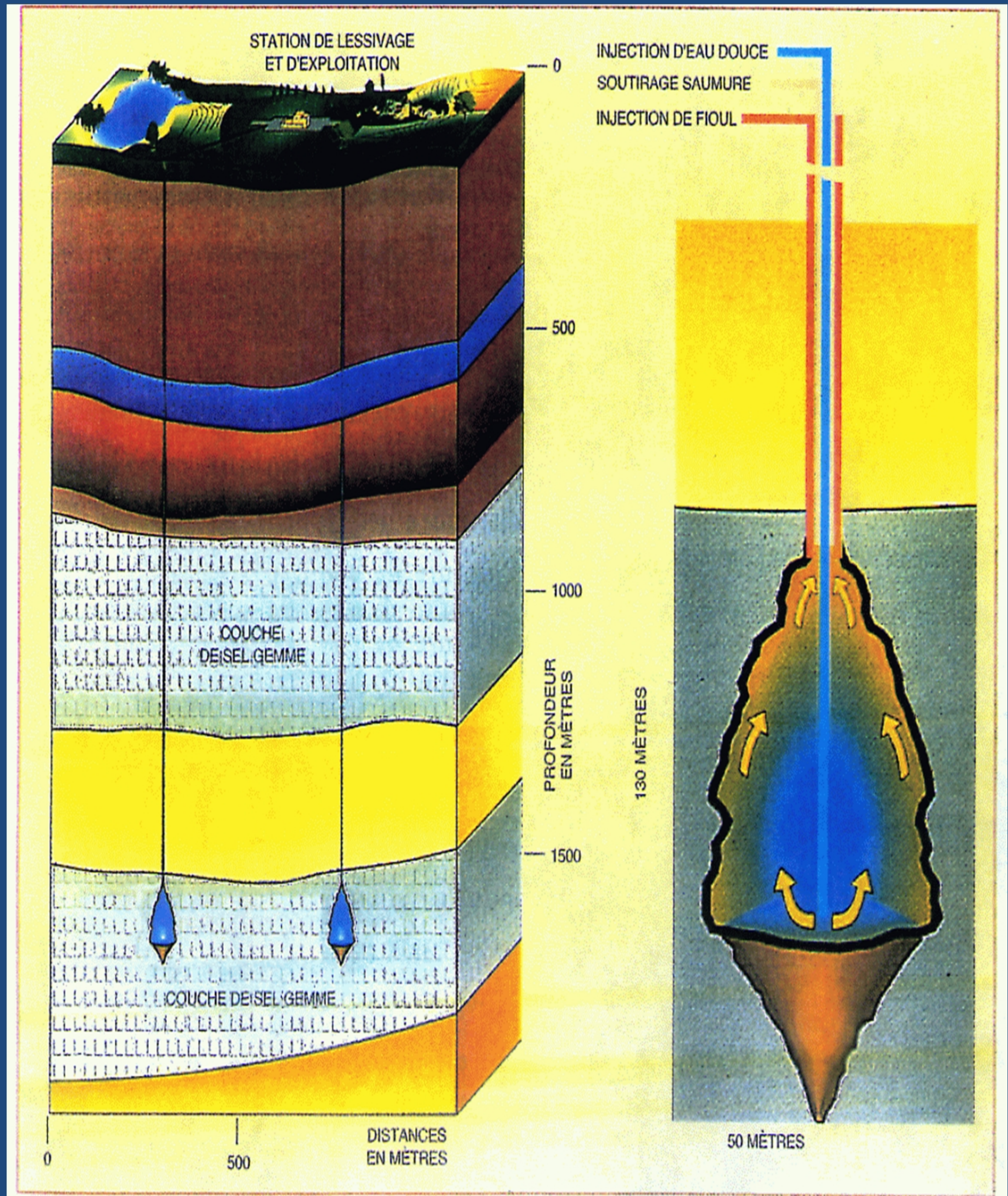
ETREZ ABANDONMENT FIELD TEST

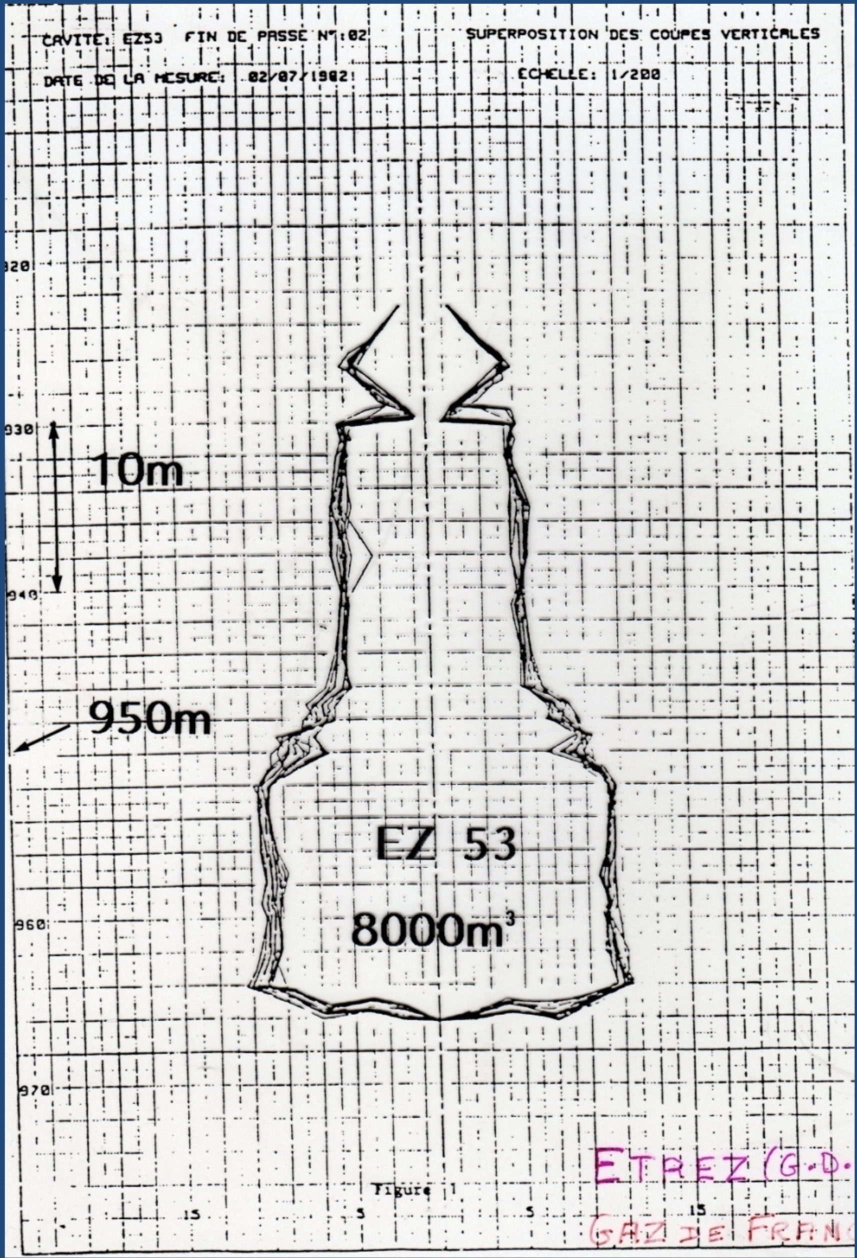
- Etrez salt formation
- Cavern compressibility
- Temperature
- Rock Mechanics
- Permeation
- Leak Detection
- Trial and error test
- 10 years later
- Conclusions

ETREZ SALT FORMATION

The upper salt layer is 700-1100 m deep

The lower layer is 1300-1900 m deep





EZ53

Leached out from the upper layer

950-m deep
45-m high
Diameter: 22 m
Volume: 8000 m^3

(Thermal Equilibrium is reached after 5 years or so)

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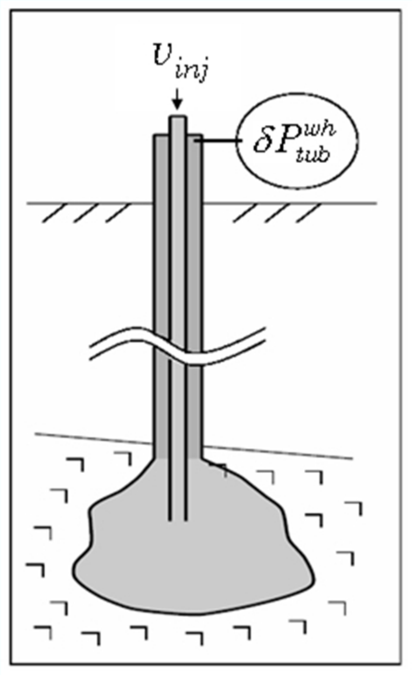
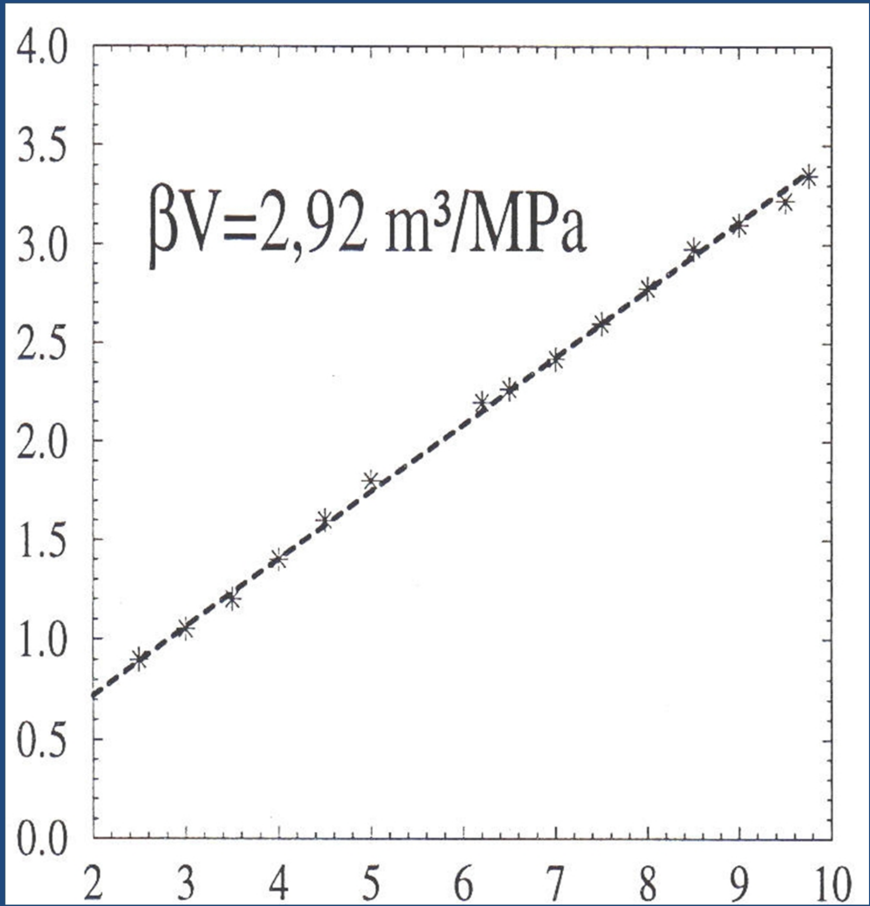
COMPRESSIBILITY TEST



MPa



m^3

V = 8000 m^3

0.00037 = β

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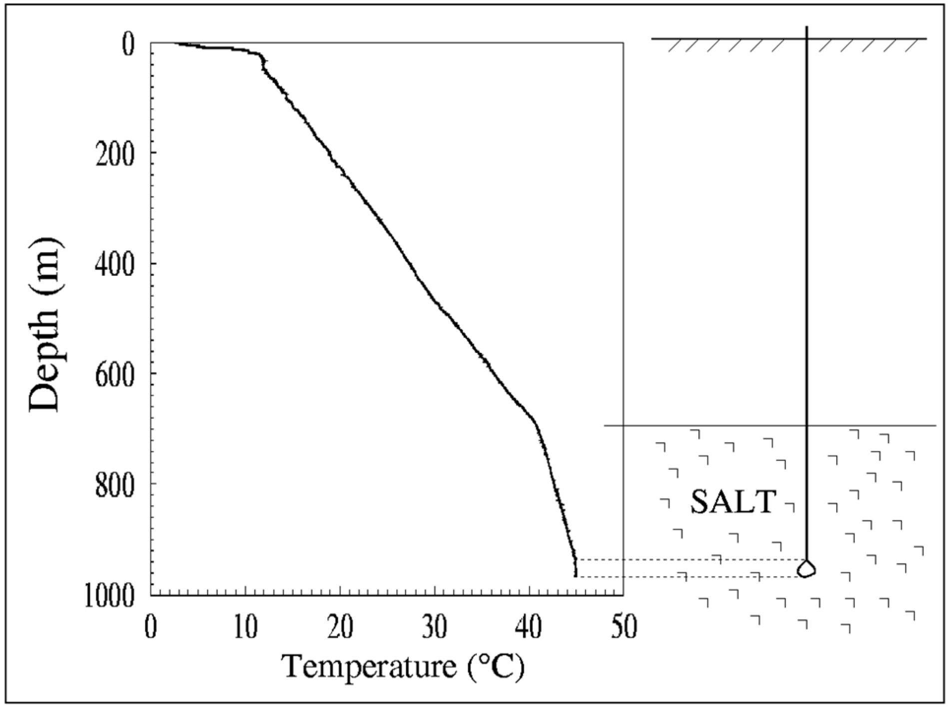
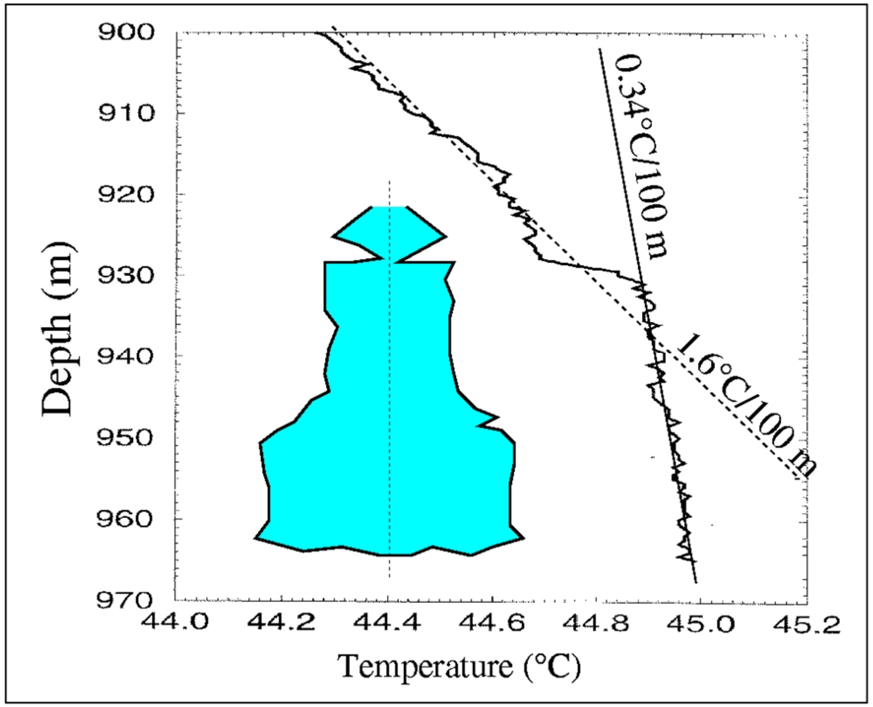
STEADY-STATE TEMPERATURE DISTRIBUTION





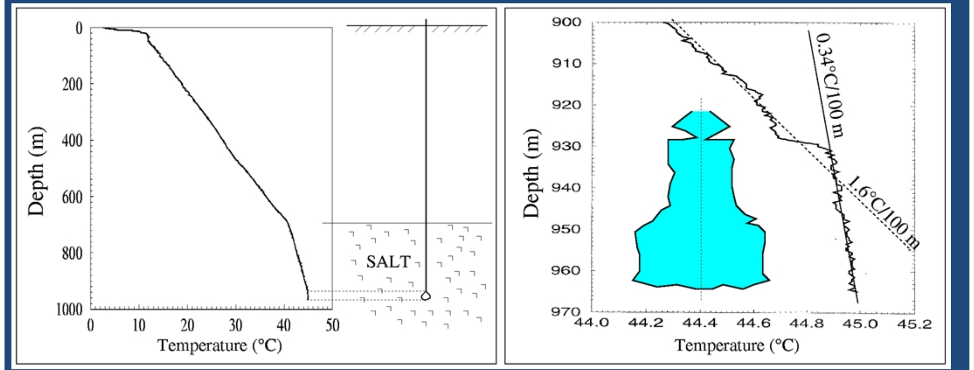
ETREZ 53 (GDF Suez) February 1996

Cavern volume: 8000 m^3

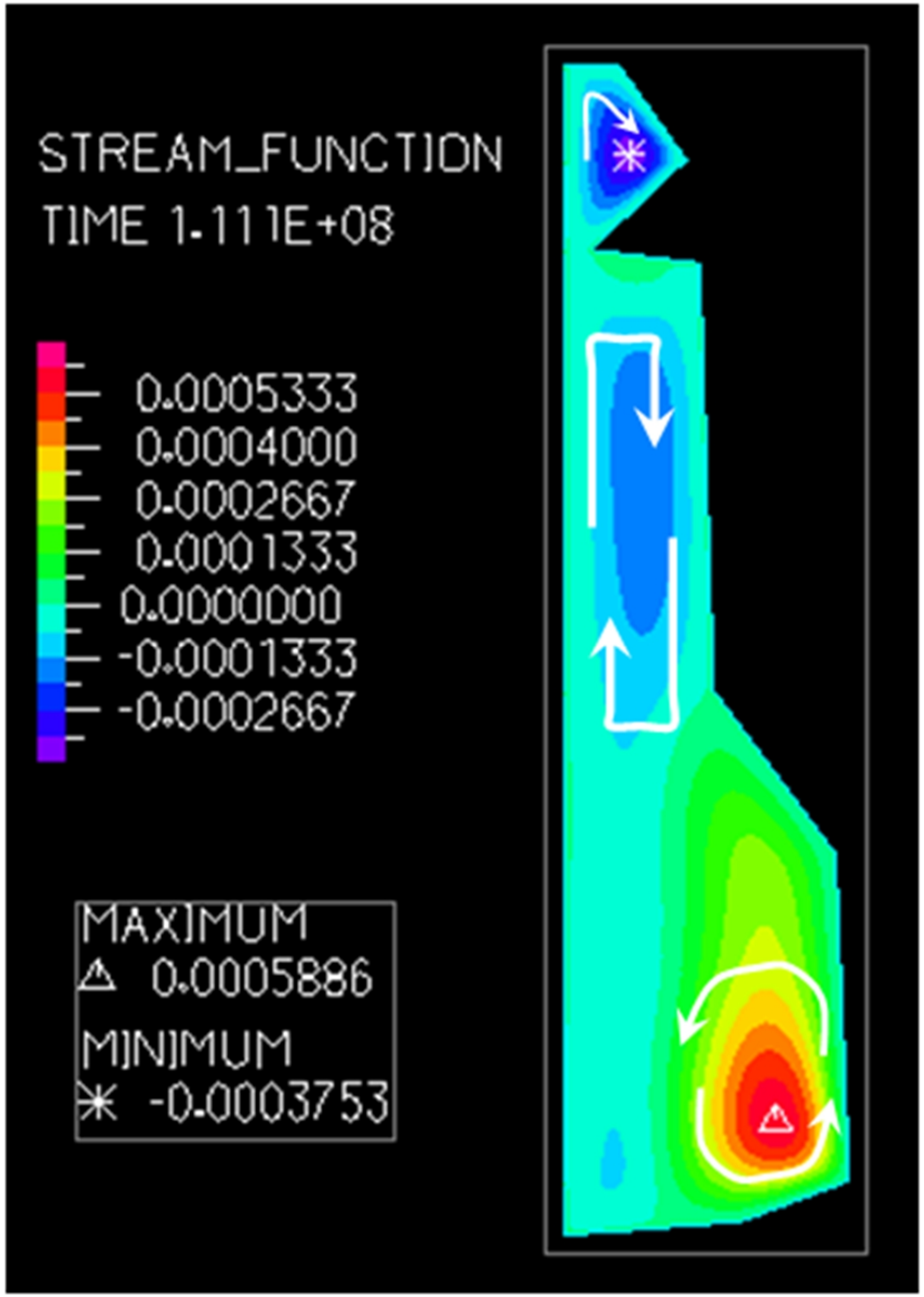
Leaching was completed by June 1982

Kept idle for 14 years

THERMAL EQUILIBRIUM IS MET

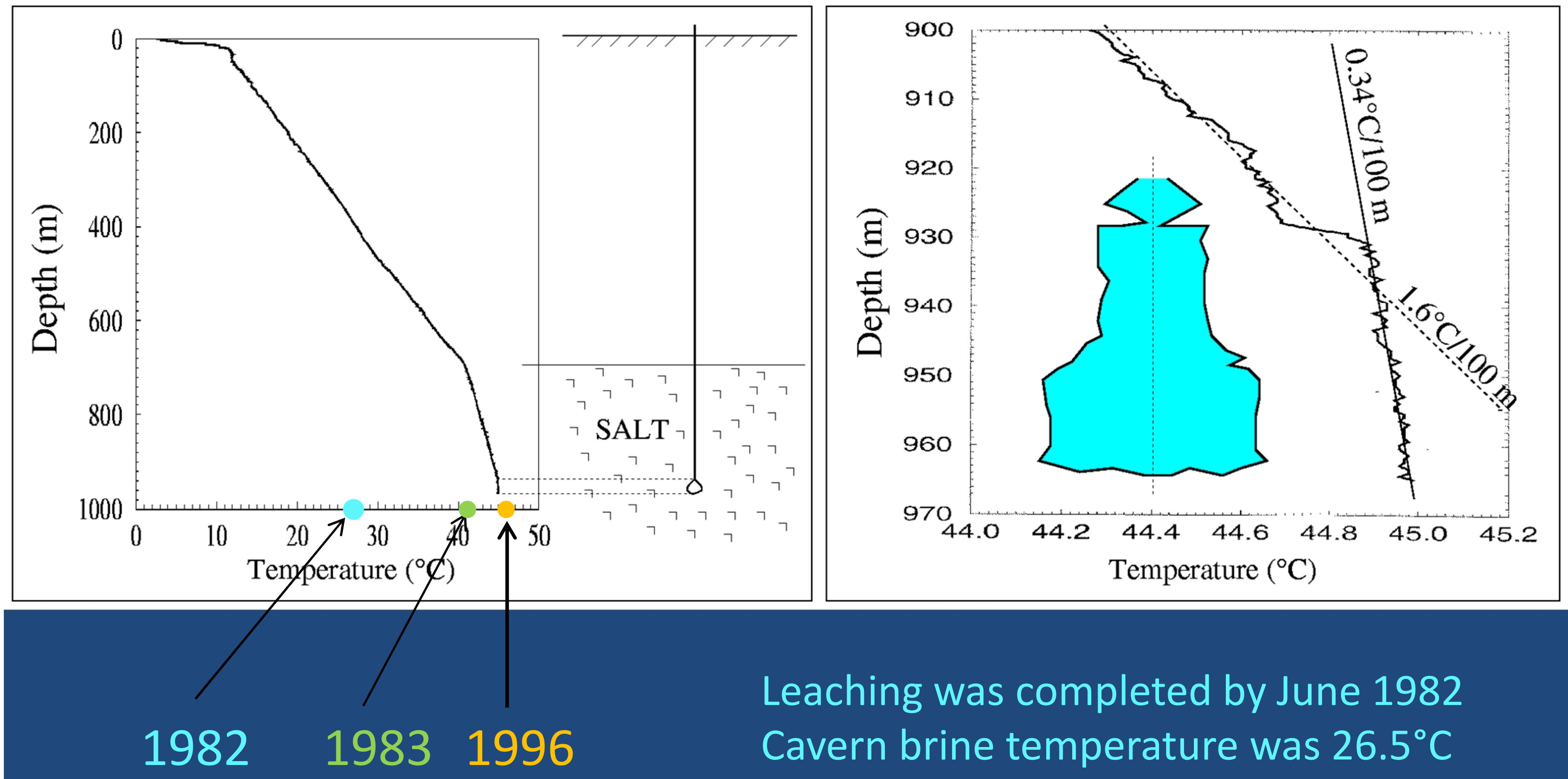


THERMAL CONVECTION IN CAVERN BRINE



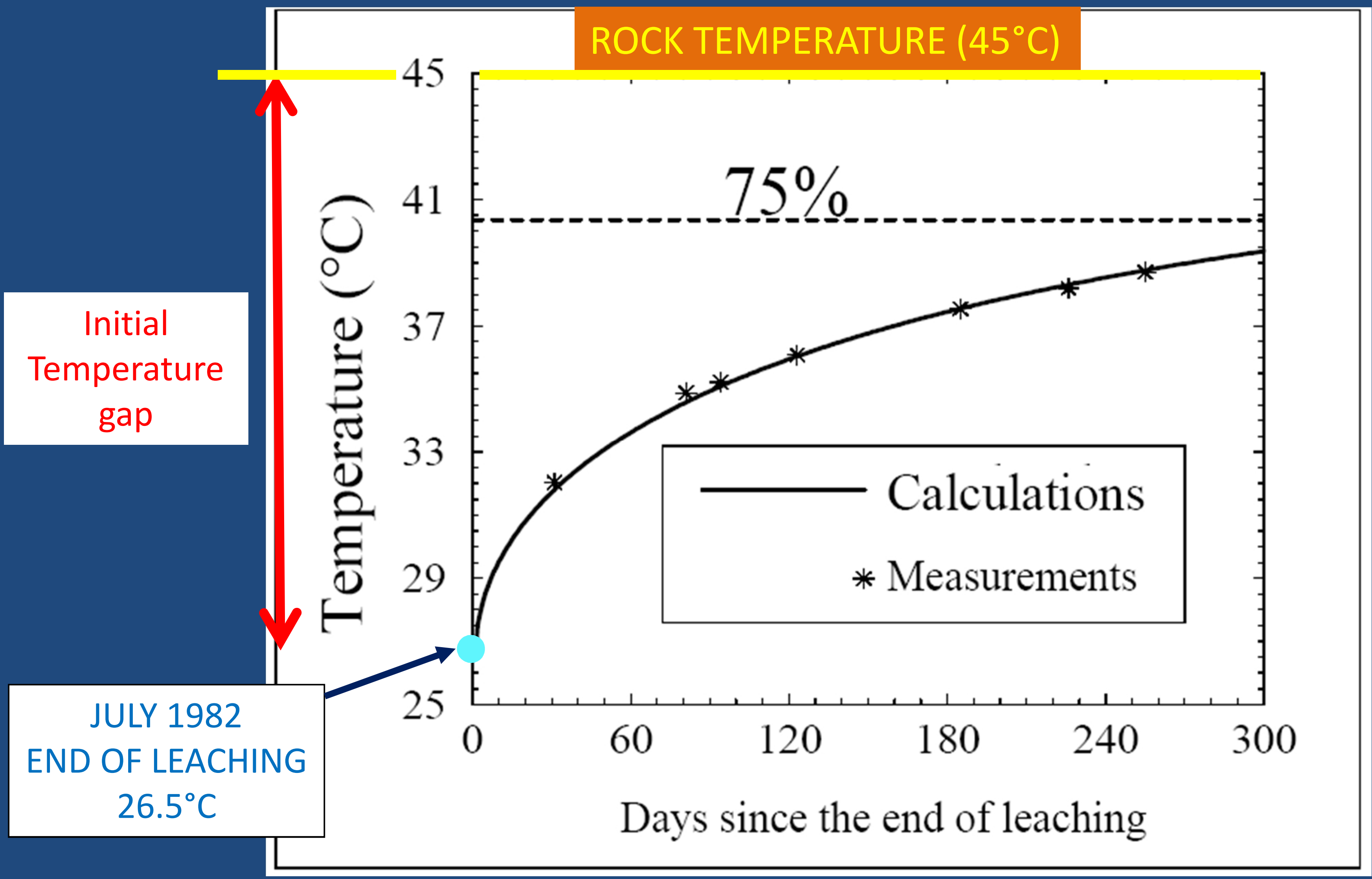
(After KARIMI-JAFARI et al., 2007)

INITIAL THERMAL DISEQUILIBRIUM

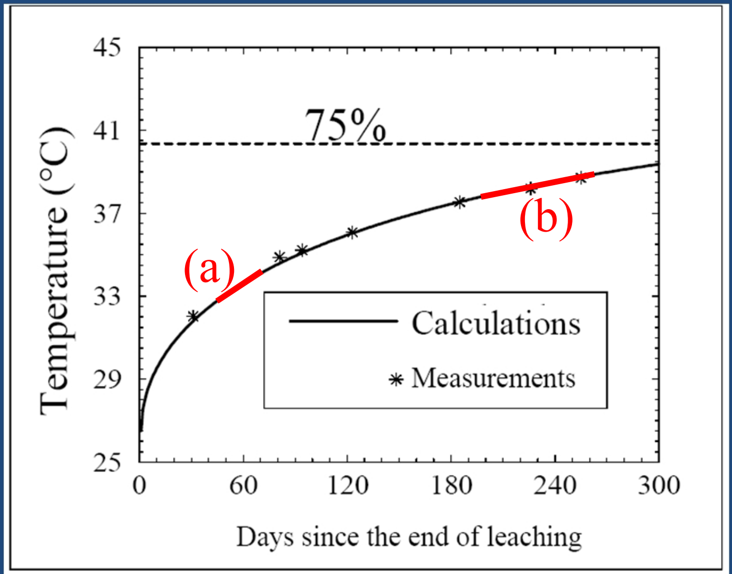


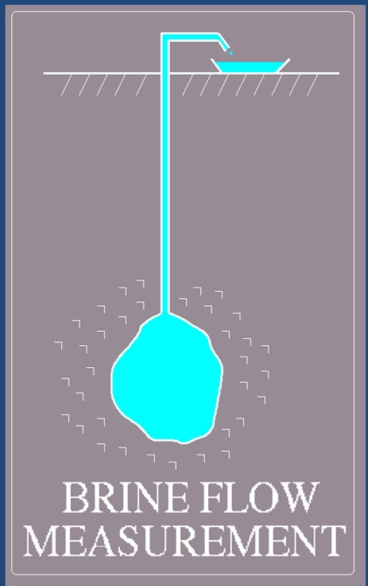
Leaching was completed by June 1982
Cavern brine temperature was 26.5°C
In February 1996, it was 45°C

TEMPERATURE EVOLUTION AFTER LEACHING END



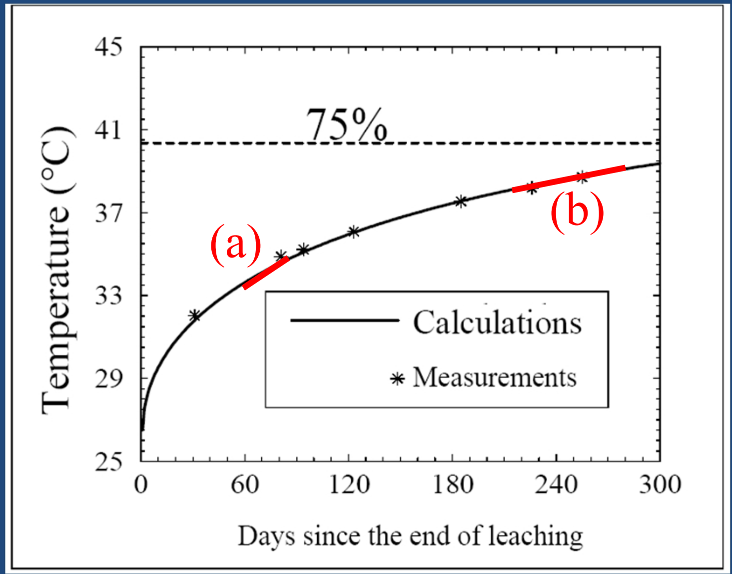
ETREZ EZ53 cavern (8000 m^3, 950-m deep)

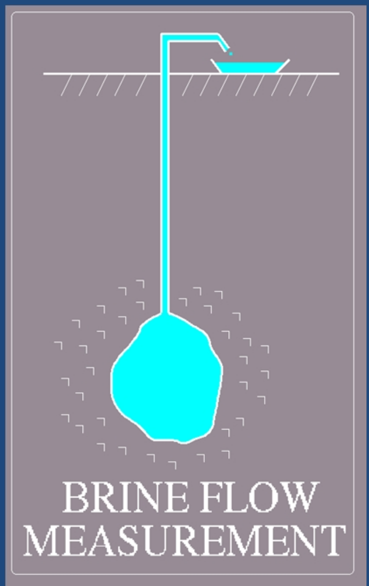


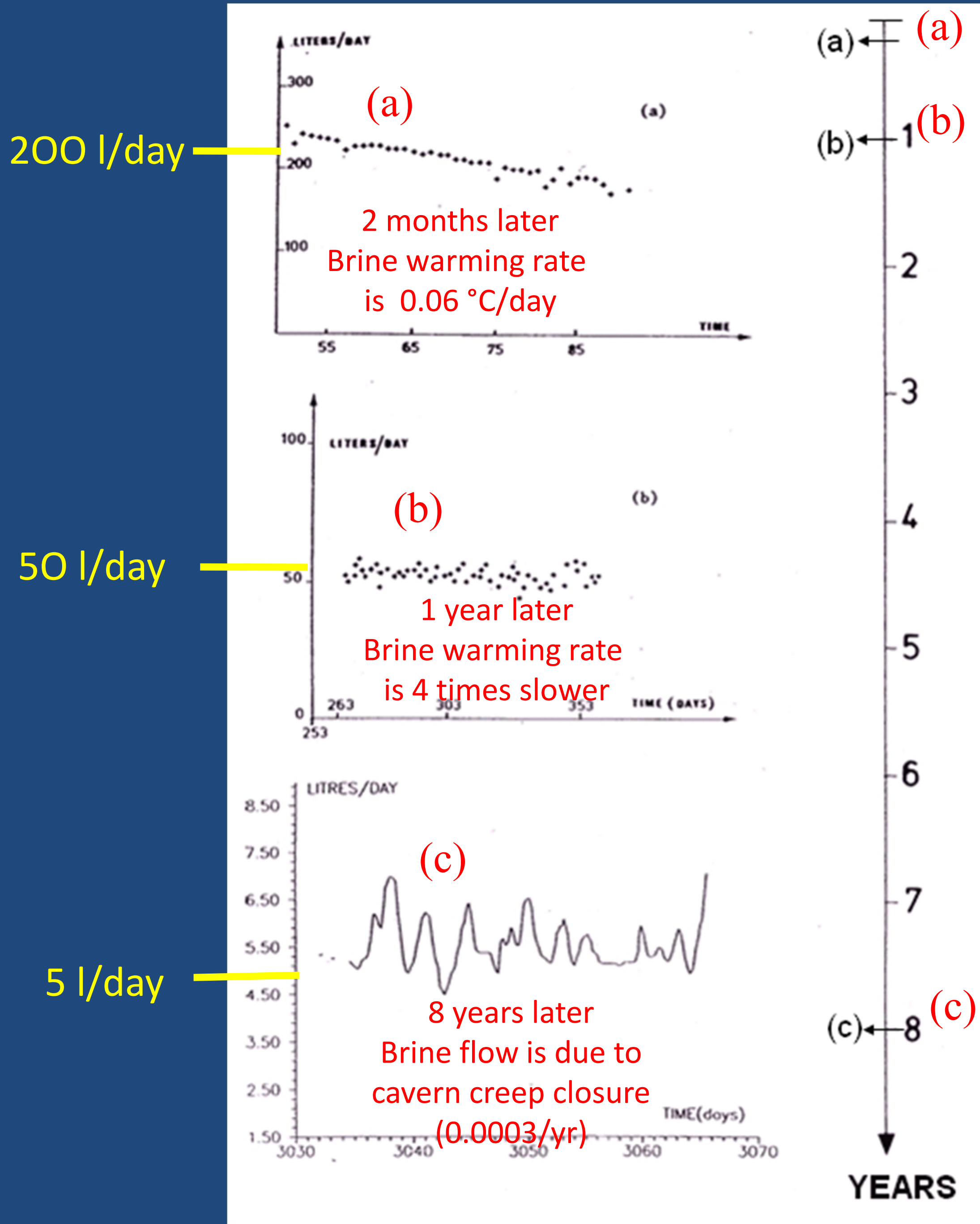


Expelled flow rate
(due to brine warming)

$$Q = \alpha\, V\, \Delta T / \Delta t$$


Temperature (°C)
45
41
37
33
29
25
75%
(a)
(b)
Calculations
* Measurements
0
60
120
180
240
300
Days since the end of leaching


BRINE FLOW
MEASUREMENT


200 l/day
50 l/day
5 l/day
(a)
2 months later
Brine warming rate
is 0.06 °C/day
(b)
1 year later
Brine warming rate
is 4 times slower
(c)
8 years later
Brine flow is due to
cavern creep closure
(0.0003/yr)
LITRES/DAY
TIME(days)
(a)
(b)
(c)
1
2
3
4
5
6
7
8
YEARS

ETREZ ABANDONMENT FIELD TEST

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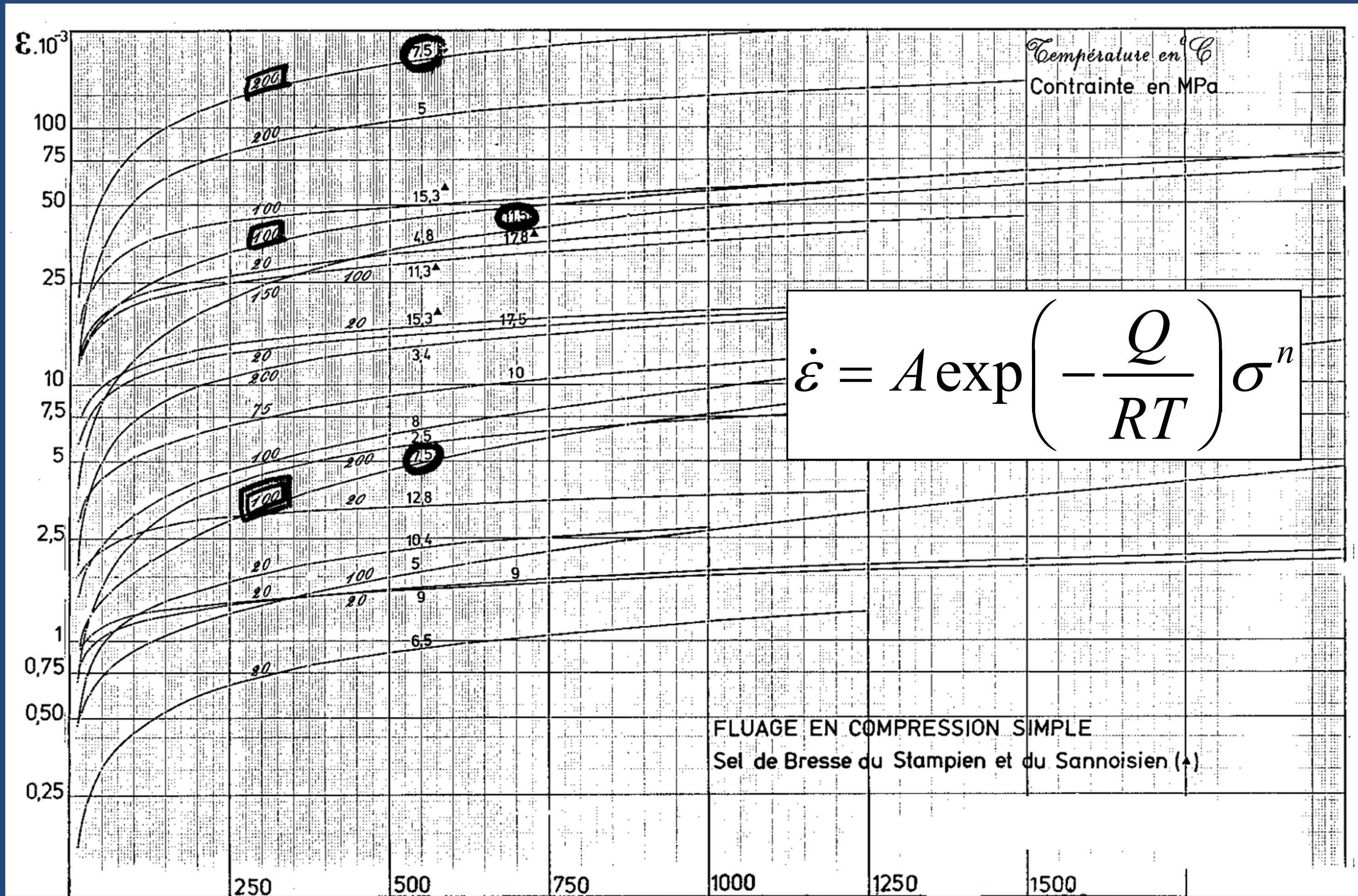
CREEP TEST (ETREZ SALT)

STRAIN



$$\dot{\varepsilon} = A \exp\left(-\frac{Q}{RT}\right)\sigma^{n}$$

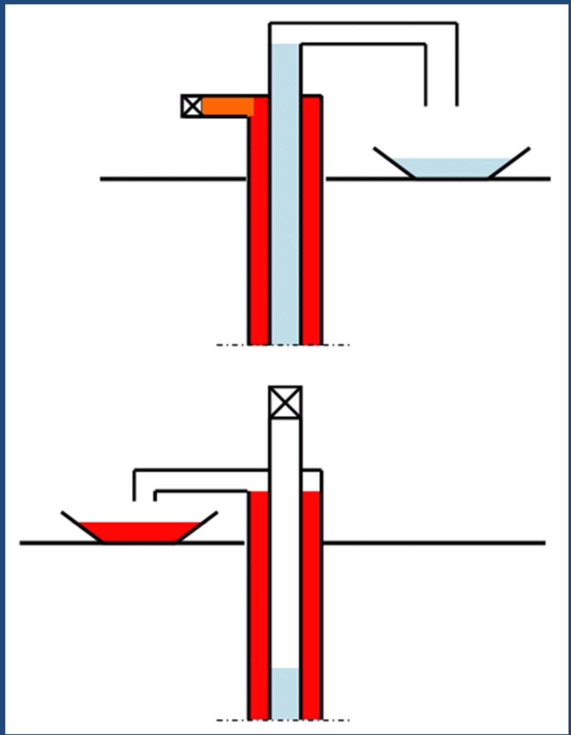
(After Charpentier)

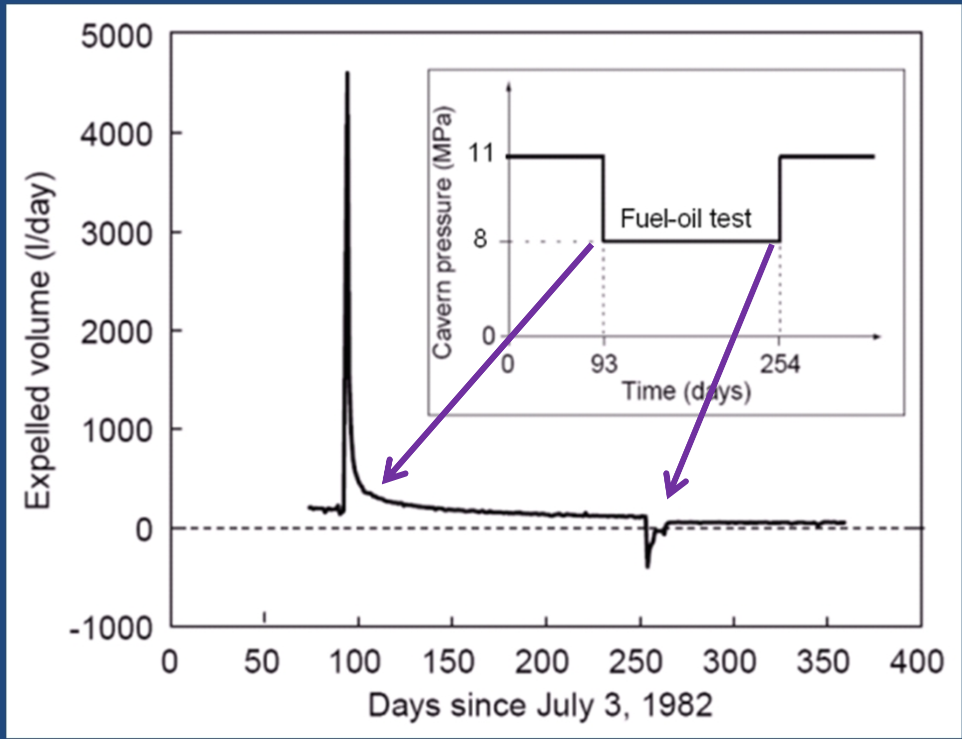
TIME
(hours)

NORTON-HOFF LAW PARAMETERS

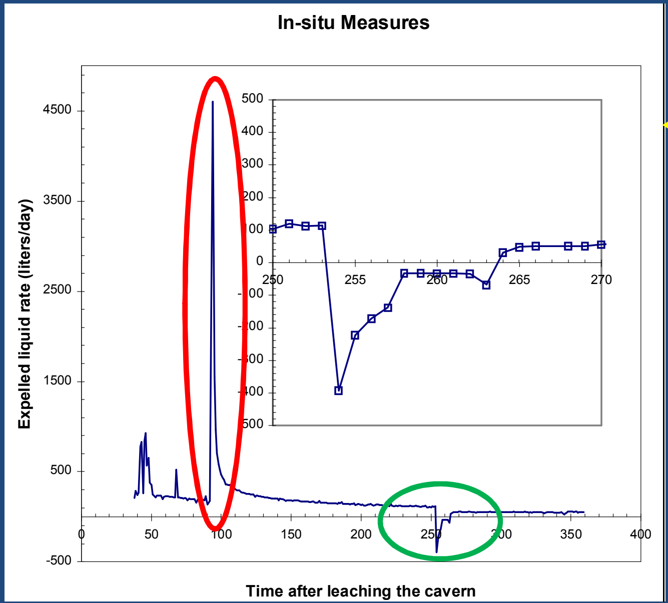
No	Facility	n	$T^\star = Q/R$ (K)	$A^\star$ (year^{-1}.MPa^{-n})
1	Avery Island (after D.V.)	3.14	6495	$1.30\ 10^4$
2	WIPP	5.0	5035	1.04
3	Salado (WIPP7)	5.09	8333	$3.67\ 10^4$
4	Asse (after W.)	6.25	9969	$2.51\ 10^4$
5	West Hackberry (WH1)	4.73	6606	452.31
6	West Hackberry (WH2)	4.99	10766	0.94
7	Bryan Mound (BM3C)	4.54	7623	$1.32\ 10^3$
8	Bryan Mound (BM4C)	5.18	8977	$1.04\ 10^5$
9	Bayou Choctaw (BC1)	4.06	5956	64.03
10	Etrez	3.1	4100	0.64
11	Avery Island (after S. and al.)	4.0	6565	2081
12	Salina	4.1	8715	$2.7752\ 10^5$
13	Palo Duro - Unit 4	5.6	9760	$1.806\ 10^5$
14	Palo Duro - Unit 5	5.3	9810	$2.52\ 10^5$
15	Asse (B.G.R.)	5.0	6495	65.7

TRANSIENT CREEP ANALYSIS



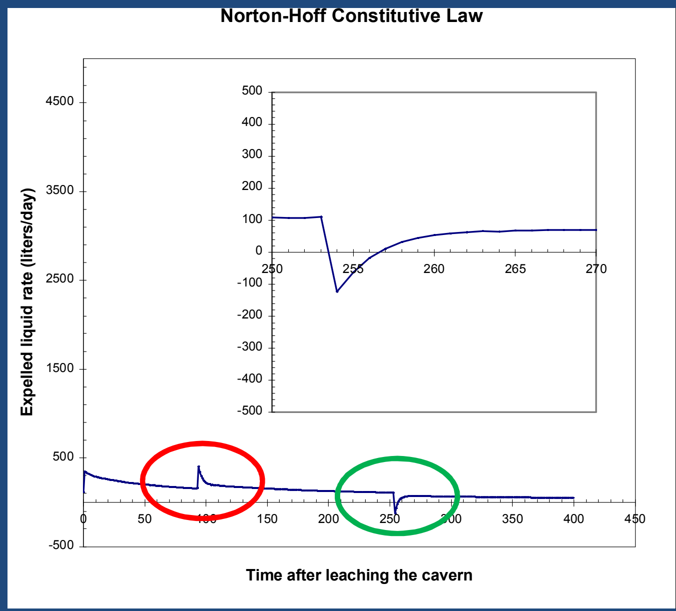


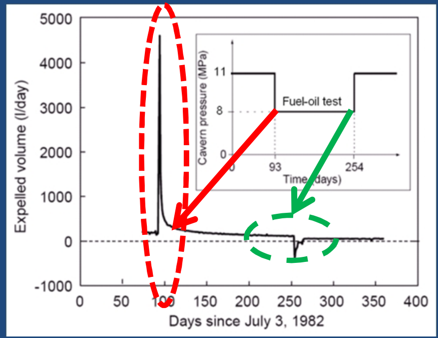
(After Hugout, 1988)

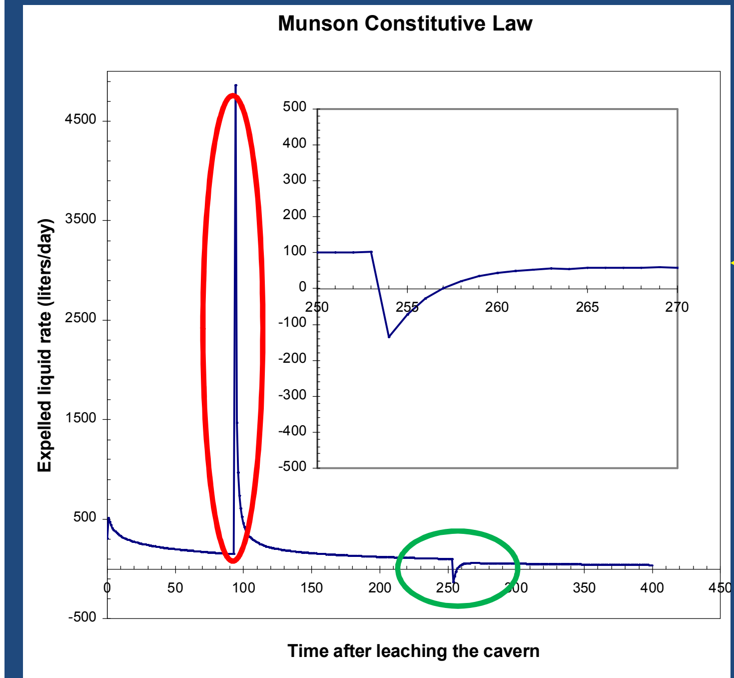


AS OBSERVED

NORTON HOFF

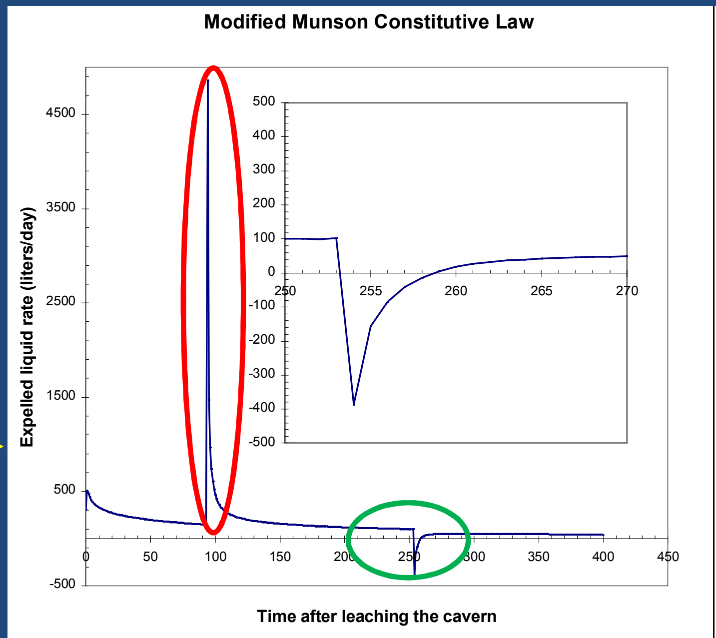




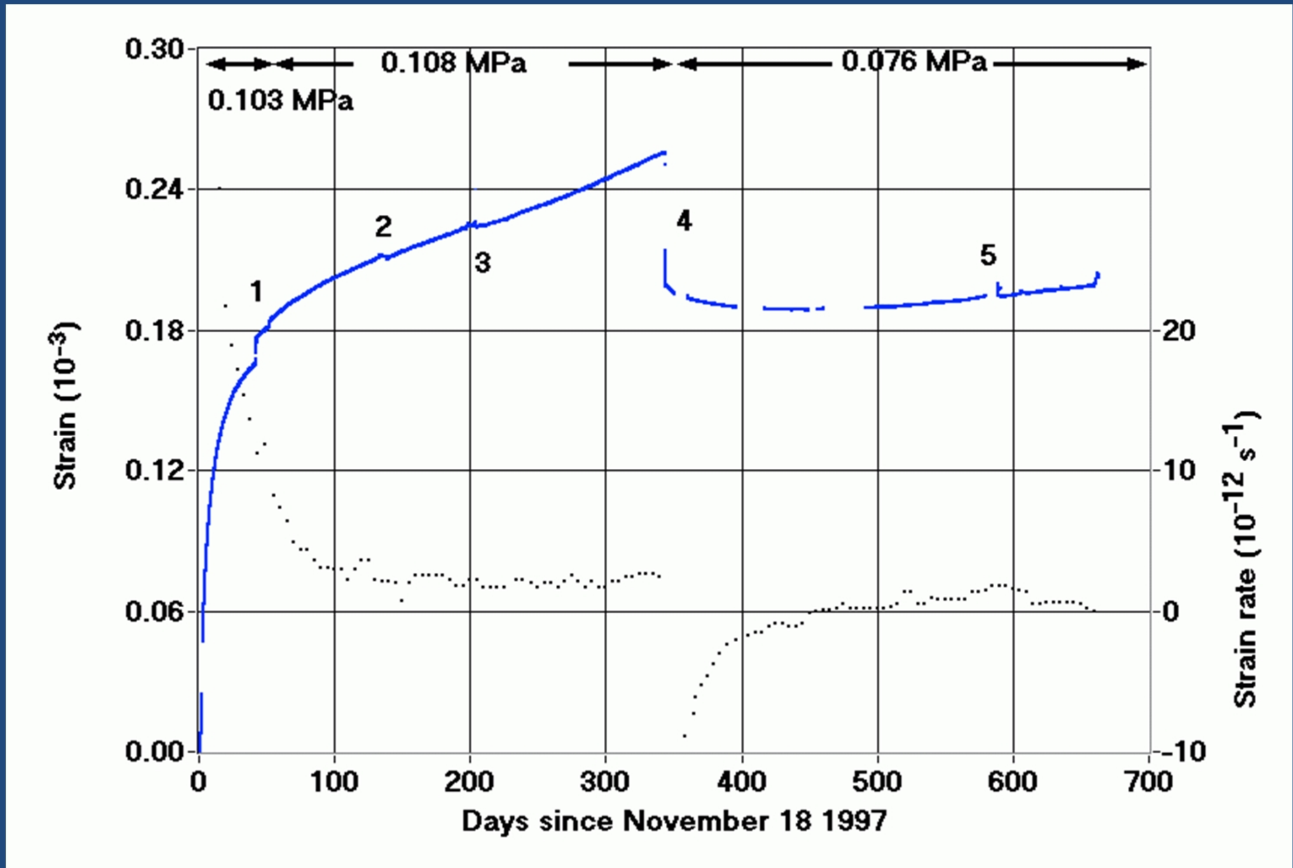


MUNSON-DAWSON

MUNSON-DAWSON + REVERSE CREEP



CREEP TESTS - SMALL MECHANICAL LOADING



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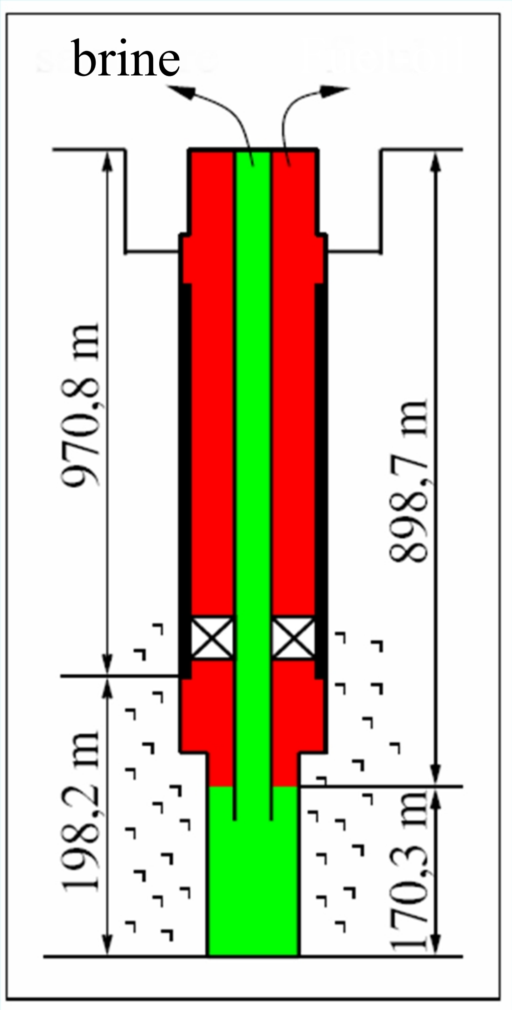
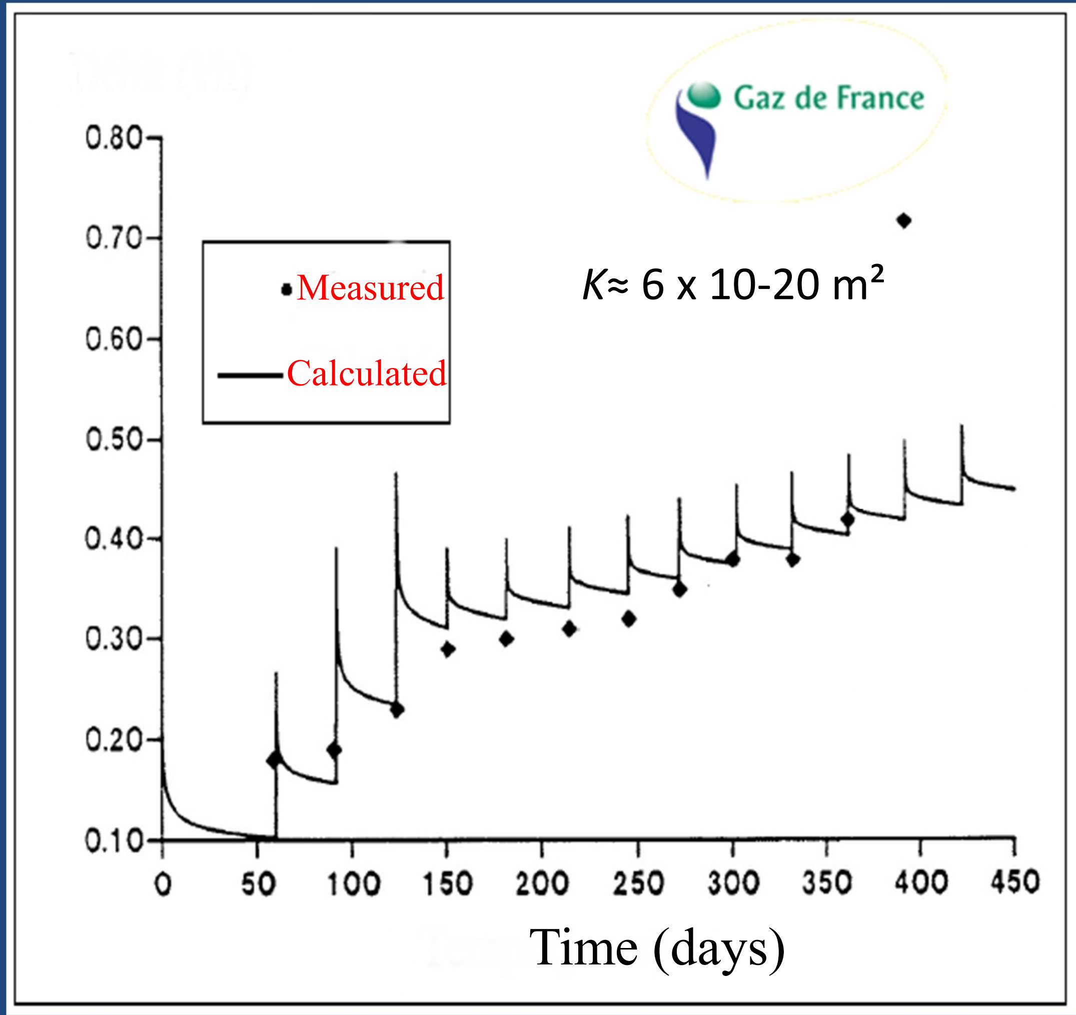
Permeability Test in the EZ58 well
(After Durup, 1996; a test supported by the SMRI)





- Permeability is small ($K \approx 6\ 10^{-20}\ m^2$)
- Darcy's law applies

SALT PERMEABLITY
AS-MEASURED DURING MIT TESTS

❖ *ETREZ (MIT tests performed by GDF Suez)*

$K = 6 \times 10^{-20}$ m² (EZ58 borehole, 1-year long test, Durup, 1996)
$K = 0.5\text{-}2 \times 10^{-20}$ m² (6 boreholes, 1300 m-deep Etrez, Brouard et al., 2001)

❖ *TERSANNE (MIT tests performed by GDF Suez)*

$K = 1\text{-}3 \cdot 10^{-21}$ m² (8 boreholes, 1400 m-deep Tersanne, Brouard et al., 2001)

❖ *OTHER SITES*

$K = 10^{-19}$ m² (SPR2 cavern, 350 m-deep, Brouard et al., 2006)
$K = 1.3 \times 10^{-17}$ m² (CUE borehole, 150 m-deep, Doe and Osnes, 2006)
$K = 1.1 \times 10^{-19}$ m² (Mitchell borehole, 250 m-deep, Doe and Osnes, 2006)

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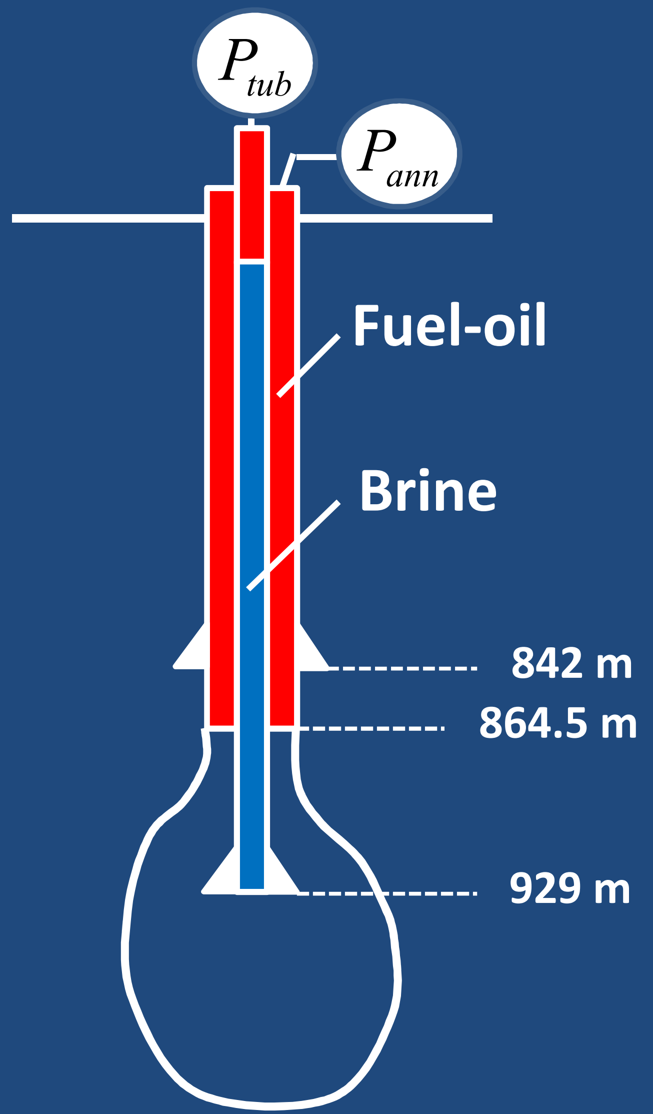
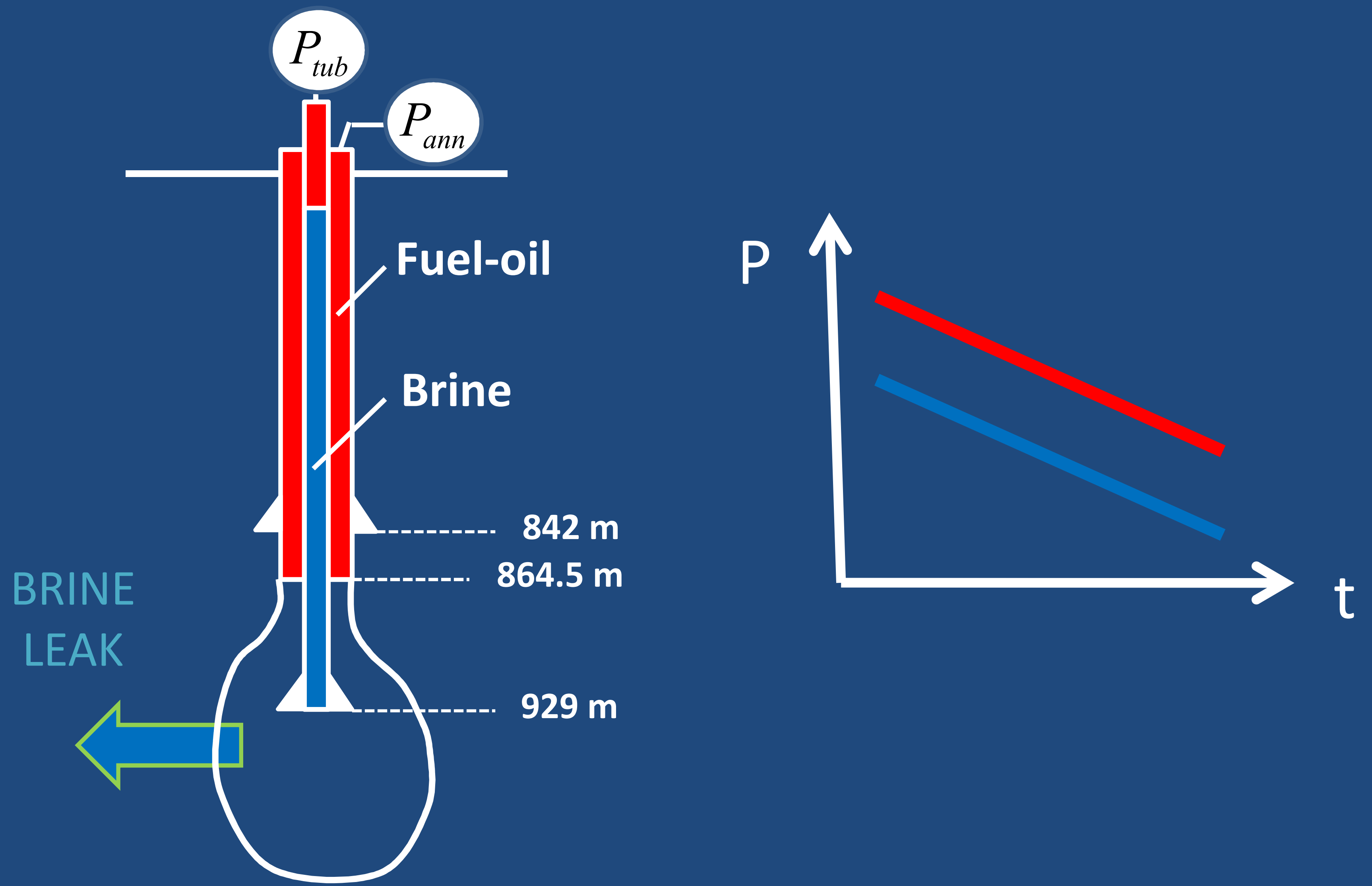
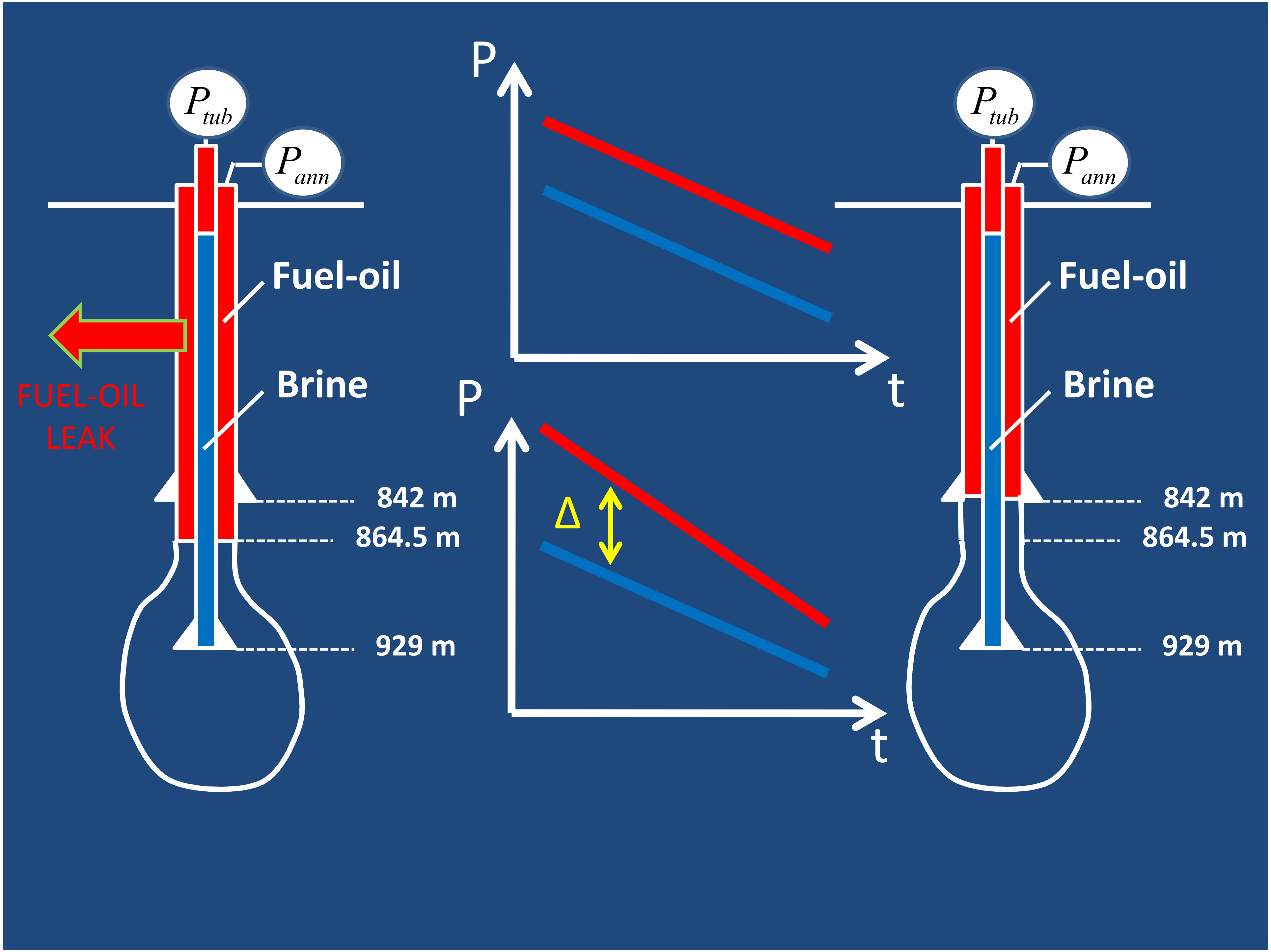
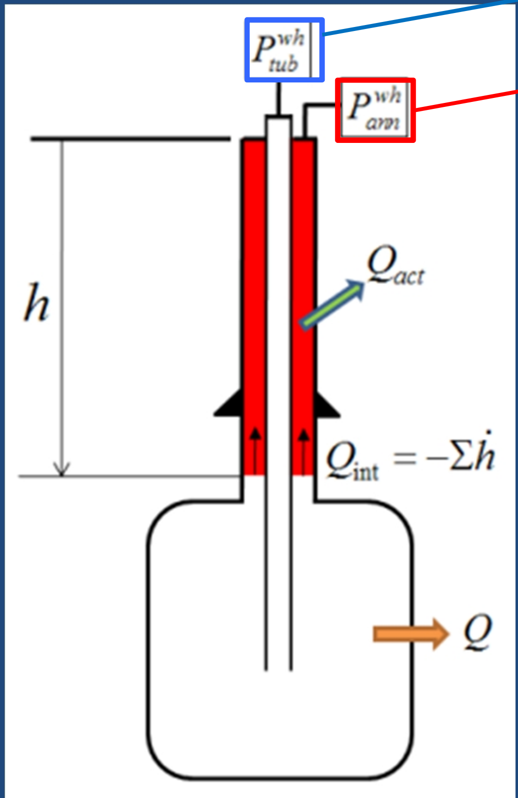

P_{tub}
P_{ann}
Fuel-oil
Brine
842 m
864.5 m
929 m

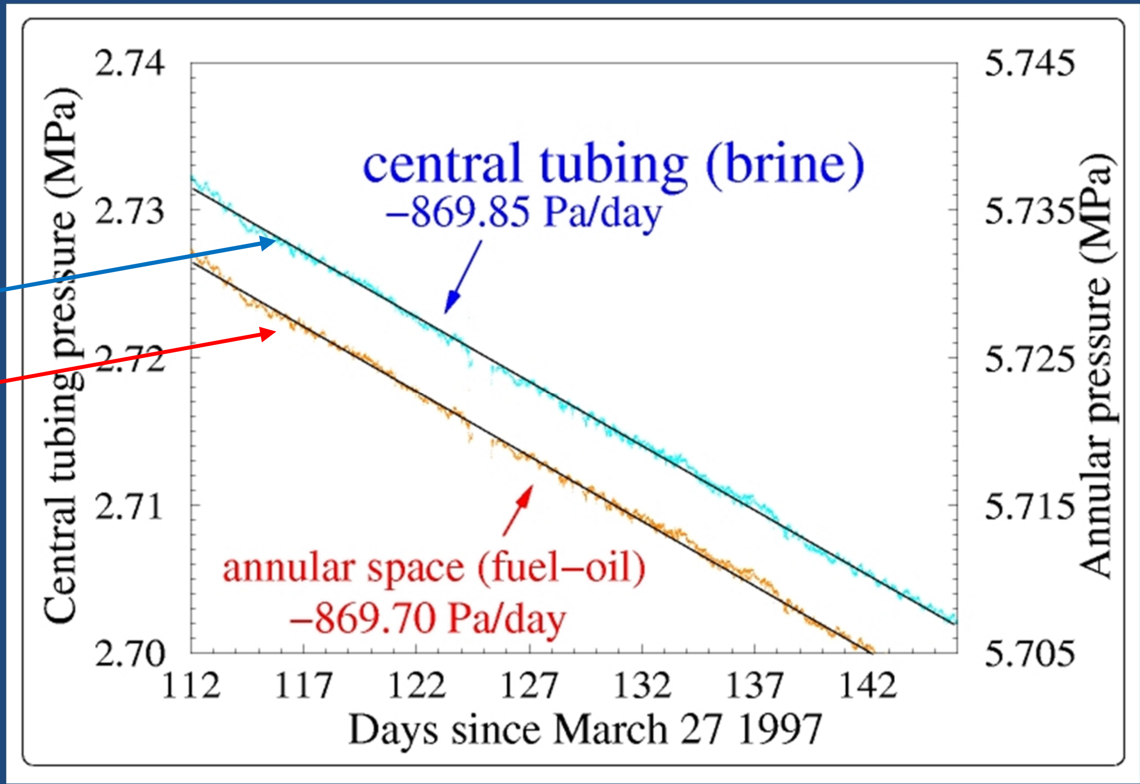

P_{tub}
P_{ann}
Fuel-oil
Brine
842 m
864.5 m
929 m
BRINE
LEAK
P
t



P_{tub}
P_{ann}
Fuel-oil
Brine
FUEL-OIL
LEAK
842 m
864.5 m
929 m
P
t
P
Δ
t
P_{tub}
P_{ann}
Fuel-oil
Brine
842 m
864.5 m
929 m



P_{tub}^{wh}
P_{ann}^{wh}
h
Q_{act}
$Q_{int} = -\Sigma\dot{h}$
Q



central tubing (brine)
−869.85 Pa/day
annular space (fuel−oil)
−869.70 Pa/day
Central tubing pressure (MPa)
Annular pressure (MPa)
Days since March 27 1997
2.74
2.73
2.72
2.71
2.70
5.745
5.735
5.725
5.715
5.705
112
117
122
127
132
137
142

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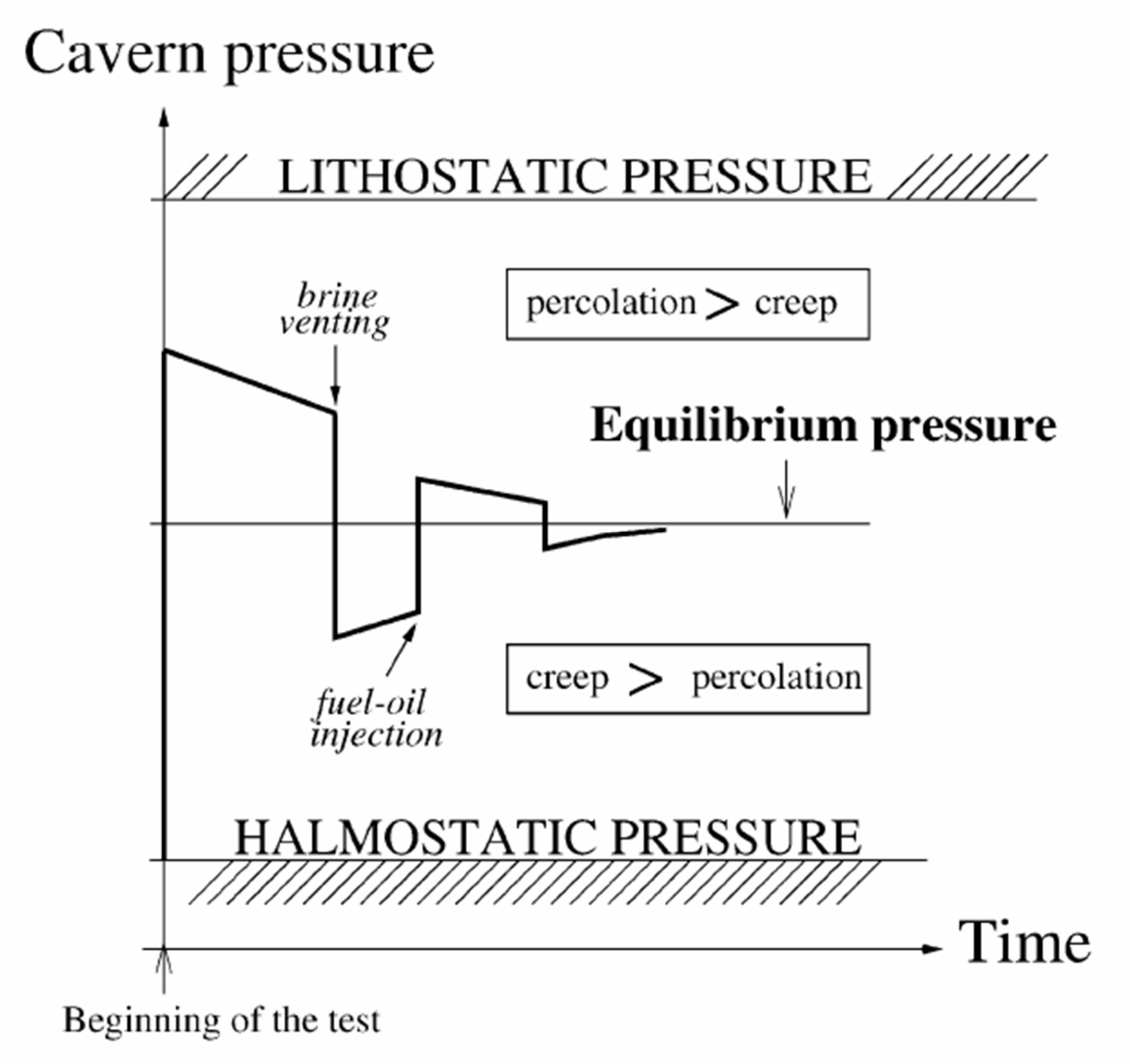
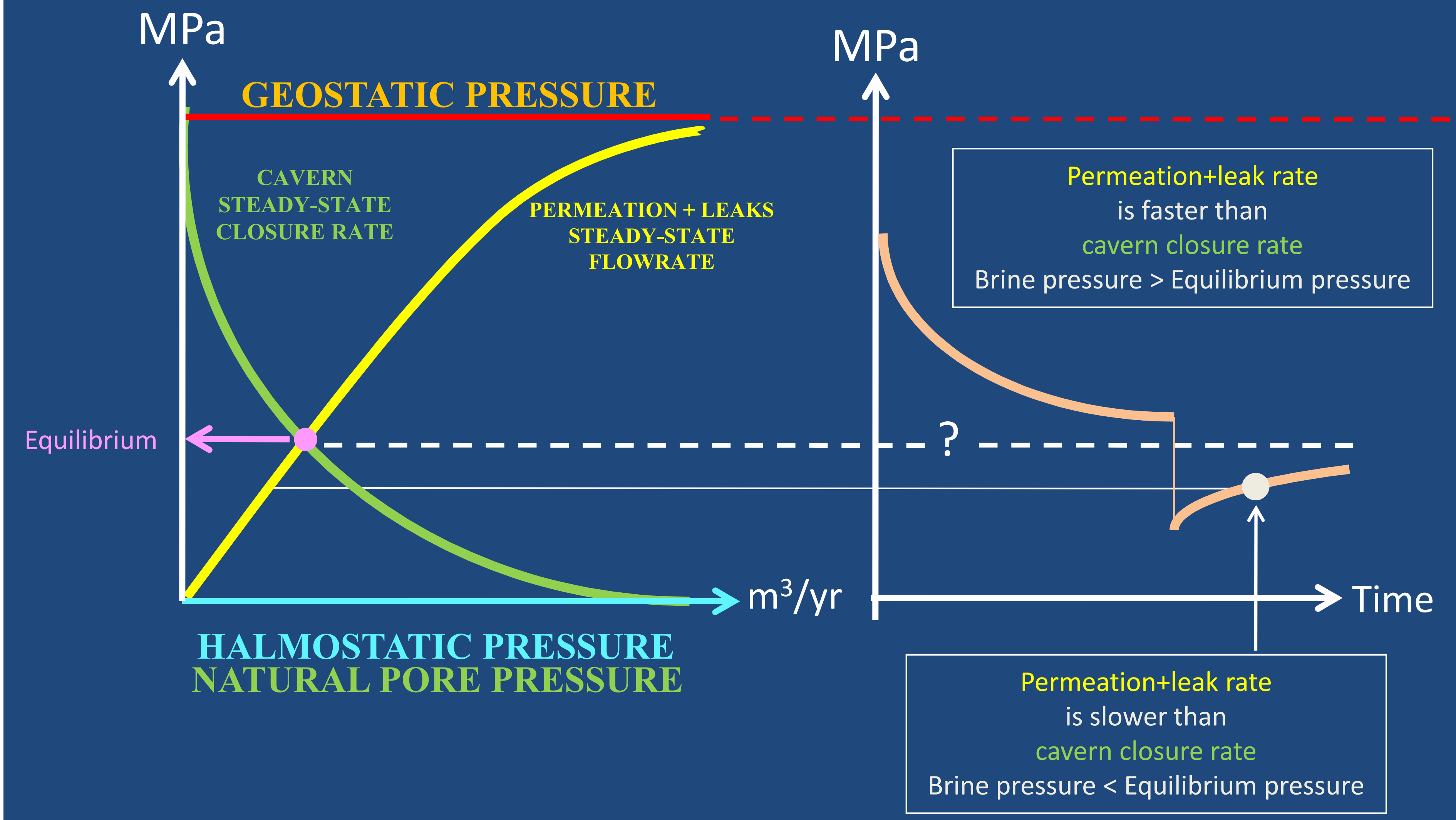
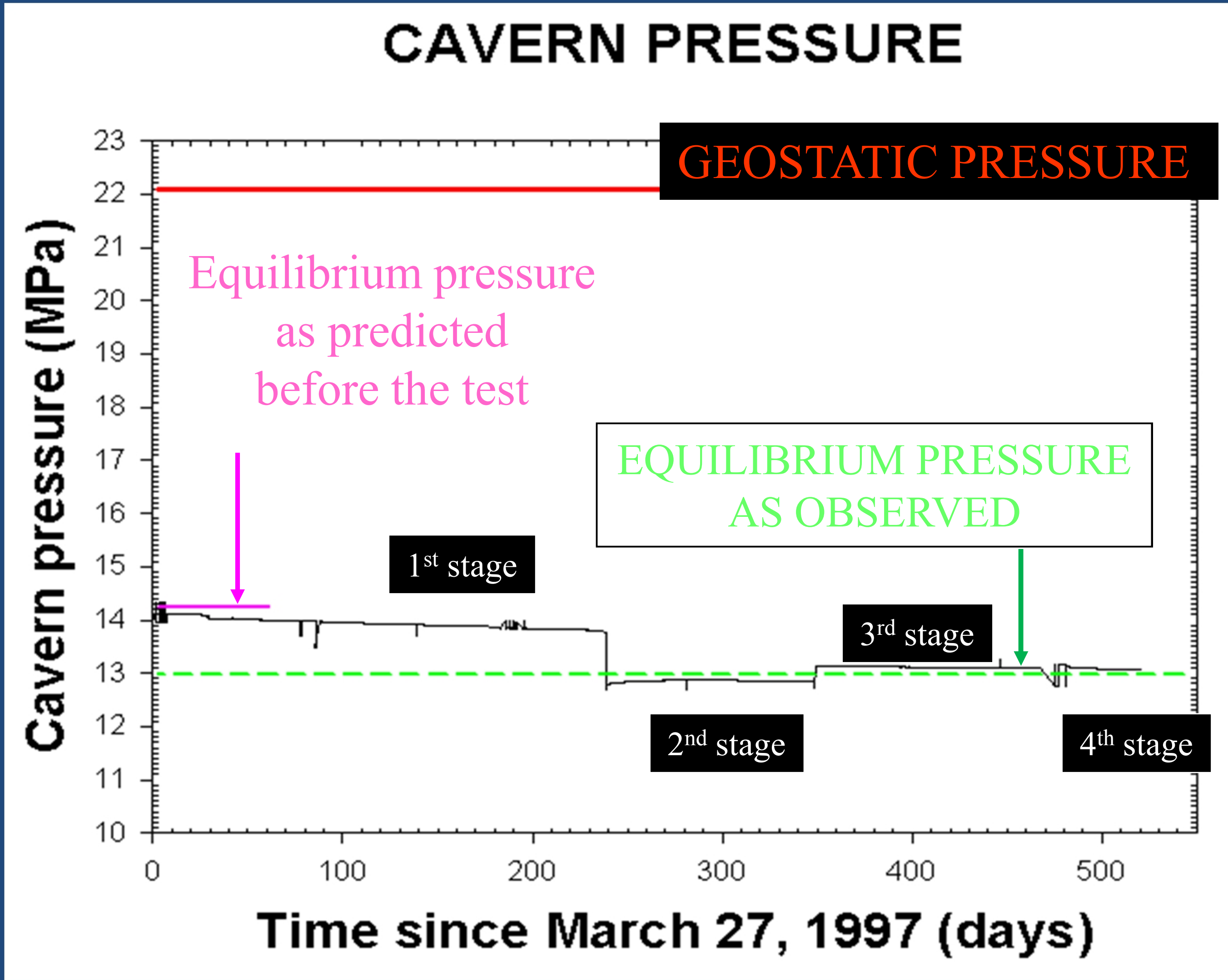
TRIAL AND ERROR



TRIAL AND ERROR TEST WHEN THERMAL EQUILIBRIUM IS REACHED



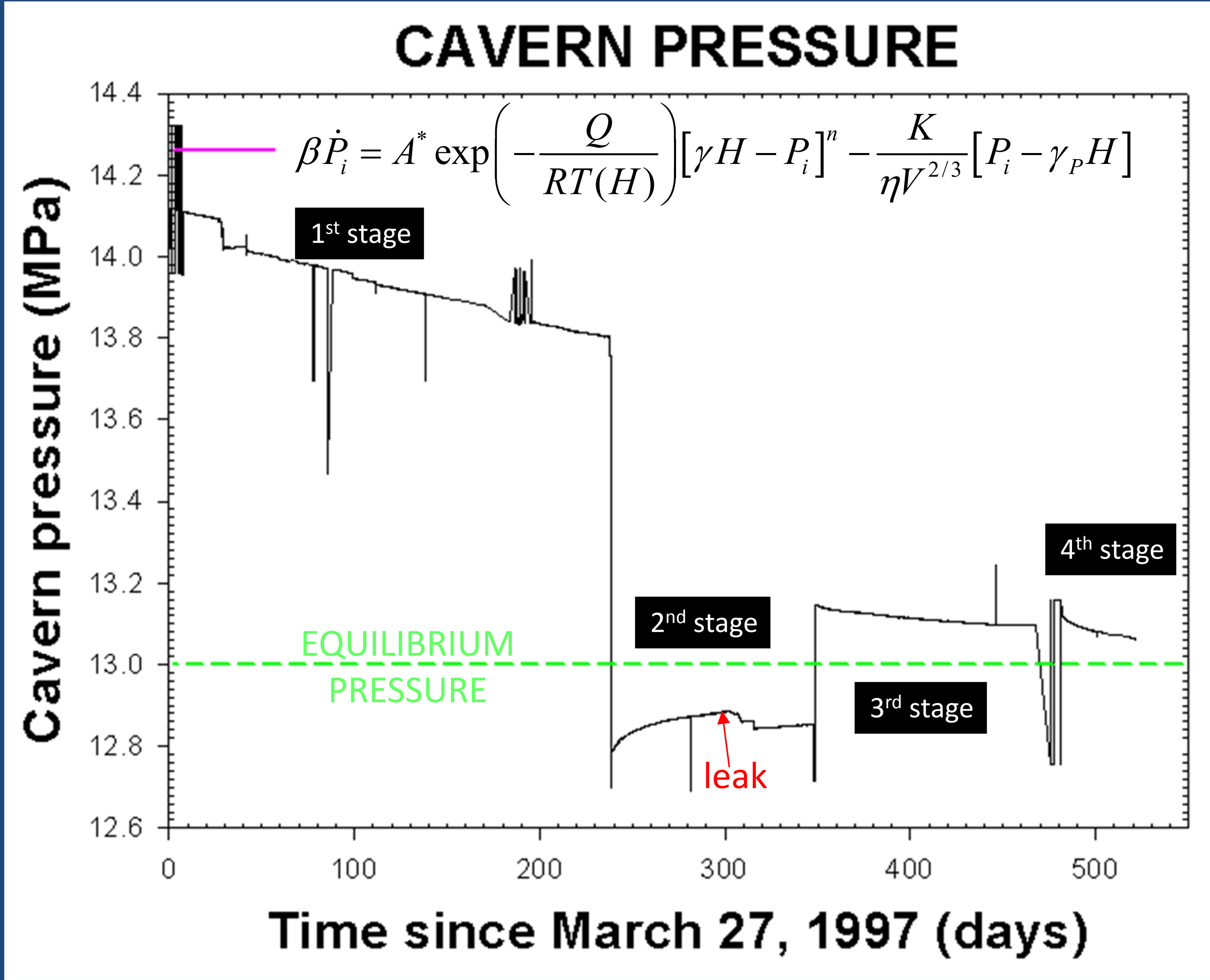
Equilibrium pressure reached in a closed brine-filled cavern when cavern creep closure exactly equals brine outflow rate

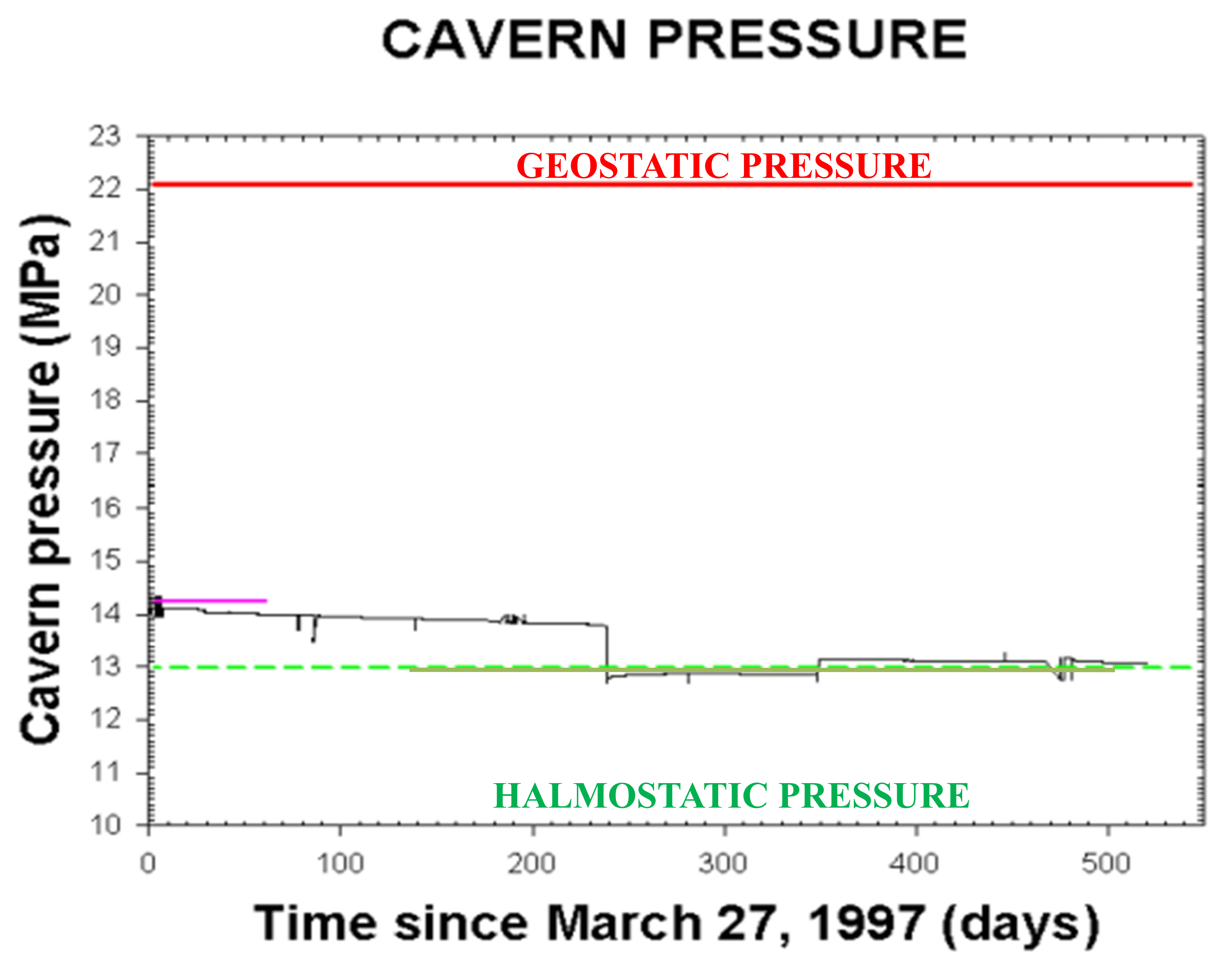


Brine permeation
Is faster than
cavern creep closure

Brine permeation
Is slower than
cavern creep closure

BACK-CALCULATIONS




CAVERN PRESSURE
GEOSTATIC PRESSURE
HALMOSTATIC PRESSURE
Cavern pressure (MPa)
Time since March 27, 1997 (days)
23
22
21
20
19
18
17
16
15
14
13
12
11
10
0
100
200
300
400
500

CONCLUSIONS

- ✓ SALT PERMEABILITY WAS PROVED TO BE

$K = 2 \times 10^{-19}\ m^2$

- ✓ CAVERN CREEP CLOSURE RATE IS

0.0002 /yr

- ✓ BRINE FLOWRATE PERMEATING TO THE SALT FORMATION IS:

$1.6\ m^3/yr$

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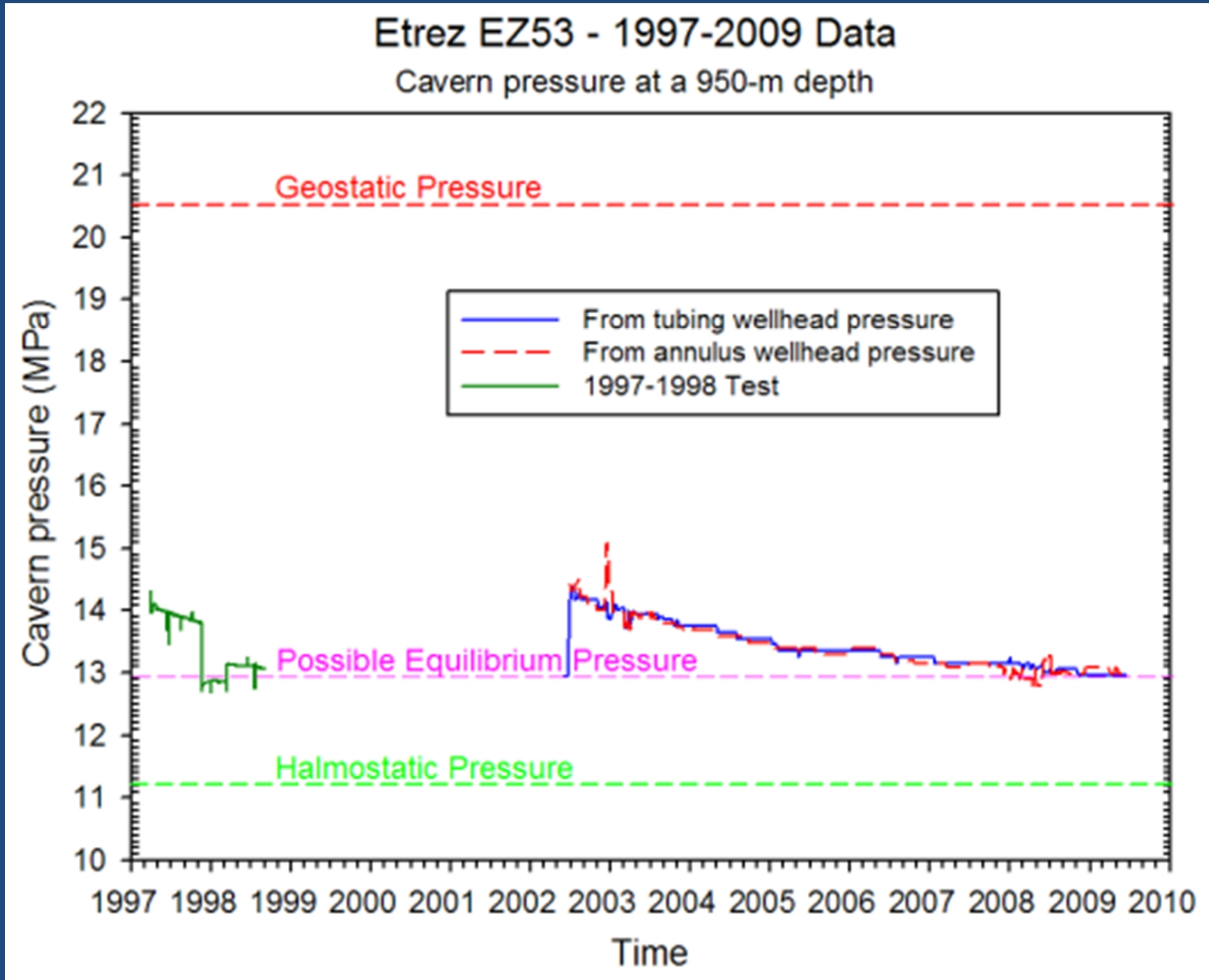
10 YEARS LATER (2002-2010)

- (Less accurate) pressure gauges were set on the wellhead by GDF Suez.
- Pressure was measured during an additional 8-year long period.


Etrez EZ53 - 1997-2009 Data
Cavern pressure at a 950-m depth
Geostatic Pressure
From tubing wellhead pressure
From annulus wellhead pressure
1997-1998 Test
Possible Equilibrium Pressure
Halmostatic Pressure
Cavern pressure (MPa)
22
21
20
19
18
17
16
15
14
13
12
11
10
1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010
Time

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CONCLUSIONS

- A 14-YEAR LONG TESTING PERIOD PROVED THAT EZ53 EQUILIBRIUM PRESSURE IS 13 MPa.

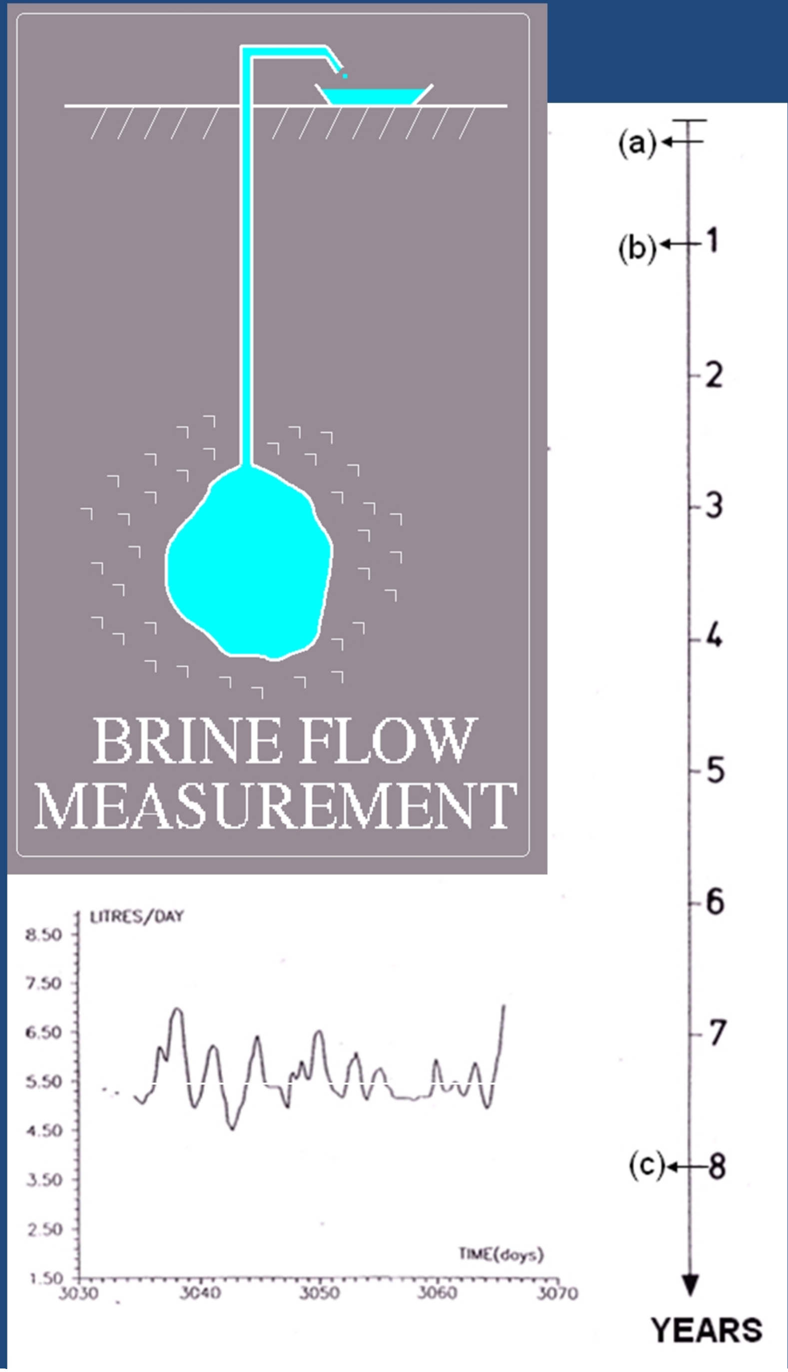
  (Geostatic pressure is 20.1 MPa, halmostatic pressure is 11.2 MPa)

- ROCK FORMATION PERMEABILITY IS 2×10^{-19} m^2.

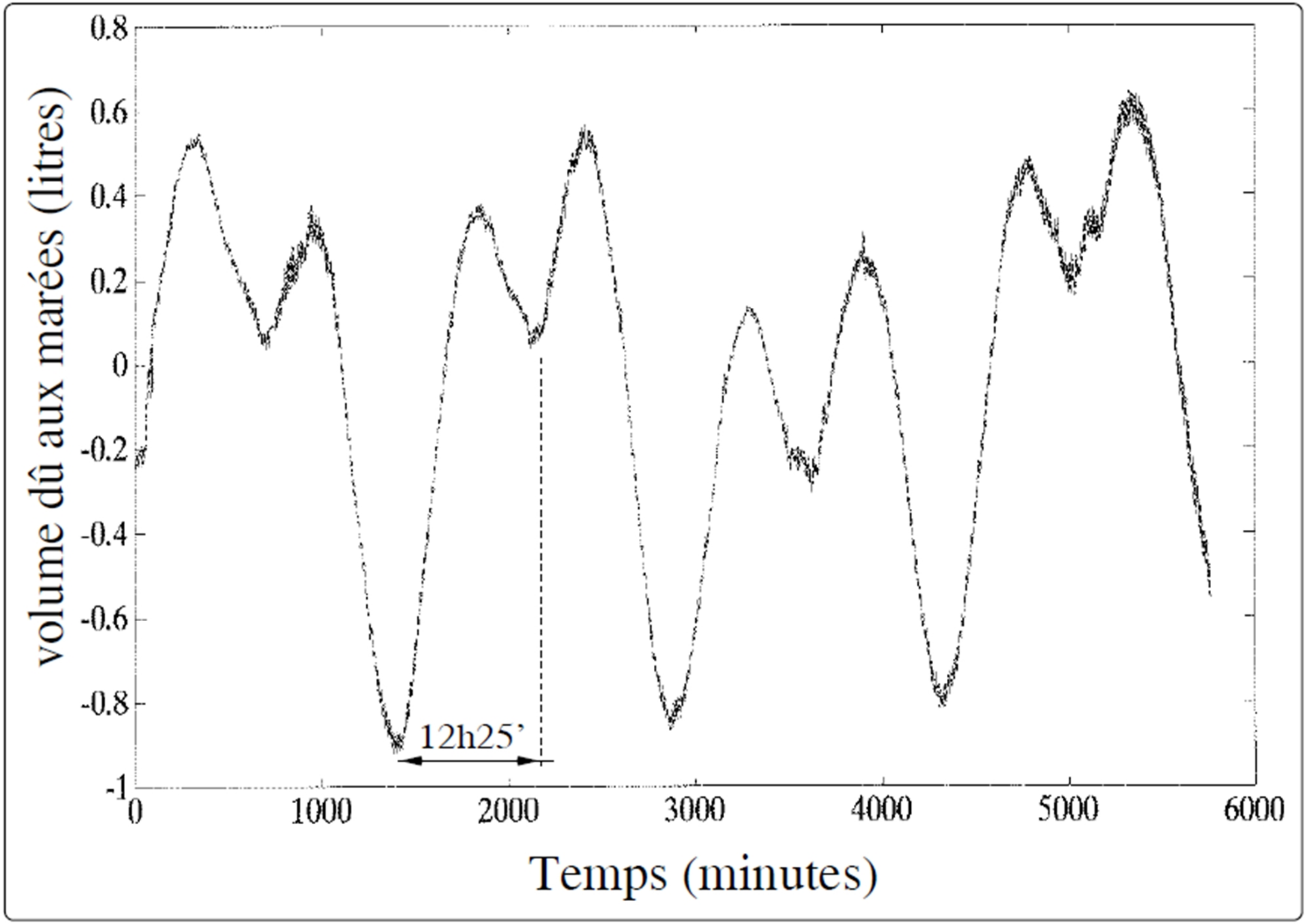
- BRINE RATE PERMEATING TO THE ROCK MASS IS

  1.6 m^3/yr

QUESTIONS?


BRINE FLOW
MEASUREMENT
LITRES/DAY
8.50
7.50
6.50
5.50
4.50
3.50
2.50
1.50
3030
3040
3050
3060
3070
TIME(days)
(a)
(b)
1
2
3
4
5
6
7
(c)
8
YEARS

t


volume dû aux marées (litres)
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
12h25'
0
1000
2000
3000
4000
5000
6000
Temps (minutes)

A MORE PRECISE INTERPRETATION

BASED ON BOTH ANNULAR SPACE AND CENTRAL STRING PRESSURE

EVOLUTIONS

ALLOWS TO COMPUTE THE ACTUAL LEAK

(Van Sambeek, Bérest, Broaurd,

SMRI 2003 Report)

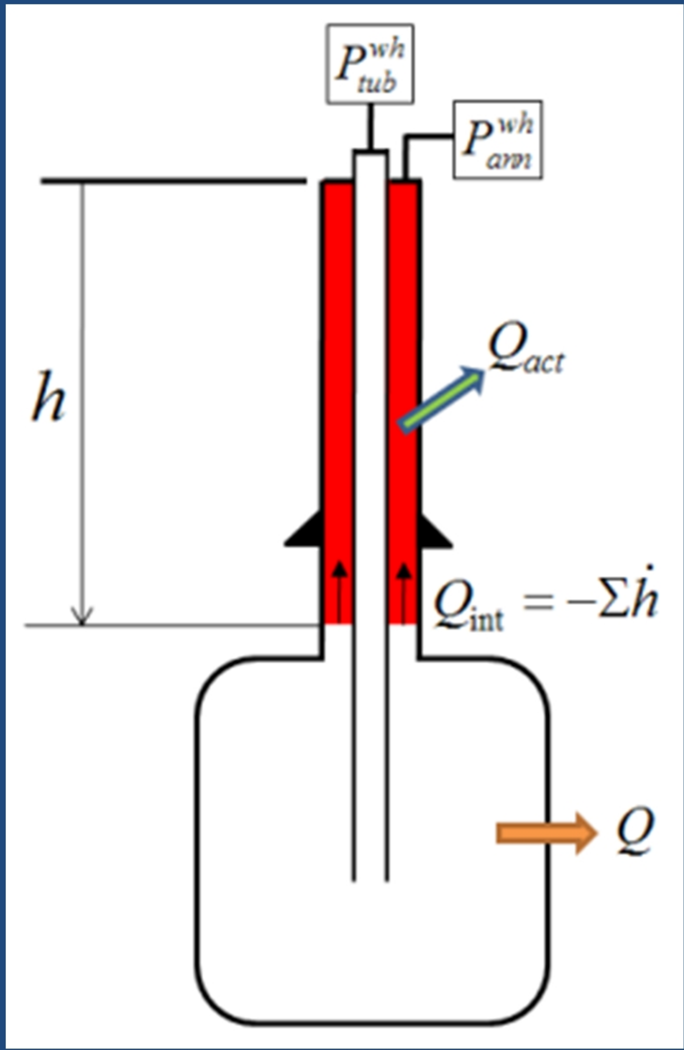
THE ACTUAL LEAK (Q_{act})

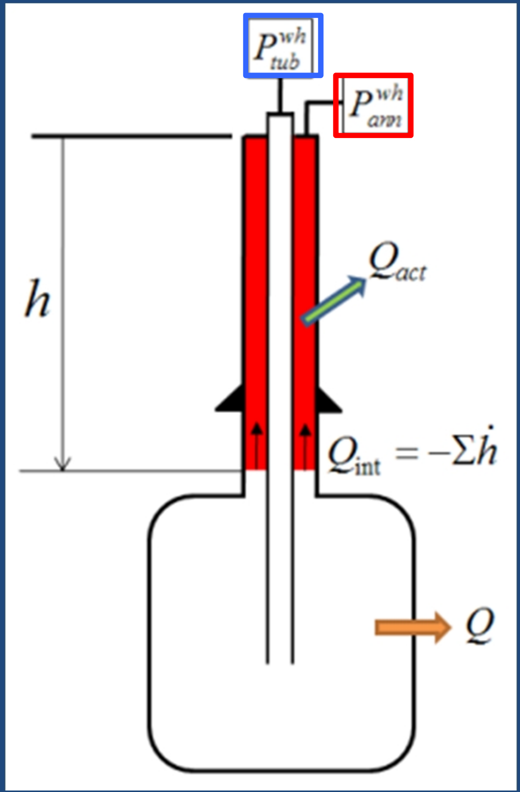
CAN BE INFERRED FROM

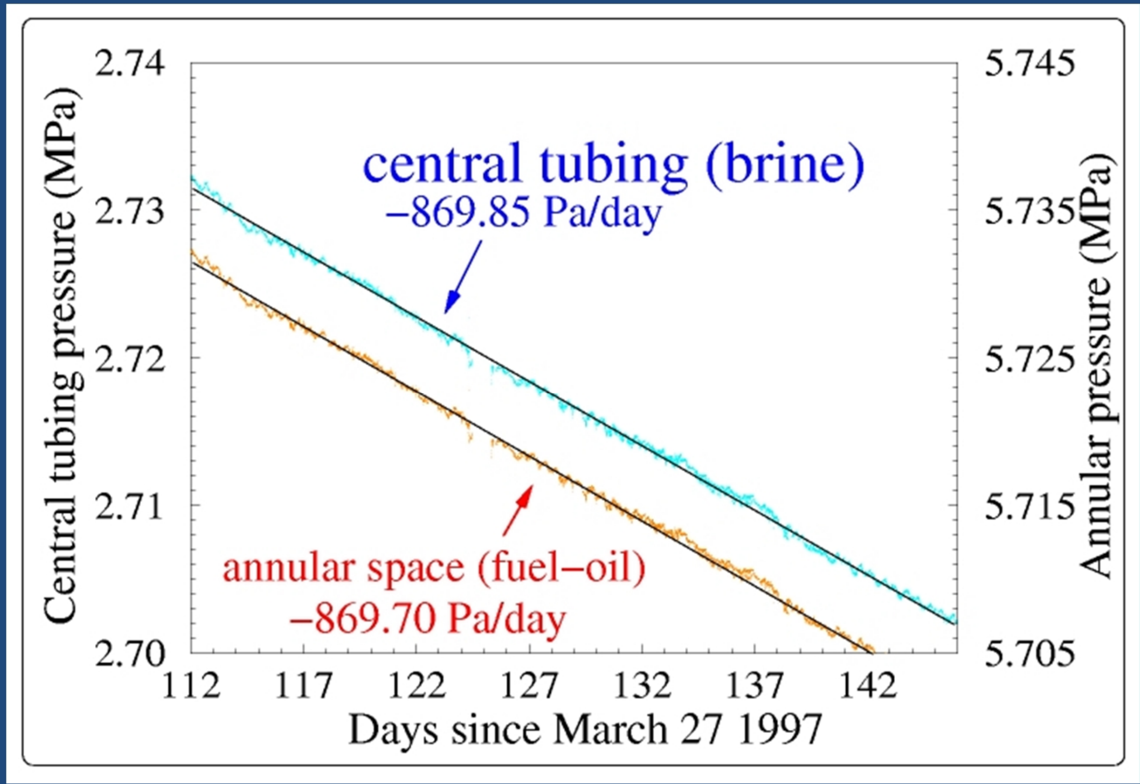
WELLHEAD PRESSURE

EVOLUTIONS

$$Q_{act}\frac{(\gamma_b-\gamma)}{\Sigma}=\dot{P}_{tub}^{wh}-\left[1+\frac{\beta V_c(\gamma_b-\gamma)}{\Sigma}\right]\dot{P}_{ann}^{wh}$$

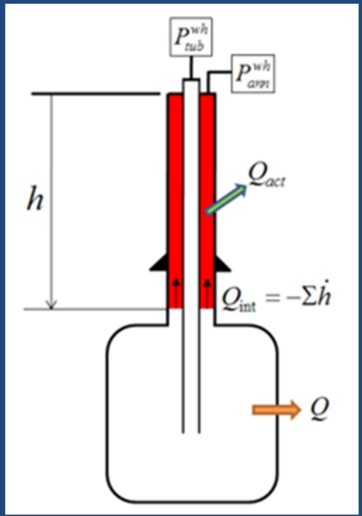


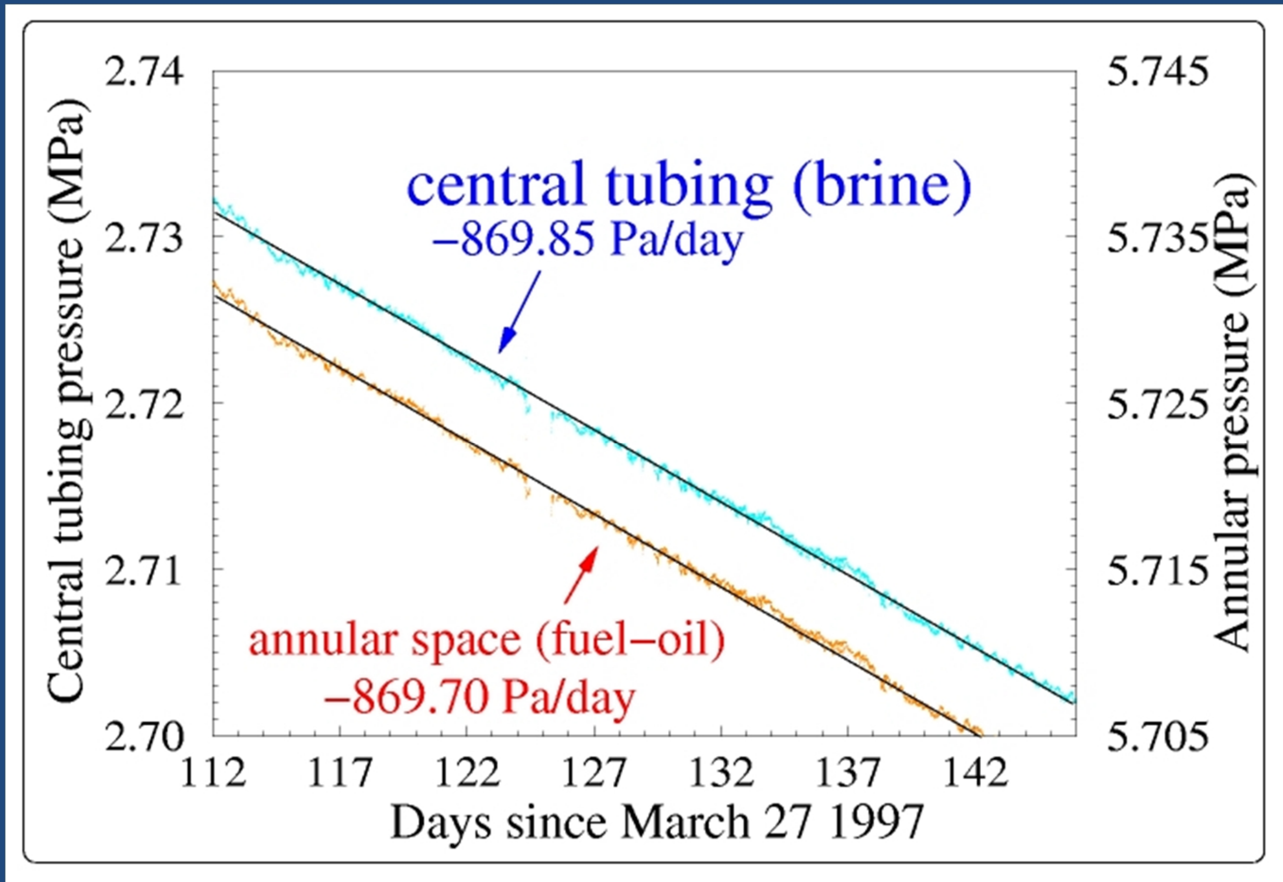




$$\dot{P}_{ann}^{wh} = \dot{P}_{tub}^{wh}$$

A CLEAR PROOF OF NO LEAK


P_{tub}^{wh}
P_{ann}^{wh}
h
Q_{act}
$Q_{int} = -\Sigma\dot{h}$
Q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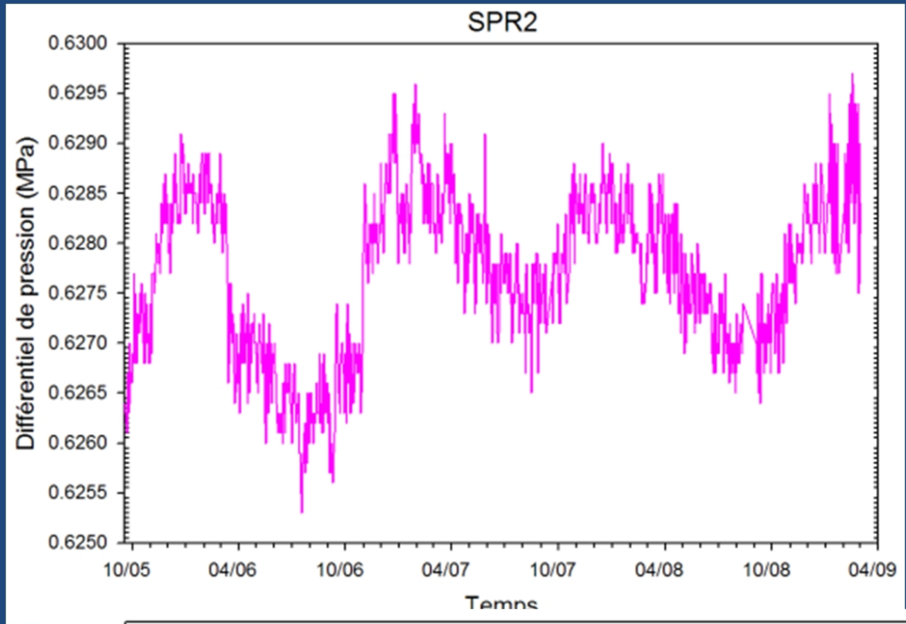
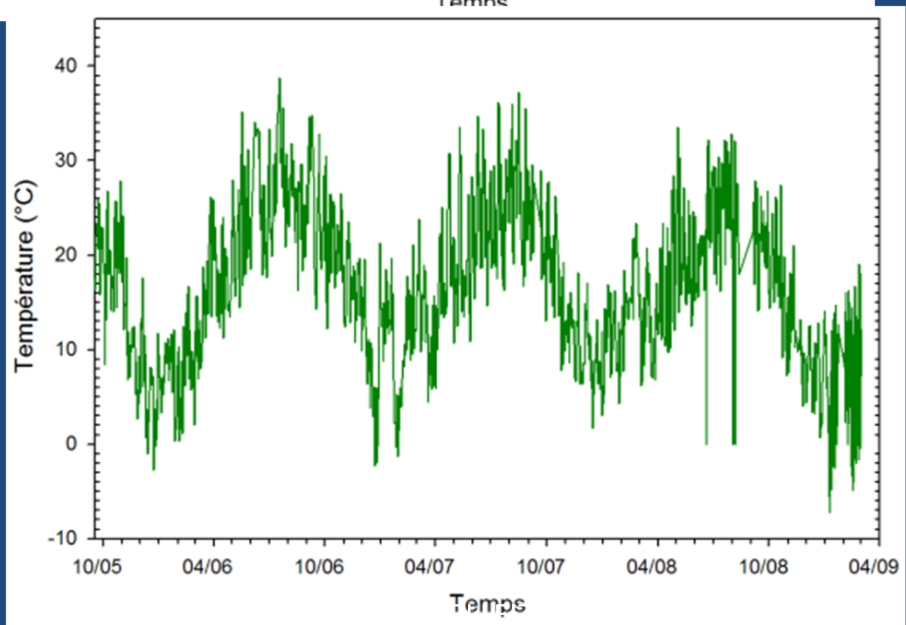
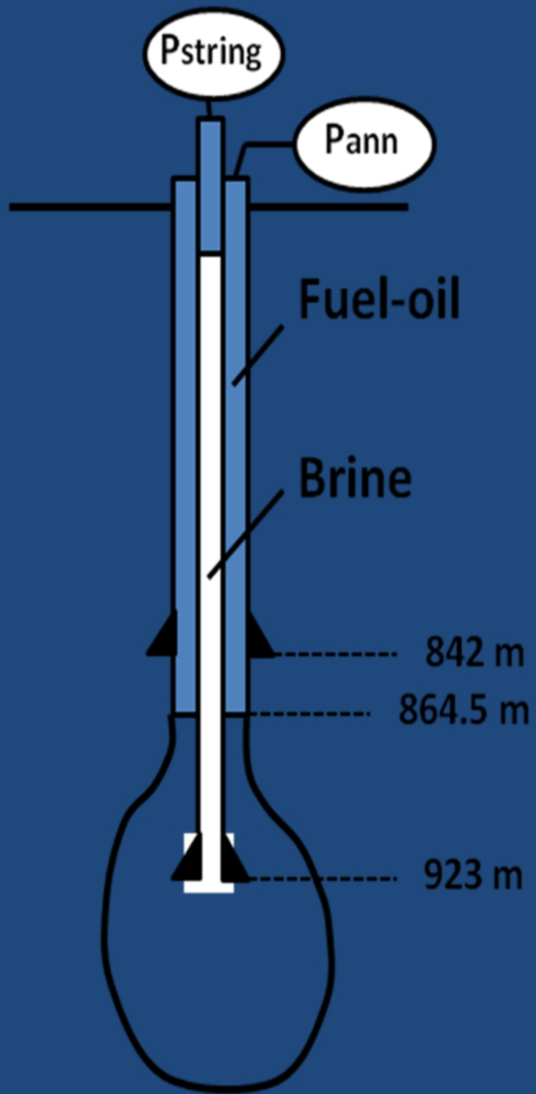
−869.70 Pa/day
Central tubing pressure (MPa)
Annular pressure (MPa)
Days since March 27 1997
2.74
2.73
2.72
2.71
2.70
5.745
5.735
5.725
5.715
5.705
112
117
122
127
132
137
142


SPR2
Différentiel de pression (MPa)
0.6300
0.6295
0.6290
0.6285
0.6280
0.6275
0.6270
0.6265
0.6260
0.6255
0.6250
10/05
04/06
10/06
04/07
10/07
04/08
10/08
04/09
Temps

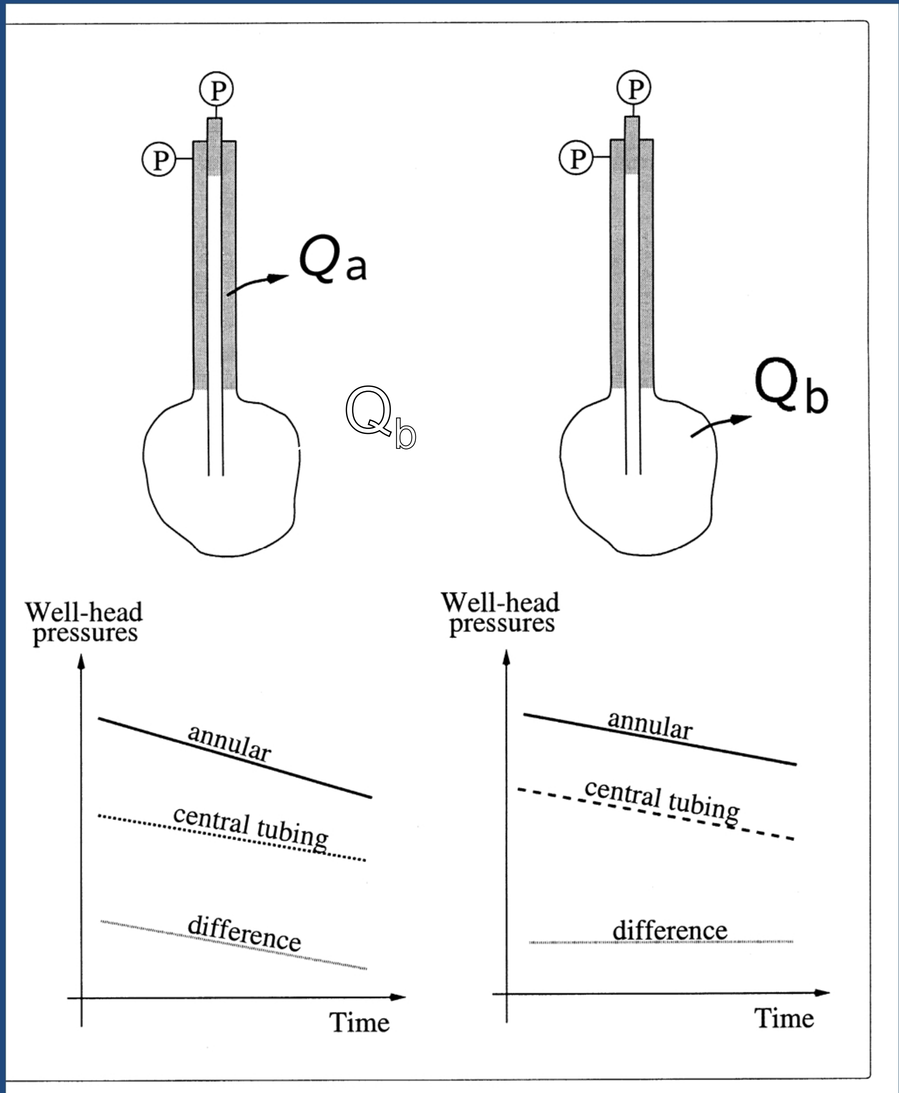

Température (°C)
40
30
20
10
0
-10
10/05
04/06
10/06
04/07
10/07
04/08
10/08
04/09
Temps


Pstring
Pann
Fuel-oil
Brine
842 m
864.5 m
923 m

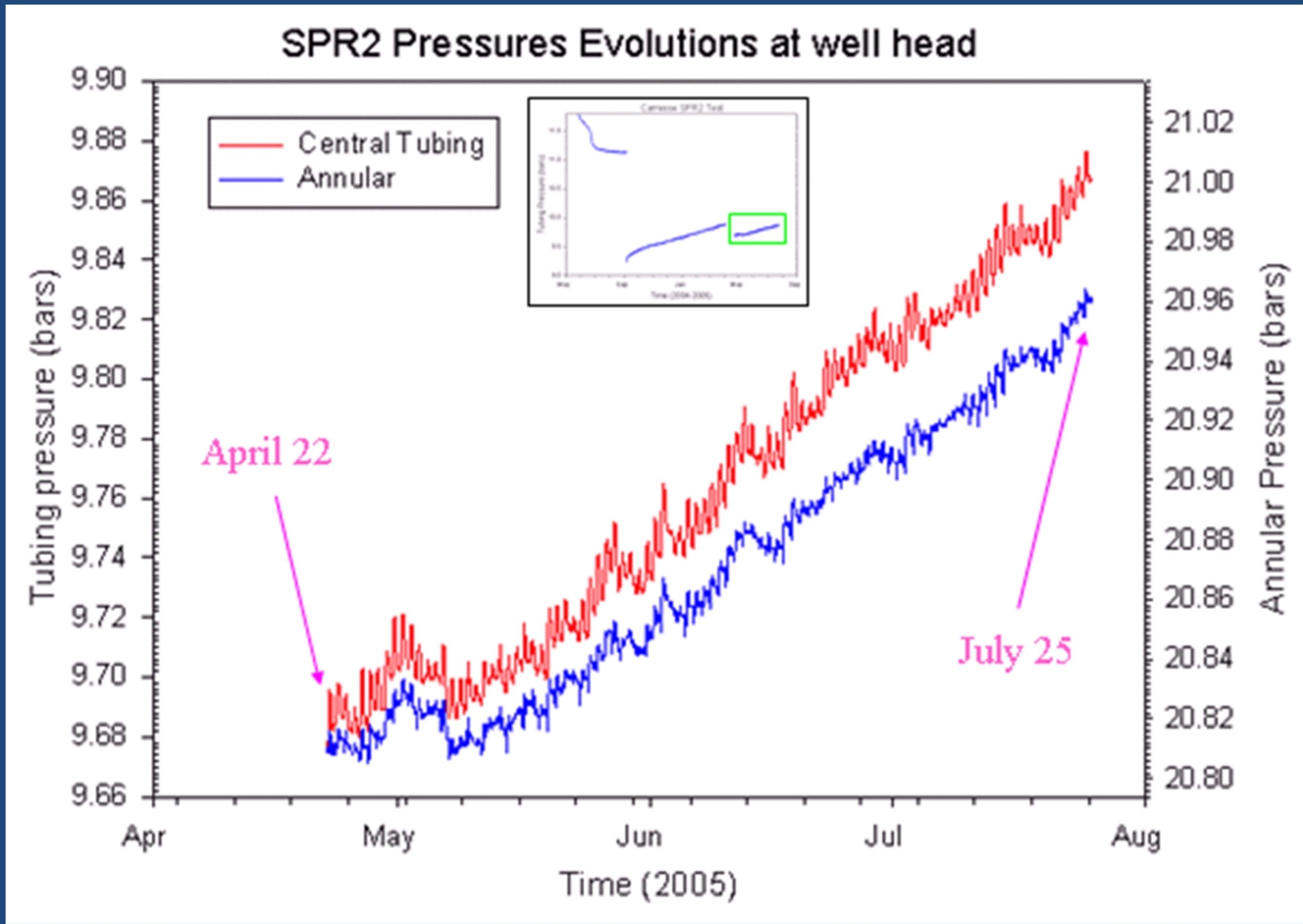
Système de détection des fuites

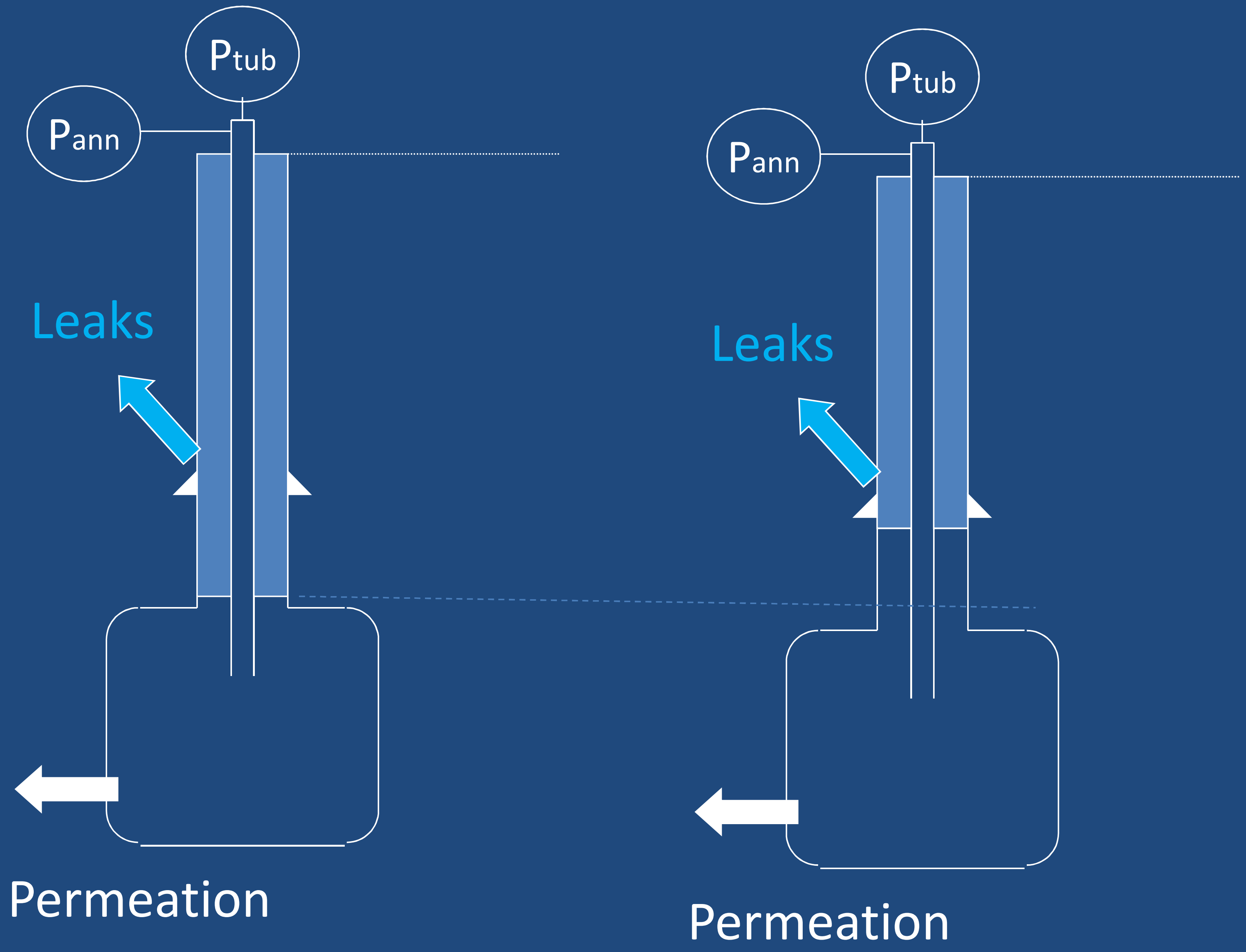
$$\dot{P}_{tub} = \frac{Q_a + Q_b}{\beta V}$$

$$\dot{P}_{ann} = \frac{Q_a + Q_b}{\beta V} - (\rho_b - \rho_h) g \frac{Q_a}{\Sigma}$$



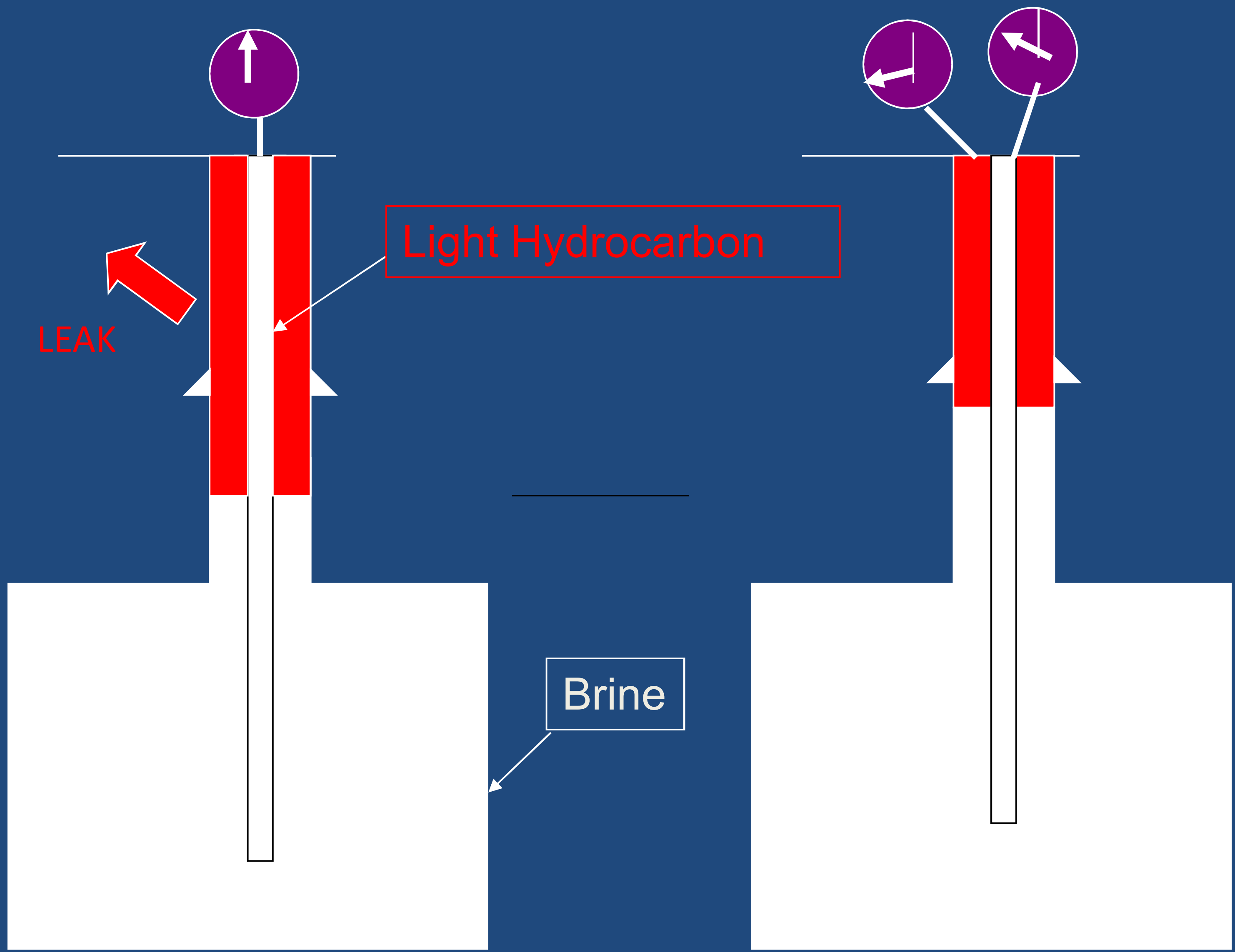
$$\dot{P}_{ann} = \dot{P}_{tub} = \frac{Q_b}{\beta V}$$

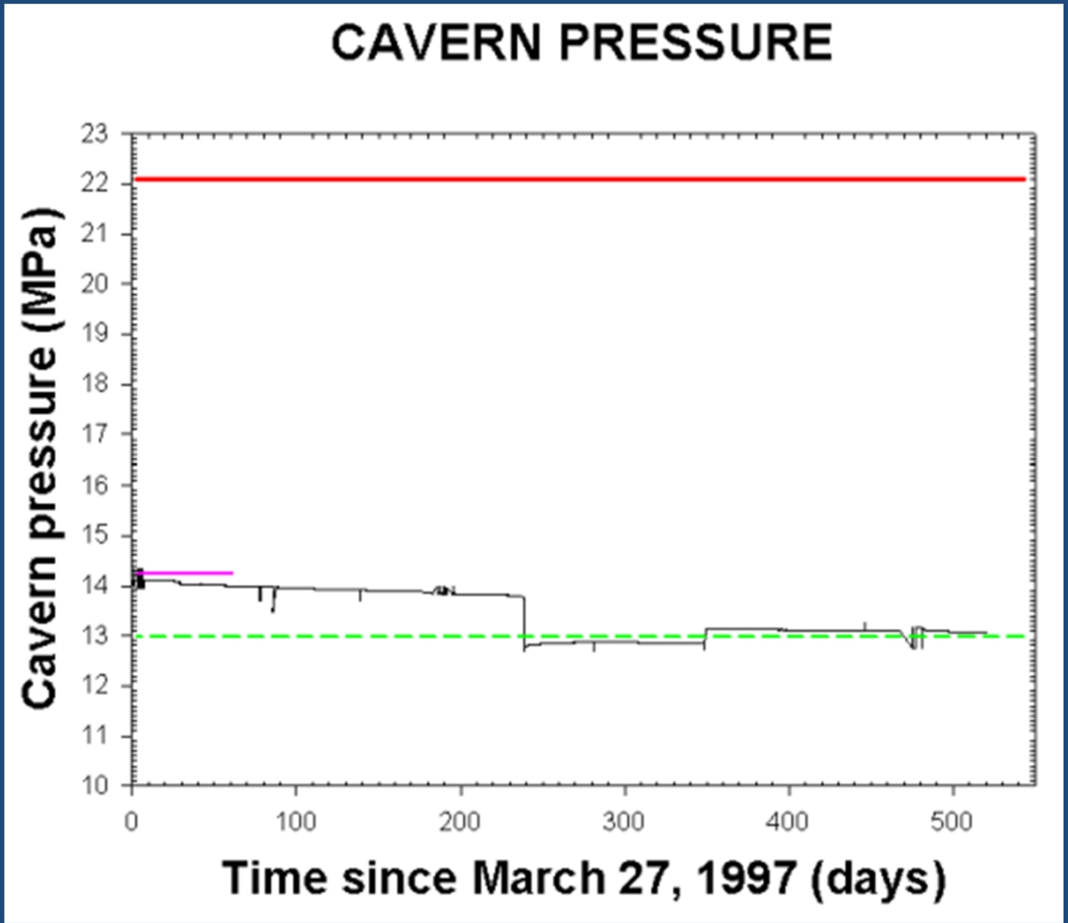

SPR2 Pressures Evolutions at well head
Central Tubing
Annular
Tubing pressure (bars)
Annular Pressure (bars)
Time (2005)
Apr
May
Jun
Jul
Aug
April 22
July 25
9.90
9.88
9.86
9.84
9.82
9.80
9.78
9.76
9.74
9.72
9.70
9.68
9.66
21.02
21.00
20.98
20.96
20.94
20.92
20.90
20.88
20.86
20.84
20.82
20.80


Ptub
Pann
Leaks
Permeation
Ptub
Pann
Leaks
Permeation

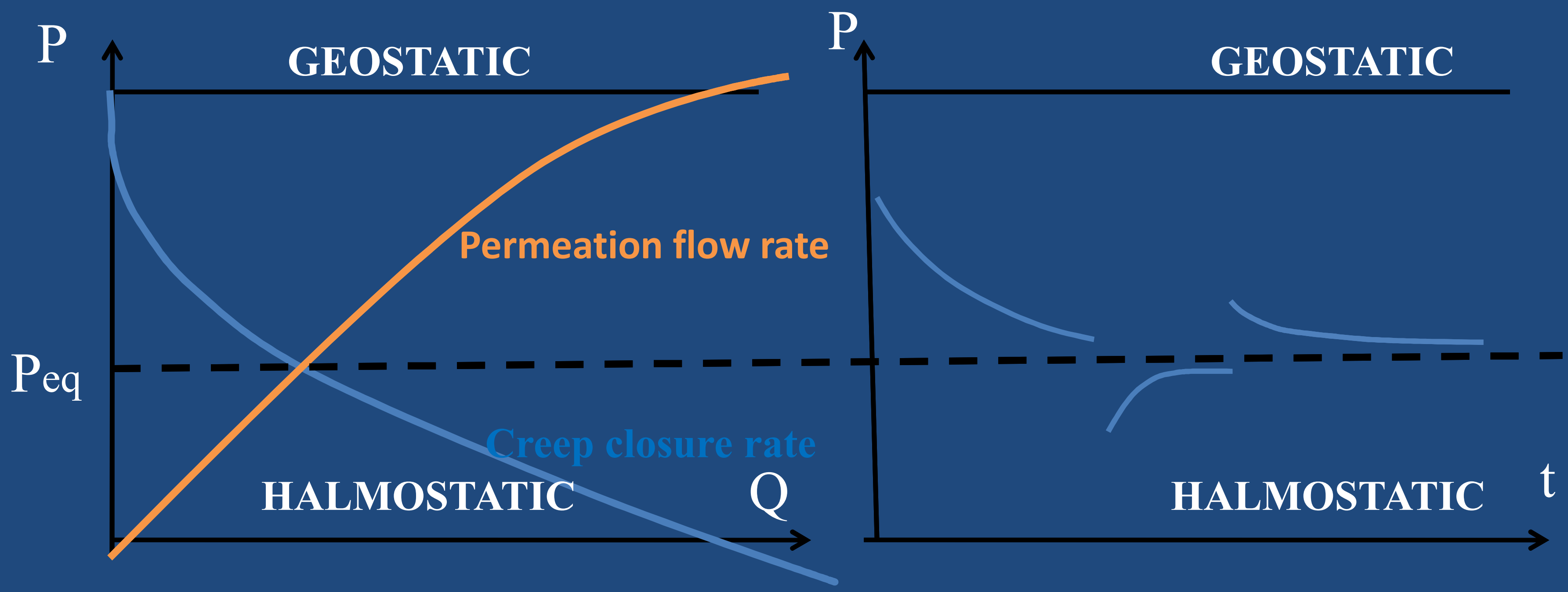
Volume Loss (ΔV) =

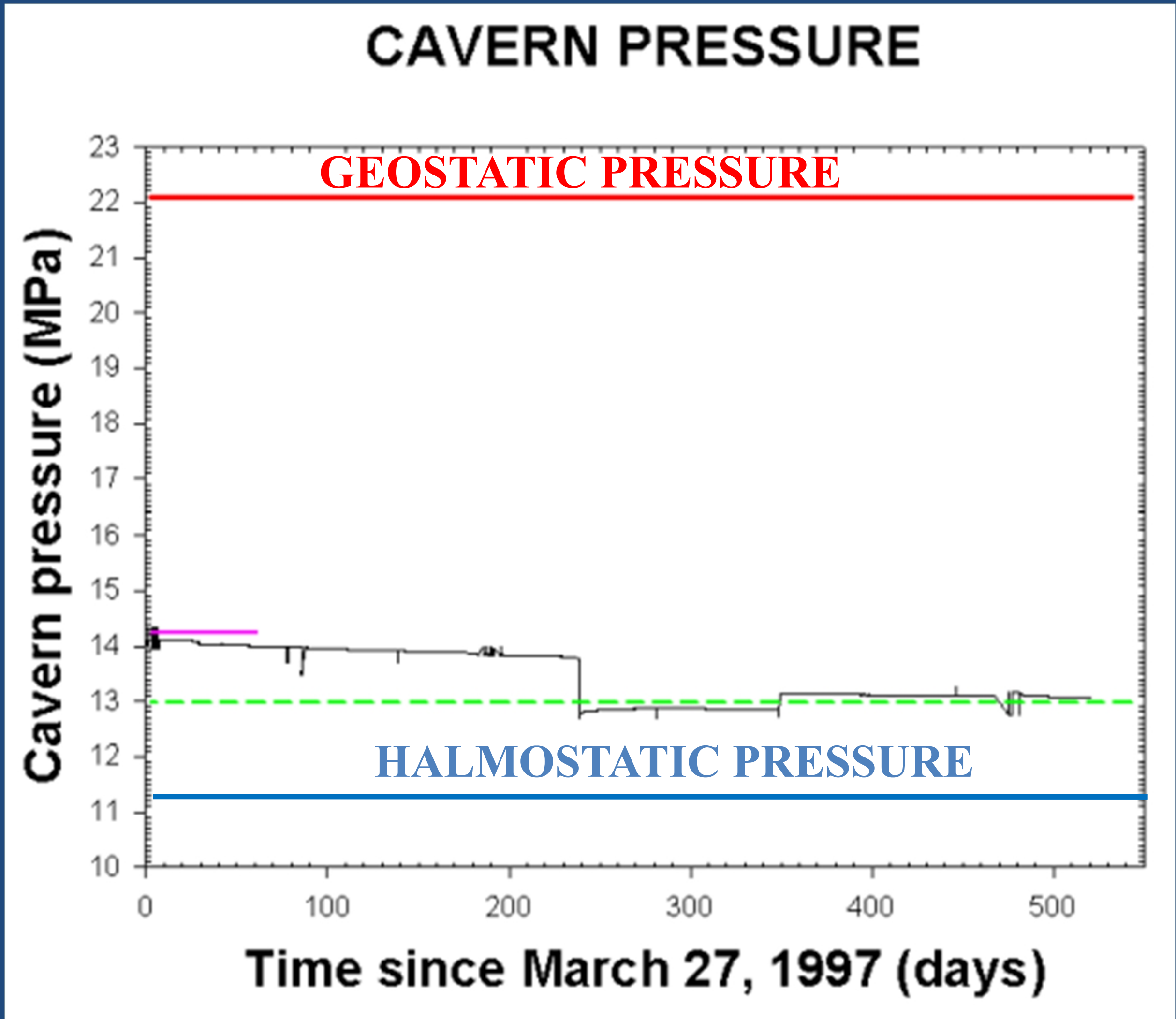
= Cavern Compressibility (βV_c) x Pressure Drop (ΔP)



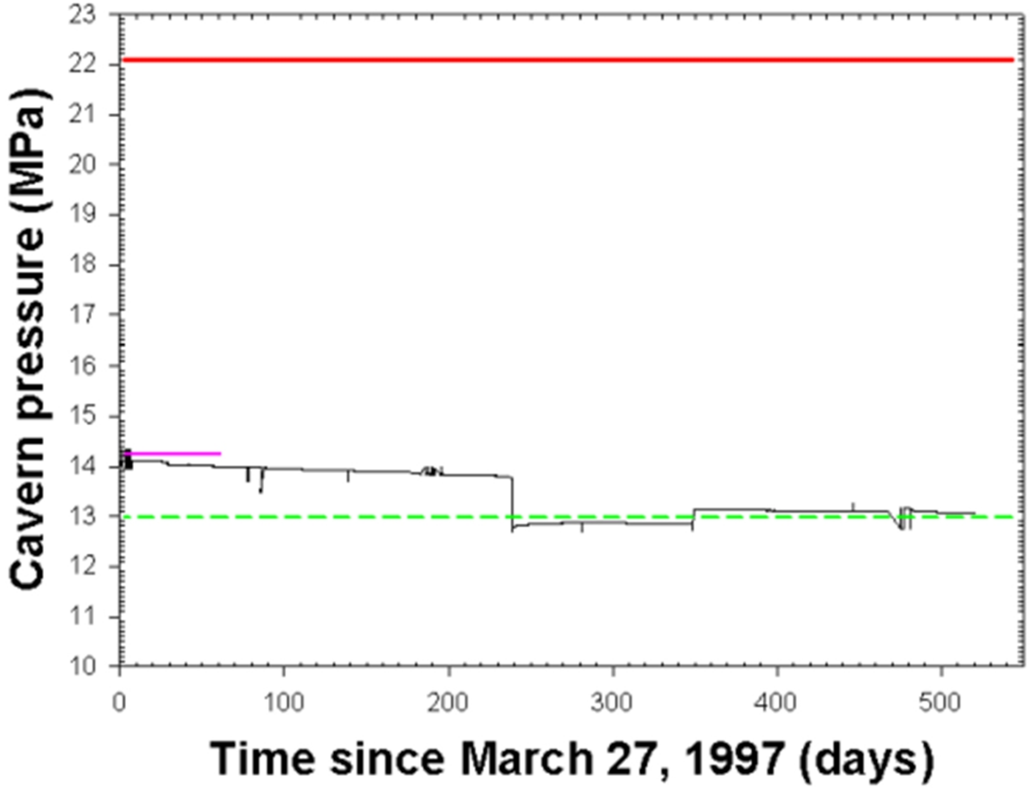


CAVERN PRESSURE
Cavern pressure (MPa)
23
22
21
20
19
18
17
16
15
14
13
12
11
10
0
100
200
300
400
500
Time since March 27, 1997 (days)

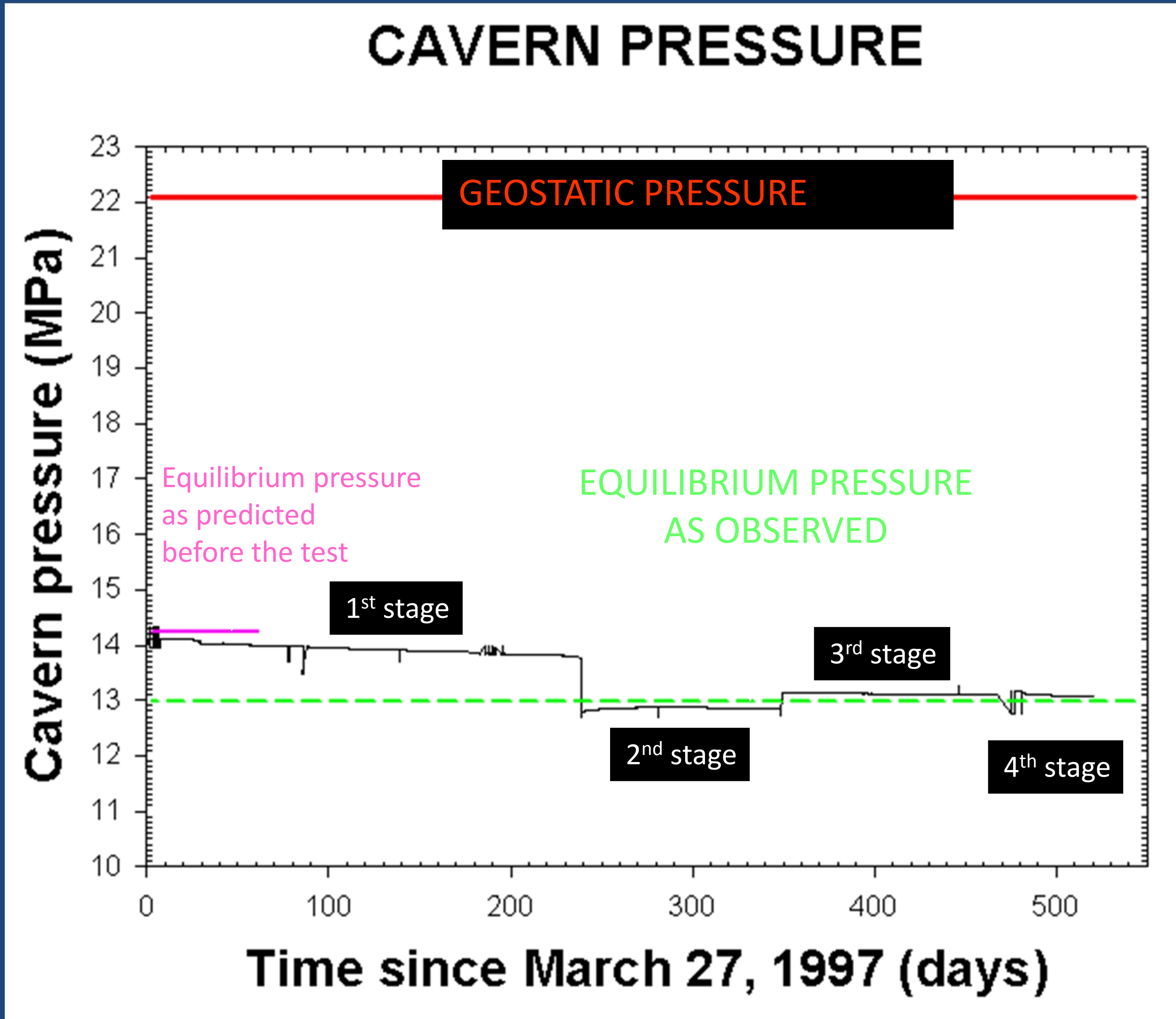

P
GEOSTATIC
Permeation flow rate
Peq
Creep closure rate
HALMOSTATIC
Q
P
GEOSTATIC
HALMOSTATIC
t


CAVERN PRESSURE
GEOSTATIC PRESSURE
HALMOSTATIC PRESSURE
Cavern pressure (MPa)
23
22
21
20
19
18
17
16
15
14
13
12
11
10
0
100
200
300
400
500
Time since March 27, 1997 (days)

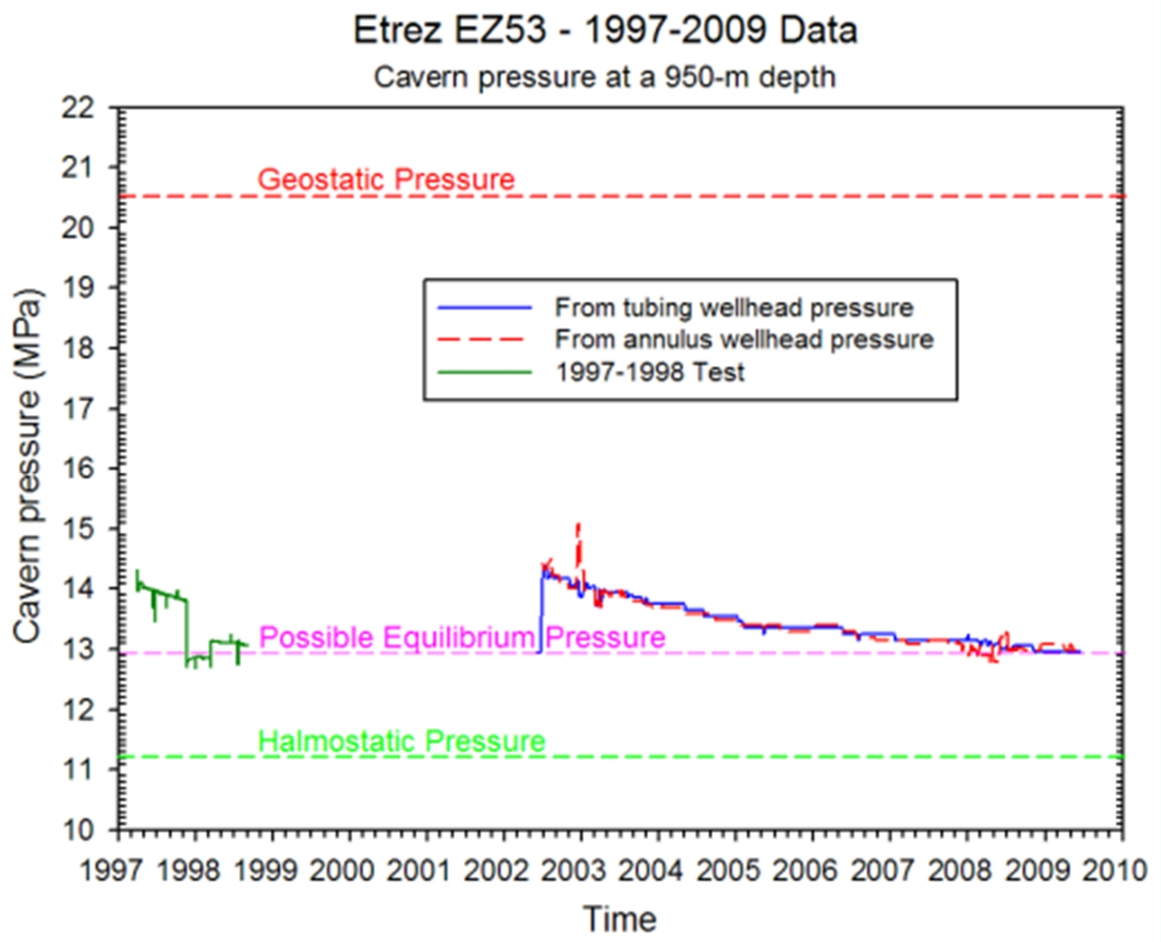
CAVERN PRESSURE



Résultats de l'essai EZ53

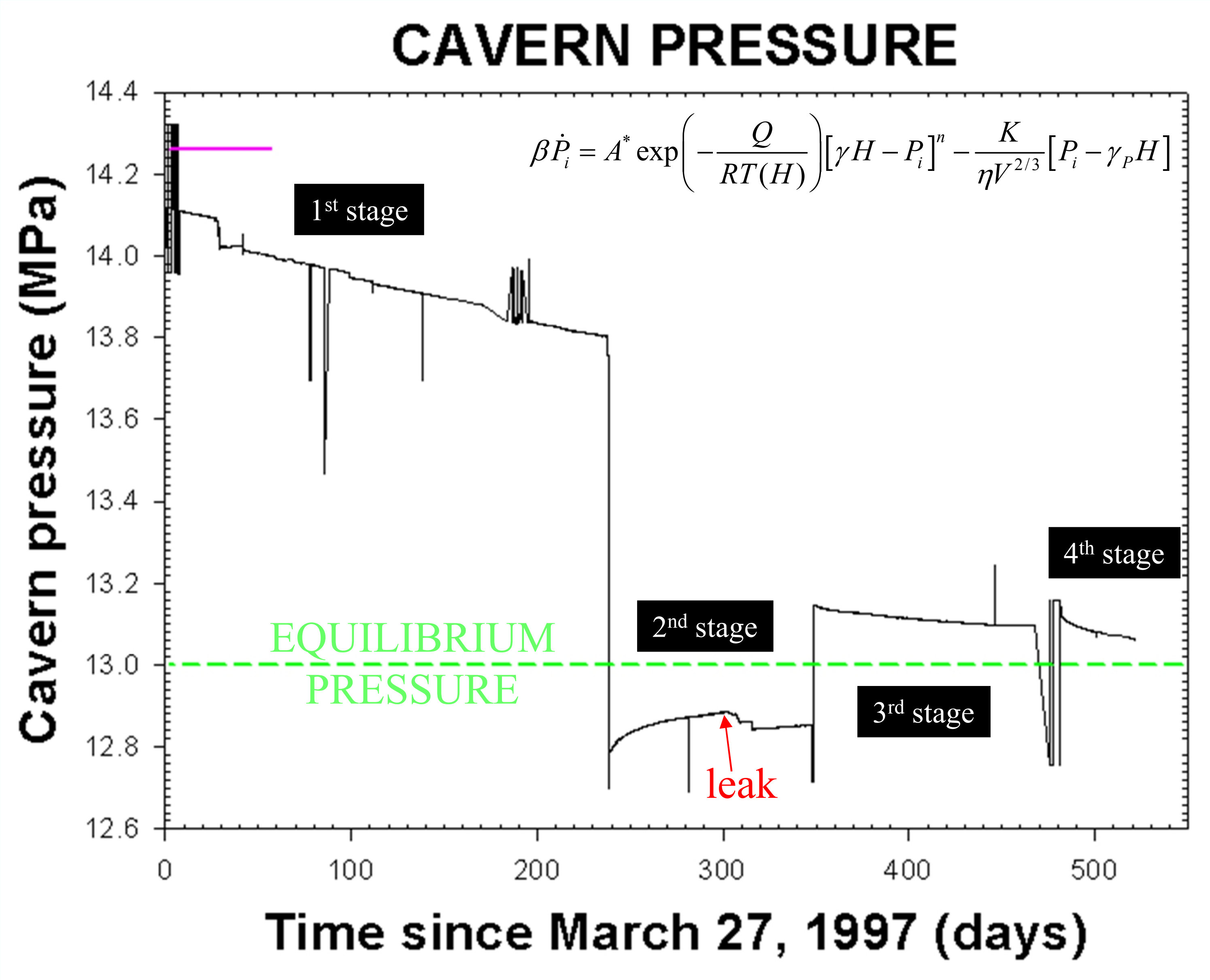


Gaz de France



Etrez EZ53 - 1997-2009 Data
Cavern pressure at a 950-m depth
Cavern pressure (MPa)
Time
Geostatic Pressure
Possible Equilibrium Pressure
Halmostatic Pressure
From tubing wellhead pressure
From annulus wellhead pressure
1997-1998 Test
10
11
12
13
14
15
16
17
18
19
20
21
22
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010

EZ53 TEST


CAVERN PRESSURE
$\beta \dot{P}_i = A^* \exp\left(-\frac{Q}{RT(H)}\right)[\gamma H - P_i]^n - \frac{K}{\eta V^{2/3}}[P_i - \gamma_P H]$
1st stage
2nd stage
3rd stage
4th stage
EQUILIBRIUM PRESSURE
leak
Cavern pressure (MPa)
14.4
14.2
14.0
13.8
13.6
13.4
13.2
13.0
12.8
12.6
0
100
200
300
400
500
Time since March 27, 1997 (days)