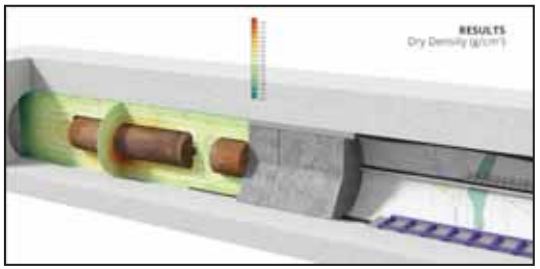
Modern2020



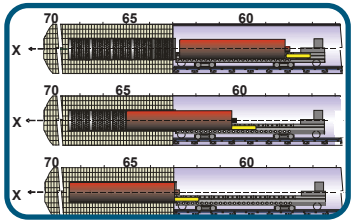
Monitoring the Full-scale Emplacement Experiment (FEBEX) over 18 years: lessons learned for future repository monitoring

Florian Kober & Jose Luis García-Siñeriz

Paris, 10 Apr 2019

FEBEX-DP Partners:

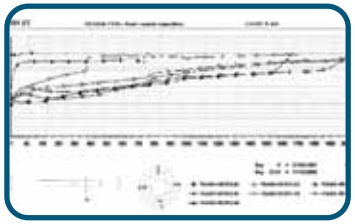
FEBEX objectives (back in 1994-1996)



Demonstration of the feasibility of handling and constructing an EBS in granitic host rock and a liner/ block concept at 100°C heater surface temperatures

- Check the "engineering soundness"

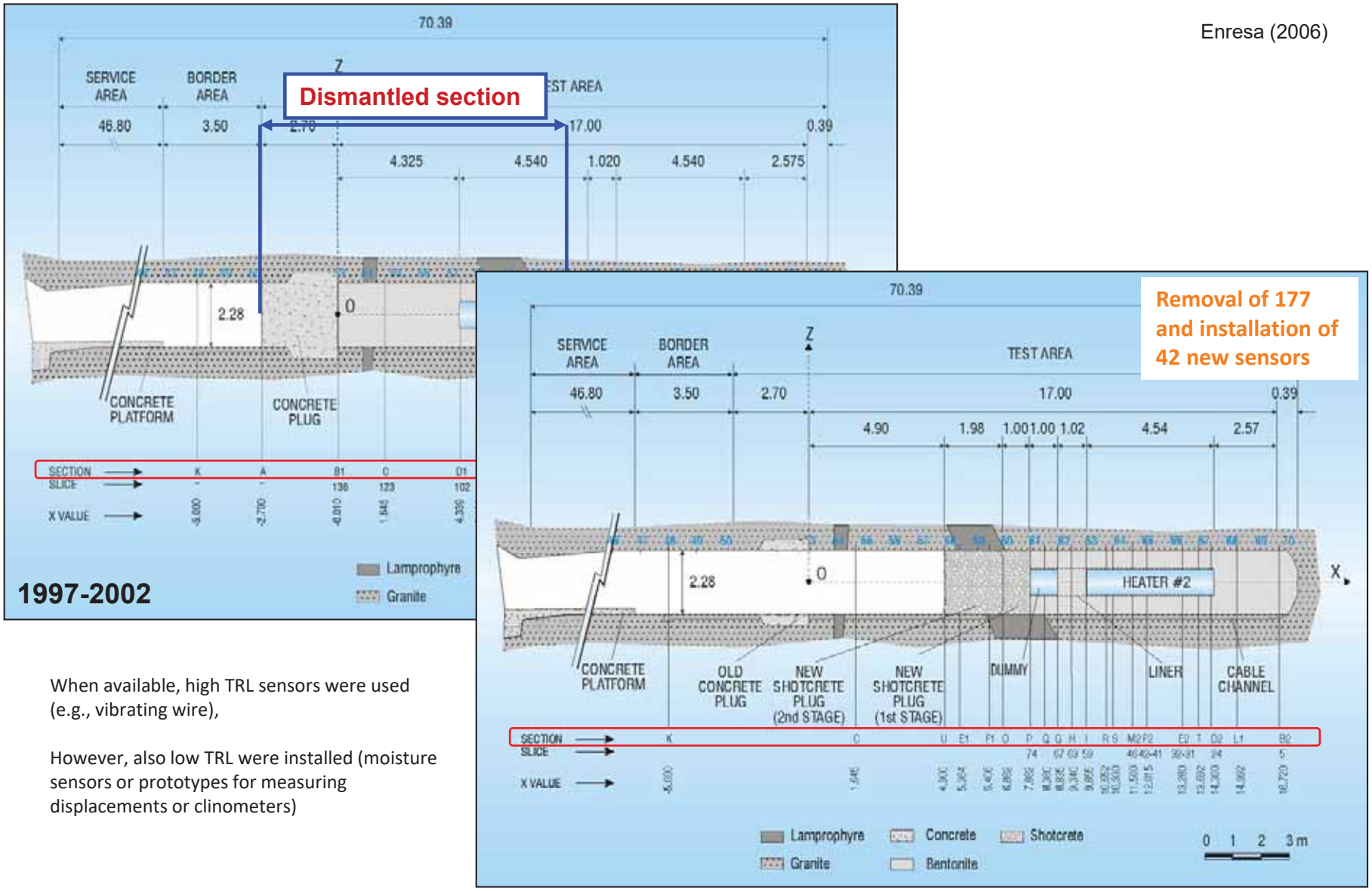
- Study under "natural conditions" the most relevant processes taking place in the early evolution of an EBS and its surroundings



- Study the thermo-hydro-mechanical (THM) and thermo-hydro-geochemical (THG) processes in the near-field by monitoring and modeling

FEBEX in situ – Partial (2002) & Final (2015) Dismantling

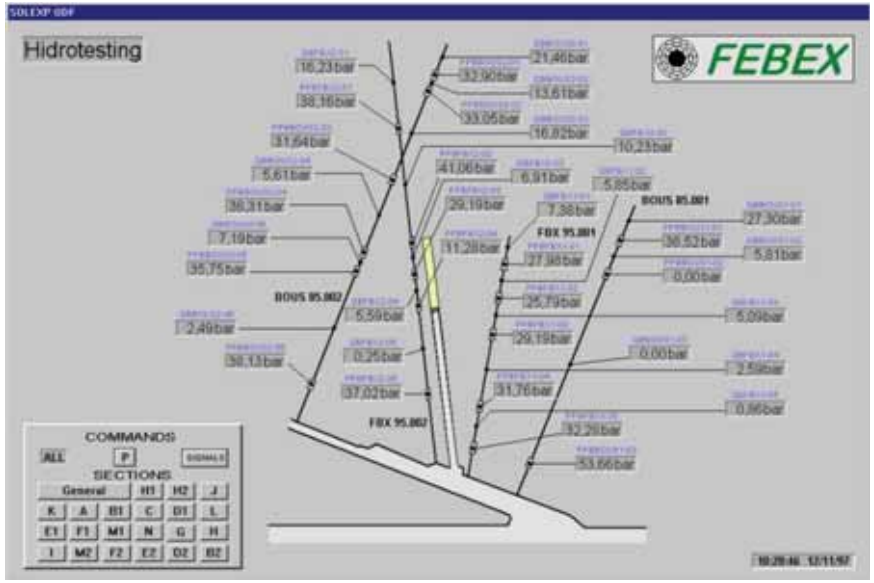
Enresa (2006)

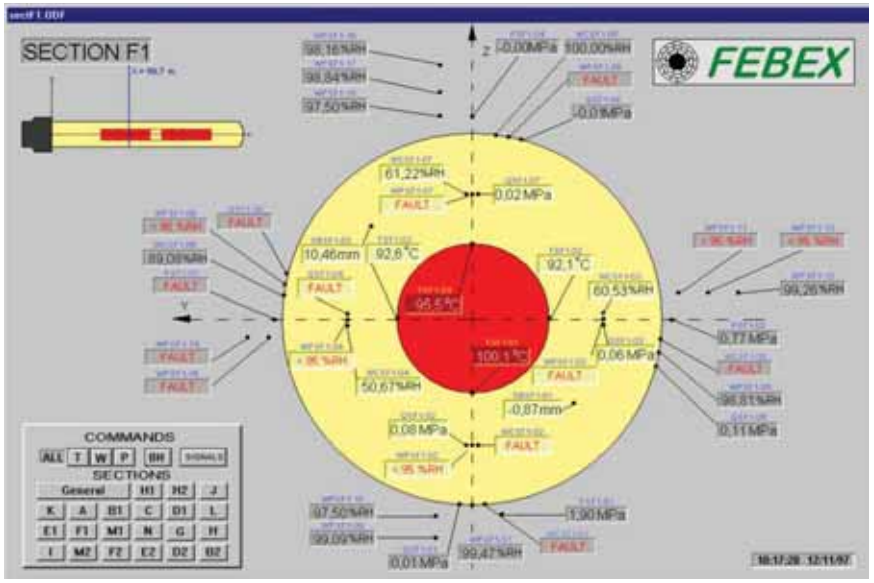


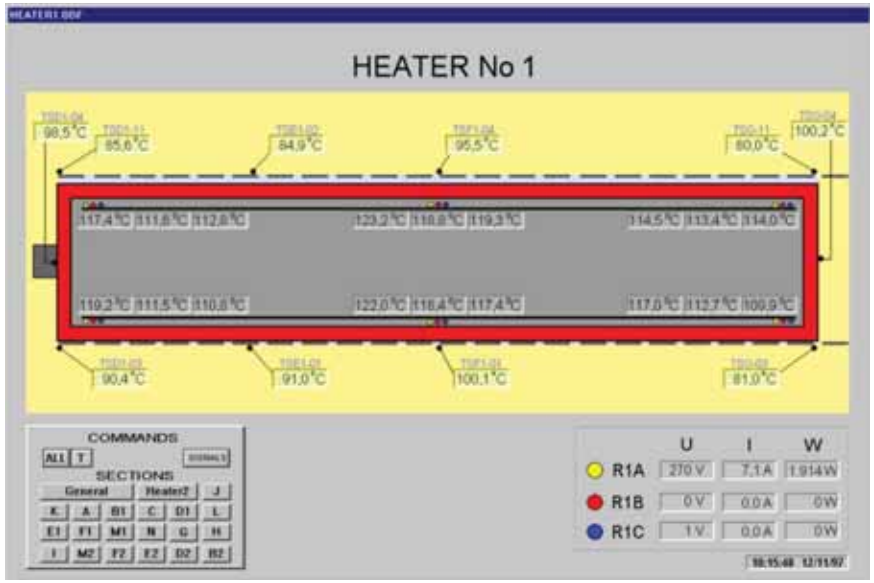
When available, high TRL sensors were used (e.g., vibrating wire),

However, also low TRL were installed (moisture sensors or prototypes for measuring displacements or clinometers)

FEBEX – The near and far field monitoring system

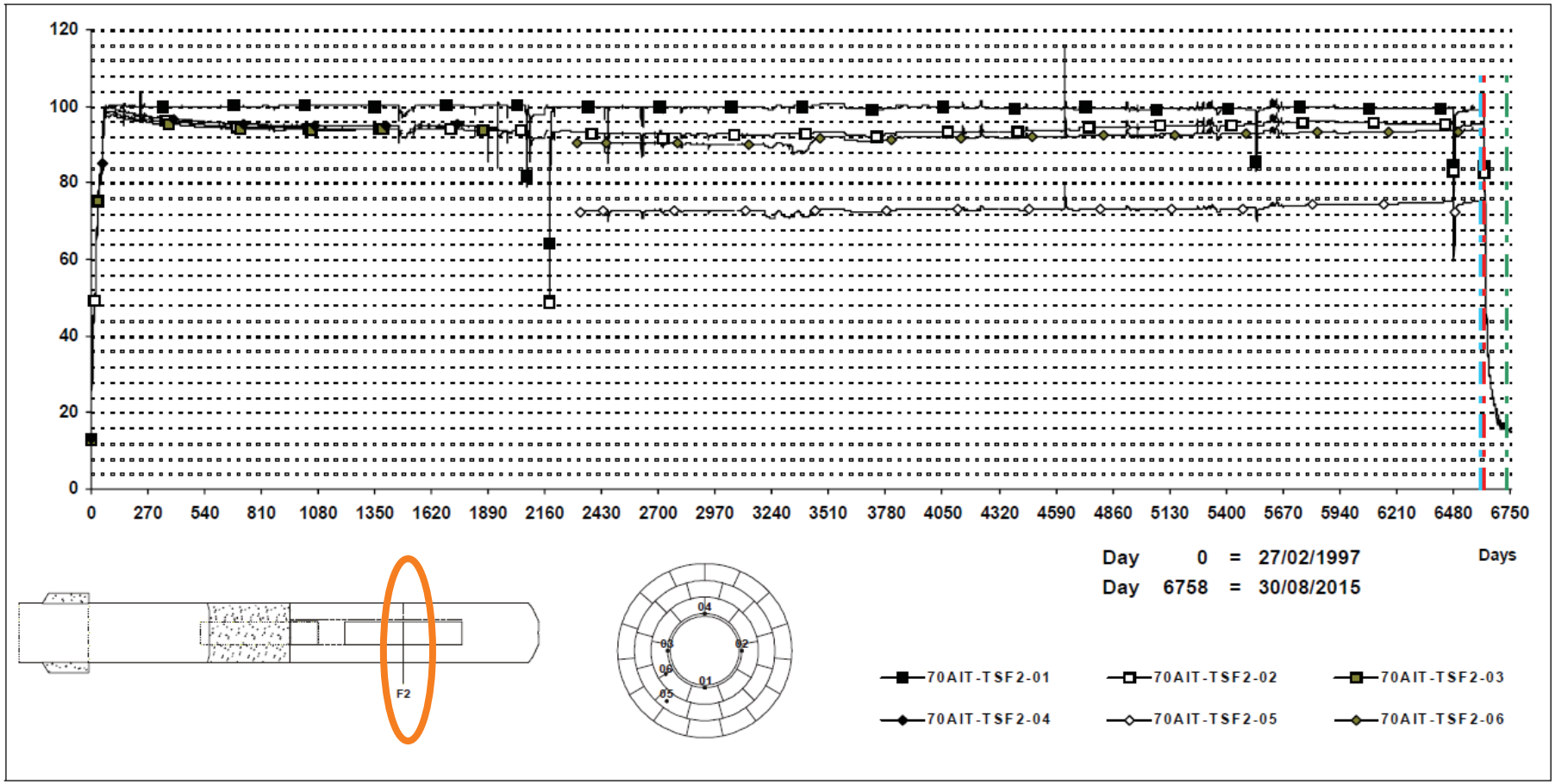






Parameter (or instrument)	Sensor type	Location area (1)				Total
		G	B	H	S	
Temperature	Thermocouple	62	91	36		189
Total pressure in rock matrix (3D)	Vibrating wire	4				4
Total pressure on drift rock surface	Vibrating wire	30				30
Total pressure on heaters/liners	Vibrating wire		6			6
Hydraulic pressure (rock boreholes)	Piezoresistive (2)	62				62
Packers pressure (boreholes)	Piezoresistive (2)	62				62
Pore pressure in bentonite	Vibrating wire		52			52
Humidity	Capacitive		58		1	59
Humidity	Psycrometers	28	48			76
Humidity	TDRs	4	20			24
Rock extensometers	Vibrating wire	2 x 3				6
Heaters displacements	Vibrating wire		9			9
Bent. blocks expansion/contraction	Vibrating wire		8			8
Buffer expansion/contraction	Potentiometer		2 x 3			6
Inclinometers	LVDT		6 x 2			12
Crack meter	LVDT	1 x 3				3
Gas pressure	Ceramic filter (2)		4			4
Gas flow	Ceramic filter (2)		6			6
Atmospheric pressure	Piezoresistive				1	1
Ventilation air flow	Hot wire				1	1
Heating elements current	Electrical converter				6	6
Heating elements voltage	Electrical converter				6	6
	TOTALS	261	320	36	15	632

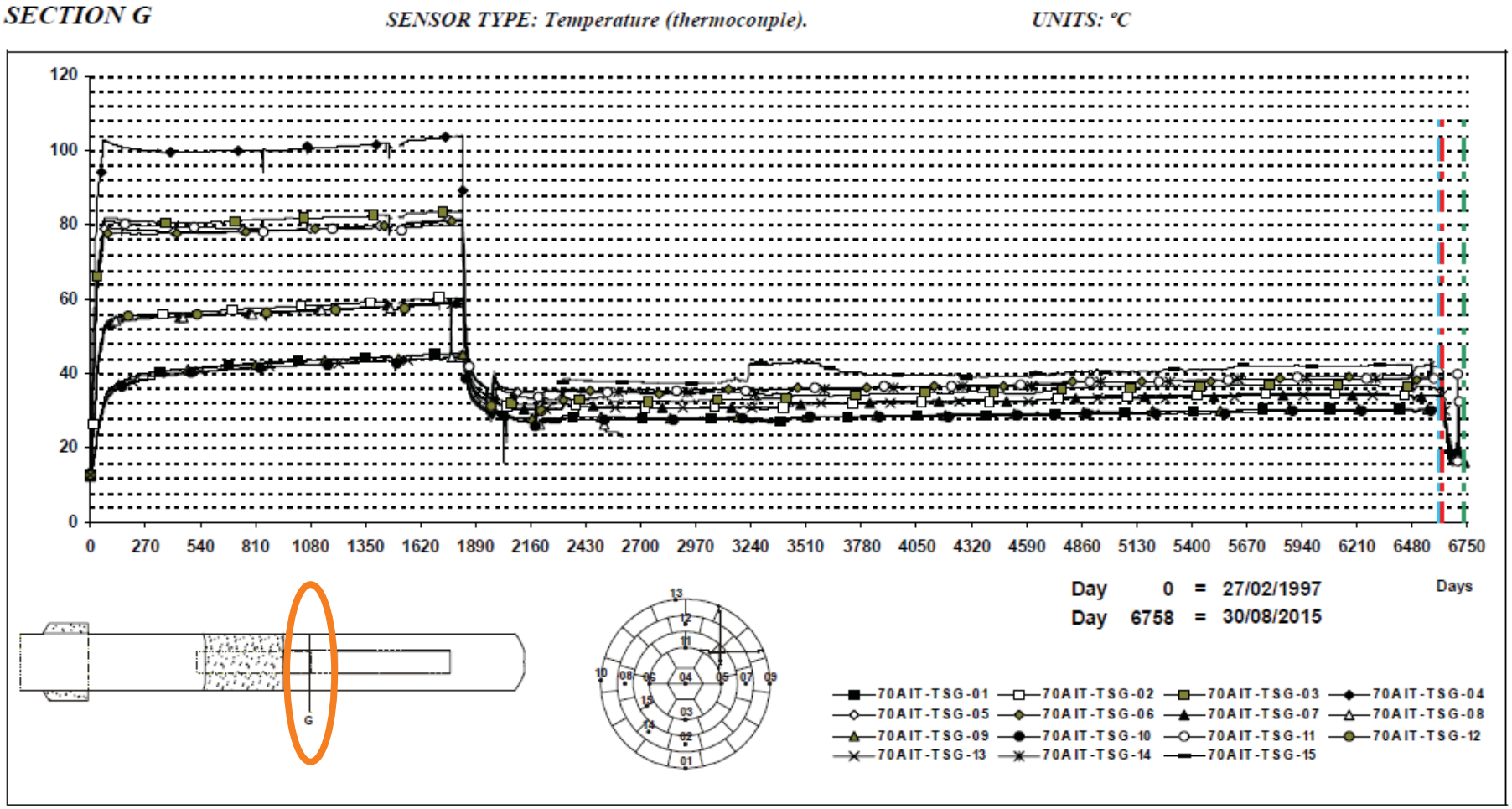
FEBEX-DP – Monitoring - Temperature



dashed vertical lines:
Blue: the start-up of the plug dismantling (day 6614)
Red: the heater switch off (day 6630)
Green: the end of the dismantling operation (day 6758)

NAB 16-019, Martinez et al. 2016, NAB 16-020, Rey et al. 2016

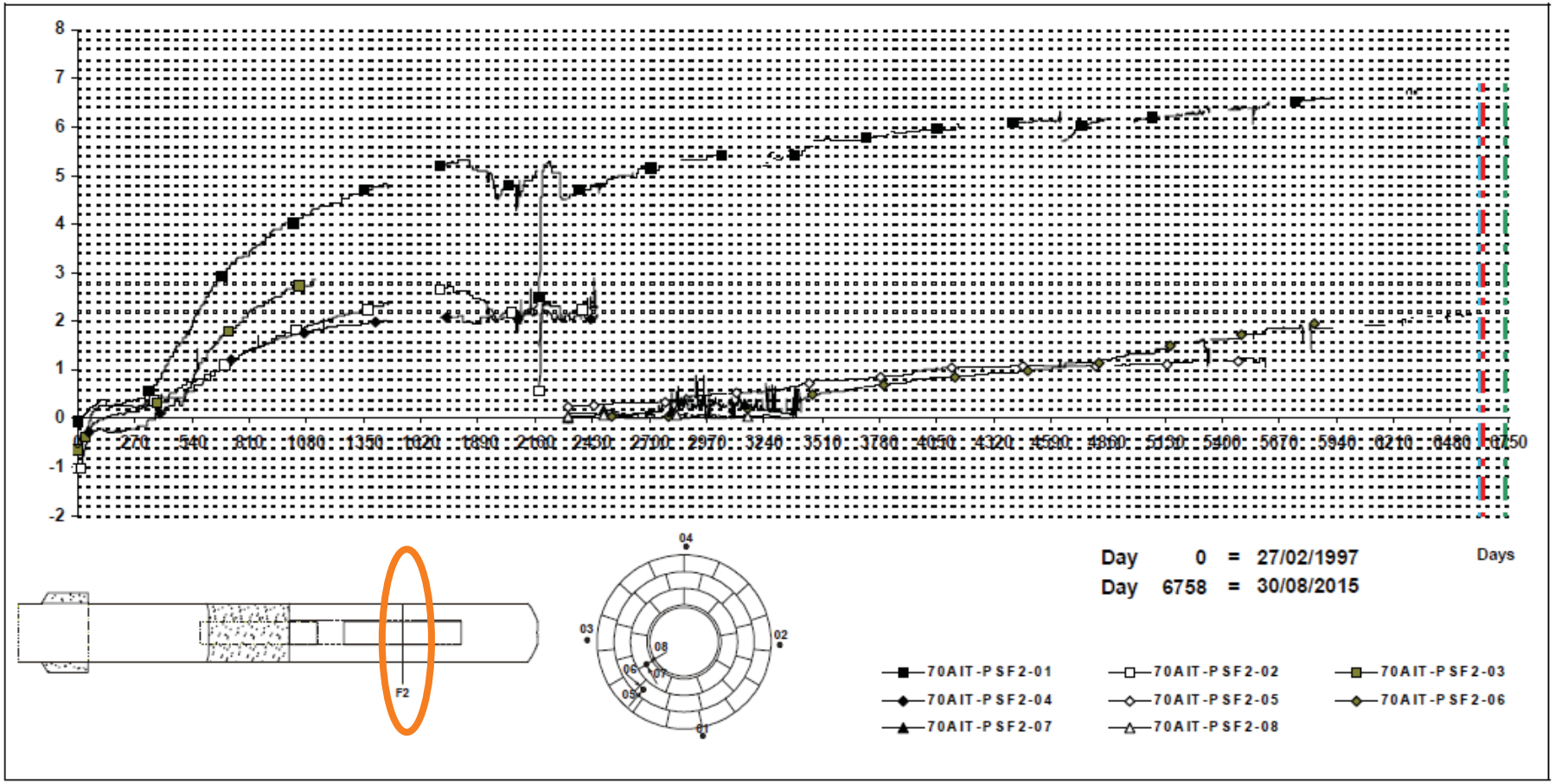
FEBEX-DP – Buffer state before Dismantling - Temperature



dashed vertical lines:
Blue: the start-up of the plug dismantling (day 6614)
Red: the heater switch off (day 6630)
Green: the end of the dismantling operation (day 6758)

NAB 16-019, Martinez et al. 2016, NAB 16-020, Rey et al. 2016

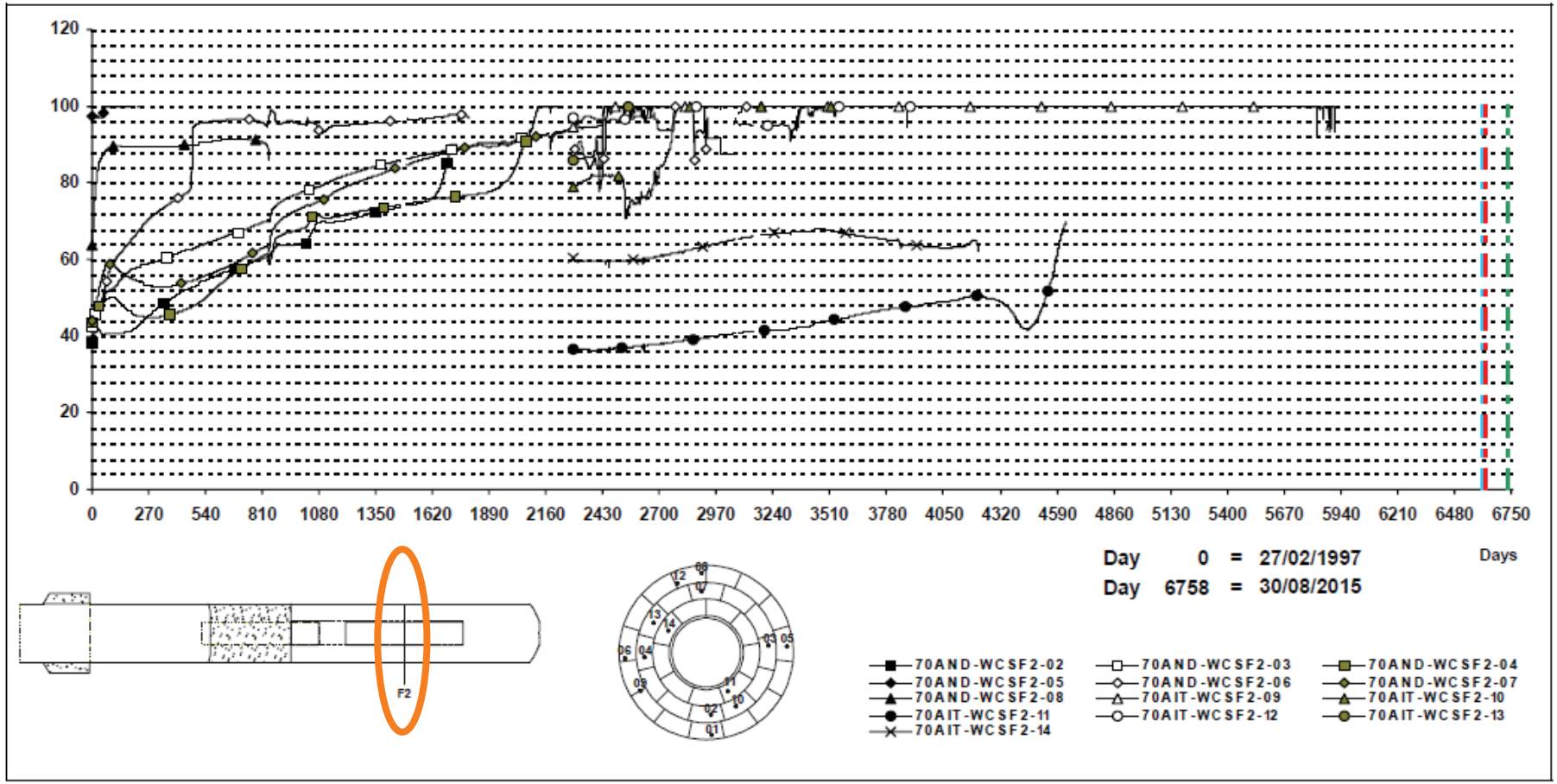
FEBEX-DP – Monitoring - Total Pressure



dashed vertical lines:
Blue: the start-up of the plug dismantling (day 6614)
Red: the heater switch off (day 6630)
Green: the end of the dismantling operation (day 6758)

NAB 16-019, Martinez et al. 2016, NAB 16-020, Rey et al. 2016

FEBEX-DP – Monitoring - Relative Humidity

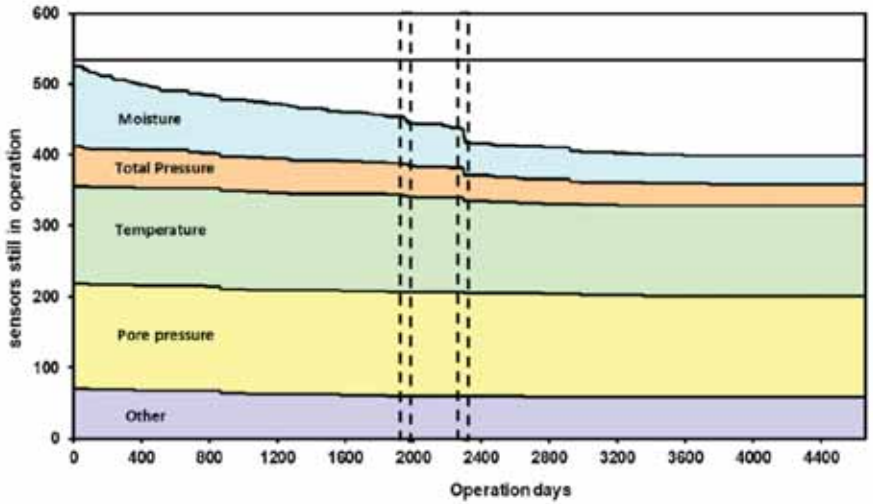


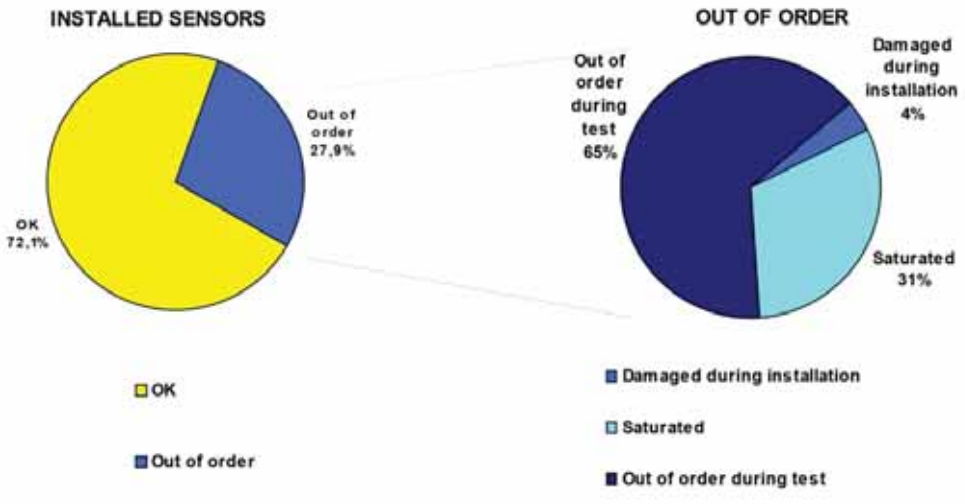
NAB 16-019, Martinez et al. 2016, NAB 16-020, Rey et al. 2016

4.- Sensors during FEBEX-DP Dismantling

Bentonite buffer (section 41)

FEBEX – Sensor status after 18 years





In general, sensors

- were in better shape than the ones from the first dismantling, showed less corrosion or mechanical damages
- displayed no noticeable changes in sensors location
- were affected by mechanical effects due to bentonite swelling (especially close to rigid surfaces)
- the ceramic filters of the psychrometers measuring head were quite fragile
- the plastic material of cables significantly degraded

→ **widely overpassed the initially expected operative lifetime of six months**, majority of the sensors survived under harsh conditions and provided valuable and reliable information about the THM parameters over 18 years

Results: Retrieved Sensor - status

Type	Retrieved	Out of Order	Causes			
			Saturated	Flooded	Mechanical	Broken. Cable
T (bentonite)	54	15			15	
T (heater)	18	2*			2	
T (Inst. pipe)	8	0				
P (Pz, plug)	2	2		2		
P (Pz, Inst. pipe)	8	5*			5	
P (VW)	6	3			3	
Q	28	11				11
WC (bentonite)	34	34	20	11		3
WC (Inst. pipe)	18	12*	12			
WP	24	19	8			11
WT	10	3			1	2
SH	7	6			6	
SB	4	3			3	
3S	3	3		3		
S	4	0				
Total	**228**	**99**	**40**	**16**	**35**	**27**
%	100,00%	43,42%	40,40%	16,16%	35,35%	27,27%
	* Not analysed at laboratory					

García-Siñeriz et al. 2019

Instrumentation – sensor type conclusions (1)

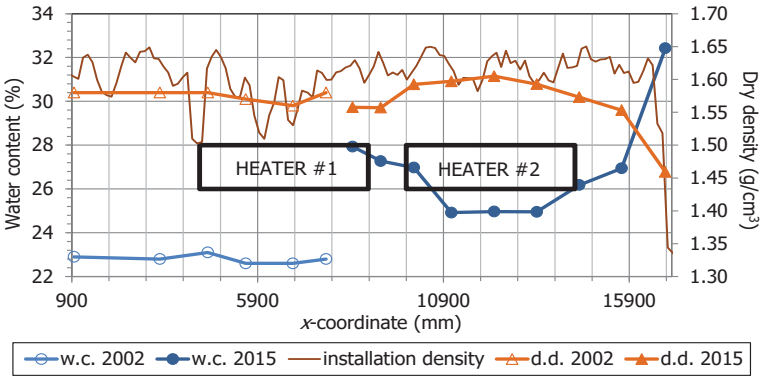
- Vibrating wire type: they showed to be robust and most of them remained operative – problems with cable entries → loss of flexibility of plastics with time combined with the differential movements cable/metal body
- Prototypes of new sensors: they need of further improvement (mechanical protection and water isolation)

Instrumentation – sensor type conclusions (2)

- Sensors that measure in a chamber isolated by a filter: they become damaged over time by water flooding, salts deposition and bentonite intrusion leading to corrosion and mechanical breakage
- Long body sensors: they showed clear deformations due to the bentonite swelling making them inoperative with time
- In general: the plastic material used for the cables were not good enough; many of them were significantly degraded, lost their initial properties and were damaged. The effects of corrosion in metals were in general negligible and not a relevant cause of malfunctioning.

FEBEX - Performance Assessment

Safety relevant aspect	FEBEX information
Low hydraulic conductivity	Properties not altered, diffusion dominated (<10^{-13} m/s)
Chemical retention of RN	Sorption properties unlikely altered
Resistance to mineral transformation	No significant transformations detected
Sufficient density	Density gradients, mean 1.59 g/cm^3
Sufficient swelling pressure	~6 MPa (for 1.6 g/cm^3); lab-scale confirmed in 1:1 exp.
Mechanical support	Sufficient support
Minimise microbial corrosion	No indication of MIC on canister or instruments
Sufficient heat conduction	Confirmed



	w (%)	ρ_d (g/cm^3)	S_r (%)
1997	14.4	1.59 (Heater 1), 1.61 (Heater 2) (uncorrected: 1.69)	55
2002	22.2	1.58	85
2015	25.5	1.59	97

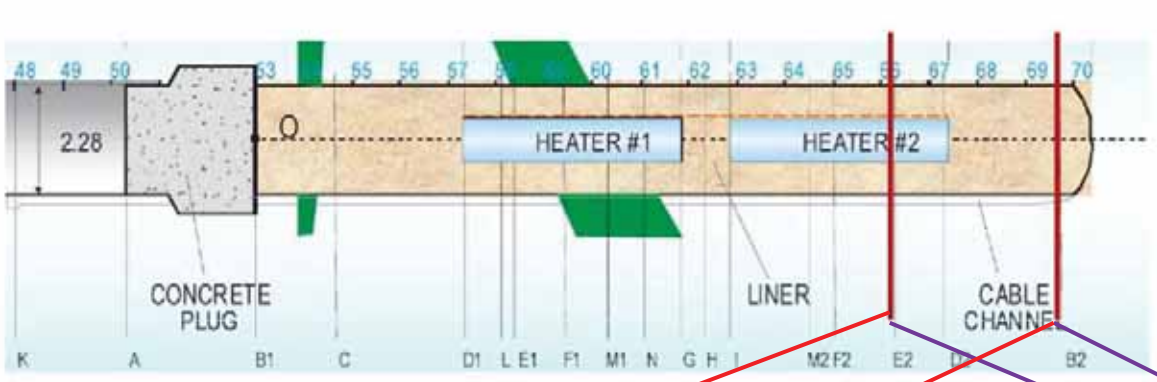
→ **Direct / indirect information by monitoring during and postmortem the experiment**

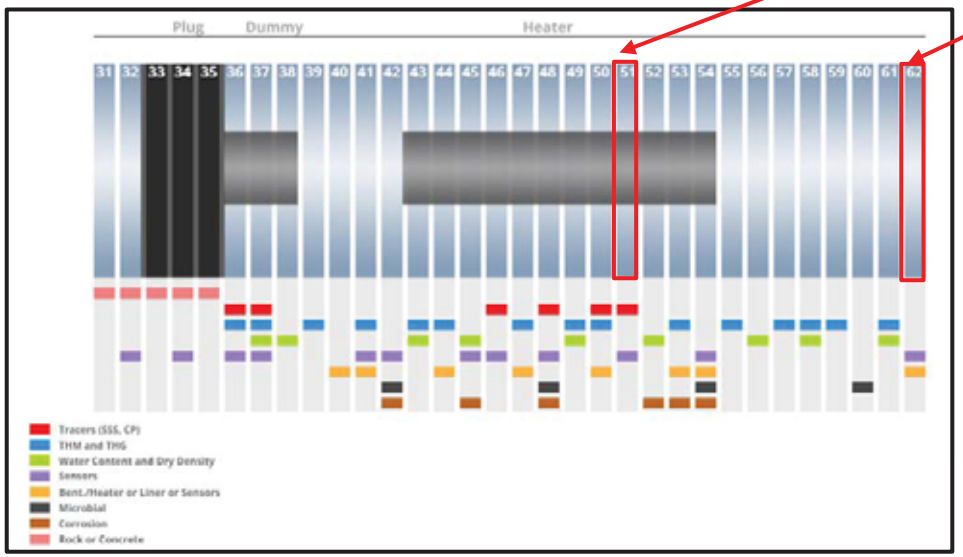
→ FEBEX-DP (19 reports) reporting available under www.grimsel.com → FEBEX-DP; numerous papers (coming out)

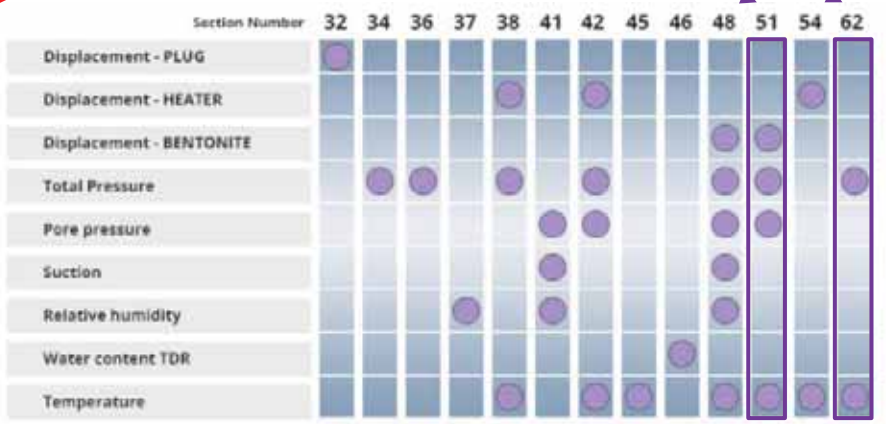
FEBEX – Modelling within Decovalex/EBS Task Force

TASK: total stress

ONGOING !







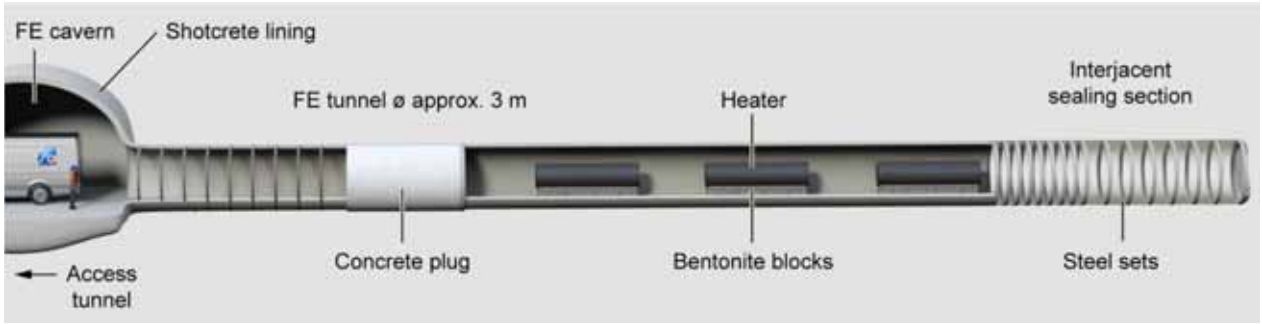
Future directions of monitoring

- Increased temperature loading (threshold reached of current TRL of sensors)
- Potential presence of radiation
- Higher mechanical and water pressures
- Long cable routing due to real scale gallery type emplacement tests
- Combination and miniaturization of sensors
- Housing of sensors and sensor connections in unfavorable positions over long timescales
- Integration in wireless solutions or MEMs (microelectromechanical system) sensors
- Remote charging and logging in case of wireless transitions with limited experience
- Demands of monitoring chemical and gas evaluation
- Increasing of new Fiber Optics based solutions, which provide multipoint measurements and large amounts of data to be processed
- Variations in buffer type (bentonite based: pellets, blocks, mixed assemblies or bentonite/cement or cement based)
- Time: requirements and demands change over decades of monitoring and developments in WMO programs and performance assessments
- Cost optimization in experiments using as little as possible but as many as necessary sensors
- Introduction of “Big Data” solutions to handle and manage the increasing amount of data to be gathered

Ongoing & Future (Monitoring)

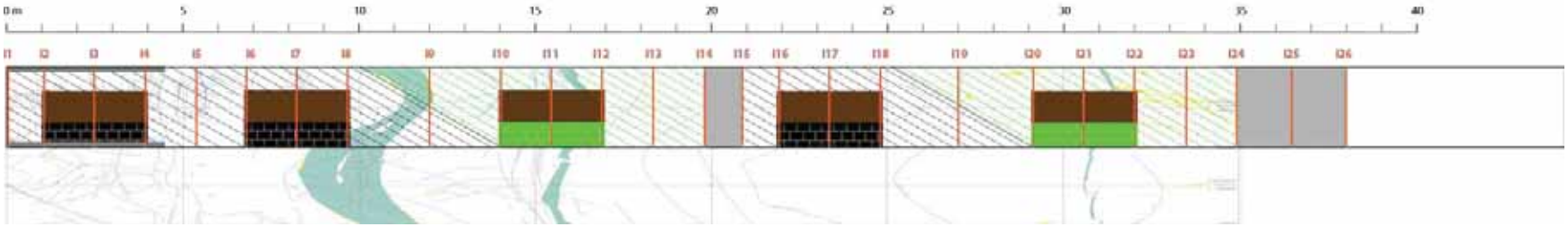
FE at FMT – running since Dec 2014

→ 3 heaters at ~130°C, Wyoming bentonite (blocks & GBM)



HotBENT at GTS – Maxi variant (under discussion)

→ 5 heaters at 175 to 200°C, for 5 to 20+ years, 2 bentonites (blocks & GBM)



thank you
for your attention

nagra.