2nd International Conference on Monitoring in Geological Disposal of Radioactive Waste, Session 8, 10th of April 2019, Paris

Lessons learned after more than 7 years of monitoring the Full-Scale Emplacement (FE) Experiment at the Mont Terri URL

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* Project Manager of the planning & implementation phase

** Project Manager of the monitoring phase

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International cooperation

- Implementation of the **Full-Scale Emplacement (FE) Experiment** @ Mont Terri underground rock / research laboratory (URL)
  - Initiator and lead: NAGRA (Switzerland)
  - Partner organisations:
    - ANDRA (France)
    - BGR (Germany)
    - DOE (U.S.A.)
    - GRS (Germany)
    - NWMO (Canada)

Mont Terri Project

- For selected tasks the FE Experiment was Nagra's participation in the EURATOM (7th framework programme) project **Large Underground Concept Experiments (LUCOEX)**
  - Partners in this EU project:
    - ANDRA (France)
    - NAGRA (Switzerland)
    - POSIVA (Finland)
    - SKB (Sweden)

Selected references

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- Garitte B., Weber H.P. and Müller H.R. (2015): Requirements, manufacturing and QC of the buffer components. Nagra Working Report NAB 15-24, Wettingen, Switzerland and EU Project LUCOEX Deliverable D2.3 www.lucoex.eu
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- Köhler S., Garitte B., Weber H.P. and Müller H.R. (2015): FE/LUCOEX: Emplacement report. Nagra Working Report NAB 15-27, Wettingen, Switzerland and EU Project LUCOEX Deliverable D2.5
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- Müller H.R., Garitte B., Vogt T., Köhler S., Sakaki T., Weber H., Spillmann T., Hertrich M., Becker J.K., Giroud N., Cloet V., Diomidis N., Vietor T. (2017): Implementation of the full-scale emplacement (FE) experiment at the Mont Terri rock laboratory. Swiss Journal of Geosciences, 110 (2017), pp. 287-306, https://doi.org/10.1007/s00015-016-0251-2
- Giroud N., Tomonaga Y., Wersin P., Briggs S., King F., Vogt T. and Diomidis N. (2018): On the fate of oxygen in a spent fuel emplacement drift in Opalinus Clay. Applied Geochemistry, 97 (2018), pp. 270-278, https://doi.org/10.1016/j.apgeochem.2018.08.011
- Firat Lüthi B. (2018): Full-Scale Emplacement (FE) Experiment - Data Trend Report - Data covering: excavation and 3 first years of heating: 01.01.2012 - 31.08.2018. Nagra working report NAB 18-39, Nagra, Wettingen, Switzerland.
- Nagra (2019, in preparation): Implementation of the Full-scale Emplacement Experiment in Mont Terri: Design, Construction and Preliminary Results. Nagra Technical Report NTB 15-08, Nagra, Wettingen, Switzerland.

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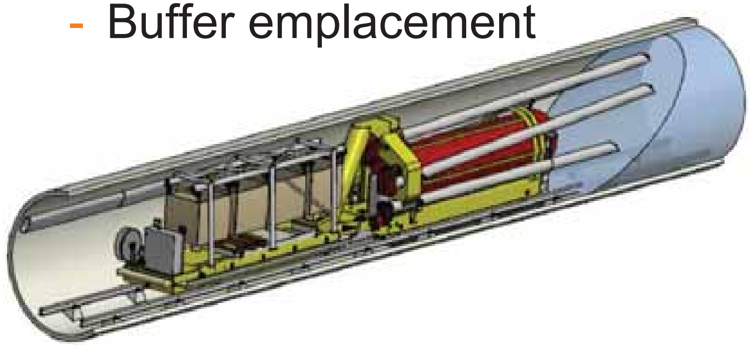
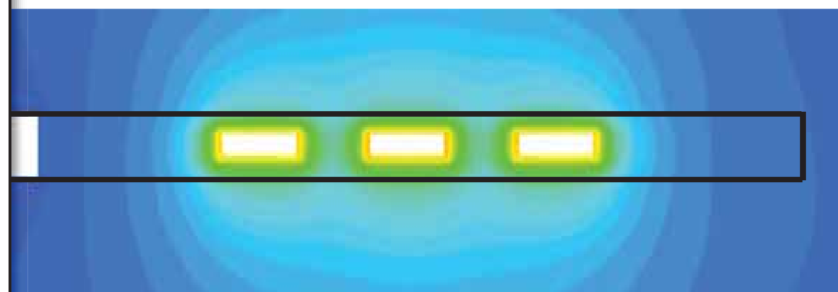
Main aims of the FE Experiment

❷ Simulation of construction and emplacement techniques
- Tunnel construction
- Bentonite buffer production
- Buffer emplacement



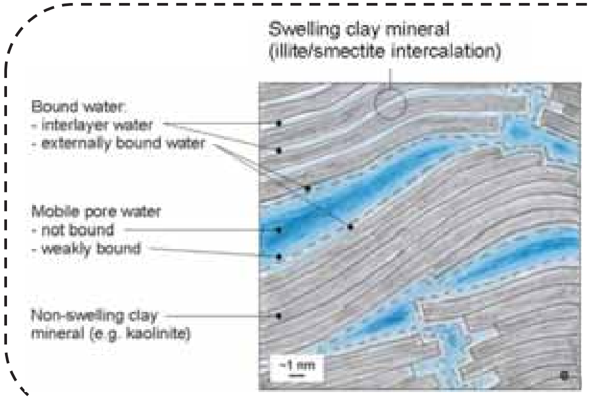
- Participation in EU project **Large Underground Concept Experiments**

- 1:1 full-scale heater experiment (according to Swiss SF / HLW concept) @ Mont Terri URL

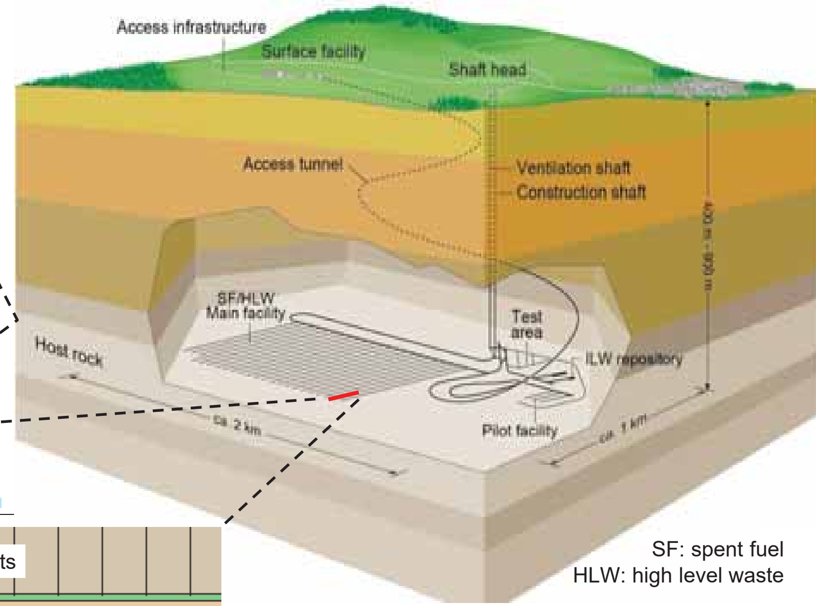


❶ Investigation of repository induced thermo-hydro-mechanical (THM) coupled effects on the host rock

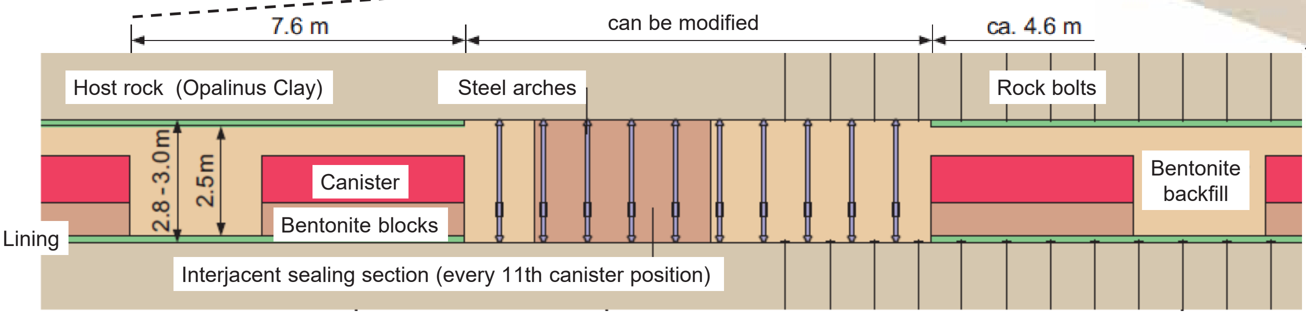
Repository concept → experimental layout



Host rock:
Opalinus Clay
over-consolidated
clay stone sedimented
approx. 175 Ma ago

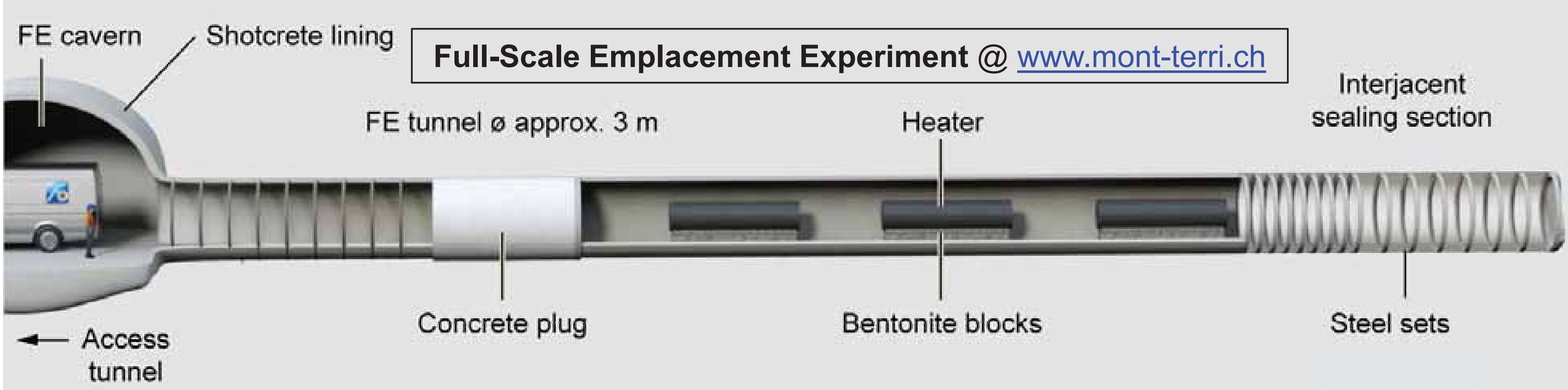


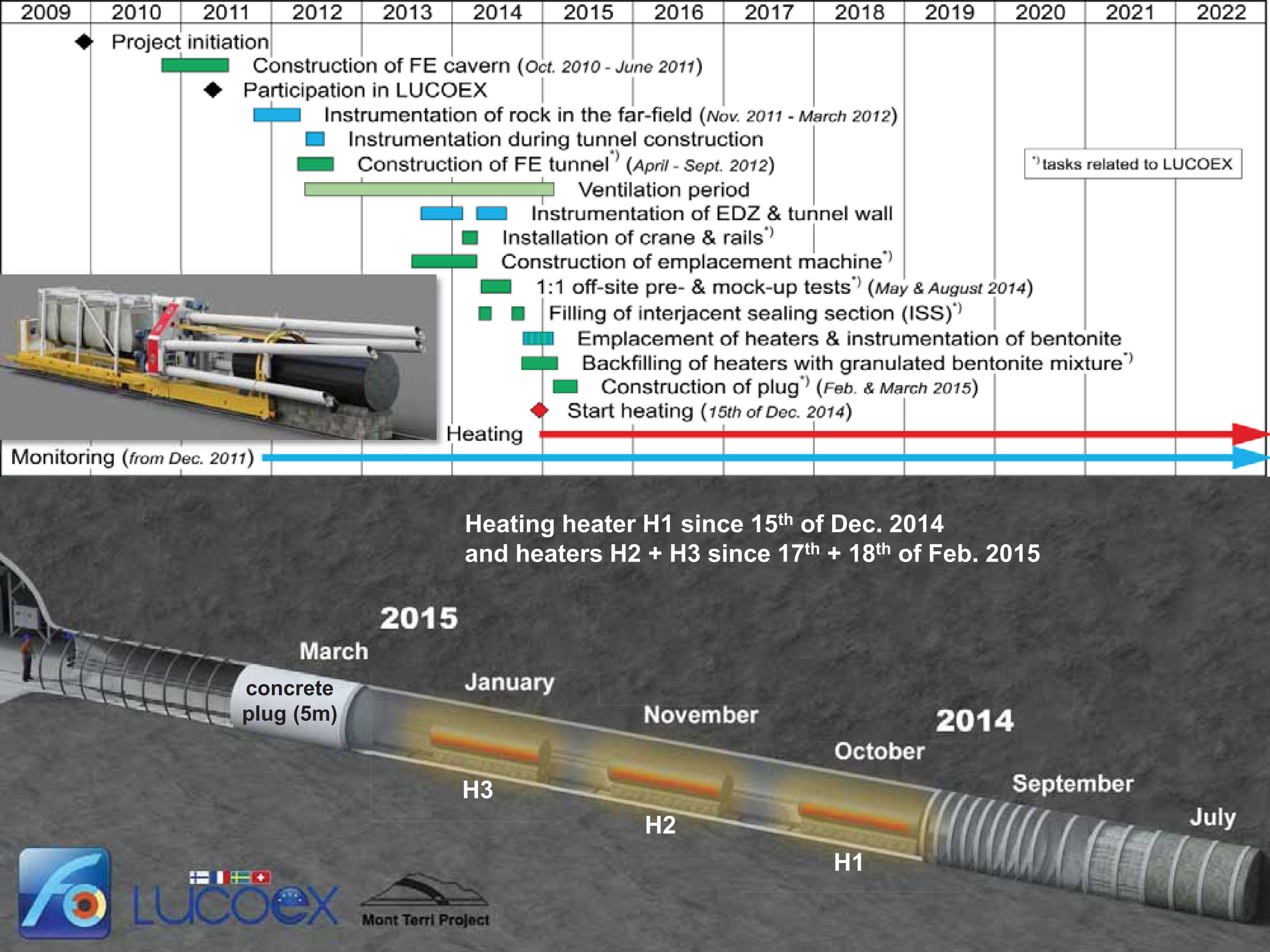
SF: spent fuel
HLW: high level waste



Longitudinal section of a **SF/HLW repository tunnel** according to the Swiss concept (cf. NTB10-01)

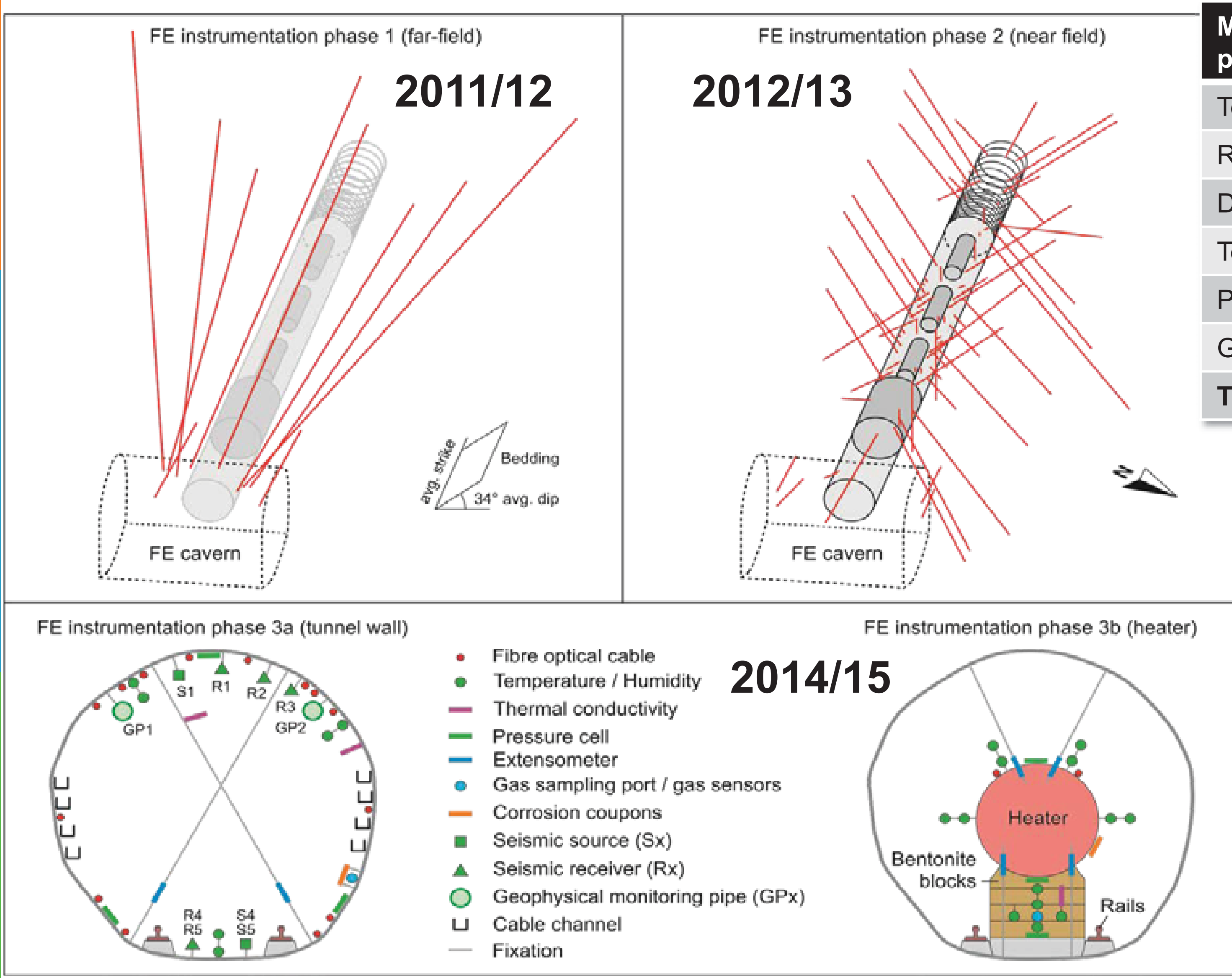
Full-Scale Emplacement Experiment @ www.mont-terri.ch





2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
Project initiation
Construction of FE cavern (Oct. 2010 - June 2011)
Participation in LUCOEX
Instrumentation of rock in the far-field (Nov. 2011 - March 2012)
Instrumentation during tunnel construction
Construction of FE tunnel*) (April - Sept. 2012)
*) tasks related to LUCOEX
Ventilation period
Instrumentation of EDZ & tunnel wall
Installation of crane & rails*)
Construction of emplacement machine*)
1:1 off-site pre- & mock-up tests*) (May & August 2014)
Filling of interjacent sealing section (ISS)*)
Emplacement of heaters & instrumentation of bentonite
Backfilling of heaters with granulated bentonite mixture*)
Construction of plug*) (Feb. & March 2015)
Start heating (15th of Dec. 2014)
Heating
Monitoring (from Dec. 2011)
Heating heater H1 since 15th of Dec. 2014
and heaters H2 + H3 since 17th + 18th of Feb. 2015
2015
March
concrete plug (5m)
January
November
2014
October
September
July
H3
H2
H1
LUCOEX
Mont Terri Project

Instrumentation



Measurement points / sensors	TOTAL
Temperature	1'200
RH, TDR, etc.	173
Deformation	147
Total pressure	72
Porewater press.	65
Gas composition	20
TOTAL	**1677**

Not listed:
- geophysical sensors
- thermal conductivity sensors
- some TDR cables
- plug instrumentation
- fibre optical systems
  → *Presentation by Tobias Vogt*
- water and gas sampling lines
- etc.

for details see Müller et al. (2017)

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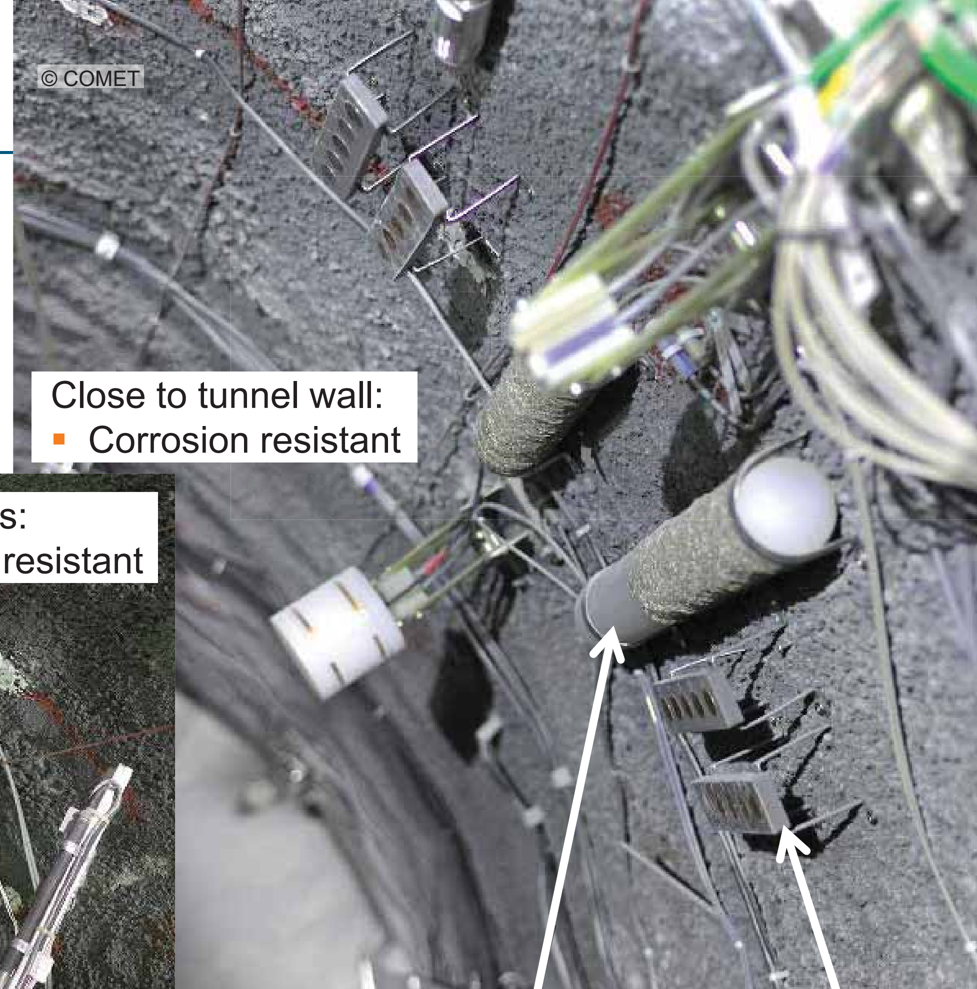
Instrumentation

- Measurements at different depths
- Foldable sensor holders to avoid space conflict with backfilling machine
- Withstand backfilling pressure
- Minimal (e.g. thermal) disturbance



- In-situ gas sensors (oxygen, hydrogen) & gas sampling lines
- Samples of different metal allowing corrosion measurements in the future in case of a potential dismantling

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FE experiment: System behaviour

- **Challenging monitoring conditions**
- **Testing sensors** under repository-like conditions
- **Scoping calculations** used for sensor choice and spacing, setting measurement range, etc.
- Regarding the THM behaviour the system evolves **as expected and predicted**
- **Broad spectrum of sensors** very valuable

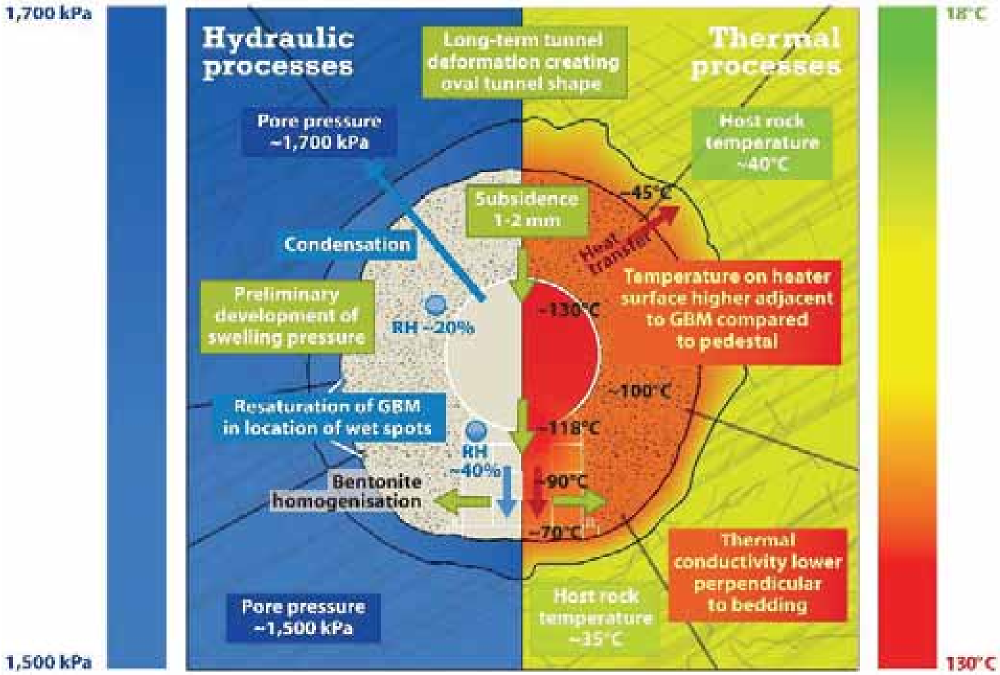
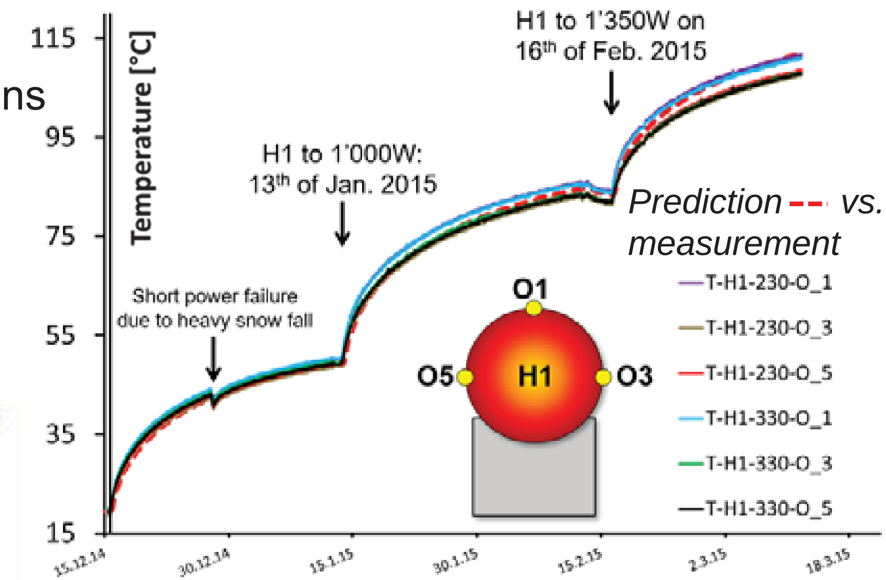
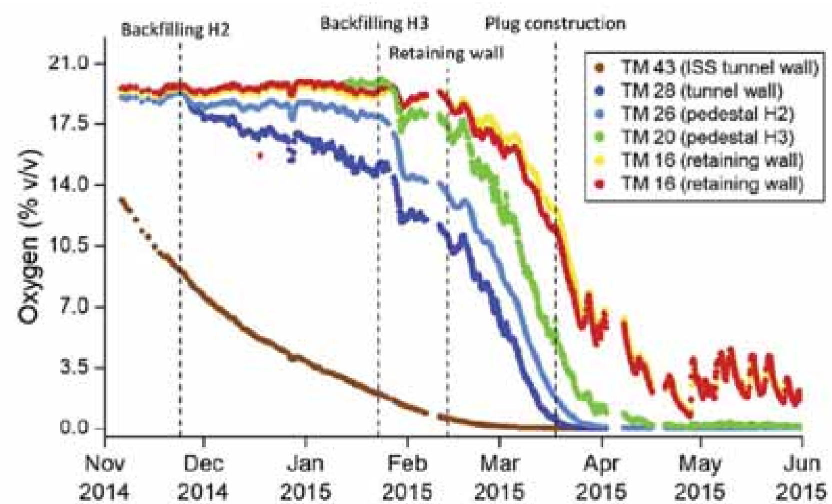


Illustration of the THM processes in the FE Experiment during heating according to NTB15-02 (in prep.)





Gas monitoring in backfilled tunnel (cf. Giroud et al. 2018)

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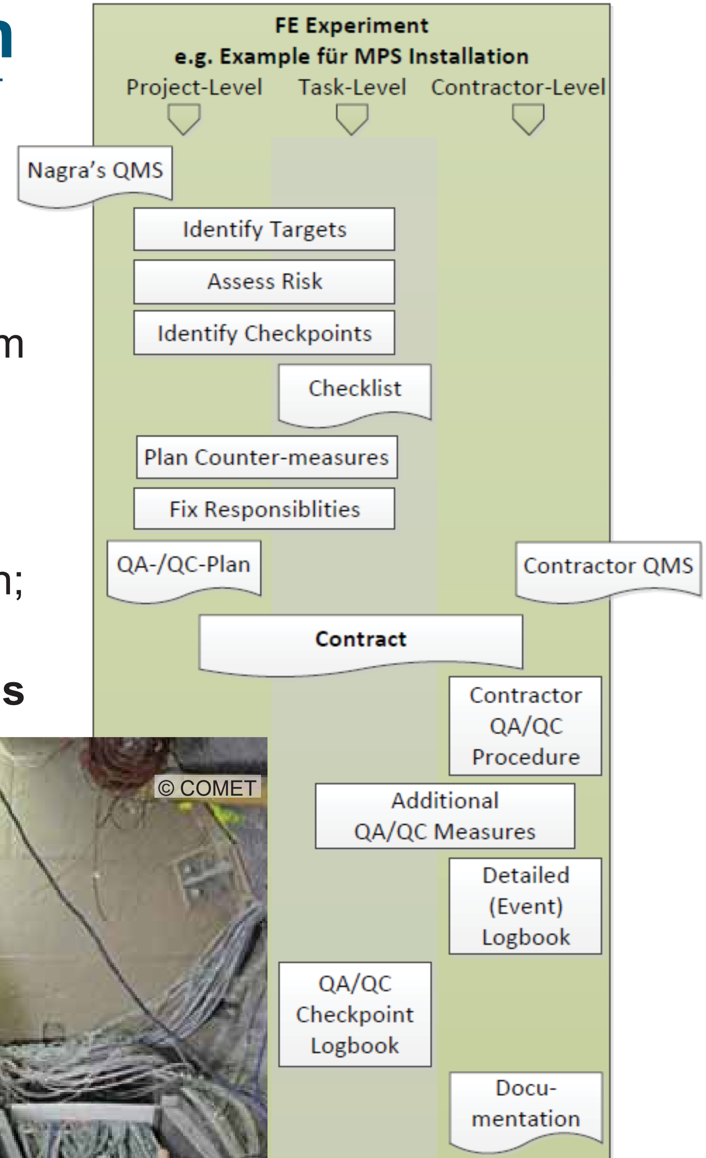
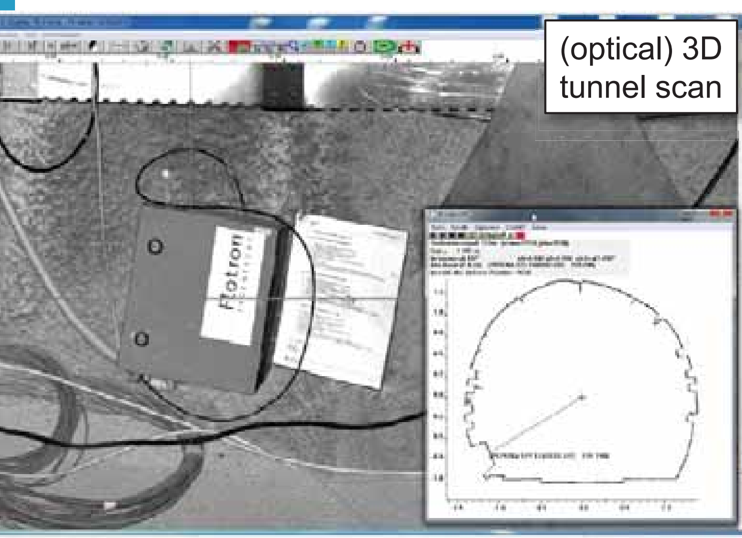
Lessons learned: Instrumentation

- Got **experienced personnel** and considered lessons learned from previous experiments
- **Planned** properly and **in advance**, especially also the quality assurance (QA) / quality control (QC) measures
  - ISO 9001: contractors with their own QA / QC system
  - Appointed personnel for QA / QC during installation
- **Worked** as clean and **organized** as possible
- **Documented everything** as detailed as possible, e.g.
  - sensors: checked labelling, specifications, calibration; surveyed location; QCed data flow to DAS; etc.
  - Took **many photos** and performed several **3D scans**





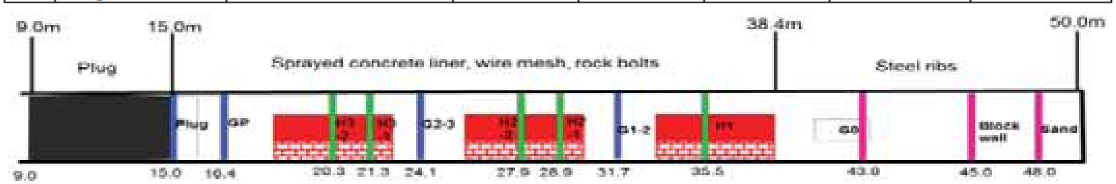
(optical) 3D tunnel scan

Routing of approx. 700 cables through plug

Lessons learned: Sensor behaviour #1

- To date the overall degree of **sensor failure is** (very) **low**
  - distributed fibre optical (FO) systems 100% operational
  - point temperature sensors approx. 90% operational
- Successful, because we
  - focused on **main aims**
  - predicted and **defined conditions** in advance
  - chose according materials and **sensor types**
  - **protected sensors** and cables (e.g. mechanically)
  - **achieved redundancy** by
    → using different sensor types for same parameter (e.g. temperature with FO, PT1000 & thermocouples)
    → special distribution of sensors (radially & laterally)

Sensor information			Sensors installed	Sensors in operation	Sensors not working	% sensors in operation	Overall % of operation
Tunnel wall	Temperature	PT1000	53	53	0	100	93
		Thermocouples in RH sensors	47	46	1	98	
		Thermocouples in/next pressure sensors	27	19	8	70	
		Thermistor FDR	9	8	1	89	
	Humidity / water content	Capacitive RH sensors	41	41	0	100	98
		Monolithic RH sensors	6	5	1	83	
		FDR	9	9	0	100	
	Total pressure	Stainless steel	8	8	0	100	89
		Titanium	10	8	2	80	
	Gas sensors	Oxygen sensors	6	6	0	100	100
	Therm. conduct.	KD2 TR1 probes	15	14	1	93	93
Rock mass (Opalinus Clay)	Temperature	Temperature chains	14	14	0	100	90
		Separate PT1000	12	11	1	91	
		Thermocouples in pressure sensors	55	49	6	89	
		Thermocouples in RH sensors	17	7	10	47	
		Thermocouples in extensometers	30	26	4	87	
		Thermocouples in inclinometers	80	80	0	100	
	Pressure	Interval pressure	68	65	3	96	97
		Pore pressure	46	46	0	100	
	Humidity / water content	Capacitive RH sensors	12	6	6	50	40
		Monolithic RH sensors	3	0	3	0	
	Displacement	Extensometer	44	44	0	100	100
		Inclinometers	80	80	0	100	100
In/on/around heaters	Temperature	TERMYA Typ T	127	120	7	94	83
		Thermocouples in RH sensors	49	26	23	53	
		Thermocouples in/next pressure sensors	3	3	0	100	
	Humidity / water content	High T capacitive RH sensors	25	8	17	32	33
		Low T capacitive RH sensors	24	8	16	33	
	Total pressure	High T TP sensors	6	0	6	0	11
		Low T TP sensors	3	1	2	33	
	Displacement	LVDT sensors	19	15	4	79	79



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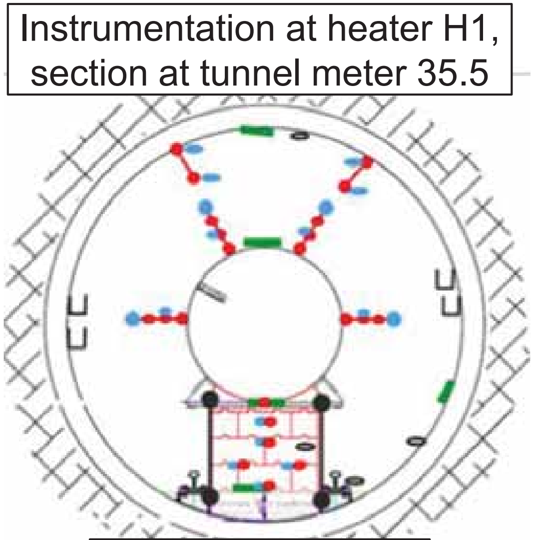
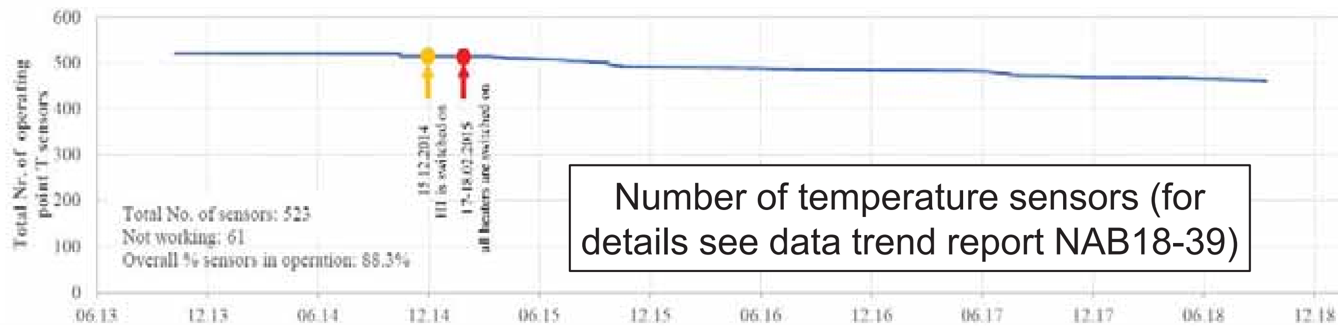
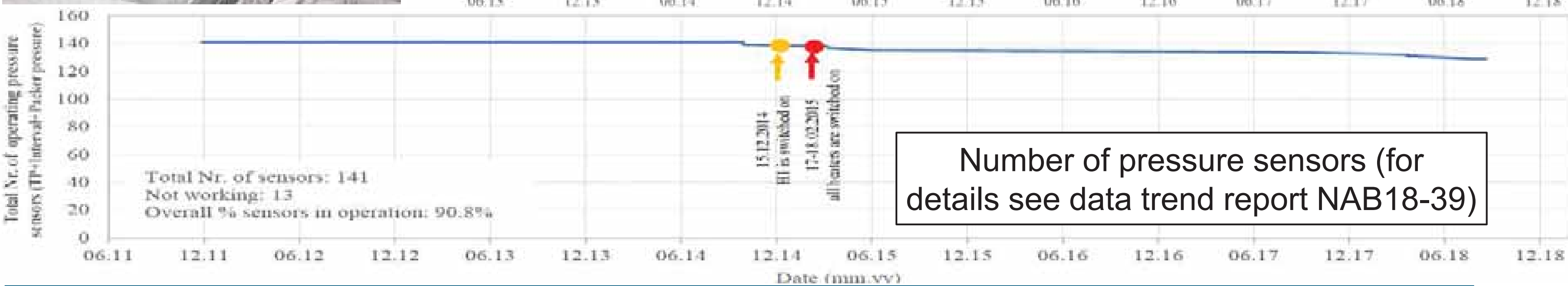
Lessons learned: Sensor behaviour #2



- Generally **higher failure rates close to the heater surface** (currently at <135°C) than close to the tunnel wall (currently at <60°C) and in the rock mass.
- **Relative humidity (RH) and total pressure cells (TP)** close to the heaters (especially in bentonite block pedestals) **provide unreliable data or have failed →** due to forces on sensors and cables because of bentonite block deformation?
- As expected: **humidity and water content measurements prove tricky:** RH sensors fail when condensation or water intrusion occurs, (multi-parameter) TDR calibration, etc.





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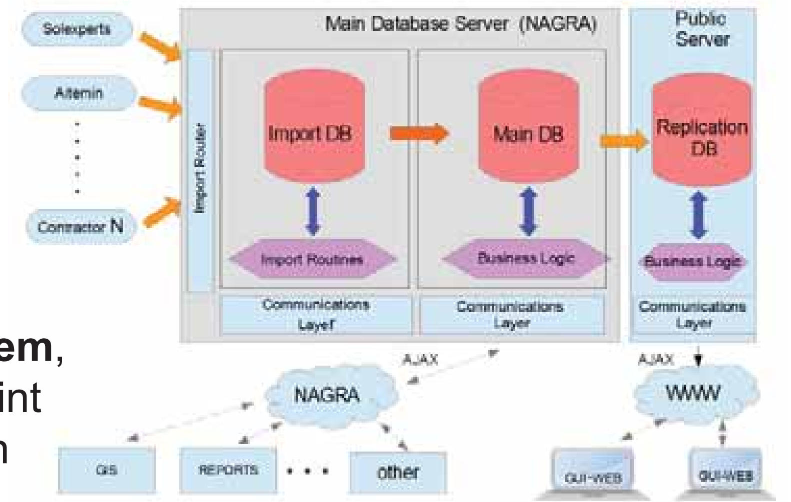
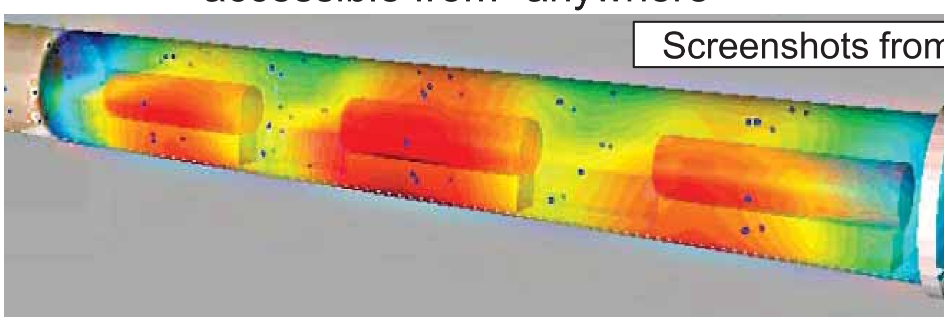
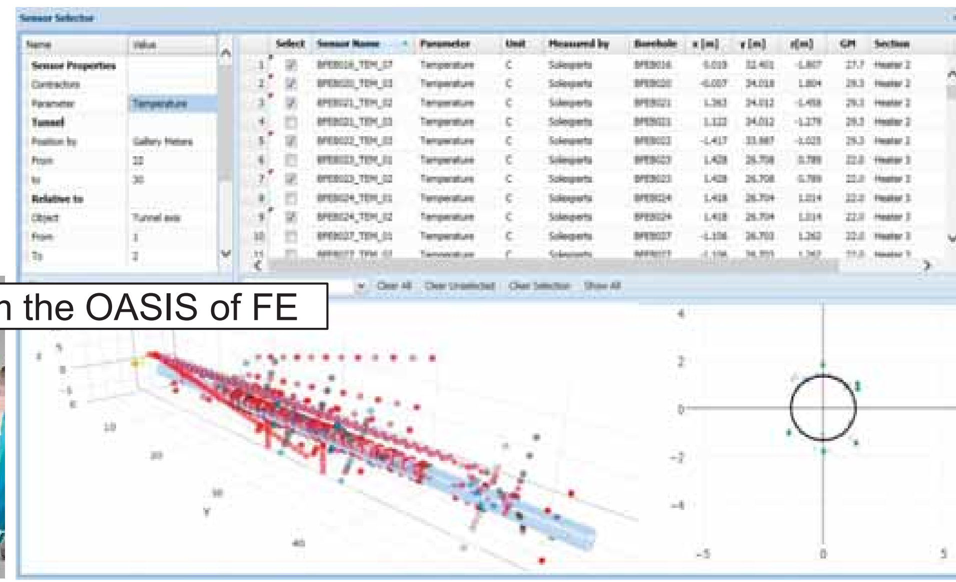
Lessons learned: Data management system

- Got **data acquisition system** (DAS) running as early as possible → relevant for all data delivering contractors (e.g. for unique sensor labeling, etc.)
  - FE experiment is being monitored since 2011
  - **1 million measurements** recorded **daily**
  - Many sensor suppliers → several local DAS feeding into a central DAS at Mont Terri
- Needed an **information & data management system**, also from an archiving & knowledge transfer viewpoint → programmed an overarching scientific information system (OASIS) *→ Poster by Robert Yeatman et al.*
  - **Open source** object relational PostgreSQL database with PostGIS and statistical R language extensions
  - Easy and fast to learn and use, accessible from “anywhere”

Architecture of the FE DAS







Screenshots from the OASIS of FE

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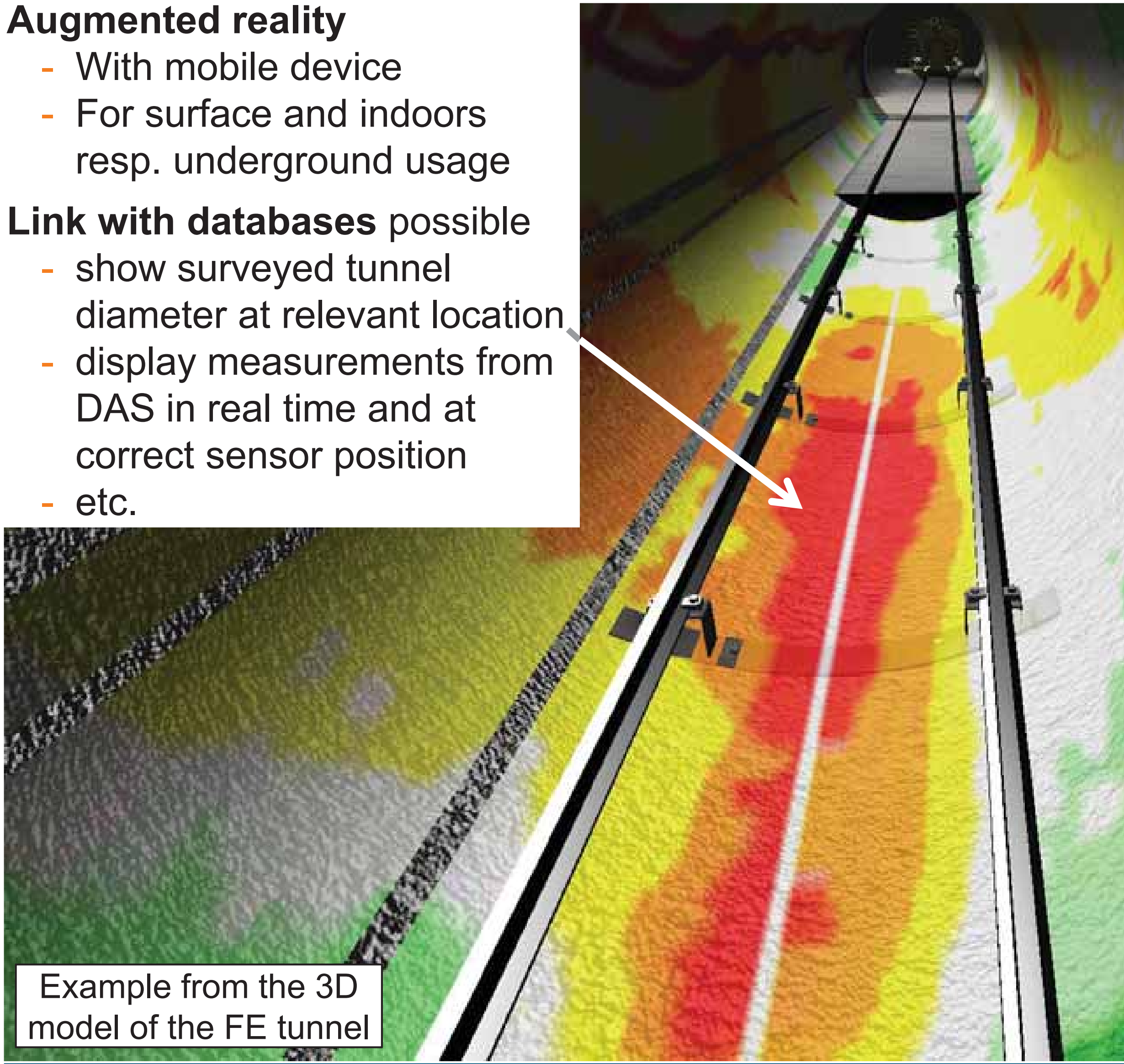
Outlook: Data management system

- **Augmented reality**
  - With mobile device
  - For surface and indoors resp. underground usage
- **Link with databases** possible
  - show surveyed tunnel diameter at relevant location
  - display measurements from DAS in real time and at correct sensor position
  - etc.



Example from the 3D model of the FE tunnel

Example from e.g. www.placenote.com

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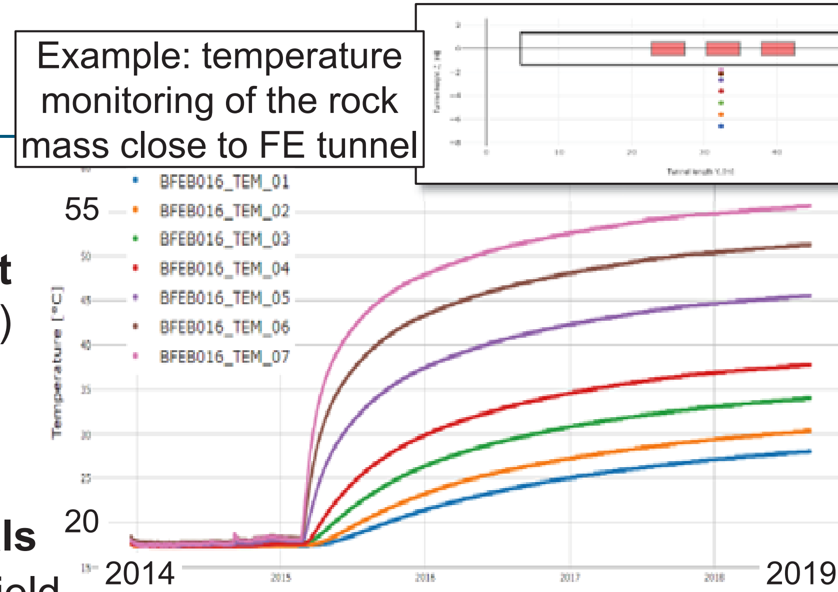
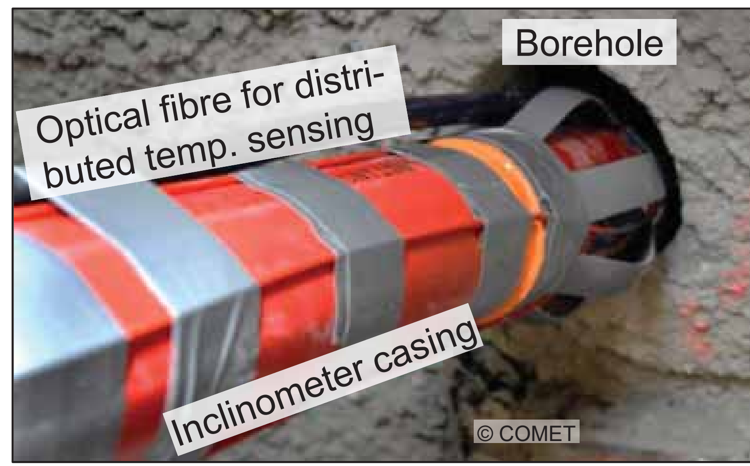
Summary & general outlook

- **Extensive experience** from many experiments such as the FE (and from borehole monitoring systems) **for long-monitoring of safety relevant parameters** (such as temperature, pressure, etc.)
  - Most sensors in the FE experiment show **low failure rates** and perform well
  - Challenging monitoring conditions in the near-field → **choice of sensors and materials**
  - Systems in the (near- to) mid- and in the far-field **allow for accessibility** and therefore -if needed- for sensor exchange and re-calibration
  - Many cables = much effort to achieve **water and gas tightness**, when routed through plug / seal
  - **Advantages of fibre optical systems** (cable = sensor, large number of measurement points, high spatial resolution and accuracy, real-time calibration, durability, etc.)
  - **KISS** [keep it simple and stupid]



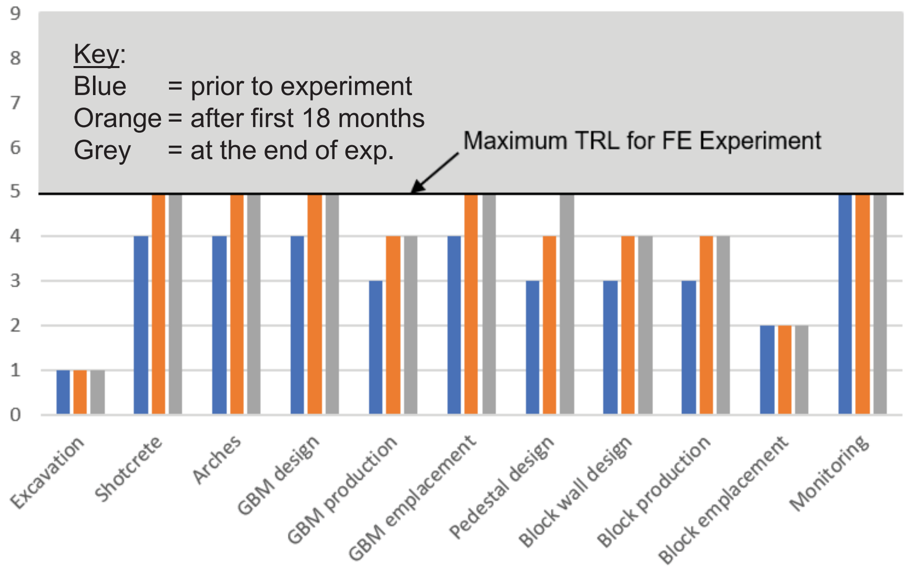


- Great **knowledge exchange** in the community (cf. EU projects such as Modern2020)
- With **general license application** Nagra will hand in an overarching **monitoring concept**
  - Construction of waste emplacement caverns and tunnels is envisaged to start >2045
- **Environmental monitoring** for underground infrastructure projects is **well established**

Technical readiness level (TRL) assessment

- To demonstrate the contribution made by the FE experiment to **the readiness of Nagra to implement a repository**, a TRL assessment was conducted (cf. NTB15-02, in prep.)
- For FE experiment a **maximum TRL score of 5 (of 9)** was assigned
  - FE experiment @ the Mont Terri URL ≠ candidate siting region for a repository
- Regarding monitoring the TRL of the FE was estimated to be 5, because the **experiment has extended the options available for monitoring the THM evolution** of the engineered barrier system (EBS) and the host rock, for example by gaining experience and improving fibre optical (FO) sensors and dielectric probes for granular bentonite material (GBM) density measurements

→ Poster by Berrak Firat Lüthi et al.
→ Poster by Toshihiro Sakaki et al.



TRL Level	Description	Definition
TRL 1	Basic principles observed.	At TRL 1, basic science and engineering is applied to describe a design concept to meet the necessary safety functions.
TRL 4	Technology validated in the laboratory.	At TRL 4, testing of candidate materials or prototype machinery is undertaken in the laboratory or in mock-ups at standalone facilities.
TRL 5	Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies).	At TRL 5, thorough testing of the candidate materials or prototype machinery is undertaken in a relevant environment (e.g. a URL in a representative geological environment) in order to develop detailed requirements and understanding of how the individual components perform in an integrated setting.
TRL 6	Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies).	At TRL 6, full-scale testing is undertaken in a relevant environment (e.g. a URL in a representative geological environment) to demonstrate that requirements can be met using an initial version of the detailed design. This full-scale test is used to develop construction procedures and QC requirements to be applied in the repository.
TRL 9	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space).	TRL 9 corresponds to the system being operational and successful operational experience being gained.

Thank you for your attention!

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