Modern2020 2nd International Conference about Monitoring in Geological Disposal of Radioactive Waste – Extended abstract

What we can learn from a full-scale demonstration experiment after 4 years of DTS monitoring– the FE experiment

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Summary
A comprehensive monitoring program using innovative technologies was realized within the framework of the "Full-Scale Emplacement" (FE) experiment experiment - a full-scale multiple heater experiment - at the Mont Terri Rock Laboratory in Switzerland. Here, the work and conclusions related to fiber-optic (FO) distributed temperature sensing (DTS) monitoring are presented. The DTS method provides a continuous temperature profile along a FO cable, which serves as distributed sensor, resulting in unique, detailed insights into the temporal and spatial variations of the temperature field in and around the heated FE tunnel. FO cables are routed in boreholes and along the tunnel wall. After more than 4 years of monitoring, all four FO cables are still providing valuable DTS data. However, a detailed assessment revealed that neither the default nor the standard calibration of the DTS device's software is sufficient for satisfying the required measurement accuracy. The observed errors became significant over time as temperature differences along the cable rose to 40 °C as a result of heating. The accuracy was greatly improved after installation of a comprehensive calibration system covering the expected temperature range. In addition, we developed the FE Information System (FEIS), which is an internet browser application based on an object-related database that offers fast access to and visualization of all sensor data including the DTS data. This development was necessary to provide easy access to the data for all stakeholders.

1. The FE experiment

The FE experiment was implemented by NAGRA to investigate repository-induced thermo-hydro-mechanical (THM) coupled effects on the claystone host rock at full scale and to demonstrate as realistically as possible the construction, waste emplacement and backfilling processes for a spent fuel / high level waste disposal tunnel according to the Swiss repository concept [1]. The FE experiment is a long-term heating experiment that will run for more than 10 years. The heating phase of the FE experiment was initiated in 2014. The waste canisters and their heat output are simulated using cylindrical heaters (Figure 1), which are placed centrically along a tunnel (2.7 m diameter, 50 m length) and have the same dimension (4.60 m length, 1.05 m diameter) and heat output (1350 – 1500 W) as the planned waste canisters. The space between the heaters and the tunnel wall is filled with buffer material consisting of bentonite blocks, to support the heaters and at the back end of the tunnel, and a highly compacted "granulated bentonite mixture".

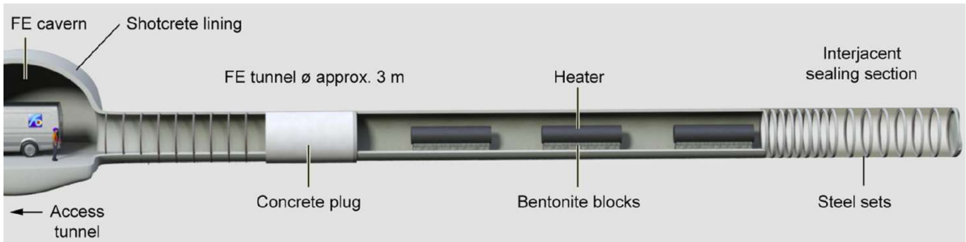

Figure 1: *Visualisation of the general layout of the FE experiment and the 50 m long FE tunnel at the Mont Terri Rock Laboratory; sensors, bentonite backfill and rock bolts are not shown. Figure taken from [1].*

The entire experiment implementation as well as the THM evolution of this full-scale heater experiment is monitored using several hundred sensors. The main monitored parameters are temperature, mechanical and water pressure, deformation/displacement and humidity/water content. The sensors are distributed in boreholes, in the tunnel lining, in the bentonite buffer and on the heaters.

The monitoring environment is challenging because of the long observation period, the high salinity of the pore water and the high temperatures of up to 130 - 150 °C at the heater surface and up to 60 - 80 °C at the tunnel wall. In addition, most sensors cannot be replaced in the case of malfunctioning or failure. Therefore, a careful selection of monitoring systems including sensors, housing materials and cables was needed.

The primary use of the monitoring data is for THM model calibration and validation at full scale. The FE experiment is also a great opportunity to identify issues, to implement developments and to gather experience related to long-term monitoring that will be of importance for the monitoring concept of the future Swiss repository. We therefore focused in our study on what we can learn from this full-scale demonstration experiment after 4 years of DTS monitoring regarding

- sensor performance and calibration,
- data management challenges and data sharing.

2. Distributued Temperature Sensing (DTS)

The monitoring data of the FE experiment teach us about the reliability and performance of sensors under repository-like conditions. Therefore, multiple sensor types and monitoring technologies were installed to evaluate and compare their performance. Within Work Package 4 of the Modern2020 project, Nagra selected two different sensing technologies for the FE experiment that were both identified as suitable in the previous MoDeRn project [2], namely time domain reflectometry (TDR) for water content measurements as well as DTS for temperature measurements. The focus of our work was mainly on the aspects of installation, calibration, operation and data handling. In this extended abstract we present the DTS related findings.

For DTS measurements the FO cable is the distributed sensor and is connected to the DTS unit, which hosts a laser as well as the detector with signal processing unit. With the DTS technique temperature profiles over several meter to several kilometers in length can be measured with a spatial resolution of 0.25 – 2.00 m. The DTS unit in this study determines the backscatter location via optical time domain reflectometer and uses the Raman backscatter characteristics of light emitted following a laser pulse into a FO cable. The Raman backscatter consists of two components of different wavelength, the Stokes and anti-Stokes color. A measurement of their ratio in time allows calculation of the temperature along the FO as a function of distance [3]. As compared to other FO sensing techniques, e.g. fiber bragg gratings as well as Brillouin and Rayleigh-based distributed systems, the most prominent advantage of the Raman based DTS is that it is sensitive solely to temperature and not to strain. In general, the temperature measurement accuracy of an DTS unit depends on sampling time (the longer the sampling time, the better the accuracy) as well as FO cable installation and properties.

Different FO cables were installed within the FE experiment, namely robust armored cables with 4 mm diameter, where the fibers are located loose in a metal tube, and a very flexible cable with 2 mm diameter, which has no armoring and no metal tube. In total four FO cables were connected to a multiplexer for permanent monitoring. Moreover, two different DTS units were used. The DTS unit for permantent monitoring had a spatial resolution (defined as the length over which 10 - 90% of a step temperature change can be detected) of 1.02 m and the DTS unit used temporarily had a spatial resolution of 0.25 m. All DTS measurements were performed in single-ended configuration where only one end of the FO cable was connected to the DTS unit.

Before the heaters in the experiment were turned on, the default calibration parameters of the DTS unit were used, because no difference could be observed to a standard calibration using the DTS device's software and two water baths (ice bath and ambient temperature bath), which were incorporated in the FO cables' measurement sections. After the start of heating, the tempearure in the FE tunnel close to the heater locations was increasing and over time temperature differences along the cable rose to 40°C. After detailed investigation, we could show that errors in temperature measurements became significant over time and that neither the default nor the standard calibration of the DTS device's software is sufficient for ~~a satisfactory~~satisfactory measurement accuracy.

To improve the temperature measurement accuracy of the DTS units, a comprehensive calibration set-up was realized covering the expected temperature range. Two very well insulated water baths with a mixing mechanism of the water body were installed including FO cable sections ranging from 10 - 30 m. One bath was at ambient temperature (19 - 20°C) and the other bath had an integrated heating element to keep the temperature stable at 65°C. Both baths were equipped with conventional high precision temperature sensors. Their data and the DTS data of the baths are used for the the newly implemented calibration routine for single-ended DTS measurements after [4]. The calibration routine is applied "on-the-fly" to every single measurement at the moment of data transfer to the FE database. The new calibration resulted in an average measurement accuracy of 0.1 - 0.3°C depending on FO cable type and DTS unit.

3. Comparison of DTS to conventional temperature sensors

DTS combined with continuous calibration has a considerable advantage over conventional electrical "point-type" temperature measurements. The latter are based on pre-installation calibration; accuracy and potential drift over time cannot be checked during the monitoring period. In addition, DTS has another advantage over conventional electrical temperature sensors, because it is possible to identify locations along the distributed FO sensor where data quality might be affected, e.g. by light step losses (e.g. at splice connections or due to cable bending) or high strain along the cable. For standard "point" sensors, these investigations are not possible. Besides the DTS instrument's raw data output and calculated temperature data, the calibration parameters are also stored in the FE database. This allows the change in the cable properties to be investigated over long time periods, e.g. in order to draw conclusions on the suitability of different cable types with respect to cable aging behavior.

Commented [GJL1]: I am not sure if I undertood this sentence clearly : Do you mean that using the standard calibration of the DTS units no differences with the conventional sensors were observed for the temperatures gathered in the tunnel and in the baths , right? However, I guess that the baths are a kind of calibration tool to detect and correct long term drift, is not it ?

Commented [GJL2]: The new baths replaced the ice and ambient temperature ones or were they additionally installed ?

Commented [GJL3]: No information at all is given about the performance of the two diferent DTS cables, why ? Besides, I understand that both DTS units, the permanent and the temporary, performed well being the only difference the spatial resolution, rigth ? It will be good is you could provide more details, very shortly, about the differences found between FOs and DTS units.

Commented [GJL4]: Note that there is a wide background about the good performace of point-type temperature sensors, in particular Pt-100, Pt-1000 and Thermocouples, showing negligible drift with time (see FEBEX results after 18 years of operation). It is true that the drift can not checked during the monitoring period but the writing you made could suggest to the reader that the drift is an issue and it is not.

Commented [GJL5]: Again you are introducing doubs about the performance of the conventional temperature sensors. These sensors are nowadays the ones with higher TRL and this is the reason you are using them for comparison with the FO. It has no sense to try opening doubts about their performace instead to use them for demonstrating that FO solutions are as good as them.

Commented [GJL6]: In my opinion the DTS has the advantage of providing a better spatial resolution with one fibre what could only done by using many conventional sensors. On contrary, as you mentioned, they need to use a sophisticated calibration system to keep the same accuracy that the conventional sensors.

Along the boreholes and within the heated tunnel, where temperature gradients of up to 6°C/m exist, a direct comparison with standard electrical point temperature sensors is difficult due to the DTS spatial resolution, which ranged from 0.25 – 1.02 m depending on the DTS device. We could show that in general a good agreement exists between DTS data with about 1 m spatial resolution and data of standard point-type temperature sensors, especially where small to moderate temperature gradients (<1°C/m) prevail along the FO cable. DTS instruments with a high spatial resolution (0.13 – 0.25 m) can even provide reliable data for sections with large temperature gradients along the FO cable. Therefore, DTS provides detailed spatial temperature data at a scale of a repository tunnel, which cannot be realized practically using conventional temperature sensors.

Commented [GJL7]: This is biased, it is feasible but will require of many conventional sensors what it is not practical

4. Data management and the FE Information System (FEIS)

The acquisition of highly detailed spatial DTS data is of great benefit from the perspective of observation and monitoring; however, it creates new challenges for data management. Compared to conventional point-type sensors, DTS generates significantly more data and the data come in the form of profiles. This specific profile format is untypical for standard databases used so far where the majority of sensors were analogic. We therefore developed the FE Information System (FEIS), which is an internet browser application based on an object-related database that offers fast access to all sensor data (point and profile data) and customizable data visualization. The FEIS relates the location of distributed measurements along a FO cable to FE project locations in 3D-space, even for complex routing of cables. The routines account for varying spatial resolution that can result from different measuring units and instrument settings. The system responds quickly, even with billions of FO measurements. Dynamic calibration coefficients are calculated for each DTS measurement as the data are added to the database. Calibrated temperatures are calculated "on-the-fly" for FEIS graphical output, data listings and exports. DTS measurements can be viewed as a profile (measurements along the cable) or as a time-series (measurements over time at a specified point) and measurements can also be compared with standard sensors.

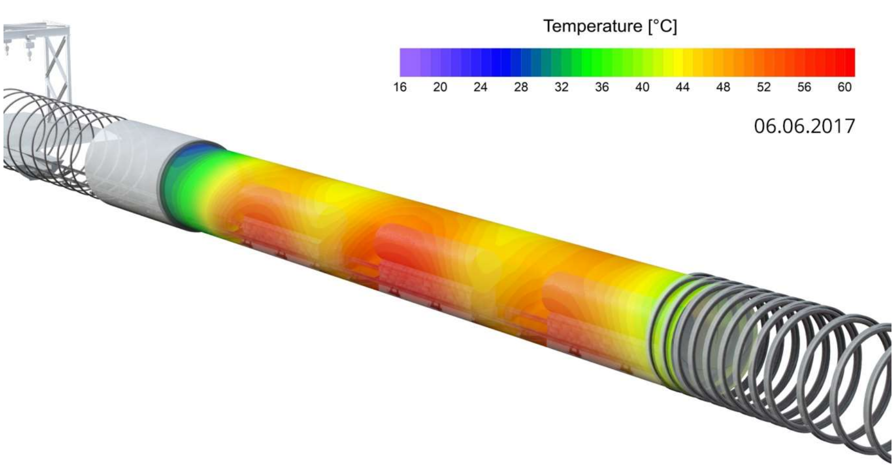

Figure 2: Temperature distribution along the tunnel wall in the FE experiment measured by means of DTS. The measurement data shown were acquired on 06.06.2017, which is equivalent to approx. 2.5 years of heating.

5. Conclusions

Within Work Package 4 of the Modern2020 project we worked on the demonstration and evaluation of the DTS monitoring technology under repository like conditions in the FE experiment. The FE set-up offered ideal conditions for comparing different novel sensing systems with conventional standard systems. For DTS, the focus of our study was mainly on the aspects of installation, calibration, operation and data handling.

DTS is the preferred technique for obtaining detailed spatial temperature datasets, opening new insights into the understanding of heat transport in the buffer and host rock as well as providing detailed temperature monitoring within a full-scale high-level waste disposal tunnel (Fig. 2). We could show that the spatial and temporal variations of the temperature field within high-level waste disposal tunnels can be determined sufficiently accurately by means of DTS. However, for long-term DTS monitoring under repository conditions, a comprehensive calibration set-up is required covering the expected temperature range. For our single-ended DTS measurements, the calibration routine after [4] was successfully applied "on-the-fly" to every single measurement at the moment of data transfer to the FE database.

Commented [GJL8]: This is a strong statement, is there a general agreement about this preception inside the project? I suggest : According to the obtained results DTS is a promising and advantageous technique for obtaining accurate and detailed spatial temperature datasets

Commented [GJL9]: Could you please include a general statement about the degree of madurity of this technique ? I mean, Is this technique ready to be implemented for future monitoring in the repository ? If not, what else is needed ?

5.1. Data sharing

Many internal and external stakeholders are interested in the FE monitoring data. Each stakeholder has a different background, a different interest and uses the FE data in a different way. Therefore, a data sharing concept is important. Although the FEIS offers various access levels for each user and all information and data can be downloaded or viewed, our conclusion after more than 4 years of DTS monitoring is that most stakeholders prefer a condensed summary of the monitoring data (e.g. annual reports and annual data deliveries), rather than having direct access to the database. In addition, modelers using 3D numerical models are not yet accustomed to high-resolution spatial data, because the level of detail is not within the scope of their modeling objectives or the models' grid or cell sizes are insufficient for handling a fine spatial resolution. Although, the users can extract selected point-specific DTS data using the FEIS, this option is hardly ever used by the modelers. Thus, more time is needed to promote the advantages of innovative monitoring technologies such as the DTS monitoring and FEIS for different stakeholders.

Commented [GJL10]: Which ones are you considering ?

Commented [GJL11]: This is interesting. The tools for monitoring-data handling were not considered in Modern2020 because they could be improved all along the repository lifetime. However, just only time is needed or/and more work to refine them too ?

6. Acknowledgements

This work was partly funded by the Swiss State Secretariat for Education, Research and Innovation (SERI) as part of the Modern2020 project (Euratom research and training programme 2014–2018, grant agreement No 662177).

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