Contribution of Metrology to a Qualified Disposal Monitoring System Stable over Centennial Timescales – 14031

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ABSTRACT

Andra currently leads research activities that will result by 2015 in an authorization application for geological disposal of radioactive wastes. Geological infrastructures as well as the surface environment will have to be monitored over a period of at least one century. Metrological studies will focus on important aspects associated to the observation and monitoring in the long-term of the exploitation site, such as the assessment of the metrological performances of the instruments installed on site or of the monitoring indicators selected by Andra. Optical fiber sensors (OFS) technology is under evaluation by the nuclear industry since it may bring promising alternatives to classical measurement techniques. This paper presents the general issues of the metrological consideration and introduces a method to evaluate the Raman optical fiber sensors.

INTRODUCTION

Many countries have already selected deep geological disposal as the reference solution for the management of high-level (HL) and intermediate-level and long-lived (IL-LL) waste. After having concluded a feasibility study of deep geological disposal for high-level and long-lived radioactive waste in 2005, the National French Radioactive Waste Management Agency (Andra) was charged by the Planning Act n°2006-739 to design and create an industrial site for geological disposal called Cigéo (The Industrial Centre for Geological Disposal) which must be reversible for at least a century-long period. Within the framework of this geological repository project, the monitoring system must fulfill the knowledge required to run the disposal and its reversible management**.**

National monitoring concepts and scopes lead to technical and operational requirements on monitoring equipment and nuclear control system. Andra should develop equipment and techniques to correct any shortcomings in the present technical capability for the long-term monitoring and also improve the characterization of radioactive waste packages with dedicated methods and possible non-destructive nuclear measurements.

Waste package QA/QC is especially important because the package is the primary barrier to radionuclide release from the storage facility and it is essential that the storage facility operator ensure that waste packages conform to the storage facility acceptance requirements. There are three phases associated with repositories, i.e. pre-

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operational, operational and post-closure, which all have an impact on quality requirements of waste packages. Parameters Andra want to control have been selected for their contribution to operational safety (gas, dose rate ...) or after closing (radiological and chemical content, void ratio, parameters related to the homogeneous nature of the waste ...). The parameters identified in the first expression of need are as follows:

- Activity of radionuclides;
- gas release (especially gaseous radionuclides);
- Presence of toxic chemicals, and complex species and / or potentially aggressive or reactive;
- Void ratio inside nuclear package;
- homogeneous character of the waste;
- external integrity of the package;

The underground installations of the Cigéo repository will be built progressively and operated over a period on the order of a century. In the framework of this project, monitoring of the environment and repository structures, which in Andra’s project is called “Observation and Surveillance”, should provide requested information for its operation and its reversible management. The measurement of various quantities will be required, for example: temperature, strain and/or stress, positive or negative hydrostatic pressures, water content, relative humidity, temperature, and chemical parameters such as pH, concentration of a compound in the gas phase of a disposal cell, macro- and micro-pollutants in water. This includes also the measurement of parameters that affects the above quantities. The Thermal, Hydraulic, Mechanical and Chemical (THMC) [2] approach has been developed in order to model any future release rate and forecast transfer of radionuclide at the vicinity and in the far environment. Measuring systems should cover the appropriate nominal range, show metrological performances compatible with the requirements in terms of accuracy and / or long term stability in order to quantify the possible slow environmental changes over the very long timescale of monitoring. In most cases, sensors will be used in a radioactive environment after installation and periodical calibration on-site by qualified operators will not be possible. Specific strategies will therefore be required to enable periodical checks and ensure reliability of the measuring system.

On-site installation of such equipment should not impair essential safety functions, such as for example barrier performance, expected to be non-invasive. Aspects that may need to be considered here are for example the absence of sensors wires through barriers. Sensors having small physical dimensions are also required to avoid impairment of the structural integrity of barriers.

The sensors should allow easy implementation in strategic areas within the repository. Comparison of measurements with models, for instance, may imply obligatory positioning of sensors.

Technological reliability and robustness of instruments used are essential requirements. Sensors technologies have been selected or rejected on basis of robustness and ageing studies. Redundancy of critical system components (e.g. sensors, cables, data processing devices) allows limiting the loss of information in case of the failure of system components, detection of defective sensors, and identification of erroneous readings. Such sensors feature electronic parts that are systematically installed apart from zones that will not be accessible to allow easy maintenance.

Many important decisions are based on measurement. Hence, good-quality results are essential. It is well accepted worldwide that traceability to stated references (e.g. standards of the International System of Units) is an essential condition to a reliable result. However absolute certainty is an unattainable ideal: metrological traceability must therefore be established together with an evaluation of uncertainty. In the field of repository monitoring, the specialist has to give confidence by a clear demonstration that the performance of the measurement process is consistent with the expected requirements.

Monitoring and control of disposal of HL-ILW-LL wastes forms an integral part of the reversibility. Andra provides a set of waste package control, monitoring and surveillance of the storage and environment during the entire duration of operation and after closure of the disposal. Geological infrastructures as well as the surface environment will have to be monitored over a large period, at least one century, in order to respect the reversibility period. Consequently, Andra develops specific instruments for chemical, mechanical, thermal, hydrous and radiological measurements, able to allow long-term monitoring of these two environments. Reliable and robust technologies of sensors have already been chosen for application to deep geological observation of the structures. Such sensor features electronic parts that are systematically installed apart from zones that will not be accessible to allow easy maintenance. First cells will be highly instrumented to allow fine observation of phenomena. The number of sensors will be close to two thousands sensors for one cell.

METROLOGY RESEACH FOR ROBUST SYSTEM

Metrology is the « *science of measurement […] made at a known level of uncertainty, in any field of human activity* ». It provides a technical framework to demonstrate and maintain confidence in the quality of measurement.

The monitoring program has been drawn up on the basis of research and development work on new instruments, and on the selection of reliable, robust existing technologies that enable Andra to match the requirements of sensor durability with the reversibility periods that are sought. Special attention is paid in an overall way to the permanence of the proposed testing devices and their correct integration into the design of the facilities. To attain this objective, Andra has implemented a multi-stage qualification procedure for each selected measurement chain:

1. Stage one consists of acquiring in-depth knowledge of the measurement instruments. It is aimed at selecting the technologies best suited to the purpose and triggering adaptations of the existing equipment to suit the specific requirements where necessary.

2. Stage two consists of carrying out tests under fully supervised and/or controlled environmental conditions, to qualify the sensitive component and assess the complete measurement chain.

3. Stage three consists of in situ tests, but without extreme temperature or radiological conditions. This is designed to provide “testing device demonstrators”, complete systems implemented under conditions that are as similar as possible to those of a disposal facility.

4. Stage four involves hardening in the light of the environmental conditions of geological disposal, and, in particular, resistance to radiation.

Qualification stages will be accompanied by a fifth transversal stage, the metrological assessment and validation of the methods, by defining two important concepts of « traceability to standards » and « measurement uncertainty evaluation » that are essential. Andra started to systematically validate measurement processes and demonstrate on field [4]. The national laboratory of metrology (LNE) provides its technical assistance to studies in its fields of expertise.

GENERAL ISSUES

Essential objective is to establish the metrological performances of the instruments installed on site. These must be compatible with the accuracy required for a given measurand, dictated by the THMC approach described above. Although sometimes used over decades – even centuries – in industry or in the field of structural monitoring, few metrological studies were found for some of these sensors. The work started therefore by evaluating the sensor technology, its implementation on-site and the possible disturbance of intrusive probes on measurands, the measurement principle and associated mathematical model. The instruments used in geological infrastructures systematically feature electronic parts that are systematically installed apart from zones that will not be accessible to allow easy maintenance - and have to be considered as consumables over the next decades. As a consequence, knowledge of the metrological characteristics of measuring systems and their sub-systems (electronics) is required, as illustrated for instance by thermo-mechanical monitoring in the cells. This will be notably performed in the repository by means of distributed sensors based on optical fibers. Optical fiber sensors (OFS) have certain advantages including immunity to electromagnetic interference, lightweight, small size, high sensitivity, large bandwidth, and case in implementing multiplexed or distributed sensors. The serial multiplexed and distributed architectures are especially relevant for structural applications which usually need a lot of measurement points. Distributed optical fiber sensors have been recently developed and have not invaded Structural health monitoring (SHM) applications yet, due to a lack of standardization in claimed performances and dedicated qualification processes. This technology enables the observation of a “distributed” signal proportional to the temperature and the mechanical strain along a fiber, typically with a spatial resolution of a few meter(s). Measurements are performed using an electronic device consisting of a laser source and a detection system, which is connected to the fiber. Figure 1 shows the signal as observed by the detection system along an 80 meters long fiber. The observed frequency is proportional to the temperature and mechanical strain applied to the fiber; the mathematical model should therefore be established as a complete system. This would require the development of calibration methodologies, assessment of the influencing factors and an evaluation of measurement uncertainties. However, the impact of the electronics on the observations should also be assessed separately in view of its future replacement.

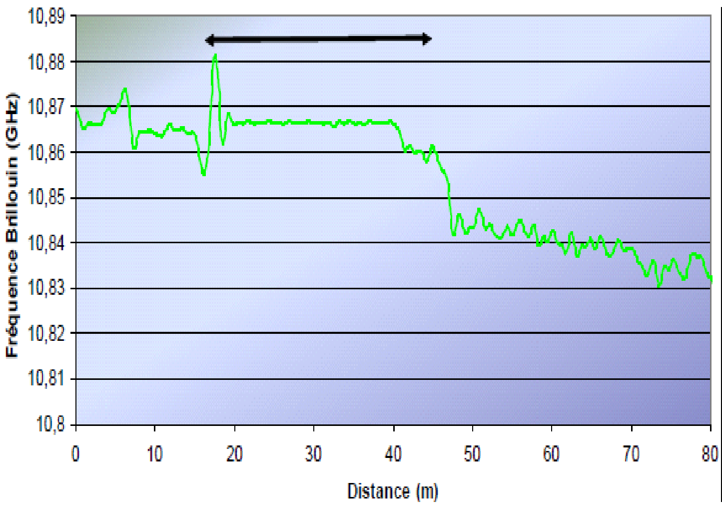

Figure 1: thermo-mechanical monitoring by optical fiber

The THMC approach described above relies on the observation of slow changes over very long timescales, typically at least 100 years. The environmental changes are extremely slow by nature. It is therefore essential that the long-term stability of sensors be assessed. Various strategies are envisaged on site for that purpose, including periodical calibrations wherever possible, the development of self-calibrating devices, redundant measurements using different sensor technologies. These will be developed together with metrological studies in laboratory conditions, prior exploitation, to improve the stability of the sensors. Figure 2 shows the example of strain monitoring in a concrete sample by means of vibrating wire extensometers; such sensors are designed for being integrated in the concrete cell structure to monitor its strain.

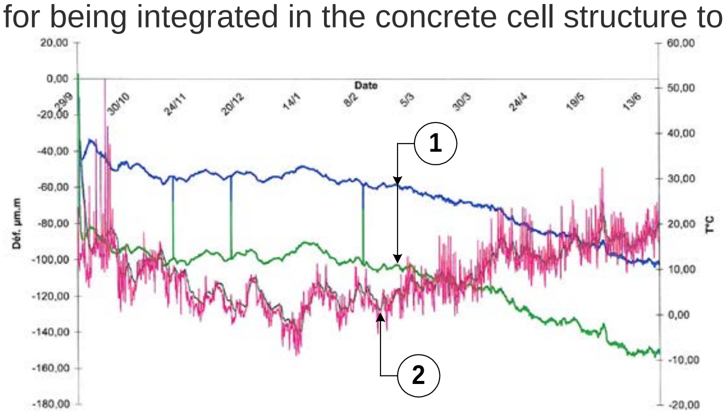

Figure 2: strain monitoring by extensometers and temperature monitoring of the extensometers

Following initial shrinkage in step due to solidification, the concrete was observed stable over a four months period. This was followed by a slow change during the last six months. The two extensometers in the sample confirmed similar tendencies and slopes. The temperature of the concrete sample (a factor that influences in principle the measurement) was simultaneously observed and also showed a change in its slope after the four month period. In the absence of metrological knowledge on this technology of sensor, the end-user can either conclude:

- that extensometers are strongly influenced by the temperature of the environment,
- that concrete samples undergo a structural modification after the fourth month,
- or that the sensors drift over time.

OPTICAL FIBER SENSORS (OFS)

Controlling the state of a structure's health, more commonly designated by the acronym SHM (Structural Health Monitoring), requires a large number of sensors. For this application like storage facilities, optical fiber sensors (OFS) are found to be exceptional tools, especially as they enable distributed measurements [4] thus providing data over the entire structure instead of being limited to point data at sensor locations. Monitoring with a single fiber can thus provide information of the overall structure behavior, and thus overcome limitations of traditional sensors, whose information is restricted to local effects. Some 20 years of developments have been necessary to overcome the initial disappointments and fully utilize the specificities of these sensors [4], whose application has since become state of the art.

A large variety of OFS have been successfully commercialized in the past three decades essentially based on Bragg-gratings and Fabry-Perot cavities (FP), providing one or several, localized measurements [1]. These technologies require a specific, localized treatment of the fiber, for example localized surface grating, to create a localized, sensitive element susceptible to produce a measurable signal. These OFS technologies remain limited in their applications by the pre-defined and “point-like” nature of data they can provide. For civil engineering, a large number of such “point-like” OFS need to be multiplexed to instrument real decametric structures [4]. A wide variety of multiplexing schemes have been developed to enable simultaneous measurement of several tens of sensors. However, even if a thousand of sensors are available, the choice of their locations may be highly sensitive, and is an intensive research topic.

In comparison, distributed sensing provides a more versatile and powerful monitoring tool as it requires much less a priori knowledge of the structure behavior. The term distributed sensor designates the case in which the optical fiber itself becomes a sensor. It is thus no longer necessary to implement anticipated sensor positions since measurements are being performed all along the optical fiber connected to the reading device (as well as within the extension cables). The remainder of this article is focused on OFS technologies allowing for such distributed sensing.

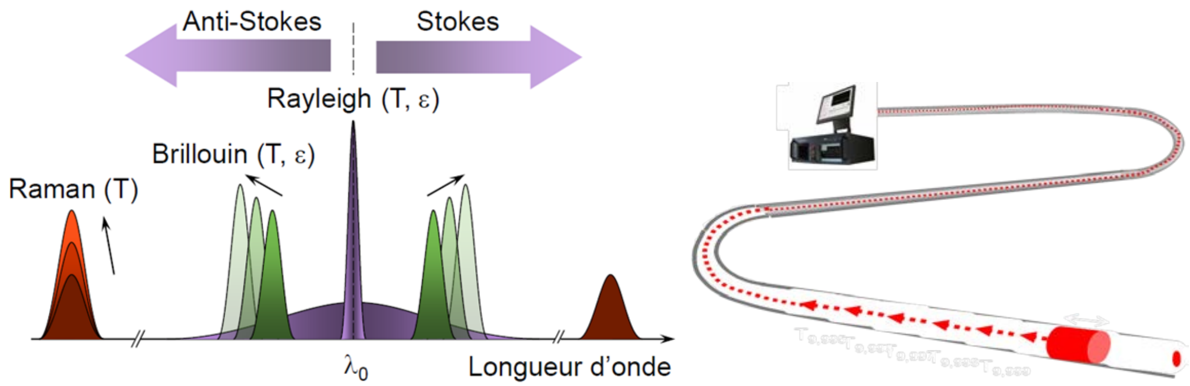

Figure 3: Backscattering spectrum of a monochromatic wave within an optical fiber (left) optical fiber sensor and unit (right)

As shown in Figure 4, the light backscattered by an optical fiber segment without any defects or abnormal characteristics is spectrally decomposed into three distinct peaks corresponding to three outstanding phenomena.

Depending on the desired accuracy, range, and expense, you have several sensors options for measuring temperature on field. In case of large structure, distributed temperature sensors (DTS) using Raman scattering by optical fibers is one of the most suitable tools for Structural Health Monitoring. Optoelectronics devices can offer temperature profile along the optical fiber sensor cables. Nevertheless, it is important to set down that optical fiber and optical installation practices used in other industries are significantly different from nuclear constraints and applications, which may be far less tolerant. The need to provide reliable and adjusted temperature measurement is also the consequence of stakes related to the evolution of standardization. Universally valid regulations for testing, characterize and certify temperature distributed measurement are not established as Bragg sensor [2]. Requirements to quantify influence parameter of measurement equipment on the measured parameter are needed for specific applications. An essential objective is to establish the metrological performances of the instruments that are installed on site. These must be compatible with the accuracy required for a given measurand. In particular, the ability of a Distributed Temperature Sensors (DTS) to detect hot spots, temperature difference on site and measure its actual temperature is a very important feature for many applications. Thermal measurements are spatially and temporally important for the end-user. Effect of non-uniformity on the sensing line can affect the interpretation is why a metrological method is developing in order to calibrate the optoelectronics unit, the sensing chain and maintain device during the life time.

The design of the monitoring system for the IL-LLW cells (Fig. 1) has to ensure the reliable operation of the measurement system for a period of at least a century, without any maintenance. The long-term stability of sensors is assessed and various strategies that are considered in situ in order to reach a require reliability, including periodical calibration wherever possible.

The development of self-calibrating devices and redundant measurements using different sensor technologies is an example. With the distributed measurements by

Optical Fiber Sensors (OFS) which provide temperatures and/or deformations at all points over the entire length of the installed cable can be compared to measurements obtained using sensors such as a Platinum probe pt100 or a vibrating wire extensometer (VWE).

Measurements obtained have to be decorrelated of influences, such as thermal effects, in order to obtain physical values for the target parameters. More specifically, to decorrelate the effects of shrinkage and creep of concrete, VWE sensors are placed in samples (cylinders of 16 x 32 cm with the same concrete used for the gallery) where only thermal and hydric effects can be measured by sensors (no mechanical transfer between the gallery concrete and the sample one).

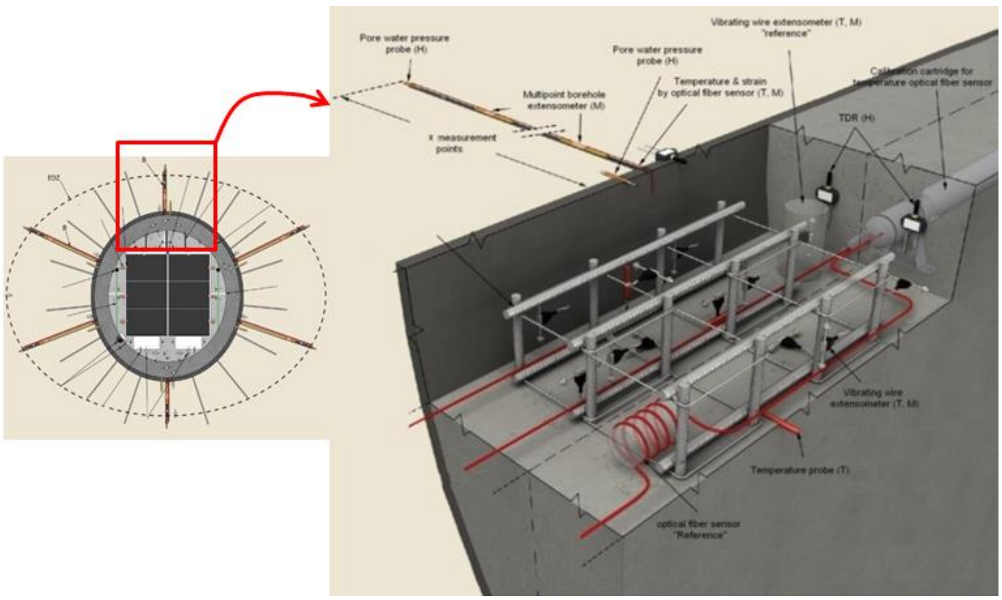

Figure 4: Example of monitoring system design for IL-LLW disposal cells (left) & Zoom on a section named B (right).

For the end-user, a key performance is therefore the “spatial resolution” of the instruments indicated by the manufacturers in their data sheets. The work presented in this paper aimed to (i) develop a new reference device (also called cartridge) able to calibrate then periodically check on site the temperature sensors based on a fiber cable connected to a DTS unit, (ii) validate the performance of a cartridge prototype, demonstrate its traceability to Temperature Standards, validate its exploitation on site, (iii) generate with the new cartridge a uniform, stable and well-known temperature over a cable portion whose length corresponds to the spatial resolution of a DTS unit under test, in order to verify the performance claimed by the manufacturer.

PRIMARY RESULT OF METROLOGY RESEARCH DEDICATE TO OPTICAL FIBERS SENSORS

A specific bench was developed, suited Raman optical fiber evaluation. Design was develop in order to avoid curvature loss for a representative distance, see Figure 5 and Figure 6. The "heater" consists of 5 tubes 23.5 m log, arranged in each other concentrically. The central tube with a diameter of 18mm is the working area, able to accommodate different cables or optical fibers. Around the inner tube, two concentric annular spaces are dedicated to regulated water circulation. Water counter-current is applied in each tube. An air gap was made between two water fulfill tubes in order to reduce heat losses. Finally, an insulating shell support called Isopirflam® was installing in the surrounding of the outer tube in order to reduce room temperature influence. A 200 liter electric water heater was associated with a Lauda bath in order to control the water temperature at 0.01°C.

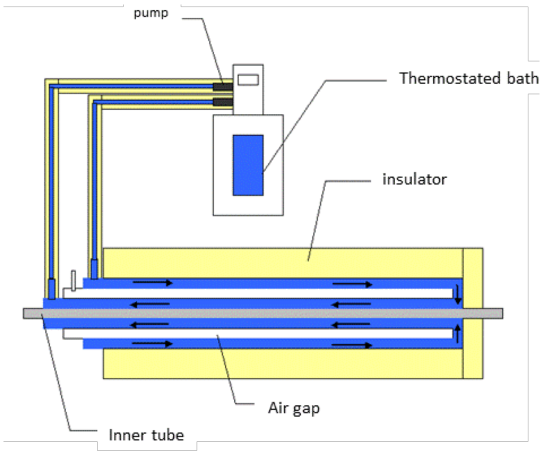

Figure 5: test bench description

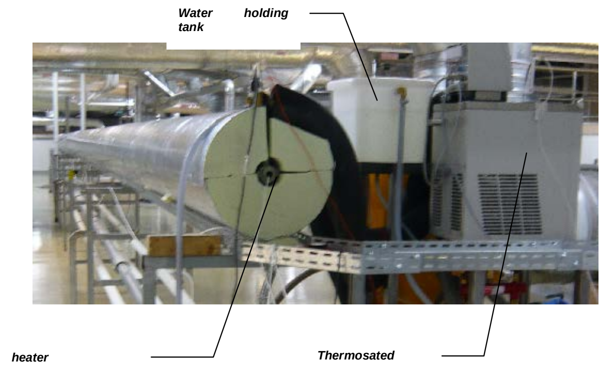

Figure 6: test bench picture

Metrological characterization of the bench is to assess stability and uniformity of the heating body, at different levels of temperature (3°C, 30°C, 60°C and 90°C). The thermal stability of the heating element is determined by measuring the temperature of the heating body with a measurement reference like resistance measurement technology. Temperature was controlled with platinum IEC 60 751 Class probe (Pt100 type) previously calibrate. The sensors are placed at 1 m inside the central tube of the heating body, result as shown in Figure 6. Temperature stability is defined as the extent of half the maximum variation in temperature observed. The stability of 0.01°C over the measuring time by two platinum probes is observed. The oscillation seen at 3°C is attributed to the regulation system.

Commercially available DTS instruments include manufacturer's calibration routines that rely on reference points or sections of known temperature on the cable. These are typically achieved in the field using sections at known, uniform temperature [4]. After doing the calibration routine, the spatial temperature homogeneity was measured. As we know that the curvature as no influence in our set up if we receipt the specification of the cable. A new chamber was used to heat the fiber at different temperature levels upstream of the homogeneous zone, the fiber being maintained at 20°C downstream in the linear heating body. The Figure 7 below shows the different temperature profiles observed according to the temperature in the fiber localized before the bench. The results show that the temperatures observed by the device in the 10 first meters of the heater are biased by the temperature upstream of the fiber, which is not the case beyond. The error of measurement is proportional to the value of the temperature in the heat zone.

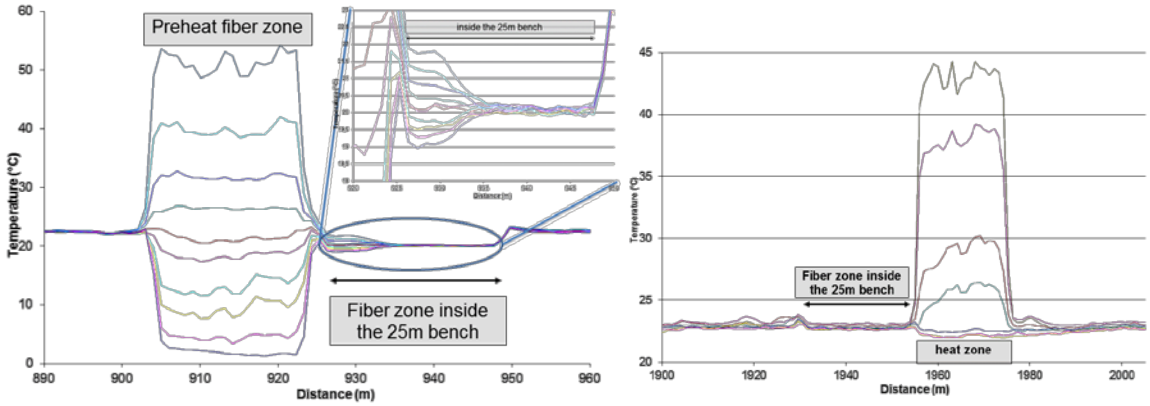

Figure 7: Temperature profiles observed in function of the level of temperature in a heat zone positioned before (left) or after (right) the 25 m linear bench.

CONCLUSION

Andra and the national metrology laboratory have been collaborating on the development of technical solutions to the durable management of radioactive waste, and more specifically on the long-term monitoring of geological disposal and of surface environment of repository.

A first result of the contribution of the metrology to the development of suitable optical sensors was introduced. Results demonstrated the influence of the temperature in the zone before the working session. The changes in the state of polarization in the two regions can explain the presence of a 10 m sensing error zone.

The development of suitable measuring equipment can be very challenging as it has been already demonstrated in several tests carried out in URLs around the world. LNE provides its technical assistance to these studies in its fields of expertise, for instance as presented above in the metrological characterization of measuring systems, for which reliable measurements and long term stability over decades are required.

Would the generation of the next century understand procedures elaborated in 2013? Andra will probably face in the future a strong evolution in the scientific domains. The concepts, language, mathematical tools used within this collaboration belong to a technical framework continuously revised by Metrology Organisations.

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