# Developing the Tools for Geologic Repository Monitoring - Andra's Monitoring R&D Program - 12045

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## ABSTRACT

The French Safety Guide recommends that Andra develop a monitoring program to be implemented during repository construction and conducted until (and possibly after) closure, in order to confirm expected behavior and enhance knowledge of relevant processes. To achieve this, Andra has developed an overall monitoring strategy and identified specific technical objectives to inform disposal process management on evolutions relevant to both the long term safety and reversible, pre-closure management of the repository. Andra has launched an ambitious R&D program to ensure that reliable, durable, metrologically qualified and tested monitoring systems will be available at the time of repository construction in order to respond to monitoring objectives. After four years of a specific R&D program, first observations are described and recommendations are proposed.

## INTRODUCTION

The French National Radioactive Waste Management Agency (Andra) is in charge of long-term management of radioactive waste produced in France. In the framework of this mission, Andra put its expertise and know-how at the service of the French State to implement safety solutions of management for all radioactive waste in order to protect the present and future generations from waste-associated risks. Andra operates two surface repositories to dispose respectively of low- and intermediate-level short-lived radioactive waste and of very-low-level radioactive waste, both located in the Aube district. Andra also manages a surface repository, which has entered its post-closure monitoring phase since 2003 and is located in the Manche district, adjacent to the AREVA La Hague facility.

After having concluded a feasibility study of deep geological disposal for high-level and long-lived radioactive waste in 2005, Andra was charged by the Planning Act n°2006-739 [1] to design and create an industrial site for geological disposal called Cigéo. The Planning Act also imposes that such a repository be reversible for at least a century-long period. An underground research laboratory for carrying out scientific and technological experiments was built by Andra during the early 2000's in the community of Bure in the Meuse district. Current planning includes assembling all elements necessary for a license application for Cigeo to be filed in 2015 and, pending authorization, the repository construction should begin in 2017 and be ready for commissioning in 2025.

The Cigeo underground installations will be built progressively and operated over a roughly 100 year period. In the framework of this project, monitoring, which in Andra's project is called "Observation and Surveillance", of the environment and repository structures - disposal cells in which waste packages are emplaced, access infrastructures including galleries and shafts/ramps, and eventually plugs, seals and backfill - should provide required information to aid repository operation, to support decisions that need to be taken during the reversible management of the disposal process, and to provide data needed to verify and support the basis for long term safety. Andra defines “surveillance” as the permanent verification of a process, of the correct state of devices and systems, and that operations remain within adequate bounds. We define “observation” as being the action of continuously considering features, events and processes. From a scientific point of view, it is an investigation process for verifying and enhancing the corresponding phenomenological knowledge. The Observation - Surveillance data should thus contribute to updating the safety analyses during operation and after closure, should emphasize evolutions likely to provide information on the flexibility available for future decisions and on the environmental conditions for carrying out any decisions.

This monitoring system also needs to respond to legal and societal expectations expressed, in particular:

- In the 2006 Planning Act on radioactive waste management and the 2006 Act on transparency and safety,
- In the French Safety Guide [2], which recommends that Andra develop a monitoring program to be implemented at repository construction and conducted until closure, and possibly after closure, with the aim to confirming prior expectations and enhancing knowledge of relevant processes,
- In Environmental laws, requiring establishment of an environmental reference state consistent with the importance of the industrial project,
- During public debates, during conferences and seminars conducted to define reversible management…

To achieve these objectives, an overall monitoring strategy including waste package characterization prior to emplacement, observation and surveillance of disposal structures and the surface environment is being developed by Andra as part of the Cigéo project. This calls for the development and emplacement of a system for characterization and compliance control of waste packages and for a dedicated observation-surveillance system. The latter would be in addition to and independent of any standard monitoring equipment implemented to contribute to operational safety. The observation and surveillance system globally considers environment, waste packages and engineering structures.

Andra is setting up a long-term environmental observatory designed to collect the data necessary to evaluate any environmental impacts before construction. As Cigéo operational phase will be roughly century-long, many changes are expected in addition to potential evolutions generated by the industrial activities related to the repository (socio-economic evolutions, climatic changes, etc.). It will be important to be able to discriminate between the relative contributions of these various evolutions and the effective impact of the repository construction and operation.

A waste package acceptance process is developed to ensure the effective compliance with the acceptance criteria and technical specifications. Non destructive methods (characterization of dose rates, toxic elements, actinides discrimination, surface contamination, integrity, geometry, and mass) and analyses of waste packages will be performed with special equipment in either fixed or mobile units as so-called second level controls of compliance to specifications. In addition, to prepare for the potential need of future waste retrieval, these monitoring methods also need to be available in order to characterize waste package conditions if retrieval of certain waste packages were to be decided. The design and implementation of adequate systems requires further R&D.

Another key element of the overall monitoring strategy of geological disposal is the observation and surveillance of the subsurface installations. To achieve this, Andra has developed a monitoring strategy and identified specific technical objectives to provide disposal process management with information on process evolutions relevant to long term safety as well as those relevant to the pre-closure management, which implements reversibility requirements. This paper aims to develop the Andra strategy and R&D program to improve the observation and surveillance system for engineering structures.

## OBSERVATION-SURVEILLANCE STRATEGY FOR UNDERGROUND STRUCTURES

In addition to the operational safety system, Andra has planned to install a system for observing phenomenological evolutions, to support the periodic re-evaluation of the long-term safety of Cigeo and reversibility conditions. Such in situ investigations (monitoring) aim at verifying, confirming and further enhancing prior knowledge. They are not motivated by a need to compensate for a lack of prior knowledge or lack of confidence in predicting repository evolutions. Current understanding and predictions are based on experimental results obtained in surface and underground laboratories, as well as on modeling and simulations. This knowledge base will be verified, confirmed and enhanced based on data obtained in-situ, in the actual repository. It will be combined with prior knowledge – and possibly knowledge acquired through a parallel R&D program - to provide information needed for decision making to manage the disposal process. Such decisions refer to a view of stepwise disposal process management, structured according to steps of progressive construction, emplacement and closure of disposal cells, disposal fields regrouping a subset of all waste, and ultimately closure of the entire repository. The stepwise process also allows progressively updating and optimizing the design for future repository components. Finally, the stepwise process needs to consider the potential for redirecting the disposal process, including the potential retrieval of some or all of the emplaced waste.

The monitoring system is based on a combination of in situ instrumentation and nondestructive methods to obtain the required level of reliable performance. To optimize the device distribution, we take into account both the repetitive design of disposal cells and the homogeneity of the rock properties. This resulted in distinguishing pilot disposal cells that are highly instrumented and standard disposal cells where the instrumentation density could be reduced; monitoring will rely mostly on robotic nondestructive evaluations. If monitoring technologies do not comply with all monitoring objectives, real withdrawal tests of high level wastes in some pilot disposal cells are also planned to provide the possibility of carrying out visual inspection, destructive analyses and samplings on construction materials. Such cells are planned to be dismantled because of the potential disturbance of their component performances from the testing process.

Based on this overall strategy, Andra has analyzed the technical requirements that must be met by its monitoring equipment. First, these must be able to provide information on key THMCR (Thermal-Hydraulic-Mechanical-Chemical and Radiological) processes, to provide a three-dimensional image of a disposal component's behavior and thus to understand the underground installation functioning. Special emphasis is placed on monitoring the disposal cell interactions with the near-field.

At the disposal cell scale, the monitoring devices and installed equipment must further resist the severe environmental conditions existing in a repository, which may include high temperatures, high pressures, humidity and/or submersion, chemically aggressive environments, and levels of radiation that may degrade electrical and optical cable performance and accelerate sensor material deterioration, as some of the sensors will be placed in the immediate vicinity of waste packages. Typical requirements also include the longevity of expected monitoring (without real possibility of accessibility to maintain equipment, except by robotic devices) and the high level of needed confidence in signal reliability.

Such a robust, reliable functioning over relatively long periods of time – several decades are aimed for in specific in-situ monitoring contexts and the overall duration prior to repository closure may call for some of the monitoring results to span a period exceeding a century – presents substantial challenges for most available monitoring equipment. It thus motivates substantial efforts to be invested in a corresponding R&D program.

Finally, the absence of interference with barrier performance, in particular as regards long term safety, is a key requirement of the monitoring system. It should not degrade the favorable conditions and expected performance for long-term safety of the repository. This also motivates specific R&D to be carried out, with an emphasis placed on those approaches not interfering with barriers.

## R&D PROGRAM FOR OBSERVATION - SURVEILLANCE OF STRUCTURES

To match these requirements, Andra has launched an ambitious R&D program to ensure that reliable, durable, metrologically qualified and tested monitoring systems will be available at the time of repository construction to respond to these monitoring objectives. The developments have emphasized (i) monitoring strategy, especially as pertaining to the distribution of monitoring systems throughout the disposal period, (ii) the design of monitoring units according to a qualification procedure, and (iii) a comprehensive set of R&D activities to adapt, complement and qualify existing technology.

Based on a thorough analysis of available state-of-art technologies, and ongoing monitoring of further developments provided by industry at large, Andra is adapting available sensors, where necessary, to meet the technical requirements for monitoring equipment to be used in the repository. In addition, developments were initiated when no adequate commercial technology was found to respond to such specific requirements. For example, Andra has launched R&D on wireless data transmissions through sealing (in collaboration with RWMC, Japans' Radioactive Waste Management Funding and Research Center) and on chemical and gas sensors, to increase their durability and/or limit the need for maintenance.

For all developments, Andra has specified a multi-stage qualification procedure, to ensure robust and thorough metrologic understanding of the developed measurement systems and aims at defining and implementing corresponding reference standards. As an example, vibrating wire sensors (VWS) have provided good results for monitoring strain or temperature in concrete structures and are foreseen for use in the repository. This type of very robust sensor has been used for many decades in Civil Engineering. Such VWS installed in Le Mont Larron dam have been in operation since 1950 and continue to provide reliable data. The principle of the measurement is based on the vibration of a steel wire, material known for its longevity. The simplicity of the measurement provides a failproof system that does not require any drift correction, nor periodic maintenance. Andra has internal feedback [3], especially from the low-level waste disposal facility, where VWSs were installed in the 1990s, and more recently in the Andra Underground Laboratory, where VWS were installed to monitor the access shafts and galleries.

VWS are however still undergoing developments focused on enhancing use of obtained measurements [3] and on hardening the units for operation in an ionizing radiation environment. The possible influence of the measurement method, and recently the method for laboratory

calibration prior to field installation were investigated. Further on, the influence of radiations on those sensors was also tested.
In addition to local sensors, distributed temperature and strain measurements by optical fiber sensors (OFS) are planned in the overall monitoring system, in order to provide a 3D image of disposal cells. Over the last twenty years, reliability issues have been detrimental to the market penetration of OFS. These difficulties have since been resolved by restricting proposed approaches to interferometry-based techniques. Given that encouraging results were obtained over the past few years, OFS are now being progressively implemented in monitoring the structural integrity of engineered systems.

The ability to multiplex sensors is very attractive for monitoring underground repositories using optical fiber sensors. Distributed technologies, i.e. continuous measurements along the optical fiber looks to be extremely promising in the field of instrumentation. Indeed, the ability to measure over a fiber's entire length removes the requirement of an initial precise designation for the measurement site positioning. Instruments providing strain and temperature distributed measurements are now commercially available. They rely on scattering phenomena within the silica cores of fibers, combined with localization processes (such as pulse-echo) [4].

However, an optical fiber is too fragile to be used without specific isolation from the repository environment by appropriate surface coatings. The fiber coating must also ensure an optimal transfer of temperature and strain fields from the host material to the optical fiber. The fiber only measures deformation transmitted to it by its coating, and thus only provides a good measure for host material deformation if that deformation is transmitted completely to the fiber. Sensing cables are designed with different materials and shapes, either to be embedded in soil, metallic or concrete structures, or attached to their surfaces. Up to now, these cables have not been exhaustively tested. Full scale laboratory experiments were carried out by Andra and its partners using various sensing cables and optoelectronic instruments, under controlled conditions. Concrete specimens [5], a soil structure and a metallic structure were instrumented. Strain measurements performed with distributed sensing systems were found comparable to values obtained with conventional sensors used in civil engineering, namely WVS.

In radioactive waste repositories and more precisely at the external surface of the metallic liners of high level waste cells, dose rates are reasonable for instrumented systems but total dose may reach $10^7$ Gy after a century of monitoring performed by OFS. Nevertheless, instrumenting the disposal cell liner is necessary to provide adequate verification of the near-field and cell processes. Andra tested various types of optical fibers and the influence of the dopants on the sensing performances [6]. We also started investigating the physics at the origin of the observed (i) increase of propagation losses and (ii) spectral shifts of Brillouin scattering: Defects induced inside silica as a function of doses and operating wavelength [7], silica compaction phenomena versus photo-blenching produced by the pump laser of the measuring device. Fluorine doped fibers were found to be suitable for a radioactive waste repository environment.

Our current developments can rely on tried and proven technology for monitoring key thermal, hydraulic and mechanical parameters. The actual developments emphasize adapting and hardening those technologies to environmental conditions and qualifying the corresponding monitoring system. Providing chemical sensors for reliable, long-term monitoring, however, presents a significantly greater challenge, that must nevertheless be met given the potential interest of obtaining in-situ data on chemical parameters. Candidates are local acidity (pH) and reducing conditions (Eh) as they influence construction material degradation rates, buffer and seal material swelling properties, and potential future waste form dissolution rates and levels of solubility. Additional candidate parameters for monitoring the repository performance include long term measurements of the concentration of environmental gases, e.g. oxygen or hydrogen.

As an example, developments on solid-state sensors manufactured with argillite components (raw Callovo-Oxfordian argillite, purified argillite, or pyrite) or silicon semiconductor technology for measuring pH are in progress. Likewise, developments onstructures for measuring conductivity and redox potential are in progress [8]. All developments are conducted in order to reduce the drift of sensors and probes over time.

The above considerations show that, while a concise R&D program to adapt and develop monitoring technologies holds promise for providing the tools needed for in-situ monitoring, it takes considerable time to progress from a good candidate sensor to a monitoring system that is fully qualified for its environment. Taking into account the technical requirements, a large part of the activities is devoted to adaptation of existing technology to match the specific needs. However, when existing monitoring technology is not suitable, as is the case for chemical parameters, it is important to consider the time needed for development of new technology, which can be from a few months to over a decade.

## CONCLUSIONS

The results derived from 4 years of Andra's R&D program allow three main observations to be shared. First, while other industries also invest in monitoring equipment, their obvious emphasis will always be on their specific requirements and needs, thus often only providing a partial match with repository requirements. Examples can be found for all available sensors, which are generally not resistant to radiation. Second, the very close scrutiny anticipated for the geologic disposal process is likely to place an unprecedented emphasis on the quality of monitoring results. It therefore seems important to emphasize specific developments with an aim at providing metrologically qualified systems. Third, adapting existing technology to specific repository needs, and providing adequate proof of their worth, is a lengthy process. In conclusion, it therefore seems prudent to plan ahead and to invest wisely in the adequate development of those monitoring tools that will likely be needed in the repository to respond to the implementers' and regulators' requirements, including those agreed and developed to respond to potential stakeholder expectations.

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