A TSO research programme on the safety of geological disposal and its necessary evolution along the development of a national industrial project

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Abstract:
In the frame of the geological disposal, this paper presents an overview of the research, past and current, carried out by IRSN to improve its technical safety evaluation of the implementor's file. This highlights the interest for a TSO to handle its own research programmes to support its expertise, and their evolution with stages towards implementation.

1 CONTEXT

The French National Radioactive Waste Management Agency (Andra) is responsible for designing, constructing and operating a deep geological radioactive waste disposal facility (DGR). Pending approval, this facility will be opened in eastern France in 2025. Meanwhile, Andra has been operating an underground laboratory in Bure (Meuse) since 1999, where it carries out studies and research.

To ensure an independent assessment of Andra's project, and due to time constraints, it is important to anticipate the development of knowledge and resources required to assess risks associated with geological repository. Thus, IRSN identified very early in the French geological repository project development the scientific issues that had to be addressed in priority. This led IRSN to carry out for the past 20 years its own research in various experimental installations, in order to examine processes that play an important role in ensuring the long-term safety. This was managed via a pluri-annual research programme, so as to develop IRSN staff skills and anticipate the needs for new knowledge. This research programme is now structured upon the new main steps related to the development until 2015 of the high-level and long-lived intermediate-level waste repository project as prescribed by the French Planning Act of 28 June 2006 on the sustainable management of radioactive materials and waste. It is updated annually and reviewed periodically by a scientific committee and organised in order to addressing several "key safety issues" as presented below.

2 OVERVIEW OF THE IRSN R&D PROGRAMME

2.1 Generalities

Four categories of major questions are addressed: i) the adequacy between experimental methods and data foreseen, iv) the knowledge of complex coupled phenomena, iii) the identification and confidence in components performances and iv) the ability of the components to practically meet in-situ the level of performances required. Addressing these questions motivated the research programme development along the following lines:

- Test the adequacy of experimental methods for which feedback is not sufficient. The assessment of their validity allows addressing the consistency and degree of confidence of the data produced;
- Develop basic scientific knowledge in the fields where there is a need to better understand the complex phenomena and interactions occurring all along the life of the repository and their influence on nuclear safety, so as to preserve an independent evaluation capability in these matters;
- Develop and use numerical modelling tools to support studies on complex phenomena and interactions so as to allow assessing orders of magnitudes of components performances and physico-chemical perturbations but independently than specified and estimated by implementers;
- Perform specific experimental tests aiming at assessing the key parameters that may warrant the performances of the different components of the repository. Such experiments are designed in particular to simulate the behaviour of components in altered conditions and allow delivering appraisal on the specifications of construction that are to be proposed by the implementer.

2.2 Evolution with time of the research topics

The topics covered by the IRSN research programme can be splitted in the following items:

- Site characterization and DGR development;
- THMC perturbations;
- Physico-chemical evolution;
- Global modelling of solutes and gaz transfer from the DGR.

The evolution with time and the research effort devoted to each items is schematized respectively in Figures 1 to 4.

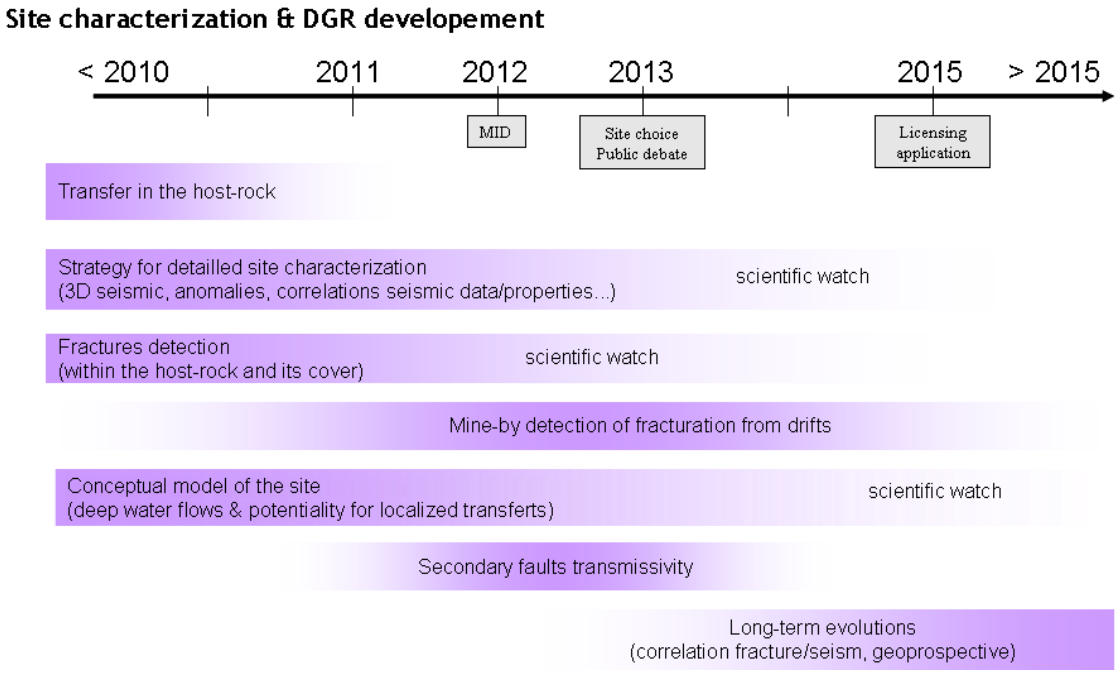

Figure 1. Time-evolution of research topics on site characterization and DGR developement

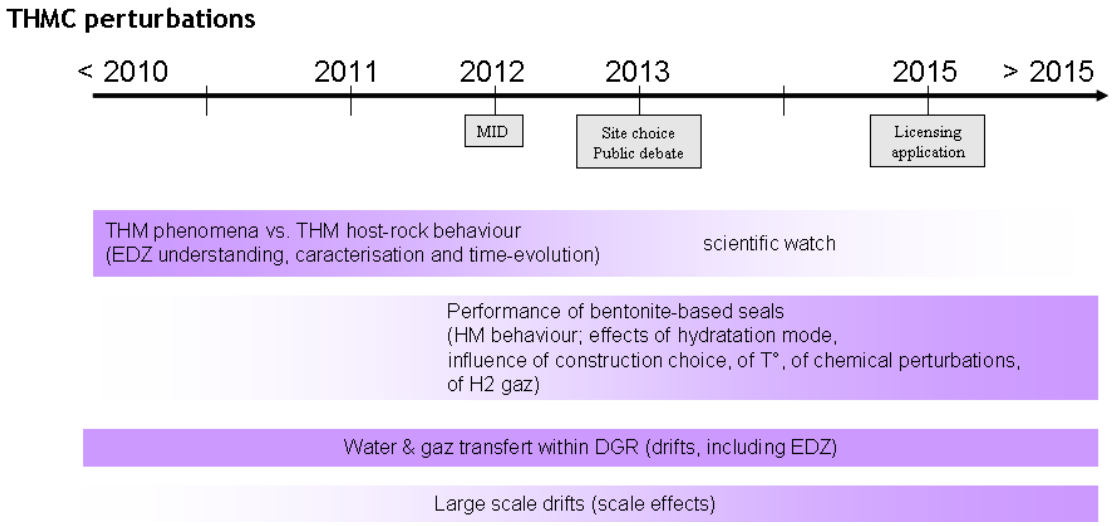

Figure 2. Time-evolution of research topics on THMC perturbations

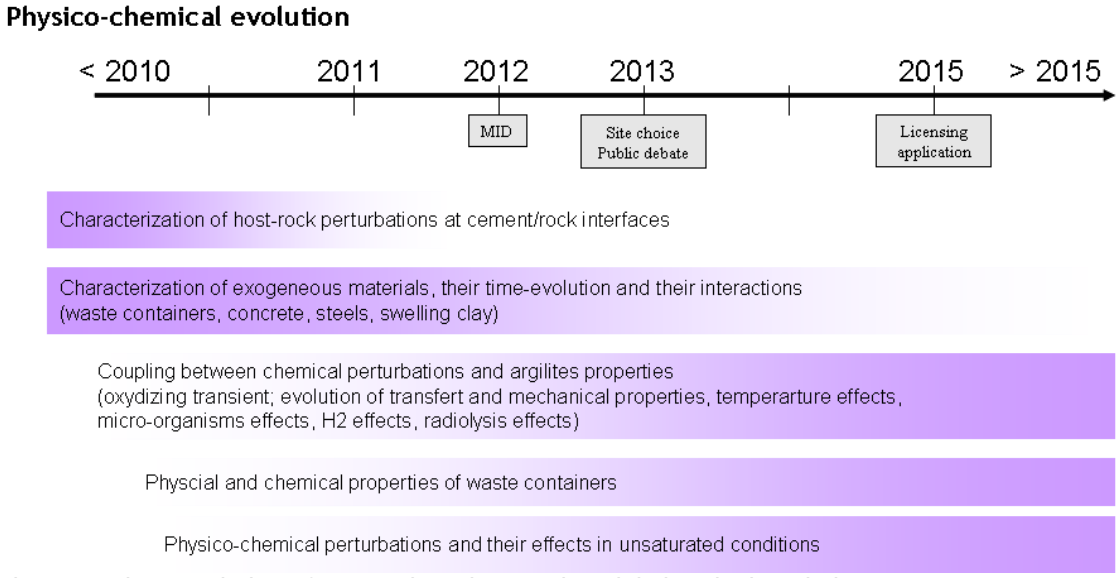

Figure 3. Time-evolution of research topics on physcial chemical evolution

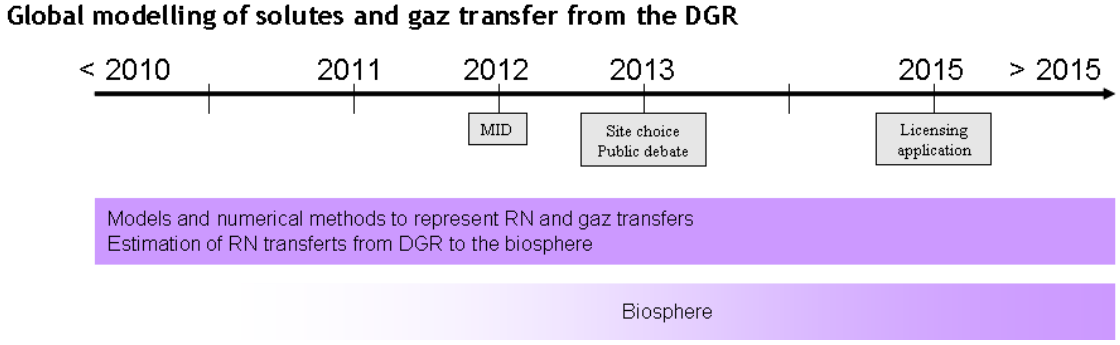

Figure 4. Time-evolution of research topics on global modelling of solutes and gaz transfer from the DGR

All the related studies were and are carried out by the mean of experiments performed either in IRSN surface laboratories (Laboratory of analyses and Experimental Resources), or in the Tournemire URL operated by IRSN.

2.3 The Tournemire URL

Acquired in 1992, the Tournemire experimental station, together with the Mol (Belgium), Mont-Terri (Switzerland) and Bure (Meuse, France) laboratories, is one of the four underground laboratories in Europe carrying out research on disposal in clay formations. Located in a former railway tunnel built over 120 years ago, this URL allows access to a clay formation that has similar geological characteristics to the Meuse-Haute Marne site.
The Tournemire experimental station is solely used for scientific and technical research. There is no intention of disposing of radioactive waste there at any time in the future. Furthermore, no radioactive components are brought to this site for the purposes of the research carried out here.

2.3.1 Geological and tectonic features

Tournemire is located in the western part of the Causses Permo-Mesozoic sedimentary basin (SW France). The basin is surrounded by gneissic and granitic Palaeozoic basement rocks. The southern limit of the basin is underlined by the regional Cévennes fault system that separates the Causses from the alpine domain (SE basin).

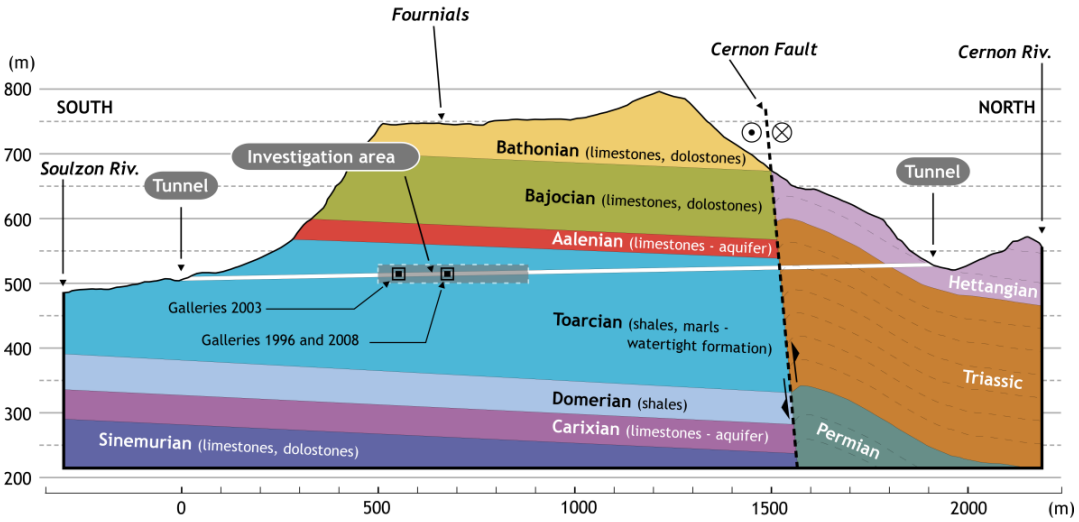

Figure 5. Geological cross-section along the Tournemire URL

The URL is located in a 250-metre thick argillaceous layer that is surrounded by limestone rocks (see Figure 5). Usually less prone to fracturing than other types of rock (limestone and granite, etc.), this argillaceous rock exhibits features some faults and fractures of various sizes (millimetric to decametric scales) that formed 40-50 million years ago (formation of the Pyrenees mountains) or issued from the reactivation of earlier structures (opening of the Tethys ocean, Middle Jurassic ≈ 170 million years ago). This clay formation is a fine-grained sedimentary rock composed predominantly of indurated clay particles, commonly referred to as argillites This rock is composed of approximately 50% clay, the remaining portion being composed of quartz, carbonates, and secondary minerals (pyrite, etc.). Compact and hard, it contains very little water (3.5-4.5% in weight), which is trapped in pores around ten nanometres in diameter (porosity ranging between 7 to 8 %).

2.3.2 Tournemire tunnel and the Underground Research Laboratory

Excavated at the end of the 19th century, the Tournemire railway tunnel is 1’885 metres long. It represents a unique opportunity, among other things, to observe the disturbances generated by an underground engineering structure excavated 120 years ago in an overconsolidated clay formation. The experimental station itself is made up of the former railway tunnel, six drifts which have a total length of 285 metres and over 225 boreholes excavated since 1999 (see Figure 6).

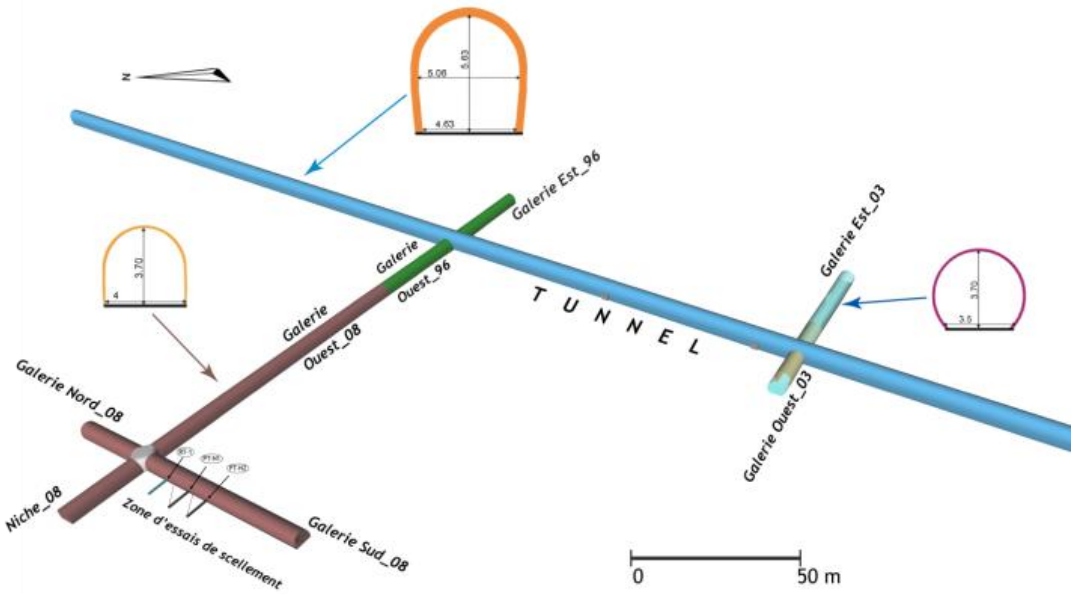

Figure 6. General view of the Tournemire URL

3 DETAILS ABOUT THE IRSN R&D PROGRAMME DEVELOPPED AT THE TOURNEMIRE URL

3.1 Main past programmes

A range of measuring equipments and observation techniques have been deployed at the Tournemire URL to analyse the argillite and its behaviour. The main experimental programs that have been developed are related to:

- Mechanisms responsible for the transfer of water and natural substances present in the clay formation;
- Effects of excavation and of using the underground engineering structures on the rock's containment properties;
- Faults and discontinuities detection techniques using a wide array of geophysical methods;
- Effects related to interaction between the rock and the exogenous materials, such as concrete and metal components;
- Performance of important components for the long-term safety of a geological repository, such as seals.

An overview of the R&D topics that have been addressed at Tournemire is given hereafter.

3.1.1 Migration of water in the argillaceous rock – Geochemical data

Apart from fractures, the rock studied at Tournemire exhibits an extremely low water permeability (< 10^{-14} m/s). The analysis of hydraulic tests and natural tracer profiles obtained for the whole argillaceous layer confirm that water circulates very slowly, about one centimetre per million years under the naturally imposed gradient. The major method of radionuclide transfer is therefore limited to the molecular diffusion process. However, through certain tectonic fractures and joints water may circulate more rapidly. Geochemical results indicate that water flowing within these fractures and joints originate from the calcareous formations located on either side of the clay layer and that they have a residence time of around 15,000 years. In comparison, water circulating through the calcareous rock on either side of the argillite layer has residence times of around 50 years.

3.1.2 Effects of excavating in the argillaceous rock – Geomechanical and Geophysical data

The mechanical properties of the argillaceous rock at Tournemire, and the fact that it is compact and hard, make it brittle. Excavation works therefore create mechanical disturbances extending from a few tens of centimetres (in the drifts) to around two metres (in the 120 year old tunnel), causing irreversible plastic deformations, manifested by the development of fractures. The extent and the intensity of this area, so-called the EDZ (Excavation Damaged Zone), evolve over time due to the different thermal, hydraulic and chemical loadings. More permeable than the undisturbed argillite layer, the EDZ is likely to be a preferential pathway for water flow and solutes migration.
In addition to the mechanical disturbance caused by excavation for the engineering structures, there is further fissuring induced by the drifts ventilation and the subsequent desiccation of the rock (hydro-mechanical coupling phenomena).
Characterising these fractures and fissures, and how they develop in space and time is therefore an essential part of assessing the safety of long-term disposal, and this was largely developped through previous works. In addition to classical methods (cores and boreholes survey), this has also been achieved using geophysical method (borehole seismic, multichannel analysis of surface waves, electrical resistivity 2D tomography).

3.1.3 Detection of tectonic faults (tectonic discontinuities) – Geophysical data

Due to the specific geological history of the Tournemire area, several families of faults occur in the argillite. Especially, strike-slip secondary faults (small vertical offset lower than 2 m, length on the order of hundreds of meters, thickness ranging from meter to tens of meters) are well evidenced by observation made from the underground drifts.
Detecting accurately such faults in clayey rocks from surface geophysical surveys and from existing underground drifts remains one major challenge, even using high resolution seismic surveys. Therefore, an important effort has been spent to pushing the methods as much as possible, including development of new interpretation methods, in order to evaluate the potentialities and limits of these geophysical methods.
Insights and conclusions gained in these research works have been used extensively for the technical expertise of the geological part of the implementor's file.

3.1.4 Disturbances to the rock associated with exogenous materials – Geochemical data

The purposes of these experimental programs were to identify and characterise the disturbances caused to the rock by materials brought into the geological environment from the outside. Dedicated experiments were thus conducted on cementitious (lime, concrete and hardened cement paste) and metal materials (iron) used in support lining or as plugs for closing the mouth of disposal cells. Interactions between these materials and the clayey minerals in the rock can alter the geochemical properties of the rock and compromise its ability to contain radionuclides (swelling and containment properties alteration). The samples analysed from the chemically-disturbed zone reveal that alteration fronts can be as large as a few centimetres in the presence of water, and this over a period of contact ranging between one to a few decades.
The Tournemire experimental station is a very useful tool for this type of test: the lime used as cementing material for the facework masonry in the tunnel, which is similar to concrete, has been in contact with the rock for over 100 years, in other words, for a period comparable to the operating lifetime of a disposal facility.

3.1.5 Performance of disposal sealing components – Geomechanical data

The safety of a long-term geological disposal facility largely depends on the effectiveness of the systems used to close up the engineering structures. In particular, these systems imply

the use of seals. These are made of a natural swelling clay-based material which ensures continuity of the containment provided by the rock.
At the Tournemire experimental station, the SEALEX research project is dedicated to assessing the effectiveness and robustness of such seals over time. This project involves examining the key factors that regulate the long-term hydraulic performance of the seals.

3.2 Ongoing R&D actions

The ongoing and planned R&D actions performed at the Tournemire URL during the next 5 years are given in the table below, and they are detailled in the following sections.

Table 1: Main ongoing experiments at the Tournemire URL.

Key issues	R&D needs	Tournemire in situ experiment
Long-term stability: Performance assessment	- Perturbations and their influence on the confinement properties of the disposal components - Technical feasibility of seals with respect to their safety functions and their expected performance level	**SEALEX** SEALing EXperiment
Long-term stability: Internal perturbation	Engineered Barrier System / Host rock interactions in saturated conditions at 70°C - Chemical evolution (solid and pore solution) - Microstructure evolution - Composite effective diffusion coefficient evolutions - Validation of numerical blind simulations	**CEMTEX** Cement Temperature EXperiment
	Estimating the duration of the oxidising transient within the steel/clay interfaces - Host rock oxygen consumption (with and without steel) at different humidity degrees	**OXITRAN** OXIdising TRANsient
Groundwater and radionuclide movement: Water flow in clay host rock	Water transport properties within a fault zone - In situ hydraulic testing - Mineralogical and petrophysical parameters - Porewater chemistry - Natural tracer profiles - Diffusion parameters (through and radial diffusion)	**FRACTEX** FRACture Transport EXperiment
	Hydraulic behaviour of faults and fractures - Porosity characterisation (nano- to microscopic scales) - Mineralogical and chemical evolutions - Magnetic properties	**PFAT** PetroFabric analysis of the Toarcian Argillite of Tournemire
	Evaluating fault seal integrity - In situ characterisation of hydraulic, elastic and strength properties - Estimation of flow times and lengths within different fault zones - Permeability-stress-strain evolution of silty claystones and mudstones - Geophysical imaging the architecture	**Hydro-Mechanical Properties of a Fault Zone**

	of a fault zone in clay rich formations	
Natural faults detection and GD monitoring	Detection of natural faults from: - the surface (very high resolution 3D seismic survey et very high resolution 2D electric resistivity profile), using advanced interpretation methods - existing drifts (very high resolution seismic at drift walls) - Feasibility test on large-scale tomography based on muons flux measurements	**Geophysical Survey**

3.2.1 Performance of disposal sealing components – SEALEX

The SEALEX project was built with specific focus on sealing systems efficiency (cell seals, gallery seals, shaft seals). The main objectives of the SEALEX experiments are to:

- Test the long-term hydraulic performance of sealing systems (in normal conditions, i.e. non altered), for different core compositions (pure MX80, sand/MX80 mixtures) and conditionings (pre-compacted blocks or in situ compacted powder);
- Quantify the impact of intra core geometry —construction joints in the case of precompacted blocks— on the hydraulic properties of sealing systems;
- Quantify the effect of altered conditions —an incomplete saturation of the swelling clay or an incidental decrease of the swelling pressure caused by a failure of the concrete confining plugs— on its performance, which tests the concept robustness with respect to the hydraulic characteristics of the system.

This project does not aim at demonstrating sealing capabilities of a geological disposal, which is the implementer's responsibility, but is devoted to test various technical parameters that could influence global hydraulic and mechanical performances of a seal.

3.2.2 Interaction between components – CEMTEX

The topic of clay/concrete interactions has been widely studied in the literature. Though a large amount of studies have been conducted on clay and/or clayey rock geochemical evolutions in an alkaline environment, very little is known on the cementitious material evolution.
During the last decade, the few studies that were performed on representative interfaces between cementitious and clayey materials (laboratory or under in situ conditions) were carried out at temperatures ranging from 15 to 50°C. However, is now generally accepted that the temperature in the future HL-ILLW geological disposal site will reach at least 70°C and will hence modify more significantly the reactive mechanisms and potentially accelerate the extension of the perturbation front in both materials.
For this reason, IRSN has started the CEMTEX project which main objectives are to:

- Create cementitious material/argillite interface in saturated conditions at 70°C to characterize accurately: 1/ the chemical evolutions of the cementitious and clayey materials; 2/ the evolution of the porosities; 3/ evolutions of the composite hydrodynamic properties;
- Cross-characterizations results between in situ and laboratory experiments to estimate the length scale influence;
- Validate blind numerical simulations (water/rock equilibrium in concrete and clays + reactive transport at the interface) at 70°C.

3.2.3 Duration of the oxidizing transient - OXITRAN

The geological disposal for high level waste (HLW) involves stainless and carbon steel components. Up to now, most studies on steel corrosion in clayey media have been focused on reactivity under reducing conditions since, at the timescale of the geological disposal, minerals such as pyrite are supposed to impose a reducing environment. However, soon after closure of HLW cells, the entrapped oxygen introduced in the disposal cell during the operational stage may induce an oxic corrosion of metallic structures until the whole consumption of oxygen. Under humid conditions, oxic corrosion may lead to drastic corrosion rates. Therefore, the assessment of steel corrosion can crucially depend on the oxidizing period and its duration
The OXITRAN (OXIdising TRANsient) project was launched to understand the evolution and the duration of the oxidizing transient in the Tournemire argillite, in presence and absence of steel, and in unsaturated in situ conditions. This project aims at answering two questions:

- What is the oxygen consumption rate by the argillaceous rock for a given volume of gas and exposed rock surface?
- What is the oxygen consumption rate by steel corrosion for a given exposed metal surface, exposed rock surface and gas volume?

The main objective of such an experiment is finally to build a sufficient knowledge on oxygen consumption in the conditions prevailing in a HLW disposal cell in order to model accurately the oxidizing transient and to transpose to long-term simulation on disposal cells.

3.2.4 Transport properties within faults - FRACTEX

The FRACTEX project aims to assess transport properties within fractures and faults through a series of in situ and laboratory experiments. The different tests aim at evaluating the contribution of both diffusive and advective processes on water flux through a (1) damaged (2) disturbed and (3) undisturbed argillite rock.
The targeted structure for this study is a narrow subvertical strike-slip fault zone displaying a 2 meter vertical offset. A 50 meter-long horizontal borehole (diameter 101 mm) intercept the structure at a distance far enough from the tunnel and drifts so as to minimize the hydro-mechanical perturbations of the excavation damaged zone (EDZ). Mineralogical and petrophysical characterization of the rock have been performed systematically along the entire borehole.
Immediately after drilling, the borehole has been equipped with a Mini Multiple Packer System (MMPS) where in situ hydraulic tests (pulse-test) are performed on the damaged, disturbed and undisturbed argillite rock. Additional laboratory hydraulic tests will be carried out on argillite samples selected to represent the different rock conditions (damaged, disturbed and undisturbed argillite).

To complete this hydraulic characterization, radial and through diffusion experiments of artificial water (HTO), anionic ($^{36}Cl^-$) and cationic ($^{22}Na^+$) radiotracers are also currently being carried out. The comparison between the time required to propagate a perturbation by advection and the diffusive transport time will allow to assess the relative significance of advective and diffusive transport for the different rock conditions.

The FRACTEX experiment should also give the opportunity to acquire a horizontal profile of natural tracers (^{2}H, ^{18}O, Cl^{-}) and noble gas (^{4}He) distribution in the pore water. The data will be obtained by means of equilibration methods (vapour-exchange and radial diffusion experiments).

3.2.5 Argilites petrofabric within undisturbed vs. fault zone - PFAT

This project aims at investigating the petrofabric (porosity, mineralogy and textural organization) of a fault zone from the Upper Toarcian argillites of Tournemire at different scales (millimetric to nanometric) by XRD, TEM, SEM-EDS, X-ray microtomography and Focussed Ion Beam (FIB) methods. The study focuses on characterising the (1) undisturbed and (2) disturbed argillite, and in particular the dark bands within one of the Tournemire fault zones that is interpreted as resulting from a phenomenon of called "clay smearing" (often suggested as fault sealing mechanism). The results will enable significant improvement in characterizing mineralogical and permeability modifications within a clay-based fault zone and could explain the hydraulic behaviour of a sealed fault (FRACTEX).

3.2.6 Hydro-mechanical properties of a fault zone - FF

This project aims to define a permeability-stress-fluid pressure law from a sealed fault zone at the Tournemire Experimental Platform based primarily on parameters measured from in situ experiments.

Two main questions will be addressed through this project:

- At what overpressure will the permeability of a clay-based fault increase for a given stress condition and tectonic context?
- In a defined condition and for a given overpressure, which mechanical conditions will cause significant permeability increase?

In order to answer these questions the project is organized in three tasks:

- A mesoscale experiment, the aim is to perform in situ permeability test in a fault zone while monitoring strain and microseismicity;
- A series of laboratory experiments which aims to characterize the evolution of Vp, Vs and permeability during deformation in the laboratory of the material from the mesoscale experimental site;
- Numerical modeling, with primary objective to test the proposed permeability-stress-pore pressure on the experimental results (both mesoscale and laboratory scale). Classical continuum mechanics approaches (Finite Element and Finite Difference Methods) will be used to assess effective properties from the mesoscale experiment. Discrete Elements (DEM), will be used to address coupled deformation processes at the micro-scale, and to provide insight on laboratory to formation scale change.

3.2.7 Geophysical survey

Advanced evaluation of detection methods for natural discontinuities from the surface, using very high resolution surveys (3D for seismic, 2D for electrical resistivity), coupled with innovative treatment methodologies (e.g. non local method based on Common Reflector Surfaces, and modeling).
From the existing undergrounds drifts, application of seismic methods (reflection, transmission, guided waves), survey of the background acoustic noise.
Last, a feasibility test is currently ongoing to test the potentialities (and difficulties) of a large-scale tomography based on muons flux measurements, which is believed to provide valuable information to follow the geological disposal evolution in time.

4 PERSPECTIVES

The current research topics are running for several years. Later on, provided the geological disposal is effectively moving towards implementation, the research programme should naturally evolve, in particular incorporating topics related to monitoring of operating rules and assessment of disposal evolution during the operational phase.