Long-lived high-level radioactive waste: The research phase in French underground laboratories

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On 9 December 1998, the French government announced that it decided to authorise the implementation and operation of an underground laboratory at Bure, in Eastern France, in order to further research on the disposal of long-lived high-level radioactive waste in deep geological formations. The Bure laboratory will provide access to the Callovo-Oxfordian sedimentary clay formation situated at a depth of approximately 450 m. The decision to implement the laboratory was combined with a request to seek another laboratory site where further investigations could take place in granitic formations.

Those decisions were formalised on 3 August 1999 by decrees stating the applicable terms and conditions to continue research activities and giving the green light for operations to start on the sites. The decrees constitute a major step in the process defined by the Law of 30 December 1991 concerning research on radioactive waste management. The Law, in fact, specifically calls for the "evaluation of options for retrievable or non-retrievable disposal in deep geological formations, particularly through the creation of underground laboratories".

The objective of the Law of 30 December 1991 is to provide the government, after 15 years of research (*i.e.,* 2006), with sufficient elements to assess whether the implementation of a repository is possible or not. Through the efforts made during the last 10 years, not only on the sites under consideration in France, but also in foreign laboratories, the necessary experience has been gathered to comply with the objective of the Law within the prescribed deadline.

1. Situation

One of ANDRA's missions is to conduct research on waste disposal in deep geological formations. Studies on projects for the implementation of underground laboratories could not be undertaken before consultations with elected officials and the populations concerned were over. The mediation mission conducted by Mr Christian Bataille, Member of the French National Assembly, led to the selection of four sites:

- In the Meuse department, in the Callovo-Oxfordian clay formation;
- In the Haute-Marne department, in the same type of formation;
- In the Gard department, again in the same type of formation;
- In the Vienne department, in a granitic formation.

As soon as the first investigation started on the sites, the Meuse and the Haute-Marne sites were combined to form the Eastern site, taking into account the continuity of the formation under consideration and the similarity of its characteristics. Survey work from the surface continued on the sites from 1994 to mid-1996. They basically consisted in drilling boreholes designed to gain a better knowledge of the formations' main characteristics and to verify the structures on the basis of geophysical measurements. At that stage, the purpose was to make sure that none of the site characteristics could compromise further research in accordance with the recommendations of Basic Safety Rule RFS III.2.f, published by the Directorate for the Safety of Nuclear Installations (*Direction pour la sûreté des installations nucléaires – DSIN*) in 1991.

During the summer 1996, implementation and operation authorisation applications (and their supporting documentation) were submitted for the creation of three underground laboratories, in Eastern France and in the Gard and Vienne departments, respectively. Those applications were submitted to a technical and administrative review by competent authorities. Public inquiries, also prescribed by the review procedure, were held mostly in 1997. In February 1998, the government requested complementary information on reversibility. A mission was entrusted in that regard to the National Review Board, whose report was presented the following June. The decision made public on 9December 1998 and the decrees signed on 3 August 1999 allow for the investigations to continue on the sites.

First of all, with regard to granite, and in accordance with the process prescribed by the Law of 30 December 1991, a consultation mission is established prior to the selection of one or several sites. Its purpose is to consult with the elected officials, associations and populations concerned and to present them with the economy of the overall project, especially with respect to the research programme, its integration into the radioactive-waste-management policy, the potential nuisance of the preliminary work to its implementation and the means taken to overcome them. ANDRA will only be allowed to launch *in-situ* research work from the surface, once the consultation mission has presented its report to the Ministers responsible for the Environment, Energy and Research. Since the decision was announced on 9 December 1998, ANDRA has endeavoured, with the support of the expertise of the Geological and Mining Research Office (*Bureau de recherches géologiques et minières – BRGM*) and on the basis of updated information, to redefine the desirable characteristics for granitic massifs as a scientific support to the activities of the consultation mission. Following the favourable opinion of a committee consisting of international experts, the pre-selection approach was submitted to the National Review Board. That approach is based on a succession of various criteria:

- A geometry of the granitic bodies with a sufficient *a priori* capacity to accommodate the disposal of the projected waste stock;
- Structural characteristics presenting a low fracture rate and, thus, favourable hydrogeological properties for a repository;
- A geochemical composition allowing the self-healing of fractures during the hydrothermal history;
- A very low attractiveness of potential mineral resources

In accordance with the decree, the purpose of the investigations and experiments to be carried out in the underground laboratory situated on the Eastern sedimentary site, is to gather the necessary data for the design, optimisation, compliance with reversibility and safety requirements of a potential repository for radioactive waste. Various themes will be examined, among which:

- The constructibility of structures and the reversibility conditions of the repository;
- The capacity to seal off the repository structures
- The extension of the disturbances due to a repository;
- The containment capacity of the Callovo-Oxfordian geological formation;
- The transfer possibilities of radioelements and toxic elements between the Callovo-Oxfordian formation and the biosphere;
- The regional seismic, geological and hydrogeological context.

Planning for the 2006 deadline requires ANDRA to prioritise experiments in the underground laboratory and to structure data acquisitions around the following themes:

- Constructibility: to show the technological possibility of building the projected structures and equipment for the repository concept under review, while taking into account the reversibility requirement;

- Geology: to define the spatial distribution of the various facies in the host geological formation (Callovo-Oxfordian) and to assess the consequences on the distribution of

its physical and chemical properties, notably in relation to the required containment function for the disposal of long-lived high-level radioactive waste;

- Modelling and safety: to verify over a period of several years the conceptual and quantitative modelling of the phenomena taken into account in the safety assessments of the repository design under review, as well as in the assessments of its reversibility. The purpose, at that stage, is to assess the envelope character of the modelling, the safety objective being to allow an assessment of the containment system in relation to the 0.25-mSv exposure limit for the public as prescribed by Basic Safety Rule RFS III.2.f.

In 1996, ANDRA submitted the main objectives of the investigation programme in its authorisation application for the implementation and operation of the underground laboratories. That programme was proposed on the basis of the acquired knowledge during the surface survey work. In parallel, for the last 10 years or so, ANDRA has gained, through its participation in experiments conducted in methodological underground laboratories abroad, the necessary feedback and knowledge for an efficient preparation of its investigations concerning implementation and planning procedures as well as instrument selection. Only projects in clay formations are concerned in the rest of this paper.

2. Research in underground laboratories

Some laboratories are qualified as “methodological”, if they have been operated by the different countries to develop the competencies and know-how for a subsequent application in underground laboratories on site. Their objective is to assess the containment capabilities of the potential repository sites. Work carried out in methodological laboratories has led to numerous investigations, technological advances and the development of specific methodologies. The continuation of those activities in methodological laboratories, notably with foreign partners, helps ANDRA (along with its French contractors or partners) to have the necessary means, when needed, to implement and carry out its own experiments in underground laboratories on site.

In that context, ANDRA participates in the experiments conducted in foreign laboratories, such as Mol in Belgium, Aspö in Sweden, Pinawa in Canada, as well as Grimsel and Mont-Terri in Switzerland. Projects are organised in associations extending beyond bilateral agreements and, in some cases, under the aegis of the Commission of European Communities. Since 1996, the large-scale experiments in the Mont-Terri tunnel, in Switzerland, have been most helpful to target studies on clays with closer characteristics to those of the Eastern site.

The first experiments organised by ANDRA in clay formations date back to 1984 on the Mol site. The main projects undertaken since then are summarised in Table 1, together with their main partners.

Years	Experiment	Subject	Main partners (1)
1984-87	Mine by test		SCK-CEN, BRGM
1986-89		Dilatometric tests	BRGM, SCK-CEN
1987-92		Arch-equipped drift	LMS, SCK-CEN, SIMECSOL
1989-93	CACTUS	Thermomechanics	G3S, SCK-CEN
1992-95	ARCHIMÈDE	Water chemistry	BRGM, CEA, SCK-CEN
1992-96	PHÉBUS	Water transfers	SCK-CEN, ANTEA, CNRS
1993-94	BACCHUS	Hydromechanics of the sealing material	SCK-CEN, ENRESA, CEA
1996-99	RESEAL	Shaft sealing	SCK-CEN, ENRESA, CEA
1997-99	CLIPEX	Effect of excavation work	SCK-CEN, ENRESA, G3S

Table 1. Main experiments conducted by ANDRA in the Mol laboratory, Belgium

(1) *ANTEA* *BRGM subsidiary company, Orléans, France.*
BRGM *Bureau de recherches géologiques et minières* (Geological and Mining Research Office), *Orléans, France.*
CEA *Commissariat à l'énergie atomique* (Atomic Energy Commission), *Fontenay-aux-Roses, France.*
CNRS *Centre national de la recherche scientifique* (National Centre for Scientific Research), *France*
ENRESA *Spanish Radioactive Waste Management Agency, Madrid, Spain.*
G3S *Groupement pour l'étude des structures de stockage en souterrain* (Study Group on Underground Disposal Structures).
LMS *Laboratoire de mécanique des sols* (Soil Mechanics Laboratory)*, Palaiseau, France.*
SIMECSOL *Bureau d'études géotechniques* (Geotechnical studies Firm).
SKC-CEN *Centre d'essais belge* (Belgian Testing Centre)*, Mol, Belgium.*

In the Mol formation, the first tests dealt with the mechanical behaviour of the formation (Boom clay). With a water content exceeding 20%, that type of clay has a high creep rate and, thus, a rapid wall convergence of the built structures. The test that ANDRA designed and carried out in an arch-equipped drift made it possible to characterise the convergence phenomenon, to block the mechanical-behaviour models and to develop the specifications of the subsequent structures in the Mol laboratory.
The CACTUS test was designed to analyse the mechanical behaviour of Boom clay under the influence of heat, by simulating the presence of a high-level waste package. As a result, the laws of thermomechanical behaviour were proposed for the design of the repository project.

Due to the presence of a significant water content in that type of clay, it was possible to test various sampling methods, as well as microbiological-characterisation tests. The Mol site also served as a laboratory for a series of geochemical tests in dynamic conditions. The ARCHIMÈDE project grouped studies on water chemistry with a view to proposing a model for the control of the chemical composition of the waters contained in the formation.

The PHÉBUS project was designed to assess the hydric properties of the Mol clay based on the water transfers under the influence of ventilation.

The purpose of the BACCHUS and RESEAL tests is to study materials and technologies for sealing structures, since it is necessary to make provisions for the closure and safety conditions of the installations once they stop to be operational with the construction of dams.

All the tests conducted required the development not only of instruments adapted to the special measurement conditions, but also of specific methods and procedures. A good example would be the drilling of boreholes from the laboratory's drifts in extremely aseptic conditions in order to characterise the formation's microbial populations, safely away from the pollution associated with human activities.

When the first characteristics of the Callovo-Oxfordian formation of the Eastern site were known, ANDRA undertook new experiments in the Mont-Terri stiff clays, since their water content is of the order of 5%. The numerous developments achieved at Mont-Terri helped to prepare and adapt the planned experiments in the Eastern underground laboratory. Work performed at Mont-Terri benefits from many international participations (France, Switzerland, Belgium, Spain, Japan).

The main ANDRA operations are summarised in Table 2.

Years	Experiment	Subject	Main partners[(1)]
1996-98	Water *in situ* (WS)	Sampling and water extraction	NAGRA, SCK-CEN, PNC
1996-98	Evaporation logging (FM)	Transport measurements and mechanisms	NAGRA, SCK-CEN, PNC
1996-98	Osmotic pressure (OP)	Interstitial-pressure measurements	SCK-CEN, SOLEXPERT
1996-93	Unsaturated zone (UZ)	Desaturation mechanisms	NAGRA, SCK-CEN, PNC
1996-98	Cement pore water (CW)	Interaction with cement water	NAGRA, ENRESA, OBAYASHI
1996-98	Hydraulic fracturing (IS)	Stress-field measurements	NAGRA, INERIS
1996-99	Excavated disturbed zone (ED)	Effect of excavation work	NAGRA, ENRESA
1998-2000	Diffusion in rock (DI)	Diffusion in rock	NAGRA, ENRESA, IPSN, PCN, SCK-CEN,
1998-2000	Heater experiment (HE)	Thermal effect	ENRESA
1998-99	Horizontal raise boring (RB)	Horizontal raise boring	ENRESA
1997-99	Hydraulic and gas permeability (GP)	Hydraulic and gas permeability	NAGRA, SCK-CEN
1998-99	EDZ self-healing (EH)	Self-healing of the excavated-disturbed zone	NAGRA, SCK-CEN
1998	Ground penetration radar (GR)	Ground penetration radar	CEA
1998	Fracture propagation (FP)	Fracture propagation	ENRESA

Table 2. Main experiments conducted by ANDRA at the Mont-Terri laboratory (Switzerland)

(1) ENRESA *Spanish Radioactive Waste Management Agency, Madrid, Spain.*
INERIS *Institut national d'étude des risques industriels* (National Institute for the Study of Industrial Risks)*, France.*
IPSN *Institut de protection et de sûreté nucléaire* (Institute for Nuclear Protection and Safety), *Fontenay-aux-Roses, France.*
NAGRA *Swiss Radioactive Waste Management Agency.*
OBAYASHI *Constructor, Japan.*
PNC *Nuclear Experimentation Centre, Japan.*
SKC-CEN *Centre d'essais belge* (Belgian Testing Centre)*, Mol, Belgium.*
SOLEXPERT *Earth Science Operator (Geotechnics, Hydrogeology), Switzerland.*

As indicated by the subject of the Mont-Terri experiments, the operations are more focused than the ones conducted at Mol. The experience feedback from Mol and the knowledge of the first characteristics of the Eastern-site clay have both been helpful not only in defining specific needs, but also in designing and conducting the Mont-Terri tests as a practical phase for the preparation of the experiments to be carried out at the Eastern underground laboratory.

The typical sequence of operations required for experiments is illustrated graphically in Figure 1.

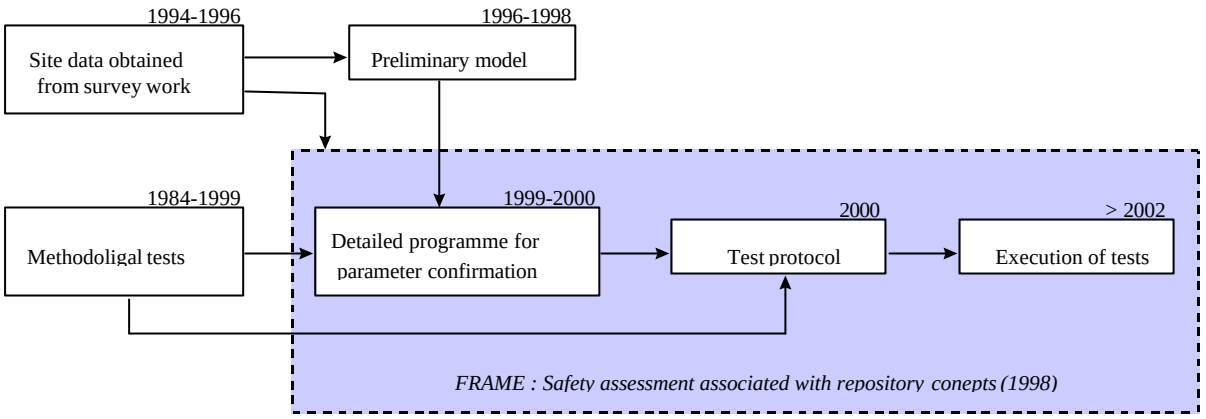


Figure 1. Synopsis of the preparation of experiments in an underground laboratory

Based on the site data resulting from the survey work carried out between 1994 and 1996, preliminary models are developed in the different earth-sciences disciplines (geology, geomechanics, hydrogeology, geochemistry). Those data and models, as well as the experience feedback of the methodological tests, help to develop a detailed programme for confirming parameters, taking into account the needs identified during the development process of the repository design. That framework serves not only to identify the determining parameters for design and safety assessment of the repository project, but also to specify the necessary resolution or precision. Once the detailed parameter-confirmation programme is approved, test protocols can then be proposed, based also on the experience feedback of the work achieved in methodological laboratories. Tests could then be carried out in the Eastern underground laboratory.

In the following paragraphs will be presented the programme of work, followed by the programme of investigation and experimentation of the Eastern underground research laboratory (now officially known as the Meuse/Haute-Marne site), as described in the supporting documentation of the implementation and operation authorisation application. That is the last stage before the implementation of the detailed programme currently in preparation.

3. Work programme of the underground laboratory of the Meuse/Haute-Marne site

Now that the authorisation decree has been promulgated, it will be possible to block the investigation schedule at the Meuse/Haute-Marne site. The first interventions consist in completing the geophysical survey by a 3D seismic programme and are planned for November 1999 on the expanse of the laboratory. A series of boreholes designed to follow up the hydraulic disturbances associated with shaft sinking is then scheduled for the second quarter of 2000. Complementary boreholes in line with the access and auxiliary shafts will be drilled during the third quarter of 2000, followed by shaft sinking during the fourth quarter of 2000. In itself, the sinking of the access shaft is an important experiment, since it provides:

- A detailed survey, at a metric scale and on the vertical plane, of the formations crossed and of the Callovo-Oxfordian host formation;
- A full-scale mechanical-behaviour test due to the vertical excavation in the Callovo-Oxfordian formation;
- With regard to hydrogeological boreholes, an observation of the hydrodynamic behaviour of the upper formations.

The shaft-sinking programme provides for necessary halts to collect samples, observations and measurements, and that explains why the sinking phase of the access shaft will extend until the second quarter of 2002. A hollow, situated at a depth of 445 m, will be available as early as the first quarter of 2002. A series of preliminary tests is planned, as well as observation boreholes to assess the damage caused by the opening of drifts. Experimental drifts, located at a depth of 490 m, will then be gradually available over a one-year period. The programme summary is shown in Figure 2.

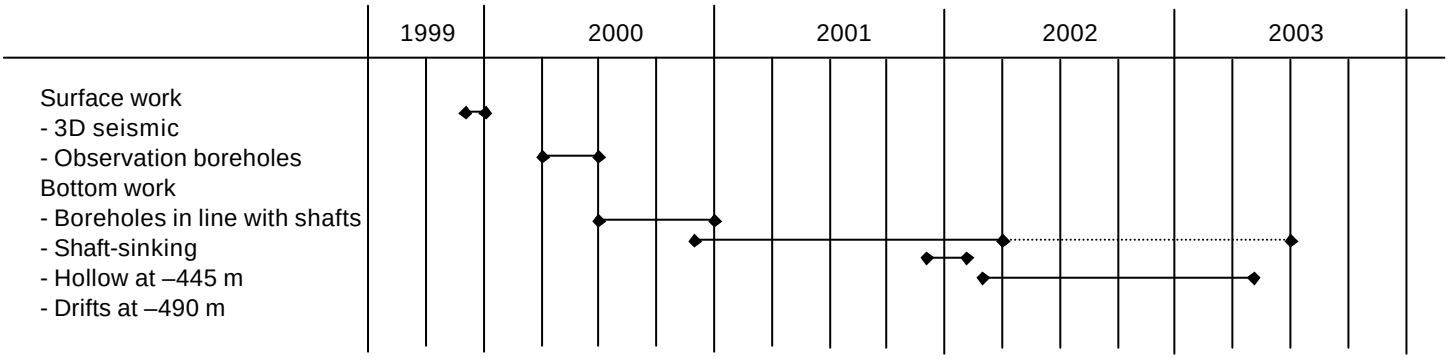


Figure 2. Simplified planning of associated scientific work and investigation operations on the Meuse/Haute-Marne site

A prospective view of the underground laboratory, including surface installations, access and ventilation shafts, the niche excavated at a depth of 445 m and the underground installations is provided in figure 3.

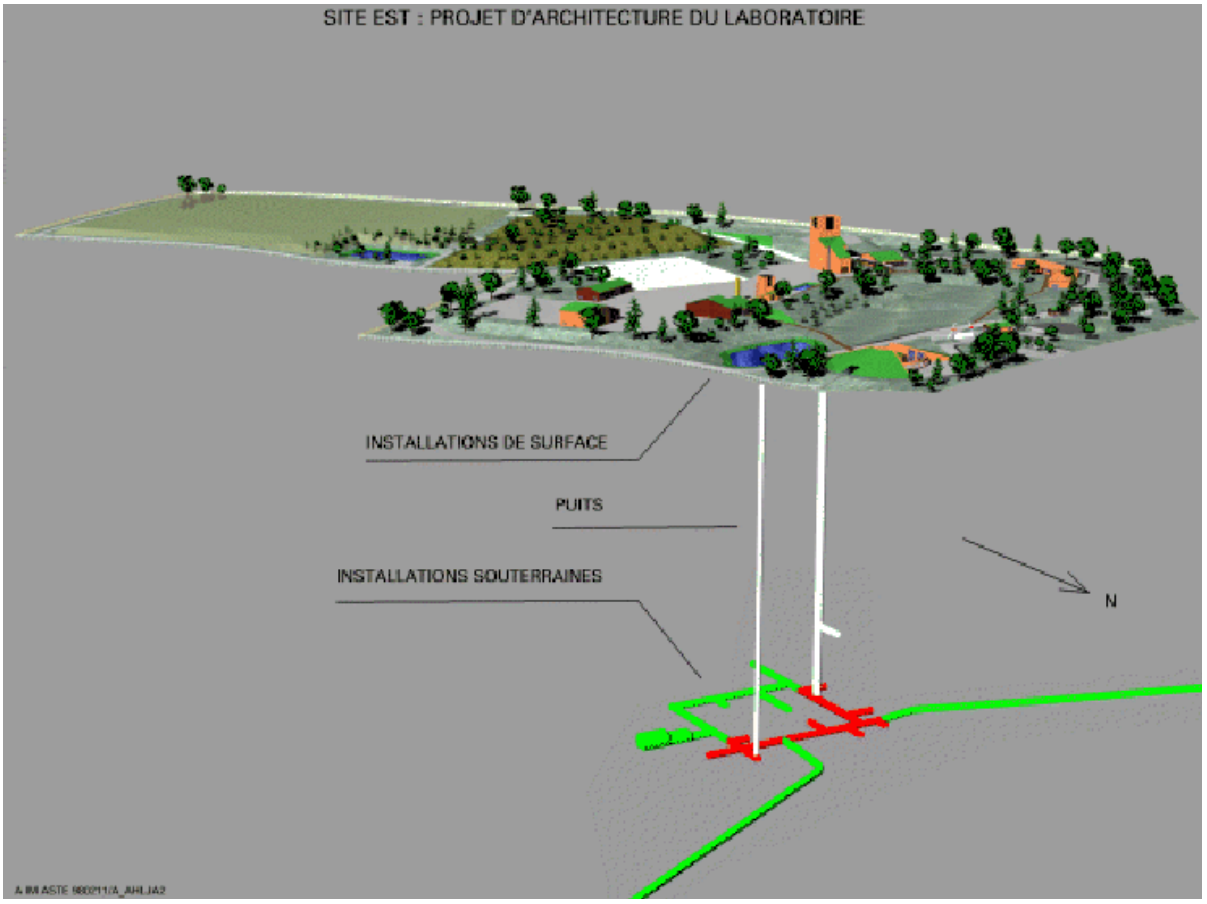


Figure 3. Prospective view of the Eastern underground laboratory

4. Objectives of the research programme of the underground laboratory of the Meuse/Haute-Marne site

The investigation and experiment programme in the underground research laboratory, together with its associated studies, are designed to provide and justify the necessary data for the design of the repository concept and its safety assessment, its optimisation and the assessment of its reversibility. The underground laboratory programme constitutes a part of the experimental phase for the modelling of the phenomena identified as important and occurring in safety scenarios.

The knowledge to be acquired during the underground-laboratory phase has been grouped together around the five major themes summarised in the synopsis shown in Figure 4.

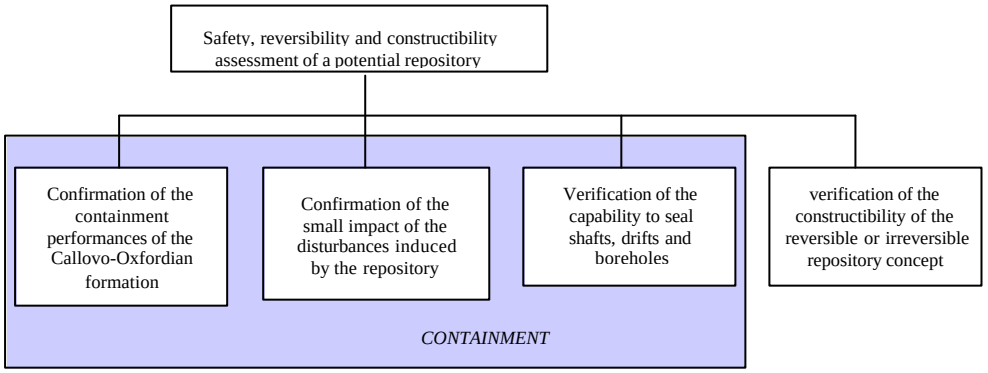


Figure 4. Synopsis of the knowledge-acquisition thmes during the experimental phase in the underground laboratory

In accordance with the provisions of the Law, ANDRA shall submit, by 2006 at the latest, a summary report containing the results of the research carried out during the previous 15 years and, as the case may be, a project for an underground repository for the disposal of long-lived high-level radioactive waste. Fulfilling this requirement implies developing a repository concept, adapted to the characteristics of the site under review. Safety, reversibility and constructibility of the repository will need to be assessed. Those three assessment tools are organised around five themes shown in the synopsis (Figure 4). They can be explained as follows, with containment with the first four themes and with constructibility for the last one.

? The capability to seal off repository structures: One of the major challenges will be to show that, at the end of the operational stage of the repository, it will be possible to close and seal off the structures in order to ensure the long-term protection of human beings and the environment. The efficiency of dams relies on the characteristics of the materials used, on the geometry of the structures and their implementation in the overall architecture as well as on the quality of their contact point with the geological formation.

? The assessment of the effects of repository-induced disturbances on containment properties: investigations conducted in the underground research laboratory relating to the assessment of the different disturbances will aim at verifying not only the nature of the phenomena involved, but also their extension around the structures. Identified

phenomena to be examined are the mechanical discharge around structures and their impact on hydrodynamic qualities, the chemical modifications associated with ventilation or the installation of exogenous materials and, finally, the effects of exothermic waste packages on the geological environment.

? The study of the containment capability of the Callovo-Oxfordian formation: the objective of that programme is to assess water transfers in the repository, their impact on package materials, the solution of radionuclides from waste matrices and the potential migration of radionuclides through the formation. Water seems to play a prevailing role for the safety assessment of the repository project. To study it properly implies having access to a good knowledge of the chemical mechanisms involved, of the interactions between water and solids, minerals and materials, as well as a good description of the system's hydraulic properties. Through hydrodynamics/chemistry coupling, it is possible to assess the possibilities of material transfers, and consequently, to contribute to the safety analysis of the system.

? The assessment of the conditions of radioelement transfers between the Callovo-Oxfordian formation and the biosphere: that study does not deal any more with the host formation of the repository described in the previous item above, but rather with the layers surrounding the Callovo-Oxfordian formation. Those layers are made of limestone whose hydrogeological characteristics and chemical properties will be studied at the regional scale. By assuming transfer pathways within the samples collected in boreholes, for example, and the use of water in the food chain, it is possible to assess the long-term impact of the potential radionuclides released by the waste packages and transferred through the various engineered and natural barriers.

? The constructibility and reversibility of the repository: the purpose here is to verify *in situ* the relevance of the contemplated architectures in relation with the mechanical characteristics of the Callovo-Oxfordian host formation and to ensure that structure-excavation and support techniques, as well as the operational methods, are well adapted. Finally, the knowledge acquired must provide the means to confirm the reversibility of the repository project.

5. Experiments in the underground laboratory of the Meuse/Haute-Marne site

In order to meet the objectives described in the previous paragraph, it will be necessary to have access to underground installations:

? Most of the necessary characterisations can only be performed *in situ;*

? Certain experiments must be carried out with site conditions and cannot be simulated, especially with regard to the impact of mechanical discharge on rock walls, the desaturation on the overall structures, the construction of the dam, etc.;

? With very little water, of the order of 5% and highly mixed with clay minerals, only a direct access can allow reliable samplings and analyses by minimising pollution and disturbance risks.

The investigation list in preparation for the Meuse/Haute-Marne underground laboratory is shown in Table 3, and the objective of each investigation is mentioned. Among major priority investigations, special emphasis will be placed first on geological observations designed to organise the extrapolation of the data collected in the laboratory at the scale

of a potential repository. Secondly, all the immediate or short-term effects must be measured and recorded, and that is particularly the case for geotechnical, hydrogeological and mechanical responses of the excavated formations. The measurements of the containment characteristics are also part of the priority investigations: permeability measurements, water samples, tracer experiments.

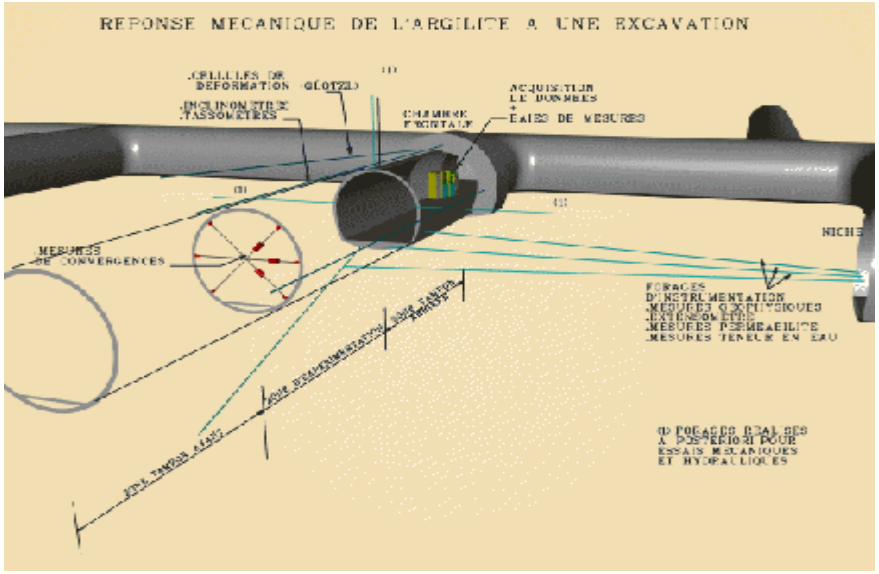
Certain investigation programmes will also bring about new complementary information, for example, in the case of desaturation tests under the effect of ventilation, fields of natural stresses or measurements of chemical disturbances induced by foreign materials contemplated for the repository, such as clays (used for engineered barriers), hydraulic binders or steels.

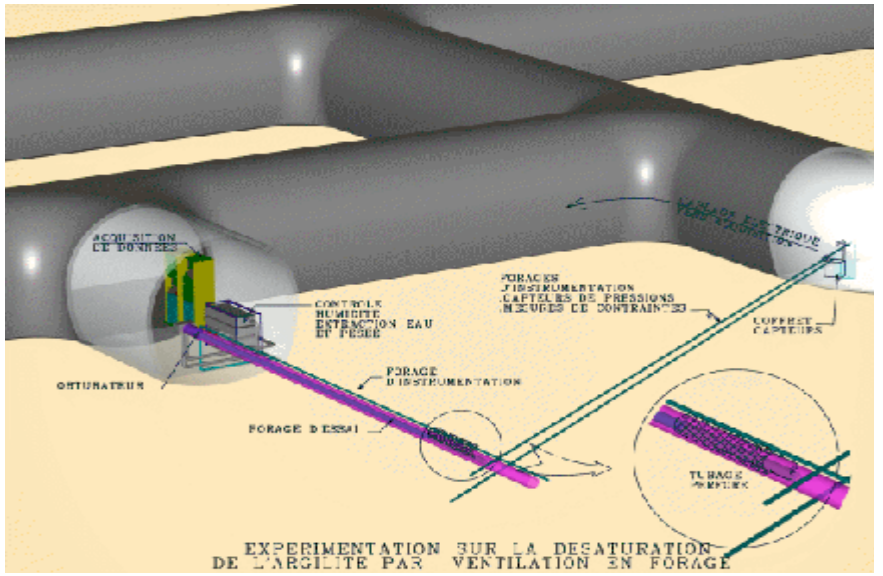
Finally, certain experiments designed to confirm technological orientations may be conducted either in the underground laboratory or in surface installations. They would concern the handling of charges, backfilling (engineered barriers around packages) or the drift-sealing processes. All those experiments associated with operational conditions are also highly oriented towards the study of reversibility.

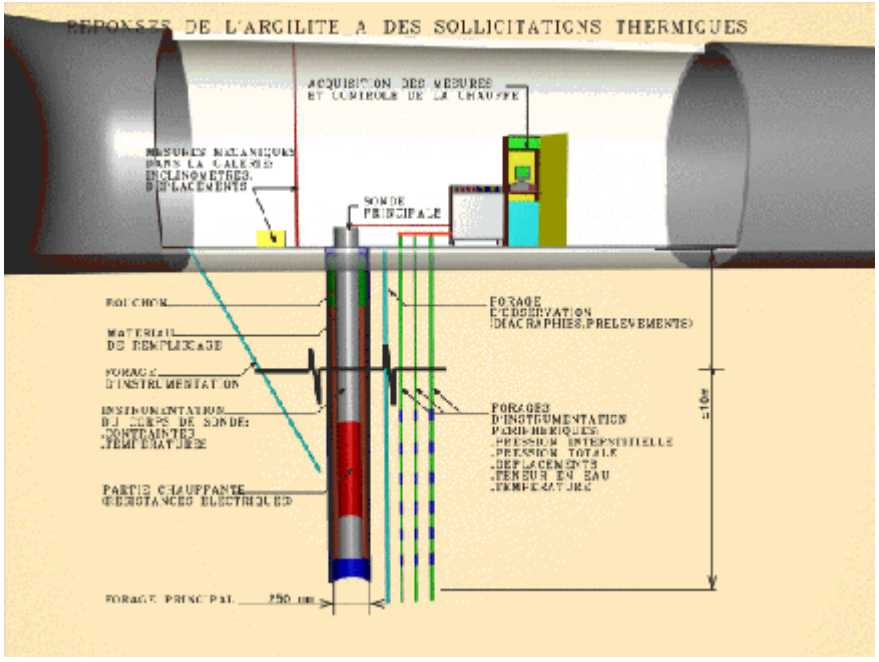
Investigation themes	Study objective
Geological observations in the underground laboratory's shafts and drifts	Data extrapolation to a repository volume
Geotechnical and hydrogeological follow-up of the underground research laboratory's shafts	Construction and reversibility conditions Transfer conditions to the biosphere
Geotechnical follow-up of the underground research laboratory's drifts	Construction and reversibility conditions
Experiment on the mechanical response of the Callovo-Oxfordian formation to drift excavation: _ Preliminary dilatometer measurements _ Associated investigations: Excavation and ventilation effects	Construction and reversibility conditions Effects of disturbances
Measurement of the permeability and of the hydraulic charge in the argillites	Containment capability
Diffusion tests and sample collection for surface measurements	Containment capability
Water sampling for detailed chemical analysis and measurement on site	Containment capability
Reactive tracer tests and sample collection to measure surface retention coefficients	Containment capability
Responses of the argillites to heat	Effects of disturbances Construction and reversibility conditions
Verification of the efficiency of small-scale dam	Sealing capability
Verification tests of building methods	Construction conditions
Argillite-desaturation test by borehole ventilation	Effects of disturbances
Measurement of natural stresses (prior to the experiment on argillites behaviour around a drift)	Construction conditions
Measurement of chemical disturbance due to the contact of materials	Effects of disturbances on containment system
Charge-handling tests	Reversibility conditions
Backfill-material installation test	Reversibility conditions
Testing of drift-sealing processes	Construction and reversibility conditions Sealing capability

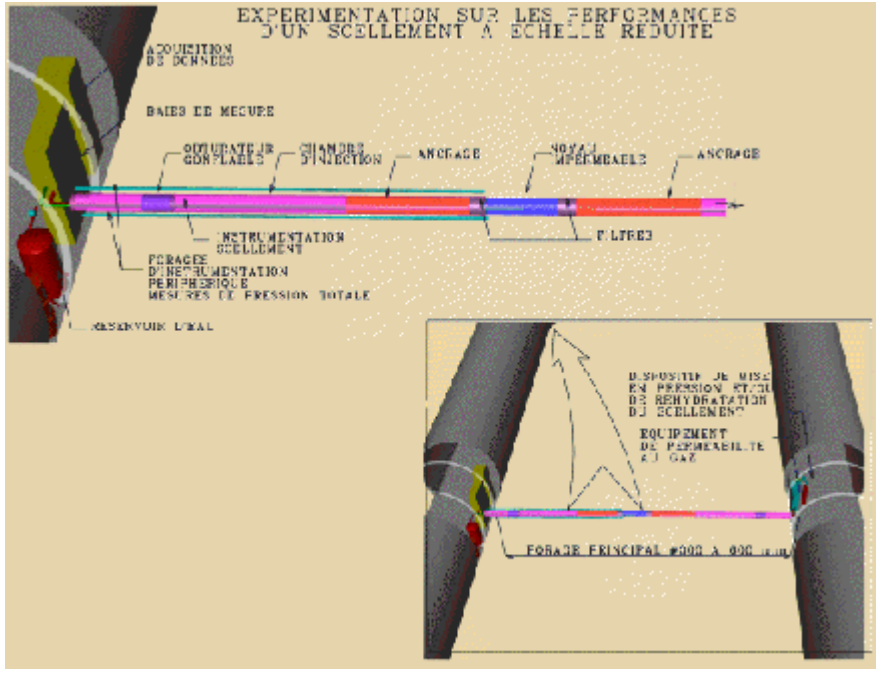
Table 3. List of anticipated investigations at the Eastern underground laboratory (according to the implementation and operation authorisation application, 1996)

Indicative descriptions of experiments appear on the illustration shown on the next page.









Indicative views of experiment projects in the Eastern underground laboratory

6. Conclusions

The decision to implement an underground laboratory falls within the scope of the process launched by the Law of 30 December 1991. That decision was the result of the efforts undertaken since the 1993 mediation mission with the survey of the geological formations from the surface and the identification of further knowledge needs as formulated in the research programmes –and especially in an underground laboratory. It also came about due to fully transparent communications with the populations and the territorial authorities and communities involved.

The new phase starting now involves a new challenge: to gather the proper knowledge necessary to design repository projects, assess their safety and their reversibility. Many teams from various scientific communities are and will be mobilised around those objectives. Appeals are being made to teams from the BRGM, the CEA and other major institutes, as well as from university laboratories and the CNRS. Foreign partners, with whom ANDRA has conducted many experiments in underground methodological laboratories before, are also associated with the project of the Meuse/Haute-Marne site.

That new phase must not overshadow, however, the other requirement of the government decision (*i.e.,* to find another site in a granitic formation). In that case, the same 2006 conditions will apply as for the Meuse/Haute-Marne site, but with a different scientific and technical questioning.