NATIONAL ASSESSMENT BOARD

FOR RESEARCH AND THE STUDIES INTO THE MANAGEMENT OF RADIOACTIVE WASTE AND MATERIALS

instituted by the law n°2006-739 of June 28, 2006

ASSESSMENT REPORT N°5

NOVEMBER 2011

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SUMMARY AND CONCLUSIONS

The law provides that long-term management of long-lived, high-level waste comprises two aspects, which are not mutually exclusive: the partitioning and transmutation of the actinides present in spent fuel from nuclear reactors, and the geological disposal of long-lived high- and intermediate-level waste.

Partitioning and transmutation

Partitioning and transmutation studies are currently being performed in conjunction with research concerning the design of the Astrid[1] prototype 4th generation fast nuclear reactor. The scientific and technical feasibility of the partitioning of the various actinides has now been demonstrated. An FNR[2] could, as long as it was paired with a pilot reprocessing facility, be used to test the industrial feasibility of the multi-recycling of plutonium and to demonstrate the possibility of industrial transmutation of minor actinides. The industrial feasibility of multi-recycling of plutonium is crucial to the development of FNRs. It would allow plutonium to be managed as a fissile material resource and not as waste to be placed in a geological disposal facility. The industrial feasibility of the transmutation of minor actinides would enable us to consider new waste management options.

The transmutation of actinides is conceivable with a set of fast neutron reactors, connected to the grid, or with accelerator-driven sub-critical fast neutron reactors (ADS), a possibility which is still being studied.

A set of fast neutron burner reactors generating 430 TWh/year and transmuting americium would require – for constant operation – the manipulation of around 900 tonnes of plutonium and 100 tonnes of americium spread among all the reactors and factories involved in the cycle. These masses are the quantities that would have to be managed at the end of the cycle. By way of comparison, the operation of a set of Mox PWRs[3] supplying the same quantity of electricity would produce increasing masses of plutonium (1,300 tonnes in 2150) that could not be reused in PWRs and would have to be placed in a geological disposal facility.

Currently, French research is being hindered by the absence of a fast neutron reactor accessible to the transmutation research community, which is preventing France's scientific, technical and technological progress in this field from being fully exploited. Yet considerable research efforts are required to demonstrate that Astrid can operate by recycling its own plutonium, and assess the advantages and disadvantages of the different conceivable strategies for transmuting minor actinides.

The Board stresses that scientific logic should not be confused with industrial rationality. The scientific project associated with the Astrid reactor must first of all serve a full R&D programme reviewing the different transmutation strategies, and enable research to be extended to include a full evaluation of the possibilities for industrialisation.

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[1] Advanced Sodium Technology Reactor for Industrial Demonstration:

[2] Fast neutron reactor.

[3] Pressurised water reactor (thermal-neutron reactor).

Storage and disposal of radioactive waste

The year 2010-2011 saw a very important stage in the deep geological disposal of radioactive waste, which, after a preparatory R&D phase, is now entering the industrial implementation phase. In September 2010, Andra presented an industrial organisational structure and strategy for the disposal project, named Cigéo (the industrial centre for geological disposal).

Yet the waste producers - EDF, Areva and the CEA - have proposed alternative design options for this structure, compiled in a dossier entitled 'STI', which was submitted to Andra in November 2010. As the Opecst has underlined, this work by producers, "*undertaken outside of the cooperation frameworks provided by law*"[4] seems to have been primarily motivated by Andra's announcement of a considerable increase in the estimated cost of the deep geological disposal project. The Board would remind readers that the law of 28 June 2006 entrusts Andra with the task of "*designing, locating, creating and managing* [….] *disposal facilities for radioactive waste…*"[5]

The Board believes that the work done by the producers contains technical elements worthy of examination. Their overall architecture proposal is part of a cost-cutting approach, but this project is not as good as Andra's 2009 project with regard to the priority objective of achieving the lowest possible radiological impact, compatible with technical and economic conditions.

The DGEC[6] asked Andra to assess the producers' proposals, and in April 2011 it implemented a review of the Cigeo project. This review aimed, before the launch of any call for tenders from contractors, to formulate an opinion on the robustness of the industrial programme, and to stipulate the potential disposal specifications and the avenues for technical and economic optimisation to be explored.

On 11 October 2011, Andra presented the Board with the document "Requirements applicable to the Cigeo project", which gives the specifications for the draft design of the disposal facility, as well as the technical specifications. Andra stated that it had "*opted to select a prime contractor for engineering studies for the period 2011-2017"* and underlined that the prime contractor must provide "*an architectural, technical and economic response*" (see Cigeo.SP. ADPG.11.0020.B).

Andra, the project owner, therefore decided, after the review of the Cigeo project, to proceed to a call for tenders with a view to entrusting the "*project management of the system"* to an external company. The Board has not had time to analyse in detail the content of the call for tenders or the form of governance of the project created by the contracting process. However, it is worried that, without having included an explicit abstract model in its call for tenders, Andra has delegated the "*project management of the system*" to an external company which will be responsible for finalising the detailed draft of the first disposal unit, the methods to be used and the costing of implementation, all in less than a year. The Board would ask Andra to assume fully all the responsibilities assigned to it by the law.

4 See Opecst report of 19 January 2011 "Nuclear Waste: beware the paradox of tranquility".

5 Ditto.

6 The Directorate-General for Energy and Climate Change, part of the French Ministry of Ecology.

Andra produced the 2005 and 2009 reports and the Zira[7] proposal. The transition from an R&D-based approach to industrial implementation is generating new difficulties. The Board would also like to underline the fact that the producers (EDF, CEA and Areva) have, over many years, developed great expertise in nuclear facilities, underground structures and the management of the related risks. The Board recommends that the producers should be involved throughout the implementation of the industrial project, and that their contribution should be put to good use, through a process yet to be implemented, in which Andra would keep all it prerogatives as project owner.

The Board would remind readers that in less than twelve months, the preparatory file for the public debate is due to be published, bringing to public attention the essential elements of the project, notably the disposal system, the reversibility conditions, the layout of the surface facilities, the shafts and the inclined drifts, the inventory of waste to be placed in the disposal facility and the estimated cost of the facility following the submission of the Court of Auditors' report on the cost of nuclear power.[8]

International dimension

The Board takes a favourable view of the international dimension of much of the research done by Andra, the CEA and the CNRS. It particularly appreciated the importance accorded to this dimension at the hearings.

Four countries (China, India, Japan and Russia) are developing FNR projects.

The Euratom directive of 19 July 2011 concluded that *"at this time, deep geological disposal represents the safest and most sustainable option"*.

Three countries are scheduled to open a deep geological disposal facility for long-lived high-level radioactive waste in 2025: Finland, France and Sweden. In Sweden, SKB submitted a planning permission application in March 2011. Sweden is the first country to reach this stage.

[7] Zone of interest for further investigation.
[8] PNGMDR report 2010-2012, p. 97.

CNE2 ACTIVITIES

The period from July 2010 to October 2011 is CNE2's fourth full year of activity and forms the subject of this, its fifth report. Between the end of June and December 2010, the Board presented report no. 4 to various organisations, including the Opecst and ministerial departments. A Board delegation visited Bar-le-Duc to present this work to the members of the CLIS (local information and monitoring council) of Meuse/Haute-Marne.

* * *

This fourth year also saw half of the Board's members replaced in July 2010 (*see Appendix I).*Visits and special work sessions were held for newly appointed members with the help of Andra and the CEA.

* * *

The Board followed the same working method used in previous years. Members of the Board, all of them volunteers, conducted 13 hearings. These included 8 full-day sessions in Paris and 2 at the Meuse/Haute-Marne laboratory at Bure/Saudron, in addition to other supplementary meetings. They received 88 people from Andra, the CEA and academic and industrial institutions in France and abroad. These hearings, each of which brought together an average of around 50 people, were also attended by representatives of the French Nuclear Safety Authority (ASN), AREVA, EDF, the Radiation Protection and Nuclear Safety Institute (IRSN), and the Central Administration. The Board spent half a day hearing about the various theoretical research actions of the CNRS Pacen[9] programme.

This year, the Board visited the Stocamine site, as well as the Masurca and Leca-Star facilities at the CEA in Cadarache.

During a research visit to Germany, the Board visited the Asse and Gorleben sites. At the Bundestag, it met with two MPs from the German Green Party ("Die Grünen"). They reminded us that they consider deep geological disposal of nuclear waste as the best solution. Their current concern is finding one or more sites of good geological quality to use for disposal. They see the Gorleben site as a possible candidate where scientific studies should be pursued.

To prepare this report, the Board held a 2-day pre-seminar session during its visit to the CEA in Cadarache, and 4 internal meetings, one of which was a 5-day residential seminar. A list of the Board's hearings and visits is provided in *Appendix II* of this report. A list of the documents it has received from the organisations it heard is given in *Appendix III*.

* * *

9 Programme on the downstream part of the cycle and nuclear energy production.

This report is organised to reflect the two complementary aspects of R&D on the management of radioactive waste and materials: partitioning and transmutation (*see chapter 1),* and the storage and disposal of LLHL[10] and LLIL[11] waste (*see chapter 2*). This year, the Board decided to go into detail on the subject of the potential impact of transmutation of actinides on the disposal of the waste produced in the future, in a set of reactors suitable for multirecycling. This question is dealt with in two chapters of the report.

The Board continues to observe the overall international situation (*see chapter 3*), and this year devoted an entire hearing to the different visions of the nuclear cycle held throughout the world. This hearing took place a few weeks before the accident in Fukushima.

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10 Long-lived high-level waste.
11 Long-lived intermediate-level waste.

Chapter 1

PARTITIONING & TRANSMUTATION

1.1. SCIENTIFIC AND TECHNICAL CONTEXT

How can the management of radioactive materials and waste be optimised? One possible route is to transmute the long-lived radionuclides that they contain, in order to reduce the duration of their radiotoxicity. The law of 28 June 2006 provides that "*The corresponding research and development [on partitioning and transmutation] is being conducted in relation with that conducted on the new generations of nuclear reactors mentioned in article 5 of law 2005-781 of 13 July 2005 on the programme setting the orientation of energy policy, as well as that conducted on accelerator-driven reactors dedicated to waste transmutation, so that we will have an assessment of the industrial prospects of these technologies in 2012 and we will be able to put into operation a prototype facility before 31 December 2020*"

Indeed, the long-lived radionuclides contained in the waste are responsible for the persistence of radioactivity for hundreds of thousands or even millions of years. Reducing the quantity of these radionuclides in the waste may therefore create greater scope to reduce the "source" term, improve the safety of the disposal facility, and significantly reduce its duration and even its area. These points should not be neglected, particularly with regard to acceptability, insofar as radioactivity should decrease considerably. However, they have significant implications for the industrial strategy, both on the type of reactors to be implemented and on the time of their implementation.

The R&D conducted in several countries, particularly in France, has shown that the partitioning and transmutation strategy could only be effectively implemented by recycling plutonium and all or some of the minor actinides in fast neutron reactors (FNRs).

We can show that, if we were to recycle the plutonium and minor actinides, it would only take 500 years for the radioactivity of the waste generated by the reactors to return to the level of the natural uranium used as the fuel.

If we were to exclude plutonium, americium and curium from the waste, the thermal power of the waste to be disposed of would become much lower after approximately a century of storage.

The implementation of such a strategy, with the knowledge we have at present, would lead to heavier and more complex assemblies than those currently used: in particular, there would be a noticeable increase in the number of steps in the cycle operations and in radiation protection requirements. It would also still be necessary to make an economic assessment of this new approach.

All these studies remain theoretical, or are based on experimentation conducted on research reactors; industrial feasibility must be examined with the aim of optimising the nature of the final waste to be disposed of. The construction of a prototype fast neutron reactor, such as Astrid, is provided for in the abovementioned law. Such a prototype should allow some of the necessary studies to be performed.

The Board considers that the research efforts already undertaken must be maintained and deepened. If this condition is met, the deployment decisions to be taken between 2030-2040 on future reactors, cycle plants, storage and disposal can then be based on the best scientific and technical studies.

This chapter presents the main lessons learned from the R&D work led by the CEA as part of numerous partnerships (Andra, Areva, CNRS, EDF, foreign institutions, etc), as well as the questions currently being asked.

1.2. TRANSMUTATION AND MULTI-RECYCLING

The question that arises is whether a reactor capable of transmutation (e.g. an FNR or an ADS[12]) actually consumes all of the actinides it produces. Such a closed cycle presupposes that the reactor is supplied with fissile material produced by the reactor itself, after reprocessing to extract the material and reconditioning it as a fuel (see report n° 4).

The scientific feasibility of transmutation has been proven by the analysis of a few fuel pins containing minor actinides, irradiated in various European reactors (Phénix, Halden, Petten). But the capacity of a transmuting system to burn all the actinides it produces has not yet been proven.

In France today, plutonium is partially recycled in PWRs, using Mox[13] fuels that allow a fraction of the plutonium produced to be burned[14]. These fuels are then stored pending reprocessing or disposal, but they still contain high proportions of plutonium and minor actinides.

1.2.1. Three important actinides potentially concerned by transmutation

1.2.1.1. Plutonium

Plutonium 239, a fissile nucleus, is produced from uranium 238 (a non-fissile nucleus) by neutron capture. Plutonium can therefore be the fissile material for a set of fast neutron reactors, which would eliminate France’s dependency on uranium resources for several centuries.

1.2.1.2. Americium

Americium 241 is, like plutonium, produced in the reactor, or results from the β decay of plutonium 241. Americium has two important properties:

[12] Accelerator Driven System - The subcritical systems devoted to transmutation are controlled by an accelerator, and include three components: a linear accelerator, a spallation target, and a subcritical nuclear reactor.
[13] Mixed oxides of uranium and plutonium.
[14] Approximately 3 tonnes/year out of the 10 tonnes/year produced.

- It makes a significant contribution to the radiotoxicity of waste packages from the current set of reactors (PWR);

- It makes a significant contribution to heat production by the waste packages, which means special spacing and geometry are required to reduce the maximum temperature in the disposal facility.

1.2.1.3. Curium

Curium is produced from americium by neutron capture. It too contributes to the radiotoxicity and heat production of the waste packages.

Curium essentially contains 5 isotopes, the masses of which range from 242 to 246. Only the higher isotopes are long-lived radionuclides, but the decay process of all the isotopes contains a long-lived, or very-long-lived, radionuclide. Due to their short radioactive half-life, ^{242}Cm (163 days) and, to a lesser extent, ^{244}Cm (18.1 years) are highly radioactive and have a high thermal power. Furthermore, the even isotopes of curium are also prone to spontaneous fission and are considerable neutron emitters. All these characteristics make manipulating curium particularly tricky.

The different curium isotopes are produced by successive neutron captures from americium, itself formed from plutonium. This means that curium production is all the higher, because it has more precursors: this is particularly true of fuels with plutonium (Mox) or fuels with a high americium content (CCAm[15]).

The partitioning processes developed at the CEA are sufficiently flexible and sophisticated to enable ‘grouped’ partitioning of minor actinides (Coex[16] process) or indeed to isolate each element and in particular americium and curium.

The transmutation of curium alone would make it possible to:

- Reduce its presence in waste. However, this reduction is of little significance when compared to the inventory of other actinides present. Conversely, the inventory of curium in the cycle increases, while remaining low compared to the levels of other minor actinides, and even more so compared to plutonium levels;
- Bring about a ten-fold reduction in package radiotoxicity over the period from 1,000-10,000 years;
- Reduce the thermal power and thus allow denser concentrations of disposal packages. However, while this is true for packages stored for 70 years prior to disposal, the benefit would disappear almost entirely after storage for 120 years, insofar as the thermal component has by this time practically disappeared naturally;
- Bring about a 15-fold reduction in the α decay dose received by the glass in disposal conditions. Nevertheless, this has no consequences on the number of packages produced, since this dose is already significantly lower than the current limit.

[15] Americium-rich blanket fuels.
[16] A process for co-extracting all minor actinides.

However, the curium's neutron emissions necessitate reinforced radiation protection systems; the thermodynamics and the criticality risks[17] make fuel fabrication and transport operations difficult if curium alone is to be manipulated.

> *These various observations lead us to believe that the disadvantages of transmuting curium significantly outweigh its advantages. In addition to considerable technical difficulties, there is a need to provide specific protection for staff.*
>
> *Therefore, given the current technical approach to transmutation, the method is not conceivable for curium, unless new scientific and technical advances are made.*

The rest of the presentation will therefore focus on the major actinide, plutonium, and the minor actinide, americium, both of which are of interest in relation to a partitioning and transmutation strategy.

1.2.2. Transmutation rate

The transmuting system (FNR or ADS) consumes actinides at the same time as producing them. In a set of FNRs operating for several decades, the inventory of actinides stabilises. The efficiency of transmutation, and therefore the level of stabilisation, depends on the neutron flux in the system and the transmutation cross-sections.

The first-order parameter influencing the efficiency and the rate of transmutation is the available neutron flux. This explains the importance of the geometry of the *"reactor and transmutation targets" system.*

The greatest degree of efficiency would be achieved by placing the actinides at the centre of the reactor core, where the neutron flux is the greatest, but this is not a configuration in which it is possible to control an FNR in a safe way. Two configurations are therefore being studied: homogenous mode and heterogeneous mode. Homogenous mode corresponds to the dilution of a low quantity (3 to 5 %) of minor actinides in all of the reactor's fuel elements. Heterogeneous mode is a configuration in which the reactor core remains unchanged, but assemblies with a high minor-actinide content (at least 10%) are positioned around it (CCAM[18] concept). This last option offers the advantage of not disturbing the classic core configuration. It allows higher minor-actinide content, but it is less favourable in terms of neutron flux.

The number of cycles depends on the efficiency of the system. The duration of the cycle is determined by the time spent in the reactor, plus the fuel processing time (extraction of fission products for vitrification and actinides for fabrication of new fuels); it is approximately 14 years for homogeneous mode and 21 years for heterogeneous mode.

[17] For example, 59 g for curium 245.
[18] Blanket fuels with a high minor-actinide content.

Whatever the technology implemented, transmutation is a slow process. Several decades would be required to stabilise the inventory of plutonium and minor actinides in the cycle. But this stabilisation is possible.

The same reasoning applies to all actinides: plutonium and minor actinides. But in reality, the option of transmuting minor actinides to improve the radiotoxicity of waste only makes sense if we are planning first to manage the plutonium, the quantities of which are ten times larger than those of minor actinides.

1.3. DEMONSTRATION TOOLS

The R&D led by the CEA in partnership with EDF and Areva is based on scenario analysis, the development of a programme called Astrid, including the prototype and the associated installations, and finally, a study of the impact of transmutation on disposal.

The Astrid prototype is the master facility of the system, which will allow full-scale transmutation demonstrations to be performed. This prototype is a sodium-cooled fast neutron power reactor, incorporating lessons learned from Phénix and Superphénix, but meeting 4th generation criteria.

As it has stated in its two previous reports, the Board considers that there is an urgent need to have a fast neutron reactor accessible to the scientific community studying transmutation.

In its last report, the Board also drew attention to the need for a pilot reprocessing facility associated with Astrid, which would be the only way of demonstrating that the reactor could be powered by its own waste. Astrid and the associated pilot reprocessing facility constitute a system for demonstrating the capacity of a transmuting system to burn the actinides it produces.

Worldwide, several scientific teams are studying the transmutation of plutonium and minor actinides in FNRs (see chapter III of this report). The Board would stress that sustained research efforts are vital to enable France to preserve its scientific and technical lead.

The different aspects of the R&D led by the CEA, in cooperation or partnership with Andra, Areva and EDF, will be examined below.

1.4. SCENARIOS

As part of the Astrid programme, case studies are being developed jointly by the CEA, EDF and Areva. These make it possible to establish a methodology for estimating the amount of radioactive waste and materials produced by a set of power plants generating 430 TWh/year (equivalent to the French reactor base), where all figures constitute orders of magnitude.

One possible scenario is the gradual replacement of the current PWR base with fast neutron reactors to reduce waste generation, which involves studying the transition from 3rd generation to 4th generation reactors and the new type of waste associated with them.

In a study conducted by the CEA, EDF and Areva, three versions of a 430 TWh/year power plant base have been examined in detail:

- A reactor base composed of PWRs, which each year would produce 10 tonnes of plutonium, 1 tonne of minor actinides and 7,000 tonnes of depleted uranium from the enrichment of uranium 238. The operation of such a base would lead by 2150 to the accumulation of approximately 1,900 tonnes of plutonium.

- A reactor base composed of PWRs using Mox (mono-recycling of plutonium), which reduces plutonium flux. This would lead by 2150 to the accumulation of approximately 1,300 tonnes of plutonium.

- A reactor base composed of FNRs, which each year would produce 2 tonnes of minor actinides and would require 50 tonnes of depleted uranium. This base would use multi-recycling of plutonium and would enable use of depleted uranium, in small quantities given the existing stock of over 220,000 tonnes. It would make it possible to do without the uranium 235 enrichment operation. It would lead by 2150 to the stabilisation of the plutonium inventory at 900 tonnes.

The first two scenarios use reactors for which the technology is mature. However, they do involve the continuation of the mining industry and of uranium 235 enrichment operations. If we continue this strategy, the plutonium from the spent fuel will be a form of waste that continues to accumulate. Ultimately, the glass packages used for disposal would contain plutonium.

The third scenario uses technology that is more innovative but based on experience feedback from the FNRs. It no longer requires uranium 235 enrichment. The stock of 900 tonnes of plutonium produced constitutes a continually recyclable resource for however long the technology is used, even if it is used for several centuries. This stock will then have to be managed as waste.

A scenario that has not yet been presented is the possibility of an early abandonment of nuclear power, which would raise the question of how to manage all nuclear materials, which would, de facto, become waste.

For the Board, analysis of these scenarios demonstrates the need to adopt a very long-term approach when devising an industrial nuclear strategy. FNR technology makes sense as part of a strategy involving the continued use of nuclear power with a focus on saving resources and reducing waste.

1.5. ASTRID PROTOTYPE

To demonstrate industrial feasibility, two simultaneous uses of the Astrid fast neutron reactor must have been validated:

- Power-generating reactor: The irradiated fuel from the reactor core must undergo, in full-scale conditions, the following phases: dissolution, partitioning of the various elements, and recycling of the plutonium, to which depleted uranium will be added to make the fuel for the new core.

- Reactor for transmutation: The americium must be isolated in the partitioning phase, and conditioned in order to fabricate the appropriate fuel, depending on whether transmutation is performed in homogenous mode (a few % of americium) or heterogeneous mode (around 10% of americium).

This reactor is designed to develop a power of 600 MWe in its power-generating version. It benefits from the experience acquired with the Phénix and Superphénix reactors, as well as the R&D undertaken worldwide as part of the GEN IV forum

1.5.1. Core

Significant progress has been made on safety through a new core design which ensures improved behaviour in accident conditions leading to heating of the core as a whole. In particular, the reactivity coefficient during expansion of the sodium is negative in the event of a general pressure drop in the primary cooling circuit, which, if there were to be generalised boiling of the coolant, would result in a negative vacuum effect overall.

This new difference from standard cores[19] seems likely to be extrapolated to high-power cores. The first studies of transient accident conditions with a loss of flow or cold source, without emergency shutdown, show that the natural behaviour of the core is favourable. These potentially useful characteristics remain to be confirmed in the rest of the studies.

1.5.2. Cooling and conversion

The innovations concerning cooling and conversion circuits aim to improve safety by partially or totally avoiding contact between sodium and water in accident conditions. Two approaches are being explored:

[19] The three partners (CEA, EDF and Areva) filed a patent in 2010.

- ‘Segmented’ water-sodium exchangers which, in the event of a break in the circuit, would limit the extension and spread of a fire and make it possible to halt it.
- An intermediate circuit between the sodium secondary cooling system and the water system. This intermediate circuit could be a gas circuit (helium/nitrogen) or a molten-metal circuit (lead/bismuth).

These intermediate circuits are designed so that they can be added later to the current Astrid ‘sodium-sodium-water’ prototype without necessarily causing delays in the construction of the whole, provided that the thermodynamic cycle is chosen sufficiently early.

1.5.3. Designs and materials for Astrid

The design of Astrid represents a compromise between an industrial electricity-generating prototype, a reactor for testing transmutation options, and a reactor for irradiating materials. This need to achieve both the flexibility required of reactors for research on innovative options, and the reliability expected from an electricity-generating facility, imposes a complex set of specifications, and the choice of a 600 MWe power range with design choices that can be extrapolated to 1,500 MWe.

The design choices are based on feedback from FNRs in France (integrated concept), and on innovations motivated by the need to improve safety. The corium collector is directly inspired by the EPRs. Phénix’s sodium/water exchangers are replaced with sodium/sodium/water exchangers, which should in principle avoid radiological pollution if there is interaction between the sodium and the water. As we saw in paragraph 1.5.2., these exchangers may develop into sodium/sodium/gas exchangers without any major ‘redesign’ or change in materials, which in any case would not be possible given the current time restrictions. The selected output temperature of 550°C makes it possible to choose traditional materials (316L(N) and 304L stainless steels and Cr-Mo steels). The engineers’ efforts on the operation (handling of assemblies to minimise downtime, inspectability of structures in a sodium environment) and organisation of the programme, with CEA as the prime contractor and clearly defined contributions from EDF and Areva, give the project a good structure, which is absolutely suited to the development of a prototype.

Sodium, chosen as a coolant in the core and the primary circuit, does not cause very much chemical damage to the materials: this type of reactor is virtually free from radiation and stress corrosion, a problem on PWRs, particularly for reactor vessel internals. The secondary cooling system and the steam exchangers have similar specifications to those of the PWRs: we can draw on past experience with confidence. Given the very tight deadlines for producing a prototype, the selection of proven materials seems very wise.

The choice of the structural materials that will initially be used in Astrid is based on experience acquired on the various FNRs that have operated in the past. The innovative solutions, notably in the cladding materials, require new studies, particularly in respect of their behaviour when exposed to irradiation.

The structural ageing problems that are central to the materials issues concerning the current reactor base must be anticipated for the FNRs. Studies may be based partly on experience acquired on PWR components made of 316 and 304 steels (reactor vessel internals materials). However, the irradiation conditions in the FNRs are noticeably different from those in the PWRs, and the irradiation behaviour of 316 stainless steels and, to an even greater extent, the cladding materials (Ferrito-martensitic, ODS[20]) may be different. The studies may not be based solely on expertise already acquired. These in-depth studies must be part of the Astrid mission. If would be wise to include control samples in the design of Astrid to enable the ageing of the reactor vessel to be monitored. Research must be pursued in terms of design and innovation.

The Board considers it vital that not only the design choices but also the effective operation of the reactor should allow the reactor to be used as a tool for research on materials and transmutation, and that this aspect of Astrid's function should not be overshadowed by the need to have an energy-generating prototype reactor.

The presentations made demonstrate convincing engineering work and outline a project that appears to be realistic. The Board requests that the industrial development plan for Astrid should be presented to it. This plan must clearly detail the existence and availability of manufacturing facilities, as well as the schedule and the lead-times required by the various participants to make the Astrid components within a reasonable timeframe.

The Board reminds readers of the need to have Astrid ready as close as possible to the deadline set and that any delay is likely to result in a loss of competencies. It would also underline that the scientific programme, of which the Astrid reactor will be the main tool, must contain a considerable research dimension. This is vital in order to achieve the innovations necessary for this type of reactor.

1.6. REPROCESSING AND FABRICATION OF FUEL

In order to validate the multi-recycling of the actinides in a fast neutron reactor, we will require the Astrid reactor and a pilot reprocessing facility to enable us to test the different operations linked to the recycling of plutonium and americium, after irradiation of the fuel.

Indeed, beyond the physics in the reactor core, if we want to implement and assess the technical feasibility of transmutation, it is necessary to perform and validate several successive operations concerning the chemistry of the solutions, partitioning sciences and material sciences. The aim is to demonstrate that we can master dissolution of the irradiated fuel, partitioning of the different elements, then reconditioning of the plutonium and the actinides in the form of a fuel with a much higher actinide content than PWR fuels. The aim of a pilot reprocessing facility, as recommended by the Board in its previous report, is to be able to test all the operations that an irradiated fuel from Astrid must undergo in order to demonstrate that it is industrially possible to recycle plutonium, i.e. to shape the actinides with a view to their transmutation so that ultimately Astrid can be fuelled by its own actinides.

[20] Ferritic steel strengthened through oxide dispersion.

1.6.1. Experience and lessons learned

The programme underway at the CEA, which is due to continue until 2013, has already validated the leaching of 4 kg of irradiated fuel. The stages of concentration of the raffinates that will enable implementation of the AmEx[21] process for the partitioning and conditioning of americium are still in progress. Several major operations have already been validated:

- Process durability: Irradiation tests on the extraction systems lasting 1,000 hours (simulating 1 to 2 years of operations) in an irradiation loop *show the stability of the various components;*

- Process control: *The use of direct spectrophotometry (americium, neodymium) in the lab enables monitoring and control of the process;*

- Co-conversion tests on minor U-actinides (synthesised solutions): the aim is to recondition the minor actinides, and the tests result in products with the good characteristics required.

The scientific feasibility of the operations to partition the uranium, the plutonium, the fission products and the actinides has been validated. In-depth research has resulted in the creation of molecules capable of specifically recognising uranium, plutonium, neptunium, americium and curium, and withstanding radiolysis[22]. Several processes have been developed for choosing the metal groups or elements to be partitioned using the solution obtained via leaching of the irradiated fuel.

The Board would like to stress the importance of the knowledge acquired by the CEA through all of the R&D it has conducted on the subject of partitioning. The trickiest issue that remains to be resolved is the industrialisation of online analysis, necessitating the development of sensors and probes.

1.6.2. Pilot reprocessing facility for Astrid

In order to establish the industrial feasibility of irradiated fuel management, and the capacity of the reactor to be fuelled by its own actinides, it will be necessary to test the performance levels of a full reprocessing chain including partitioning and fabrication, on a scale bigger than that of lab trials.

[21] AMericium EXtraction.

[22] Decomposition of a chemical body by ionising radiation.

A pilot reprocessing facility must enable the management of actinide concentrations that are noticeably higher than those encountered during the reprocessing of irradiated fuel from the current PWRs. It must also demonstrate that americium can undergo appropriate processing for its conditioning and transmutation. Indeed, based on ‘non-traditional’ assemblies with a high minor-actinide content (at least 10%), the management of americium-rich blanket fuels (CCAm) is necessarily separate from that of the core. In addition, as they are subjected to a lesser flux due to their peripheral location, the CCAm assemblies must remain in the reactor for much longer than in homogenous mode. This brings about an increase in the inventory of minor actinides.

With regard to the plutonium, partitioning should be optimised so that the vitrified waste from reprocessing of the spent fuel from an FNR only contains very low quantities of plutonium. This is technically possible with the processes developed if the number of stages in the partitioning unit is adjusted so as to obtain the desired content at the end.

> *The usefulness of an industrial strategy based on Astrid cannot be totally established without a pilot reprocessing facility (see CNE2 report n° 4), a fuel fabrication unit and a specific line for managing reprocessing of the high-content blanket fuels.*
>
> *The CEA seems to have understood this, but it would be advisable to ensure that the idea is, in practice, implemented in conditions that allow industrially representative quantities of minor actinides to be managed (a few kg of americium).*

1.7. TRANSMUTATION IN ADS[23]

The subcritical systems devoted to transmutation are controlled by the ADS accelerator and include three components: a linear accelerator, a spallation target, and a subcritical nuclear reactor.

Transmutation is carried out in a specific system, not connected to the electricity-generating reactor. In principle, the core in subcritical mode enables a high minor-actinide content. To operate, as it is subcritical, the reactor must be supplied with neutrons by an external source composed of a proton accelerator and a spallation target.

Such a system is technologically very complex and many uncertainties remain to be resolved with regard to its feasibility and the control of its safety. R&D on the ADS is being undertaken as part of the European programme Eurotrans, but to date there is still no experience feedback about this type of machine.

> *The Board notes the considerable research efforts made by CNRS-Pacen concerning the accelerator and the beam, as well as the CEA’s work on the fuel (with a high actinide content) and the materials. The other technological research is mainly being done outside of France as part of European or national programmes.*

[23] Accelerator-Driven System.

1.8. TRANSMUTATION AND DISPOSAL

The benefits of reducing the quantity of minor actinides in the waste can be assessed using at least two criteria: the radiotoxicity of the inventory and the area occupied by the disposal site. Andra, in partnership with the CEA, has presented a study of a number of scenarios to estimate the impact of transmutation on the disposal facilities that would be implemented for a new set of nuclear power reactors in geological conditions similar to those found in Meuse/Haute-Marne.

1.8.1. Radiotoxicity of the inventory

The radiotoxicity of the inventory characterises the intrinsic harmfulness of the waste. It is defined as the dose that would be received in the event of internal exposure to all the radioactive material contained in the waste (source term).

In a favourable theoretical scenario in which only fission products could be disposed of – after partitioning and transmutation of all the actinides (plutonium and minor actinides) - ingestion radiotoxicity would be reduced by one or two orders of magnitude, after 500 years.

If only americium were to be transmuted, we would achieve a reduction of one order of magnitude during the first millennium, but this reduction would then be tempered due to the plutonium 240 produced by the radioactive decay of curium 244.

With no change in electricity production, the transition to a reactor base composed entirely of FNRs cannot be made without building up a stock of plutonium from pressurised-water reactors (existing or to be built), the waste from which would be glass packages identical to those in the current inventory. Consequently, by 2150, for example, when the entire reactor base would be made up of FNRs, as the minor actinides from this PWR waste will not have been recycled, the radiotoxicity of the waste generated would remain close to the level achieved without transmutation.

> *In any case, unless we can eliminate all actinides (including plutonium) from the waste, the improvement in radiotoxicity remains modest, due firstly to the waste already produced without transmutation and secondly to the presence of some very long-lived actinides.*

Andra has shown high retention of actinides in a reducing geological environment. Consequently, in such an environment, the dosimetric impact of the actinides is nil. The transmutation of the actinides would therefore have no influence on the radiological impact of the disposal facility, unless there were to be an intrusion.

1.8.2. Residual thermal power in LLHL waste

The residual thermal power in LLHL waste after reprocessing and storage causes a rise in temperature in the disposal facility. The long-term safety conditions have led Andra to calculate a temperature limit of 90°C in contact with the rock.

The fission products (caesium 137 and strontium 90) make a significant contribution for 120 years. Beyond that, the thermal power of the LLHL waste packages is essentially due to americium 241. This is why transmutation of the americium, and a storage period sufficient to allow the power of the fission products and the curium to decrease, could bring about a reduction in the area of the underground disposal facility.

In comparison to the scenario in which the LLHL waste packages produced by the FNR reactor base contain fission products and minor actinides (but do not contain plutonium, like the current glass packages), the transmutation of americium alone would offer the following advantages:

- A reduction of a factor of 2 to 2.5 in the area of the disposal facility for LLHL waste and a 30% reduction in excavated volume, after 70 years' storage;

- A reduction of a factor of 4.6 in the area of the disposal facility for LLHL waste and a 50 % reduction in excavated volume, after 120 years' storage;

There is therefore a significant gain in terms of the area and the excavated volume, even in the case of transmutation of americium alone. However, this gain is limited to the LLHL waste disposal facility. It should also be noted that simply increasing the storage period of the packages only reduces the area of the LLHL waste disposal site by 23%. Americium 243 has a half-life of more than 7,300 years, which slows down the reduction in heat emissions and limits the possibility of reducing the size of the disposal site.

The transmutation of americium also makes it possible to reduce the duration of the thermal phase – the period during which the interface between the steel and the rock is at a temperature of more than 50 °C - from 2300 years to fewer than 200 years.

While partitioning and transmutation of americium only does have an impact on future disposal, given its contribution to the thermal load of the disposal facility, the Board notes that this impact only concerns the area of the disposal site and the volumes excavated. It would stress that the future disposal site could require new designs so as to be better able to take advantage of the possibilities offered by transmutation.

Theoretically, as the minor actinides remain immobilised in clay with reducing properties, leaving them in the disposal facility does not present any major disadvantages from the point of view of the safety calculations, except in the event of human intrusion. However, the significant reduction in the required area, the reduction in the excavated volumes and the reduction in radiotoxicity for part of the source term constitute quite marked advantages and merit consideration by decision makers.

1.9. OTHER SCENARIOS

To date, the management of plutonium in the event of continued electricity generation by PWR-type reactors, as well as the management of depleted uranium, have not been taken into account in the envisaged disposal projects.

Other scenarios should also be explored:

- Would it be wise to condition the americium and curium in isolation so as to dispose of them in a specific compartment? This would lead to disposal of fission products only, reducing the area of the disposal site, the radioactivity of which would, after a few centuries, return to the radioactivity level of a uranium ore. This scenario would mean studying the specific conditioning of the actinides using knowledge acquired during the development of matrices for transmutation on Phénix, HFR, and Halden. To give you an idea, a few tonnes of minor actinides are currently produced in Europe each year.

- Must spent fuel be reprocessed after a short time in storage? The significant decrease in the quantity of americium would have a considerable impact on the thermodynamics of the waste and therefore on the size of the disposal site ('endogenous' transmutation as it would take place before the actinide decay process).

The Board would like the CEA to present it with a research strategy for exploring the reprocessing of spent fuel after the shortest possible storage time.

In conclusion, the issue of the impact of partitioning and transmutation on a future disposal site raises questions relating to the new flows of materials and waste to be considered. In this context, thought should be given, without any preconceptions, to optimisation of use, in the light of the different options that, as we can clearly see, significantly affect the space and time parameters of the disposal site.

1.10. CONCLUSION

Partitioning and transmutation only makes sense if it is first applied to plutonium with the implementation of FNRs. The partitioning and transmutation of minor actinides is scientifically possible. It is feasible for americium, and very difficult for curium. This partitioning and transmutation offers a number of advantages, including a reduction in the radiotoxicity of the waste and the size of the disposal site, and may help with public acceptance.

In the decision to be made by the legislator regarding the appropriateness of this strategy, these facts must be weighed up against the technological difficulties and the probable additional costs.

Chapter 2

DISPOSAL AND STORAGE

2.1. INTRODUCTION

To produce this report, the Board worked with the disposal concept established by the 2005 Report and expanded upon in the 2009 Report, which was the result of a coherent scientific and technical approach.

The results of its assessment, within this framework, are presented in chapter 2 of this report through the following points: the design inventory for the geological disposal facility, the Zira[24], the surface installation areas (ZIIS), the scientific work (thermodynamics, geomechanics, underground laboratory experiments), reversibility, and finally the memory of the disposal site. Furthermore, based on the documents received at the end of the period (from June to October), the Board gives a brief initial analysis of Andra's Cigeo[25] project.

The recent events in Japan have drawn attention to the particular sensitivity of surface storage facilities, particularly pits. The Board has made plans to analyse in 2012 the studies undertaken by the waste producers on the storage conditions planned for their respective sites.

2.2. INVENTORY

The waste that it is currently planned to handle in geological disposal is long-lived intermediate- and high-level waste produced by the current reactor base. A list will be established in a document entitled 'Industrial Waste Management Programme' (PIGD), produced by Andra using the data provided by producers. It must include an overall inventory established for a precise scope fixed until the submission of the Dac[26]. It will include space for future expansion in order to take into account uncertainties in the inventory and uncertain production of certain types of waste.

The waste package flow management system will be used for storage at the Cigeo site that could replace that of the producers, but only for 'buffer' storage for waste packages that will be disposed of 'just in time'. Provisional timelines for delivery of the packages will be established to ensure that instantaneous disposal capacity is compatible with producers' needs.

If a disposal site were to be opened in 2025, it could not be closed before 2125. Before that date, France's energy policy may change significantly in ways that it is difficult to anticipate. For example, our country may decide to abandon nuclear power and/or fuel reprocessing. It is likely, in such a scenario, that considerable quantities of highly exothermic irradiated fuel assemblies would have to be disposed of. Andra's 2005 Report examined this possibility, which is no longer present in the 2006 law. Conversely, our country may choose to develop EPR reactors and perhaps, beyond 2040, FNRs, which will, in turn, generate waste.

24 Zone of interest for further investigation.
25 Industrial centre for geological disposal.
26 Application for authorisation to create the disposal facility.

In both scenarios, there would be at least two options. The first would be to create a new disposal facility. The other would be to expand the existing storage facility in the Callovo-Oxfordian layer, which current knowledge would suggest could have more extensive geologically suitable capacity than what is required for today's envisaged disposal requirements. When the time comes, this decision must be debated within a proper legal framework.

> *The Board would stress that, with 18 months to go until the public debate, it is essential that the disposal site design inventory that will feature in the Dac, which constitutes a form of contract with all stakeholders, is decided in a precise and constrictive manner.*

With regard to LLLL waste[27] (radiferous and graphite waste), for which no disposal site has yet been envisaged, Andra is monitoring the latest graphite technologies to study the optimum conditions for disposal.

2.3. ZIRA

Since 1995, a great many boreholes have been made in the Meuse-Haute Marne region, and many 2D and 3D 'seismic reflection' profiles have been reprocessed (as in the case of the old reflection seismology for petroleum) or acquired by Andra (15 km of 2D in 1995, 4 km^2 of 3D in 1999) in order to survey the subsoil architecture and characterise the degree of heterogeneity within the Callovo-Oxfordian argillites and the surrounding rocks. These data firstly made it possible to define a transposition zone of approximately 250 km^2 where one or more zones of interest for further investigation (Zira) could be identified, each around thirty km^2 in area, as possible sites for a disposal facility.

These subsurface data, completed with detailed geological surveys conducted in the underground laboratory, enabled Andra to select a Zira of 28.5 km^2, where the future underground disposal facility could be installed. This zone was approved by the Government at the end of 2009. The Zira is currently undergoing in-depth investigations according to a scientific programme established by Andra, of which the essential component in 2010 was the performance and interpretation of a 3D geophysics campaign.

The elements below summarise the key geological and hydrogeological findings concerning the Zira.

2.3.1. Contributions of the new 3D geophysics campaign

The 3D geophysics campaign conducted in 2010 over 37.1 km^2 covered the whole of the Zira (28.5 km^2). The campaign was successfully conducted, with excellent coverage of the measuring area and data of excellent quality. The speed of processing has enabled Andra to already make initial interpretations.

[27] Long-lived, low-level waste.

The processing of the data initially concerned static corrections. The structural interpretation is complete and has produced maps that have not yet been converted into depths. Lithostratigraphic interpretation has begun.

The geophysical data now available about the Zira show that there are no structural objects identifiable by seismic reflection - and which therefore have throw of over 5m according to Andra – in the walls and roof of the Callovo-Oxfordian layer (Cox). If such objects had been found, they would have appeared after the deposit of the Cox argillite and would therefore be likely to pass through this formation. In the absence of seismic markers in the Cox layer, we cannot, however, exclude the existence of fractures of lesser throw, due to different settlements within the sedimentation. But such fractures should remain confined to the seals, without any risk of spreading into the surrounding layers above and particularly below these formations.

The new seismic reflection campaign confirms the excellent homogeneity of the Zira. After the first interpretations of the seismic data, the 3D geological model appears sufficiently robust for us to exclude the presence of structural discontinuities passing through the Callovo-Oxfordian layer and capable of providing a hydraulic link with the surrounding aquifers. The presence of small discontinuities within the layer cannot be totally discounted at this stage. It must be noted that no object of this type has been found to date, neither in the various vertical and inclined boreholes, nor in the underground laboratory. Such objects will only become visible as the digging of the disposal facility progresses. A decision to undertake new inclined boring operations within the Zira, before the disposal facility is excavated, should not be taken lightly, as such boreholes could form potential transfer routes between the Callovo-Oxfordian layer and its overburden.

2.3.2. Knowledge of lithostratigraphic variations in the Callovo-Oxfordian layer

Andra has made considerable efforts to compile and summarise the data. The petro-physical properties[28] of the Cox clays, acquired partly from tunnels in the underground laboratory and partly from boreholes[29], are thus linked to the conditions for the deposit of sediments from the Cox and its surrounding layers.

The very low variability of the petro-physical properties is now well understood within a vertical column in the Cox layer. These properties can therefore be extrapolated to any point in the layer using the data from the real shafts. The horizontal variability of these properties may be anticipated based on the regional paleo-geographical models and the deposit environments.

Andra now has a conceptual geological model justifying the transposition to the Zira of the data produced using the information acquired in the underground laboratory.

[28] Mineralogy, heat conductivity, permeability, porosity.

[29] Where the data are obtained by macroscopic and microscopic analysis of the drill cores and cuttings, but also from logs.

2.3.3. Knowledge of regional and local hydrogeology

At regional level, the Cox clays are framed by the carbonate formations of the Bathonian series and the Oxfordian/Kimmeridgian/Tithonian series, which have higher porosities and permeabilities and are therefore likely to constitute horizontal drains for fluids.

Around the edges of the transposition zone, outside of the Zira, a set of structural accidents (sub-vertical faults passing through the whole Mesozoic series) has been recognised and mapped thanks to the successive geophysical campaigns.

The vertical throw of these different accidents bordering the transposition zone, which were taken into account in the definition of this zone, are less than 100 m and seem, because of this, to be insufficient to disrupt the hydrogeological continuity of the aquifers surrounding the Cox. These accidents may, however, create preferential vertical circulation routes between these aquifers, thus directly influencing the conditions at the hydrogeological limits of the transposition zone. This justifies the considerable efforts undertaken by Andra over many years to characterise them.

At sector level, the flow of groundwater of meteoric origin is constrained by the carbonate layers of the Upper Jurassic strata, above the Cox, with a recharge zone to the south. To the north-west, a thin overburden of Cretaceous clay has been preserved from erosion, as its distribution is directly controlled by the hydrographic network.

At local level, within the Zira and its immediate environment, the 19 boreholes made for static correction of the 2010 3D seismic reflection campaign have been used to acquire additional information about the structure and hydrogeology of the limestones of the Barrois region, which make up the outcropping aquifer formation.

A programme of piezometric monitoring and monitoring of the source flow rates has been instigated. This point is important for characterisation of the initial state and for evaluating, and potentially minimising, the future impact of underground works, particularly the inclined drift that will pass through the Barrois limestone.

Andra currently has hydrogeological data, essentially of bibliographic origin, for the whole of the Paris Basin, as well as data from its own surveying work at sector level, including the transposition zone, which can be used to create a digital hydrogeological model simulating underground flows in the near and distant environment of the disposal site.

2.3.4. Hydrogeological modelling situation

Various digital modelling tools have already been implemented at regional level to simulate the flow of fluids in the geological layers of the Paris Basin, using a well-documented 3D geological block model to describe the architecture of the faults and strata, based on seismic reflection and borehole data. This architecture is described using calculation codes developed at the IFP[30]: Dionisos for the lithostratigraphic model and Fraca for the fault networks.

[30] French Institute for Petroleum and New Energies.

Hydrogeological modelling was resumed in 2008 by the University of Neuchâtel, which, using its own simulation tools, undertook the construction of a single model covering both the regional problem and the sectoral problem. The work is still under development and no significant advances were presented to the Board in 2010.

The Board considers that an effort must be made to complete regional and sectoral hydrogeological modelling as quickly and as well as possible. Such a modelling tool is necessary to make a final determination as to the hydraulic role of the faults bordering the transposition zone, which could play a role in the definition and behaviour of the radionuclide outlet channels that may, in the very long term, provide routes from the disposal facility to the surrounding aquifers. The modelling tool will also be essential in predicting and then monitoring the hydrodynamic impact of digging the disposal facility access shafts and the inclined drifts. The Board would like the hypotheses and conclusions on hydrogeological modelling to be presented to it in detail before the Dac.

2.4. ZIIS – INTEGRATION OF THE STRUCTURES IN THE SURROUNDING LAND AND THE ENVIRONMENT

The surface facilities are an integral part of the underground disposal centre project.

Because of their dimensions, their impact on the environment and their socio-economic consequences, these facilities must be studied with the same care as the underground facilities, even if their creation will use well-known, long-standing techniques that have been tried and tested in all companies handling and storing radioactive waste and materials.

These facilities will constitute the most visible part of the disposal centre and will therefore have a decisive effect on the acceptability of the project by nearby populations.

During the hearing of 15 October 2009, Andra had presented a preliminary project defining the ZIIS locations:

- A nuclear zone of approximately 25 hectares where the primary packages will be received, temporarily stored and then reconditioned;
- An industrial zone of approximately 35 hectares which will house the non-nuclear technical workshops;
- An administrative zone;
- A stockpile of approximately 120 hectares for disposing of and storing excavated material.

The total area of these four zones, not including access roads, should therefore be nearly 200 hectares.

If the choice to link the bottom to the surface via one or two inclined drifts is maintained, it will be possible to offset most of the surface facilities from the disposal structures, which should make it easier to find a location for them, perhaps in a different department. Indeed, all that would remain on the surface above the underground disposal facility would be the shafts necessary for transporting certain equipment and for ventilation.

While the definition of one or more potential zones for the installation of surface facilities (ZIIS) is primarily a matter of negotiation with the local authorities and the various stakeholders, the technical criteria relating to safety, geography, geology and the environment must remain decisive factors.

2.4.1. Safety and security constraints

Some of the surface facilities will constitute a Basic Nuclear Installation (BNI), where all the regulatory constraints governing this kind of facility will apply.

Thus, although the region where the disposal centre is due to be installed experiences only minor seismic activity, the fundamental safety rule, ASN 2006, nevertheless requires some parts of the BNI to be designed to meet the specifications of a standard model adjusted by a safety coefficient. The storage facilities may also constitute a considerable source of risk.

The fundamental safety rules imposed by the ASN will result in all other risks, such as falling planes, flooding and fire, being taken into account.

One of the arguments most often put forward to justify underground disposal of radioactive waste is the capacity of such facilities to withstand external attacks. However, it must not be forgotten that, before being placed safely at the bottom of the disposal facility, the waste will be kept in much more accessible surface facilities, which must therefore be designed to withstand any attempted intrusion.

2.4.2. Environmental constraints

The possibility of using an inclined drift to separate the ZIIS and the surface footprint from the underground disposal site allows quite a lot of flexibility in the choice of location for the surface facilities.

Nevertheless, it remains the case that environmental constraints may prevent their installation in some sites such as inhabited zones, water catchment areas, floodplains, Natura 2000 sites, areas of ecological interest and remarkable landscapes.

In 2009, Andra produced a map summarising constraints on surface installation, which, while not very precise, has the advantage of identifying the areas with high constraints where any installation is theoretically excluded.

The arrival in an essentially rural region of industrial facilities, over an area of 200 hectares, will have a definite effect on the environment and land planning, which must be studied in order to derive maximum benefit from this new activity.

The creation in 2009 of a long-term environmental observatory, and the establishment of a reference report on the biodiversity and quality of the premises, should make it possible to monitor any disruptions that may occur on the site itself and on its access routes.

2.4.3. Reversibility constraints

The possibility of removing waste packages from the disposal facility is an essential aspect of the safety approach. If a package has to be removed, the surface facilities should be equipped with decontamination and storage equipment. This type of operation is already well mastered by waste producers, but there would be a capacity problem if a whole series of packages had to be stored for any length of time.

Reversibility, or even recoverability, can therefore only be conceived of if the surface facilities have, from the beginning, been designed and sized to withstand all potential incidents, as it could be difficult to send defective packages back to their original producers.

To this end, Andra is studying the possibility of acquiring a storage module of 100 to 500 m^3 in 2050. Will this volume be sufficient for the necessary handling operations?

If this equipment can be considered as forming an integral part of the underground disposal centre project, could the same be said of a storage module for the thermal decay of LLHL waste packages?

This project, mentioned several times in Andra documents, would provide a 725 to 2,000 m^3 structure for storing packages whose thermal power had already decreased during an initial period of storage in the Hague. Would this not be a separate project, distinct from the underground disposal centre? In this case, it should be the subject of a specific procedure that is made public.

2.4.4. Advantages and disadvantages of connecting the bottom to the surface via an inclined drift

It is undeniable that the choice of a bottom/surface link via one or two inclined drifts would make it possible to expand the potential area of installation for surface facilities, which would make negotiations with local bodies easier.

This type of link has been adopted for underground disposal centres in Sweden and Finland, but for these projects the excavations to be made are in granite formations. In France, we will have to dig through water-bearing and possibly karstified limestone. We must ensure that the water in the formation does not soak into the underlying layers.

Before the public debate, the Board would like to see studies to enable it to assess the scientific and technical appropriateness of the choices that will be proposed during the debate. Indeed, while dialogue with the politicians and the various stakeholders is an essential part of the process for selecting locations for the surface facilities, the final choice of these locations must nevertheless be primarily based on the results of objective studies of the geographical, geological and environmental constraints of the candidate sites.

As soon as the location of the surface facilities is specified, the Board believes that it is essential to have a study of the hydraulic and geological disturbances that may be caused by the digging of the inclined drift(s).

2.5. Moving towards the creation of a geological disposal site: the industrial centre for geological disposal (Cigeo)

2011 was a very important step for all French participants in the underground disposal project, particularly for Andra and the waste producers, since this project is now transitioning from an exploratory phase devoted essentially to R & D work, to the industrial implementation of the Cigeo project.

While the 2006 law specifically mandates Andra, and Andra alone, to develop the disposal project, a major factor that first emerged in mid-2010, and came to full prominence in 2011, was the promotion by waste producers of an alternative project to Andra's. This project has been developed by EDF, Areva and the CEA using their experience in nuclear energy and civil engineering projects. As Opecst[31] underlined in its assessment report on the PNGMDR[32], this approach seems to have been motivated by the prospect of a considerable increase in the cost of Andra's geological disposal project.

The cost of the underground disposal facility had been estimated in 2005 at 14.1 billion euros (2003) by the DGEMP[33] (now the DGEC), which is now equivalent to 16.2 billion euros (2010). The figures being put forward today are noticeably higher. Figures of 20 to 35 billion euros (2010) are being quoted. According to the law, it is for the administrative authority to decide. Before reaching a decision, it will probably wait for the submission of the report on the cost of the nuclear industry requested by the Court of Auditors. This report should be available in January 2012.

We should also have access to information on the structure of the costs: i.e. the proportion of fixed costs independent of the rate of waste burial, and the proportion of variable costs linked to the quantities disposed of. The date of use of the site and the rate at which waste is disposed of should have an impact on the apportionment of costs among the various waste producers.

The Board would draw readers' attention to the fact that, for several years, it has repeatedly asked for information on the costs of the disposal site. It would like to be kept informed of the figures that will be used. It would also like to have precise information about how costs will be apportioned, and on the additional costs linked to reversibility. The Board wonders whether the delay in publishing the costs may reflect lasting divergences between Andra's point of view and that of the producers, which would be damaging to the progress of the disposal project.

[31] See Opecst report of 19 January 2011 "Nuclear Waste: Beware the paradox of tranquility". – pp 37-38.

[32] National Plan for the Management of Radioactive Materials and Waste.

[33] Directorate General for Energy and Raw Materials.

Until May 2011, the Board only had a very limited knowledge of the operators' project. Deeming the information it had to be insufficient, it decided to delay publication of its report n° 5, initially planned for June 2011, to the end of the year.

The Board has since received additional information:

- Through its participation as a guest at the Cigeo project review held by the DGEC. At the start of June, this review formulated an opinion on the reference data necessary for the launch of the draft phase and on the requirements that will be imposed on the project's prime contractor, as well as recommendations to achieve convergence between some aspects of the projects proposed by Andra and the producers;
- Through access to the technical documents for the producers' STI project;
- Through a private hearing with EDF, during which the design options of the STI project were presented and justified;
- Through a hearing with Andra, during which the technical specifications for the preliminary needs of the Cigeo project were presented. These constitute the outline of the specifications used in the call for tenders for the draft phase prime contractor, launched by Andra in July 2011.

The Board now considers that it has sufficient information.

The assessment that follows gives a summary analysis of the principles and design choices of the STI project, then covers the essential technical requirements of the Cigeo project.

2.5.1. Brief analysis of the STI project

The project proposed by producers offers a certain interest, as it allows certain principles that should govern the design of a disposal facility to be clarified.

This project has been conducted within a framework resulting from the geological surveying performed by Andra. It pushes to the limit, sometimes in ingenious ways, the cost-reduction strategies already mentioned in Andra's studies. It has a number of qualities. It takes an overall view of disposal and subjects the architecture project to a safety study. It emphasises the difficult problems posed by gas generation in the cavities. It organises the design of the structures in a systematic fashion, using the geomechanical behaviour model based on Andra measurements and laboratory tests. The Board was not, however, informed of the detailed content of this model until very recently.

The producers' project essentially involves: significantly lengthening the LLHL waste cavities from 40 to 130 m, even though the latter value results from technical and economic optimisation, the results of which appear to be fragile to say the least; significantly increasing the diameter of LLIL waste cavities and making a more modest increase to their length; and, conversely, shortening the length of the tunnels linking the cavities to the bottom of the access structures. Reducing the length and number of these tunnels leads, in the interests of simplifying ventilation paths, to the air return shafts being positioned as far as possible from the access shafts. Access to the bottom is via two distinct inclined drifts, which makes it possible, in the access zone, to separate the excavation work from the transport of the packages. Outside of the access zone, however, this separation is less clear than in the Andra project, due to the reduced number of tunnels.

The architecture has the advantage of great geometrical simplicity and the major disadvantage of reduced flexibility, as the LLIL waste disposal zone is produced in one go and the whole of the LLHL waste zone is made in only two stages, which does not facilitate adaptation to unforeseen circumstances or design changes. This architecture leads to the creation of a small number of very long tunnels, rather than a rectangular network. It enables systematic use of the tunnelling machine, which has cost advantages and possibly also results in a smaller EDZ and safer excavation work, but requires large curve radii in the access tunnels. This excavation method offers much less flexibility than a boom-type road header. It also poses risks of jamming, which can probably be overcome. It is not a method traditionally used in argillites in the Cox layer, but the prospects of feasibility seem quite good, and Andra had already envisaged its use.

The shafts are made by '*raise-boring'* (bottom-up).

The abandonment of rectangular geometry leads the STI project to attribute less importance to the orientation of the cavities in the horizontal stress field, whereas Andra, based on observations made on site, had chosen systematically to orient these cavities in the direction of the major stress, in order to reduce the extent of the EDZ.

Fire safety is based on a principle of tunnel sectioning (fire doors every 400 metres), very different from that envisaged by Andra.

Calculations of the effective individual dose rate at the outlets are presented, in accordance with the requirements of the Safety Guide published by the ASN[34]. The numerical approach is probably simpler than that proposed by Andra in the 2005 Report and the interpretation sometimes lacks detail. It does, however, offer a number of interesting features. The results are not very different from those of Andra and therefore constitute a form of partly independent confirmation of the validity of the calculation methods when the same data are used, at least in terms of orders of magnitude. The dose rates are low in comparison to the criterion of 0.25 mSv/year set (for the normal scenario) by the ASN Guide. This consistency in calculation results is not surprising and confirms a conclusion already posited by Andra: given the favourable properties of the Cox layer, the dose rates remain more or less the same regardless of the disposal facility architecture. In fact, the rates found by STI are slightly higher than those obtained by Andra. It is likely that this result is partly due to the shorter distance travelled by the radionuclides from the cavities to the shafts, which results from the decision to make shorter tunnels. This is why, significantly, the results of the STI project are considerably worse in the "all seals defective" scenario, an extreme scenario in which Andra had shown that it was still fairly comfortably able to satisfy the 0.25 mSv/year criterion. With STI, the molar flow rate of I^{129} is noticeably higher. In contrast, the decision to have longer cavities for LLHL waste is not detrimental in terms of the dose rate criteria; the problems it poses tend to concern the recoverability of packages and, above all, the excavation process – Andra has as yet only established, after some trial and error, the feasibility of cavities 40m in length.

The main problem posed by the STI project is that it limits verification of the safety objectives to the issue of compliance with a dose rate criterion which, as we have said, depends little on the architecture of the disposal facility. We than therefore apparently simplify this architecture, reducing the number and length of the tunnels, without having any real effect on the dose calculation. However, the Safety Guide stresses a second principle: *"Besides the comparison of the effective individual doses calculated at the values indicated, be it in the reference situation or the degraded situations, the assessment of whether the radiological impact of the disposal facility*

34 French Nuclear Safety Authority.

is acceptable depends above all on the analysis of the efforts made by the designer to ensure that individual exposure is as low as is reasonably possible, given the economic and social factors".

This means that, as well as writing a mathematical model of the disposal system which allows the doses to be calculated, it is also necessary to check that the structure and its implementation possess qualities that are less easily quantifiable, such as robustness, redundancy, demonstrability and flexibility. From this point of view, the producers' project is less flexible: the reduction in the length of the linking tunnels and their linear organisation, the logical consequence of which is the separation of the shafts, provides less safety in terms of the long-term circulation of fluids in the disposal facility. In contrast, the only disadvantage of lengthening the cavities, besides the potential impact on recoverability, is that its industrial feasibility is as yet far from proven.

This also means that the overall quality of the structure is measured by assessing all the efforts made to reduce its radiological impact. Considered in isolation, the STI project may appear to have merits. But the very existence of the Andra project shows that another design is possible, and the Andra project can be credited with having made greater efforts to seek to reduce the radiological impact. Indeed, it was on the basis of these efforts that the essential points of the project were approved by all assessors in 2006 and 2009. Consequently, the STI project does not take into account as well as the Andra project does the safety objectives prescribed for deep geological disposal, notably those linked to the Alara[35] principle.

The Board considers that the STI project has raised issues for discussion that can stimulate reflection with a view to the industrial implementation of the underground disposal project. This project benefits from the experience of companies well-versed in the design and management of nuclear facilities. However, it lacks flexibility, and has not been subjected to full analysis with regard to compliance with essential safety objectives. The Board regrets that the opposing points of view were not brought to the attention of the assessors earlier and more calmly.

2.5.2. Design of the Cigeo project draft phase

Given the current state of progress of the research work and borehole tests being conducted in the Bure underground laboratory, and the plethora of knowledge acquired on regional geology, particularly in the Zira, during the 2D and 3D geophysics campaigns and targeted boring operations, Andra, the project owner, decided, after the review of the Cigeo project, to conduct a call for tenders to select the prime contractor. The prime contractor selected must, in 2012, help to finalise the detailed draft of the Cigeo disposal project and cost its implementation as accurately as possible. These two pieces of information must be available by the end of 2012, to allow preparation for the public debate scheduled for 2013.

35 "As Low As Reasonably Achievable".

Andra has formalised the safety specifications and the other requirements that the prime contractor's proposals must satisfy. These specifications reproduce, with a more operational focus, the recommendations formulated in 2009. They are expressed firstly as imposed design principles establishing a general framework, which leave no room for interpretation, secondly as imposed design options, which have some flexibility and may change if there is a good reason for them to do so, and finally as imposed or prohibited design solutions, which refer to an object or piece of equipment involved in the design.

The main requirements include:

- The preservation of 60 m of argillite on either side of the (roof and walls of) the tunnels and cavities dug in the Cox;
- The preservation of a minimum spacing between the cavities, making every effort to ensure compact storage, and the obligation, at least in the initial stages of implementation, to orient the cavities in the direction of the maximum horizontal stress;
- The obligation to organise each disposal area so that it is blind with regard to the rest of the underground facility, in order to reduce possible water circulation.
- The obligation to group together the shafts and accesses to the Cox layer;
- The obligation to use excavation methods that limit rock damage (EDZ), both for the tunnels and for the disposal cavities;
- The obligation to make control cavities for LLHL and LLIL waste during the first stage of construction, which will be instrumented and used for full-scale reversibility tests;
- The obligation to create two sealing demonstrators as part of the first stage of construction.

At this stage, the prime contractor is given some leeway to explore and cost different technical solutions for excavation and for the detailed architecture of the tunnel network, with Andra reserving the right to assess their conformity and to make the final decision based on safety criteria (first priority) and budgetary criteria (cost optimisation should only be applied to solutions which already meet safety requirements). Tests concerning the excavation of the cavities and the monitoring of their ageing are anticipated as part of the first stage of the disposal facility.

Andra is also mindful of the need to avoid beginning the creation of all the tunnels straightaway, so that infrastructure expenses are only committed in a modular fashion, one stage at a time, thus leaving more flexibility and adaptability over time, and making it possible to use the technological lessons learned in one stage for the benefit of the next.

The Board has not had time to analyse in detail the content of the call for tenders or the form of governance of the project created by the contracting process. However, it is worried that, without having included an explicit abstract model in its call for tenders, Andra has delegated the "project management of the system" to an external company which will be responsible for finalising the detailed draft of the first stage of the disposal facility, the methods to be used and the costing of implementation, all in less than a year. The Board would ask Andra to assume fully all the responsibilities assigned to it by the law.

Furthermore, the Commission regrets the introduction, at least as possible lines of enquiry, of options that have not been sufficiently debated, such as the possible switch to LLHL cavities with flow-through ventilation (i.e. open on both sides), and the lack of clarity regarding the maximum temperature objective for the rock in contact with structures after 1000 years.

2.5.3. Development of the Cigeo project

The producers (EDF, CEA and Areva) have, over many years, developed great expertise in nuclear facilities, underground structures and the management of the related risks (contamination, fire, etc.). One of the recommendations of the Cigeo project review, to which the Board subscribes, is that there should be dialogue between Andra and the producers throughout the implementation of the industrial project. While retaining its prerogatives as project owner, and thus avoiding any conflict of interests with the producers, who will play an advisory role, offering guidance and expertise, Andra has informed the Board of its current wish to finalise an exchange agreement with EDF and the CEA in order to be able to integrate into its own teams experts seconded from EDF, the CEA and Areva and benefit from their expertise throughout the implementation and key stages of the Cigeo industrial project.

In general, the Board would underline the fact that the various concerns governing the design of a deep geological disposal facility must be clearly arranged into an order of priority. Long-term safety, operating safety, worker safety, and the protection of the health and well-being of the populations concerned must be the main objectives. Once these objectives have been met at the requisite level, the recoverability of waste packages and the reversibility of disposal are also important objectives. The Board also recognises the importance of cost concerns, but these must remain secondary to the abovementioned objectives. From this last point of view, the Board would once again express its regret at having only received a very small amount of information on these issues, at a time when the emergence of a proposal from producers would appear to suggest that they were a major issue in debates between Andra and the producers. The Board fears that, without the desired level of transparency, these problems will continue to weigh heavily on the decisions to be made, particularly as this question will be central to the public debate scheduled for 2013.

2.6. SCIENTIFIC WORK

2.6.1. Thermodynamics

Waste in disposal facilities emits heat. The power emitted decreases over time. For the hottest waste, this decrease is primarily due to the radioactive decay of the fission products (caesium and strontium). After a century, thermal decay is slower and dominated by the decay of americium. Andra has established an assessment of the large-scale effects of the thermal load on deep disposal, as conceived of in its 2009 Report.

The Board summarises the main points of its analysis below.

2.6.1.1. Thermal disturbances

The rise in temperature within the Cox layer causes several disturbances, notably affecting the pressure of the pore water and the mechanical stresses.

From the point of view of safety after closure, the most restrictive criterion concerns vitrified waste, as the leaching of the glass is much faster above 50°C. It is therefore necessary to be certain that the temperature will be less than 50°C when the water may come into contact with the glass. To satisfy this condition, Andra calculated that the maximum temperature to be observed in the short term is 90°C in the walls of the LLHL waste cavities.

The temperature differences between the different areas of the disposal facility will stem primarily from the nature of the waste present. Andra has performed many three-dimensional thermal simulations. These show that the return to equilibrium is quite slow. There is still a difference of a few degrees from the natural temperature, after 10,000 years, at the centre of the LLHL area that is home to the hottest waste.

The most noteworthy fact is probably the appearance of overpressures in the argillite pore water. These are caused by the thermal expansion of the water contained in the pores. They may reach a few MPa and dissipate slowly due to the low permeability of the environment.

Andra has estimated the mechanical stresses in the Cox layer by means of a digital calculation assuming elastic behaviour from the environment. The order of magnitude of the increase in average stress and deviatoric stress (which measures shear intensity) is a few MPa. A preliminary calculation suggests that this increase in the stresses does not lead to rupture at the interfaces between geological layers with different thermomechanical properties (Callovo-Oxfordian and carbonated Oxfordian). Furthermore, after several decades, a significant proportion of the heat from the waste has already been produced and stresses of a few MPa have been generated. It will be necessary to check the possible consequences of the coexistence of parts that are still in operation and parts that have been heated for several decades.

> *The Board believes that more detailed research must be conducted on this thermomechanical problem and it would like the results of this research to be presented to it.*

At the end of the disposal facility's operating life, the hydrogen produced by corrosion migrates into the rock layer. The risk is not of an explosion in the layer, due to the absence of oxygen. These two disturbances (temperature and hydrogen) are not very intense, but it is unusual to find them together in conventional underground structures. We therefore have no experience feedback.

> *The Board recommends that the mutual interaction of these two disturbances and their potential impact on the environment should be studied.*

2.6.1.2. Thermal experimentation

Andra has conducted, or is planning to conduct, several thermal tests in the underground laboratory in order to confirm the thermal parameter values measured in the laboratory, so as to bring to light and analyse the hydraulic and thermal phenomena associated with the increases in temperature in the rock mass and prepare a concept demonstration test for the most exothermic HL waste cavities.

The lessons learned from the TER[36] test completed in 2009 have been used to design and size a new test (TED[37]), which is more complex, as it includes three parallel heating probes. Heating began in January 2010. The interpretation work will probably be tricky, due to the complex effects of the increase in temperature on the thermohydromechanical properties of the argillite.

> *The Board notes that the tests in the underground laboratory, during which all these effects occur simultaneously, are closely linked to experimentation in the surface laboratory, performed in simpler conditions. It recommends that modelling efforts should be continued so as to derive maximum benefit from the experimentation underway.*

2.6.1.3. Thermodynamics and transmutation

One of the Board's concerns has been to assess the advantages that transmutation of minor actinides would bring from the point of view of the thermal load, taking a disposal facility in the Cox layer as an example. It should be remembered that such transmutation could only be used beyond 2040, with a new generation of reactors.

The transmutation of minor actinides, particularly that of americium, would significantly reduce the thermal load, which is higher in the waste packages of the 4th generation reactors than in the current waste packages. This reduction in thermal load would be a considerable advantage when it came to reducing the area of the disposal site. Such a reduction in area would present several advantages: the probability of unintentional intrusion would be lower and the distance from geological accidents such as faults would be increased. On another note, people also mention the idea of *"preserving a rare resource"*: transmutation would make it possible to dispose of significantly more waste and therefore get the most out of a favourable zone. The reduction in thermal load, while it does not in itself justify use of transmutation, is a real advantage of the method.

2.6.1.4. Conclusion

The Board would like to have a better idea of the state of research on thermal load, particularly as this is closely linked to other questions, such as the horizontal extent of the disposal facility, the advantages of transmutation, and determining the duration of cooling prior to disposal. Although some uncertainties remain, the acquisition of the parameters necessary for the thermal calculations is on the right track.

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[36] Experiment concerning the response of argillite to thermal stresses.
[37] Experiment on the overpressure field in the argillites around two or three heat sources.

Further efforts should be made on the analysis of the thermomechanical effects, as suggested above. The maximum temperature of 90°C in the cavity walls plays an important role in sizing the disposal facility. It seems reasonable in the light of the choices made by other countries. The reduction in the size of the disposal site appears to be the most substantial advantage offered by a reduction in thermal load. This gain can only really be assessed once a precise disposal concept has been defined.

Full-scale tests must be conducted in the underground laboratory in order to advance knowledge.

2.6.2. Geomechanics

Geomechanical studies are a key element of the design of the disposal facility, because they make it possible to take into account the existence of a zone damaged by the excavation of the tunnels and cavities and they determine sealing possibilities. The studies necessarily have an empirical component, but they must be supplemented by modelling that incorporates all of the physical and chemical factors responsible for the mechanical behaviour of the argillite in the Cox layer.

The Board summarises the main points of its analysis below.

2.6.2.1. Excavation-Damaged Zone (EDZ): safety issues

The excavation of the tunnels, then the long period during which they remain open, allows the development of an excavation-damaged zone (EDZ) in which the natural properties of the rock may be profoundly affected. From the point of view of long-term safety, this zone is home to fracturing or cracking that may considerably increase hydraulic conductivity, with the risk of forming a short-circuit in the geological barrier, which would enable fast circulation of gases, water and radionuclides along the tunnels and shafts.

Andra has performed a detailed characterisation of the EDZ, including a structural analysis of the state of the facing of the tunnels, an examination of the drill cores, and water and gas permeability measurements.

The Board thinks this characterisation work is remarkable.

Different types of fractures have been observed in the vicinity of the walls: 'chevron' fractures (shear marks), sub-vertical oblique fractures and ‘extension’ fractures in the immediate vicinity of the wall. Starting from the wall then, we can make out a zone containing a network of fractures, some better connected than others, that is much more permeable than the healthy rock, an intermediate zone with poorly connected fractures, and finally a zone that has few cracks but remains more permeable than the healthy zone. The extent of these zones depends to a large extent on the orientation of the tunnels. These data establish that, even if they do not reach worrying proportions, the extent and intensity of the EDZ are greater than Andra’s 2005 predictions suggested. These new data must be taken into account in the safety calculations and show the importance of the seals designed to interrupt the continuity of the EDZ.

The formation of the EDZ is influenced by the method used to excavate and coat the tunnels. The first option is very quickly to install, immediately behind the facing, a rigid support to maintain the rock in place. The opposing choice is to allow the land to approach by installing a light provisional coating and only completing it after several months. To assess these different approaches, Andra has a model of the short-term behaviour of the argillite rock mass, but it seems that this model is not systematically used for designing the coating. As the tunnels must remain open for around a century, the choice of the best method must also take into account an estimate of the long-term extent and speed of the movements. A better assessment of the size of delayed movements over the course of a century would be of precious help in designing the tunnels, sizing the metal casing of the LLHL waste cavities and supporting the LLIL cavities with concrete.

The experiments on flexible tunnel design (GCS) and rigid tunnel design (GCR) aim to compare the two support methods from the point of view of the formation and development of the EDZ and its influence on hydromechanical behaviour. The creation of the GCR tunnel began in January 2011 and will be completed in January 2012; a comparison with the GCS tunnel, which is already complete, will then be possible. The displacement measurements are interpreted using the convergence and containment method traditionally used with tunnels. It would also appear necessary to use a short-term behaviour model, developed by Andra, in order to move beyond certain simplifications and perform a complete hydromechanical analysis.

A technological test of excavation with a tunnelling machine, with segments installed as excavation progresses, will be performed from 2012. This will help to assess the impact on the EDZ of excavation with a tunnelling machine and support via segments. The test will involve the successive excavation of two perpendicular tunnels in the two directions of the principal horizontal stresses. It will not benefit from the progressive approach that led Andra to choose the boom-type road header as its reference option, and will be completed shortly before the Dac is submitted.

The Board would stress that the use of a tunnelling machine may lead to quite a radical change in the design of the disposal facility and that there will be little time left to analyse it. It will monitor the results of this test carefully.

Many observations suggest that the formation of an EDZ could be a partially reversible phenomenon. Indeed, after closure, the resaturation of the argillite, together with the prolonged application of increasing pressure, could have a healing effect.

The Board approves of the pursuit of research on self-plugging phenomena, a good understanding of which may provide additional room for manoeuvre with regard to the long-term safety analysis.

2.6.2.2. Tests conducted in the LLHL waste cavities

Andra has conducted excavation tests with cavities 40 m long and 70 cm in diameter, lined with a steel tube of a slightly lower diameter. The main function of this lining is to enable the easy introduction and, if necessary, removal of LLHL waste packages.

The first risk is that the movements of the land that quickly comes into contact with the lining will cause it to come out-of-round, leading to additional friction, and perhaps even causing the package to become jammed during removal. The out-of-roundness calculations performed in order to determine the design thickness of the lining steel still have some uncertainties. The need for reversibility requires these problems to be solved.

> *The Board has not heard a full presentation on this subject. It would ask that the specifications of the functions that the lining must fulfil should be quantified.*

The second risk concerns the alignment of the tubes along the cavity. Andra has checked with its surface demonstrators that removal was possible even with a considerable curve, but it remains to be determined whether the margins are sufficient in all cases.

In mid-2011, Andra will install instrumentation in the lining of a cavity to monitor changes in the argillite/lining interface. A second phase, beginning in mid-2012, will include a test of the procedures for plugging the cavity head and a full-scale test on a cavity equipped with its insert and its base plate. In this last test, a heat source will reproduce the conditions of the LLHL packages (C0)[38] , which should be the first to be disposed of. This test must last around ten years.

> *The Board takes a very favourable view of this programme but believes that it is also essential to observe, over a long period, an LLHL waste cavity without a lining, in the direction most suited to the project proposed by Andra. The presence of the lining complicates observations and makes interpreting them difficult, given the interactions it causes. This would allow us to observe directly the movements of the walls over time, the local ruptures, any loss of alignment and the development of the EDZ.*

2.6.2.3. Sealing

The sealing of the structures will probably only take place after a century or more. It may provide an effective barrier in the event of short-circuits in the geological barrier.

Andra very recently told the Board that it would be performing a detailed review of its programme with regard to the sealing concept. The Board, while worried about the short timeframe available before the submission date of the Dac, takes a favourable view of Andra's decision.

38 'Old' glass packages and Atalante.

2.6.2.4 Geomechanical modelling and conclusions

In its underground laboratory, Andra is conducting a programme of geomechanical experiments that is remarkable for its scale and for the density of the measurements performed. Modelling of the thermo-hydro-mechanical behaviour of the argillite is made difficult by the simultaneous presence of varied physical and chemical phenomena, which are often closely linked.

For short-term behaviour, several different models are still being proposed, and it would be desirable for them to converge to form a stable single solution. The study of the delayed behaviour of the tunnels and cavities over the century is less well advanced.

The Board approves of the efforts made by Andra on this subject and would like to be presented with a report on the studies and experiments conducted on delayed behaviour.

The Board would like the initial modelling efforts to be expanded to include the main links between physical and chemical phenomena that govern the behaviour of the argillite.

The Board believes that the geomechanics programme is a reflection of a desirable shift towards integrated experimentation conducted on a near-industrial scale. It nevertheless recommends that care should be taken to ensure that scientific modelling of behaviour is not dissociated from the implementation of tests geared more towards industrial application.

2.6.3. Underground laboratory experiments

2.6.3.1 Experiments in the Meuse/Haute-Marne underground laboratory

The experimentation already underway and yet to come in the underground laboratory is very rich. It emphasises the technical and practical aspects of the excavation of the disposal facilities and the behaviour of the host rock and the materials in the near-field interfaces. These experiments appear to be increasingly integrated and are precursors to the full-scale experiments that may be used to characterise the hydro-thermo-mechanical behaviour of an LLHL waste cavity. Other experiments are conducted further upstream and are intended to supplement theoretical knowledge on some aspects of mechanics, gas migration and geochemistry.

The performance of these experiments requires considerable technical infrastructure within the lab. In a year, between March 2010 and March 2011, 180 m of tunnels and around one hundred boreholes were dug, 2000 m drill cores of rock were sampled and 1200 sensors were installed.

The recent authorisation to prolong the lab's activities will allow these programmes to continue until 2030.

2.6.3.2. Experiments aimed at characterising the near field

Their aim is to characterise the hydro-thermo-mechanical mechanisms occurring in the host rock disturbed by the presence of the disposal structures.
Concerning the LLHL waste cavities, Andra considers that it has mastered excavation and lining of a cavity 40 m in length. For this test, however, it used thinner linings that would be usable in disposal conditions. It is now focussing on optimising the drilled length and observing the mechanical loading of the lining by the surrounding land, with or without thermal influence. Experiments with reduced-diameter tubing (140 mm) are underway. Actual-diameter tests are being prepared.

Concerning the long-term degradation of the materials, Andra is conducting long-term experiments to examine corrosion of the steel in contact with the pore water and the reactions at the interfaces between different materials (glass, iron, argillite). It is anticipated that these experiments will last around ten years, with checks along the way.

Concerning the geochemistry in the argillite, Andra considers that it has mastered modelling of the water-rock interaction, making it possible to report on the chemical composition of the pore water[39] in the Cox layer. On the geochemistry front, Andra has focussed on gas migration in the near field and the relationship of these gases with the chemical composition of the pore water. The experiments concern natural gases emanating from the rock (nitrogen, methane, light alkanes), as well as the effect of the oxygen in the air in the tunnels on the oxidation of the elements dissolved in the pore water and on the fate of the hydrogen produced by the degradation of the steel. Comparisons have been made between Mont-Terri and the Meuse/Haute-Marne underground laboratory. The experiments with oxygen are being conducted in the underground laboratory. They show low penetration of the oxidising disturbance in the Cox layer. The experiments with hydrogen are being conducted in the Mont-Terri tunnel, due to the potential danger of conducting them in the more confined conditions of the Meuse/Haute-Marne underground laboratory.

With regard to hydrochemical modelling, the models reflect well the calco-carbonic equilibriums, even if the partial CO_2 pressure in the gaseous phase in equilibrium with the water is still poorly rendered by the calculations. Modelling efforts must focus on describing the effect of temperature on the very slow dissolving kinetics of the silicates.

The role of bacteria is being studied at Mont-Terri, in order to determine and quantify the processes by which, within the argillite, the composition of the solutions from the B2[40] cavities changes. To do this, solutions containing nitrates and acetates have been circulated in contact with the clay, and the denitrification and development of bacterial strains that could contribute to catalysing this reaction have been monitored. Bacterial development, under the effect of seeding by the structures and ventilation, is being studied in another experiment in the Meuse/Haute-Marne underground laboratory. The growth of sulphur-generating flora has been observed, which is probably due to the conditions of the experiment, but the presence of indigenous bacteria has not been excluded.

[39] In particular, this makes it possible to artificially produce the water necessary for experiments on material degradation or resaturation, which results in an appreciable time saving in the preparation of the experiments, in light of the difficulty of retrieving the natural pore water.

[40] Cavities containing bituminous mud.

The migration of the gas in the argillite and resaturation are being studied through experiments involving gas injection at different flow rates. The results show penetration of the gas into the rock and suggest a concomitant decrease in permeability. Tests of the same type have been undertaken in the horizontal boreholes at the laboratory to study the time taken to resaturate a core of clay used for sealing. These experiments are set to be extended, as it appears that resaturation is still not complete after 500 days.

2.6.3.3. Experiments aimed at characterising the far field

The aim of this type of experiment is to characterise the behaviour of the Cox layer far away from the disposal structures, beyond the zone affected by drilling. An essential parameter of the migration of solutes through the Cox layer is the diffusion coefficient. The diffusion experiments conducted in boreholes between 2005 and 2009 demonstrated excellent consistency between the results and the measurements taken in the surface laboratory. They are currently on hold. Given the slowness of the diffusion mechanisms, the transfer distances did not exceed a few centimetres.

Andra is currently preparing an experiment over longer distances (from a few decimetres to a few metres) and is, for this purpose, developing mini-sensors for detecting beta and gamma radiation, which should allow *in situ* monitoring of radioactive tracers, permitting non-destructive measurements over a long period.

As part of the Trasse GNR[41] incorporated in the Pacen programme, the CNRS and the IRSN have pursued the analysis of migrations at a distance in the argillites of Tournemire, based on the distribution of radiogenic helium in the pore water. This analysis shows that the current profile in terms of the levels of this rare gas at depth can be explained by a diffusion mechanism spanning 17 to 30 million years. This confirms the slowness of this type of transfer mechanism.

A considerable experimentation programme is currently planned by Andra, with three main aspects:

- Continuation of testing on LLHL waste cavities, including integrated experiments to produce full-scale reproductions of thermo-hydro-mechanical behaviour;
- Additional data on the characteristics of the clays from the point of view of geomechanics and transport/retention;
- Testing of the tunnel sealing components.

The Board considers that Andra is showing great creativity in devising and implementing, in conditions representative of the disposal facility, experiments in the underground laboratory and with its partners in other places. An impressive quantity of data has been acquired, and more should be added, notably through the programme planned until 2013.

[41] Transfer of radionuclides in the ground, bedrock and ecosystems.

The Board would like modelling to be systematically strengthened, so as to get the most out of scientific testing. It would stress the importance of continuing full-scale tests concerning the excavation of cavities. It would also underline the importance of forthcoming experiments aimed at characterising the behaviour of LLHL waste cavities on a real-life scale. Their results will be essential in assessing the recoverability of packages.

2.7. REVERSIBILITY

2.7.1. Introduction

The law requires reversibility to be guaranteed for at least 100 years. Nevertheless, the word ‘reversibility" is, in the Board’s view, ambiguous. The Board believes that it is essential to provide appropriate information to all those concerned by the disposal facility, and in particular to citizens, in order to overcome this ambiguity by adopting more precise terms of reference. It suggests that three different words should be used to describe three different realities:

- *Reversibility*, in the precise and unequivocal sense in which it should be used, would denote the possibility, at any point of the project, to return to a previous point, bearing in mind that, the farther the project advances, the less possible it becomes to return to the earliest points. In other words, reversibility tends to give way to irreversibility when the stages of implementation are farther apart;
- *Retrievability* is the capacity to reach the packages in the disposal facility and to extract them from their position in the facility, so as to be able to apply to them any treatment required by their condition at different times, whether due to accidents or the conversion of waste into usable resources;
- *Flexibility* describes a disposal project management mode, applied at all stages of development and implementation, whereby the project is designed in such a way that it can be constantly and perpetually modified, so as to be able to identify, process and integrate any new information concerning the efficiency of the company.

Reversibility is the result of social demand that has been recognised by the law. It means that the partial or full retrieval of the waste must remain credible for a century or more. During this time, removal becomes less and less easy. A scale with five successive levels of reversibility was adopted by the AEN (Nuclear Energy Agency). Andra contributed to its development. Andra also contributed to the organisation of a conference held in Rheims by the AEN in December 2010 on reversibility and retrievability. This conference showed that Andra is at the forefront of international work on reversibility.

Any removal of waste must be prepared in advance. It is necessary to anticipate the circumstances in which it could be necessary, have elements that enable a decision to be made about retrieval, including an estimate of its costs and the risks for operators, prepare retrieval plans incorporating the difficulties that may occur, be able to adapt the rate of retrieval to the nature of the event that made it necessary, and check that the retrieval plans are consistent and applicable.

In order for the recovery of the waste to remain easy, given the reversibility level achieved, several conditions must be satisfied throughout the reversibility period. There must be no uncertainty as to the nature and location of each of the waste packages. The shafts and access tunnels of the cavities containing the waste packages must remain in a state that allows circulation of transport and handling devices. A sufficient gap must have been left between the packages and the cavity coating or lining. This gap calculated must include a margin that takes account of the land pressure effects that will gradually act on the cavities' coating or lining and may reduce their cross-section or disturb their alignment. During the period under consideration, the steel or concrete containers surrounding the waste must only change to a limited extent. Similarly, it is important to limit physical and chemical changes affecting the air, the water and more generally the materials in the vicinity of the packages that may cause difficulties for recovery. The systems for capturing, extracting, handling and transporting the packages must have been kept in working order. Observation and monitoring facilities must supply useful information about changes in the packages and their environment. It must be possible for the retrieved packages, regardless of their quantity, to be stored on the surface, on site or at a distance, in safe conditions.

The Board's analysis is presented below.

2.7.2. Circumstances that may lead to retrieval

The Board had asked Andra to consider the scenarios that may lead to retrieval of the packages. For this purpose, Andra used a survey conducted among local stakeholders to confirm and complete a list of the most frequently envisaged scenarios.

Some seem unlikely (choice of a new management approach, recycling of waste in disposal), and some less hypothetical (fault in a package or in the barrier constructed), while some reflect societal concerns (control of the disposal process, risk of disposal site being abandoned) or a possible handling incident.

Some circumstances could necessitate rapid retrieval from disposal. This is why the Board recommends that Andra should specify the fastest retrieval rate possible using the resources currently envisaged.

2.7.3. Changes in the cavities and packages during the reversibility period

Changes in the cavities and packages during the reversibility period are a major concern for the Board, as they will be a key factor in the ease of implementation of the reversibility process. The handling equipment used for retrieval will be the same as that used for disposal, which guarantees that this equipment will be maintained. This will, however, impose certain constraints in the event of a technological change in the equipment, which is not unlikely over the course of a century.

With regard to the retrieval of the LLHL packages, two essential problems arise: firstly, the corrosion of the packages' outer containers or the cavity linings, and secondly, out-of-roundness or loss of alignment in the cavity linings.

Andra estimates that the corrosion rates remain sufficiently low so as not to significantly change the conditions of retrieval. Apart from the direct effects on the state of the lining and the outer container, which Andra considers to be modest, the corrosion effects in the event of reopening of the cavity will bring the tunnel atmosphere into contact with a fluid phase containing liquid water, steam and hydrogen, a product of anoxic corrosion, at high pressure and temperature (several MPa and a little under 100°C). The reopening of the cavity must take into account this situation.

The out-of-roundness and loss of alignment of the lining may result from the stress it undergoes as a result of the hydrostatic pressure at the depth of the disposal facility, and, in the longer term, the weight of the land. The calculations that Andra proposes to report on the phenomena would be more credible if consolidated and validated models were available of the delayed behaviour caused by the various joint effects of creep, changes in pore pressure, thermal expansion, and any physical and chemical transformations affecting the rock mass.

> *The Board would like to be presented with the design calculations concerning the risk of out-of-roundness. It considers that it will be necessary, as soon as possible, to set up tests completely representative of real conditions, which is the only way to be totally sure about the risk of out-of-roundness.*

The removal of LLIL packages is, more so than in the case of LLHL packages, the mirror image of the package installation operation, as the packages are not extracted by pulling but removed by the same robot that installed them. The final plugging of the LLIL waste cavities is not immediate. Quite the contrary: ventilation is organised to expel the gases produced and, to a lesser degree, to cool the packages. Ventilation facilitates monitoring of the atmosphere in the cavity. By maintaining a dry atmosphere in the cavity, it considerably reduces corrosion rates. In contrast, after plugging, water may be present, locally at least, with, for some packages, hydrogen formation or an increase in temperature to values of around 40 to 70°C. Particular attention must be paid to the retrievability of bitumen packages.

> *In conclusion, the Board appreciates Andra's examination of the changes in the cavities and the conditions within them. It notes that this examination contributes to the analysis of the specific conditions in which packages are retrieved. The Board would stress the importance of checking this examination, in the near future, by means of tests that are completely representative of actual disposal conditions.*

2.7.4. Reversibility and storage

The PNGMDR provides that it is necessary to "take into account the reversibility of disposal, notably by systematically identifying storage solutions for packages retrieved from the disposal facility".

The Board considers that the storage of waste retrieved from a disposal facility is a question that must be considered thoroughly in order to establish the specifications for the ZIIS, but that it does not call for a practical response in the short term. Its solution depends partly on changes in the French energy landscape over the next thirty years, which are difficult to predict. It observes that Andra must continue to devote sufficient research resources to the issue to provide adequate responses within the required timeframe.

2.7.5. Reversibility exercises

Andra is performing tests on a surface prototype and drawing useful lessons about retrieval from tests performed in the underground laboratory. But retrieval is a complex overall operation for which checking every link in the chain is probably not sufficient.

With a view to the submission of the Dac, the Board invites Andra to propose elements for the definition of a periodic review of reversibility, which should include the performance of reversibility exercises.

2.7.6. Conclusions

At the current stage of the project, given the forthcoming deadlines (public debate, submission of the Dac, law on reversibility), the Board would now like the influence of the 2006 law's demand for reversibility on the disposal project to be examined in a thorough and precise manner. The following questions are raised:

- *Are there limits to reversibility?*
- *In the disposal concept presented, what elements are rendered essential by the requirement for reversibility?*
- *What are the consequences of these measures on the safety of the disposal facility?*
- *What are the consequences of these measures on the cost of the disposal facility?*
- *Are there any processes that need to be improved or made more reliable (inspection of packages, traceability)?*
- *Accordingly, what parameters need to be monitored, and what instrumentation has to be developed? Analysis of the conditions that would prevent the retrieval of packages from a cavity, out-of-roundness, alignment, atmosphere, risk for operators, conditions for fast retrieval from the disposal facility, storage of packages, etc.?*

2.8. MEMORY OF THE SITE

The project for the deep geological disposal of nuclear waste in Meuse/Haute-Marne is notable for its boldness and the complexity of its implementation.

At a time when society has resolved to take responsibility for the waste it produces, particularly radioactive waste, the Board considers that it would be appropriate not to forget about the energy expended and the talents displayed in this process, but rather to make sure that they are remembered for a long time by seizing the opportunity to create an edifying and profitable monument to them.

The Board appreciates Andra's intention to archive the sources that could one day be used to study the history of the site. It would like the Agency to tell it more about its intentions, so that an outside perspective can be used to perfect them. The Board would also like to be informed of the options being studied by Andra to perpetuate the memory of the site.

Chapter 3

INTERNATIONAL OVERVIEW

This chapter only describes the most recent aspects since publication of the Board's report n° 4. It does not take account of the impact of the accident at Fukushima, given that currently the exact impact of the accident is not yet known, and will only concern the waste management programmes indirectly.

Three countries are scheduled to open a deep geological disposal facility for long-lived high-level radioactive waste in 2025: Finland, France and Sweden. In Sweden, SKB submitted a planning permission application in March 2011. Sweden is the first country to reach this stage.

The success of the projects in these three countries could provide a useful example. It would show that rational management of radioactive waste is possible.

Conversely, in the USA, the Yucca Mountain project has been stopped and the President has appointed a commission, the "Blue Ribbon Commission", to recommend long-term solutions for the management of the country's irradiated fuel and radioactive waste. No tangible projects are expected in the foreseeable future.

The Board takes a favourable view of the international dimension of much of the research done by Andra and the CEA. It particularly appreciates the importance accorded to this dimension at the hearings.

During this evaluation exercise, one hearing with the CEA was devoted to the international scene and the nuclear cycles chosen by the various main nuclear countries, as well as the related R&D (cf. Appendix II of this report).

3.1. DIFFERENT OPTIONS FOR MANAGING LL, IL AND HL WASTE

With regard to short-lived LL or IL waste, most nuclear countries have a disposal centre that is already operational or under construction. Because of this, there are no more major challenges to be met with regard to the management of this type of waste. The most important efforts remain those concerning the demonstration of safety, quality assurance, and guaranteeing that the scheduled capacity will take into account future production.

For long-lived LL and IL waste (transuranium elements, chlorine 36, etc.), processing and management technologies still have to be developed. There are few sites in operation, under construction or even under development. In the USA, the WIPP (Waste Isolation Pilot Plant, located at a depth of 700 m in the salt layer in Carlsbad, New Mexico) has been operational since 1999, and is used for the final disposal of transuranium waste from the military programme.

In Germany, the abandoned iron mine in Konrad is being redeveloped so that the site can accommodate waste from 2014. In April 2011, Ontario Hydro Power in Canada applied for an operating licence for a disposal facility in the sedimentary layer in Kinkardine, Bruce County.

For the disposal of LLHL waste, several countries have R&D programmes being conducted in underground laboratories (Germany, Belgium, France, Sweden, Switzerland, etc.). In Europe, in terms of concrete projects to install geological disposal facilities for irradiated fuel or LLHL waste, Finland, France and Sweden are the most advanced countries, each with a similar schedule. Construction is set to begin in 3 to 5 years and operation between 2020 and 2025.

In all nuclear countries, there is a strategic choice to be made with regard to the management of irradiated fuel. There are three basic options:

- Direct disposal: The fuel is stored for a few decades, then disposed of in the geological layer (Finland, Sweden, etc.);
- Recycling: The fuel is reprocessed, the uranium and plutonium are mono-recycled in pressurised-water reactors. The LLHL waste resulting from this reprocessing and the Mox fuels are disposed of (LLHL) and stored (Mox) (France);
- “Wait and see”: Long-term storage (for a few decades) is planned pending the emergence of a clear vision of the future of nuclear energy and/or the time required to develop processing, disposal and site selection techniques.

In their recent publications, the IAEA and the European Union have reiterated that geological disposal is the reference solution to guarantee the long-term safety of LLHL radioactive waste management.

Around 15% of the world’s irradiated fuel has been reprocessed. France is the country where this strategy has been taken the furthest (two-thirds of fuels are currently reprocessed). Other countries, such as China, Japan, India and Russia, have reprocessing facilities, but these countries have, until now, only processed limited quantities. The future of reprocessing is closely linked to the development of fast neutron reactors, which would allow a processing and recycling strategy to be pursued to its conclusion.

The "wait and see" strategy stems from the fact that many countries have not yet decided about reprocessing. It is strengthened by the difficulties encountered in selecting locations for geological disposal facilities. This situation will probably last for a long time yet, which is why it is important that the few countries that are currently making progress on a clearly defined programme should be able to complete it and thus provide examples of best practice.

3.2. INTERNATIONAL LEGAL CONTEXT

Radioactive waste management and, by extension, R&D on waste management, takes place within a national and international legal context. There are no significant new developments to report this year.

3.3. RESEARCH LABORATORIES AND UNDERGROUND DISPOSAL FACILITIES

In Europe, the main research concerning geological disposal is being conducted in Belgium (Mol, GIE Euridice), Finland (Olkiluoto, Posiva Oy), France (Meuse/Haute-Marne site, Andra), Sweden (Äspö, SKB) and Switzerland (Mont Terri and Grimsel sites, Nagra). Depending on the local geological characteristics, research into the host medium focuses on clay, granite or salt.

- **Germany**

Pending the emergence of solutions accepted by the political and safety authorities, high-level waste is stored in various sites spread throughout the country. The glass packages from reprocessing are stored on the surface at Gorleben (a former salt mine, 840 m in depth). After several years of political disagreements and lawsuits, the current government has decided to resume studies and permit operation of the site again. In November 2010, the transport of vitrified waste from the Hague to Gorleben gave rise to violent protests.

Work is continuing in the Konrad mine (a former iron mine with a depth of 800 to 1,300 m), in order to ensure that the site is operational and ready to welcome non-exothermic waste in 2014.

- **Belgium**

Ondraf[42] is currently finalising its Waste Plan. It will then submit it to the authorities, together with the report on the environmental effects, the report from the social responsibility conference and the comments received during social and legal consultation.

Belgium has, since 1982, had the Hades laboratory, at a depth of 225 m in a clay layer under the nuclear energy research centre in Mol. The Praclay thermo-hydro-mechanical and chemical experiment has now begun there. It simulates the heat field around a tunnel for burying high-level waste. To this end, a tunnel with dimensions equal to the Belgian disposal concept will be heated to 80°C for 10 years over a length of 30 m.

- **Canada**

The R&D programme continues on the Bruce peninsula (Kinkardine, Lake Huron, Ontario) with the goal of deep limestone disposal of LLLL and LLIL radioactive waste (at around 1,000 m). Planning permission was applied for in April 2011 and is expected to be granted in 2012.

- **China**

The Beijing Research Institute of Uranium Geology, a institute dependent on the CNNC[43], is responsible for R&D on a high-level waste disposal facility, including the search for a suitable site.

Five potential sites have been identified for more detailed study. The host rocks are granite, slaty clays and tuff. The granite site at Beishan in the Gobi desert is being studied, although the final choice of site has not been made. Construction is set to begin in 2020.

[42] National organisation for radioactive waste and enriched fissile material.
[43] China National Nuclear Corporation.

- **South Korea**

Following a decade of research, a disposal concept in a crystalline environment was made public in 2006. In 2008, a law governing the management of radioactive waste was passed. Solutions for managing high-level waste are being studied, but no decisions have been made.

- **United States**

For more than two decades, Yucca Mountain in Nevada has been the main site studied for the disposal of LLHL waste in the United States. Following a drastic reduction in the project's budget , which has effectively undone all progress made on the waste problem – the American government has created a new commission, the "Blue Ribbon Commission on America's Nuclear Future", in order to propose alternatives to the project. In May 2011, the commission published some preliminary conclusions. One of them recommends that *the development of one or more geological disposal sites should be begun rapidly. The commission also stipulates that disposal will remain essential, regardless of the scenarios envisaged. It considers that a site can only be selected by a consensus reached in transparent fashion and based on a body of R&D results and relevant standards. According to the commission, no current or future reactor or fuel cycle technology will fundamentally change the challenge posed to countries by waste management.*

- **Finland**

Posiva Oy, which manages Finnish radioactive waste, has undertaken the construction work for the Onkalo research laboratory at the Olkiluoto site, in granite at a depth of 400 m. Ratified by Parliament in 2000, the disposal site for the irradiated fuel from the reactors currently in service, the EPR under construction, and the reactors to be built in the future, is also the disposal site for Olkiluoto. It will be an extension of the research laboratory. Planning permission is set to be applied for in 2012. The Finnish law provides for operation to begin in 2020.

- **France**

Reminder: R&D continues at the Meuse/Haute-Marne laboratory. The supporting documents for the public debate will be presented at the end of 2012.

- **India**

For 8 years, India has studied, through experimentation, the reaction of the host rock to a thermal load in an old gold mine 1000 m underground. Other experiments are planned in abandoned mines. Currently, potential sites have been identified in granite, among which a 4 km^2 area will be chosen.

- **Japan**

Two research laboratories are currently under construction, one in Mizunami in crystalline rock, and one in Horonobe in sedimentary rock. At the Mizunami laboratory, a depth of 460 m has been reached, the ultimate goal being a depth of 1000 m. Studies concerning the hydrology and mechanics of the rock are continuing. At the Horonobe laboratory, hydrological tests and hydrochemical measurements are continuing. A depth of 250 m has been reached, out of the planned 500 m. The projects are coming up against strong opposition from local people.

The Japanese organisation for the management of radioactive waste, NUMO, is calling upon willing local authorities to take part in preliminary studies concerning the selection of a disposal site.

- **Russia**

No geological disposal site is currently available, but the Krasnoyarks region has been proposed. A report will be submitted to define the concept of an underground laboratory and a disposal facility to be built from 2025. The first phase of the facility is set to accommodate 20,000 tonnes of LLIL and LLHL waste, guaranteeing its recoverability.

- **Sweden**

In Sweden, the management of radioactive waste is the responsibility of SKB (Svensk Kärnbränslehantering AB).

SKB's Aspo laboratory near the city of Oskarshamn has been dug into granite at a depth of 460 m. Unlike the Finnish approach, the laboratory will not be a part of the final disposal site, but rather will serve to approve the selected concepts. The research being conducted there is mainly focusing on construction techniques, hydrogeology, radionuclide migration, and modelling.

SKB has submitted an authorisation request for the construction of the disposal facility in Fonsmark, the chosen site, in accordance with the legal regulations set out in the Swedish Act on Nuclear Activities. In parallel, SKB has applied for planning permission for a temporary disposal site and Clab encapsulation plant at Oskarshamm, all within the context of the Swedish environmental code. The start of construction is planned for 2015, if the decisions of the government, the safety authorities, the environmental court and the communes concerned are taken in 2013 – 2014. The disposal facility is set to be operational in 2025.

- **Switzerland**

Switzerland has two research laboratories: Grimsel and Mont Terri. The Grimsel laboratory is located in the granite on one side of the Aar mountain. The Mont Terri laboratory is located along a highway tunnel in an opaline clay layer. Andra is taking part in numerous experiments there due to the similarity between the Mont-Terri clays and those of the Meuse/Haute-Marne laboratory.

The host rock selected for deep disposal is opaline clay. The Federal Energy Office (OFEN) has designated provisional locations in order to determine which local/regional authorities need to be consulted. 202 communes are concerned, 190 of them in Switzerland and 12 in Germany.

3.4. SOURCES OF FAST IRRADIATION

The number of reactors that offer the ability to irradiate using fast neutrons is extremely limited on the global level. Such a situation significantly compromises the R&D necessary to develop new technologies and implement transmutation experiments.

- **Belgium**

  The BR2 research reactor (1963-2026? 50-70 MWt) can irradiate a small volume (1.5 to 3 cm in diameter) with a fast-spectrum high flux.

- **China**

  The 65 MWt (20MWe) sodium-cooled CEFR research reactor has been in service since July 2010.

- **France**
  Since the Phenix shut down, there is no longer any fast reactor in France. The Jules Horowitz research reactor, which is under construction, will make it possible to irradiate a small volume with a fast-spectrum high flux. It is set to enter into service in 2015.

- **India**
  Since 1985, India has had the 40 MWt Fast Breeder Test Reactor (FBTR) in Kalpakkam. The 500 MWe **Prototype Fast Breeder Reactor** (PFBR) is in the final phase of construction. One of the objectives is to study the thorium cycle.

- **Japan**
  The Joyo and Monju reactors have been shut down following various incidents.

- **Netherlands**
  The HFR in Petten allows limited irradiation.

- **Russia**
  The Bor-60 (1969-2015) is a 60 MWt sodium-cooled research reactor. The BN-600 (1980-?) is a power-generating reactor.

3.5. R&D ON ADS

- **Germany**
  The Karlsruhe Institute of Technology (KIT) was the coordinator of the Eurotrans project; it is an important partner of the CDT project. The Jülich research centre (FZJ) proposes a gas-cooled ADS (AGATE).

- **Belgium**
  Guinevere is a fast research reactor, driven by a very low-power accelerator (ADS) of only a few hundred Watts, and a precursor to MYRRHA. The reactor is the fruit of collaboration between the SCK•CEN, the CEA and the CNRS. The Génépi-C accelerator was built by the CNRS in Grenoble, and the fuel was supplied by the CEA.

  Myrrha will be a 100 MW subcritical, lead-bismuth-cooled, fast neutron ADS, which will demonstrate the feasibility of an accelerator / spallation source / subcritical reactor coupling in a pre-industrial installation. The reactor is also designed to operate in critical mode. It will offer the teams working on fast neutron reactors (SFRs, LFRs and GFRs) a machine for testing materials and fuels. Myrrha will also allow them to obtain essential data for industrial transmutation.

- **China**
  The Chinese Academy of Sciences (CAS) has decided to build an ADS for transmutation research. The road map provides for a test facility in 2017, an ADS of 80-100 MW in 2022 and a 1,000 MW demonstration facility in 2032.

- **South Korea**
  An ambitious ADS project is being developed at Seoul University. Kaeri is evaluating different options for changing the nature and reducing the volume of the waste to be disposed of. A decision is expected in the next few months.

- **United States**
  Since the 1990s, several ADS transmutation projects have been proposed. The shutdown of the Yucca Mountain project has reawakened interest in ADS.

- **France**
  Reminder: R & D is being conducted as part of international collaborations.

- **India**
  The ADS programme, launched in 2000, aims to set up a thorium cycle by producing fissile U-233 from non-fissile Th-232.

- **Italy**
  Several research centres (ENEA, INFN, etc.) and industries are participating in European projects concerning ADS.

- **Japan**
  The Omega project, launched in 1988, is conducting R&D on partitioning and transmutation in order to reduce the area of a disposal site. The first phase of the project provides for a lower-power spallation target. There are then plans for a high-power target but without a subcritical core. The project includes an experimental ADS of around one hundred MW and an industrial ADS of 800 MW.

3.6. R&D ON DEEP GEOLOGICAL DISPOSAL

3.6.1. Performance levels of the disposal facility

CARBOWASTE[44] The graphite-moderator reactors are representative of the first generation of reactors being dismantled. Irradiated graphite contains carbon 14 and chlorine 36 in varying concentrations. These two radionuclides are highly mobile and prone to absorption by living matter. The aim of the project is to develop techniques for processing this waste prior to disposal.

[44] Treatment and disposal of irradiated graphite and other carbonaceous waste; 2008-2012, FP7, 16 countries, 28 partners including ANDRA, CEA, CNRS, Areva, EDF, UCAR-SNC and the Ecole Normale Supérieure.

CATCLAY[45] Following the results of the Funmig project, CatClay should make it possible to understand the migration of cations in densely compacted clay. For certain cations, the experiments have shown deeper diffusion than expected.

FEBEX 11[46] In the underground laboratory at Grimsel, the Febex experiment simulated the heating of a bentonite barrier and measured its consequences. As most of the sensors are still operational, Febex II is continuing the observation phase of the experiment in order to improve and validate the data and codes for the study of the geochemical processes, the generation and transport of gas, corrosion, and the performance of the measuring instruments.

FORGE[47] The objective of the project, which combines experimentation and modelling, is to improve knowledge of the gas transfer processes in the main materials present in the various radioactive waste disposal concepts currently being studied in Europe.

IGD-TP[48] The European IGD-TP technology platform on the geological disposal of nuclear waste is the culmination of the work begun during the 6th Framework Programme and continued by radioactive waste management organisations in Sweden, Finland and France. A policy document summarises the technical measures to be implemented over the next 10-15 years so that Member States can develop geological disposal of nuclear waste. IGD-TP is now establishing a strategic research agenda to coordinate the necessary scientific, technological and socio-political efforts for the geological disposal of nuclear waste.

LUCOEX[49] The objective of the project is to conduct *in situ* tests to demonstrate the various disposal concepts for LLHL waste: the horizontal concept at Mont Terri and in Meuse/Haute-Marne; the horizontal concept in granite at Aspö, and the vertical concept in granite at Onkalo. Andra will perform a heating test on a LLHL waste cavity in Meuse/Haute-Marne.

MODERN[50] The project aims to supply a design reference for a monitoring system for use during the various disposal phases, in accordance with the needs and constraints specific to each country.

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[45] Processes of Cation Migration in Clay Rocks; 2010-2013, FP7, 5 countries and 7 partners including the CEA (coordinator), Andra and BRGM.

[46] Full-scale High Level Waste Engineered Barriers; 1994-2012, 22 partners including Andra, the BRGM and the Institut National Polytechnique de Toulouse.

[47] Fate of repository gases; 2009-2013, FP7, 12 countries, 24 partners including Andra, the CEA, the IRSN, the CNRS, EDF and the Ecole Centrale de Lille.

[48] IGD-TP European technological platform for the geological disposal of nuclear waste; founding members: waste management organisations in Belgium (ONDRAF), Finland (Posiva), France (Andra), Spain (ENRESA), Sweden (SKB), Switzerland (Nagra), UK (CND) and the German Federal Ministry of the Economy and Technology (BMWi).

[49] Large Underground Concept Experiments; 2011-2014, FP7, 4 countries and partners, including Andra (coordinator), Nagra, Posiva and SKB.

[50] Monitoring Developments for safe Repository operation and staged closure; 2009-2012, FP7, 12 countries, 17 partners, including Andra, the coordinator.

NWD[51] The aim of this action is to provide both experimental data and calculation results in order to understand the long-term behaviour of high-level waste from current and future fuel cycles.

PEBS[52] Using a global approach, integrating experiments, models and studies of the impact on long-term safety functions, PEBS will assess the performance of structural barriers. The experiments and models will cover the complete spectrum of conditions, from the start of operation (high temperature, resaturation of the barrier) up to thermal equilibrium and resaturation with the host rock.

RECOSY[53] The goal is to understand the redox phenomena that govern the fixation and release of radionuclides during the underground disposal of irradiated waste.

SORPTION II[54] The goal of this AEN project is to demonstrate the possibility of using several thermodynamic modelling techniques to assess the safety of disposal facilities. The project has taken the form of a comparative modelling exercise with a series of data sets on the sorption of radionuclides by materials.

3.6.2. Environmental impact of the disposal facility

A study of the environmental impact of the disposal facility is essential in assessing the potential risk for future generations. By necessity, it is based on an advanced model that draws upon the most accurate possible data on radionuclide migration through various artificial and natural barriers.

BIOPROTA[55] The goal of Bioprota, launched by Andra in 2002, is to identify biosphere models, determine the surface environment data acquisition protocols and analyse the state of knowledge about transfers into the biosphere of radionuclides such as chlorine 36, selenium 79, carbon 14, iodine 129 etc.

EMRAS[56] The Emras programme, launched within the framework of the IAEA, focuses on radioecological modelling, particularly the consequences of the release of radionuclides into the environment.

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[51] Nuclear Waste Disposal action, Euratom CCR (Joint Research Centre), 11 countries, 21 partners including the CNRS and CEA.

[52] Long-term Performance of the Engineered Barrier System; 2010-2014, FP7, 8 countries, 17 partners including Andra.

[53] Redox phenomena controlling systems ; 2008-2012, FP7, 15 countries, 32 partners including Andra, the CEA, the CNRS, the BRGM and the Association pour la Recherche et le Développement des Méthodes et Processus Industriels d'Armines.

[54] Sorption II project; 2000- ?, AEN, 11 countries, 20 partners including Andra.

[55] Key Issues in Biosphere Aspects of Assessment of the Long-term Impact of Contaminant Releases Associated with Radioactive Waste Management; 2002-?, 15 countries, 18 partners, including Andra and EDF.

[56] Environmental Modelling for Radiation Safety; 2003-2011, IAEA, 30 countries, 100 participants.

RADIOECOLOGY AND WASTE TASK GROUP[57] In 2002, Andra and the International Union of Radioecology launched an international working group in order to promote scientific collaboration between radioecologists in the field of radioactive waste.

3.6.3. Governance and participation of stakeholders

Public participation in decision-making processes and access to justice in the environmental field have become a right.

ERDO working group[58] Following the success of the SAPIERR projects, a multinational workgroup was appointed by the participating governmental organisations to study the possibility of creating an association that could establish one or more European disposal centres ten to fifteen years from now.

3.7. NEW TECHNOLOGIES FOR PARTITIONING AND TRANSMUTATION

Transmutation strategies primarily rely upon fast neutrons, whether in critical (FNR) or subcritical (ADS) systems. The Generation IV initiative and the Sustainable Nuclear Energy Technological Platform (SNE-TP) aim to develop new types of reactors, including fast neutron reactors enabling multi-recycling of actinides (4th generation). These new types of reactors will require the development of new materials and innovative fuels that incorporate radionuclides derived from partitioning.

3.7.1. R&D on partitioning and transmutation

ACSEPT[59] The Acsept project is the successor of Europart and Pyropep. Its goal is to select and optimise actinide partitioning and recycling processes compatible with the advanced fuel cycle options. The feasibility of hydrochemical processes (selective and grouped extraction and back-extraction of actinides) and pyrochemical processes (electrolysis and liquid-liquid extraction) must be demonstrated, taking into account the constraints of the industry.

ACTINET-I3[60] The goal of the project is to enable the European scientific community to benefit from laboratory infrastructures for research concerning actinides.

ANFC[61] Comparative studies of alternative fuel cycles based on partitioning and transmutation.

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57 http://www.iur-uir.org/en/task-groups/id-5-radioecology-and-waste.

58 European Repository Development Organisation, with representatives from Austria, Bulgaria, the Czech Republic, Denmark, Estonia, Ireland, Italy, Latvia, the Netherlands, Poland, Romania, Slovakia and Slovenia.

59 Actinide recycling by separation and transmutation ; 2008-2012, FP**7**, 12 countries, 34 partners including the CEA, EDF, the Compagnie Générale des Matières Nucléaires, Alcan Voreppe Research Centre, Louis Pasteur University, the CNRS, and Pierre et Marie Curie University.

60 Actinet Integrated Infrastructure Initiative, FP7, 5 countries, 7 partners including the CNRS, LGI and CEA.

61 Alternative Nuclear Fuel Cycles; 2010-..., FP7, 6 countries, 14 partners including the CEA.

ASTRID[62] The Astrid prototype sodium-cooled FNR, planned for 2020.

CDT[63] The project picks up where Eurotrans DM1 left off. CDT aims to obtain an advanced engineering design for Myrrha using a European team of experts. CDT should make it possible to give component suppliers and engineering firms the necessary specifications for the construction of the infrastructure. The CDT design team will also study operation in critical mode.

CP-ESFR[64] The project is linked to the development of the ESFR European sodium-cooled fast reactor. The goal is to optimise safety levels within the context of a comparable financial risk and flexible but robust management of nuclear materials. Optimisation studies will be conducted on the cores comprising oxide or carbide fuels. The fabrication of fuels with high minor-actinide content will be studied.

EUFRAT[65] The project continues the work done by the Nudame project, aiming at very accurate cross-section measurements spanning a broad energy spectrum.

FAIRFUELS[66] This project aims to optimise combustion of fissile material in reactors, in order to reduce the volume and potential danger of LLHL waste. Fairfuels is concentrating on minor actinides. Dedicated fuel will be produced and a sufficiently complete irradiation programme will be established to study transmutation capabilities. In parallel, the programme includes post-irradiation analyses on certain older fuels to develop models. A training programme is also planned.

F-BRIDGE[67] The aim of the project is to establish a link between theoretical research on 'ceramic'-type fuel and cladding materials on the one hand, and technologies for the reactor fuels of the future on the other.

GACID[68] The experimental programme, established through collaboration between the CEA, the DOE (USA) and the JAEA (Japan), provides for the production of a fuel assembly with a high minor-actinide content and its irradiation in a sodium-cooled FNR. The irradiations are due to take place between 2015 and 2025. The project requires the construction of a pilot workshop for the manufacture of the assembly and sufficient operating feedback from Monju, which has not yet been obtained.

[62] The Astrid prototype sodium-cooled fast neutron reactor, a project led by the CEA.

[63] Central Design Team for a Fast Spectrum Transmutation Experimental Facility; 2009-2011, FP**7**, 8 countries, 19 partners including the CEA, the CNRS and Areva.

[64] Collaborative project on the European sodium fast reactor; 2009-2012, FP7, 10 countries, 25 partners including the CEA, Areva NP, IRSN and EDF.

[65] European facility for innovative reactor and transmutation neutron data; 2008-2012, FP7, CE-CCR.

[66] Fabrication, irradiation and reprocessing of fuels and targets for transmutation; 2009-2013, FP7, 6 countries, 10 partners including the CEA and Lagrange-LCI.

[67] Basic research for innovative fuels design for GEN IV systems; 2008-2012, FP7, 8 countries, 18 partners including the CEA, the CNRS, Areva, Materials design, Nathalie Dupin and Lagrange-LCI Consulting.

[68] Global Actinide Cycle International Demonstration; DOE, JAEA, CEA.

GETMAT[69] This is a collaborative project between the European research laboratories working on materials for the reactors and transmutation systems of the future, including 4th generation and fusion reactors.

GIF/GEN-IV[70] The Generation IV forum initiative aims to develop new types of reactors, including fast reactors producing minimal waste. Two options are being explored in Europe: a sodium-cooled fast reactor (SFR) and a gas- or lead-cooled fast neutron reactor. The aim is to commercially exploit fast reactor technology by the year 2040.

JHR-CP[71] The Jules Horowitz Reactor (JHR) is a 100 MWth research reactor, currently under construction in Cadarache. It is for studying the behaviour of irradiated fuels and materials, in response to the industrial and public needs for 2nd, 3rd and 4th generation power reactors (pressurised-water reactors, boiling-water reactors, gas reactors, sodium reactors, etc.) and the associated technologies. The JHR-CP organises the international networks collaborating on the Jules Horowitz reactor, prepares the irradiation systems needed for these programmes and defines the training that will be useful to the future operators of these systems.

LEADER[72] This is the follow-up to the ELSY project. Its aim is to optimise the technological design choices for a lead-cooled prototype reactor with a power of 600 MWe, and to design an LFR demonstrator.

LWR-DEPUTY – This project is studying the possibility that the current pressurised-water reactors (PWR) may generate less waste by burning fuel based on inert matrices. It aims to eliminate plutonium from reactors by seeking new fuel types.

NURISP[73] This project is part of the follow-up to the FP6 Nuresim project. Its aim is to integrate the digital and physical state of the art into a European simulation software platform in the nuclear reactor domain.

PATEROS[74] This action aims to implement, on a reduced scale, all the steps and components necessary for the partitioning and transmutation technology.

[69] Gen IV and transmutation materials; 2008-2013, FP7, 11 countries, 24 partners including the CEA, the CNRS and EDF.

[70] Generation IV International Forum; 2001- ?, Euratom + 12 countries including France.

[71] Jules Horowitz reactor collaborative project; contribution to the design and construction of a new research infrastructure of pan-European interest, the JHR material testing reactor; 2009, FP7, 5 countries and 6 partners including the CEA, which is managing the project.

[72] Lead-cooled European Advanced Demonstration Reactor; 2010-2012; FP7, 12 countries and 17 partners including the CEA.

[73] Nuclear reactor integrated simulation project, 2009-2012, FP7, 14 countries, 22 organisations including EDF, IRSN and the CEA.

[74] Partitioning and Transmutation European Roadmap for Sustainable Nuclear Energy; 2006-2008, FP6, 11 countries, 17 partners including the CEA, the CNRS and Areva.

SNE-TP[75] The European technology platform for sustainable nuclear energy offers a short-, medium- and long-term view of the development of nuclear fission technologies. It includes consideration of the management of all sorts of waste. The platform also proposes to extend the use of nuclear energy beyond electricity production, notably to hydrogen production, heat generation and seawater desalination. The platform supports a European industrial initiative, the European Sustainable Nuclear Industrial Initiative (ESNII), which is estimated to be worth between 6 and 10 G€, and includes the Astrid and Myrrha projects.

THINS[76] This project includes the design and performance of thermo-hydraulic experiments in support of different innovative liquid metal-based systems.

3.7.2. Nuclear databases

The new reactor concepts and corresponding safety studies will require modelling methods based on nuclear data that are currently less well-known than that available for the current generation of reactors (Generations II and III).

FAR[77] This project aims to set up a reference centre for the activities of the Joint Research Centres working in the fields of nuclear fuels and materials.

ND-MINWASTE[78] This project aims to obtain nuclear data for assessing the safety of current and future reactors and the management of radioactive waste.

TDB[79] The goal of the TDB project concerning thermodynamic data on chemical species, launched by the AEN, is to meet the specific modelling needs of safety evaluations of sites for the disposal of radioactive waste.

3.7.3. Economic and geopolitical aspects

ARCAS[80] A technical and economic study of the performance of critical and subcritical systems such as machines dedicated to the transmutation of radioactive waste.

[75] The European Technology Platform on Sustainable Nuclear Energy; 2007- ?, ≥19 countries, > 60 members including the CEA, the IRSN, the CNRS, Areva, EDF and GDF-SUEZ.

[76] Thermal-Hydraulic research for Innovative Nuclear Systems; 2010-2014, FP7, 11 countries, 24 partners including the CEA and IRSN.

[77] Fundamental and Applied Actinide Research; CCR (Joint Research Centre) action, 12 countries, 26 partners.

[78] Nuclear data for radioactive waste management and safety of new reactor developments; 8 countries, 15 partners including the CNRS, CEA and the Université Louis Pasteur.

[79] Thermochemical Database project; AEN.

[80] ADS and fast reactor comparison study in support of the SNETP's SRA; 2010-2012, FP7, 8 countries and 14 partners, including the CNRS.

3.8. EDUCATION, TRAINING AND KNOWLEDGE MANAGEMENT

One of the key elements in developing nuclear power is a potential lack of human resources, available laboratories, and competent institutions for providing nuclear education and training. Another is knowledge management.

HeLiMnet[81] Following on from the Vella project, this project enables the exchange of researchers between laboratories with infrastructure for studying heavy liquid metals such as sodium and lead.

PETRUS II[82] This project enables European professionals working in the field of radioactive waste management, whatever their initial field of study, to undergo training on geological disposal, recognised throughout Europe.

KTE[83] Archiving, maintaining and deepening knowledge in nuclear research are the aims of the project. High-level training will be offered to young students and researchers through courses and internships in laboratories participating in the project.

81 Heavy Liquid Metal network; 2010-..., FP7, 9 countries and 13 partners including the CEA.

82 Towards a European training market and professional qualification in Geological Disposal; 2009-2012, FP7, 10 countries, 14 partners including the European network for training in the nuclear sciences, ANDRA and the Institut National Polytechnique de Lorraine.

83 Knowledge Management, Training and Education; 2007-..., FP7, Karlsruhe CCR (Joint Research Centre).

Appendix I

MEMBERS OF THE NATIONAL ASSESSMENT BOARD
NOVEMBER 2011

Jean-Claude DUPLESSY – President of the National Assessment Board – Member of the Académie des Sciences - Research Director Emeritus at the CNRS.

Jean BAECHLER – Member of the Académie des Sciences Morales et Politiques – Emeritus Professor at the Sorbonne (Paris IV).

Pierre BÉREST – Research Director at the Ecole Polytechnique.

Yves BRÉCHET – Member of the Académie des Sciences; Professor of Materials Science, Grenoble-INP – Phelma; IUF Senior Member - "Physical chemistry and structural materials"; Adjunct Professor, McMaster University.

Frank DECONINCK – Professor Emeritus at Vrije Universiteit Brussel - Chairman of the Nuclear Research Centre in Mol, Belgium.

Hubert DOUBRE[*] – Professor Emeritus at the University of Paris XI-Orsay.

Maurice LAURENT – General Secretary of the National Assessment Board - Honorary Director of the Parliamentary office for assessing scientific and technological choices.

Emmanuel LEDOUX – Vice-President of the National Assessment Board – Research Director at the Ecole des Mines de Paris.

Maurice LEROY – Vice-President of the National Assessment Board - President of the Fédération Française pour les Sciences de la Chimie (FFC) – Emeritus Professor at the University of Strasbourg.

Jacques PERCEBOIS – Professor at the University of Montpellier I, Director of CREDEN (Centre de recherche en économie et droit de l'énergie).

François ROURE – Professor and scientific expert at the IFP-Energie Nouvelles – Extraordinary Professor of IFP-EN at Vu-Amsterdam University (2004-2014).

Claës THEGERSTRÖM – President of SKB (Swedish company responsible for the management of nuclear waste and fuel) – Member of the Swedish Royal Academy of Engineering Sciences.

[*] Did not take part in the drafting of this report.

Appendix II

BODIES HEARD BY CNE2

17 November 2010:	Andra – Reversibility – Recoverability (½ day).
18 November 2010:	CEA – Global nuclear prospects: cycle options; R&D in partitioning and transmutation.
1 December 2010:	Andra – Inventories and disposal scenarios.
2 December 2010:	CEA – The Astrid project.
5 January 2011:	CEA – Materials cycle for Astrid.
6 January 2011:	Andra – Thermodynamics of the disposal facility (½ day).
9 February 2011:	CNRS – Research and Development – PACEN (½ day).
10 February 2011:	CEA - Partitioning research.
23 March 2011:	CEA – CEA waste management.
6 April 2011:	CEA – Case studies – Review about Curium.
11 October 2011:	Andra – Cigéo project: applicable requirements and initial milestones.

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6 October 2010:	Andra – Restricted hearing – Andra's view of the Board's report number 4 – Review of the latest Andra news – Lessons and suggested actions arising from report number 4.
11 October 2010:	Presentation of CNE Report no. 4 (June 2010) to the CLIS (local information and monitoring council).
28 October 2010:	CEA – Restricted hearing – Research conducted by the CEA in relation to the 2006 law – Studies conducted by the CEA for the disposal facility – Transmutation scenarios – CEA 2012 report (½ day).
24 February 2011:	Andra – Work meeting on geology for the new Board members (½ day).
24 & 25 March 2011:	Andra – Visit to the Meuse/Haute-Marne site and restricted hearing.
30 March 2011:	Andra – Restricted hearing – Cigeo management plan – Discussions underway with producers on design options.
31 May 2011:	Meeting with the ASN (French Nuclear Safety Authority).
28 September 2011:	EDF – STI documents.

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VISITS BY THE CNE2

10 March 2011:	Visit to the Stocamine site
24 March 2011:	Visit to the Bure (Meuse/Haute-Marne) underground laboratory.
5 April 2011:	Visit to Masurca and Leca-Star (CEA Cadarache)
20-23 September 2011:	Visit to the Asse and Gorleben sites (Germany)

Appendix III

LIST OF DOCUMENTS PROVIDED TO THE BOARD

Andra

- Design and general architecture of a disposal facility –Meuse/Haute Marne site - C.NSY.ASTE.08.0171/A.
- LLIL/LLHL waste project – 2009 Report – Design options studied – Summary of the performance assessments with regard to the Post-Closure Safety Criterion (SAF) – C.NT.AEAP.09.001 0/A.
- Preliminary analysis of the risks linked to the transfer and handling of long-lived high- and intermediate-level waste (Underground Facilities) - C.NT.ASSN.09.0039/A.
- LLHL waste project – Service of the disposal centre's surface facilities - Diagnosis of transport infrastructures and networks – General report - C.RP.OBLC.09.0004/A.
- Mid-term report for the "Gas Transfer" Lab Group - C.RP.ASCM.09.0002/C.
- Mid-term report for the Glass/Iron/Clay Lab Group – Volume 1: Summary and models - C.RP.ASCM .09.0003/8.
- Mid-term report of the Glass/Iron/Clay Lab Group - Volume 2 – Collection of research progress sheets - C.RP.ASCM .09.0003/6.
- Mid-term report of the Cement Structure Changes Lab Group - C.RP.ASCM.09.0004/B.
- Setup of the long-term environmental observatory (OPE - Observatoire Pérenne de l'Environnement) - 2007/2008 environmental assessment – 2009 milestone Level 5 - C.RP.ASTR.09.001 0/A.
- Mid-term report of the Transfer Lab Group programme - C. RP.ASTR. 09.0011/B
- ThermoChimie project - Mid-term report - C.RP.ASTR.09.001.
- Meuse/Haute-Marne underground research laboratory – Draft specifications - DAIE: document n° 8 - D.DO.ASAJ.09.0045/A.
- Biosphere – Procedure for selecting and describing one or more biospheres - SUR.GU.ASSN.09.0045/A.
- Chronic Reference Toxicology Values for the toxic chemicals in Andra's basic list (updated end 2007). - Summary note - As, B, Be, Cd, Cr(III), Cr(VI), Hg, Pb, Sb, Se, U, CN-, asbestos - SUR.NT.AMES.08.0035/A.
- 17 articles concerning geomechanical modelling – 23 June 2010 (should they all be cited?)
- Scientific programme 2010-2014 – long-lived HL/IL waste project – C.PE. ADS. 10.0005 - 15 June 2010.
- Activity report - Managing today to prepare for tomorrow – 2009.
- Sustainable development report - Managing today to prepare for tomorrow – 2009.
- Internal document on the industrialisation strategy for the LLHL/LLIL waste project: moving towards the creation of the 'Cigeo' industrial centre for geological disposal – 09/09/2010.
- Confidential document – Design options – Joint analysis by Andra/Areva/CEA/EDF – May 2011.
- Internal memo – Digital simulation tools at Andra – Strategic elements for the period 2006-2014 and review at end 2010 (reference: DS/EAP/10-0138) – 8 December 2010.

- Internal document – International monitoring of LLHL/LLIL waste projects and the radioactive waste situation in 2010 – 22 December 2010.
- Memo concerning the assessment of the total thermal energy released by the disposal facility – 12 January 2011.
- Internal memo – Drip corrosion process of the metallic components of a HL waste cavity. – 10 January 2011.
- Internal memo – C.NT.ADIP.11.0001 – Cigeo project – Summary of the management plan – Study phase – 31 January 2011.
- Internal document – (Thermo)hydraulic behaviour of argillites: from the material to the structure (reference: C.NT.AEAP.11.0026/A) – 22 March 2011.
- Cigeo project review report.
- Andra Report – Cigeo.SP.ADPG.11.0020 Applicable requirements – Cigeo Project – 27 April 2011.
- Recommendations of the engineering contract review: Andra follow-up of the Cigeo project review – 30 August 2011.
- Engineering and industrial implementation of Cigeo and the appendix: "excerpts from the technical specification for the preliminary need (STBp)" – 14 October 2011.
- Cigeo Project – Technical specification for the preliminary need (STBp) – 17 October 2011.

CEA

- Milestone report – Summary note – Technical and economic evaluation of transmutation options - September 2010 (confidential document).
- Note by Philippe Billot and Jean-Louis Seran – Materials requirements to support research of the Generation IV – Systems Development (VHTR, GFR, SFR) 2005 (confidential document).
- Summary report on the feasibility of partitioning of minor actinides – DEN/DRCP/RT 2010/03 – Christine Rostaing – 2010 (restricted circulation).
- DEN technical report – Technical and economic evaluation of transmutation options - September 2010 (restricted circulation).
- DEN technical note – Summary of storage concepts for minor actinides 04/2007 – Entam Project – September 2007.
- DEN Technical Report – New model for the long-term behaviour of glass packages: presentation of the Graal model – Yves Minet, Stéphane Gin, Pierre Frugier, Magaly Tribet, Isabelle Ribet – November 2010.

EDF

- Summary presentation of the industrial disposal facility (STI) designed by the nuclear operators – EDF/AREVA (ref. D5262 2010/05529) – 14 October 2010.
- Inventory of long-lived HL and IL waste for the STI 2009 scenario – EDF – (ref. D5262 2010/02337) - October 2010.
- STI – Operating safety – EDF (ref. ELI1000098) – October 2010.
- Note confirming the geological hypotheses for the civil engineering design of the underground facilities – EDF – (ref. EDTGG100511 B) - 2009.

- Compatibility of the STI disposal concept with reversible management – EDF – (ref. T29-2010-01705-FR) – 14 October 2010.
- Description of the structures in the STI 2009 underground architecture – EDF – (ref. IH HAVL STI/N1 00001 B BPE – October 2010.
- Surface facilities in the inclined drift area – Estimated investments – AREVA – (ref. NT 100496 00 0005 B) – 11 October 2010.
- STI – Feasibility and architecture of ventilation – EDF – (ref. ELIMF1000680 B BPE) – 2010.
- Surface facility in the inclined drift area and underground equipment – estimate of operating costs, periodical costs and decommissioning costs – AREVA – (ref. 011908/LTA/10.0039) – 8 October 2010.
- Design of the structures in the underground architecture – EDF – (ref. IH HAVL STI-N2 00001 C BPE) – December 2010.
- Useful lengths of high-level waste cavities (C5 module) – Influence on costs – EDF – (ref. IH HAVL STI-N2 00002 C BPE) – 25 February 2011.
- Determining the loading of high-level cavities (C0, CU3, C1, C5, C6 and C8) – EDF – (ref. IH HAVL STI-N2 00003 B BPE) – 25 January 2011.
- Assessment of the effect of the orientation of the disposal structures on the anisotropy of the initial stress conditions – EDF – (ref. IH HAVL STI-N2 00004 B BPE) – 19 January 2011.
- Assessment of stresses in the concrete in the access tunnel to the C5 packages when a peak in temperature is reached in the Geological Barrier – (ref. IH HAVL STI-N2 00005 B BPE) – 26 January 2011.
- Long-term safety studies in a normal development scenario (SEN) and a degraded development scenario (SEA) for the STI 2009 architecture – EDF – 2 February 2011.
- Technical note on deep disposal – Surface facilities – Conditioning/disposal process for LLIL and LLHL waste packages – Technical description – AREVA – (ref. NT 100496 20 0001 C) – 25 January 2011.
- Appropriateness of using a tunnelling machine to excavate the underground structures for the long-lived IL/HL waste project – EDF - (ref. IH HAVL STI-N2 0007 B BPE) – 7 February 2011.
- Effects of delayed behaviour on tunnel excavation – Alexandra Kleine – EDF/CIH Engineer.
- Modelling of excavation with consideration of the delayed effects and hydromechanical coupling – Roland Plassard, François Laigle, Roméo Fernandes, Albert Giraud and Dashnor Hoxha.
- Hydromechanical modeling of an underground excavation with an elastoviscoplastic behavior law and regularization – Roland Plassart, Roméo Fernandes, François Laigle, Albert Giraud and Dashnor Hoxha.
- Hydromechanical modeling of an excavation in an underground research laboratory with an elastoviscoplastic behavior law and regularization by second gradient of dilation - Roland Plassart, Roméo Fernandes, François Laigle, Albert Giraud and Dashnor Hoxha.
- Effect of delayed behaviour on tunnel excavation – Alexandra Kleine, François Laigle, Albert Giraud.
- Hydromechanical modelling of the delayed behaviour of underground structures – Application to the Meuse/Haute-Marne radioactive waste disposal facility laboratory - Roland Plassart, François Laigle, Albert Giraud and Dashnor Hoxha – Review of Tunnels and underground space – n° 225 – May/June 2011.

- An elastoplastic strain-softening constitutive model for deep rock – three-dimensional applications for nuclear waste repository problem – Alexandra Kleine, François Laigle, Albert Giraud.
- Digital modelling of the behaviour of underground structures through a viscoplastic approach –PhD thesis of Alexandra Kleine – 14 November 2007.
- Hydromechanical modelling of the behaviour of underground structures with an elastoviscoplastic model – PhD thesis of Roland Plassart – 15 December 2011.

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