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°4

JUNE 2010

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SUMMARY AND CONCLUSIONS

General context

During the year 2009-2010, the Board assessed the progress of research and development in the geological disposal of long-lived, high and medium level waste, and the partitioning and transmutation of actinides in spent fuel from nuclear reactors.

Research into geological disposal is entering a decisive phase: Andra has proposed a zone of interest for further surveying (ZIRA), with a view to establishing a reversible geological disposal facility, and the French Minister of Ecology, Energy, and Sustainable Development has validated this choice. Provided that this survey leads to positive results, and following a public debate to be held in 2013, a request for authorisation to construct the disposal facility will be submitted by Andra at the end of 2014 for examination in 2015. Parliament will then take a decision on the reversibility conditions. Only three years remain to conduct the necessary research and illuminate the public debate.

Partitioning and transmutation studies are currently being performed in conjunction with research into the design of the Astrid prototype for the 4th generation fast nuclear reactor. The complete demonstration of the feasibility of the partitioning-transmutation strategy involves a demonstration of the multi-recycling of plutonium and minor actinides with the aid of Astrid. This means that the plutonium and minor actinides in the spent fuel from this reactor may be separated and recycled.

Research and development is conducted by legal professionals, their partners and the academic community, forming part of an international framework and, working together, offering expertise of the highest quality.

Storage and disposal of radioactive waste

Studies conducted for the project on reversible deep disposal for long-lived, high and medium level waste were intensified by Andra in 2009-2010. The Board has received no new information on long-lived, low level waste or its management methods.

The dimensioning inventory model (MID) enables Andra to estimate the quantities of long-lived waste to be taken into account in the design of the disposal facility. This will play a role in the public debate by presenting a closed list of the waste intended for geological disposal. The Board is asking Andra, in conjunction with all players involved, to justify the margins (quantities of waste) used for the design of the future disposal facility, based on calculated data.

In accordance with the National Plan for the management of radioactive materials and waste, Andra proposed a ZIRA to the Government in the autumn of 2009. The Minister of Ecology, Energy, and Sustainable Development requested the opinion of the Board, which recognised the excellent quality of the scientific report produced by Andra. The proposed ZIRA fully satisfied the geological criteria selected for the construction of a disposal facility.

Research projects were actively pursued in the underground Meuse/Haute-Marne laboratory, a number of which led to publications in international journals. The long-term diffusion experiments in the Callovo-Oxfordian argillite confirmed the remarkable qualities of this rock for the containment of radionuclides. However, the Board regrets that Andra does not yet have a validated operational model of the hydro-thermomechanical behaviour of the rock. Such a model is indispensable for planning the facility’s structural development and its consequences for safety and reversibility.

Since 2009, research into radioactive waste disposal technologies has benefited from the establishment of the Experimental Technical Centre in Saudron, Haute-Marne. Given the wide range of different canisters used for medium-level waste, the Board recommends improved standardisation of the disposal canisters and the size of the cavities.

The progress made by Andra in defining options for a reversible design must not allow us to forget that the disposal facility will ultimately need to be sealed to guarantee its long-term passive safety. Nor must it let us lose further sight of any disadvantages that the prolonged opening of the facility might have on the effectiveness of the seals.

Studies appear to increasingly confirm the good containment qualities of the Callovo-Oxfordian formation. Similar attention must now be paid to the safety consequences of the underground structures' design options. If any contradictions emerge between safety during the use of the facility, reversibility and long-term passive safety, then the highest priority should be given to long-term safety.

This being a unique project, in which certain technical options are still the subject of research, the request for authorisation to construct the facility must reconcile the precision required by the administrative procedure and the flexibility needed to satisfy requirements in terms of reversibility and the incorporation of new technical developments. Moreover, between them, these areas of research fully justify Andra's request to keep the underground laboratory at Meuse/Haute-Marne operational until 2030.

The Board commends the scale and diversity of the disposal site observation and monitoring programme. It also underlines the need to establish close links between this programme and all activities associated with modelling the chemical and thermo-hydro-mechanical behaviour of the disposal facility. With regard to environmental monitoring, the Board is highly appreciative of the efforts made by Andra to develop a permanent monitoring station in close collaboration with local organisations and recognised research teams.

The costs of the different options proposed for the facility will form an essential part of the discussions due to take place during the various phases in which the construction authorisation request will be prepared and examined. In accordance with the Safety Guide published by the Nuclear Safety Authority, it is important that we retain the options that enable us to *"keep the radiological impact of the facility at the lowest reasonably achievable level, in light of* [in particular] *the social and economic factors"*. The Board requests that detailed data be regularly provided on the cost level, structure and calculation methodology used for the deep disposal facility.

Partitioning and transmutation

The partitioning and transmutation results are supported by a solid basis of radiochemical research activity, for which the CEA is internationally recognised. The commissioning of the Astrid fast neutron reactor is an essential step towards the success of the partitioning-transmutation strategy. The purpose of this prototype is, on the one hand, to prepare the launch of an industrial technology for future reactors (4^{th} generation) and, on the other, to test the transmutation of minor actinides.

The Board believes, without underestimating the difficulties involved, that these two objectives should be tackled head-on and that they should be included in the specifications for Astrid in the 2012 file. Furthermore, it is concerned that the calendar presented by the CEA, EDF and Areva may not be compatible with the plan for commissioning in 2020, as set out in the law of 28 June, 2006.

The Board draws attention to the need to construct an essential addition to the Astrid prototype, namely a pilot reprocessing plant capable of demonstrating in full scale that the fuel cycle can be closed, and the Astrid reactor supplied through the reprocessing of its own spent fuel. Feedback from within France shows that before long we should be able to manage all stages of this reprocessing on an industrial scale, provided that we build the appropriate plants, and take account of the high content of plutonium, fission products and minor actinides.

Exploratory studies conducted by the CEA-EDF-Areva have made it possible to simulate the technical and economic consequences of the different options for implementing partitioning and transmutation when deploying fast neutron reactors (FNRs) and accelerator-assisted systems (ADSs). The CEA is due to submit an assessment of the industrial perspectives of the fast neutron reactor technologies in 2012. The Board recommends that this report includes all conceivable options, specifies the duration of the transient phases leading to a group of power plants consisting entirely of FNRs, and identifies the most difficult technical issues, relating to both the reactors and the associated fuel cycles. It must also explain the advantages and disadvantages of transmutation, particularly for the disposal of the waste produced.

International dimension

France is actively participating in around twenty new projects and shared actions identified at international level, most often through Andra, CEA, CNRS and IRSN.

Andra continues to play a leading role in European research and development in the field of geological disposal. Finland, France and Sweden are the three most advanced European countries in terms of preparing for the construction of a geological disposal facility, and their respective agencies (Posiva, Andra and SKB) are managing a new European technological platform.

The CEA is coordinating, or taking part in, the major international research and development projects on partitioning and transmutation. The CNRS is very active in new projects concerning fuel cycles and ADSs. The IRSN is participating in new projects relating to the safety of current and future reactors, and aims to open the Tournemire laboratory for European collaboration. Furthermore, all of these organisations are contributing to international education and training programmes.

Outside of France, the most significant recent event has been the decision taken by the new American administration to drastically reduce the budget for the "Yucca Mountain" project. The licence request was withdrawn in March 2010 and the administration has created a committee, comprising members of Congress, scientists and industrialists, which is responsible for proposing alternative projects.

FOREWORD

The period from July 2009 to June 2010 is the third full fiscal year for the CNE2, and is the subject of this report. From late June to December 2009, the Board presented report no. 3 to various audiences, the top tier of which included 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. One of its members presented the Board’s opinions on reversibility to the High Committee for Transparency and Information on Nuclear Safety (HCTISN).

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The Board followed the same working method used in previous years. Members of the Board, all of them volunteers, conducted 12 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 76 people from Andra, 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 Nuclear Safety Authority, Areva, EDF, the Radiation Protection and Nuclear Safety Institute, and the Central Administration. The Board devoted half a day to hearing about the various fundamental research projects under the CNRS Pacen programme[1] and, in response to a request from the OPECST, a Board delegation met at the Tournemire site on 4 and 5 May 2010, at the invitation of the IRSN, with the aim of updating the Board’s knowledge of the experiments conducted there. Work carried out by the CNRS and IRSN, the impact of which is recognised nationally and internationally, is described in Chapter 3.

This year, the Board’s study visit focused on the SKB laboratories in Sweden (the underground Äspö laboratory and the Oskarshamn container laboratory), the presentation of the site proposed as a future deep geological disposal centre at Forsmark, and a visit to the operational centres: the underground disposal facility for short-lived technological waste (SFR) and the spent fuel storage centre (CLAB) at Oskarshamn.

To prepare this report, the Board held a 2-day pre-seminar session during its visit to Sweden, and 3 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 submitted to the Board by organisations during the hearings is provided in Appendix III. In order to complete the Board’s information, some of its members attended international conferences.

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During the previous fiscal year, in addition to assessing research and development in long-lived, high-level waste (HAVL) and actinide partitioning-transmutation, the Board assessed R&D in long-lived, low-level waste (FAVL), tritiated waste, mining waste and historical waste. It also recommended giving a new impetus to socio-economic studies and assessing as accurately as possible the costs of the various options for the geological disposal of long-lived, high and medium-level waste (HA-MAVL) and FAVL waste.

[1] Programme on the downstream part of the cycle and nuclear energy production.

This year, following the withdrawal of the two municipalities approached with regard to conducting geological studies to assess the feasibility of constructing a FAVL disposal facility, the Board has not been led to consult with Andra on this type of waste. Its assessment has focused on R&D conducted in two domains with particularly important implications, namely the geological disposal of HA-MAVL waste (Chapter 1) and the partitioning-transmutation of actinides (Chapter 2). In a letter dated 13 November 2009, the Minister of Ecology, Energy, and Sustainable Development asked the Board to give its opinion on the zone of interest for further surveying (ZIRA) proposed by Andra. The Board submitted its opinion on 16 December 2009. The corresponding scientific elements are presented in §1.2.5 of Chapter 1. Finally, Chapter 3 includes an update on the international overview.

Chapter 1

DISPOSAL AND STORAGE

Radioactive waste is classified according to whether its level of activity is high, medium, low or very low, and whether it is long or short-lived, having a lifespan longer or shorter than 30 years. For long-lived, high and medium-level waste (HA-MAVL), the option selected by all countries concerned is deep disposal, which must also be reversible in the case of the French project. The project presented by Andra is the subject of this chapter.

An additional approach is partitioning-transmutation, which involves transforming certain long-lived radionuclides to eliminate or reduce their long-term harmful effects. This approach could not be effectively implemented until after 2040, with a future generation of nuclear reactors that remain to be designed and constructed. It does not, therefore, concern the current disposal project in the Callovo-Oxfordian formation. Research and development in partitioning-transmutation are the subject of Chapter 2. The relationship between transmutation and thermal load is discussed in §1.2.3 of this chapter.

1.1. CONCEPT OF DEEP DISPOSAL

The radioactive waste that may be deposited at a deep geological disposal facility would, for the most part, result from the processing of spent fuel from current nuclear power reactors in France, including an EPR reactor in the course of construction.

1.1.1. Concept of disposal in 2005

Deep disposal, in the design presented by Andra on the occasion of the 2005 Argile Report[2], involves surface facilities for receiving the primary canisters, encapsulating them in disposal canisters and storing them until they are placed below ground. The functions of these facilities must be specified; they may be conventional installations, but for a long time to come, they will be the sole source of concern from a public safety point of view. Access to the underground structures is via four specially designed vertical shafts. In the 2005 design, these shafts are grouped together and located at some distance from the underground disposal areas, in accordance with the general "dead end" design of the structural works. At the bottom, leading from the bases of the shafts, are four main parallel tunnels, with access tunnels for transferring canisters, personnel, materials and ventilation air to the disposal cavities. These are grouped together in two distinctly separate horizontal areas, located mid-way through the argillite layer of the Callovo-Oxfordian formation.

One area receives the MAVL waste, which is stored in several dozen parallel cavities comprising horizontal tunnels measuring 250m in length and between 9 and 12m in diameter, supported by a sufficiently thick layer of concrete cladding. The primary MAVL waste canisters are encapsulated in a concrete disposal canister, with a cover measuring a maximum of 3m by 3m by 3m. There is a wide range of different disposal canisters, which makes it difficult to completely standardise the handling methods used. This point is examined in §1.2.1.

The second area receives the HAVL waste, which is stored in several hundred parallel cavities grouped into modules. These cavities measure approximately 40m in length and 80cm in diameter. A steel casing enables the disposal canisters to be easily positioned and removed if necessary (the primary canisters are placed in an outer steel container). The successive casings protect a glass matrix in which the waste is incorporated. Recent developments in the design of the cavities and the excavation tests are discussed in §1.2.2.

2 Noted in the rest of the report: 2005 Submission.

HAVL waste releases an appreciable amount of heat, but distributing it over a large horizontal surface area prevents the clay from reaching excessive temperatures. So although the volume of this type of waste is considerably smaller than that of MAVL waste, it occupies a larger surface area (see §1.2.3.).

This project is characterised by its compactness (the stored waste occupies the smallest surface area possible within the limits set particularly by the problem of the thermal load), its modularity (the waste is divided into relatively independent sub-sets), its tree-like architecture with "dead end" cavities and, in comparison with other projects, the reduced use of expanding clay, which is limited to the seals at the heads of the cavities in the tunnels and shafts.

1.1.2. Changes to the concept since 2005

During the period 2005-2009, the project was re-examined by Andra. The idea of using rail as the principal means of transport was abandoned. The number and length of tunnels was reduced for reasons of cost and simplicity, but this may have consequences for degraded situations. The principle of the "dead end" cavity design was partly overturned, particularly by allowing passive ventilation for the MAVL cavities and considering the separation and repositioning of the shafts due to risks during site operation (ease of ventilation and fire hazards). Issues relating to ventilation are discussed in §1.2.4.

The diameter of the MAVL cavities could be reduced to prevent the disposal canisters from falling; 14 different types of canister are envisaged to cover the complete inventory. Andra is also examining the possibility of using several different types of cover to facilitate the use of the canisters. A sealing function is envisaged for the HAVL cavity casing discussed in §1.2.4. The design of the cavity cover and the way in which the waste is handled have been reconsidered from the perspective of reversibility, and some improvements have been made with regard to safety. The idea of an access point via a 5km inclined drift, in addition to the vertical shafts, was accepted to offer flexibility for the construction of the surface installations.

The Board will express its opinion on these modifications at a later stage.

1.1.3. ZIRA

In view of establishing a new disposal facility, the "2005 Dossier" defined a transposition area in which the properties of the Callovo-Oxfordian layer appeared to be similar to those identified in the laboratory, and favourable to the construction of a disposal site. In 2009, a restricted zone (ZIRA) was selected within this area, where further surveys would be conducted. This decision is discussed in §1.2.5.

1.1.4. Cost of the disposal facility

The cost of the disposal facility is an essential subject for public debate, which must legally take place before the request for authorisation to construct the facility is examined. The year 2013 has been suggested for this debate by the OPECST and the National Plan for the management of radioactive materials and waste (PNGMDR). The fundamental objective of protecting the people and environment associated with a disposal facility is explained by a general principle: the concept adopted for disposal must make it possible to keep the radiological impact at the lowest reasonably achievable level, in light of the scientific knowledge available, the state of the art, and social and economic factors. The "2005 Dossier" provided some information on this issue, calculating effective doses lower than 1µSv/year at the outlet in the normal development scenario for a glass canister disposal facility costing approximately 15 billion euros. Andra has also provided the Board with some useful additional information. The discussion between 2013 and 2016, which will include a public debate, an examination of the authorisation request and a Parliamentary vote for a law on reversibility, will provide the opportunity to describe the compromise that our society seeks between the cost of the facility and concerns for short and long-term safety. It is the responsibility of the government bodies to ensure that the information given to the public and the transparency of the debates, still in their preliminary stages, are sufficient. This point is examined in §1.3.

1.1.5. Analysis of the facility's operation

The operation of the disposal facility is examined using a grid provided by the safety analysis. This considers, on the one hand, the normal development of the disposal facility and, on the other, degraded situations including the scenario of human intrusion.

- ***The disposal facility in use***

The period during which the disposal facility remains open will be marked by the introduction of exogenous materials below ground level, which will disturb the site's natural state: canisters, steel, expanding clays, concrete and ventilation air. The latter will introduce new bacteria, cause temporarily oxidising conditions, and desaturate the rock in the areas around the tunnels, which will already be affected by damage resulting from the excavations. The ventilation air must also carry the hydrogen from the waste canisters (see §1.2.4.). Some of the canisters will release heat. As with any underground structure, the risk of fire must be considered very carefully; its prevention may lead to a shift in the emphasis of some of the proposed principles to ensure long-term safety. The coexistence of mining and nuclear activities calls for the introduction of particular design measures for the protection of workers. The risk of canisters falling or becoming blocked must be avoided when they are handled and inserted into the cavities. The mechanical forces applied by the land formations must be managed to limit the damage around the cavity walls and to allow for canister removal for as long a period as possible.

From this point of view, the Board hopes that the tests conducted by Andra will now result in a proven ability to make credible predictions.

In this context, the reversibility required by the law of 2006 for reasons of acceptability, adds constraints that must not be detrimental to safety, either before or after the disposal facility is closed. Reversibility involves monitoring the structure, at least during the period when the facility is open. The reversibility and monitoring of the disposal site are discussed in §1.2.6. Particular attention must be given to observing the environment; this must start in good time before the construction of the facility to provide a sufficiently long series of reference observations. This point is examined in §1.2.6.

- ***Closing the facility***

The cavities are progressively closed by inserting an expanding clay plug. When the entire disposal facility is closed, seals will be fitted in the tunnels and shafts. The gradual return to a configuration close to the earlier quasi-equilibrium will then begin; this will be slowed down over a long period by the continued release of heat, the effects of which will remain appreciable for several thousands of years, and subsequently by the generation of large volumes of hydrogen due to corrosion. The increase in temperature will shift the physical and chemical balance, accelerate the kinetics of the reactions, and lead to thermal stresses in the rock or the canisters (see §1.2.3.). The oxygen from the ventilation will be consumed very quickly. The damaged concrete will release alkaline elements, creating a chemical environment with a high pH value, and the iron from the containers will interact in a complex but very localised way with the clays (see §1.2.2.). The walls of the tunnels and cavities will become resaturated with water from the rock, all the more slowly because they will have been exposed to the effects of ventilation over a long period.

- ***Corrosion***

When water is available, the modified natural clays expand and provide their sealing function; but the arrival of water also allows the metal canister casings and steel supports to start corroding. Corrosion generates large volumes of hydrogen, the fate of which must be analysed, particularly as there are practically no similar phenomena available to enable a comparison. After several thousands of years, most of the activity associated with the short and medium-lived radionuclides will have disappeared through natural decay. However, the corrosion damage to the containers will enable water to come into contact with the glass, and leaching will begin. Laboratory experiments have shown that this will occur initially at speeds of a few micrometres per year; the glass, in combination with the water, will then form a modified surface layer, which will reduce the initial speeds by several orders of magnitude. These phenomena, which have already been analysed in several reports by the CNE1, are discussed in §1.2.2.

- ***Leaching, dissolution and diffusion***

The leaching of the glass, which could extend over a period of several tens of thousands of years, will enable the radionuclides to dissolve and then migrate. This process will be extremely slow, as the host rock is highly impermeable, to such an extent (the natural displacement of the water is less than one decimetre every 100,000 years) that the migration of the radionuclides outside the disposal area would largely occur by diffusion into the water in the pores of the clay. The migration speed will vary considerably depending on the substances considered: the electrically charged flakes of clay will offer a very large exchange surface for the water and the ions that it contains; the cations will be adsorbed on the surface; the anions will be repelled so that they will only have a reduced fraction of their total porosity to be able to diffuse. The minor actinides, which will become highly insoluble, due to their chemical form in the reducing context imposed by the clay massif, will only move a few metres in 100,000 years. However, if the behaviour of the dissolving radionuclides is well established up to 50°C, migration could be quicker above this temperature. This phenomenon conditions the design of the disposal facility (see §1.2.3.).

Important results in the area of diffusion were presented in 2010 (see §1.2.2).

Andra calculates that, in the reference scenarios, after a few hundreds of thousands of years, only a small number of soluble and particularly mobile radionuclides, ^{36}Cl, ^{129}I and, to a lesser extent, ^{79}Se, would be released in significant proportions from the Callovo-Oxfordian layer. However, the effective doses calculated at the outlets are very low. They prove to be very stable with regard to the design modifications for the basic installations, due to the thickness of the layer, their low permeability, their argillite retention properties and the reducing context that they impose. This is a strong point of the project, but it complicates the assessment of the impact of the modifications made to the concept, for which only rather qualitative criteria are available.

This general overview must obviously be subjected to a critical examination. The scientific knowledge that has enabled it to be established, and which concerns much longer periods than those associated with ordinary human activities, remains to be completed, confirmed and examined more closely, beyond the 2014 deadline.

- ***Degraded situations***

Unlikely, but not excluded, events associated with human activity, such as unintentional intrusion into the disposal area, or natural events such as an exceptional earthquake or thrust fault, are also taken into account. Other scenarios are also examined, in which canisters close to the primary tunnels become defective prematurely and migrate towards the shafts under the effect of horizontal and vertical hydraulic load gradients, with the seals assumed to be faulty.

The Board has not yet obtained detailed information on the status of the research and development in this area, particularly the design of the seals. It draws attention to the fact that the design of the disposal facility and the seals will prove essential to long-term safety.

Following the examination of the concept of deep disposal, the Board notes that the R&D appears to increasingly confirm the good containment qualities of the Callovo-Oxfordian formation. It believes that similar attention should now be paid to the safety consequences of the underground structures' design options. The Board recommends that any contradictions that might emerge between safety during the use of the facility, reversibility and long-term passive safety should be highlighted. The highest priority must be given to long-term safety.

1.2. ASSESSMENT OF R&D

1.2.1. Radioactive waste and dimensioning inventory models for geological disposal projects

- ***National inventory of radioactive waste***

In June 2009 Andra published the third national inventory of radioactive waste and the inventory of radioactive materials. These inventories are based on information declared by the waste producers. The first inventory comprises a database of the dimensioning inventory models (MIDs), which support the design of the disposal installations. In late 2009, Andra updated the MID produced in 2005 concerning the disposal of MAVL-HAVL waste; the MID for FAVL waste is still in the process of being defined. The MID for MAVL-HAVL waste includes a description of the disposal canisters and the families of primary canisters. Finally, Andra conducted a prospective analysis of the frequencies at which the disposal canisters would be deposited in the cavities.

The inventory of radioactive waste is a very complete document which presents, in addition to the inventory itself, a projection of the quantities of waste expected up to 2030. This enables decisions to be taken at the appropriate time, to avoid any delays in the management of the primary canisters (disposal of FMAVC[3] or TFA waste[4], and storage of FAVL, MAVL and HAVL waste). The prospective aspect of the inventory is also valuable for monitoring the progress of the resorption of waste while awaiting containment.

The Board recommends developing the prospective aspect of the waste inventory (stock, projected flows, containment percentages) to allow programmes concerning the management of non-contained waste and dismantling to be monitored from one inventory to another. This involves all players, particularly with regard to progressing from orders of magnitude to more precise values for the quantities of waste concerned.

- ***Recyclable materials***

Most of the radioactive materials included in Andra's corresponding inventory are, or will ultimately be, recyclable. However, the ability to recycle some of the materials is uncertain, and these could become waste. In this case, it is important to know whether particular research should be conducted to focus on their management.

The Board has not been informed of the properties of recyclable radioactive materials. It would like to be better informed on the recyclability of the materials in the 2009 Andra inventory before it can assess the relevance of the current programmes and determine whether new R&D is necessary. In the same spirit, if certain materials currently considered to be recyclable are requalified as waste, it would like to know how these materials would be managed.

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[3] Short-lived, low and medium-level waste.
[4] Very low-level waste.

- ***Uncertainties over the dimensioning inventory model***

The MAVL-HAVL MID was established by taking into account all waste in both of these categories, that has already been produced, and that will be produced, by all installations that have been granted authorisation by the end of 2014. The number of primary canisters was estimated according to realistic assumptions concerning the operation of the current PWRs until their extinction in 2052, fuel development and waste containment. All spent fuel is assumed to be reprocessed in order to launch the FNRs. To make provision for the PWRs achieving a longer lifespan, and for various unknown factors, Andra is increasing the number of canisters in the MID by 50%. The dimensioning inventory model should be finalised in 2012.

The Board believes that Andra should better motivate this overall increase of 50% and specify the numbers of canisters to be stored on a given date, based on the adopted assumptions. It therefore recommends that Andra justifies the margin of 50% presented in the 2009 MID, based on calculated data from scenarios involving the continued operation of current reactors over several decades, coupled with scenarios based on the launch of the FNRs. It should also justify the time structure for this increase in view of the design of the future disposal facility.

- ***Diversity of canisters***

The number of families of primary canisters in the MID is considerable. Disposal constraints mean that the MAVL waste canisters must be divided into a large number of disposal canisters, which must then be inserted into differentiated MAVL cavities. Andra is working on the rhythm at which the canisters would be deposited, essentially dictated by the storage capacities at any given time for the MAVL waste canisters, and the thermicity for the HAVL waste canisters.

The Board believes that the R&D work conducted by Andra is essential to the project, from the perspective of using the disposal facility, but is currently resulting in a complicated management system. It recommends that such work be pursued and refined, particularly with regard to the simplification and increased standardisation of the MAVL disposal canisters.

The disposal projects pursued by Andra provide an overview of how the long-lived waste produced by the PWRs will be managed. A study is currently in progress to optimise the intended use of these canisters and the containment of waste, in view of their limited capacities. R&D focusing on new containments for MAVL waste is required.

The Board appreciates the effort made by the CEA to clarify matters on the historical waste that will need to be disposed in the geological facility. It recommends that R&D undertaken to adapt the containment of this waste to the requirements of the facility should be pursued consistently. It also recommends conducting R&D in innovative processing methods, particularly at high temperatures, applicable to raw waste and even to canisters that have already been prepared.

The fate of the MAVL-HAVL waste from the current PWRs included in the MID is clearly defined by the law, with the exception of unknown factors. The renewal of these reactors has begun with EPRs. No industrial scenario exists involving the launch of FNRs that multirecycle plutonium or, more importantly, minor actinides.

The Board has questions over the fate of the waste produced by the next phase of reactors.

1.2.2. On-site experiments at the Meuse/Haute-Marne laboratory

The underground laboratory at Meuse/Haute-Marne provides an excellent environment for assessing the physical and chemical behaviour of the argillite in the Callovo-Oxfordian formation (Cox) over time, and for conducting experiments on the containment of elements that could be introduced to the site.

- ***Interaction between materials***

Several experiments have been set up since 2009, with the purpose of checking the models of the physico-chemical behaviour of glass, iron, concrete and argillite *in situ*. Originally based on laboratory experiments, they are dynamic (kinetics measurements) and/or dormant. The data obtained *in situ* derive from the intact argillite a few metres from the tunnels, and therefore reflect the phenomena in the disposal cavities after resaturation. Some measurements have already been recorded (continuous measurements of concentrations of leached elements or corrosion gas), but most of them are yet to be taken, as the experiments have been designed to span a period of approximately ten years. The POX experiment aims to monitor possible bacterial activity.

- ***Migration***

The main phenomenon that contributes to the migration of elements in the intact argillite of the Cox is diffusion (2005 Dossier). Andra has presented some examples to the Board to demonstrate the R&D work undertaken, and has also assessed the progress made in conceptualising the transfer of elements in the Cox.

The migration experiments conducted *in situ* (DIR, 6 experiments from the underground laboratory and 1 experiment while drilling) are the most complete. These started in 2005, as the true containment capacity of the argillite in the Cox needed to be demonstrated over as long a period as possible. The diffusion parameters of HTO, Cl^-, I^-, Na^+, Sr^+ and Cs^+ were measured by monitoring the decrease in the concentrations of the elements (their levels of radioactivity) over time, in the solutions circulating in a measuring chamber in contact with the argillite. They were also calculated by analysing the concentrations according to the distance to the contact surface in the argillite, in a sample taken by overcoring after the experiment was dismantled. Two regions of the Cox with different mineralogy were explored. The diffusion kinetics measurements were distributed over a period of more than 3 years, and the spatial measurements were taken using a 100cm sample. Their quality is highly reliable. An analysis of all of the data obtained *in situ* shows the homogeneity of the formation and provides diffusion parameter values (effective diffusion coefficient D_e and accessible porosity ω_{acc}) which are consistent with one another, and also with the values obtained in the laboratory (to within a factor of 2 maximum for D_e). These results are based on 3 different calculation codes used by 3 independent teams. Measurements for Cl^- are still being taken. Andra is also taking part in diffusion experiments conducted in other underground laboratories outside France; the results obtained show comparable diffusion coefficients.

Following this success, Andra is considering conducting a new experiment in around 2012, in which the measurements in the argillite will be taken in real time using mini beta and gamma radiation detectors placed around the source of the radionuclides. This will eliminate the unknown factors associated with overcoring, and will provide better measurements over very long periods, well after the radionuclides have penetrated the damaged mini-zone (EDZ of a few centimetres) resulting from the setup of the experiment. The diffusion of the actinides will be tested. The final results are expected in 2020/2025.

The Board considers that the set of results for migration by diffusion in the Cox for the most mobile elements clearly demonstrates the containment capability of this environment. This being an essential characteristic of the disposal facility, the Board approves the new plans for in situ diffusion measurement experiments proposed by Andra.

The set of results already acquired illustrates the importance of long-term measurements taken in the underground laboratory. This importance will be reinforced with the opening of any future disposal facility, as the laboratory will be the preferred site for making progress in terms of its implementation. The Board approves the continuation of the long-term phenomenology experimentation programme planned by Andra and highly recommends renewing the authorisation for the Meuse/Haute-Marne laboratory until the end of 2030.

- ***Cavity excavation tests***

The HAVL waste canisters are intended to be stored in blind parallel cavities of approximately 40m in length and 80cm in diameter, grouped into modules; each module will contain between one and several hundred cavities. The canisters will be placed in the last 30 metres of the cavity, which has a steel casing made up of welded sections measuring 2m in length and between 2 and 2.5cm in thickness.

From the point of view of utilising the disposal facility, excavating the cavities and fitting the steel casing must be relatively easy, as these operations will need to be repeated several thousands of times. The main function of the casing is to make it easy to insert the canisters, and remove them if necessary. For this reason, the sections must be correctly aligned, and prevented from becoming out-of-round under the effect of the weight of the rock mass, the water pressure and the temperature. Andra is also considering assembling the casing components with screws, rather than by welding, to facilitate this operation.

In 2009-2010 Andra conducted an initial campaign in the underground laboratory to demonstrate the feasibility of the excavation work and the installation of the steel casing in the cavities. The initial programme was to involve the excavation of five cavities from the GRM tunnel, using a laser-guided auger. These were to measure 20m in length; two would be fitted with steel casing, and follow the direction of minor stress, while the other three would have no casing and take three different horizontal directions. Several bore holes were made prior to the excavations to measure the pore pressure. The shape of the hole was then examined by video and scanner. The variations in diameter were measured using a tool with multiple skids inserted into the hole, and the level of damage was to be analysed. Poro-mechanical calculations had been performed in advance to anticipate the movements and pore pressures caused by the excavation. When the experiment was put into practice, certain problems were encountered and only three cavities were made. Work on the first cavity (cavity 1), which was perpendicular to the axis of the GRM tunnel, was stopped after 9.5m as the casing was blocked. This problem was attributed to the annular space being too small, the accumulation of debris that had not been removed properly, the incorrect alignment of the sections, and the fact that there was only one shift of workers per day, leaving time for the rock to deform and the walls to deteriorate. A second cavity (known as cavity 5) was excavated from the end of the tunnel, following its axis, to avoid any influence from other tunnels. The objective of excavating a length of 20m was achieved, but with significant overbreaks (of up to 14cm) compared with the circular shape desired for the straight section of the cavity. The third cavity (known as cavity 4), parallel to the first, reached a length of 21.4m, but again, the sections of the casing were not very well aligned, flakes of rock were falling and the shape of one section was irregular. Various improvements were attempted during the course of the programme, with regard to the screw conveyor, the thickness of the annular space, and monitoring the excavation parameters; the number of shifts was increased to three per day.

The measurements revealed distinctly higher pore overpressures than expected, but a wall convergence rate, several months after the excavations, that was consistent with the observations in the tunnels: between 1.5 and 2.4% per year, implying a possible rapid loading of the casing through the reduction in the diameter of the hole. The campaign will continue with several modifications to the excavation technique. Certain assumptions (heat released by the cutting, the force of the tool on the rock) will be examined to explain the observed unexpected behaviour.

The Board considers the problems encountered by Andra to be normal during the course of an initial test. These difficulties illustrate the importance that should be attached to the technological tests. The Board recognises that the poro-mechanical modelling still requires considerable work before extrapolation based on longer time periods, larger structures or greater depths, can acquire the desired degree of credibility.

- ***TER test***[5]

The heat released by HAVL waste is one of the main disruptions to the natural environment. It shifts the hydromechanical, physical and chemical balances and modifies the kinetics of the changes. It plays an important role in the design of the disposal facility, which must be constructed so that the temperature at the cavity/rock interface is lower than 50°C when the corrosion of the containers has allowed the water to come into contact with the glass.

The aim of the TER rock heating experiment, which lasted a little over three years and ceased in March 2009, was first to analyse the diffusion of heat in the rock and then to identify the mechanical and hydraulic effects by measuring deformations, pore pressures, increased permeability and modifications to its mechanical properties. The experiment *in situ* was supplemented by measurements taken from laboratory specimens.

In terms of the principle involved, the TER test is comparable to many other tests conducted over the last thirty years or so in other underground laboratories, and has benefited from their feedback. In this experiment, a heating sensor was placed at the end of a bore hole, between 6 and 9 metres from the tunnel, to measure the thermal power emitted. Three parallel bore holes were used to measure the temperature at several points in the rock, four holes were made to measure the pore pressures and two further holes were made to measure the relative movements at their axes. Inclinometers and convergence, temperature and relative humidity sensors were fitted to the walls of the tunnel. Until July 2007, the emitted power tended to vary quite irregularly, due to various technical problems that were resolved during the following phase.

The analysis of the results highlighted several important points:

- the thermal expansion of the water in the pores significantly increased the pore pressure, which dissipates very slowly due to the low permeability of the rock;
- all of the properties concerned by the test (permeability, thermal conductivity, elasticity) were found to be clearly anisotropic, which significantly complicates the calculations;
- the determination of the thermal conductivity was rendered inaccurate due to the uncertainty over the position of the sensors. Often this problem can only be solved by conducting tests on a larger scale;
- the area immediately surrounding the heating sensor was very clearly damaged (increased permeability) at the end of the test. Undoubtedly this effect was partly due to the rapid cooling when the heating phase stopped;
- the model takes account of the observations, at least qualitatively.

A test similar to TER, known as TED[6], will begin in 2010, but this will involve three different heated bore holes, in which the superposition of the effects will be analysed, and a phase 2 test, which aims to analyse the behaviour of a heated metal tube placed in contact with the rock in a bore hole. These experiments will contribute to the preparation of a larger test planned for 2012, to simulate the behaviour of a high-level waste cavity of around 20m in length.

[5] Experiment on the argillite's reaction to thermal stresses.
[6] Experiment on the field of overpressure in the argillites surrounding two or three heat sources.

The Board notes that the thermo-hydro-mechanical models, created by very good teams, appear to be dispersed, and there has been no obvious effort to make a synthesis. The Board has not received any document that sums up the current state of these models, which are essential for gradually forming reliable predictions of time scales compatible with the opening period of the facility and beyond. The unquestionable difficulty of the problem must not allow us to satisfy ourselves with a more empirical approach, which may be sufficient for many civil engineering structures, but would be inappropriate in the case of a disposal facility, demanding a much stronger ability to make predictions.

1.2.3. Thermal load

The Callovo-Oxfordian layer considered for the disposal of radioactive waste has only experienced very slow, natural changes over several tens of millions of years. An implicit principle of the French project is to minimise disruption to the natural environment caused by the disposal of this waste. There are five main causes of this disruption: the excavation of the tunnels and cavities, their ventilation while the facility remains open, the insertion of exogenous materials, the production of hydrogen due to steel corrosion, and the heat caused by the exothermic waste.

- ***Temperature changes***

The natural ("geothermic") temperature of the rock increases with depth; at 500m it is approximately 22°C, and remains very stable over tens of thousands of years. The temperature will be modified by the ventilation provided to the structures, but particularly by the heat produced by certain types of waste.

In the areas around the shafts, main tunnels and secondary tunnels, the hygrometry and ventilation air temperature will contribute to the development of the damaged zone (EDZ), but changes in the temperature of the rock will remain moderate. MAVL waste releases a small amount of heat. However, certain types of HAVL waste are highly exothermic. The total amount of heat released is difficult to specify due to the uncertainty over the waste inventory. The Board has no accurate data on this point. The order of magnitude is likely to be 10^{16} Joules, if all of the fuels are reprocessed and the waste is deposited after 60 years of cooling. The heat is released gradually and at an increasingly slow rate. The decrease in thermal power can vary depending on the radionuclides concerned; it is slow for americium, for example. However, most of the heat will be produced after a few centuries. At the moment, it is still completely contained in the bedrock, with the exception of a small amount which has been evacuated by the ventilation air. The heat will not be evacuated by the ground's surface until long after the facility has closed.

The heat essentially disperses by conduction within the rock (convection and radiation only play a role in the immediate vicinity of the canisters). Andra has measured the values of the physical parameters that govern the conduction. The thermal diffusivity of the argillite is clearly anisotropic, and in the region of $30m^2$/year, which is slightly lower than the average value for rocks. The uncertainty over the calculated temperatures, even in the long term, must be reduced.

The increase in temperature is maximal in the containers. Andra's decision, which is discussed later, is to limit the maximum temperature at the interface between the cavities and argillites to 90°C, which would be reached after 10 to 20 years. In layers measuring tens of metres in thickness above and below the level of the waste, the temperature will gradually increase by some tens of °C, before slowly decreasing. After 1,000 years, the maximum temperature will have fallen to 40-45°C. Ultimately, all of the heat produced will be evacuated through the ground's surface. The thermal disruption will become appreciable after approximately 5,000 years; this does not appear to be sufficient to have perceptible effects.

It is therefore within the Callovo-Oxfordian layer, and particularly around the waste canister disposal level, that the increase in temperature will be appreciable. Moreover, it will vary due to the fact that the canisters will only be put in place gradually. Therefore, before the facility is closed, hot and cool modules will coexist. It will be more complicated to retrieve canisters from a hot module.

- ***Effects of temperature changes***

The increase in temperature has varied effects, which the Board has attempted to document in the form of a list, which is undoubtedly not exhaustive:

- on a thermomechanical level, the rise in temperature modifies the mechanical properties of the rock (elastic characteristics, viscosity), but it is the thermal expansion of the steel, concrete, glass and water contained within the rock, that causes the most significant effects, particularly additional mechanical stresses. These stresses can modify the extent and quality of the EDZ. On the greatest scale, the average stress will increase in the bedrock and large shears will develop around the disposal facility. The argillite's thermal expansion coefficient is quite low, close to 10^{-5}/°C, but the fact remains that released thermal energy of 10^{16} Joules would increase the volume of the rock by approximately 150,000m^3. This increase would be reduced by the closure of the excavations and fractures in the rock, or a rise in the ground's surface. However, this rise would be hardly noticeable, as it would be distributed over the horizontal surface of the HAVL waste disposal area, which would be several millions of m^2. Particular attention should be drawn to the differential expansion of the water/rock; Andra's initial tests showed that the pore water pressures caused by heating were not easily dispersed in the impermeable argillite, and were seen to increase, with possible consequences for the movement of water towards the cavities and tunnels. With the exception of this latter area of research, the Board has received little information on the progress made since the 2005 Dossier.

- on a chemical, physical and biological level, the increase in temperature shifts the balances and accelerates the kinetics of the reactions. Andra is studying many of these phenomena which concern, for example, the interactions between concrete, steel and rock in the presence or absence of water and oxygen, the permeability of the rock or diffusion properties in the EDZ and intact rock, and the mineralogical transformation of the clays, which is possible if a temperature above 70°C is maintained over several thousands of years. Certain other phenomena do not appear to have been studied to date, such as the effect of the temperature on the dissolution of hydrogen in the water in the rock. Special attention should be devoted to the behaviour of dissolving radionuclides after the glass has begun to leach: above 50°C this behaviour is less well known and diffusion is likely to be much more rapid. This is currently the main heat-related phenomenon taken into account for the facility's design.

The Board requests that Andra assesses the effects of increased temperatures to prioritise their importance, ensures that an exhaustive list is produced, and identifies the priority areas for research.

- ***Temperature and behaviour of glass in the presence of water***

The behaviour of dissolving radionuclides with the effects of heat is the parameter deemed by Andra as being critical to the design. The disposal facility project was designed so that the temperature of the glass would not exceed 50°C at the point at which it could come into contact with the water in the rock, in other words, when corrosion has pierced the protective metal casings. The estimation of the rate of steel corrosion, along with the calculation of the decrease in temperature, led Andra to suggest a thickness of 5cm for the unalloyed steel outer container, so that the initial contact between the glass and water would be deferred to several thousands of years after the facility is closed. To limit the deterioration of the glass in the presence of water, its outer surface temperature at this time must have fallen to below 50°C.

The temperature change calculations are reasonably reliable and will be even more so when sufficiently long tests are implemented. The calculations show that in order to verify this condition, the maximum temperature must be limited to 90°C (around twenty years after the containers are put in place) at the extrados of the casing. This decision seems reasonable, given the options selected by other countries. Sealing the casing in the cavities provides an additional margin before the water comes into contact with the containers.

- ***Disposal facility design***

To limit the maximum temperature of the cavity walls to 90°C, several design parameters can be modified. The first is the time during which the exothermic primary canisters are left to cool in storage before they are deposited at the facility. This period was set at 60 years in the 2005 Dossier. However, a longer waiting time is conceivable: doubling it would halve the footprint of the HAVL disposal area, but a facility that remains open too long before the waste canisters arrive, would risk seeing certain qualities of its structures deteriorate over time.

Another design parameter is the extent of the area covered by the disposal facility, which aims to reduce the average amount of power emitted per unit of horizontal surface area. For the most exothermic waste, an inert separator would be placed between two consecutive canisters in the cavity. A certain distance is also left between two consecutive parallel cavities, then between two modules containing several hundreds of cavities. These distances could be increased. However, extending the area of the facility also has its limits, due to excavation costs and, in particular, the total horizontal footprint of the site: a more compact disposal facility allows considerable margins to be maintained, in terms of the distances to identified geological accidents (faults), or political choices that break with those prevailing today, such as putting a stop to reprocessing; this would result in the storage of spent fuel assemblies, which are more exothermic than reprocessing waste. Such an eventuality would call for a longer cooling period and/or a larger space between the canisters.

The third parameter, which in practice only concerns a future second disposal facility, is the transmutation of all or some of the minor actinides. Indeed, one benefit of transmutation is to reduce their quantity in the waste. Long after the fission products have decayed, the minor actinides, particularly americium, will be the main contributors to the release of heat. This strategy, which does not concern the facility currently considered for the ZIRA, is discussed in Chapter 2.

- ***Implication of a reduced thermal load***

There are several possible options for reducing the thermal load, but each presents disadvantages in terms of cost and safety. The main difficulty at present is the absence of simple selection criteria. For each of the different options, Andra has produced calculations or estimations of the safety benefits and drawbacks for the main development scenarios. However, the containment qualities of the Cox counteract all sensitivity of the calculated flows to the choice of design options. Furthermore, the various possibilities can be compared with regard to more general principles, such as simplicity, redundancy, robustness and caution. This comparison does not yet appear to have been made, in spite of its importance for the design of a disposal facility in the Callovo-Oxfordian formation, or for the selection of the transmutation option.

The Board requests that immediate consideration be given to the advantages and disadvantages of the current level chosen for the thermal load. This consideration will be an important part of the debate preceding the examination of the request for authorisation to construct the disposal facility.

1.2.4. Phenomenological analysis of disposal situations during operation (APSS-E)

Andra updated the APSS during the operating period as presented in the 2005 Dossier. The analysis described the operation of the facility in broad terms, and mainly endeavoured to describe the configuration that would be reached when the facility was finally closed. The updated APSS-E provides a much more detailed and complete description. It takes better account of the concerns for safety during operation, and reversibility, and describes the design of the observation and monitoring system that these concerns demanded. It also incorporates the results from the research and development conducted in engineering and safety since 2005, particularly in the underground laboratory. The analysis was produced by combining a breakdown of the disposal system into its basic components, with a time progression, from the construction of a cavity to the closure of the facility. The description of the time progression is undoubtedly the most delicate: it is not simultaneous for all of the cavities; the reference scenario can be greatly affected by disposal management decisions, such as choices relating to reversibility or the date on which the waste that releases the most heat is deposited in the facility. Andra also envisages, with good reason, incident situations likely to disturb normal progress (such as unavailable ventilation or unsealed casings in the high-level waste cavities), and even significant divergences, which are unlikely in principle.[7]

The Board approves of the principles that inspired the preparation of the APSS-E. Real progress has been made, even though the 2009 milestone is clearly only one stage in an ongoing process. With regard to the method, it would like Andra, between now and the submission of the authorisation request, to specify the content of the notions of robustness and durability, to which wide reference is made in its documents. More fundamentally, it requests that the time limits for the facility's operation be explored, namely the period after which the initial quality of the disposal structures could be significantly affected by disturbances caused by the facility being open over too long a period. The Board regrets that the critical points, towards which future efforts should be logically directed, are not sufficiently highlighted.

- ***Release of hydrogen***

During the operating phase, hydrogen is produced through the radiolysis of the "organic" MAVL waste, irrespective of the presence of water, and also in the MAVL and HAVL cavities, through the corrosion of the metal components in the presence of water during the liquid or steam phase. This second mechanism concerns the casing and containers surrounding the unventilated HAVL canisters, the reinforcements, metal waste and anchor bolts in the HAVL cavities once they are closed, and the return to a sufficient hygrometry. The hydrogen produced must be prevented from ultimately entering the air in the tunnels or cavities in a concentration that creates explosive conditions, whether during normal operation or after the ventilation is temporarily cut off.

In the case of the MAVL cavities, in principle the hydrogen would migrate easily through the dry concrete of the containers. It would then be diluted in the cavity's ventilation air, where its concentration would depend on the air flow rate, which would vary between the waiting and the active phase. If the ventilation was cut off, the hydrogen would spread towards the access tunnel in a few years, and much more slowly once the cavity was sealed. It would take a few tens of minutes to purge the hydrogen from the cavity if the ventilation was resumed.

With regard to the HAVL cavities, when the casing was sealed, the hydrogen would only be produced at its extrados, when the gap between the rock and the casing filled with water after a few years. It would then migrate towards the adjoining tunnel, notably through the EDZ. If the casing was not sealed, its intrados and the outer container would also produce hydrogen. Even in this case, the concentrations in the ventilated tunnels would remain low and would only pose risks several months after the ventilation was cut off.

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7 Following the "*what if*" methodology, in accordance with the international state of the art, and used by Andra.

The Board observes that Andra has taken into account the problem of the production of hydrogen in the cavities. However, it would like a better explanation of the lessons learned from the feedback from the existing waste storage facilities. It notes that the design of the disposal facility has changed recently, with the choice of passive ventilation for the MAVL waste and a sealed casing for the HAVL waste. It would like the reasons behind these choices, and the role played by the question of hydrogen, to be presented more systematically.

- ***Phenomenology of high-level waste cavities***

The APSS-E produced in 2009 includes a refined description of the phenomena that affect the HAVL cavities, and particularly the effects of the thermal load, the role of the clearances at the extrados and intrados of the casing, and the gradual elimination of the gap between the casing and the rock.

The heat released by the waste is considerable for the HAVL C5[8] and C6[9] type canisters, which has led to the notion of using inert separators between these canisters; the level is lower for the HA C0 waste[10]. Andra has chosen to limit the temperature at the extrados of the casing to 90°C. The French project thus appears to be inspired by an implicit principle of caution, which requires the disruption to the natural environment to remain as low as possible. The Board approves of this position, which is discussed in §1.2.3. The increase in temperature has important consequences from a chemical, hydromechanical and physical point of view. However, Andra believes that the change in temperature itself can be calculated without taking combined effects into account, using conduction equations. This prognosis appears to be correct, with the exception of a few subtle points. Andra has conducted a detailed examination of the effects of factors such as the clearances, skids, etc., on the temperature distribution.

As far as the Board is concerned, certain convective effects remain to be examined more closely, such as those relating to the movement of steam in the gaps following the axis of the tunnel. On the whole, this part includes appreciable improvements in comparison with the 2005 Dossier, whose main conclusions it does not challenge.

When the casing is no longer sealed, the rate of corrosion of the outer container is influenced by the increase in temperature, but remains moderate, at a few nanometres per year. Furthermore, it is likely that a certain proportion of the casings will not be sealed from the start, so the presence of water, which could be at a high pressure and temperature in contact with the hot outer containers, will make it difficult to reopen the cavity if required. This must be taken into account when preparing for reversibility.

The thermomechanical effects are more considerable, due to the risk of the casing becoming out-of-round. This point is not sufficiently underlined, despite its importance for reversibility. The initial HAVL cavity excavation tests showed that the appearance of contact stress heterogeneities between the casing and the rock cannot be dismissed out of hand.

The casing dilates with heat. However, it is not integral with the base or the head of the cavity, which should limit the axial stresses caused. Provided that there is clearance, the moderate radial expansion of the casing will not cause any additional stress. The differences in temperature, depending on the axis, could also cause internal stresses, but Andra believes that these differences will be quickly reduced to around 15°C, even in the case of high-level C5 and C6 canisters.

[8] UOX glass, including the glass produced according to the 300 AQ 60 specification.
[9] Future canisters of glass for reprocessing PWR Mox fuel and spent fuel/re-enriched uranium.
[10] "Old" and Atalante glass.

The effects due to the temperature in the bedrock are far more considerable, as a result of the contrast between the thermal expansion coefficients of the water and the clay skeleton. Additional high pore pressures are created several metres around the cavities; in a few years, the clearance between the rock and the casing will fill with water at a pressure that could reach 7.5 MPa given the most severe assumptions. This phenomenon deserves attention. If a sealing function is attributed to the casing, to delay the point at which the outer container begins to corrode, then it seems appropriate to check that such a pressure is not detrimental to this capability. However, the main function of the casing is to enable the canisters to be removed easily. From this point of view, the risk of it becoming out-of-round should be better analysed, as controlling this phenomenon is essential in terms of maintaining reversibility.

A second mechanical effect is due to the excavation work itself, which causes particular damage to the argillites, undoubtedly including chevron fractures which may cause flakes of rock to detach, and an increased level of permeability around the walls. The cavity will then close and the initial clearance left between the rock and the casing should fill in.

Measurements available from the No. 5 high-level demonstrator show very different deformation rates depending on the direction, but with an order of magnitude between 3.10^{-3} and 3.10^{-2} per year, corresponding to a clearance filling period of 1 to 10 years. These measured values are, however, indicative, as they correspond to a very different configuration from that of a filled cavity (active desaturation of the rock, no thermal load or differential expansion). Andra has highlighted a complex behaviour, marked by strong thermo-poro-mechanical couplings, which may lead to the development of high total radial stresses on the casing of up to 17 MPa.

These particular measurements are highly useful but the conclusions that can be drawn from them remain largely empirical and difficult to apply generally. This is due to the absence, regretted in some of the Board's previous reports, of a comprehensive mechanical behavioural model that clearly separates the various effects, is strongly validated by the numerous measurements available, and is compatible with the theoretical opinions formed on a smaller scale. Only a model of this kind would enable us to legitimately extrapolate observations made over longer periods, such as those concerning operation and reversibility. If such a model appeared difficult to achieve within a reasonable time frame, it would be important to quickly conduct scale 1 tests to compensate for the absence of a robust theoretical model.

Given the reversibility requirement, it is imperative that a solution is found to the problem of the out-of-roundness of the casing, and the methods for reopening an unsealed HAVL waste cavity, before the authorisation request is submitted.

- ***Hydric and thermal state of the disposal facility in relation to ventilation***

The ventilation air influences the thermal, hydric and gaseous states of the structural components and the Cox. These states, in turn, have an impact on the durability of these components due to the consequences for their mechanical and chemical properties. In the 2005 Dossier, Andra established the key ventilation principles and confirmed them with new studies that would be ongoing until 2009. In its aeraulic, thermal and hydric approach, Andra made a distinction between the ventilated connecting structures (shafts and tunnels), the unventilated HAVL disposal modules, the ventilated MAVL disposal cavities and, finally, the structures after site closure. It was shown that with the expected air flows, reaching several hundreds of m^3/s for the entire facility, the atmosphere in the tunnels would stabilise at a temperature of around 22°C and a relative humidity of 40% after an air trajectory of approximately 2km. The temperature would increase by 5°C in the air return from the HAVL disposal modules 10 years into the active operation phase. For the MAVL cavities, the purpose of the ventilation is not to evacuate the thermal load but to dilute the released hydrogen. A maximum temperature increase of 20°C is expected at the exit of the cavity. The results from the calculations showed typically long time periods, amounting to dozens of years, for both the variations in temperature and saturation within the bedrock, under the effect of the immense thermal inertia of the Cox.

These environmental conditions have favourable consequences, which should be reflected by a decrease in the chemical degradation kinetics of the metal corrosion, the carbonation of the concretes, and a slowing down of the delayed mechanical processes in the Callovo-Oxfordian formation due to the desaturation of the rock.

The Board notes that Andra has carefully examined the phenomenological analysis of the disposal atmosphere within the different modules and during the different operating periods. The Board considers that the consequences of the air circulation have strong implications for the reversibility of the disposal facility, and would like an analysis of this issue to be submitted.

1.2.5. Research conducted by Andra for ZIRA selection

The PNGMDR[11] asked Andra to propose "a restricted zone of interest suitable for installing a disposal site where deep exploration techniques would be implemented (ZIRA)" to the government by the end of 2009. The ZIRA, whose surface area will be approximately 30km^2, primarily concerns the site on which the underground disposal facilities will be constructed; it will be located within the 250km^2 transposition area. The ZIRA could be associated with one or more surface facility installation areas (ZIIS), whose locations will be defined in conjunction with concerns over the land use.

In Report no. 3, the Board emphasised that the criterion determining the choice of the ZIRA should be its geological quality; in March 2009, Andra presented a review to the Board, detailing the geological constraints that it would take into account when making this decision. In October 2009, at the Board's request, Andra presented details of the geological data (bore holes, surface prospecting) and 2D seismic geophysical data obtained within the transposition area, in addition to the approach applied to the choice of the ZIRA.

In October 2009, Andra submitted a proposal for a ZIRA to the government, seeking to optimise the technical criteria and criteria associated with land use and installation within the local environment, in accordance with the following principles:

- favour the establishment of the ZIRA in an area identified as being more advantageous in terms of the geological and safety criteria;
- enable the reference underground architecture to be constructed in the ZIRA, as presented in the 2009 design options;
- ensure compatibility with the construction of the entrance in the inclined drift, located in the Meuse/Haute-Marne border area, enabling access to the underground environment;
- ensure compatibility with the construction of the access shafts in a wooded area;
- avoid construction below the villages.

The Minister of Ecology, Energy, and Sustainable Development consulted the Board in November 2009 regarding the proposal submitted by Andra.

[11] National Plan for the management of radioactive materials and waste.

The Board recognises the excellent quality of the scientific report produced by Andra and considers the area in which a ZIRA could be chosen to be consistent with the geological and technical criteria necessary for the possible construction of a geological disposal facility. On the basis of the data obtained, the Board considers that the in-depth investigations conducted in the ZIRA should be brought to a successful conclusion during the course of 2010-2011. Among the questions that should be answered by these investigations, the Board is particularly interested in the following:

- *the possibility of extrapolating, at a depth of 600m, observations made on the mechanical behaviour of tunnels excavated at a depth of 500m in the underground laboratory;*
- *the need to present an accurate description of the surface installations, together with their technical objectives, in the file produced for the public debate preceding the submission of the authorisation request;*
- *the opportunity to provide a detailed description of the prevailing geological and hydrogeological conditions, when the inclined drift is excavated for access to the disposal facility, and to check that the construction work will not modify the qualities of the ZIRA.*

The Board has also examined the conclusions drawn by Andra on the geothermal potential of the Grès du Trias (Triassic sandstone). It does not believe that this formation represents an attractive geothermal resource.

1.2.6. Reversibility – Observation and monitoring

- ***Reversibility of the disposal facility***

In accordance with the deadline set by the decree of 2008 relating to the PNGMDR, Andra produced a document at the end of 2009, summarising the "reversibility options for a disposal facility in a deep geological formation". This document integrates, in a comprehensive contribution, the most recent findings obtained from R&D concerning the content and methods of a reversible management system for the disposal site. It also introduces the next R&D phase in preparation for the public debate, due to take place before the authorisation request is submitted in late 2014, and before the law to be introduced in 2016, defining the reversibility conditions over a period which, as we already know, must not be less than 100 years.

The general problem already proposed is reaffirmed here: it combines the recoverability of the canisters with the progressiveness of the decision-making process, offering the possibility of backtracking to the management method initially chosen (ability to influence the waste disposal process and develop its design, particularly due to the ten-yearly assessments). It is enriched with concrete solutions favourable to recoverability (sealed casing for the HAVL waste cavities, skids for contact with the outer container and casing, a reduced stacking height for the MAVL containers, etc.), and the formulation of variants open to later decisions, concerning both the overall organisation of the deep disposal facility and associated surface storage area, and practical methods for performing the different handling, insertion and removal operations for the HAVL and MAVL canisters and cavities.

These proposals are based on a more precise, and partially quantitative, analysis of the phenomena at work in the different parts of the disposal system during its entire operational phase. This enables to support different design choices or ranges (waste canisters, containers, steel casings, clearances, disposal cavities, etc.), by revealing some of the time periods that characterise different phenomena (thermal, chemical, mechanical, diffusive, etc.) on the different levels of the reversibility scale formulated previously (see CNE2 Report no. 3, 2009); it also allows to produce approximate "sliding time charts" for each of these levels.

The provisions for construction, insertion and removal incorporate, and will continue to incorporate, results from long-term tests in the underground Meuse/Haute-Marne laboratory (behaviour of the materials, structures and sensors) and from technological tests, which also involve demonstrations of the insertion and removal processes.

They are accompanied by a methodological consideration of the distribution of observation and monitoring instrumentation, sensor installation plans for the HAVL and MAVL cavities during the entire operational phase and beyond, refined sensor qualification procedures, and a definition of the specific areas requiring further research and development.

In parallel, Andra is maintaining national and international exchanges, which are often multi-disciplinary, on the notion of reversibility, and is continuing in its effort to trigger the interest of researchers in human and social sciences on this question. An important event in this domain will be an international conference on reversibility, due to be held in France in late 2010, under the auspices of the OECD.

The Board positively appreciates Andra's commitment to the different aspects of reversibility, in terms of the technical and societal, national and international dimensions that it has given to this question, and the refinement of its scientific and technical analysis. For the continuation of this work, the Board has formulated the following recommendations:

- *the reversibility scale initially proposed by Andra has now been adopted by the international study group coordinated by the NEA, after being simplified into 5 levels, in the more limited form of a container recoverability scale. It is in our interests that Andra does not abandon its wider approach to reversibility, which includes the progressive character of the decision-making process and specifies the milestones associated with covering each level of this scale;*
- *the analyses forming the basis of the APSS must be conducted in greater depth and extended to take account of the relationships between phenomena, to incorporate a tested and robust mechanical model of the behaviour of the clay massif, and to make reliable quantitative predictions of the reactions of the different elements of the disposal facility over time. It is essential that these predictions take full account of the disturbance caused by the disposal work itself throughout the operating phase (maintaining an oxidising atmosphere, desaturation of the clay, etc.), so that not only the authorised latitude with regard to the term of the reversibility period, but also the practical considerations of the reversibility requirement, can be accurately assessed. This, in particular, will give us the grounds to settle the question of when the, at least secular, reversibility period set by the law should begin;*
- *more generally, Andra's studies on the implementation of a reversible system for the geological disposal facility must not overshadow the need for such a facility to be closed after a defined period, following which time its safety must be ensured in a passive way. Let us remind ourselves that closing the facility will not mean that observation and monitoring will stop; nor will it prevent access to the waste by mining work. If it is essential, by introducing measures to guarantee true reversibility, to let future generations choose the patterns and methods used to manage the disposal facility, it is also important to allow them to finally close it under the best possible conditions when the time comes;*
- *finally, it is clear that only an assessment of the "extra cost" of reversibility during its different stages will enable us to establish a truly reversible waste management system and the available choices associated with it (see §1.3.).*

- ***Observation and monitoring of the disposal facility***

The aim of Andra's R&D concerning the observation and monitoring of HAVL and MAVL waste, is to design, install, use and maintain monitoring and measuring devices, which are useful for the facility's operation and staged reversible management, as well as for safety analyses during the site's use and after its closure. This activity is closely linked to the modelling process, by providing input data and validating the models.

Andra's efforts focus on:

- selecting and developing long-term monitoring systems (the period concerned is at least secular), requiring redundancy and complementarity;
- defining an optimal distribution for the instrumentation *in situ*, based on a graduated distinction between "control", "test", "standard" and "non-measured" structures, each requiring decreasing levels of instrumentation;
- selecting monitoring equipment, including analysing internal and external feedback, approving the selected instruments after adapting them to the geological disposal conditions where necessary, and identifying shortcomings requiring specific R&D work (particularly with regard to monitoring the hygrometry, detecting and analysing gases and chemically analysing materials).

R&D activities, which have been supported for two years by the work of an important group of laboratories, cover the inventory of available technologies, the establishment of thermo-hydro-mechanical-chemical monitoring with the decorrelation of phenomena based on their characteristic time differences, the "hardening" of measurement methods in real conditions and an assessment of their ageing processes, and the management of time drifts. In particular, we can highlight:

- the preparation of two instrumentation tests in the Meuse/Haute-Marne laboratory, based on a HAVL waste cavity casing in 2010, and a MAVL type section in 2011;
- the qualification of the thermomechanical monitoring method, involving measurements distributed over optical fibres by Brillouin backscattering;
- the use of feedback from measurements, taken over 15 years, of the water content on the experimental cover structure at the CSFMA;
- the localised monitoring of gases and changes in materials through the targeted development of more durable and reliable chemical sensors (creation of a miniature spectrometer for gas analysis);
- the development of a qualification procedure for vibrating wire strain gauges, progressing from laboratory tests in a controlled temperature to tests *in situ* with the production of demonstrators, followed by hardening for irradiation resistance.

The Board positively appreciates the scope and diversity that the observation and monitoring programme is acquiring for the reversible storage of HAVL and MAVL waste. It also highlights the need to establish close interactions between all of the modelling activities. This must involve not only the definition and verification of specific acceptability criteria, but also the validation of spatio-temporal models of the appropriate variables throughout the entire field of waste disposal. Given the importance of this programme for the operation of a reversible disposal management system, the wealth of expected feedback, and the rapid progress made in this scientific and technical domain, the Board would like the possibility of continuing the programme, throughout the duration of the facility's operating phase, to be seriously considered and investigated when the time comes.

- ***Permanent environmental monitoring station***

In conjunction with the impact study prior to the submission of the authorisation request, environmental monitoring constitutes an essential aspect of Andra's research programme. It involves proposing a system for providing the data needed to establish the initial environmental state, within a zone incorporating the transposition area, and monitoring the site if the disposal facility is created. During this period, environmental monitoring will contribute to studies analysing the impact of the facility's construction and operation. It is envisaged that monitoring will continue after the site has closed, through the "Observatoire des sciences de l'univers lorrain".

Andra set up a permanent environmental monitoring station (OPE) in 2007, the purpose of which is to establish the standard state of the environment around a possible radioactive waste disposal facility, and to monitor the environment during its construction and operation.

The objectives of the R&D work conducted over the last two years have been:

- to define an observation area of approximately 900km^2 and a restricted area of 250km^2 around the ZIRA (30km^2);
- to establish a hierarchy of zones within the observation area for the construction of surface installations (ZIIS), by identifying the ecologically sensitive sectors and spaces;
- to prepare a long-term environmental observation and monitoring plan if the facility is constructed;
- to prepare for the creation of an ecological data bank, which will gather together all of the acquired observations and will be freely accessible to the scientific community and, therefore, the public.

The OPE's scientific programme includes:

- the study of the operation of ecosystems, from the scale of a land parcel to a catchment area;
- the refinement of indicators and the development of environmental sensors, with the benefit of skills from the University of Lorraine and the Troyes University of Technology, where two industrial Chair posts will be created;
- the detection of environmental changes and the characterisation of the relative contributions of climate change, socio-economic developments and industrial activities;
- the characterisation of the ecosystems' sensitivities and vulnerabilities to these disturbances and associated uncertainties.

The implementation of this programme began in autumn 2009 with the establishment of a standard state for the biodiversity and quality of the soils. The pedological characterisation was accompanied by radiological measurements, which show that the radioactivity of the soils is due to the elements naturally present within them (^{40}K, chains of ^{238}U and ^{232}Th, and cosmogenic ^{7}Be) and also due to the ^{137}Cs associated with the Chernobyl accident and airborne nuclear weapons testing.

The Board recommends that these calculations be supplemented by measurements taken from plants that naturally concentrate pollutants and ambient radioactivity, such as mushrooms, mosses and lichens. The latter are integrators of radioactivity throughout their entire lives and are likely to live for over a hundred years. The Board also recommends supplementing the measurements used for radioactivity monitoring with measurements associated with the chemical species carrying the radionuclides, to understand any later changes that would involve these chemical species.

In order to monitor environmental changes, and particularly the chemical composition and quality of the air and water, Andra has set up a group of equipped measurement stations in forests, grasslands and cultivated areas. High-performance instruments are being implemented or currently developed. These will be used to quantify the biogeochemical cycles. The temporal monitoring of changes in the various ecosystems will also benefit from the combined use of airborne and satellite remote sensing methods. In addition, Andra is preparing for the implementation of a test site in 2012, which will be used to compare the environmental changes on two ecological sites, which are close to one another, but far enough apart to be subject to different industrial and socio-economic constraints.

Acting as the programme agency for the R&D work it conducts, Andra called upon around twenty research departments and specialised laboratories to obtain the observations needed for the OPE. It favoured collaboration with local organisations (the National Forestry Commission, National Hunting and Wildlife Organisation, local Chambers of Agriculture, hunting and fishing federations, etc.), and made use of national scientific teams specialising in the environment when required (CEA, CNRS, INRA, universities, etc.). Ultimately, the work of the OPE will be integrated, within the framework of the Observation and Experimentation System for Environmental Research (SOERE), with the Observatoire des sciences de l'univers in Lorraine, which will be responsible for establishing a common scientific council and operational management group with Andra.

The Board positively appreciates the effort made by Andra to develop a permanent environmental monitoring station. It believes that the creation of a scientific council, in association with the Observatoire des Sciences de l'univers in Lorraine, will guarantee the quality and scientific independence of the programme, and ensure the publication of the results obtained, offering transparent information to the public on environmental change. It approves of the creation of an ecological data bank, an essential long-term environmental monitoring device, on a local and regional scale.

The Board has also noted the modelling work conducted to refine knowledge of the local climate and air quality monitoring. It recommends that this initial modelling be extended to fully exploit the observations gathered in the ecological data bank. This will constitute a unique database in France, enabling us to understand changes to regional environments.

The Board approves of the work conducted in the area of environmental monitoring. It recalls that in Report no. 2 (2008), it emphasised the importance of having databases available on the health of populations.

1.3. COSTS OF THE DISPOSAL FACILITY

In its previous reports, the Board regretted not having more complete economic data on the cost of a disposal facility and, more generally, the cost of the long-term management of the radioactive waste. The law of 28 June 2006 explicitly states that such data must be available and made public. Article 14 of this law obliges Andra to submit "*an assessment of the costs pertaining to the implementation of solutions for the long-term management of long-lived, high and medium-level radioactive waste, depending on its nature*" to the Energy Minister. Indeed, it seems difficult to pass appropriate judgment on scientific and technical options without taking the economic and financial dimension into account. Once the project enters a concrete implementation phase, it will become necessary to obtain a sufficiently accurate assessment of the possible options.

The application of the so-called Alara principle, which is internationally recognised, leads us to take account of the cost criteria when selecting the best of the various technically possible solutions, without questioning the priority given to long-term safety. By modifying the composition of the Board in the law of 2006, the legislator implicitly believes that the skills of the Board's members must extend to the economic and social aspects of the projects to be studied. Welcoming the Board on 22 October 2009, the Minister announced the establishment of a workgroup at the DGEC[12], bringing together waste producers, the Nuclear Safety Authority and Andra, with a view to updating the assessment of the cost of the facility.

In February 2010, a Board delegation was received at the Ministry by the Director of Nuclear Industry, who explained that this workgroup, set up at the DGEC in late 2009 to re-estimate the figures published by Andra in 2005, had focused its work on methodological problems, in a particular effort to progress from unit costs to overall costs. New estimates should be available during 2011.

The Board has noted this decision and would like to obtain any new available data as soon as possible.

The costs of the disposal facility must be supported by the waste producers, who are obliged by law to make provisions, in accordance with the "polluter-payer" principle quoted in the Environmental Code. In view of the assumptions made, based on the inventory of waste to be stored (MAVL and HAVL), and in accordance with the so-called "industrially conceivable" scenario, several figures were advanced by Andra in 2005. The range was between 13.5 and 16.5 billion euros (€ 2002) and took account of unknown factors and opportunities associated with various risks, both during construction and site operation. In principle, the costs also covered so-called support measures, corresponding to various types of assistance provided by Andra to the communities affected by the disposal facility.

These figures (between 13.5 and 16.5 billion euros) were repeated by Andra during the hearing on 18 February 2010. Andra explained that they had been obtained by adopting a global approach. It should be noted that in proportion to the total costs of the nuclear industry, this figure estimated in 2005 represented approximately 1% of the nuclear kWh cost. It should also be highlighted that these estimates did not take account of reversibility costs which, before the law of 2006, was only an option. Furthermore, these amounts must now to be updated, by taking account of a rate of time preference discount factor, to calculate the sum of the provisions to be made. The question is knowing which rate to select: 8% (or 4%?) for up to 30 years, and 3% after that time, as already suggested?

If knowledge of the overall cost of the underground facility, even if incomplete, proves to be highly important for both the waste producers and the political authorities, it is the estimates of the unit costs in particular, operation by operation, that will enable appropriate assessments to be presented.

A new calculation method is therefore now used to estimate the full costs of the facility, based on a life cycle analysis (LCA) type approach. This tracks all of the costs in the chain, from the waste producer to the final disposal of the waste at the selected site. It must take account of the direct and indirect costs, or "externalities", which are sometimes hard to quantify, as certain impacts have a market value that is difficult to estimate.

This methodology allows us to obtain the structure, level and development of the cost of each of the options to be studied.

[12] Directorate General for Energy and Climate.

Compared with the previous calculations, this analytical approach represents progress, since:

- each operation (excavation, support, digging of cavities, etc.), is divided into basic tasks;
- the resources and methods needed to perform each basic task are described (number of personnel, equipment, materials, etc.);
- the costs are then converted into work units, similar to linear metres for the construction of tunnels, for example.

These calculations are based on the unit costs provided by specialised subcontractors. Of course, certain costs, linked to unknown factors for example, can only be estimated using ratios established from direct costs, and changes to environmental or health legislation standards will affect the costs of certain operations. The rates of development and subsequent facility usage will be the greatest sources of uncertainty in terms of changes to these costs. Better knowledge of these unit costs will then make it possible to review the overall cost and guide decisions.

Furthermore, during its hearing, the CEA (I-Tésé) presented an economic analysis of several different waste transmutation scenarios, and assessed the additional cost based on each one (see Chapter 2 of this report). This study does not concern the underground disposal facility currently being studied in Meuse/Haute-Marne.

The Board notes the efforts undertaken by Andra, the waste producers and the DGEC, to increase knowledge of the overall cost and unit costs of an underground disposal facility for long-lived, high and medium-level radioactive waste.

The Board believes that the calculations currently in progress must reflect not only the level, but also the structure of the full costs of the facility, and changes to this structure in the various envisaged scenarios. It would like to be kept regularly informed of the methods used for calculating the costs, and the results from the various calculations made. It believes that particular attention should be paid to the integration of unknown factors. The calculations must obviously take account of indirect costs: environmental expenditure and the cost of support measures, but also costs relating to the economic and industrial repercussions in the regions concerned.

Among the questions deserving particular attention, the Board would like to raise the following points:

- *What are the respective costs of the different reversibility options set out in the law?*
- *What would be the cost differential between disposing of graphite waste in dedicated sub-surface installations and disposing it in a deep disposal facility?*
- *What would be the cost differential if we opted for a longer storage period on site for certain types of waste that release an appreciable amount of heat, instead of burying them quickly?*
- *What would be the cost differential between the different modifications to the design options conceived since 2005, such as the choice of an inclined drift as opposed to an "all vertical shaft" option?*

Chapter 2

PARTITIONING-TRANSMUTATION

2.1. General introduction

In accordance with the law of 28 June 2006, research and development in the field of separation and transmutation must be conducted in association with work on the new generations of nuclear reactors. It is in this context that the Board examines changes in the management of nuclear materials.

In the case of the current PWRs, the cycle relies on a supply of enriched natural uranium upstream of the reactor, and produces uranium, plutonium, minor actinides and fission products downstream of the reactor (see Figure 1). Using Mox[13] fuel enables some of the plutonium to be recycled once in the PWRs. This mono-recycling process means that the plutonium stock incorporated in the spent fuel increases by approximately 7 t per year for a fleet of PWRs generating 430 TWh per year, as is the case in France.

The recycling of actinides in a PWR is limited by the physics of the reactors themselves, which operate with thermal neutrons[14]; the multi-recycling of plutonium is therefore very difficult in this case. However, in fast neutron reactors, which are not very sensitive to the isotopic quality of the plutonium, all of the plutonium isotopes contribute to fission. Moreover, fast neutron reactors have a favourable neutron balance[15] which makes them very suited to transmutation through the fission of minor actinides. As a result, the prospective scenarios for replacing the current reactors envisage deploying FNRs in a so-called 4th generation, due to their better performance and strict safety requirements[16]. These reactors would be the only ones able, on the one hand, to use plutonium as a multi-recyclable resource and, on the other, to transmute the minor actinides in industrial conditions.

Thus, in the case of a fleet of isogenerating[17] FNRs producing 430 TWh/year, it would be possible to completely close the uranium and plutonium cycle. The cycle would be supplied upstream by approximately 450 t of Mox[18] and around 40 t of depleted uranium[19]; the downstream part of the cycle would lead to the reprocessing of the 450 t of spent Mox to provide 80 t of plutonium and 330 t of recycled uranium in the reactor, together with 40 t of final waste, comprising minor actinides and fission products (see Figure 2). Furthermore, these reactors would also enable the transmutation of certain minor actinides.

As far as the Board is concerned, the advantages of such a material cycle are as follows:

- the absence of waste from mining activities, and the conversion and enrichment of uranium;
- the ability to stop producing depleted uranium, of which France currently has a considerable stock (7,000 t produced annually, and a stock of approximately 250,000 t);
- a stable plutonium inventory at a level of approximately 900 t, which becomes the basic resource.

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13 Uranium and plutonium oxide.

14 In a thermal spectrum, the only fissile isotopes are plutonium 239 and plutonium 241; the even plutonium isotopes behave like poisons for the chain reaction. To multi-recycle the Pu in a PWR, the core would need to be loaded with an increased amount of plutonium 239, which is limited for safety reasons.

15 Operating with fast neutrons, FNRs favour fission reactions, and therefore release more neutrons per event, whereas the operation of PWRs favours neutron capture.

16 The Phénix and Superphénix reactors are 2nd generation FNRs.

17 A reactor is said to be isogenerating if it produces as many fissile materials as it consumes.

18 The FNR Mox contains 20% Pu. The Mox for PWRs contains between 7 and 9% of Pu on average.

19 The depleted uranium results from the enrichment of the natural uranium.

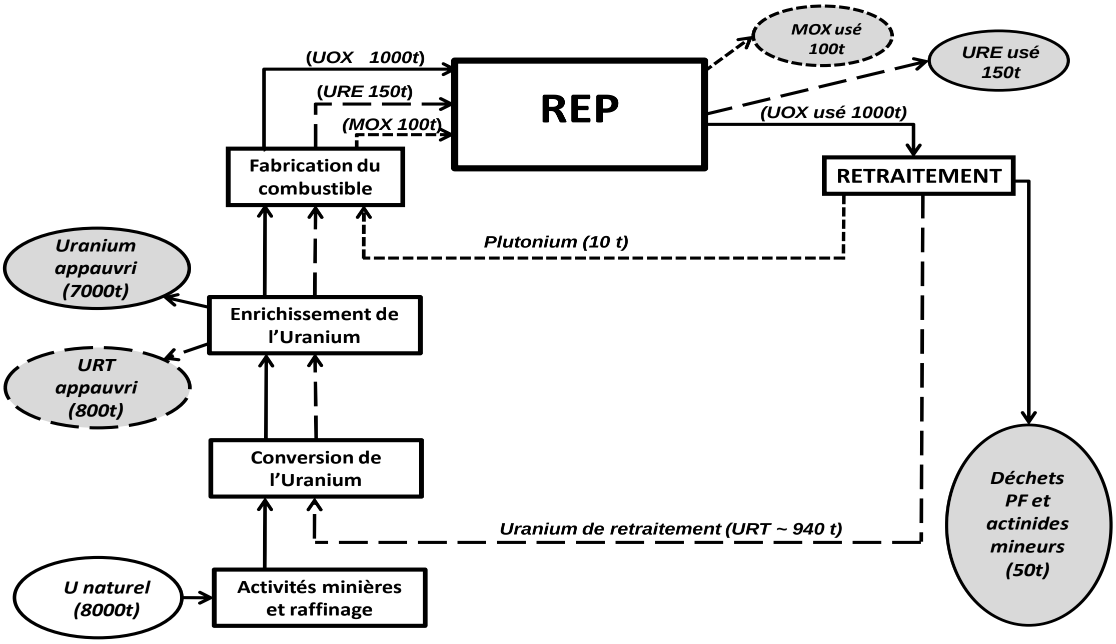

Figure 1: **Annual flows of materials for 430 TWh/year in a fleet of PWRs with <u>plutonium mono-recycling</u>** *(CEA-EDF-Areva; 2010 data)*

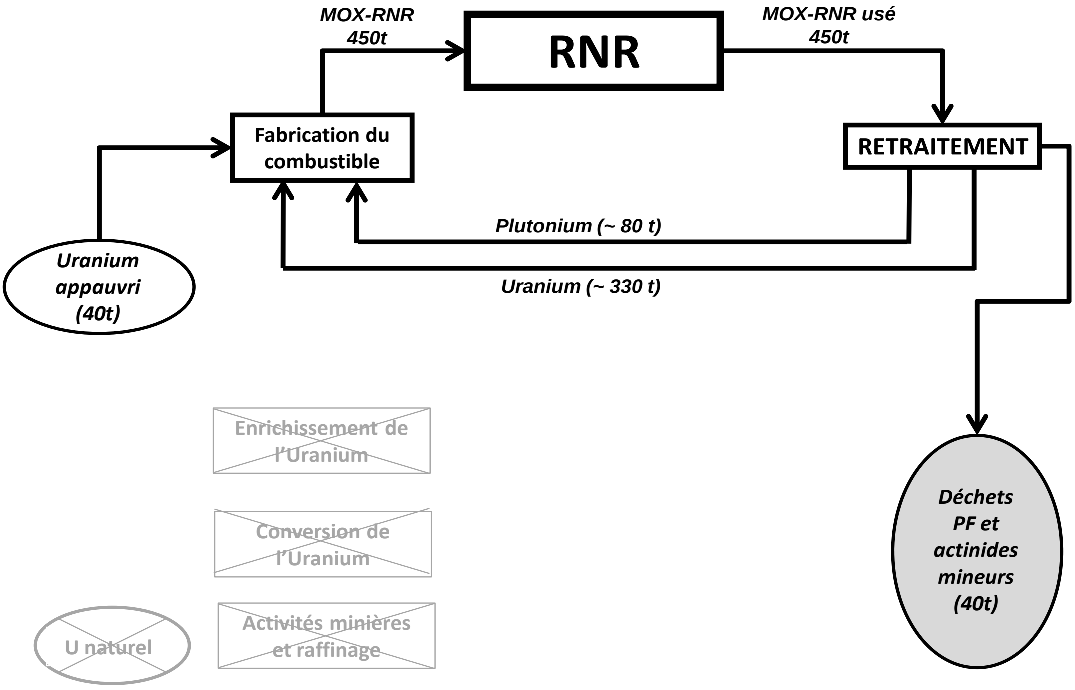

Figure 2: **Annual flows of materials for 430 TWh/year in a fleet of FNRs with <u>plutonium multi-recycling</u>** *(CEA-EDF-Areva; 2010 data)*

A set of FNRs can therefore optimise the management of nuclear materials, in terms of the consumption of plutonium, use of depleted uranium, and possible transmutation of minor actinides. The novelty of this form of management is that the "downstream" reprocessing, which is essential, becomes the strategic link to ensure the operation of the technology: the upstream part of the cycle is completely dependent on the downstream part (see Figure 2). The feasibility of reprocessing new FNR Mox fuels, which have a much higher plutonium content than PWR Mox fuels, in a closed cycle, will therefore be decisive for supplying the process in a loop.

In its previous report, the Board recommended focusing R&D on the 4th generation FNR prototype reactor, Astrid[20], which would be essential for demonstrating the multi-recycling of plutonium and the transmutation of minor actinides on a full scale.

This year, the Board draws attention to an essential addition to the Astrid programme, namely a pilot reprocessing plant capable of demonstrating in full scale that the closed cycle can operate autonomously, with the Astrid reactor being supplied through the reprocessing of its own waste. Astrid and its associated pilot reprocessing plant are therefore conceived as integral tools for demonstrating the feasibility of a long-term 4th generation technology.

In this Chapter, the Board describes the various aspects of this analysis, based successively on the status of the Astrid programme, initial results presented from scenario studies, findings on the impact of partitioning-transmutation on the disposal of radioactive waste and, finally, fuel cycle research and development.

Furthermore, in accordance with the law, an update will be provided on the current status of R&D in the field of ADSs[21], a solution for waste transmutation, in which the current scenarios show a particular interest in case the use of fission nuclear power is discontinued.

2.2. PARTITIONING AND TRANSMUTATION STRATEGY

The spent UOX fuel (enriched uranium oxide) from the PWR nuclear reactors contains a large proportion of uranium, plutonium and many other radiotoxic elements (fission products and minor actinides). Currently, its reprocessing involves extracting the uranium and plutonium to produce Mox fuel or UOX (re-enriched uranium oxide). The other elements, fission products and minor actinides, are vitrified to form HAVL waste.

The transmutation of the most radiotoxic long-lived radionuclides would, in principle, facilitate the management of waste in the very long term. To do this, we need to think beyond the current simple partitioning of plutonium and uranium. The R&D conducted in several countries, particularly in France, has shown that the partitioning-transmutation (P&T) strategy could only be effectively implemented by recycling the plutonium and minor actinides in the fast neutron reactors (FNRs). Only the fission products would become waste. The R&D has also shown that the expected advantages of P&T should be weighed against the major difficulties in handling large quantities of radioactive material in the FNR

[20] Astrid: Advanced Sodium Technology Reactor for Industrial Demonstration:
[21] ADS: Accelerator Driven System: this system includes an accelerator, a spallation target, and a subcritical nuclear reactor.

fuel cycle, whether these reactors recycle the plutonium alone, or both the plutonium and the minor actinides.

In France, the P&T strategy does not involve the spent fuel from the current PWRs: all of the MAVL and HAVL waste produced by these reactors is intended for the geological disposal facility currently under study. This strategy can only be implemented in a group of reactors comprising FNRs or ADSs, and many problems remain to be solved.

In Report no. 3 (2009), the Board presented the status of R&D in P&T, which was coordinated by the CEA. This work concerns two domains, the recycling of plutonium and minor actinides in FNRs and the associated fuel cycle (partitioning/conversion of recyclable elements, production of fuel assemblies or targets, and waste containment). The Astrid prototype must enable the testing of actinide transmutation and, in accordance with the law of 2006, be commissioned before the end of 2020. The Board attaches great importance to the consistency of the report on the perspectives of the industrial implementation of P&T, to be submitted to the government by the CEA in late 2012. It also recommends that the CEA pay great attention to the P&T implementation scenarios, to identify the advantages and difficulties that must be expected.

In all of these domains, the CEA has refocused its activities and collaborations and has, therefore, taken the Board’s recommendations into account. The Board presents its new recommendations in the remainder of this report, including some assessments which are detailed in various appendices.

2.3. ASTRID PROGRAMME

2.3.1. Astrid reactor

The construction of the Astrid prototype fast neutron reactor involves decisions on the reactor and the associated installations currently envisaged.

The Astrid reactor project incorporates feedback from the Phénix and Superphénix reactors, and from research conducted on the EFR[22]. The CEA hopes that the construction of Astrid will not be delayed too much, for fear of losing the skills inherited from the construction of the French FNRs and from studies during the EFR project. The preliminary design is presented in two phases, separated by the deadline of 2012. The first phase is essential to increase exchanges with the Nuclear Safety Authority over the major safety principles, and will limit the Astrid safety report in 2012 to these principles. The choice of the reactor concept, finalised based on the technical results, will take account of the predictions from technico-economic scenarios (investment costs, planning of the following stages, etc.). The period between 2012 and 2014 will be devoted to drafting the final safety report.

The CEA is not questioning the work scenario of commissioning the Astrid reactor in 2020; EDF estimates that it will take 3 years from 2014 to draft the detailed preliminary design report and does not envisage the construction of the reactor before 2020.

Given the desire to develop an innovative prototype, and the associated safety requirements, the Board fears that Astrid will not be commissioned before the end of 2020.

[22] European Fast Reactor.

The technological installations for the component tests, which began in 2010, will need to be brought up to date for R&D on the reactor. The installations currently associated with Astrid are a reactor driver fuel production workshop (AFC) in La Hague, and a minor actinide-loaded pin production workshop (ALFA) in Marcoule. The Astrid programme anticipates that basic preliminary design report for the AFC will be drafted for 2011, and the detailed report drafted for 2013. The AFC workshop should begin operation in 2017.

The Board notes that this calendar is consistent with the date of 2020.

In accordance with the law, the deadline of 2012 calls for an examination of the report to be submitted by the CEA on the industrial perspectives of P&T. The Board believes that the commissioning of the Astrid reactor, in accordance with the law, must remain the CEA's priority. It reaffirms that if the Astrid reactor is not constructed, the P&T programme will be reduced to zero, whereas continuing the programme will leave two possibilities open: solving the resource problem by multi-recycling plutonium, and helping to reduce the long-term harmful effects of the waste by transmuting one or more minor actinides.

The period 2010-2012 will be an important planning stage. To achieve the objectives set by the law, the Astrid programme, defined in the context of a three-way collaboration between the CEA, EDF and Areva, results from a compromise between two points of view. EDF, in its industrial role, would like to see a prototype that tests the safety and performance of a commercial technology in operation. The CEA, in its role as an R&D organisation, also wants to test the transmutation of significant quantities of minor actinides.

For the purpose of clarification to enable choices to be made, the Board believes it necessary to distinguish, in the 2012 report, the R&D results on the sodium-cooled FNRs multi-recycling plutonium, from the findings on the P&T of minor actinides. Furthermore, economic assessments must clarify the reciprocal implications and the limits associated with the simultaneous pursuit of both objectives (the industrial project and transmutation).

Without underestimating the difficulties involved, the Board would like to see both of these objectives, demonstrating safety and transmutation, continue simultaneously until 2020. It expects the CEA, in consultation with its partners, to present a clear strategy for meeting these objectives by 2012. The Board also deems it essential to include these two aspects in the Astrid specifications.

2.3.2. R&D in sodium-cooled fast neutron reactors

The FNRs of the future must be innovative on various levels. Feedback from the Phénix and Superphénix reactors, which was summarised and documented remarkably well, shows that for the future FNRs, operational performance, economic competitiveness and safety must be significantly improved through simplification, but also by making true technological breakthroughs. From 2007 to 2009, four major innovative domains were explored: acceptability from a safety perspective, investment costs, exploitability and the management of fissile material resources.

The Board believes that the R&D on the sodium-cooled FNRs is progressing well and is very impressed by the level and extent of the work already achieved. The R&D conducted in this area has focused on a commercial size reactor (1,500 MWe). The Astrid prototype, whose power will probably not exceed 600 MWe, will undoubtedly provide the opportunity to test some of the innovative options from this R&D. However, it is difficult to know what can already be planned for Astrid, in terms of particular projects or results. In view of the close deadline for decisions on Astrid, the Board recommends that the options selected for the commercial model, which could be tested on Astrid, be expressed immediately.

One particularly important domain covers, on the one hand, the metal materials needed for the fuel cladding and reactor structure and, on the other, the ceramic materials for the fuel and transmutation targets. All of these must have exceptional, well-identified, behavioural properties under exposure to radiation, at a high temperature and for a period of around 60 years, for the structural materials at least. These properties are largely superior to those required by the Phénix reactor. The current R&D programme on metal materials appears to cover all of these requirements appropriately. However, the results from this R&D will only have very little influence on Astrid, which will be constructed using known materials, or materials whose development is almost complete.

As the Board has already highlighted in Reports no. 2 and 3 (2008 and 2009 respectively), it believes that it is crucial that the sodium-cooled FNR construction projects, and particularly Astrid, benefit from major innovations in materials research. In particular, the Board is favourable to any cooperative research on the refinement and development of ODS steels for fuel cladding, which would bring together university teams, the CEA and nuclear industrialists.

Finally, the Astrid driver fuel must be prepared in the AFC, at a rate of 5 to 10 metric tonnes per year from 2017, using the Coex[23]-co-conversion process. This requires the refinement of progressive technologies for the Melox plant and R&D in the qualification of the Mox-Coex and assemblies.

As far as the fuel is concerned, the Board believes that the schedule is uncertain due to the current absence of geometric specifications for the Astrid pins and assemblies. In addition to this, the Board highlights the uncertainty over the validation of the co-precipitation/co-conversion processes.

The selection of fuel or targets loaded with minor actinides for transmutation, goes through various stages. The last of these, the irradiation of pins containing hundreds of grams of minor actinides (or even kilograms on the scale of an assembly), will only be overcome by using Astrid to perform the irradiation process. Preparing the pins will require the Alfa (Atalante production line for minor actinide bearing fuels) to operate with a capacity of 1 to 5kg of oxides per year. The Alfa installation will need to respond quickly to a wide variety of demands and also provide a test bench for remote production. An installation project has been outlined, and initially, only americium would be used.

[23] A process for co-extracting all minor actinides.

The size of the Alfa workshop will not be sufficient to test, for example, the self-transmutation of the americium produced by Astrid, which would require tens of kilograms of americium per year. No experiments on curium are planned for Alfa in the short or medium term. Its coupling with the Atalante CBP cell[24] would enable the recycling of actinides (uranium, plutonium, americium and curium) to be tested after passing through Astrid.

The Board believes that the Alfa project is essential to R&D in the P&T of minor actinides. It recommends that research in this area be actively pursued, taking into account the workload schedule at Atalante and possible international collaboration, even though the construction deadline for the Astrid programme still seems far away.

The fast neutron irradiation programmes required to qualify homogeneous recycling (Gacid[25] experiment) have come up against the unavailability of the Japanese reactors, and ambitions have been reduced. Gacid is now limited to pin irradiation with the deadlines of 2015, 2020 and 2025. An initial assembly could also be irradiated in Astrid. To test heterogeneous recycling, particularly in CCAM (minor actinide-loaded blanket) mode, the irradiation will begin in some reactors with a high flux but in thermal neutrons. The important results for selecting the Astrid transmutation option will not be available until after the 2012 deadline.

The Board has already recommended increasing R&D on the CCAM transmutation mode, which seems to be particularly attractive. It now renews this recommendation, so that knowledge of uranium oxide, loaded with a high americium (or plutonium and americium) content, and irradiated by neutrons, can be increased to the same level as current knowledge of other materials used for fuels or transmutation targets.

In 2012, the CEA will have at its disposal a large number of irradiation results, for both homogeneous and heterogeneous recycling[26], as these processes have been continuing over a very long time. The Board suggests that the document presenting these results be in the form of a clear, exhaustive report (conditions and results); this document will be particularly useful.

With regard to the Astrid programme, the Board has reached the following conclusions:

The approach presented on the development of the Astrid programme until 2014 and beyond, is a progressive one, involving a series of stages. It focuses on innovations for the reactor, in addition to the transmutation fuels or targets, and goes as far as to suggest the demonstration of P&T on a quasi-industrial scale after 2020. However, presenting the characteristics of a 1,500 MWe core to the Board, when the power of the prototype would be closer to 600 MWe, has made the identification of innovations that could be tested on Astrid rather unclear. This ambiguity must be quickly removed.

[24] Shielded process chain.

[25] Global Actinide Cycle International Demonstration.

[26] In homogeneous mode, the minor actinides are diluted to a few % in the fuel; in heterogeneous mode, they are contained in the target pins or loaded blankets (CCAM concept), in which the maximum minor actinide content will be 20%).

The R&D on the reactor components and different transmutation options will be at different stages in 2012. The Board notes that certain aspects will not have been covered, such as the transmutation of curium and the multi-recycling of the elements to be transmuted.

The Board considers that the aspect of reprocessing FNR Mox fuel (see §5) is lacking in the Astrid programme. Although the programme takes good account of the production of driver fuel and transmutation targets, it does not tackle the question of reprocessing, which will be necessary for closing a cycle in an FNR of Astrid's size.

Indeed, the reprocessing of FNR Mox fuel will result in actinide flows that are not in the same quantities as the hundreds of kilograms handled every year at La Hague. The problem of criticality risks will become more acute with a Mox that is richer in plutonium. In this respect, we should note that the current plants at La Hague operate with equipment geometries that were not designed for this process, hence the importance of a pilot project, designed specifically to reprocess this type of fuel.

The Board recommends that as part of the Astrid programme, as it is currently presented, a pilot scheme be developed for Mox fuel reprocessing, to ensure that the upstream-downstream cycle characteristic of multi-recycling is completed in due time, namely a few years after Astrid.

2.4. NUCLEAR PLANT DEVELOPMENT SCENARIOS AND THEIR CONSEQUENCES

2.4.1. Role of the scenarios in R&D projects

The Board has stressed on several occasions the importance that it assigns to the following two questions:

- Would the transmutation of minor actinides enable us to reduce the footprint of an underground disposal site for HAVL and MAVL waste and, if so, to what extent?
- Would the transmutation of minor actinides enable the nuclear materials to be managed in such a way as to reduce their stock and inventory in the fuel cycle?

A technico-economic and scenario workgroup (GT-TES), established in 2007 and comprising members from the CEA, EDF and Areva, is analysing the possible technical and economic consequences of the transmutation of minor actinides. The scenarios assume the deployment of a set of sodium-cooled FNRs from 2040 and provide support for R&D. They are not based on industrial decisions: the only industrial assumption they rely on is the replacement of half of the current reactors with EPRs. They are built on the technical concepts of the moment, even though the time frames normally associated with nuclear power are sufficiently long for significant progress to be made before the considered deadlines.

So far, the GT-TES has taken the assumption that the current reactors will be replaced while maintaining a constant total capacity, producing 430 TWh per year with a power of 60 GWe. Two thirds of this power would be deployed with EPRs between 2020 and 2040, and FNRs would add 20 GWe between 2040 and 2050 at a rate of 2 GWe per year. When the first EPRs come to the end of their lives in around 2080, 40 GWe would be commissioned at the same rate, via a second set of FNRs, to provide a 60 GWe group of reactors in 2100, made up entirely of FNRs.

The plutonium needed to supply the first set of FNRs will be separated from the spent fuel from the EPRs and the first FNRs. The second deployment will involve reducing the cooling time for the spent fuel to around 3.5 years, and perhaps even using plutonium produced in any of the fertile blankets from the first FNRs to be commissioned.

Between 2020 and 2100, three successive reprocessing plants would extract the uranium and plutonium, and possibly minor actinides from the spent fuel. The scenarios show that to deploy the fleet of FNRs, these plants must offer a maximum capacity of around 1,100 t/year over a period of at least 55 years (including the transient phases between 2020-2050 and 2080-2100, characterised by a sharp increase in the production of separated minor actinides). When the entire fleet is made up of FNRs, this capacity must be maintained at 500 t/year.

The GT-TES presented a few extreme scenarios to the Board:

- the deployment of reactors without any form of transmutation other than plutonium recycling;
- the deployment of reactors with the transmutation of americium or all minor actinides;
- and finally, the deployment of reactors with transmutation in accelerator-assisted systems.

The GT-TES presented materials reports (plutonium and minor actinides in the cycle and in the waste) for each of these scenarios, and described the consequences for the cycle processes, the operation of the reactors and the costs. Other situations are also being examined. These include the progressive use of transmutation and the resorption of in-process materials when the FNRs are shut down, an increase in installed power, the presence of fertile blankets, sensitivity studies, and assessments of reactor availability, industrial risks and the impact on natural resources. The workgroup promises to deliver a complete report in 2012.

The Board now draws attention to the fact that the production of the entire amount of plutonium needed to deploy the FNRs will be technically difficult, and will require considerable investment.

2.4.2. Main results and findings

Without transmuting minor actinides, a set of FNRs could achieve a balance between the production and destruction of plutonium in around 2100. The reactors would contain a total of 900 t of plutonium. It is estimated that from a century of reprocessing, a total of 7.5 t of plutonium (waste created during reprocessing operations), and 385 t of minor actinides, would need to be contained in a geological disposal facility. If the minor actinides are transmuted, the balance achieved by the reactors will differ depending on the transmutation method (homogeneous or heterogeneous). Compared to multi-recycling plutonium alone, the amount of plutonium in the cycle would be approximately 1,000 t with around one hundred tonnes of minor actinides.

If the transmutation process uses accelerator-assisted systems, and in anticipation of the final report from the Eurotrans integrated European project (see Chapter 3 of this report), transmutation will lead to estimates close to those shown above.

All of the envisaged scenarios confirm a reduction in long-term radiotoxicity. However, the thermal power of the new and spent fuel assemblies increases during the transmutation process, leading to serious heat problems when the assemblies are transported and handled. Difficulties during the assembly production stage are alleviated by not transmuting the curium, which is a very radioactive neutron emitter. Even in this case, reinforced radiation protection equipment and remote operation devices must be used.

In the future, EDF hopes that the scenario-based R&D projects will take into account the pace of an industrial deployment of purely power-generating FNRs, followed by the progressive introduction of transmutation, which EDF hopes to limit to americium. Such an approach would be more progressive and EDF presents it favourably.

Like EDF, Areva would also like to see more realistic scenarios than those currently presented, based on feedback from the mono-recycling of plutonium in PWRs; the studies must enable the careful examination of the changes affecting the plants in the cycle, resulting from the reprocessing of the EPR and FNR Mox fuel. For Areva, the rate of FNR deployment at 2 GWe/year, already seems difficult to maintain.

The Board has already drawn attention to the technical difficulties associated with the use of P&T. The initial data from R&D based on the scenarios highlight the extent of the measures and innovations that will be needed to overcome these problems (reactors, production, handling, transport and fuel processing). They throw serious doubt on certain scenarios (such as curium transmutation and the introduction of accelerator-assisted systems). Generally speaking, the current status of R&D rarely enables us to situate the difficulties associated with a given problem on a technical or financial level.

The Board recommends that the 2012 Dossier completes all of the deployment scenarios, and specifies the duration of the transient phases before the fleet consists entirely of FNRs, together with the associated quantities of available plutonium. It should highlight the most difficult technical points, for both the reactors and the cycle and, finally, clearly explain the advantages of transmutation and its impact on the operation of the power plants. The Board has greatly appreciated the opportunity to hear the initial results from this work.

The initial data show that we already have a considerable stock of depleted uranium produced by the PWR technology. This quantity is much greater than needed for a fleet of FNRs which, moreover, would not lead to the production of depleted uranium.

The Board recommends that each scenario be accompanied by an assessment of the total amount of depleted uranium, so that decisions can be made on its fate.

2.4.3. Economic data

Comparative economic data were presented to the Board by the CEA's I-Tésé Institute, with reference to a set of FNRs that do not transmute minor actinides. The item breakdown based on the price per kWh seems well-established: 37% for reprocessing, 54% for production and 9% remaining for future expenditure (discount factor). The transmutation of minor actinides in the FNRs would increase the first two figures by 100% and 50% respectively. In total, transmutation would increase the cost of a kWh by 10% for FNRs and 20% for accelerator-assisted systems. All of these estimates are surrounded by considerable uncertainty and provide no indication of the costs of managing the waste.

EDF fears that the economic studies only take account of some of the risks and would prefer to see cost ranges and a cost-benefit analysis.

I-Tésé has also presented a quantitative projection of the gross annual expenditure up to 2150. It states that this would reach €500m to €1,000m per year from 2040 for transmutation with a fleet of FNRs, escalating to €4,500m per year in 2100 for transmutation with accelerator-assisted systems for a balanced fleet.

2.5. IMPACT OF PARTITIONING AND TRANSMUTATION ON THE GEOLOGICAL DISPOSAL FOOTPRINT

The scenarios enable us to assess the impact of P&T on the footprint of the disposal of waste from reactors that multi-recycle plutonium and transmute minor actinides. Other aspects of this impact are discussed in Chapter 1 of this report. To estimate the sites' underground footprints and their costs, the CEA and Andra adopted three scenarios (plutonium multi-recycling, the transmutation of americium alone, and the transmutation of all minor actinides, between 2040 and 2150) in which they examined the expected number of canisters and their disposal at one or two facilities, constructed after the site due to open in around 2025, following 70 or 120 years of storage.

The vitrified primary waste canisters (CSD-V[27]) must adhere to two operational limits: the maximum alpha emitter content, and the maximum fission product and actinide content; their number, which is close to 100,000, depends little on the scenarios. The determining parameter for disposal is the heat of these canisters. The production flows differ depending on the phase (transient or balance) but the time sequences are well-established.

The concept of the future disposal facilities is identical to that of the site studied in the Callovo-Oxfordian formation in Meuse/Haute Marne. For the waste from the multi-recycling of plutonium, containing fission products and minor actinides, the durability of the outer container, in which the CSD-Vs are stored, should be doubled to endure the heating phase, which would be longer (2,300 years) than that associated with the waste currently produced (1,000 years). A first disposal facility would be used for the waste from the period 2040-2100 (transition between the current reactors and the fleet of 100% FNRs) and a second site (or extension of the first) would cover the period 2100-2150 (balanced FNR fleet). For each disposal configuration envisaged by Andra, the transmutation of americium or minor actinides would reduce the footprint of the HAVL area by a factor of 2 to 2.5, and the excavated volume by 30 to 40%. Furthermore, the duration of the heating phase would only be 200 years. A long storage period would reduce the footprints (by 60%, for example, for the canisters that only contain fission products). The scenario involving the P&T of minor actinides, and the storage of the glass canisters for 120 years before disposal, would make it possible to achieve the compactness limits of the current geological disposal concept. The costs proportionate to the excavated volumes have not yet been calculated by Andra.

27 Acronym used for standard vitrified waste containers.

The Board notes that the results presented this year on the impact of P&T on disposal provide us with a first set of quantitative elements. R&D must continue on the missing scenarios, using the same methodology, and must better determine the projections by refining the values for the underground footprints. We can already deduce that the benefits of P&T for the footprint of the disposal sites, for a glass canister storage period of 70 years, would be close to a factor of 2, compared with the disposal of waste from a set of FNRs that do not transmute the minor actinides. However, these figures would be more fully illustrated by making a rigorous comparison with the facility envisaged for 2025, for the waste from the current reactors.

The Board particularly recommends pursuing R&D relating to the situations that currently appear to be the most realistic for the fuel cycle (progressive use of the americium transmutation process).

It notes that the heat from the waste is the major constraint to extending the current disposal facility concept, when we examine the maximum compactness compatible with the upper limit of 90°C on the outer surface of the casing in contact with the clay. However, the Board recommends analysing other concepts compatible with the implementation of P&T, such as reducing this heat limit, if it would allow us to reduce the amount of damage to the rock at the cost of a slight increase in the facility's footprint.

2.6. FUEL CYCLE

2.6.1. Reprocessing of mixed oxide fuel

When the FNRs are launched, the French plutonium stock will essentially consist of the spent PWR Mox fuel assemblies stored in the fuel pits. This storage does not pose any problems. If the FNRs are launched in around 2040 as announced, the Mox assemblies will have to be reprocessed from 2035 in the La Hague plant, which is designed for reprocessing UOX assemblies. The Board hoped to obtain information on the possibilities of supplying the first FNRs with plutonium, given the feedback received from within France, and was keen to ensure that the R&D to overcome any difficulties would be in progress or envisaged.

The Board also hoped to be informed of the expected difficulties concerning the reprocessing of the spent FNR Mox fuel assemblies, when we reach the point of multi-recycling the plutonium and minor actinides, if the P&T strategy is implemented.

The reprocessing of the spent PWR Mox fuel assemblies benefits from feedback from several campaigns at La Hague, based on around 60 metric tonnes of fuel. Areva does not envisage any new industrial demonstration campaigns. Provided that the fresh PWR Mox fuel meets certain specifications, which is the case, reprocessing the irradiated fuel will not pose a problem. However, for management and criticality reasons, the Mox fuel can only be reprocessed at half the rate of the UOX assemblies. To comply with the operational limit for incorporating alpha activity in the CSD-V canisters, the solutions to be vitrified must be diluted with other solutions of the same type. The volume of HAVL waste will increase compared to the volume generated from the reprocessing of UOX fuel.

The Board notes that the reprocessing of the spent PWR Mox fuel assemblies could begin at the UP2 800 plant in La Hague, and would not hinder the launch of the first FNRs.

The feedback from the reprocessing of the spent FNR Mox fuel assemblies related to several dozens of metric tonnes, at a rate of a few tonnes per year. This enabled difficulties to be identified. Apart from the shearing of the FNR Mox fuel assemblies, which were very different from the PWR assemblies, these were PWR Mox reprocessing problems, amplified by the higher plutonium, fission product and minor actinide content.

The Board has examined data on the reprocessing of spent FNR Mox fuel assemblies. The feedback from France shows that we could manage all of the reprocessing stages in new plants, although many technological and fundamental questions remain. The Board recommends developing basic studies on the reprocessing of FNR Mox fuel, with a view to preparing the launch of a pilot reprocessing plant associated with Astrid.

2.6.2. Partitioning/conversion for transmutation

The R&D in this domain is progressing well, at both a fundamental level and in terms of the processes (Ganex, Diamex-Sanex and ExAm). Following the dissolution of the spent fuel, Ganex aims to group partition the actinides, from plutonium to curium; Diamex-Sanex separates the neptunium, americium and curium; ExAm extracts only the americium. The co-conversion of the actinides must result in ceramic materials for producing transmutation fuels or targets.

The ExAm process was recently validated by a test on a solution from the Purex process; all of the minor actinide separation processes have therefore now been tested. Certain processes will probably be optimised by 2012. As far as the assessment of the industrial implementation is concerned, unquestionable progress has already been made. The CEA has shown that the delicate operation of the processes downstream of Purex can be managed by taking measurements in real time. This is an important point to consolidate. The test performance predictions based on simulation codes are generally well substantiated by the measurements, showing that the empirical modelling of the processes is correct, and that they can be transposed and optimised in an industrial context. The recycling of solvents is almost finalised. R&D is currently in progress to convert actinide solutions from partitioning into solutions for co-precipitation, to produce the best mixed oxides by co-conversion. The waste management plan is only partly complete at present.

The CEA is planning a test in 2011-2012, using a few kilograms of spent fuel to demonstrate the possibility of sequencing the separation and co-conversion processes, from dissolution to the preparation of mixed oxide uranium and americium pellets. This experiment will test dissolution-clarification, the Coex and ExAm processes, the concentration of the americium solution, the co-precipitation of mixed uranium and americium oxalate, and the calcination-sintering of the oxalate.

The CEA is currently setting aside the plan to obtain direct results from experiments on FNR fuel and multi-recycling, which a pilot reprocessing plant would be able to provide. Only transposition information will be acquired.

The Board notes that the R&D in partitioning and co-conversion is being pursued with the aim of presenting consolidated results in 2012, which will enable the industrialisation options to be assessed based on scientific foundations. It recommends that, as far as possible, R&D should diverge from the hearts of the processes, to remove any question over the management of the reagents and effluents. The Board recommends demonstrating the full nature of the partitioning and co-conversion operations. As far as the processes are concerned, it recommends pursuing, or even intensifying, the R&D on the identification of species found in the two-phase systems and the mechanisms involved. This will reinforce the empirical models and, ultimately, supplement them with more fundamental models to improve the separation predictions.

Chapter 3

OTHER NATIONAL ACTIONS & INTERNATIONAL OVERVIEW

3.1. OTHER NATIONAL ACTIONS

3.1.1. Actions taken by the CNRS in the context of the Pacen programme

- **The Pacen programme (Programme on the downstream part of the cycle and nuclear energy production)**

The Pacen programme at the CNRS coordinates the work of six national research groups (GNRs) and four joint research programmes (PCRs); these are internal CNRS structures created to explore options not covered by the national strategy. This work focuses on R&D in accelerators, the nuclear applications of molten salts, activities in the humanities and social sciences on nuclear energy, and the geology/geochemistry of uranium and thorium. The GNR and PCR activities are very well supported. Current work in the humanities and social sciences covers:

- the use of Germany as a laboratory of new ideas on nuclear energy;
- "nuclear law";
- the characterisation of nuclear materials (geography, law, sociology).

The Board appreciates the efforts made to involve researchers in the humanities and social sciences in the Pacen approach, and welcomes the CNRS's insistence on reminding us of the programme's responsibilities in these fields.

The Gédépéon[28] GNR has provided a record of its participation in the Eurotrans European integrated project, which includes designing the reference accelerator and the spallation target, and involvement in the "Central Design Team" during 2009-2012. The CNRS is committed to a detailed study of the Myrrha research reactor at the SCK-CEN site in Mol. It is designing the line taking the proton beam to the spallation target, and is involved in preparing for the possible start of the Myrrha construction phase, which may occur in 2012-2015. For the Guinevere experiment in Mol, which began in April 2010, the CNRS provided a deuteron accelerator (deuterium nuclei), capable of operating in a pulsing or continuous beam, which is intended to validate the in-line checking method for the reactivity of a subcritical accelerator.

The Board points out that the conclusions from the Eurotrans integrated project, which ended in 2007, have still not been submitted to the European Commission. It regrets this delay, which has demobilised the scientific community. It hopes that the Gédépéon GNR will be able to refocus on critical reactors.

The Matinex[29] GNR is concerned with research on the ceramic materials for future reactors. The preparation and management of the properties of actinide carbides or light elements (Si, Zr, Ti) for gas-cooled reactors, pose the most arduous problems (with regard to the fuel and the plate or pin cladding).

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[28] New options for energy production and waste management.
[29] Innovative materials in extreme conditions.

The Paris[30] GNR is in the very early stages of R&D on the separation of actinides from current, and even future, spent fuel, and the migration of elements in the geosphere. It is interested in the phenomena that occur at the interfaces of various two-phase systems, representative of reprocessing (water channel and molten salt) and disposal in severely damaged argillite. Its objective is to create multi-scale models.

The goal of the Momas[31] GNR, in the context of waste disposal, is to consolidate the mathematical bases of the physical models used, and to propose computer models and methods for simulations and the assessment of their uncertainties. This research group has a very close relationship with Andra (benchmarks); it is taking part in the FP7 framework programme and also contributes to the major calculation codes. Momas has irrevocably demonstrated that a discipline considered to stand relatively far apart from practical realities can make a useful contribution.

The Forpro[32] II GNR has supported Andra's efforts to define a zone of interest for further surveying (ZIRA), by launching fundamental research work in the Earth sciences domain. With a focus on understanding the mechanisms transferring water, gas and solutes through the virtually impermeable formations in the eastern Parisian Basin, this research concentrates on five areas: the geological, hydrogeological and structural history of the area, the source of the water in the impermeable formations, the thermal effects associated with the burial of sediments, the migration of gases in the clay rocks, and the role of bacteria. This work has largely benefited from the deep Triassic drilling carried out by Andra, and has shown that there is no link between the Triassic waters and the carbonated Oxfordian and Dogger formations.

The Board highly values the Forpro II research group's scientific programme and the innovative nature of the analytical approaches taken by the scientific teams. It is disappointed that the academic teams have not been mobilised further to present high quality projects to the National Research Agency (ANR), which would have enabled us to fully benefit, at a fundamental level, from the efforts made by Andra to complete its 2,000m Triassic drilling work and retrieve exceptional material for understanding the geology of the Parisian Basin.

The Trasse[33] GNR, formed in 2008, brings teams from the CNRS and universities together with groups from the IRSN to study the transfer of radionuclides in the ground and bedrock, and into the ecosystems. It has two main focuses: the study of the transfer of radionuclides in the environment from a waste storage trench in the Chernobyl exclusion zone, and the analysis of the containment abilities of the clay formation at the Tournemire experimental station. This second research area takes account of any short circuits that might favour the transfer of radionuclides into the biosphere, resulting from natural discontinuities of tectonic origin, or damage to the rock from tunnel excavations. In addition, the 3D seismic data acquired from the Tournemire region in 2001 was reprocessed to detect small-throw faults in the argillite formation where the experimental station is located.

The R&D work conducted by the Pacen GNRs has very close structural links with the problems faced by those involved in Andra law, the CEA, EDF and Areva, but comes prior to any industrial concerns. The results obtained are generally published in the best scientific journals. This gives resonance to the work conducted according to the two focuses of the law of 2006. The Board believes that this form of collaborative work successfully integrates the complementary aspects of the R&D that needs to be performed. It recommends that the work carried out by the national research groups should continue.

30 Physicochemistry of actinides and radionuclides at interfaces and in solutions.
31 Mathematical models and computer simulations for nuclear waste management problems.
32 Deep geological formations.
33 Transfer of radionuclides in the ground, bedrock and ecosystems.

The Board will carefully monitor the development of the Pacen programme. It does not wish to see Pacen be dissolved into a major energy programme. Indeed, it believes that many specific problems relating to nuclear waste still remain to be examined by the CNRS. The Board encourages CNRS researchers to form even closer links with the other major players in the nuclear industry.

3.1.2. Actions taken by the IRSN at Tournemire

- **The IRSN experimental station at Tournemire**

In response to a request from the OPECST, and at the invitation of the IRSN, a Board delegation visited the Tournemire station on 4 and 5 May 2010, seven years after a previous visit by the CNE1, with a view to updating the Board's knowledge of the experiments conducted there. The choice of R&D projects conducted or coordinated by the IRSN clearly demonstrates the particular position of this organisation in the context of geological disposal. The research aims to reinforce the IRSN's ability to evaluate safety demonstrations for the underground disposal solutions proposed by Andra. The methodological aims of this work are first and foremost on a relatively general level, as in the case of its analyses of natural or artificial discontinuities in the clay massif, or generic studies on the transport mechanisms in the argillites. In addition to this are original development concerns relating to instrumentation and the use of measurements, such as for the interpretation of 3D seismic data, and exploratory studies likely to be relayed by Andra when required, such as migration studies at the concrete/clay or iron/clay interfaces.

The Board believes that the IRSN's methodological position is pertinent. Many common points justify the importance of the studies conducted at Tournemire in parallel with Andra's research, from the perspective of geological disposal in the Meuse/Haute-Marne Cox. However, the argillite massif at Tournemire differs from the Cox argillite in certain essential ways: the tectonic and hydrological contexts, the stresses in the massif, the stiffness and fragility of the rock, the state of fracturing, etc. The results from observations and measurements taken at Tournemire cannot be transposed as they stand for the purpose of the research conducted by Andra or other European organisations at Mol in Belgium and Mont-Terri in Switzerland.

However, provided that the relevance of the results obtained is clearly appreciated in each case, the Tournemire station undoubtedly represents, over and above the benefits drawn by the IRSN and its partners for their own research and training needs, a source of information and knowledge, a reference test bench and a comparison opportunity of great importance to the R&D conducted by Andra and its European counterparts. Shielded from the constraints of a preindustrial installation, and benefiting from particular interesting conditions (the more than secular age of the tunnel excavations, ease of access to the tunnels, direct exposure of the walls without the need to cover them with shotcrete, etc.), the station offers favourable conditions for an in-depth investigation. For example, the analysis of the short-circuit formation processes by the water circulation in Tournemire's system of discontinuities, the determination of detectability thresholds using 2D and 3D seismic data on fault throws in the argillite massif, the study of interactions between iron, concrete and clay, the investigation of fissuring modes or migration mechanisms in the rock, and the analysis of the performance of the cavity sealing processes, can only be beneficial to a better understanding and ability to manage the specific conditions for geological disposal in clay rock formations.

In conclusion, the Board highly values the scientific and technical activity at the Tournemire station. This contributes to the IRSN's assessment abilities and enables mutual information to be exchanged between the IRSN, Andra and European organisations concerned by the geological disposal of radioactive waste. The Board believes that the IRSN teams' participation in the Trasse GNR is a fruitful source of collaboration with the university teams. It notes with interest the IRSN's idea of offering access to the Tournemire station to the European organisations involved, for their training needs.

3.2. INTERNATIONAL OVERVIEW

The broad outline produced last year remains valid, and this year's report only describes the most recent aspects. Moreover, the Board is planning to study the overall situation in China and Korea next year.

3.2.1. International legal context

Radioactive waste management and, by extension, research into waste management, takes place within a national and international legal context.

The European Commission formed the High Level Group on Nuclear Safety and Waste Management (ENSREG) in 2007. One of its duties is to prepare new European rules for the safety of nuclear facilities and the management of spent fuel and waste.

- **Euratom Treaty, Article 37**

Article 37 of the Euratom Treaty specifies that *"Each Member State shall provide the Commission with such general data relating to any plan for the disposal of radioactive waste in whatever form as will make it possible to determine whether the implementation of such plan is liable to result in the radioactive contamination of the water, soil or airspace of another Member State"*.

- **Directive EC/97/11**

This Directive of 3 March 1997 modifies Directive 85/337/EEC concerning the assessment of the effects of certain public and private projects on the environment. The Directive is the transcription of the Espoo convention into European law. It requires that "*Member States shall adopt all measures necessary to ensure that, before consent is given, projects likely to have significant effects on the environment by virtue, inter alia, of their nature, size or location are made subject to a requirement for development consent and an assessment with regard to their effects."*

- **Resolution EC/17438/1/08**[34]

In order to continuously improve the safety of radioactive waste management within the European Union, the resolution aims to:

- establish, for each Member State, a national plan for the management of spent fuel and radioactive waste, which is accessible to the public and must include an inventory of financial arrangements or a regulatory framework;

[34] European Union Council Resolution on the management of spent fuel and radioactive waste, 16 December 2008, 17438/1/08.

- ❖ implement waste management policies in a transparent way and involve the public, particularly concerning decisions on the construction of a disposal facility;
- ❖ reinforce the use of peer reviews.

3.2.2. Research laboratories or underground disposal facilities

In Europe, the main research concerning geological disposal is 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.

Finland and Sweden have opted for granite. The disposal concepts are very similar; however, the laboratory being constructed in Finland will eventually become part of the disposal centre, whereas the one in Sweden will not. In Belgium, France and Switzerland, the preferred host layer is clay. Spain has examined all three options, but is currently focusing on long-term storage. In the United States, a disposal centre for military-generated long-lived, medium-level waste has been established in a salt layer. Known as the Department of Energy's Waste Isolation Pilot Plant (WIPP), this has been in operation since 1999.

- **Belgium**

A large-scale thermo-hydro-mechanical and chemical experiment, Praclay, is in its final installation phase. Its purpose is to simulate the heat field around a tunnel for burying high-level waste. To this end, a tunnel designed to meet the needs of the Belgian disposal concept has been excavated. A 30m stretch of the tunnel will be heated for 10 years at 80°C.

As part of the European Forge project, an experimental device measuring 40cm in diameter will be installed in the laboratory to study the effect of stresses *in situ* on the flow of the gases. In addition to this experiment is a major surface-level laboratory research programme, involving modelling.

- **United States**

For more than two decades, Yucca Mountain in Nevada has been the main site studied for the disposal of HAVL waste in the United States. In 2002, the Yucca Mountain Development Act was approved by US Congress and signed by the President. Yucca Mountain therefore became the site officially proposed for a disposal facility. In June 2008, the Department of Energy (US-DOE) submitted a licence request for the site to the competent authorities (Nuclear Regulatory Commission, NRC). However, the budget allocated to the project was drastically reduced by the new administration. The licence request was withdrawn in March 2010 and the administration created a new, high-level committee to propose alternatives to the project.

- **Finland**

During the last few years, the Finnish spent fuel management organisation, Posiva Oy, has submitted several requests for "*decisions in principle*" on the construction of a spent fuel disposal site. The organisation is planning to request a construction licence for disposal tunnels beyond the laboratory in 2012.

- **Japan**

Two methodological research laboratories are currently under construction, one in Mizunami in crystalline rock, and one in Horonobe in sedimentary rock. At the Mizunami laboratory, excavations have reached a depth of 400m and studies concerning the hydrology and mechanics of the rock are continuing. At the Horonobe laboratory, hydrological tests and hydrochemical measurements are continuing. The damaged mini-zone (EDZ) is being studied around a tunnel at a depth of 140m. An *in situ* test using shotcrete with an HFSC (High Fly ash Silica fume Cement) with low alkalinity has proved to be very promising.

The Japanese organisation for the management of radioactive waste, Numo, is responsible for developing a disposal site for HAVL waste. A site will be selected in three phases: a preliminary investigation zone, detailed investigation zones, and a construction zone. Numo invited applications in 2002, but to date, its request has been unsuccessful. If any proposals are received, Numo will conduct a bibliographic study on the volcanic activity, faults and other geological characteristics. In the meantime, Numo is continuing to approach various municipalities likely to volunteer for these preliminary studies.

- **Sweden**

Since the mid-1970s, SKB has been acquiring knowledge of the Swedish bedrock. This knowledge forms the basis of work on the safety and environmental impact of a spent fuel disposal site. During the 1990s, preliminary studies took place in eight municipalities. These were completed in 2002, following decisions by the Oskarshamn and Östhammar municipalities to authorise studies on the construction of disposal sites on their land. Investigations began in the same year, and in mid-2009 the Forsmark site in Östhammar was selected by SKB. At the end of 2010, SKB is due to submit an authorisation request for the construction of the facility, in accordance with the legal regulations set out in the Swedish Act on Nuclear Activities. At the same time, it will request authorisation for the containment plant and final disposal facility, all within the framework of the Swedish environmental code. The facility is expected to be operational in 2025.

3.2.3. International R&D in deep geological disposal

- **CATCLAY**[35]: Following results from the FUNMIG project, CatClay is aiming to solve the problem of the migration of cations in the argillite. For certain cations, the experiments have shown a diffusion over a greater distance than expected. A scientific explanation is essential for the safety studies on the concepts of disposal in clay.

- **IGD-TP**[36]: The IGD-TP European technological platform for the geological disposal of nuclear waste is the culmination of work that began during the 6th Framework Programme, conducted by radioactive waste management organisations in Sweden, Finland and France, in collaboration with the German Federal Ministry of the Economy and Technology. A policy document describes the platform's objectives and organisation. It also summarises the technical measures to be applied during the next 10-15 years in order for the Member States to implement geological disposal. IGD-TP is now going to draw up a strategic research agenda, to coordinate the efforts associated with the scientific, technological and sociopolitical challenges relating to geological disposal.

- **MODERN**[37]: This project aims to provide a reference describing the technical objectives, resources and methods for designing a monitoring system for the different disposal phases, while respecting the needs and constraints specific to each country.

- **NWD**[38]: The aim of this project is to provide data from experiments and calculation results, to help our general understanding of the long-term behaviour of high-level waste from current and future fuel cycles.

- **PEBS**[39]: 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 initial conditions (high temperature, resaturation of the barrier) up to the thermal balance and the resaturation of the host medium.

[35] 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.
[36] 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).
[37] A joint EC/NEA EBS project synthesis report; 2008-2009, FP7 and NEA.
[38] Nuclear Waste Disposal action, Euratom CCR (Joint Research Centre), 11 countries, 21 partners including the CNRS and CEA.
[39] Long-term Performance of the Engineered Barrier System; 2010-2014, FP7, 8 countries, 17 partners.

- **ERDO workgroup**[40]: 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.

3.2.4. New technologies for partitioning-transmutation

- **ACTINET-I3**[41]: The purpose of this project is to enable the European scientific community to establish a network of infrastructures for actinide research.

- **ANFC**[42]: Alternative fuel cycles based on partitioning-transmutation will be studied and assessed. Methods for the long-term recovery of radionuclides, the optimisation of technologies for the production of innovative fuels, and the characterisation of fuel properties before and after irradiation will also be studied.

- **CP-ESFR**[43]: This project will allow key questions to be studied relating to the development of the European sodium fast reactor (ESFR). Its particular objective is to optimise the safety levels and financial risks. Optimisation studies will be conducted on the cores comprising an oxide fuel or carbide. The production and determination of the physical properties of the minor actinide-bearing fuel will be studied.

- **EUFRAT**[44]: The CCR-IRMM neutron physics unit has a unique infrastructure for the highly accurate measurement of cross sections covering a wide energy spectrum. This project is continuing the work carried out during the Nudame project.

- **FAIRFUELS**[45]: The aim of this project is to optimise the management of fissile material (fuels and targets), to reduce the volume and potential danger of HAVL 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.

- **GUINEVERE**[46]: In March 2010, the Guinevere reactor was opened at SCK•CEN (Mol). Guinevere is a fast research reactor, driven by a very low powered accelerator (ADS) of only a few hundred Watts, and a precursor to MYRRHA. The reactor is the fruit of collaboration between the SCK•CEN, CEA and CNRS, within the framework of the Eurotrans project. The Génépi-C accelerator was built by the CNRS in Grenoble, and the fuel was supplied by the CEA.

- **JHR-CP**[47]: 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**[48]: 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.

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40 European Repository Development Organisation, with representatives from Austria, Bulgaria, the Czech Republic, Denmark, Estonia, Ireland, Italy, Latvia, the Netherlands, Poland, Romania, Slovakia and Slovenia.
41 Actinet Integrated Infrastructure Initiative, FP7, 5 countries, 7 partners including the CNRS, LGI and CEA.
42 Alternative Nuclear Fuel Cycles; 2010-..., FP7, 6 countries, 14 partners including the CEA.
43 Collaborative project on the European sodium fast reactor; 2009-2012, FP7, 10 countries, 25 partners including the CEA, Areva NP, IRSN and EDF.
44 European facility for innovative reactor and transmutation neutron data; 2008-2012, FP7, CE-CCR.
45 Fabrication, irradiation and reprocessing of fuels and targets for transmutation; 2009-2013, FP7, 6 countries, 10 partners including the CEA and Lagrange-LCI.
46 Guinevere: Generator of Uninterrupted Intense Neutrons at the lead Venus Reactor; 2006-..., collaboration with the CEA and CNRS.
47 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.
48 Lead-cooled European Advanced Demonstration Reactor; 2010-2012; FP7, 12 countries and 17 partners including the CEA.

- **MYRRHA**[49]: 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. As a flexible, fast spectrum irradiation tool, this will offer the fast reactor communities (SFRs, LFRs and GFRs) a machine for testing materials and fuels, which will be essential to their development. Its expected applications include:

  - the study and development of technology for the transmutation of minor actinides;
  - the development of materials and the testing of components irradiated by fast neutrons, for advanced fission and fusion reactors;
  - the provision of researchers to study a high-energy, high-power particle accelerator;
  - the training of young scientists and technicians.

Following a study of the Myrrha project by the NEA, the Belgian government has decided to support this SCK•CEN project. A first phase will be devoted to safety studies, advanced design work to allow calls for tender to be produced, and the creation of an international consortium.

- **NURISP**[50]: 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.

- **THINS**[51]: This project will design and conduct thermo-hydraulic experiments in support of different innovative liquid metal-based systems.

3.2.5. Sources of fast irradiation

- **Japan**

Monju was reactivated in May 2010.

3.2.6. Nuclear databases

- **FAR**[52]: The purpose of this project is to make basic and applied knowledge available in the field of nuclear materials and fuels, and become a reference centre for the CCRs (Joint Research Centres) in these domains.

- **ND-MINWASTE**[53]: This project aims to generate results from experiments for assessing the safety of current and future reactors, spent fuel and radioactive waste management.

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[49] Multipurpose Hybrid Research Reactor for High-tech Applications; 1998-?, collaboration with the Eurotrans partners, including the CNRS, CEA, Areva, Advanced Accelerator Applications and ENEN.

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

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

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

[53] 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.

3.3. ECONOMIC AND GEOPOLITICAL ASPECTS

The finance mechanisms for the management of high-level radioactive waste, spent fuels and the dismantling of nuclear facilities, are gradually being put into place. Electricity suppliers in Sweden, Finland and the United Kingdom are building up financial resources to contribute to funds managed by the State. Companies in Belgium, Canada and Spain are doing the same. Switzerland has adopted an equivalent system, but has two different funds: one for managing high-level waste and spent fuels, and the other for dismantling the facilities.

- **ARCAS**[54]: A technico-economic study of the performance of critical and subcritical systems, as machines dedicated to the transmutation of radioactive waste, will be conducted in a dual-layer approach.

3.4. EDUCATION, TRAINING AND KNOWLEDGE MANAGEMENT

- **HeLiMnet**[55]: The goal of this project, which follows on from the Vella project, is to enable the exchange of researchers between laboratories with an infrastructure for studying liquid metals such as sodium and lead.

- **PETRUS II**[56]: This project enables European professionals, active in the field of radioactive waste management, irrespective of their initial training, to attend a course on geological disposal, which would be widely recognised in Europe.

- **KTE**[57]: This project aims to maintain and further knowledge in the field of nuclear research. Training will be offered to young students and researchers through courses in laboratories participating in the project and seminars.

[54] ADS and fast reactor comparison study in support of the SNETP's SRA; 2010-2012, FP7, 8 countries and 14 partners.
[55] Heavy Liquid Metal network; 2010-..., FP7, 9 countries and 13 partners including the CEA.
[56] 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.
[57] Knowledge Management, Training and Education; 2007-..., FP7, Karlsruhe CCR (Joint Research Centre).

Appendix I

MEMBERS OF THE NATIONAL ASSESSMENT BOARD
JUNE 2010

Bernard Tissot - Honorary Chairman of the Institut Français du Pétrole - Member of the Académie des sciences – Member of the Académie des technologies - President of the National Assessment Board.

Pierre Berest – Research Director at the Ecole Polytechnique.

Frank Deconinck – Professor at Vrije Universiteit Brussel - President of the Nuclear Research Centre in Mol, Belgium.

Hubert Doubre – Professor Emeritus at the University of Paris XI-Orsay.

Jean-Claude Duplessy - Research Director Emeritus at the CNRS.

Robert Guillaumont – Honorary Professor at the University of Paris XI-Orsay - Member of the Académie des sciences - Member of the Académie des technologies.

Philippe d'Iribarne – Director of Research at the CNRS.

Maurice Laurent – Honorary Director of the OPECST (Parliamentary office for assessing scientific and technological choices).

Emmanuel Ledoux – Director of Research at the Ecole des mines de Paris.

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

Claes Thegerström – President of SKB (Swedish company tasked with managing nuclear waste and fuel).

André Zaoui – Associate member of the Académie des sciences – Member of the Académie des technologies.

Appendix II

ANDRA, CEA AND CNRS HEARINGS

16 December 2009:	Andra – Inventory and reversibility.
17 December 2009:	CEA – The Astrid prototype.
06 January 2010:	CEA - Irradiation programmes for transmutation.
07 January 2010:	Andra – HAVL and MAVL cavities.
10 February 2010:	Andra – Transfer.
11 February 2010:	CEA – Mox fuel recycling.
17 February 2010:	CEA – Partitioning research (half day).
17 February 2010:	CNRS – Results on the National Research Groups (half day).
18 February 2010:	Andra – Observation, monitoring and disposal costs.
24 March 2009:	CEA – Study of scenarios, impact of partitioning/transmutation on disposal.

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15 October 2009:	Andra – Geological analysis leading to the definition of the ZIRA – Opinions and constraints expressed locally.
26 October 2009:	Presentation of CNE Report no. 3 to the CLIS (local information and monitoring council).
24 November 2009:	CEA – The CEA's programmes.
25-26 March 2010:	Andra – Experimental programme and demonstrators in the underground laboratory, ETe technological area and ZIRA.

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VISITS BY THE CNE2

12 to 16 April 2010:	Visit to the SKB facilities in Sweden.
4 and 5 May 2010:	Visit to the IRSN's underground laboratory at Tournemire.

Appendix III

LIST OF DOCUMENTS SUBMITTED BY ANDRA AND CEA

Andra

- Annual report: sustainable development report and activity report – 2008.
- Steel casing design for high-level waste cavities – Sensitivity study – May 2008.
- Preliminary analysis of the operation and phenomenological development of installations/the storage concept – April 2008.
- Reversibility and the social sciences – Proceedings from the research day on 2 October 2008.
- Inventory pack 2009 – Geographical inventory – Family description catalogue – Synthesis report – Summary – 2009.
- National inventory of radioactive materials and waste – Andra – 2009.
- Phenomenological analysis of disposal situations (APSS) – Objective and methodology (reference C.DO.AHVL.00.138/E) – 16 January 2009.
- The state of calculation tools at Andra for phenomenological and performance/safety assessments– (reference C.NT.AEAP.09.0012/A) – June 2009.
- The HA-MAVL project – Simulation programme – Summary of hydrogeological models (C.NT.ASMG.09.0015/A) – June 2009.
- Documentation plan for the 2009 HA-MAVL Milestone – 30 June 2009.
- Summary of the transposition zone survey programme 2007-2008 – Meuse/Haute-Marne Centre – D.RP.ALS.08.1356 – 21 July 2009.
- Provisional version of the Meuse/Haute-Marne site's reference system – 2009 Milestone – 28 August 2009.
- HA-MAVL project – 2009 Report – Design options studied – Detailed report on the performance assessments with regard to the Post-Closure Safety Criterion (SAF) – September 2009.
- DVD containing basic data from the 2007-2008 transposition zone survey – 28 September 2009.
- Phenomenological analysis of disposal situations (APSS) during operation – Update for the selection of options (reference C.NT.AEAP.09.0014/A).
- Safety elements for the selection of potential zones for the installation of nuclear surface facilities – 21 October 2009.
- Deep reversible disposal – suggested zone of interest for further surveying and surface installation scenarios.
- Opinions from Andra's scientific council on the 2009 Report – Elements supporting the choice of ZIRA and ZIIS – HAVL project – 26 November 2009.

- ZIIS/ZIRA circuit – visit handbook – 30 November 2009.
- 2009 Report CD - submitted to the CNE on 7 January 2010.
- International monitoring document for projects – HA-MAVL – and for the situation of irradiated graphites (reference INT.RP.ADAI.0.0002/A).
- Andra report D.NT.ASG; 10.0013/a – Transposition Zone Survey Campaign, assessment of the geothermal potential of the Triassic – 1 February 2010.
- Opinions of the associate consultant - D.NT.OCFG.090001/A 6 – Triassic investigations and EST433 drilling.
- CLIS report – meeting of 27 November 2007.
- HA-MAVL project – Scientific activities – 2009 Assessment.
- Deep disposal site installation plan – Validation of the restricted area proposed by Andra - 26 March 2010.
- Progress of the FAVL project – March 2010.

CEA

- Summary of the concepts of reactors with loop coolant systems - 2009.
- Summary of the concepts of reactors with integrated coolant systems - 2009.
- SFRs – Summary report on other innovative FNR-Na concepts - CEA - 2009.
- Summary of the effect of the level of power and modularity - 2009.
- Summary of fuel handling - 2009.
- Summary of the FNR-Na core and assembly – 2009.
- Three-part summary of safety and serious accident research - 2009.
- Three-part summary of the potential of using 99% CR as a structural material – CEA - 2009.
- Three-part summary of the materials reinforced by ODS oxide dispersion for FNR-Na cladding – CEA - 2009.
- Three-part summary of in-service inspection and repair (ISI&R) - 2009.
- Preliminary analysis to guide the choice of the power capacity of the future French Sodium Fast Reactor prototype – G. Mignot, M.S. Chenaud, N. Devictor, L. Paret, G. Rodriguez, P. Dubuisson, P. Dufour, J. Rouault 6 – Proceedings of ICAPP '10 - San Diego, CA, USA, June 13-17, 2010.
- Conclusions report of the CEA Visiting Committee – Fundamental Research in Chemistry at CEA – April 27-29, 2009.
- Innovative core design for generation IV sodium-cooled fast reactors – L. Buiron, P. Dufour, G. Rimpault, G. Prulhiere, C. Thevenot, J. Tommasi, F. Varaine, A. Zaetta - Proceedings of ICAPP 2007, Nice, May 13-18, 2007.
- Report on partitioning-transmutation research - Presentation of international programmes.

- Technical report – ECRIX-H experiment – Summary of post-irradiation analyses and simulations – CEA – March 2010.

- The CEA's radioactive waste management strategy – CNE Report of 6 April 2010 – Extract from the Permanent Group of Waste Experts summary report, distributed to the ASN on 31 March 2010.

- Report on the asphalt-coated drums stored at Marcoule – April 2010.

- Report on the ExAm process test at Atalante: preliminary findings.

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