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SUMMARY AND CONCLUSIONS

The two parts of the study and research programme on nuclear waste management are at different stages of maturity. Feasibility studies on the underground disposal of LLHL[1] and LLIL[2] waste are sufficiently well advanced for this method to have been included in the law of 28 June 2006; it now incorporates very specific details of the operation of the disposal site, particularly mining engineering, which is the subject of a new research plan. The partitioning/transmutation method will require considerably more studies before its feasibility can be proven and a judgment can be made about its advantages.

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The programme of scientific research into geological disposal is being well organised by Andra so as to complement the work already done. The Board is waiting for additional data to be presented for the year 2008-2009. This information concerns the delayed deformation of the clay mass, the desaturation of mudstone, the production of hydrogen through corrosion, the formation of the damaged zone, whether or not it is possible to seal it, and the migration of radionuclides. Several of the questions asked on these subjects by the Board (CNE1 and CNE2) in the past have not been answered. While the Board appreciates the quality of the experimental work that has been carried out, it encourages Andra to utilise this research more effectively by pursuing efforts to model the results obtained.

Mining engineering is, rightly, becoming an increasingly important part of the LLHL project. The Board takes a favourable view of the re-examination of certain basic choices, particularly the way in which shafts and tunnels are dug, the layout of shafts and the underground transport of heavy goods. It would like Andra to explain clearly the reasoning behind its choices if it were to change certain options, such as that concerning access by shaft or inclined drift.

When the different engineering options have been specified, debate could extend, as Andra has already considered, to the twin issues of reversibility and safety, as well as the cost of the various envisageable reversibility options.

The key challenge for 2009 is to determine a zone of interest for further surveying, where qualification work will be undertaken on a possible disposal site. The initial results of the ongoing campaign correlate closely with the current geological reference framework. We can expect that the objective for the 2009 milestone will be met. The Board will take care to ensure that geological quality is a decisive factor in the choices made.

Two special waste situations require in-depth consideration: old LLIL waste and long-lived low-level (LLLL) waste, which comprises two main families – radiferous waste and graphite waste. These different types of waste do not necessarily require the same disposal concept or site

The generic studies carried out by Andra show that radiferous waste must be capable of being disposed of in safe conditions in a sub-surface site.

The major problem is the disposal of graphite waste, due to their Chlorine 36 content (a radionuclide with a half-life of 300,000 years, which is highly mobile in its environment). A site must be found that is capable of containing Chlorine-36 and maintains its performance levels for

[1] Long-lived high-level waste.

[2] Long-lived intermediate-level waste.

approximately one million years, despite erosion. A specific site must now be studied to assess its suitability and its radiological capacity. The generic studies show that it is necessary to find a clay formation with a sufficient hectometric thickness, which enables structures to be installed at a sufficient hectometric depth.

Bearing in mind these constraints, the Board recommends conducting a parallel study on the consequences and additional cost of disposing of graphite waste in the LLHL and LLIL disposal sites.

The diversity of ‘old LLIL’ waste poses an issue with regard to responsibility. The Board has no questions about the waste encapsulation technology but believes that it is necessary, for LLIL packages other than those retreated using the current process, to specify how the decision chain works that leads from encapsulation to disposal, and which participants are involved: producers, Andra, public authorities, etc. It would appear to be desirable to seek to optimise management based on technological and financial considerations, something which does not appear to have been done as yet.

More generally, the Board would point out that, for each end object destined for geological disposal, it is necessary to have an inventory of its contents and precise specifications concerning its encapsulation, as well as tests to check that the object meets these specifications.

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The socio-economic dimension must not be underestimated. The Board finds the work that has been done in this area insufficient.

A nuclear waste management site should be treated as a real industrial facility, where all external costs – positive and negative – are taken into account.

An underground disposal centre is designed to have no impact on health. Nevertheless, in order to address the legitimate concerns of local populations, epidemiological studies, based on long and rigorous data series, are necessary. To study a particular zone, it is necessary to have access to data for a much wider territory. The Board therefore recommends that all departments that do not currently keep one should immediately establish a register of pathologies related to the natural or industrial environment. Such a register will be useful in all fields of public health.

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In the field of partitioning and transmutation, studies and research are being pursued in the context of the development of fourth-generation reactors and with a view to industrialisation. The Board considers that the prototype sodium-cooled Fast Neutron Reactor (FNR) is an important element of this strategy.

There are various possible ways to achieve the partitioning and transmutation objectives. The Board considers that, by 2012, the knowledge truly necessary to make decisions should be defined, together with a set of minimum specifications for viable partitioning and transmutation. In addition, an informed view of the advantages and disadvantages of partitioning and transmutation, as well as the real short- and long-term industrial commitments to which it leads, must be established.

The Board considers that research on hydrochemical partitioning has already given rise to considerable knowledge and experience feedback and could reach maturity by 2012. There is little chance of other new, viable methods being turned into industrialisable processes between now and then. Pyrochemistry research is particularly suitable for the treatment of fuels with a very high level of minor actinides, but will not result in an industrialisable process by 2012.

Considerable progress made in the conversion of partitioned products will make it possible to prepare samples for transmutation tests on schedule.

The new avenues of minor actinide transmutation research made possible by FNRs indicate that recycling of transuranium elements is theoretically possible without excessive constraints. The Board considers that the ambitious programme on transmutation scenarios should offer the various scientific and socio-economic participants and communities a framework for discussing future nuclear energy production problems and the interdependence between partitioning/transmutation and disposal.

Transmutation research requires FNRs. The overall schedule requires the first significant results to be available by around 2012. Phénix will be shut down at the start of 2009 and the availability of FNRs in Japan and Russia over the next few years would seem to be limited. The Board finds the foreseeable lack of experimentation sites alarming.

ADS[3] research is the subject of a European programme. It is not finished and a three-year extension is being requested.

The Board considers that structural materials are a key factor in the feasibility of Generation IV nuclear systems. The studies necessary to define, test, optimise, produce and implement these materials will be considerable, difficult and time-consuming. This is a very difficult point. In particular, innovative steels will be essential if a prototype sodium-cooled FNR is to live up to expectations. The Board would like to stress the need to mobilise and build a considerable skills base and to have comprehensive feedback on lessons learned on Phénix and Superphénix.

The number and scope of the problems to be solved in the area of partitioning and transmutation fully justify the establishment of an order of priorities in these diverse fields of research.

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

FOREWORD

The law of 28 June 2006 confirmed that the second National Assessment Board (CNE2) would take on all of the roles and responsibilities of the first Board (CNE1), as defined in the 1991 law:

- Annually assess the progress and quality of research on the management of long-lived high-level radioactive waste;
- Submit an annual report to Parliament, and inform it of any research carried out abroad.

The law of 28 June 2006 extended the remit of CNE2, conferring upon it a number of additional duties:

- The assessments must concern the sustainable management of radioactive materials and waste;
- The assessments must be made with reference to the guidelines set out in the 'National Plan for the management of radioactive materials and waste' (PNGMDR), which has broadened the scope of subjects to be studied;
- The law, its implementing decree and the PNGMDR establish a precise schedule for all the decisions to be taken; this schedule is therefore imposed upon CNE2, which must take it into account in the organisation of its work;
- Changes in the process for appointment of CNE2 members reflect the fact that assessments must include economic and social research.

The period from July 2007 to June 2008, which is the subject of this report, is the first full year for CNE2.

Over the course of 14 hearings, each lasting a full day, as well as a number of complementary meetings, the twelve members of the Board[4] (CNE2), all volunteers, have heard 96 people, principally from Andra, the CEA and the CNRS. These hearings, which generally involved around fifty people each, were also attended by representatives of the ASN, Areva, EDF, the IRSN and the central government.

The members of the Board travelled to the Meuse/Haute Marne site, where they spent two days visiting the underground laboratory and hearing Andra scientists and engineers. They also visited the Andra presentation area in Limay (Yvelines), where full-scale technology demonstrators are on display pending their transfer to a dedicated centre in Meuse/Haute-Marne.

The Board held a meeting with the French Nuclear Safety Authority (ASN).

In order to prepare this report, the Board held seven internal meetings, including a five-day residential seminar.

The scope of the Board's assessment of studies and research on waste management has been expanded considerably, but it remains focussed on long-lived waste, storage, geological disposal and partitioning and transmutation of actinides.

[4] See List of members in appendix I.

In addition, by setting out a precise schedule, the law of 28 June 2006 requires the Board to prioritise issues and distinguish between studies and research affecting short-term, and sometimes very short-term, decision-making (disposal and storage) and those that will extend over several decades and whose completion remains hypothetical for the moment (partitioning and transmutation).

The Board's limited resources (12 voluntary members and one scientific adviser) have led it to make choices, opting this year not to examine studies and research on waste containing tritium, sealed sources, waste with high natural radioactivity and mine tailings.

The Board is aware that the radiation protection problems associated with waste management worry the public, be it the potential effects of stored or disposed waste on health, or their use for illicit ends. It has focussed its efforts on matters specific to the material and waste management methods currently used, which implicitly include the protection of workers and the general public. Research into non-proliferating waste management methods essentially concerns the monitoring and control of the fuel cycle, including spent fuel and waste. The Board pays attention to these problems in its deliberations.

In this report, the Board assesses the studies and research conducted since 2006 in several key areas in order to meet the objectives set by the law. This study and research work will be continued over the next few years. The Board is formulating recommendations about it and from next year it will turn its attention to monitoring.

A list of the subjects of the hearings is given in Appendix II. A list of the documents received by the Board is given in Appendix III. In order to obtain additional information, some of the Board's members took part in international conferences.

The 2006 law sets out a schedule of decisions to be taken between now and 2015, which in the nuclear field is a very short timescale. It is therefore incumbent upon the Board to assess whether the current state of studies and research is such that it will be possible for reports to be submitted in accordance with the deadlines set by law.

During the current year, particular attention has been paid to the following five issues (although other issues have also been considered):

1. **Location of an underground disposal facility for LLHL[5] and LLIL waste[6]**

   The aim of the studies and research in progress is to submit an application, by 2015, for authorisation to create a disposal facility. There are therefore only five or six years remaining to complete this research and obtain results and conclusions that can be presented to the supervisory authorities and the populations concerned. According to Andra, three stages must be successfully completed in order to meet this deadline:

   - In 2009: marking-out of a zone of interest for further surveying[7] (Zira), measuring approximately 30 km^2,
   - In 2013: presentation of a report that will serve as a basis for public debate;
   - In 2014, preparation of the application for authorisation to create the disposal facility.

2. **Creation of a disposal facility for graphite waste and radiferous waste:**

   According to the 2006 law, disposal solutions must be developed so that a disposal facility can be opened in 2013. There are therefore five years remaining in which to find technical solutions, validate them, select a site, get it accepted and finally build the facilities. In its previous report, the Board stressed that it would be extremely difficult to meet this deadline.

3. **Current storage and encapsulation of waste:**

   According to the 2006 law, new storage facilities should be created, or the existing ones modified, in 2015. This issue may appear less urgent than the two previous ones. However, the Board must take an interest in the studies and research on the subject, as they concern the encapsulation of waste, particularly old waste, in connection with disposal containers. The impact on the storage and disposal facilities depends on this work.

4. **2012 choices on partitioning and transmutation:**

   The law of June 2006 sets the target date for commissioning of a prototype fast neutron reactor as 2020, based on choices to be made in 2012. 2012 is also the year when the industrial outlook for the nuclear cycle associated with partitioning and transmutation will be assessed. The law establishes a strong link between studies and research into partitioning/transmutation, and those on new generations of fast neutron reactors. In this context, the Board must examine the quality and overall coherence of the studies and research underlying the choices, paying particular attention to international developments.

5. **Socio-economic dimension of disposal:**

   A site for the reversible disposal of nuclear waste is an industrial facility which will have positive and negative consequences on the well-being of local populations, depending on the options selected. All of these consequences must be thoroughly evaluated, with particular attention paid to the environment.

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[5] Long-lived, high-level waste.

[6] Long-lived, intermediate-level waste.

[7] The ‘restricted zone of interest’, as defined in the law, has been renamed by Andra as a ‘zone of interest for further surveying’ or ‘Zira’. This is the term used in this report.

Chapter 1

SOCIO-ECONOMIC ISSUES

In its 2007 report, the Board drew the attention of the public authority to socio-economic issues.

1.1. ECONOMIC ASPECTS

Andra, the CEA and the CNRS have presented the socio-economic studies currently being pursued in the nuclear field, particularly in the downstream part of the cycle.

Andra has indicated that its aim is to get the public, both nationally and locally, to understand the challenge of radioactive waste management. To do this, it must explain the scientific and technical issues, without underestimating the socio-economic dimension. A disposal site must be presented as what it really is – an industrial facility. For Andra, it is important to place the emphasis on the macro-economic consequences in terms of jobs created or taxes levied, but without underestimating certain externalities with positive and negative short- and long-term effects.

The CEA has presented the socio-economic studies currently being pursued at the *Institut de technico-économie des systèmes énergétiques* (I-tésé). The aim of this body is to bring together in a single place all its skills in the technical and economic evaluation of nuclear systems and other systems. The CEA has presented the assessment criteria, which take into account direct and indirect costs (externalities) as well as the Institute's contacts with various research centres across France. A presentation of the nuclear kWh cost calculation was made, with a focus on the downstream part of the cycle, particularly dismantling costs and the cost of waste management in a geological disposal facility. A comparison has also been made with the studies conducted at other research centres (particularly MIT[8]). One of the questions being asked by the Institute is how two apparently very different approaches can be reconciled: the liberal approach, where investment choices are left to industrial operators, and the public-minded approach, where the role of politicians is to ensure that the general public interest is respected. The CEA presented the case of the Meuse/Haute-Marne site, emphasising the planned economic support measures; it also presented various studies on the future of coal, which is considered as nuclear energy's main competitor in worldwide electricity generation.

The CNRS, too, stated that socio-economic studies have been conducted by various teams, particularly with regard to the social acceptability of large-scale projects, but such studies remain relatively rare worldwide. In reality, much to the Board's regret, there are very few teams working on these issues.

In the economic field, the Board has identified three major issues: the direct and indirect monetary cost of disposal, the system of provisions made by operators for waste management, and insurance against industrial risks.

8 Massachusetts Institute of Technology.

1.2. SOCIAL SCIENCES AND NUCLEAR WASTE

Why is it that the development of social science research on nuclear waste seems to be running into difficulty?

Generally, approaching a subject from a social sciences perspective leads to consideration of two types of issue:

- The existence of a wide range of stakeholders, each having its own interests and pursuing strategies to defend them, particularly through negotiation with other stakeholders;

- The fact that the way in which situations are experienced brings into play questions of meaning, which are shaped by culture, imagination and myth.

The way in which each of the many schools of thought that exist within the social sciences approaches a clearly defined question, such as nuclear waste, cannot be separated from its overall view of how society functions and the myths about what would make it function better. The debates between schools of thought in social sciences broadly reflect the confrontations we find in society as a whole between such contrasting overall views. Even the way in which one school is distinguished from another is shaped by the world view of the person making the distinction.

We can, however, in relation to nuclear waste, differentiate five approaches, connected to five different visions of society.

Three approaches could be described as positive and militant. They are based on three visions of how we could build a better world:

- Approach (a) holds that the way to build a better world lies in enlightenment, the triumph of reason and the eradication of prejudice; the learned must lead the improvement of society and it is up to them to educate the ignorant masses;

- Approach (b) holds that the way to build a better world is for the dominated to fight against the dominant, who try to exploit the world for their own advantage;

- Approach (c) holds that the way to build a better world is through consultation, listening to one another, dialogue and taking all points of view into account.

Two further approaches could be described as sceptical approaches:

- Approach (d), a rather cynical approach, holds that we are faced with a series of people who are driven solely by their own interests, but who hide behind lofty principles and pretty speeches. It believes that this is true not only of the dominant, but also of those who claim to be the dominated;

- Approach (e), inspired by Pascal, holds that we are faced with a series of people who act in good faith, but whose perception of the world is largely shaped by myth.

Those involved in the social sciences are themselves trapped in the phenomena they describe: that is to say, in the pursuit of power and self-interest, and in imagery that shapes their perceptions. Each of them has a strong tendency in their analysis to select the elements that chime with and support their pre-existing vision of society. The way in which they present the information they have is shaped by their ideology.

Nowadays, we have virtually no scientific debate between the schools of thought inspired by these different approaches - that is to say, debate based on the analysis of observed facts and the discussion of alternative interpretations of these facts.

In respect of nuclear waste, the various approaches mentioned above are present to differing degrees:

- Approach (a) can be seen in the work done by communications consultants, who are interested in finding ways of better informing the public in order that they might develop a more rational attitude to nuclear waste;

- Approach (b) dominates in the document 'Research and Nuclear Waste: An interdisciplinary analysis' published in February 2006. Some researchers criticise the actions of the 'major nuclear operators' (who, they claim, 'take scientists hostage, some willingly, some less so'), and call for the advent of 'technical democracy'. It can also be seen, in a more moderate form, in the presentation made to the Board by a representative of the Pacen programme;

- Approach (c) can be seen in Andra's communication policy. The aim is to foster 'engagement and mutual recognition, allowing local populations to influence the development of the project and play a role in decision making', based on 'interaction with local knowledge, culture and know-how' and 'knowledge-sharing';

- Approach (d) is absent for the moment; it could be useful for nuclear operators to get analysis done from this perspective on the strategies of their opponents and the ways of combating these strategies;

- Approach (e) was taken in the ethnological research project '*French People and Nuclear Waste' conducted in* 2005 (report for the Minister for Industry); the aim was to obtain a better understanding of pre-conceived ideas and imagery surrounding nuclear waste, in the minds both of the man on the street and of experts.

The ideological questions raised by social science research concerning nuclear waste are clear.

The same does not go for questions concerning the types of advances in knowledge that would be useful to help put in place a better waste management policy. Obviously, the answer to these questions depends on the vision of society to which you adhere, and thus what you consider to be a 'better' policy. For example, your view will not be the same if you think, to cite just two extreme positions:

- That the big nuclear operators, assisted by mercenary scientists, are trying to deceive populations to make them buy in to policies that serve their interests;

- Or, on the contrary, that the big nuclear operators, properly informed by scientists with the public interest at heart, devise reasonable policies, and that it is their opponents, and the social science researchers that serve them, whose motivations are dubious (a reaction against the frustrations born out of their perception that society does not accord sufficient weight to their point of view).

Approaches that are based on such conflicting visions of society make it difficult to incorporate different schools of thought in the same research programme.

In nuclear waste, as in all other fields, there is no neutral ground where an ‘objectively’ satisfactory social science research policy could be built.

Perhaps we could make progress by trying to formulate some subjects for research that are narrower than the problem of nuclear waste in general, each time seeking out the researchers likely to be interested by these subjects. These questions could be formulated as follows:

- How much room should be left in a large-scale technological project for locally initiated changes?
- How can the public be provided with information that is clear, complete, accessible and as objective as possible?
- Risk and perception of risk by populations: what can a sociological approach teach us?

Of course, each of the participants in this exercise would probably only participate to serve his/her own interests!

1.3. CONCLUSIONS

The Board considers that:

1. A waste management site must be analysed as an industrial facility and not simply as a disposal site; it is important to take into consideration in economic calculations positive and negative external costs (effects on employment, grants awarded, tax collected, health spending, value of real estate, image of the region in terms of tourism, etc.).

   The Board wishes to have more detailed information about the medium- and long-term cost of the disposal of long-lived high- and intermediate-level waste and its impact on the cost price of the nuclear kWh if externalities are included in the calculation. An international comparison would be welcome.

   The Board wishes to know whether the data provided in the Court of Auditors’ Report of January 2005 have been updated.

2. The potential health impacts are a concern for the public and the socio-economic approach pays little attention to them.

   In any case, and this applies far beyond the bounds of the single issue of radioactive waste management, a key element of a scientific approach would be to keep a register of pathologies that may be linked to the sufferer’s natural or working environment in all French départements*. This would provide long data series on which to perform epidemiological studies when the time comes;*

3. *It is regrettable that so few university teams are working in this socio-economic field; we must encourage them to do so.*

4. *Various economic issues merit initial or deeper study, including:*

- *The investment and operating costs of the disposal site over a long period (cost deviation hypotheses);*
- *The impact of the cost of waste management on the cost price of a kWh (international studies); comparison with the scenario of direct disposal without reprocessing;*
- *The amount, distribution and future of provisions in a context of operator privatisation (risk of the cost being passed on to the taxpayer);*
- *Externalities, including the impact on the environment and health;*
- *Industrial impact on the French economy;*
- *The impact on the trade balance (taking into account the cost of reprocessing foreign fuel).*

The Board would stress that the socio-economic dimension must not be underestimated.

History teaches us that public decisions often depend on emotional considerations linked to an underestimation of social issues. It is therefore important to clearly explain the variables that will play an important role in this field (information and credibility of sources, aversion to risk of the participants concerned, etc.), particularly in the public debate to be held in 2013, as required by law.

Chapter 2

DISPOSAL AND STORAGE

2.1. STUDY AND RESEARCH FRAMEWORK

The law of 28 June 2006 sets out a precise research schedule for Andra. Andra's scientific research programme is based on partnerships with the main French research organisations, an active policy on doctoral theses and post-doctoral research, and six groups of laboratories working on major multi-disciplinary topics. Finally, Andra is taking part in several European projects as part of FPRD6 and in preparation for FPRD7.

The design inventory model (Mid), essential for determining the nature and quantity of the waste to be taken into account in studies and research (E&R), is currently being developed by Andra for the design of disposal facilities and the scoping of storage needs. The version expected at the end of 2009 will be an update of Mid 2005, taking into account changes in the law.

The waste considered is that from the current population of pressurised water reactors (PWR), which comprises 58 units with a service life of 40 years and one EPR that will enter into service in 2012 and is taken into account until 2040; together they will generate 50,300 tonnes of spent fuel. The reference scenario is that in which all of the spent fuel is reprocessed and in which it is supposed that nuclear electricity generation will continue beyond 2040. We also consider a scenario in which operating waste, such as control rods, is included. The interim solution is direct disposal of Mox[9], UOX[10] and Ure[11] assemblies.

In addition, non-reprocessed spent fuel from UNGG reactors, EL4, Célestin reactors, ship propulsion reactors and experimental reactors must be taken into account.

The Board would point out that the request for authorisation to create a disposal site (DAC) will only cover waste for which the draft specifications for disposal acceptance have been prepared by 2014.

2.2. INTERIM STORAGE AND PACKAGES

The function of interim storage is to allow waste packages to be managed in safe conditions between production and disposal. In the case of thermal packages, it also allows supervised cooling. It must be possible to retrieve the packages throughout the storage phase.

The law no longer considers storage as a definitive management method, but provides that studies must be conducted in the field of storage with a view to '*creating new storage facilities or modifying existing facilities in order to meet needs, particularly in terms of capacity and service life, by 2015 at the latest*'. It stipulates that it is the responsibility of Andra '*to conduct, or have conducted, research and studies on storage and geological disposal and to coordinate them' and 'to produce, in accordance with nuclear safety rules, specifications for the disposal of radioactive waste and to give to the competent administrative authorities an opinion on the specifications for the encapsulation of waste'*. This is what motivated Andra, as part of the LLHL

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9 Mixed OXide; nuclear fuel based on depleted uranium oxide and plutonium oxide.

10 Uranium oxide.

11 Ure: Re-enriched uranium; designates reprocessed uranium (URT) that is re-enriched in order to be used again in the fuel cycle.

project[12], to also study the management of LLIL waste[13] and to develop specific programmes concerning the storage, management, monitoring and transport of packages.

2.2.1. Storage

The Board approves of the various directions taken by this programme and its corollaries: the appropriation by Andra of long-term storage experience, and involvement in the project to extend storage in The Hague. It notes, in particular, that the programme addresses several of its own recommendations made in 2004 on long-term storage, adapting them to the new context of hundred-year storage: complementarity between storage and disposal, consideration of the choice of site for the design and operation of the storage facility, the need for study of the ageing of reinforced concrete structures, use of digital and physical simulations to control natural heat convection, etc.

The Board notes that the choice between natural and forced ventilation remains open, the first having the advantage of being passive, but the disadvantage of being more difficult to adjust, and the second, according to Andra, being technically guaranteed for a duration of 100 years.

The Board wishes to have at its disposal in 2009 a dossier giving a comprehensive overview of storage needs and future prospects.

2.2.2. Management, monitoring and transport of packages

In close connection with the previous programme, the ‘packages’ programme must update the design inventory model (Mid) by 2009, particularly, but not exclusively, for LLIL and LLHL waste and CU3 fuels[14], which are only taken into account for the request for authorisation to create a facility (DAC). It must also develop various package management scenarios based on the production records supplied by producers, formulate various forms of specifications, analyse problems related to transport and provide means for controlling waste packages.

In order to develop Mid 2009, Andra is asking producers to update existing knowledge files and establish new ones.

These knowledge files must meet the specifications defined by Andra, as revised in 2007, which set out the parameters that must be included: the knowledge files represent a first level of specification. Beyond that, Andra must contribute to the development of future specifications for acceptance in disposal, and formulate to this end ‘level 2 specifications’ which characterise the primary packages as considered in the disposal study: these are used to analyse the encapsulation projects proposed by the producers. They will be regularly updated between now and 2014, in order to provide the content of the draft acceptance specifications which will be attached to the DAC file; these may continue to be changed until the final acceptance specifications are produced in time for commissioning in 2025. Such a schedule therefore represents a considerable source of uncertainty for producers in respect of LLIL waste.

This is the reason for the inspections of the packages by Andra, which are performed by sampling, will preferably be non-destructive and will pose the lowest radiological risks in terms of radiation protection. When possible, these will be supplemented by inspections of samples taken at source. A study and research programme has been defined to develop non-destructive testing and radiological and chemical analysis techniques suited to packages for deep

[12] Long-lived, high-level waste.

[13] Long-lived, intermediate-level waste.

[14] Spent fuel from military and research activities, known as ‘exotic’ fuel.

geological disposal, which go beyond those that have been used for several years on packages received at the disposal centre for long-lived low- and intermediate-level waste (CSFMA). This programme will be fed principally by the proposals of the Andra-CEA working group set up in 2007. The CEA has been Andra's main partner in this field for a long time, but in principle, this partnership will not be exclusive in the future. The programme distinguishes between several categories:

- LLIL packages with their disposal containers;
- Packages of HL[15] waste which is less urgent because it will need to be stored for a long period prior to disposal;
- Packages of old high-level waste and spent fuel destined for direct disposal.

The list of parameters to be included in the specifications, as well as the hierarchy of package families, will be definitively decided in 2009, a date which constitutes an important milestone in the programme. More important still is the milestone at the end of 2012, which will be the date of an initial assessment of the feasibility of the inspections in respect of the DAC file for 2014. The industrial roll-out of the inspection procedures is expected to begin in 2018.

The Andra hearing enabled us to obtain an extremely useful initial clarification of a fairly vast, diverse and complex field, of which the Board still has only a piecemeal and, in places, imprecise view. The presentation to the Board of some dimensions of the programme is worthy of further, more detailed study in the future. For example, if it is clear that the transport of the waste to the disposal site is the responsibility of the producers, the extent to which Andra is concerned by this aspect, which features explicitly in the title of the programme, beyond the definition of acceptance infrastructures at the disposal site, remains unclear. Similarly, the management of uncertainty concerning the characteristics of the existing packages, the specific issue of containers and their inspection, coordination between storage and disposal and its implications in respect of the development of some package characteristics and thus the purpose of the inspections, should be clearly explained. Finally, outside of long-standing close relations with the CEA, the question of a framework of existing or planned national and international collaborations has hardly been mentioned up to now.

The Board would like the 'packages' programme to be developed further during 2009.

[15] High level.

2.2.3. Management and packaging of long-lived intermediate-level waste

Andra has asked waste producers to consolidate knowledge concerning LLIL waste packages that could remain in storage for around 100 years in various conditions. This requirement also concerns packages that will be deposited in a disposal facility pending the closure of this facility.

Despite the variety of LLIL waste packages, the CEA manages them all properly. The storage of LLIL packages will be assured. That said, there remain some problems to solve with regard to historic LLIL waste (asphalt) whose situation is still under discussion to determine to which disposal facility they belong.

The Board considers that the studies and research conducted by the CEA on behalf of the producers on the development of packages are on the right track, particularly as they are based on considerable prior knowledge. Furthermore, the CEA often conducts its own studies and research on encapsulation and characterisation in order to rationalise and improve current practices and test new encapsulation methods. The Board encourages producers to pursue this path in order to master the encapsulation of old waste.

The Board has no questions about the waste encapsulation technology but would like to know, for LLIL packages other than those retreated using the current process, how the decision chain works that leads from encapsulation to disposal, and which participants are involved: producers, Andra, public authorities, etc. It would appear to be desirable to seek to optimise management based on technological and financial considerations, something which does not appear to have been done as yet.

2.2.4. Short- and long-term behaviour of spent fuel

The 2006 law restricts the disposal of spent fuel or irradiated fuel to fuels that there is no intention to reprocess and which are classed as LLHL waste. For the moment, they are kept in storage. This year, the Board has not examined any particular case concerning their disposal. At a later date, it will evaluate the specific studies and research concerning this particular subject within the studies and research on spent fuel.

The Board would point out that knowledge of spent fuel from PWR reactors concerns multiple aspects and that robust but overestimating models exist to report and predict their behaviour. They are based on studies and research that have been conducted for a very long time in numerous programmes (many countries envisage direct disposal of spent fuel). In France, the latest programme was Precci I[16](see report n° 11, CNE1, page 103).

The reprocessing of spent UOX (45,000 MTHM[17]), Ure (1,550 t) and Mox (2,900 t) fuel from EDF plants in the facilities in The Hague is due to extend until 2040, in the scenario in which FNRs are deployed until this date. This implies that the spent fuel assemblies will be stored in the pits at The Hague before being retrieved for reprocessing. This storage will last 8 years in the case of UOX and 20-25 years for Mox in the reference scenario. The envisaged rates are 850 t/year of UOX until 2030, then 1250 t/year of UOX and Mox (diluted Mox) until around 2040. The spent Ure fuel would be reprocessed between 2030 and 2040 (100 t/year). 2030 will see an increase in the capacity of the facilities. Today; 13,000 t of spent UOX fuel have been reprocessed. However, the deployment of PWRs could be delayed until near the end of the century, thus further increasing the duration of underwater storage of spent fuel.

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16 CEA research programme on the long-term evolution of irradiated fuel packages.

17 MTHM: Metric tonnes of heavy metal.

As an interim measure, the PNGMDR[18] envisages the possibility of disposal of part of the spent fuel that is not reprocessed upon shutdown of the nuclear programme after the reactors have operated for 40 years. In this case, decay storage of spent Mox fuel is estimated at 100 years.

It is in this context that studies and research have been reoriented within the framework of Precci II (2^{nd} phase of the programme). Furthermore, EDF's constant desire to improve its knowledge of spent fuel is leading to broader study and research projects than those undertaken with disposal in mind.

The Board considers that the Precci II programme is on the right track. It aims to complete knowledge concerning the behaviour of spent fuel during the stages which take it from the reactor to the reprocessing facilities, and when in the disposal facilities. The latest results confirm the operational models (Mop) of long-term behaviour. Thus, the estimates based on these models remain valid (spent fuel dissolution < $mg.m^{-2}.j^{-1}$, calculated over 10,000 years).

Although, under the 2006 law, studies and research on the behaviour of spent UOX and Mox fuel did not appear to be a priority, since only some experimental or ship propulsion assemblies (CU3) are destined for disposal, it is important to maintain a high level of knowledge in this field. Indeed, for the moment, all spent fuel must be reprocessed within the next few decades, but precautions should be taken to protect against any change which would lead to the very long-term storage of spent fuel under water, or even, in the event of a change in policy, the disposal of numerous spent fuel assemblies. In the reference scenario, no short-term problems were encountered with century-long underwater storage, or during dry transport. For the long term, the current models concerning the alteration of spent UOX or Mox fuel are sufficient to design a disposal facility.

The Board recommends that the Precci II programme should be completed with the appropriate resources, and that it should be determined whether particular studies and research are necessary for the disposal of CU3. If studies are required, they must finish before 2012 so that Andra can take account of the results when producing its reports.

2.2.5. Long-term behaviour of glass

The manufacture of R7T7[19] glass packages and their storage in The Hague are industrial operations. Thanks to studies and research that began in 1960, these operations have been mastered since 1990. The packages that are set to be put into geological disposal contain fission products, minor actinides produced in nuclear power reactors and 0.1 to 0.2 % of uranium and plutonium from the UOX and Mox fuels of these reactors.

13,000 CSD-V[20] packages have already been produced. The other types of glass packages produced (3,200) or to be produced (a few hundred) concern the reprocessing of UNGG[21] fuels from the military programme or experimental programmes. They are stored in Marcoule. In a geological disposal facility, corrosion of the metallic containers of the disposal packages could occur after several thousand years, bringing the glass, the water and other materials (corrosion products, iron, clay) into contact. This is why numerous study and research projects have been conducted on the alteration of nuclear glass not only in France but also in other national programmes and as part of the Euratom Framework Programme for Research and

18 National Plan for the Management of Radioactive Materials and Waste.

19 Name of the glass manufactured for high-level waste in the Cogema workshops (R7 for the UP3 plant; T7 for the UP2 800 plant).

20 Standard waste packages: containers likely to be filled with vitrified (CSD-V) or compacted waste (CSD-C).

21 Natural uranium/graphite/gas reactor.

Development, in order to provide the scientific elements necessary for safety analysis. The knowledge that has been built up is considerable.

The 2006 law asks waste producers to carry out studies and research on the encapsulation and intrinsic long-term behaviour of waste, and asks Andra to study the long-term behaviour of waste in disposal situations. The CEA is involved in these study and research projects, which scientifically speaking are not unrelated. It has presented to the Board the current and planned studies and research on glass packages.

The results acquired up to 2003, particularly in the Vestale project[22] (2000-2005) have been assessed (CNE1 report; n°10 ; page 61). This project was reoriented in 2006 in accordance with the requirements of the law, taking into account the need of industrial operators for knowledge of glass packages (Vestale II). Vestale II is linked with the group of 'glass/iron/clay' laboratories implemented by Andra, and all of the studies and research projects are coordinated by several committees under the authority of COSRAC.

In 2005, the results of the studies and research on R7T7 nuclear glass made it possible to estimate the longevity of the glass matrix of a damaged CSD-V disposal package in clay, that is to say, the time necessary for it to suffer corrosion damage through contact with its environment. It is in the region of several hundred thousand years. This estimate is based on the use of a robust phenomenological model. The results obtained since 2005 confirm the model's parameter values and thus do not change the estimates based on the model. In 2010, Andra will have consolidated corrosion models for all glass packages.

2.3. DEEP GEOLOGICAL DISPOSAL

2.3.1. Introduction

The years immediately preceding the 2006 deadline were marked by intensive scientific activity, with the opening of the Meuse/Haute Marne underground research laboratory, the acquisition of a large volume of data through core-drilling or geophysical drilling from the surface and in the underground laboratory, and the creation of a wide-ranging summary in preparation for the '2005 Clay Report'. The current study is progressing at a similar rate, with seismic studies and core-drilling of the transposition zone. This study is a prerequisite to the identification, in 2009, of a restricted zone of 30 km^2, known as a Zira[23], which will be proposed as a potential location for a future disposal facility. Drilling in the Triassic layer, a geological stratum beneath the Callovo-Oxfordian layer, in order to determine geothermic potential, completes the programme.
Apart from this programme, the level of activity in 2007 and at the start of 2008 may appear less spectacular from the point of view of the volume of scientific results obtained. This period was devoted to the organisation of the new study and research phase which is due to be completed in around 2010, and particularly the definition of all of the programmes, their scheduling and their priorities, as well as the coordination of the simulation and engineering programmes with the scientific programme proper. The issues raised by the '2005 Clay Report' have been the subject of an internal and external review but have for the most part been retained, with some minor changes. Some of these are mentioned below; generally the Board approves of the emphasis placed on the study of the transient phase of several thousand years that follows the closure of the disposal site.

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22 CEA research programme on vitrification processes for fission products and actinides, and the study of the properties of the vitrified residue.

23 Zone of interest for further surveying, or Zira, is the name given by Andra to the restricted zone of interest stipulated in the law.

The experiments begun in the Meuse/Haute-Marne underground laboratory have been continued, with complementary results and the preparation of numerous new experiments. The laboratory has expanded; it has moved successfully from the initial operation phase, which was a success, to the consolidation phase, which aims to make the underground laboratory the scientific and technological instrument necessary for the performance of the LLHL programme.

It will be possible to assess the full effect of the results of the work in progress when the 2009 milestone is reached; the Board would like the scientific content of the hearings to be reinforced as we move away from the initial implementation phase of the programmes. It recommends greater interaction between the acquisition of new results and simulations. In this context, any new experiment must be preceded by a predictive model.

The present evaluation concerns essential aspects of the work on rock mechanics, hydrology and geochemistry and the study of the transposition zone. It is based on hearings held in 2007-2008 with Andra and some of its partners, a visit by the Board to the underground laboratory, and the documents provided on these occasions.

2.3.2. Delayed deformation of the rock mass

Digging a tunnel or a shaft causes deformations of the rock mass, and particularly a damaged zone which is made more permeable in the vicinity of the walls, known as the EDZ. Subsequently, these phenomena continue to develop, generally at a low rate. The mechanical properties of the mudstone in the Callovo-Oxfordian layer would be sufficient to support an ordinary tunnel and does not present any particular difficulties in such cases. However, creating a disposal facility introduces some additional requirements.

It is anticipated that the tunnels will remain open for a century or more. It is also important that the cavities do not close prematurely, as this would make it difficult to remove the packages if required, given the constraints involved in the handling of radioactive packages. It is also necessary to prevent the damage to the rock created by the opening of the structures from becoming more intense or more widespread, in order to avoid the risk of creating a hydraulic short-circuit in the geological barrier. This is why the structures are coated; the *quid pro quo* is that the coating bears an increasing proportion of the weight of the earth over time.

Andra must ensure that these coatings are properly designed from the outset, seeking both to keep their thickness within reasonable limits and to limit movements of the rock mass.

In the much longer term, we must be able to describe with sufficient precision the mechanical condition of the rock mass, because it, along with its temperature, its chemical state, the pressure of the fluids within it, and the framework within which the disposal facility operates, determines resaturation with water, swelling of the barriers in which the structures are installed, operation of the seals, degradation of the containers, and finally, migration of radionuclides. There are at least five possible causes of delayed changes in the rock mass: purely mechanical deformation (creep), variations in the pore pressure of the water, variations in temperature, variations in the water saturation near the wall, and physico-chemical changes such as the swelling associated with pyrite oxidation. The assessment of these phenomena, the effects of which only reveal themselves slowly, is not easy. Their respective impacts must be determined in a test on a specimen or in the underground laboratory. Furthermore, the properties of the rock vary, at least along the vertical axis (creep is faster in the tunnels than in the niche, which is less clay-heavy). Finally, the tests are necessarily of limited duration, whereas we need them to predict very long-term behaviour.

Andra must therefore make the most of the experimental possibilities of the underground laboratory, which is an important asset, as it constitutes a kind of full-scale test facility: in 2015, we will have ten years of data to look back on.

The interpretation of the PWR experimentation [24], which is now complete, involved numerous scientific teams. It has clearly shown the hydromechanical couplings and therefore the role of pore pressure, at least in the zone around the niche and the shaft. The effects of variations in temperature in the shaft are modest, but clearly visible. It is likely that, in the current phase, desaturation and creep will play a major role, but in the opposite direction. The fact that desaturation and resaturation phenomena have still not been studied much in the underground laboratory is to be regretted, as their assessment is crucial for an interpretation of delayed phenomena, and more generally for the transient evolution of the disposal facility after its closure. They will be the subject of dedicated SDZ[25] experimentation after 2009.

In the '2005 Clay Report', Andra presented quite a large number of creep tests performed on specimens. The experimental difficulties were clearly noted. The rates measured during the long tests for unit B (which includes the tunnels) were very low, towards the lower limit of the range of values we are able to properly measure. In the constraint window tested, viscosity was of the order of 10^{17} Pa.s, assuming a linear correlation between the stress applied and the deformation rate. The cumulative deformation over a hundred years under a load of 1 MPa (for example) could therefore be approximately 3%, whereas it is indicated elsewhere that the damage increases when deformation exceeds 2%. While not acute, problems with the resistance of the coatings and increased damage cannot be discounted.

The 2005 Report does not come to a definitive conclusion on the existence of a stress threshold above which creep occurs. The presence of a state of anisotropic stress in the rock mass, clearly highlighted by Andra, would tend to suggest such a threshold, but the tests, which are very difficult, do not appear to confirm this. Finally, this report acknowledges that the downward trend in deformation rates, clearly visible in a test lasting a few months under a constant load, must continue indefinitely; for the time being, there remains insufficient evidence to support this hypothesis, particularly as it may lead to more optimistic conclusions than the hypothesis whereby the rates stabilise, which is supported by some of Andra's scientific partners.

Andra is pursuing laboratory tests as part of the group of 'Geomechanics' laboratories set up in 2007, and it is too early to make an assessment of the results; however, it is not impossible that some conclusions of the 2005 Report may be revised. The measurements performed in the Meuse/Haute-Marne underground research laboratory provide precious information. The rates of variation in the diameter of the tunnels (4.5 metres) decrease rapidly during the first year and are in the region of 4 mm/year after two years, but they vary according to the location and direction of the tunnels. This decrease may be linked to an intrinsic property of the material, the effect of the structure and the effect of the desaturation of the rock mass.

The Board wishes to know Andra's detailed interpretation of the measurements, the quality of which should allow us to make progress in the understanding of the phenomena and their respective roles in the changes measured. This is essential in order to find a suitable design for the coatings, which must allow the packages to be removed (for example, the thickness of the metallic jacket installed in the LLHL waste cavities).

After 2009, the laboratory test programme plans to conduct tests comparing the performance of various coatings.

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[24] Studies of the response of the rock mass to the effects of shaft digging.

[25] The aim is to identify the physical phenomena that occur around a tunnel subjected to variations in hygrometry.

2.3.3. Desaturation and resaturation

The ventilation of the tunnels means that the hygrometry of their walls is variable (depending on the season and the position along the ventilation circuit) but generally quite low. Water is therefore extracted from the rock mass in the form of vapour much more quickly than water is brought towards the tunnels by drainage. Consequently, a desaturation front progresses through the rock mass.. After the closure of the cavities and then that of the entire disposal facility, the phenomenon reverses: the rock mass is resaturated and the voids left in the disposal facility fill up with water. Andra has established that resaturation is much slower than desaturation. This mechanism therefore actually contributes to a safety function, since it delays for a long time - albeit unequally depending on the nature of the packages placed in the cavities - the arrival of water which comes into contact with the containers and packages.

The Board has requested that these phenomena, which are very important for the transient phase following closure, be carefully studied, and that the system proposed by Andra, which is not unreasonable, be backed up by scientific evidence, in light of its importance for safety. For the moment it seems that, in the underground laboratory, the desaturation front progresses quite quickly until the limit of the fractured zone of the EDZ. These observations are interesting but do not answer the more general question of long-term changes, about which the Board would like Andra to present an up-to-date review of current knowledge.

2.3.4. Hydrogen production

In the '2005 Clay Report', Andra highlighted the process of hydrogen production through corrosion of the steel abandoned in the disposal facility after its closure. The hydrogen is evacuated by dissolution and diffusion in the water in the rock mass. However, with the hypotheses selected, which Andra deliberately understated in respect of the transfer processes in the rock, these processes do not allow sufficiently rapid evacuation to prevent a significant increase in the pressure of the hydrogen gas in the cavities. This is obviously the quid pro quo of the general tightness qualities attributed to the disposal system. The maximum pressures calculated vary from 6 to 9 MPa according to the nature of the packages contained in the cavities. These values are quite high. Indeed, the pressure due to the weight of the ground is approximately 12 MPa, so the margin we have with regard to a local fracture (of the rock wall, the plugs or the seals) is not large, particularly as the phenomena to be described are complex and their interpretation is still uncertain.

The database we have for writing behaviour laws is limited at present. The laboratory tests, and the modelling of the behaviour of the mudstone that these tests aim to achieve, use a series of notions (diffusion, two-phase flow, gas inflow pressure, retention curve, micro-cracking, permeability hysteresis) which have more often than not been established for more permeable rocks.

Andra must conduct studies to validate their application to mudstones.

For both the cavities and the entire disposal facility, modelling is difficult, as hydrogen is produced at a very unequal rate, depending on the cavity. The pressure increase changes the water flows, desaturates the rock slightly and therefore changes the conditions that enable corrosion. Generally, the processes are noticeably more complicated than in the case of desaturation/resaturation without hydrogen production, the modelling of which has not yet been completely validated. We also have few examples of underground structures or natural processes that would bring into play similar phenomena.

The validation of the models and calculations therefore remains insufficient and requires particular attention from Andra.

In the 2005 Report, Andra presented overestimating hypotheses aimed at assessing the scale of the phenomena, with relatively reassuring results. However, the complexity of the problem and its modelling still gives rise to uncertainty. Several avenues for progress are envisageable. The first avenue, which is in any case essential, involves improving knowledge.

From this perspective, the Board approves of the choice made by Andra to give priority, between now and the 2009 milestone, to the improvement of gas production and migration models, and to propose a European research programme on this subject.

Another possibility would be to limit the quantity of steel introduced into the disposal facility. The maximum pressures reached would probably not be changed, but the total mass of hydrogen produced would be reduced. Andra is therefore studying the use of ceramics as a replacement for non-alloyed steel overpack for LLHL waste packages (although ceramics do have the disadvantage of being more fragile), and the use of mineral materials for jacketing, in order to enable easy installation and, if necessary, removal of the packages.

These studies must be completed.

It will also be important to assess more comprehensively whether the phenomenon is unfavourable or not. Clearly, it would appear to be desirable to be able to eliminate the risk of local fracturing, but Andra also highlights in its '2005 Clay Report' the possible benefit of a delay in resaturation, to which hydrogen production contributes, which would delay the arrival of water coming into contact with the packages. The safety analysis would benefit from a clearer ranking of the advantages and disadvantages of the consequences of gas production. As yet, Andra has not presented its approach in this area, and the Board would like it to be presented at an upcoming hearing.

In addition to the long-term corrosion phenomena, hydrogen is generated in the much shorter term by radiolysis in the LLIL waste packages. During the operating period of the disposal facility, the cavities that contain these packages are ventilated in order to prevent the hydrogen concentration from reaching the flammability limit. Andra has presented digital simulations of these phenomena, which use fairly detailed geometrical descriptions of the fluid circulation network. These simulations show that the residual hydrogen concentrations are very low.

These results must be confirmed by comparison with experience; the Board would like a review to be conducted of experience feedback from similar facilities presenting a hydrogen-related risk.

2.3.5. EDZ

The observations made in the underground laboratory confirm the existence, on the wall of the tunnels, of a damaged zone or 'EDZ', composed of a fractured zone and a micro-cracked zone in which permeability is noticeably increased. These zones could form a short-circuit for the transfer of fluids and, later, radionuclides. The measurements made in the underground laboratory have allowed an initial survey to be made of the extension and permeability of these zones. Changes in these zones must be carefully monitored. The measurements have benefited from the experience acquired in other underground laboratories and the test results, which are delicate, are nevertheless consistent enough to allow a model to be built. We expect this model to be presented at the 2009 milestone.

The digging of the tunnels has brought to light the formation of several fracture systems, with progression of the front and particularly chevron cracks that are metres in length. Andra has been able to begin to identify the parameters influencing this formation (direction and speed of digging and installation of the support). These fractures are likely to play an important role with regard to the hydraulic characteristics of the EDZ, in comparison with that played by more diffuse damage. Several avenues for research are available. The first is to improve knowledge. The formation of chevron cracks has also been observed in the very different clays at the Mol underground laboratory in Belgium. This may therefore be a relatively universal phenomenon, at least for a certain class of rocky materials, which has gone unnoticed until now due to a lack of suitable experimentation. Andra presents an initial interpretation, in the context of classical field theory, but it must continue its work, mobilise resources more widely in the field of theoretical mechanics - for example, in ultimate strength design, advanced digital simulation and fracture mechanics – and review the interpretations made of similar phenomena observed with other materials and in different contexts. A second, more pragmatic approach would be to experiment with several digging, support and coating techniques, with variants in their implementation, checking that they do not introduce other disadvantages. The corresponding programmes will be conducted from 2009 onwards.

The Board recommends that Andra pursues both avenues. With regard to the second avenue, the Board recommends that Andra conduct a full review of the techniques used to dig classic galleries and tunnels, and particularly the processes for consolidation of the rock ahead of the front, before it is dug.

2.3.6. Sealing

Andra has suggested interrupting the hydraulic continuity of the EDZ by creating cavities perpendicular to the axis of the tunnels and filling them with swelling clay. Very early on, Andra started an initial experimentation programme called ‘KEY’ at the Meuse/Haute Marne underground laboratory, which showed the importance rightly given to the topic of EDZ interruption. This experimentation continues. However, it lacks a clear definition of the problem (at what point will the sealing be effective? What will be the fluids present at that time, their pressure, the stresses in the key?) and a justification of the design selected (does the selected shape not concentrate stresses at the bottom of the cavity? How can we avoid the formation of an EDZ due to the digging of the cavity?). The ongoing test has allowed valuable technological lessons to be learned, and the measurements, taken with great care, also provide precious information on the EDZ. But this test only concerns partial sealing in an open tunnel, conditions which are not conducive to checking the efficiency of the process fully. A more ambitious test will be implemented from mid-2012.

As stressed in previous reports, the Board recommends that a critical assessment be conducted of the scientific and technical studies already carried out.

2.3.7. Migration and diffusion

The scientific study programme on radionuclide migration is currently being conducted by a group of laboratories. It is also covered by the FunMig[26] project (part of FP6), in which Andra is a participant.
The capacity to master the geochemical model for pore water is vital, as it will make it possible to design migration experiments in both the surface and underground laboratories in conditions representative of the transfer of radionuclides.

Since 2005, it has been possible to characterise the pore water *in situ* at five depths between -430 m and -505 m using different experimental systems. The results obtained are convergent and reasonably consistent with the model, except for potassium and strontium. This discrepancy is attributed by Andra to a misunderstanding of the equilibrium constants of certain chemical reactions, which are being re-examined. In the new phase of the geochemistry programme, Andra has scheduled experimentation to assess the impact of the oxidising disturbance and that of the bacteria that will be introduced by human presence.

During the period ending in 2012, Andra is planning to focus firstly on understanding, at a fundamental level, the differences in the behaviour laws of the diffusion and retention phenomena on the different scales (from molecular to millimetric) and secondly on understanding the effects caused by the transient thermal and hydrochemical regimes in the vicinity of the disposal cavities. Results will be available in 2009 at the end of the FunMig programme.

The Board approves of this small-scale upstream research approach, which is essential to support the more empirical approaches at macroscopic level.

On a macroscopic scale, DIR experimentation on *in situ* diffusion of inert and reactive tracers in the underground laboratory, has produced results consistent with the measurements taken on samples on a centimetric scale, confirming the differences in behaviour between anionic and cationic species. The longest experiments took place over two years; they will be dismantled in 2008 to examine the migration of tracers within the rock by overcoring. New diffusion experiments, using the knowledge acquired in the initial experiments and designed to be developed over several years, will only be launched in 2009 at the earliest (DRN experiments, diffusion of radionuclides).

It is essential for tried and tested techniques to be used in order for overcoring, which should provide results essential to the design of new experiments, to be a success in 2008.

As the diffusion phenomena are very slow, experimentation on distances related to disposal situations is not possible; this is where modelling becomes a valuable option in the assessment of long-term behaviour. We can certainly expect Andra's scientific programme to produce significant advances in progressing from the microscopic to the macroscopic scale.

The Board stresses that the change in scale is much less easy to master when moving from the macroscopic scale to the scale of the host formation. In respect of this essential point, the only possible validation method is to use natural chemical or isotopic markers.

Andra's programme is unclear on this very difficult point, which requires the collection of a great deal of *in situ* data and the construction of geological and geochemical change scenarios to be compared with the migration models. The research that will be conducted by Andra and GDR

[26] European project (2005-2008) for the study of the 'Fundamental processes of radionuclide migration'.

Forpro[27] on drilling in the Triassic layer should contribute to this type of approach by providing limit conditions for transfers of natural indicators.

The Board wishes to be informed next year of Andra's projects to address this point.

2.3.8. Engineering

The engineering programme is of growing importance within the LLHL project. In particular, it concerns surface nuclear facilities, disposal containers, the transfer and handling of these disposal packages, mining engineering, disposal facility architecture, the design of the cavities, sealing and backfill. It includes the performance of technological and demonstrator tests; results have already been obtained within the framework of cooperations with the CEA (disposal containers) or the European programme ESDRED[28] , which is coordinated by Andra. It includes the creation, in Saudron, of a technological experimentation centre, close to the site of the underground laboratory and destined to be open to the public.

In respect of engineering, the '2005 Clay Report' intended to present 'simple, robust and available' theoretical solutions. Since then, following assessments of this report, Andra has conducted an internal review and benefited from several external reviews. The new programme, which takes into account these assessments, is divided into three phases. The first, from 2007 to 2009, concerns the choice of the basic safety options and the major technical options regarding the design. The period from 2010 to 2014 will be devoted to the production of the engineering file, in support of the request for authorisation to create a disposal facility (DAC). Detailed studies will begin from 2013. Simultaneously, and progressively (mock-ups, prototypes, then, in some cases, full-scale demonstrators), materials and operating methods will be tested, with variants, for the disposal containers, transfers and handling, in addition to the excavation and sealing tests performed in the underground laboratory. A programme to define and test a complete system for installing LLHL waste packages seems to be on the right track.

The choices made in engineering take into account concerns about operating safety, long-term safety, reversibility, cost and, for surface facilities, environmental impact. Some of them are difficult to reconcile, which means trade-offs are necessary. These choices must be guided by the conclusions of the simulation, monitoring and information/consultation programmes, as well as the scientific programme. Engineering therefore interacts with many other activities; the programme adopted by Andra endeavours to take it into account as effectively as possible.

The Board had previously emphasised that the technical solutions should not be decided upon prematurely and that they should be based, to the greatest possible extent, on mature scientific knowledge. From this point of view, the engineering programme appears to be a little tight, as it takes place downstream of the scientific programme, at a stage when various important phenomena (EDZ formation, delayed behaviour of the rock mass, gas generation) have not yet been fully understood or modelled. We can go some way towards mitigating this problem through sensitivity studies. Data of a more technological nature will also be necessary but, as far as excavation is concerned, the selective heading machine will only be available in 2009 and the comparison of the flexible and rigid coatings will only be able to be performed in 2010-2012. However, in respect of the design of zones containing waste which emits heat, we already have

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[27] Research group involving the CNRS and Andra, created on 1 January 1998, for the research to be conducted in the underground qualification laboratories (FORmations géologiques PROfondes – Deep Geological Formations).

[28] Engineering Studies and Demonstration of REpository Designs, project incorporated in the 6th Euratom Framework Programme on Research and Development.

more solidly established elements - for the heat conduction properties of the mudstone, for example.

The Board would stress that the best solutions from the point of view of long-term safety will not necessarily be the same as those that are best for operating safety or reversibility. In particular, the legislative framework in which the principle of reversibility will be enshrined will, according to the 2006 law, only be defined in 2015. For the time being, it will mainly be for Andra to identify the risks of contradiction between these different concerns, clearly explain them and suggest trade-offs.

From this point of view, the Board looks favourably upon the principle of re-examining basic options such as the offsetting or grouping of shafts, or underground transport of heavy goods by rail; it suggests examining whether reversibility is compatible with quick backfill, which would make it possible to avoid some of the disadvantages of storage of backfill in the open air. However, the Board would have liked the inclined-drift or shaft alternative to have been studied in detail.

The Board also wonders about reconsidering other options selected in the 2005 Report, such as the blind nature of the cavities. This option could, in the case of LLIL waste, make reversibility and operating safety more difficult (for example, the evacuation of the gases formed during the phase when the disposal facility is open), but it did provide valuable guarantees from the point of view of long-term safety. This is the time to emphasise that the design of a disposal facility is based partly on models which allow a direct comparison between the different options, and partly on a set of general principles, such as simplicity, robustness and redundancy. It is not practical to integrate these principles in quantified estimates, as they aim to offer additional margins in respect of phenomena that are more difficult to identify or describe. They must not, however, be treated as secondary concerns; the Board wants Andra to explain clearly the principles guiding its choices in terms of engineering with regard to safety and reversibility concerns.

2.3.9. Reversibility

The law of 28 June 2006 provides that the deep geological disposal of final radioactive waste must be done 'in accordance with the principle of reversibility'. The scientific and technical report in support of the 2014 DAC must therefore take specific account of the reversibility of the proposed disposal facility and contain proposals as to its management. After assessment of the DAC file, it is anticipated that the Government will present a draft law setting the conditions for reversibility and the authorisation, if it is given, must in particular set the minimum duration for which reversibility of the disposal facility must be ensured, a duration which, the current law stipulates, cannot be less than one hundred years. Andra has therefore defined, within the LLHL project, a ‘cross-functional activity’ concerning reversibility, while also, in the interests of complementarity, taking account the whole of the radioactive waste management process, including storage, disposal and encapsulation of waste upstream. On the technical front, this cross-functional activity interfaces considerably with the programme of observation and monitoring of the surface environment and the LLHL project facilities. What we are looking at here is therefore all studies and research concerning reversibility and observation/monitoring.

In the 2005 Report, Andra had defined reversibility as the possibility of progressive and flexible management of the disposal process, breaking it down into three aspects: the retrievability of packages, the capacity to intervene in the disposal process and the capacity to change the design of the disposal facility. For 2009, it has set itself the objective of being able to present possible scenarios for the management and design of storage and disposal facilities incorporating safety and reversibility. These elements will be integrated in the summary pre-project on disposal for the 2012 milestone. This will require some elements of the 2005 Report to be updated. These updates will take into account feedback from the assessment of the 2005 Report and discussions with the stakeholders; it will gradually incorporate the results of the different study and research programmes that will be conducted over the period 2007-2014.

On the scientific front, there must be a deepening of knowledge about the behaviour of packages and structures during the reversibility phase. The following will contribute to this:

- The results of the scientific programmes, simulations and experiments in the underground laboratory;
- The responses to the needs expressed for additional knowledge, to be provided by producers, concerning certain aspects determining the behaviour of the packages (particularly gas production);
- Additional studies and research on the mechanical behaviour of the structures (delayed hydro-mechanical behaviour, effects of saturation/desaturation), on the physico-chemical changes in materials *in situ*, particularly hydraulic binders, and on the transfer of gases.

On the technical front, engineering studies will be conducted until 2009 in order to:

- Assess the possibilities and the technological limits in terms of reversibility (for example, sensitivity to the design of the disposal facility components, such as the nature and thickness of the coatings of the underground structures);
- Indicate the specifications of the containers according to the requirements concerning durability and retrievability after one hundred years in disposal;
- Give the specifications of the disposal structures (geometric configuration of cavities and changes therein, nature and dimensions of jacketing, cavity cover design, ventilation and management of radiolysis gases, coating of tunnels, etc.);
- Give the specifications for the operating processes (installation of packages, pre-closure procedure, closure procedure, package removal techniques, procedure for returning a package to a cavity in which hydrogen produced by corrosion of the steels has accumulated, overall architecture and operation of the disposal facility, etc.).

The studies and research on reversibility must interact closely with the results of the observation/monitoring programme to help define the procedures for management and progressive closure of the structures. With a view to the public debate in 2013, considerable efforts will be made to produce, and present to the public, demonstrators illustrating the reversibility of the disposal facility (Saudron technology centre, mentioned in § 2.3.8 above).

The international state of the art will be taken into account, notably to promote the introduction of a shared set of reference guidelines on reversibility; in particular, Andra is participating in the NEA/OECD ‘Reversibility and Retrievability’ project and is organising a national seminar in France in 2009, followed by an international conference in late 2010.

In international discussions, Andra has proposed a scale of reversibility/retrievability levels which will be submitted for national public debate and to the scientific community. This scale is graduated in order to structure the decision-making process for management of the disposal site ‘in accordance with the principle of reversibility’.

The Board acknowledges the more extensive approach taken by Andra to reversibility since the 2005 Report. The actions defined to date are incorporated in a schedule that is compliant with deadlines set by law. For the moment, there are few new scientific and technical results suitable for assessment.

The Board will restrict itself to making a few general recommendations about some of the directions to be taken in future work:

- *The very concept of reversibility as defined by Andra is in need of clarification. It is clear, for example, that it is not possible to move along the scale defined by Andra in the same way in the opposite direction. It is important to be aware that any return to a previous situation will require its own procedures when the time comes;*

- *One obvious condition of the reversibility option is to demonstrate the retrievability of the packages already in disposal, particularly packages that are damaged or assumed to be damaged. Andra has envisaged some of these situations; the Board would invite Andra to consider the matter in greater depth, perhaps with a view to defining the circumstances of 'standard' incidents, in order to define suitable intervention methods;*

- *A balance must be found between reversibility and safety, in which the essential elements of both are preserved. While it is clear that the more reversible a disposal facility is, the lower the level of passive safety will be, it will be useful to cost the various reversibility options (in monetary terms, or in terms of safety or worker safety). Andra has made provision for consideration of this subject as part of the cross-functional 'cost' activity. The Board wishes, in the future, to be kept regularly informed of the progress of these studies.*

2.3.10. Monitoring

This field, to which Andra has accorded fresh importance since the 2006 law, is now covered by the specific programme of 'observation/monitoring of the surface environment and the LLHL project facilities'. The elements concerned are the surface environment, the surface facilities of the disposal site, the underground facilities of the disposal site, and the storage facilities. Such observation/monitoring activity reflects the general concerns in terms of safety, reversibility, traceability and transparency. It is justified by the size of the structure, the duration of its operation, and experience feedback needs.

The surface environment monitoring activity entered the operational phase in 2007. Its ultimate aim is the implementation, in the near future, of a permanent environment observatory within the transposition zone, as well as a test site. This observatory must allow an initial state to be established, taking into account natural variability, as well as enabling understanding and modelling of the interactions between the various natural environments and analysis of medium- and long-term changes, including those in health, independent of the disposal activity. It is essential for this observatory to be well integrated, as planned, in the national environmental observation system.

Work is being done on the specific measurement needs of each phase of the disposal facility's lifetime (construction, operation, sealing and closure). Studies and research are planned to develop resources and a strategy for monitoring, which meet the specific needs of the disposal facility (conformance and miniaturisation des sensors, improvement of their range, energy self-sufficiency, etc.). A dense network of national and international collaborations is under development to support these study and research projects.

The Board would emphasise that there is no guarantee that new, reliable monitoring solutions can be developed and rendered operational within the timeframes imposed by the law. It is therefore important, in parallel, that an order of priorities be clearly established among the numerous parameters suitable for *measurement, and the means for achieving them. The Board wishes, in the future, to be kept regularly informed of the progress of these studies.*

The Board recommends that sight should not be lost of the fact that the measurements are only meaningful or useful in conjunction with modelling, whether it be modelling of the monitored environment and the changes in it, or that of the measurement system itself. Modelling work, the intensity and complexity of which may vary depending on the subject and the period, must become an integral component of the programme.

The Board also expects further details on the following specific issues:

- *Use of satellite data;*
- *Measurements of displacements and deformations, on the surface or along the shaft, on a very large scale (hectometric, or even kilometric);*
- *Management of adverse trends over time and ageing of materials over very long periods (sensors, cables, electronics and associated data acquisition).*

2.3.11. Hydrogeological model

The purpose of the hydrogeological model is, firstly, to provide a framework for the simulation of potential migration of radionuclides after their diffusion within the mudstone layer and, secondly, to provide information about the paths taken by groundwater in the water-bearing formations of the host rocks, which must ultimately be used for the safety analysis. The knowledge acquisition aspect of the development of the hydrological model is part of Andra's scientific programme; the use of the knowledge acquired is part of the 'simulation' programme, not forgetting that simulation is a way of checking the coherence of scientific knowledge.

Andra has progressively implemented the hydrogeological model since 1996, with the assistance of various external laboratories. In its 2005 Report, Andra presented a modelling chain produced by the IFP[29], based on a regional hydrogeological approach spanning the Parisian Basin, relayed by a local model including the potential outlets of the aquifers in the host rocks. The results obtained in the upper host rock (Oxfordian limestone) are satisfactory in that they respect the flow directions and the hydraulic gradients observed; they are less convincing for the lower host rock (Dogger), for which the flow direction is incorrectly reproduced by the model. This discrepancy between the model and the observations may have several causes: the fact that the flow velocities in the Dogger are very low and therefore poorly defined, as shown by the high apparent ages of the water (more than 1 million years); the fact that there are few constraints imposed on the circulations in this aquifer by natural drainage conditions; and finally the limited number of boreholes (4) which allow the piezometric level of the Dogger to be checked.

Andra has taken account of the comments of the assessors of the 2005 Report recommending that the hydrogeological model be better constrained through consideration of the distribution of natural indicators such as water salinity in the Dogger, and through a better representation of the role of faults in the sector model. This model must be extended to the east in order to include the outcrops of the Triassic layer and thus better simulate its aquifer, which is probably responsible for the salinity of the water in the Dogger. Furthermore, the new drilling programme

[29] French petroleum institute.

will provide additional information by allowing better observation of the piezometric levels and the salinity of the Dogger. Finally, deep drilling in the Triassic layer will make it possible to characterise the fluids in the underlying aquifers in the Dogger and probably propose a source-term model in order to explain the salinity of the water in the Dogger.

The Board considers that the validation of the hydrogeological model will not be able to be truly improved until new data covering a sufficient period are available. What is required, then, for the 2009 deadline, is the completion of the setup of the modelling tools and the performance of exploratory simulations. The consolidation of the hydrogeological model and its use to simulate long-term changes will only be possible after 2010.

2.3.12. Delimitation of the zone of interest for further surveying (Zira)

The 2005 Report presented a very elaborate geological model of the Meuse/Haute Marne site and its environment, which made it possible to define a 'transposition' zone of around 250 km^2 in which the properties of the Callovo-Oxfordian host layer are expected to be reasonably homogeneous.

The key challenge for the 2009 deadline is the determination of a restricted zone of interest, henceforth referred to as a 'zone of interest for further surveying' (Zira). It is within the Zira that the final qualification work for a potential disposal site will be carried out.

The planned surface area of such a zone is 30 km^2, which leaves open the possibility of designing several locations for the building of a disposal facility, adapting as effectively as possible to the non-geological constraints on the site.

With regard to Zira research, Andra is implementing a programme based on experience feedback from the 2005 Report. This programme is ambitious and will mobilise numerous teams from the groups of laboratories. It is in progress and the first observations and measurements made in the new boreholes at the end of March 2008 are very much consistent with the current geological reference framework.

The Board considers that the specific elements necessary for the delimitation of the Zira will be available by 2009.

During the hearings, it became apparent that Andra already had a good level of confidence in its geological model and that it considered that the regularity of the properties in the Callovo-Oxfordian layer made the interpolations between the available observation points credible. Andra is therefore expecting few surprises at the end of the additional 2008-2009 campaign, so the choice of the Zira might not only be founded on geological criteria, but also perhaps on other criteria including socio-economic constraints.

However, the Board considers that the determining criteria in the choice of the Zira must be geological quality.

2.3.13. Boring in the Triassic layer

Boring in the Triassic layer is planned on the platform located at the centre of the transposition zone; it will be done by deepening the borehole whose initial target is the Callovo-Oxfordian layer.

According to the safety guide on the final deep geological disposal of radioactive waste (ASN; 12 February 2008), '*the site shall be chosen so as to avoid zones that may be of exceptional interest in terms of underground resources*'. The geological indications already acquired in the Triassic layer did not suggest that such resources existed. However, Andra wanted to conduct a direct investigation through boring. One of the objectives of this boring is the surveying of the geothermal potential of the Triassic layer, for which we can expect to find a temperature of 80° towards 2000 m and a high level of salinity. It should be noted that the characterisation of geothermal potential must not be limited to the mere acquisition of the temperature and the productivity parameters of the reservoir, but must also consider its capacity to absorb the re-injected water. Indeed, it is foreseeable that the mediocre quality of the water will make this reinjection necessary, and we know that previous reinjection tests in the sandstone of the Triassic layer have encountered difficulties (geothermal characteristics in Melleray in the Loiret department, brine injection tests in Lorraine). The other scientific objective is to obtain a vertical profile of the composition of the fluids present at the base of the Dogger; this point is essential if we wish to improve the Dogger salinity model, as the Triassic layer represents a potential source of this salinity.

A point that is not specified in Andra's programme is the measurement of the piezometric level in the sandstone of the Triassic layer; it appears that the boring, as predicted, will not allow an individual level to be identified in the Vosgian sandstone of the base. Such an absence of information would hinder the consolidation of the hydrogeological model.

The Board recommends that Andra take care to acquire all the data necessary for the validation of the hydrogeological model.

Boring has been proposed to the scientific community for research actions coordinated by GDR Forpro, which will be submitted to the ANR in 2008.

The Board approves of this initiative, which could be a precursor to a TGI[30] *programme associated with the Meuse/Haute-Marne laboratory. To this end, the Board recommends that the borehole in the Triassic layer, which will constitute an exceptional structure providing access to a deep aquifer in the Parisian Basin, should be conserved so as to be included in Andra's long-term monitoring system and allow future research on the hydrodynamic and hydrochemical behaviour of the Triassic layer.*

2.4. DISPOSAL OF LONG-LIVED LOW-LEVEL WASTE (LLLL)

Andra is conducting studies and research into the possibility of disposing of radiferous and graphite waste classed in the LLLL waste category in deep geological disposal facilities. The law calls for a disposal facility to enter into service in 2013. In its first report, the Board set out the reasons why meeting this deadline will be virtually impossible. The Government Commissioner has asked Andra to propose a new schedule. This would open up the possibility of acquiring the necessary data to produce a scientific report, once the potential disposal site(s) has/have been chosen for the waste.

Radiferous waste and graphite waste do not pose the same disposal difficulties, due to their nature and the quantities to be deposited. The waste contains short-lived radionuclides which will have disappeared after a century and long-lived radionuclides which require long-term disposal precautions.

We can deduce that the radiferous waste to be disposed of would, pending a more precise inventory, have a volume of 35,000 m^3 (30,000 t) with a specific activity in the order of MBq/kg

[30] Research infrastructure labelled as a 'Très grande infrastructure' or 'Very large infrastructure'.

(of waste) in around one hundred years. In sub-surface disposal, it is advisable to trap the decay products of radon, a gaseous element, which can be done with a covering of earth, saturated with water and about ten metres thick. The chosen concept must, however, minimise the risk of human intrusion and guarantee the sustainability of the covering in future.

However, the graphite waste would, subject to the same proviso stipulated above, have a volume of 100,000 m^3 (23,000 t) with a specific Chlorine-36 activity (^{36}Cl) in the order of MBq/kg. Although this waste contains another long-lived radionuclide, ^{14}C (500 times more active), it is above all ^{36}Cl which poses disposal problems because it is not at all well retained by the graphite in the presence of water and it is very mobile in the geosphere. It must therefore be contained for periods of several hundred thousand years, as its half-life is 300,000 years. Andra's '2005 Clay Report' clearly showed that ^{36}Cl is one of the major contributors to radiological impact in the case of deep disposal.

Andra has already conducted studies and research on the disposal of radiferous and graphite waste, and relaunched them in 2005 by considering generic sites, within modified or intact clay. It has presented to the Board some preliminary calculations performed using a suitable methodology and using values that were optimistic but not unreasonable, key parameters (release of chlorine by the graphite, permeability of the concrete of the containers, the host clay and the rock mass, chlorine diffusion coefficients), and varying the thicknesses of the clay and the distances from the outlet.

These initial calculations do not leave very large margins in respect of the radiological objectives expressed in terms of dose constraints, whatever the disposal concept. Furthermore, without being inaccessible, the permeability values envisaged will probably not ordinarily be met by a surface clay formation, particularly if it is modified. They assume in all cases that the concrete will maintain high performance levels over a long period. These calculations cannot provide a solid basis for a decision, but they do suggest that the requirements of a safety analysis should be able to be met in the case of sufficiently deep disposal in sufficiently thick clay, of a quality comparable to that of the mudstones of the Callovo-Oxfordian layer studied in the Meuse/Haute Marne underground laboratory. Given the long half-life of ^{36}Cl, care must be taken to ensure that erosion does not reduce coverage to the extent that the site loses its good containment qualities during the entire period for which ^{36}Cl comes out of the outlets (at least 300,000 years). It appears that the concept using an inclined drift would offer the greatest level of safety and flexibility in the design of a disposal site for graphite waste. This is the concept, at the generic studies stage, that Andra favours in a document provided to the Board on 18/4/08, but the Board would emphasise that this is an extremely complex problem.

All of these comments demonstrate the overriding need to rapidly conduct studies on a real site about which there is a minimum of knowledge available. Andra has clearly defined the main geological criteria on which the choice of sites in clay formations will be based, but the actual potential sites will not be proposed to the public authorities until 2010. We will then have a very short time in which to gauge the performance levels of a site, design a disposal facility and conduct radiological impact studies. Some areas of knowledge could still be insufficiently consolidated at this stage, leaving room for considerable uncertainties. The first of these is the inventory of ^{36}Cl and other radionuclides in the graphite, and their location. Serious studies and research projects are underway to reduce such uncertainties.

Finally, the installation depth of the graphite waste disposal facility is an essential parameter. The cost of the underground structures is more than proportional to their depth. The principle of coherence mentioned in the PNGMDR would appear to require that the depth of a disposal facility be suitable for the harmfulness of the waste deposited in it. It must be sufficient to reduce the radiological impact due to the migration of chlorine at a given stage, and limit the effects of geological changes (erosion) as well as human intrusions. We can thus see that the concept using modified covers is not suitable for graphite waste. In the case of an intact clay layer, the Board's estimates, based on Andra's generic calculations, show that the reference situation for the installation of a disposal facility is a depth of over one hundred metres, and the presence of a layer of clay that is approximately 100 m thick.

Thus, to date, it has not been envisaged to dispose of the graphite waste packages along with the LLHL/LLIL waste packages, because this would double the planned surface area for LLIL waste (100,000 m^3 of graphite for 80,000 m^3 of LLIL), which would increase the area of the deep disposal structure by a third. However, the abovementioned considerations show that the problem of disposing of graphite waste is more complex than it appears, despite the fact that it is LLLL waste. While continuing the search for sub-surface sites suitable for the disposal of such waste, it would be useful, by way of comparison, to have a study on the consequences and additional cost that would be engendered by disposing of this waste, or some of it, in the disposal site for LLHL and LLIL waste.

Studies and research are underway on the disposal of radiferous and graphite waste. These two types of waste do not necessarily require the same disposal concept or site.

The studies and research will only be able to serve as the basis for a report built on solid scientific data once these data are known:

- *The waste inventory;*
- *The physico-chemical and radiological characterisation of waste (heterogeneity, distribution of radionuclides, hot spots, mean specific activity);*
- *Real sites whose geological characteristics have been sufficiently surveyed;*
- *The characteristics of the waste packages;*
- *The rate of release of radionuclides over time, in the presence of natural water, and the parameters that control their migration in the disposal materials and the selected geological environment.*

The generic studies show that radiferous waste must be capable of being disposed of in safe conditions in a sub-surface site.

The major problem is the disposal of graphite waste. Only the availability of a specific site will make it possible to acquire the knowledge necessary for the design of a facility, as well as the assessment of its containment performance and its radiological capacity. The generic studies show that it is necessary to find a clay formation that is sufficiently thick and allows the structures to be installed at a sufficient depth, for hydraulic reasons and to protect against long-term erosion and the risk of human intrusion.

Bearing in mind these constraints, the Board recommends conducting a parallel study on the consequences and additional cost of disposing of graphite waste in the LLHL and LLIL disposal sites.

Chapter 3

PARTITIONING AND TRANSMUTATION

3.1. STUDY AND RESEARCH FRAMEWORK

The 2006 law guides studies and research towards the industrial possibilities for transmutation of minor actinides in critical (FNR[31]) or sub-critical fast neutron reactors (ADS[32]), in relation with those conducted on the new generations of nuclear reactors. These are Generation IV reactors, whose principal aim is to optimise fissile material resources. In the case of FNRs, the energy and waste management policies are linked; in the case of ADS, they are not (ADS). However, it will only be possible to implement one option or the other when facilities exist for the partitioning of minor actinides (including neptunium, americium and curium), and the production of fuels or targets that incorporate them, as well as transmutation reactors. Their respective roll-outs will depend on numerous factors, including the weight that is given to studies and research in the different fields: partitioning, production of targets and fuels, reactor prototypes, irradiations for transmutation tests.

The first deadline is in 2012, when, according to the law, the CEA must '*provide a report assessing the prospects of the different industrial partitioning/transmutation processes'*, including a section on the benefits that partitioning/transmutation could offer for geological disposal. A review must be conducted in 2009.

Studies and research on partitioning and transmutation aim to change the nature of LLHL (long-lived high-level) waste from the reprocessing of spent fuel, by considerably reducing the minor actinide content in glass packages. However, this strategy will not apply to glass packages from current nuclear power plants, which will be disposed of by geological disposal, as discussed elsewhere. There are plans to reprocess all of the spent fuel from these thermal reactors (PWR[33]) by 2040. The implementation of a partitioning/transmutation strategy therefore concerns only future nuclear reactors, including FNRs. It must be noted that the renewal of the current reactor population has just begun, with the construction of EPRs[34].

After the promulgation of the law of June 2006, the following strategic decisions were taken by the Atomic Energy Committee on 20 December 2006.

The studies and research on critical reactors will concern sodium-cooled reactors (SFR) and gas-cooled reactors (GFR). For sodium-cooled reactors, the priority in terms of studies and research is the design and production of a prototype in 2020. The technologies and operating principles of a gas-cooled FNR will have to be examined within a European framework in order to produce a demonstrator (ETDR[35]), a decision about the construction of which could be made

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[31] Fast neutron reactor.

[32] Accelerator Driven System; subcritical accelerator-driven systems comprise three elements: a linear accelerator, a spallation target, and a subcritical nuclear reactor.

[33] Second-generation pressurised water reactors.

[34] European Pressurized Water Reactors; third-generation pressurised water reactors.

[35] ETDR: European Technological Demonstrator Reactor – a research and development reactor for gas-cooled fast neutron reactor technology.

in around 2012. Studies and research on ADS will be conducted as part of the Eurotrans programme [36].

The studies and research for these techniques will focus on advanced recycling processes and will concern both the partitioning of minor actinides and the production of transmutation targets or fuels. The studies and research on partitioning must pursue several alternative options until the time comes to make decisions. Priority is given to hydrochemical options (linked to the FNRs) over pyrochemical options (linked to the ADS). Studies and research on the production of uranium and plutonium fuels for the prototype sodium-cooled FNR take priority over those on the production of fuels or targets with minor actinides. Two pilots must be built on schedule in The Hague to produce a few tonnes of driver fuel for the core of the prototype sodium-cooled FNR and a few tens of thousands of kilograms of fuels and targets based on uranium, plutonium, americium and neptunium, or even curium, depending on the options.

The studies and research on partitioning and transmutation must examine the following operations: the partitioning of the minor actinides in the spent fuel, their incorporation in appropriate materials and their irradiation in fast neutron transmutation systems. An effective partitioning/transmutation strategy also requires these operations to be performed industrially and, to achieve an overall transmutation rate of at least 99%, they must be repeated on increasingly radioactive materials with increasingly short lifespans.

On the international front, the Board notes that countries with a nuclear power industry generally subscribe to the international programmes on Generation IV reactors, but in practice, their situations vary. Japan and France are clearly committed to partitioning and transmutation, performing transmutation tests on FNRs. At present, there is no common international programme on partitioning and transmutation, beyond the search for convergence and complementarity in irradiation experiments.

The Board noticed at the Global 2007 international conference that France was playing an important role, with a coherent vision of reactor development and waste management. At European level, France continues to drive long-term actions, for example within the SNE-TP[37] platform, which aims to organise European studies and research on nuclear fission.

Thus, France appears to be the country where the conditions for the pursuit of studies and research on partitioning and transmutation are favourable and relatively unaffected by developments abroad. In this respect, the French deadline of 2012 will be particularly important for the nuclear energy of the future.

The Board considers that, by 2012, the knowledge truly necessary to make decisions should be defined, together with a set of minimum specifications for viable partitioning and transmutation. In addition, an informed view of the advantages and disadvantages of partitioning and transmutation, as well as the real short- and long-term industrial commitments to which it leads, must be established.

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[36] EUROpean Research Programme for the TRANSmutation of High-Level Nuclear Waste in an Accelerator Driven System; Euratom Framework Programme for Research and Development.

[37] Sustainable Nuclear Energy Technology Platform.

The law implies that these study and research projects should be conducted with a view to industrial development. At national level, the Board considers that the studies and research are well coordinated between the different organisations (CEA, CNRS, EDF and Areva). The Board notes the care taken by the CEA to link its research on new reactor options to its research on the partitioning and transmutation of minor actinides. However, for Areva and EDF, partitioning and transmutation appears to be an option that may be considered within industrial and commercial strategies. For industrial operators, it would be useful, as soon as possible, to have consolidated options for a Mox[38] fuel with uranium and plutonium for a sodium-cooled FNR, rather than fuels or targets for transmutation.

The Board recommends that the studies and research should make it possible, as soon as possible, to move beyond the energy policy of using FNRs to recycle only uranium and plutonium, as in the past with the second-generation fast reactors (Phénix, Superphénix). The delay between the establishment of a population of fast neutron reactors and the implementation of a partitioning/transmutation strategy should be kept to a minimum in order to reduce the harmful effects of LLHL waste, as required by the law.

The choices to be made in 2012 will require quite advanced studies and research to have been carried out both in fast neutron irradiation and in fuel cycle processes. This will require fast neutron irradiation equipment and use of Atalante in order to perform partitioning with significant quantities of actinides in respect of industrial processes. The shutdown of Phénix in 2009 raises the question of how studies and research can be continued until 2020, as heavy-duty irradiation equipment will be required.

The Board wishes to alert the public authorities to an almost total lack of available fast neutron irradiation systems between now and 2020, be it in France or abroad.

The Board wishes to be kept regularly informed of the technological developments planned to perform irradiations and operations using significant quantities of minor actinides, as well as to implement, if necessary, a storage facility for minor actinides before the production of fuels and targets for transmutation.

Other problems may arise in studies and research.

The Board recommends that the public authorities take into account, when scheduling studies and research, the possibility that what it is decided to do may not be done in accordance with the schedule envisaged in the PNGMDR 2007-2009.

3.2. TRANSMUTATION

3.2.1. Scenarios

The study of scenarios should enable the coherence of a set of technical, industrial and economic data to be analysed.

The Board has familiarised itself with the studies and research conducted jointly by the CEA, the CNRS (via Pacen[39]) and EDF, on scenarios involving transmutation by recycling of minor actinides, based on the hypothesis of a reactor population constantly supplying 430 TWhe per

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[38] Mixed OXide; nuclear fuel based on depleted uranium oxide and plutonium oxide.

[39] Programme on the downstream part of the cycle and nuclear energy production; interdisciplinary CNRS programme.

year, assuming that the operation of the technical systems, i.e. fuel cycle plants and reactors, are totally mastered, with regard to the working hypotheses. The data expected are the long-term radiotoxicity of the waste, the heat properties of the objects to be disposed of, and the area covered by a disposal facility connected with partitioning and transmutation. The results presented confirm a number of points that were already known.

Multi-recycling of plutonium alone, or with minor actinides, in PWR (thermal reactors) is not viable; it would lead to the stabilisation of the plutonium in the cycle at a high level (100 t), with isotopic decay and an increase in minor actinides, particularly curium, hence the unacceptable emission of neutrons.

The advantage of transmutation using ADS is that it contains the minor actinides outside of the nuclear power station facilities (two levels). However, fast neutron transmutation appears preferable in FNRs. Indeed, with 400 MWth ADS as envisaged by the CEA, more than 100 t of minor actinides would be in equilibrium in the cycle, while spending most of the time outside of the ADS. In addition, the production of a fuel with a high minor actinide content (intense neutron source, high thermal power) is extremely difficult.

The new avenues opened up by FNRs show that the recycling of all of the transuranian elements (plutonium and minor actinides) is theoretically possible, without excessive constraints, particularly in respect of neutron emission. The balanced inventories of minor actinides in the cycle can nevertheless reach 50 t. The advantages of the critical FNRs are their breeding capacity, which provides independence in terms of fissile material resources, and their potential industrial application. The impact of minor actinides on the production and reprocessing of the fuel is judged by the CEA to be '*significant, but not totally unacceptable*, although no real study of this impact has been presented to the Board.

The CEA has also presented to the Board a work programme on scenarios concerning the period 2007-2012, as part of a working group involving the CEA, EDF and Areva.

The working group examines scenarios using the following criteria: industrial feasibility, industrial risks, impacts on safety, radiation protection of human beings and the environment, economic assessments and non-proliferation. This analysis is combined with 4 families of scenarios envisaged for waste management: recycling of plutonium alone in PWRs or FNRs, recycling of plutonium with minor actinides, incineration of minor actinides in ADS, and a reference PWR scenario. These scenarios have implications for the management methods and disposal of future waste. Preliminary analysis reports are due in 2010 for 4 scenarios and by the start of 2012 for all scenarios.

This programme plans to study the transient conditions at the end-of-life of the facilities, that is to say, the consequences of the existing 'work-in-progress' in the facilities and reactors when partitioning/transmutation stops. This is a study of a phenomenon that will only occur in the distant future, but which is important due to the enormous quantity of plutonium and minor actinides that have not yet been transmuted, and in terms of intergenerational ethical criteria: can we envisage leaving this work to future generations? How can everything be resolved? Do reactors need to be kept in operation in order to eliminate the 'work-in-progress' and how effective would such a scenario be?

Another application of these scenario studies is in the forecasting of transitions between reactor populations, for example the switch from 2^{nd} and 3rd generation reactors to fourth-generation reactors. This issue is directly related to partitioning/transmutation. The two factors that will determine the date of deployment of the FNRs are the price of uranium and the availability of plutonium. The aim of the scenarios is to find coherency in a cycle with the objective of economic optimisation (lifespan of the Hague plant and implementation of the FNR fuel production plant). The aim is to put nuclear energy in France, together with partitioning and transmutation, in perspective with regard to Generation IV nuclear energy. This approach is not without consequences on future waste management and disposal methods.

The Board considers that this ambitious programme on scenarios is worthy of the combined efforts of the best experts. It would be desirable for the CNRS to be fully involved. The Board recommends that the programme should be conducted within the timeframes indicated in order to shed light as early as possible on the priorities and essential areas of the different fields analysed, particularly the studies and research on partitioning and transmutation.

Because the scenario studies predict the consequences of the partitioning and transmutation strategy more than a century into the future, the Board considers that they are essential and that they must comply with a certain number of rules:

- *The technical working hypotheses must be set out precisely and shared by all of the different participants;*
- *The quantified values produced by different approaches during the sequence of cycle stages and the use of codes must be compared using clearly defined criteria;*
- *The criteria must be established and prioritised;*
- *The economic implications, at each stage of the cycles, must be examined in depth;*
- *The calculation hypotheses must be clearly stated.*

The work on scenarios is an ideal opportunity for the different participants and the different scientific and socio-economic communities to come together. It enables thought to be given to the problems that nuclear energy generation may raise for the future, particularly by including partitioning/transmutation in the overall consideration of the problem of future waste management. In this vision, in which partitioning/transmutation and disposal are interdependent, despite the fact that the deadlines are a long way off, we should start optimising studies and research now in order to take better account of them.

3.2.2. Impact of partitioning and transmutation on a future disposal facility

Most of the work done has focussed on the consequences of disposal of glass packages with a low minor actinide content. The working hypotheses are those underpinning the studies and research stemming from the 2006 law. The glass packages would be produced by partitioning/transmutation implemented in a balanced reactor population. The consequences of the existence of 'work-in-progress' uranium, plutonium and minor actinides when partitioning/transmutation stops in the FNR are not envisaged. The results of the exercise presented to the Board complete previous studies without adding any truly new elements.

The radiotoxicity inventory of 'low-content' glasses would be lower than that of the glasses currently used, but the performance levels of the underground disposal facility remain unchanged because the minor actinides do not migrate in the clay.

The area covered by the LLHL disposal facility depends on the thermal properties of the glass packages, and generally any extension in the storage period will allow the area to be reduced. The release of heat is mainly due to the minor actinides after 300 years, particularly the presence of americium 241. In their absence, the cooling time of these packages (currently 60 years for interim storage) and the area of the disposal facilities would be reduced. Thus, the minimum storage time would decrease from 60 to 50 years and if the storage time were maintained at 60 years, we could then reduce by 30% the area of the part of the disposal facility dedicated to LLHL. In addition, the duration of the thermal phase would be reduced to around a hundred years, due to the fission products alone.

The close relationship between minor actinide content, storage time and the underground area covered by the disposal facility allows storage/disposal to be optimised in respect of other criteria, particularly economic criteria.

The radiotoxicity inventory of the current glass packages reduces slowly over time. It is sensitive to the presence of minor actinides after a few hundred years. In their absence, however, it is necessary to wait 10,000 years for it to become ten times lower than that of the current packages. So, after this period, any intrusion into the disposal facility would have a reduced radiological impact.

The studies and research undertaken should lead to an initial assessment at the end of 2009, taking into account the results of the scenarios being studied.

For the Board, the impact of partitioning/transmutation on disposal is an essential point to assess in 2012 with a full report. The report should include several assessments: radionuclides assessment, thermal power assessment, storage and disposal volumes assessment, radiotoxicity inventories assessment, radiological assessment of workers and economic assessment, particularly concerning the potential additional cost of partitioning/transmutation and savings on disposal. In each case, the periods of time over which the assessments have been conducted must be specified, and care must be taken to ensure a coherent whole. Finally, it is necessary to have final assessments corresponding to the end of partitioning/transmutation, even if that is a long way in the future, due to the need to use partitioning/transmutation over more than 100 years in order to benefit from it.

The Board recommends that the participants designated by the law should not allow a gulf to develop between the studies of partitioning/transmutation scenarios leading to quantified assessments of the production of radioactive waste and radioactive material flows, on the one hand, and the studies to identify the advantages and disadvantages that partitioning/transmutation would have on storage and disposal on the other.

3.2.3. Partitioning/transmutation and availability of tools for Studies and Research

Studies and research on transmutation require the availability of experimental thermal and fast neutron reactors: thermal reactors for the study of the physical phenomena linked to the irradiation of materials (flows greater than 10^{14}n/cm^2.s) and fast neutron reactors for transmutation tests (flows greater than 10^{15}n/cm^2.s).

In Europe, experimental thermal reactors are all over 40 years old. Osiris will be shut down by 2015. The Jules Horowitz Reactor (JHR), which will be available in 2014, will have a considerable fast neutron component, but will only deal with very small volumes, which will only allow the irradiation of a very small number of fuel pins. The same goes for the EBR2 reactor operating in Mol (Belgium).

Phénix is the demonstration tool for sodium-cooled FNR technology, but it will be shut down at the start of 2009. In Europe, there will remain only the Russian fast neutron reactors: BOR-60, BN-600 (until 2025) and BN-800 (under construction). In Japan, the Joyo reactor is currently shut down and Monju could go back into operation in 2008 after more than ten years of inactivity. China is building the CEFR[40], due to start up in 2009. India has an FBTR[41] experimental fast reactor, and is building the PBTR reactor, which could be commissioned in 2010.

The Board wishes to alert the public authorities to an almost total lack of available fast neutron irradiation systems between now and 2020, be it in France or abroad. The Board finds the current lack of FNR experimentation sites alarming, at a time when new, sustainable nuclear technologies, allowing the transmutation of minor actinides, are being presented as references for this century. This technology, for which France no longer has any full-scale experimental tools, is the one that is being worked upon worldwide, including in China and India.

The demonstration of the technical feasibility of partitioning/transmutation with FNRs requires demonstrations to be performed with minor actinides according to a schedule that will make the first significant results available towards 2012. Only these demonstrations will make it possible to make decisive progress.

3.2.4. Transmutation processes

Studies and research on the French prototype due in 2020 have the twin aims of developing a system that not only recycles plutonium and uranium, but is also suitable for the recycling of minor actinides. Transmutation is being studied with a view to implementing it in two large families of reactors: FNR and ADS.

Transmutation in sodium-cooled FNRs (SFR) can be performed homogeneously by diluting the minor actinides in the nuclear fuel, or heterogeneously by transmuting the minor actinides in the radial blankets of an SFR while keeping a classic core. This choice enables the reactor core and the transmutation targets to be managed separately, while allowing both to be reprocessed together. It introduces an element of flexibility from the point of view of the plutonium breeding gain, and makes it possible to optimise the concentration of minor actinides in the blankets. With a relatively high content of approximately 15%, transmutation performances are good, but these blankets would be difficult to manipulate, as they are brought to a high temperature and constitute an intense neutron source. Irradiation experiments are planned by the CEA on the Russian BOR-60 reactor and these could be followed, in around 2015, by irradiations in the Joyo reactor, provided that it is operational. The characteristics of the SFR prototype for 2020 will be chosen in 2012.

The gas-cooled FNR (GFR) would allow homogeneous transmutation with a fuel with twice the minor actinides content of that in the sodium-cooled FNR: 5% as against 2%. The difficulties encountered with regard to the fuel are such that transmutation in this kind of reactor is still only considered in general terms. For example, the presence of minor actinides results in a considerable quantity of helium being released, imposing an additional constraint on the fuel. A decision could be made in 2012 on the construction of a GFR demonstrator generating around 50 MWth, ETDR[42], based on a feasibility report produced as part of the Gen IV forum.

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[40] China Experimental Fast Reactor.

[41] Fast Breeder Test Reactor.

[42] European Technological Demonstrator Reactor (research and development reactor for gas-cooled fast neutron reactor technology).

Studies and research on ADS are currently being conducted as part of the European programme Eurotrans, which should be completed at the end of 2009; a proposal has been submitted as part of FP7 to continue this work for three years. The subcritical character of the reactor of an ADS system means that, in theory, it is possible to envisage high minor actinide contents, as the shutdown of the accelerator beam allows the chain reaction to be stopped. But this system is complex and uncertainties remain about the fuel, the transmutation capacities, and even the operating capacity, efficiency and economic viability of an ADS. The subject of the benefits of this type of research is a sensitive one, given the hopes it raised at the start of the nineties.

Given the timeframes involved, the Board wishes to see the ADS transmutation studies pursued with vigour. The Board notes that conclusions will not be drawn from the Eurotrans programme before 2009.

3.3. MATERIALS FOR REACTORS

Transmutation using Generation IV nuclear systems poses critical problems in terms of structural materials for fast neutron reactors and ADS reactors.

Research on sodium-cooled FNRs (SFR) benefits from the experience acquired with Phénix and Superphénix. The materials problems stem from the extension of the design lifespan of the reactors (60 years), and the increases in combustion rates (200 GWj/t), doses (up to 200 dpa) and temperatures (up to approximately 550 °C or even 700 to 850 °C). This means significant innovations are required with regard to the use of new materials for the core, the vessels and the cooling systems.

In research on gas-cooled FNRs (GFR), materials are a critical issue. The doses to be considered are moderate, but the temperatures range from 550 to 1,200 °C. The main elements concerned are the fuel rod cladding and the heat exchanger.

For ADS research, specific materials problems are posed by the lead spallation target module for the accelerator window and for the inert medium for the actinides in the transmutation targets.

The Board considers that structural materials are a key factor in the feasibility of Generation IV nuclear systems. The studies and research necessary to define, test, optimise, produce and implement them on an industrial scale are considerable, difficult and time-consuming. One of the pre-requisites for success is to be able to build and mobilise considerable human expertise in accordance with the required schedule. The Board wishes to monitor closely the development of the national situation in these fields.

The Board would emphasise that the necessary studies and research require detailed understanding of the phenomena, the technological developments, and the often complex and time-consuming experimentation involved; models are essential at several levels in the interests of industrialisation, codification and standardisation. More often than not, the developments are long-term undertakings, involving numerous partners, in a fairly constrictive context of precise deadlines and industrial and commercial competition. This requires in-depth explanation of the various components of the overall effort, about which the Board only has a fairly imprecise idea at present.

With regard to the major deadlines (2012, 2020), the Board wishes to be informed of the planning of the main operations, which range from codification to materials production, as well as the preparation of transmutation demonstrations.

In the short and medium term, the sodium-cooled FNR is the main focus. The industrial operators concerned are focussing most of their R&D efforts on this area. The Board would, however, stress that sustained and continuous study and research work, making the best possible use of international cooperation, is essential in order to study the transmutation possibilities in gas-cooled FNR and ADS.

The Board would place particular emphasis on the following points, on which it will be monitoring progress closely: complete capitalisation of experience feedback from Phénix (including incident situations) and Superphénix; planning of access to irradiation facilities; development of atomic models and irradiation tests under thermo-mechanical stresses; forecasting of in-service inspection facilities.

3.4. FUEL CYCLE

To be transmuted, the minor actinides must be extracted either from the spent fuel or from materials that have been previously irradiated for the purposes of transmutation. After this partitioning, it is necessary to convert the products obtained into compounds for the production of transmutation fuels and targets. They are generally shaped into ceramic pellets, which are then inserted into metallic cladding which constitute the pins of the fuel assemblies. Studies and research on partitioning and conversion must lead by 2012 to processes that can be transferred to plants.

3.4.1. Partitioning and conversion

The CEA has considerable experience feedback on the modelling of engineering processes on radioactive materials, which has allowed it, along with Areva, to optimise the Hague plants using reduced-scale partitioning facilities. This process modelling allows transpositions of scale. It underpins all of the studies and research conducted in the Atalante facilities on hydrochemical (Diamex-Sanex, Ganex or others) and pyrochemical processes.

The study and research projects are considering current spent fuel first. Studies and research on materials that have been irradiated for transmutation purposes, aiming for necessary multi-recycling of actinides, will follow on from the previous studies after 2012, and may even continue until 2020.

The Diamex-Sanex processes enable the partitioning of minor actinides after the partitioning of uranium and plutonium has been performed via the Purex process. Two possibilities exist for implementing them after Purex. This is why the CEA's programme between now and the end of 2009 is designed to favour one of these, which will then be pursued with a view to possible industrialisation. Based on the Purex fission products solutions, the CEA is examining the possibility of extracting americium alone, given the questionable benefits of transmuting curium. This is a new aspect which is being considered in the light of the experience feedback from the CEA, obtained in 2000, on the partitioning of americium and curium.

The Ganex process developed by the CEA concerns grouped partitioning of actinides, from uranium to curium, based on a solution for the dissolution of spent fuel, in such a way that the respective proportions of the elements can lead directly to a minor actinide transmutation fuel in homogeneous mode in FNRs. Such partitioning is also envisaged in other countries.

The CEA has set itself the following objectives between now and 2012:

- To consolidate the Diamex-Sanex processes, particularly those concerning secondary waste, the synthesis of large quantities of reagents, the stability of radiolysis-hydrolysis reagents, solvent regeneration and the performance of equipment, while simplifying the sequences of steps involved in chemical operations;

- To test the Ganex process, which seems to offer guarantees that non-proliferation requirements will be met; this comment should however be weighed against the control difficulties that arise if all the actinides are mixed;

- To develop a process to extract americium only;

- To consolidate conversion processes for the partitioned products to prepare particular fuels and targets;

- To prepare for the processing of oxides and other compounds, such as carbides, which may be used in transmutation targets and fuels.

The Ganex process could be a rational process for engaging in homogeneous transmutation in SFR (dilution of minor actinides to approximately 2% in the fuel). However, the grouped extraction of actinides leads to a radioactive material containing curium, which is difficult to manipulate in the co-conversion operations following the partitioning operations, then the production of transmutation fuels and targets. This would impose severe constraints.

The alternative for homogeneous transmutation would be the Diamex-Sanex process, which must in any case be implemented in order to perform heterogeneous transmutation in the SFR reactor core blankets with a high minor actinide content. This transmutation mode seems to be promising and the CEA is studying it (concept of a blanket with a high minor actinide content or 'CCAM'). The Diamex-Sanex process thus appears to be more flexible than the Ganex process. In principle, part of the Diamex-Sanex process is a step in the Ganex process. In any case, it seems to be an urgent priority to conduct the studies necessary for the development of the Diamex-Sanex process.

In connection with the advanced partitioning processes, the CEA has for several years been conducting studies and research on the obtention of mixed actinide oxides obtained by co-precipitation of compounds, followed by heat treatments (co-conversion). The fact that the elements involved form solid oxide solutions makes the mixed actinide oxide ceramics obtained all the more suitable for the creation of a Mox[43] type fuel. This is what co-precipitation allows.

Furthermore, co-conversion simplifies the manipulation of oxide powders, which is always difficult and a source of pollution during the production of fuel. Studies and research focus mainly on the co-precipitation of oxalates and their transformation into oxides. The CEA and Areva have a long experience on an industrial scale of the precipitation of tetravalent plutonium oxalate from a plutonium nitrate solution and its transformation into plutonium dioxide. However, studies and research on co-conversion of actinides are at the laboratory stage, with only a few grams involved.

The CEA has for a long time been conducting studies and research on the partitioning of actinides in molten fluoride or chloride environments. The many results it has collected have led it to give preference, in the context of the 2006 law, to the grouped retrieval of actinides and therefore to focus on the heterogeneous multi-recycling of highly radioactive targets. Two avenues are being explored, the first using electrolysis and the second by reductive extraction in molten aluminium. The second avenue is being specifically developed by the CEA.

[43] Mixed OXide; nuclear fuel based on depleted uranium oxide and plutonium oxide.

Most of the studies and research on advanced partitioning have taken place as part of the integrated Europart[44] project, relayed by the Acsept project (34 organisations; 2008-2012). Acsept includes studies and research on co-conversion. In parallel, the CEA is developing bilateral and tripartite cooperations with Japan and the USA.

The Board considers that:

- Studies and research in hydrochemistry benefit from considerable acquired knowledge and wide-ranging experience feedback;

- The CEA has developed some solid concepts in the field of partitioning and co-conversion of actinides (uranium and plutonium only or with minor actinides). The results of the experiments planned between now and the end of 2009 could lead to choices being made at that date with regard to the development of the Diamex-Sanex and Ganex processes with a view to bringing them to maturity and industrialising them by 2012. These two processes offer flexibility to adapt in respect of the transmutation choices;

- After 20 years of research on the partitioning of minor actinides, many systems have been explored, and those which seem to be viable in the current context of the nuclear industry are known. Studies and research on new partitioning methods are unlikely to lead to new process concepts by 2012.

The Board therefore recommends that, between now and 2012, efforts should be concentrated on partitioning and conversion processes that could be industrialised, even if industrialisation is only a distant prospect in the partitioning and transmutation strategy.

The Board also considers that studies and research on pyrochemistry, which are more forward-looking than studies and research on hydrochemistry, are particularly suited to the processing of fuels with very high minor actinide contents for their recycling in ADS. However, they will not lead to an industrialisable process by 2012.

The Board observes that:

- The equipment available at Atalante for both partitioning and co-conversion will be increased. Atalante remains a very important, efficient and enviable tool for taking studies and research on partitioning and conversion to an advanced stage. However, Atalante can only supply sufficient quantities of compounds to create a few experimental pins for testing purposes, quantities which are not sufficient for an entire assembly;

- The research scheduled by the CEA on partitioning and co-conversion processes for minor actinides coincide with those supported by the 7th Euratom Framework Programme on Research and Development with a view to demonstration at pilot level.

The Board also notes that, according to Areva, the modelling of processes and the experience feedback from the Hague plants should allow a new plant to be designed for advanced partitioning, by extrapolation of the chemical engineering facilities at Atalante. If this is true, then only the design of a micro-pilot would be necessary for co-conversion and production of targets and fuels containing minor actinides. Thus, there would be no need for an advanced partitioning pilot. The co-conversion micro-pilot would be built as part of a collaboration, the details and timeframes of which remain to be specified.

[44] EUROpean Research Programme for the PARTitioning of Minor Actinides.

The Board recommends that suitable assessment of the technological means required for industrial implementation of partitioning/conversion and production of transmutation fuels and targets should begin now.

3.4.2. Targets and fuels for transmutation in FNRs

Very many study and research projects have been conducted to select the non-metallic materials that might be used in the production of transmutation fuels and targets. Since 2006, new results have been provided by some irradiation experiments in reactors, mainly Phénix. However, most experiments are still ongoing.

In order to feed the core of the 2020 prototype sodium-cooled FNR, a Mox fuel manufacturing pilot will be built in The Hague. A new Mox production process is being studied, based on solid uranium-plutonium solutions. The programme for testing this Mox will consist of irradiating two experimental pins in Phénix, with a plutonium content of a few per cent (Copix experiment), in order to check that the performance levels of this Mox are at least the same as those of that prepared using the classic industrial process. Next, prototype pins will be irradiated between now and 2012 in the Joyo reactor, then in a 'fast' zone of the JHR reactor towards 2014. Finally, a full assembly may be irradiated in the Monju reactor, subject to availability.

Compounds other than uranium and plutonium oxides would, in theory, be much better for making FNR fuel. Alternatives to the oxide method are being explored, with carbides, nitrides and metal alloys. These developments are of interest in fields other than SFR fuel, particularly fuel for gas-cooled FNRs (GFR). The compound envisaged for this is mass ceramic made of mixed uranium-plutonium carbide, the synthesis and shaping of which from oxides are currently being optimised at the CEA.

With a view to transmutation in GFRs, the incorporation of minor actinides in such compounds is, for the moment, at the laboratory experiments stage. Until 2012, there will be an important programme dealing with all of these technological aspects, in connection with irradiations in several reactors. A wide collaboration is being set up on the cycle associated with GFRs, which is expected to bear fruit some time after 2020.

The irradiation of compounds to test the homogeneous transmutation possibilities in SFRs (with a mass concentration of minor actinides of less than 2% in the Mox) have shown that at a combustion rate of 96 GWj/t, the behaviour of the pellets remains approximately the same as that of an FNR Mox with the same linear power density. There are not sufficient, however, to ensure suitable behaviour from a transmutation fuel, for which a combustion rate almost twice as high would be required.

The Gacid programme *(Global Actinide Cycle International Demonstration),* launched in 2007 by the CEA in partnership with the USA and Japan, aims to solve this problem. Fuel pin irradiations are planned in Joyo in 2010, then in Monju in 2015. An assembly containing approximately 1.5 kg of minor actinides distributed homogeneously will then be tested, either in a prototype SFR towards 2020, or in Monju. In order to prepare this assembly, a micro-pilot in The Hague will be necessary, which will be defined with potential manipulation of curium in mind. Significant results are expected in around 2025.

Studies and research to test compounds and composites for heterogeneous transmutation in SFRs are being pursued. Studies and research concerning the promising concept of CCAM (uranium oxide with 15% minor actinides) have begun; currently, few experiments provide information about the behaviour of such an oxide with a high minor actinide content, in which, during and after neutron irradiation, a lot of helium is released.

An experimental programme of irradiation of uranium oxide with a very high americium (or even curium) content, in thermal and fast neutron reactors, will be launched in Osiris and in the high-flux reactor (HFR) at Petten, in 2011. A potential extension is planned in Joyo in 2015. The CCAM programme is being finalised, but from 2009 the Tribor project in the Russian Bor 60 reactor will aim to test the behaviour of mixed uranium-americium oxides (with 10-40% americium content) with and without curium.

Finally, the studies and research necessary for the development of a fuel for an ADS are being conducted as part of the Eurotrans programme. They concern compounds containing 15-30% plutonium and 15-30% minor actinides. The aim is to show that it is possible to manufacture and reprocess such fuels and test their performances. The constraints imposed by a fuel containing so much fissile material are numerous, both during manufacture and after irradiation, as the phenomena related to fission and production of helium cause considerable damage. Numerous irradiations are in progress or planned, some of which will be followed by post-irradiation inspections between now and 2012.

The Board considers that:

- *Studies and research on the Mox fuel for the 2020 prototype SFR have made reasonable progress. In 2012, the development of the process for obtaining mixed uranium-plutonium oxide by co-conversion should be sufficiently advanced to enable a choice to be made between this process and the traditional process for preparing Mox for FNR. The manufacture of Mox fuel for the SFR prototype in new facilities does not pose any major fundamental problems, except the need to complete the necessary technological developments before 2020;*

- *Considerable efforts on mixed uranium-plutonium carbide fuel for a GFR is being undertaken in an international framework. In 2012, the results obtained should make it possible to orient future studies and research. However, the development of carbide ceramic envisaged for the GFR fuel will require many more study and research projects;*

- *the results acquired on the various materials envisaged for making transmutation targets or fuels confirm those acquired in 2006. A general quantitative assessment of the modifications observed on the various irradiated materials is beginning to emerge. It shows, as a function of temperature and chemical composition, the respective shares of the damage caused by the neutrons, the fission products and α radiation. This assessment will allow choices to be made;*

- *Concerning homogeneous transmutation in the Mox fuel of SFRs, significant results from the Gacid programme are only expected towards 2025, as convincing irradiation experiments will only begin after 2009 in the Japanese FNRs Joyo and Monju, subject to their availability. In 2009, the results that will allow selection of the oxides to be irradiated will be known;*

- *Numerous study and research projects have been conducted on the subject of heterogeneous transmutation with targets in the core of an SFR (up to 20% minor actinides). Between now and 2012, the experiments in progress will produce new results. There will be information that will allow choices to be made regarding the potential development of CerCer targets (composed of minor actinides and a refractory oxide) or CerMet targets (composed of minor actinides and a refractory metal). For uranium-*

based fuels in the SFR core blanket (10-40 % minor actinides), the studies and research in the CCAM programme will have produced some results in 2012. Choices will then be able to be made to develop fuels which have good transmutation performance levels and can be reprocessed, for multi-recycling with SFR core fuels;

- *In respect of transmutation in fuels for ADS (in two levels), the studies and research will only produce significant results after 2012. There is reason to fear that the future of the studies and research, which is linked to that of the Eurotrans programme, will not be decided before these results have been collected;*

- *Very few results have been collected on ceramics containing curium, due to the experimental difficulties. The results of the studies and research planned on this area are only expected a long way in the future.*

In conclusion, the Board observes that studies and research are progressing at a satisfactory rate; it would point out, however, that the preparation of test samples, their irradiation and the post-irradiation inspections take years, and that the CEA will only reach decisive conclusions after a decade, if irradiation equipment is available in FNRs.

Chapter 4

INTERNATIONAL OVERVIEW

Studies and research on deep geological disposal of spent fuel are being pursued in various countries other than France. Except the DOE's[45] application for a building permit for the Yucca Mountain geological disposal site, there were no particularly significant events in the years 2007-2008. The situation described in the Board's first report remains valid (see report n° 1; CNE2; 2007).

Although national approaches for setting up a geological disposal facility differ, many international cooperative efforts are undertaking research which goes beyond informal discussions. Andra is a stakeholder in a number of these. It has even become the leading player in European programmes and the preferred partner of counterpart agencies in other nuclear countries. This development is due to two factors. First, the Meuse/Haute-Marne laboratory is open to the world, and secondly, the French research programme conducted by Andra is supported by the institutional means that the law of 2006 instituted, with a firm view on opening a disposal site in 2025.

The main European and international study and research projects developed in the area of disposal are presented in the paragraphs below, which focus on geological disposal, human sciences, and partitioning/transmutation.

4.1. GEOLOGICAL DISPOSAL

In Europe, the main research regarding geological disposal is performed in Belgium (Mol, GIE Euridice), Finland (Olkiluoto, Posiva Oy), France (Meuse/Haute-Marne site, Andra), Sweden (Âspô, 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. In Belgium, France and Switzerland, the preferred host layer is clay. Germany has opted for disposal in a salt layer, but the choice has become politically controversial. Spain has examined all three options, but is currently focusing on long-term storage.

In Japan, there are plans to use granite or sedimentary rock, while the United States have chosen volcanic tuff[46].

4.1.1. Excavation-damaged zone and delayed mechanical effects

Studies on the mechanical properties of clay are being conducted in Mont Terri and in Mol. The plasticity of the clay at Mol is higher than that at Mont Terri or at the Meuse/Haute-Marne site; it allows sealing phenomena to be studied over shorter periods. In contrast, it is easier to study clay fracturing in formations that are harder than those at Mont Terri and the Meuse/Haute-Marne site.

[45] United States Department of Energy
[46] High-porosity, low-density rock.

The excavation-damaged zone (EDZ) was studied in depth during the digging of a connection tunnel in the Hades underground laboratory (at Mol in Belgium). At the end of a tunnel already dug, a large number of instrumented boreholes in the undisturbed clay enabled data to be obtained on the disturbance induced by the approaching excavation, until the moment when the two tunnels were joined. Similar research is being conducted at Mont Terri (clay) as well as in Sweden, Finland and Canada (granite). As the EDZ may provide migration paths in the event of radionuclides being released, the role of the filling of the tunnels is essential in reducing the long-term effects of the EDZ.

The Selfrac[47] programme, which was part of the Fifth European Framework Programme (FP5) aimed to characterise the EDZ and the changes in it over time. The main objective was to understand and quantify the EDZ processes and assess their impact on the performance of geological disposal sites for radioactive waste. Two potential geological formations have been studied for deep geological disposal of radioactive waste: Opalinus clay at Mont Terri (Switzerland) and Boom clay (in the Hades underground laboratory). In the same context, the Clipex[48] programme concerned the hydromechanical reaction of the clay during the excavation of a new tunnel.

Over the period 2006-2010, the ongoing project Timodaz[49] aims to study the thermal impact on the disturbed zone around the host clay of a radioactive waste storage facility..

4.1.2. Desaturation

Ventilation during the operational phase of a disposal site may provoke desaturation of the host clay which, in turn, will have an influence on the hydromechanical properties of the disposal site; it may give rise to long periods of desaturation for bentonite-based filling materials. The studies performed in the plastic Boom clay have shown the desaturation phenomenon to be insignificant, while studies in hardened clay have revealed possible desaturation in the vicinity of the tunnel wall.

The VE[50] project is a ventilation test performed in the Mont Terri laboratory.

4.1.3. Sealing

Sealing studies, mostly using mixtures of bentonite-based swelling clays, have been or are being performed in various laboratories. These studies concern, among other subjects, hydrology, expansion and migration through the seal.

The European RESEAL project in Mol (1996-2005) allowed the study of the sealing of a borehole in the experimental shaft at the Hades underground laboratory.

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47 Experiments on fracturing, self-healing and self-sealing processes in clays.

48 CLay Instrumentation Programme for the EXtension of an underground research laboratory.

49 Thermal Impact on the Damaged Zone Around a Radioactive Waste Disposal in Clay Host Rocks ; 14 partners, 8 countries; FPRD 7.

50 Ventilation Experiment; assessing the alteration in the hydro-mechanical conditions of the Opalinus clay in Mont Terri, caused by ventilation, its amplitude and its extension.

4.1.4. Gases

Due to the very low levels of gas transport through diffusion and convection, gas formation can easily give rise to local pressure which causes fractures and modifies the hydrology of the disposal environment. This mechanism could provide paths for the release of radionuclides.

In the plastic Boom clay (MeGAS experiment), these paths close rapidly as soon as the gas pressure disappears. However, this is not the case in hard clays such as the Opalinus clay in Mont Terri (HG-A and HG-C experiments). In granite, these studies are principally focussed on the bentonite barrier; this research is performed within the context of the Lasgit[51] experiment in Äspö (Sweden).

4.1.5. Engineering

The excavation techniques in the granite and clay at Mont Terri are based on standard digging techniques such as the "drill and blast" technique or the use of rotating-head excavators. Over time, the techniques used for plastic clay have evolved from a manual approach in frozen clay to digging in non-frozen clay, using mechanical techniques similar to those used for the London Underground (for example). The feasibility of industrial excavation in very deep clay, associated with the *wedge block lining* technique, has been demonstrated in Mol.

The objective of the Esdred[52] programme is to demonstrate the technical feasibility, on an industrial scale, of the activities conducted to build, operate and close a deep geological disposal site, while at the same time meeting long-term safety requirements.

4.1.6. Geological barrier

The FP6 programme NF-PRO (2004-2007, 40 partners, 10 countries) has made it possible to study the key processes influencing the performance of the barrier formed by the immediate environment of the geological sites.

Long-term corrosion studies are being performed in Mol as part of the Coralus[53] project; this project allows assessment of the combined *in situ* effects of high temperature and γ rays at the glass/clay interface.

The FP6 programme Micado[54] aims to assess uncertainty in the modelling of mechanisms for the dissolution of spent nuclear fuel in a disposal site.

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[51] Large scale gas injection test.

[52] Engineering Studies and Demonstration of REpository Designs ; 2004-2009, 13 partners, 9 countries.

[53] CORrosion of Active gLass in Underground Storage conditions.

[54] Model uncertainty for the mechanism of dissolution of spent fuel in a nuclear waste repository ; 2006-2009, 18 partners, 6 countries.

4.1.7. Diffusion/Migration

Diffusion measurements and assessment of the respective contributions of diffusion, sorption and advection in the clay are being performed at Mol and Mont Terri. Although the characteristics of the rock are quite different, there is a significant degree of consistency between the results from the different laboratories. Diffusion is hardly influenced by the water pressure gradients, the representative radionuclide diffusion coefficients in the different clay environments are very low. The main transport determination processes are the same in the different environments (anion exclusion, ion exchange, surface complex formation).

The main objectives of the European programme FunMig[55] are the fundamental understanding of the radionuclide migration processes in the geosphere and the assessment of safety performance levels.

4.1.8. Microbiology

The presence of dissolved oxygen, nitrates or sulphates may induce a certain form of biological activity, the origin of which may be endogenous or exogenous. Organic materials such as asphalts may also induce microbial activity. This activity may have an influence on the corrosion of containers and other structures. These mechanisms have been studied at Äspö, Mol and Mont Terri, as well as in Canada and the United States.

4.1.9. Other aspects

During the period from 2003 to 2005, the Sapierr[56] project was devoted to pilot studies on the feasibility and conditions of shared regional disposal facilities for the use of European countries. The objective of the second phase of the programme, Sapierr II (2006-2008, 8 partners, 8 countries) has been to develop potential implementation strategies as well as organisational structures. The participating countries are Slovenia (Arao), Switzerland (Arius), the Netherlands (Covra), Slovakia (Decom), Italy (ENEA), Spain (Enviros), Lithuania (Rata) and the United Kingdom (Sam). Other organisations from Croatia, Romania, Austria, the Czech Republic, Hungary, Spain and Serbia have also been involved with the project. The Netherlands (Covra) coordinate the project, while technical support is provided by Switzerland.

The Theresa programme (2007-2009, 16 partners, 7 countries) aims to develop a methodology for assessing the capacities of the mathematical models and codes used for the assessment of the performances of a disposal facility. In particular, these models and codes are used for design, construction, operation, safety and performance analysis, and for monitoring of geological disposal sites for nuclear waste after their closure. This methodology is based on a microscopic representation of the chemical and thermo-hydro-mechanical processes and mechanisms in geological materials and systems.

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55 Fundamental processes of radionuclide migration; 2005-2008; 51 partners and 15 countries; FPRD 6.

56 Support Action: Pilot Initiative on European Regional Repositories ; 2006-2008, 8 partners, 8 countries.

4.2. HUMAN SCIENCES

The FP6 programme Argona[57] (2006-2009, 13 partners, 7 countries) examines the way in which approaches to transparency and cooperation are interrelated. It also assesses how such approaches relate to the political system which will ultimately take the decisions with regard to the final disposal of nuclear waste. The project also examines the role of mediators in efforts to involve the public in the issue of nuclear waste.

The main objective of the FP6 programme CIP (usually known as the COWAM project) (2007-2009, 11 partners, 6 countries) is to contribute to the development of radioactive waste management in Europe. There is a national group working on the processes through which interest groups are involved in the taking of decisions concerning the management of radioactive waste in France, Romania, Slovenia, Spain and the United Kingdom.

The FP6 programme Obra (2006-2008, 10 partners, 7 countries) aims to implement mechanisms to give interest group access to the knowledge generated by the European research programmes in both science and social science.

4.3. PARTITIONING AND TRANSMUTATION

4.3.1. Reactors

The European Technology Platform on Sustainable Nuclear Energy[58] (SNE-TP) proposes a vision for the short-, medium- and long-term development of nuclear fission energy technologies, as well as ideas for the development and implementation of potentially sustainable nuclear technologies, including the management of all sorts of waste.

Transmutation strategies primarily rely upon fast neutrons, whether in critical or subcritical systems (ADS). The Generation IV forum initiative aims to develop new types of reactors, including fast reactors producing minimal waste. Two technological options have been developed in order to allow decision makers to make a choice and limit the risks related to development and to the research schedule: a sodium-cooled fast reactor (SFR), which is the first technology based on current experience in Europe, and an alternative gas- or lead-cooled fast neutron reactor technology. The objective is to be able to use fast reactor technology commercially by the year 2040. In terms of sustainable development, these two technologies may contribute to the minimisation of radioactive waste and to non-proliferation.

In terms of waste minimisation, the critical and subcritical systems should be considered according to the combustion options chosen: centralised (ADS) or distributed (critical).

The Jules Horowitz reactor (JHR) is intended to meet many future research needs in the field of thermal reactors. An experimental fast neutron system such as Myrrha/XT-ADS, which is part of

[57] Arenas for Risk Governance.

[58] The European Technology Platform on Sustainable Nuclear Energy.

the Eurotrans[59] programme, should, by 2020, meet material and fuel testing needs for fast reactors, and could contribute to the demonstration of lead technology.

4.3.2. Fuel cycles

The impact of advanced partitioning and transmutation systems, designed to reduce the burden on geological disposal, has been studied as part of the Red-Impact[60] programme. The European network ADOPT has coordinated the R&D activities of the Fifth FPRD, as well as activities in ADS development, partitioning and transmutation.

The Europart[61] programme concerned the study of various techniques for the hydrochemical partitioning of minor actinides.

The objective of the ongoing European programme, Pateros[62], is now to establish a plan for implementing the test systems and pilot plant necessary for the industrialisation of the advanced fuel cycle.

Finally, the majority of European research on pyrochemical partitioning is done at the Itu research centre in Karlsruhe. In Japan, the JAEA and Criepi also have an important programme in this field. In the United States, pyro-reprocessing, mainly of metallic fuels, is mainly studied at ANL[63] (Argonne) and INL[64] (Idaho).

In conclusion, while the situation described in the Board's first report continues to exist, it should nevertheless be noted, in the context of the current worldwide resurgence in nuclear energy, that fresh importance must be given to the quality of partnerships and their development and to competition between teams from France and abroad.

59 European Research Programme for the Transmutation of High Level Nuclear Waste in an Accelerator Driven System; FPRD 6 (2005-2009, 29 partners, 11 countries).
60 Impact of Partitioning, Transmutation and Waste Reduction Technologies on the Final Waste Disposal ; FPRD 6; (2004-2007, 22 partners, 10 countries).
61 EUROpean Research Programme for the PARTitioning of Minor Actinides; FPRD (2004-2006, 24 partners, 11 countries).
62 Partitioning and Transmutation European Roadmap for Sustainable nuclear energy.
63 Argonne National Laboratory.
64 Idaho National Laboratory.

Appendix I

MEMBERS OF THE NATIONAL ASSESSMENT BOARD AS OF 30 JUNE 2008

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 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 – Research Director at the CNRS.

Maurice Laurent – Honorary Director of the 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 (the Swedish company tasked with managing nuclear waste and fuel).

André Zaoui – Research Director at the CNRS – Associate member of the Académie des Sciences – Member of the Académie des Technologies.

Appendix II

ANDRA, CEA AND CNRS HEARINGS:

4 October 2007:	Andra: Simulation programme – Engineering programme.
25 October 2007:	CEA: Partitioning research.
14 November 2008:	Andra: Scientific programme – Observation/monitoring programme.
12 December 2007:	CEA: Scenario studies – cycle concepts – Assessment of the benefits of partitioning/transmutation.
13 December 2007:	CEA: Materials for the 2020 prototype and Generation IV reactors.
16 January 2008:	Andra: Packages and storage programme – Radiferous/graphite waste project.
17 January 2008:	CEA: Fuels, targets and irradiation programmes.
6 February 2008:	Andra: Reversibility – International overview – Information and consultation programmes (PIC).
7 February 2008:	CEA: Glass and spent fuel: Long-term behaviour (CLT).
9 April 2008 – Morning:	CEA: Encapsulation of intermediate-level waste.
9 April 2008 – Afternoon:	CNRS programmes on nuclear waste.
10 April 2008:	Andra: Initial results of programmes.

VISITS BY THE CNE:

11–12 October 2007:	Visit to the Meuse/Haute-Marne underground laboratory.
17 April 2008:	Visit to the Andra presentation area in Limay (Yvelines).

Appendix III

LIST OF DOCUMENTS SUBMITTED BY ANDRA, THE CEA AND THE CNRS

Andra

- Statement of requirements for development of the ThermoChimie thermodynamic database – C.NT.ASTR.06-003 – 23/01/2006.
- Programme of surveying from the surface – 2007 – 2014 – LLHL project at the Meuse/Haute-Marne site – D.RP.ADPE.06-0254 - 27/04/2006.
- The simulation programme for the LLHL project – C.NT.ASIT.06-0006 – 06/2006.
- Objectives of the experimentation and demonstration tests programme in the Meuse/Haute-Marne underground laboratory – LLHL project – C.RP.AHVL.06.0018 – 04/07/2006.
- Programme of engineering studies and technological tests for the LLHL project – C.NT.ASTE.06.0170 – 09/2006.
- Surface Environment/Facilities Observation and Monitoring Programme – LLHL Project – Reference: C.PE.AHVL.07.001A – 01/09/2006.
- 'Transfer' laboratories group - R & D programme 2007-2010 – 02/2007.
- Laboratories group on Changes in Cement Structures - R&D programme 2007/2012 – C.PE.ASCM.07.0002 – 02/2007.
- Description of cross-functional reversibility activity – LLHL project (C.PE.AHVL.07.0007 A) – 15/02/2007.
- 'Geomechanics' laboratories group - R&D programme 2007-2010 – C.PE.ASMG.07.0012 – 16/04/2007.
- 'Glass/iron/clay' laboratories group - R&D programme – C.PE.ASCM.07.0003 – 05/2007.
- 'Gas transfer' laboratories group - R&D programme – C.PE.ASCM.07-0001 – 05/2007.
- Storage programme for the LLHL project – Reference: C.PED.AHVL.07.0022A – 07/2007.
- Information and consultation programme – LLHL project – Approach proposed by Andra – Reference: COM.PE.ACOC.07.0011A – 24/09/2007.
- List of experimentation abbreviations for the period 2006-2012 - 10/2007.
- Package management, monitoring and transport programme – LLHL projects – Reference: C.PE.AHVL.070006A - 12/2007.
- Summary of radioactive waste management abroad – Reference: INT.RP.ADAI.07.0039A – 18/12/2007.

- Disposal project for radiferous and graphite waste – Development plan – Reference: F.PDD.APRG.07.0012A – 21/12/2007.

- Conferences and publications on the concept of reversibility - C.LI.AHVL.08.0012 A – 13/03/2008.

- Technology demonstrators – Research and studies on the disposal and storage of high-level and long-lived intermediate-level waste – 04/2008.

- Specifications on high-level and long-lived intermediate-level waste packages - C.NT.AHVL.08.0019 A – 04/2008.

- Progress report on LLHL and LLLL waste projects - Z.NSY.ADSD.08.007 A – 18/04/2008.

CEA

- Technical document DMN/SEMI/LCMI/PU/2006-016/A – *'A Creep Model for CWSR Zircaloy 4 Cladding taking into account the Annealing of the Irradiation Hardening'* – C. Cappelaere, R. Limon, C. Duguay, P. Bouffioux, V. Chabretou – July 2006.

- La lettre de l'I-tésé – Issue 1 – June 2007.

- La lettre de l'I-tésé – Issue 2 – November 2007.

- La lettre de l'I-tésé – Issue 3 – March 2008.

- Note DEN/DEC/SA3C – *'Development status of irradiation devices for the Jules Horowitz Reactor'* - G. Gonnier, D. Parrat, S. Gaillot, J.P. Chauvin, F. Serre, G. Laffont, A. Guignon, P. Roux – 3 February 2008.

- Note – *'The JRH project: a new material testing reactor of European interest'* – 3 February 2008.

- Note SESC/DIR 08-003 (DO) – Experimental irradiation programme for the systems of the future and the transmutation of minor actinides – March 2008.

CNRS

- MOMAS Scientific assessment 2002-2007 – G. Allaire, A. Ern and M. Kern – 7/07/07.