NATIONAL ASSESSMENT BOARD

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

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

ASSESSMENT REPORT N°6

NOVEMBER 2012

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CNE2 OPINION ON THE MANAGEMENT OF RADIOACTIVE MATERIALS AND WASTE

(Submitted to the OPECST on 21 September 2012)

The nuclear industry produces long-lived radioactive substances. Some of these are waste. Ethics and sustainable development prohibit us from passing on the burden and concern to future generations. Surface storage must only be a medium-term stopgap. Based on expert advice, the countries concerned have concluded that the solution providing all the necessary safeguards is deep geological disposal. The law of 2006 adopted this method for the management of French waste, in conjunction with a reversibility clause for a period of at least one century. Others, including plutonium and depleted uranium, could be used as resources for a new generation of reactors. These must first be made more effective and even safer. Their implementation would ensure France's independence, in terms of electricity production, for several centuries. The same law of 2006 confirmed the mission given to CNE2 to annually submit to Parliament a report and an opinion on the progress and quality of the studies, research and developments carried out in the fields of deep geological waste disposal and the transmutation of radioactive materials by means of Generation IV reactors.

Drawing on more than twenty years of experience, gained through listening to those concerned and the assessments of facilities and laboratories contributing to this initiative both in France and abroad, CNE2 believes it is justified in saying today that:

1. the glass packages and clay in deep geological repositories are effective barriers for containing fission products and actinides for hundreds of thousands of years. This is enough time to reduce their harmfulness to a level where it no longer constitues a problem for people living near the disposal facility;

2. the Meuse/Haute-Marne geological site was selected for detailed studies because a clay layer more than 130 metres thick and at a depth of 500 metres below surface, demonstrated excellent containment qualities: stability over at least 100 million years, very slow water circulation and a high holding-capacity of radionuclides;

3. the design of the structure to be built - shafts, tunnels, cavities, ventilation, seals - and the development of the methods and procedures necessary for its safety, during its operation and after its final closure, are currently being studied. They are advanced enough to enter the industrial phase in accordance with the law. This is a specific implementation project, with all the necessary development, innovation and engineering steps. It must be carefully monitored. The review in 2015 of the application for authorisation to create the disposal facility will be an important milestone in this monitoring;

4. the plutonium produced in the fuel cycle is a dangerous substance, but it may also become a valuable resource if used in fast neutron reactors. These reactors have the added benefit of consuming depleted uranium, for which there is currently no use, which would relieve the heavy burden on mining and enrichment. Moreover, they could potentially be used to transmute minor actinides into shorter lived isotopes. Research and development dedicated to fast neutron reactors have already validated its the scientific and technical feasibility. In order to test the industrial and economic viability, an experimental reactor and its corresponding cycle - fuel fabrication and reprocessing - are essential. Its implementation, under the law of 2006, preserves the range of energy choices, strengthens French expertise in the civil nuclear industry and ensures that France and Europe are competitive on the world stage.

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SUMMARY AND CONCLUSIONS

Under the provisions of the law of 2006, the long-term management of LLHL (long-lived high-level) waste comprises two complementary aspects: the partitioning and transmutation of the minor actinides present in the spent fuel of future nuclear reactors and the geological disposal of long-lived, high- and intermediate-level waste.

Partitioning and transmutation

The law of 2006 makes provisions for combining research on partitioning and transmutation with R&D on the new generation of reactors (fast neutron reactors (FNR) and subcritical accelerator-driven reactors (ADS)[1]).

Partitioning processes have reached a level of technical maturity that makes it possible to envisage industrial transmutation operations. In particular, the CEA has demonstrated the technical feasibility of multi-recycling the plutonium produced by MOX fuels in FNRs with the aid of the extractant molecules and partitioning techniques it has developed.

ADS are being studied, within the framework of a European strategy, for their potential to transmute minor actinides. The Belgian teams from SCK•CEN, together with those from the CEA and the CNRS are currently developing the GUINEVERE project, a model experiment simulating an ADS. GUINEVERE is the first step of the MYRRHA programme, which aims to build a lead-cooled ADS powerful enough to prepare for the transition to industrial operation well beyond 2040.

Combined with an operational PWR fleet, ADS do not allow all the plutonium produced from reprocessing to be burned nor, consequently, for the fuel cycle to be closed, unless most of the plutonium is managed by implementing a fleet combining FNRs with ADS.

Regarding FNRs, the CEA has initiated R&D in partnership with EDF and Areva with a view to building in the 2020s an industrial prototype of a power reactor called ASTRID. This prototype will make it possible to use plutonium combined with depleted uranium in the fuel and remove the need for imports of natural uranium. Research is focused on making significant improvements to the level of safety, which must be at least equal to that of Generation III reactors. The most significant advances are the negative void coefficient in the core, which provides increased passive safety, the heat exchanger with an inert gas to eliminate the risks of contact between sodium and water, and improved in-service inspection. The Board greatly values these innovations.

The research reactor ASTRID and its corresponding cycle - fuel fabrication and reprocessing - are essential for testing the industrial and economic viability. The construction of an industrial prototype requires in-depth research on the materials that will have to withstand high burn-up levels. A thorough analysis of the radiation protection during the loading, unloading and cooling of the fuel is required. A comprehensive programme, making it possible to establish the industrial feasibility of americium transmutation, will require, during a second stage, the industrial development of americium partitioning, followed by the construction of a fabrication and reprocessing unit for americium-rich blanket fuels.

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1 Accelerator-Driven System

Geological disposal

The argillite layer more than 130 metres thick and at a depth of 500 metres below the location of the Meuse/Haute-Marne site has been studied for over fifteen years. It demonstrates excellent containment qualities: stability over at least 100 million years; a high holding-capacity of radionuclides, demonstrated by geochemical studies; the lack of fluid transfers, confirmed by the analysis of the deep borehole drilled down to the base of the Triassic; a radionuclide transfer time calculated at hundreds of thousands of years; very slow water circulation in the surrounding aquifers, confirmed by an experimentally validated hydrogeological model.

The design of the structure to be built - shafts, tunnels, cavities, ventilation, seals - has been entrusted to a System Integrator. The development of the systems and procedures necessary for its safety, during its operation and after its final closure, are currently being studied. Andra, the project owner, still assumes full responsibility. These studies are advanced enough for the industrial phase to begin in accordance with the law. This is a specific implementation project, with all the necessary development, innovation and engineering steps. The Board is still awaiting details on the cost of the structure.

The Board will devote special attention to considering the design choices for the Cigeo disposal site and the surface facilities selected by Andra. Uncertainties regarding the long term mechanical behaviour of the rock mass must be taken into account for the design of the LLHL waste cavities and seals. The Board recommends moving as quickly as possible towards a summary of the measures in place and the development of a sound hydro-thermo-mechanical predictive model, which is essential for the engineering of this project. The board draws attention to the fact that, to meet the reversibility requirement imposed by the legislature, full-scale sealing tests must be carried out. However, this will only be possible in a project conducted both in the underground laboratory and in a dedicated part of the disposal facility itself.

Andra plans to build the disposal facility progressively. The first phase of the Cigeo project involves building the facilities required to begin operations and receive a first batch of waste. The review in 2015 of the application for authorisation to create the disposal facility will be an important milestone; it will give the Board an opportunity to check whether satisfactory responses have been given to the questions raised in this report. If this was not the case, the Board would recommend delaying the authorisation to build.

The waste package inventory to be taken into account for sizing the Cigeo disposal facility was developed jointly by Andra, Areva, the CEA and EDF. In accordance with the law of 2006, the direct disposal of spent fuels, excluding the fuels of the EL4 heavy water reactor, is not provided for in this inventory. Should it be in the future, several decades of storage, after unloading the fuels from the reactors, will be needed for them to cool. Their management under the Cigeo project will also be addressed by a public investigation in order to modify the authorisation decree.

With the exception of bituminous waste, there is a satisfactory level of knowledge concerning the packages considered for the first phase of disposal. Bituminised sludge packages raise a number of specific problems. Given current knowledge and the uncertainties about their behaviour, especially in the short term, in case of fire, the recommended course of action is to not include them in the first phase of the disposal facility's operation. In order to give a definitive ruling, the Board must be presented by December 2014 with a full-scale demonstration including a safety analysis of the behaviour of the primary package and its container in the disposal facility, under the severest of conditions. The safety analysis must be jointly conducted by the CEA and Andra. Should the demonstration not be convincing, the Board would recommend investigating, prior to any decision, ways in which the bituminous packages could be processed in order to transform them into other final waste.

International dimension

By supporting, in 2012, more than 60 projects devoted to optimising technical solutions or training in the field of long-lived waste or that of new reactor concepts, Europe has shown the great importance it attaches to these areas.

France is involved in 53 of these projects. Andra logically focuses on projects that relate to waste management and disposal. The CEA conducts research on new reactor concepts. The CNRS is particularly active in research on lead-cooled subcritical systems and the design of the accelerator that drives them.

Although the major French players in the nuclear industry (Andra, Areva, CEA, CNRS, EDF, IRSN) contribute to a significant number (53) of international projects (60), there is low participation in European projects dealing with social aspects or the involvement of stakeholders.

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FOREWORD

The issue of waste is not separable from that of the entire nuclear cycle, or the choice of reactor systems behind the waste needing to be managed. The problem with nuclear waste is therefore a problem with the entire cycle and must be treated as such.

Following the debate on energy transition, the decisions to be taken, including those concerning existing reactors, must take into account their repercussions – in terms of waste management – on the reprocessing strategy, on new reactor systems, on their implementation for the recycling of plutonium and the potential transmutation of minor actinides, and on the geological disposal project.

CNE2 ACTIVITIES

The period from November 2011 to October 2012 is the fifth full fiscal year for CNE2, and is the subject of this Report No. 6. Since the publication of its previous report in December 2011, the Board presented its Report No. 5 to various audiences, the top tier of which included the OPECST and ministerial departments. A Board delegation also visited Ligny-en-Barrois (Meuse, Lorraine) on 13 March to present this report to the members of the CLIS (local information and monitoring council) of Meuse/Haute-Marne.

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The Board followed the same working method as used in previous years. It held 16 hearings. These included six full-day sessions in Paris and two at the Meuse/Haute-Marne laboratory at the Bure/Saudron site, as well as a number of additional meetings. The members of the Board, all of them volunteers, listened to 93 people from Andra and the CEA, as well as from academic and industrial institutions from France and abroad. These hearings, each of which attracted an average of around fifty people, were also attended by representatives of the French Nuclear Safety Authority (ASN), AREVA, EDF, the Radiation Protection and Nuclear Safety Institute (IRSN), and the central government. With the CNRS' Pacen programme being restructured[2], the Board deferred the examination of its performance to the following fiscal year.

This year, the Board visited the facilities of the Areva site in the Hague as well as the GUINEVERE facility[3] at the SCK•CEN site in Mol, Belgium.

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

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This report is organised to reflect the two complementary aspects of R&D on the management of radioactive waste and materials: partitioning and transmutation in Chapter 1, and storage and disposal of long-lived high-level (LLHL) and long-lived intermediate-level (LLIL) waste in Chapter 2.

Consistent with its mission, the Board continues to observe the overall international situation. The main elements are reported in Chapter 3 and Appendix VI.

2 Needs (Nuclear: Energy, Environment, Déchets [Waste], Society) is the new programme.

3 Generator of Uninterrupted Intense NEutrons at the lead VEnus Reactor.

At the request of the CLIS (local information and monitoring council) of Meuse/Haute-Marne, the Board received at its offices a delegation of the CLIS and the President of the Institute for Energy and Environmental Research (IEER). The IEER presented its process for assessing the research conducted by Andra in the underground laboratory and the main findings of a report commissioned by the CLIS, given to the IEER in February 2011. The Board's analysis of this report can be found in Appendix IV. As a result of its visit to the StocaMine site in March 2011, the Board learned some lessons on the reversibility of deep waste disposal, presented in Appendix V.

Finally, in the context of the national debate on energy, the Board submitted in September 2012, to the OPECST, an opinion summarising its position on two major topics that currently govern the issue of nuclear waste: on the one hand, its disposal in deep geological repositories, and on the other hand, optimised management of future waste produced by Generation IV reactors. This opinion can be found at the beginning of this report.

2012 is an important milestone for legislators. Under the provisions of the law of 28 June 2006, the National Programme for the Management of Radioactive Materials and Waste (PNGMDR) has set them the following deadlines:

- **31 December 2012 at the latest:** *"Andra shall provide the ministers responsible for energy, research and the environment with the case supporting the organisation of the public debate",* which will be held prior to the filing of an application for authorisation to build a deep geological disposal site.

- **31 December 2012 at the latest:** the CEA shall provide the ministers responsible for energy, research and the environment, respectively, with a file presenting the results of research on partitioning and transmutation.

At the time of writing this report (mid-October 2012), it was too early for the Board to know the content of these files. It has therefore based its opinion on the information gathered during the hearings, but has not at this stage prepared technical appendices, pending content it will receive towards the end of 2012.

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Chapter 1

PARTITIONING & TRANSMUTATION

1. 1. INTRODUCTION

In order to manufacture the fuel for PWR power reactors, an enrichment phase is required to transform natural uranium into uranium-235. The residual depleted uranium is then held in industrial storage. The spent fuel from these reactors contain uranium, plutonium, fission products and minor actinides. France has chosen the partitioning and reprocessing strategy: fission products and minor actinides are vitrified for eventual deep disposal; plutonium, which has an energy value, is used as a mixed oxide of uranium and plutonium (MOX) in the current fleet of reactors. In practice, however, plutonium can only be recycled once, while it can be recycled indefinitely in a fast neutron reactor. The use of plutonium in the MOX used by PWRs is therefore only a transitional stage of the French reprocessing strategy, which in fact forms part of the broader perspective of implementing fast neutron reactors.

In these reactors, the plutonium and uranium produced by enrichment and reprocessing are fuel elements that are independent of any external supply. These reactors would also make it possible to explore the transmutation of certain minor actinides, including americium.

It is in this context that the law of 2006 calls for research to be conducted on partitioning and transmutation in connection with R&D on new generation reactors (FNRs and ADS[4]). ADS are being studied within a European framework with the MYRRHA project. As for FNRs, the CEA has undertaken with its partners EDF and Areva, R&D in order to develop and implement the industrial prototype of a fast neutron reactor called ASTRID.

This chapter reports on the state of the art as it was presented to the Board during the fiscal year 2011-2012, pending the file that the CEA must submit at the end of 2012 in order for the Government to have an assessment of the industrial prospects of these technologies.

1.2. PARTITIONING

Since the law of 1991, the CEA has developed and led a major R&D programme on the partitioning and transmutation of long-lived radioactive elements, which it has pursued and completed under the provisions of the law of 28 June 2006.

New molecules with extractant properties have been created. Their synthesis can be carried out on an industrial scale. These molecules are stable and resistant to radiolysis in real partitioning operating conditions.

4 Accelerator Driven System.

Partitioning processes (columns, pulsed columns, etc.) have reached an indisputable level of maturity. The CEA has a unique set of patented processes able to achieve the various strategies for partitioning actinides (uranium, plutonium, americium, neptunium, curium) or partitioning groups of elements (fission products, groups of elements containing uranium and plutonium and/or minor actinides) in order to meet their implementation requirements.

The MOX fuels to be used for future FNRs differ significantly from the MOX fuels used in PWRs, manufactured at the Melox plant. In order to develop on an industrial scale the multi-recycling of plutonium derived from MOX used in FNRs, the CEA launched a series of studies with a view to separating the reusable materials (uranium and plutonium) and using them to produce a new fuel. The management of the processes applied to the MOX fuels used in PWRs, has been validated. This is an important achievement that establishes the feasibility of reprocessing these fuels and in turn the availability of the plutonium they contain for the development of fuel for future FNRs. Furthermore, solutions emulating those that would be achieved by leaching around one kilogram of irradiated FNR fuel, have successfully been processed and show that plutonium could be isolated for multi-recycling. This demonstrates the applicability of the extractant molecules and partitioning techniques developed by the CEA, to all irradiated MOX fuels from PWRs (including EPRs) and from future FNRs.

Finally, the effluents arising from partitioning operations have been characterised; R&D continues concerning their processing and conditioning. Thus, in order to meet the requirements of a deep disposal for iodine, several matrices are being investigated.

1.3. TRANSMUTATION

There is now an alternative for implementing the transmutation of actinides: ADS, including the European MYRRHA project in which France is involved, and fast neutron reactors, including the French ASTRID project.

1.3.1. ADS

ADS are a potential means of transmuting minor actinides. R&D on ADS is being undertaken as part of the European programme MYRRHA, which aims to build a low-power prototype in Mol (Belgium). The Belgian teams from SCK•CEN, together with those from Areva, the CEA and the CNRS, are playing a leading role in this project, which is but a first step towards the construction of an industrial ADS.

The MYRRHA project is the culmination of a decade of European projects (IP-Adopt, Pateros, Eurotrans, Arcas) having developed a strategy for the partitioning and transmutation of actinides. This strategy is based on Europe-wide ADS implementation, which would make it possible to transmute the actinides generated by European reactors.

The construction of a high-power accelerator designed to drive a subcritical reactor is a very innovative project. The experiments conducted have shown its scientific feasibility. Within the framework of the MYRRHA programme, the teams from SCK•CEN are currently operating the GUINEVERE system. The aim of this model experiment is to validate the control and supervision procedures of a subcritical reactor and to study the different core configurations considered for MYRRHA.

Combined with an operational fleet of PWRs, ADS are not likely to close the fuel cycle without the simultaneous use of FNRs capable of consuming the plutonium derived from reprocessing the irradiated fuel of PWRs (12 Kg Pu/MTIHM[5]).

In fact, a 385-MWth ADS could multi-recycle the 2.5 tonnes of plutonium introduced into its fuel at start-up, but this amount is only part of the total plutonium that would be available. The levels of plutonium and minor actinides in the fuel are high. As a result, the reprocessing of the irradiated fuel is not a simple transposition of the method developed for FNRs, because the chemistry and radiation protection must be specific.

In order to close the fuel cycle through the use of ADS to transmute the minor actinides, it is therefore necessary to manage the bulk of the plutonium derived from reprocessing and that means operating on two levels:

- The fuels of a PWR fleet are processed to separate the uranium, plutonium, minor actinides and fission products. The minor actinides are transmuted in ADS.

- The plutonium is partially consumed at start-up of the ADS and most of it is converted into fuel for FNRs.

Finally, an ADS would be able to produce the energy needed to operate the accelerator associated with it.

1.3.2. Astrid

1.3.2.1. Safety and technological specificities

Although the possibility of transmuting plutonium in FNRs was established in the Phénix reactor, it will be necessary to demonstrate that the tool to be used in the future meets the safety requirements of 2040.

The most significant development relates to the change in reactor safety standards. For any project after Flamanville III, a safety standard consistent with that of Generation III reactors and including the feedback from the Fukushima incident will be required. This change of standards is not simply about making marginal adjustments; it often means making real breakthroughs in order for significant progress to be achieved in decreasing the probability of core meltdown or external contamination. It draws on feedback about reactors from all over the world.

With ASTRID, the most significant advances proposed by the CEA in the context of a very large collaborative effort involving numerous industrial companies (Areva, EDF, Alstom, etc.) relate to:

❖ A lower probability of a core meltdown:

- A core with low reactivity loss throughout the whole cycle allows for reduced control rod penetration during operation, which makes incidents caused by the inadvertent withdrawal of a control rod manageable;

[5] Metric tonne of initial heavy metal.

- A core whose reactivity is made very low, even negative, due to sodium voiding and which has a favourable Doppler coefficient. The core designed in this way prevents high energy releases in the event of loss of flow, loss of heat sink or loss of power;

- A diagnostic system based on the acquisition and online processing of signals from different sensors and using the latest signal processing techniques.

❖ The elimination of the risk of significant energy release caused by reactions between sodium and water, either through the use of modular heat exchangers or through the use of an inert gas (nitrogen) in the tertiary circuit, prior to the first two sodium-cooling circuits;

❖ Strengthening of the containment building, which reduces the probability of chemical or radioactive releases outside, with a level of safety at least equal to that of EPRs:

- A corium recovery device equipped with a cooling system, to prevent the contamination of the subsoil and the environment;

- A reactor building design with anti-seismic bearings;

- The consideration of internal and external hazards, as well as aircraft crashes.

❖ A more efficient in-service inspection for which significant developments are underway at the CEA, EDF, Areva and Comex (improving the reliability of new sensors under extreme temperature and irradiation conditions).

Expertise and acquired knowledge

The scientific feasibility of the transmutation of americium was proven at CEA by the analysis of a few fuel pins containing minor actinides, irradiated in various European reactors: Phénix prior to its shutdown; HFR in Petten (Netherlands) and BWR in Halden (Norway), high-flux reactors able to irradiate very small fuel pins, charged with actinides. It should be noted that the operating conditions of these reactors are in no way representative of those of power FNRs; an FNR prototype is therefore required to establish the industrial feasibility of transmutation. Based on current knowledge, among the minor actinides, the first reactor experiments should be conducted on americium. Regarding curium, scientific and technological advances do not currently make their transmutation envisageable without the use of heavy-duty equipment to provide workers with effective protection against radiation.

Implementation:

Besides its function as power reactor fuelled with plutonium and depleted uranium, ASTRID will be able to transmute americium, without changing its design. Thus, in the event of industrial deployment of a fleet of FNRs, it would not be necessary to use a reactor design dedicated to the transmutation of americium.

Two different modes could be explored for adding the americium to be transmuted[6] to the reactor:

[6] The cross-sections still insufficiently known in 1991 were measured and the new values were introduced into the simulation codes for estimating transmutation levels.

- Homogeneous mode, which, for safety reasons, consists in adding only a small amount of americium (2-3%) to the reactor core. Homogeneous mode has the advantage of optimal neutron irradiation and therefore provides a high level of transmutation. It requires handling the americium at all stages of the fuel's fabrication and processing, and therefore huge dedicated facilities;

- Heterogeneous mode, which allows the use of blankets fuels with an americium content of around ten percent. The americium to be transmuted is then placed on the edge of the core. Implementing this mode of transmutation requires dedicated americium handling facilities for the fabrication of blanket fuels and for their reprocessing after cooling in a sodium bath.

A comparison of the two modes, homogeneous and heterogeneous, seems to favour the heterogeneous mode due to the complexity of managing the core (U, Pu, Am) compared to managing americium-rich blanket fuels. In the case of a homogeneous fleet of FNRs deployed at the end of the century, using 900 t[7] of plutonium, the total amount of americium introduced in the various phases of the cycle would be 100 tonnes, whereas the heterogeneous mode would not require loading all the reactors with americium.

Although it is difficult to establish the exact costs, it is estimated that the cost of the transmutation of americium only, would be equivalent to that of the geological disposal of all the waste, to be compared to the savings due to the reduced area of the disposal site and the volumes excavated.

1.3.2.2. Demonstration of the industrial feasibility

Thanks to scientific and technological advances made since 2006, the construction of an innovative prototype Generation IV reactor, meeting safety requirements higher than those of EPRs (Generation III) is now technically possible. This is a major technological breakthrough because the Phénix and Superphénix reactors, as well as other projects around the world, such as the BN-600 and BN-800 reactors in Russia or the Indian PFBR-500, meet a lower safety standard.

In order to maintain and make best use of the expertise and skills developed over many years in France, a series of necessary measures should be adopted, the sequence of which could be as follows:

Materials for ASTRID:

Essential innovations for ASTRID relate to core materials. Structural materials (vessel etc.) benefit from the feedback from Phénix and Superphénix.

ASTRID will have high burnup rates and subsequently high irradiation doses. The proposed solutions for obtaining a negative void coefficient, and therefore increased safety, depend on the core having excellent dimensional stability. To do this, it is important that the core materials, and in particular cladding materials, have good stability against swelling. Ongoing studies on AIM1 cladding materials and its progression AIM2 provide a reference material that meets these specifications, but their use is limited to doses of 130 displacements per atom (dpa)[8].

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7 See Reports No. 4 and No. 5, 2004, and 2005.

8 Dose unit to express radiation damage.

In order to achieve higher burnup rates, and subsequently higher irradiation doses (up to 180 dpa), studies have been initiated on oxide dispersion strengthened (ODS) ferritic steels. They focus on their development, implementation, heat resistance and resistance to swelling. Unlike AIM2 materials, which are merely a progression of AIM1 alloys, ODS alloys are a very innovative solution that requires an extensive research programme. This programme will involve fundamental research on the role of interfaces in irradiation damage and on the specificities of high doses.

For cladding materials falling into the category of "consumable materials", the issues of industrial reliability and the development of a high-tonnage manufacturing tool are crucial, and should be quickly addressed. The schedule, forecasting its transfer to industry in 2020, is appropriate and must be adhered to.

Vanadium alloys and woven SiC/SiC[9] composites, alternative solutions to ODS alloys, are not understood to the same degree and have a longer schedule for implementation. Vanadium alloys, like all refractory metal materials, exhibit poor resistance to oxidation. Solutions based on SiC/SiC composites woven around a metal liner[10] to ensure a tight seal are beyond innovative; they would be a real technological breakthrough. The expected problems associated with differential expansion and irradiation damage in the bulk material as well as at the interfaces, make this a potential long-term solution that should be treated as such in terms of priorities in programmes with very tight schedules.

The Commission recommends prioritising studies and research on AIM2 and ODS.

Transition to the implementation of the project:

Along with the development of materials and the construction of the ASTRID reactor, the following actions are essential:

- Construction of a pilot reprocessing facility and a fuel fabrication unit in order to demonstrate full-scale control of all the industrial operations, namely to show that the ASTRID power reactor can actually be powered by plutonium derived from reprocessing its spent fuel, to which depleted uranium is added;

- Assessment, from the point of view of radiation protection, of the different operations: transport, loading, unloading, cooling in a sodium "pool" and then water, and their impact on the various designs.

In order to perform the transmutation of americium, the following actions are essential:

- Construction of a fabrication and reprocessing unit for americium-rich blanket fuels;

- Industrial development of AmEx (Americium Extraction) partitioning in order to:

  − isolate the americium content in the irradiated fuel of the ASTRID reactor,
  − isolate americium by processing the irradiated americium-rich blanket fuels.

9 Silicon carbide.
10 Liner with composite overwrap.

The law of 28 June 2006 provides that "The corresponding research and development [on the partitioning and transmutation of radioactive waste] is being conducted in connection with that conducted on the new generations of nuclear reactors mentioned in Article 5 of Law 2005-781 on the programme establishing the directions of the energy policy...".

The Board considers that only by undertaking, without delay, the programme described above, will it be possible to bring together the scientific, technological and industrial knowledge required to strictly meet the demands of the law of 28 June 2006.

Not initiating this programme risks definitively closing the door on the range of choices.

1.3.3. FNR scenarios associated with a PWR fleet

Today the French fleet of power nuclear reactors consists solely of PWRs. Part of this fleet uses MOX for fuel, which allows a 20% saving of natural uranium. No FNR is in operation. This scenario is likely to continue for as long as we agree to import and enrich uranium. Various scenarios can be considered for introducing FNRs into a power-generating fleet. Report No. 5 of the CNE2 (2011) described a fleet in its final state, consisting solely of FNRs. A scenario that progressively introduces FNRs into the fleet is also possible. It reflects the outcome of studies aiming to use depleted uranium and plutonium as resources to generate electricity. This FNR deployment scenario has been analysed in collaborative studies (Areva, CEA, EDF) that take into account the current fleet and its possible developments. It projects a transition in several stages:

- the renewal of existing PWR units, in line with their useful lives, with more efficient PWRs such as EPRs ensuring the mono-recycling of reprocessed plutonium (about 15% of the plutonium derived from reprocessing) and uranium;

- the deployment towards 2040 of a first series of eight 1500-MWe FNRs, which, while being power reactors, would ensure the multi-recycling of the plutonium derived from processing the MOX PWR fuels accrued to that date, i.e. approximately 172 tonnes of fissile plutonium;

- In this scenario, the fission products are separated and vitrified prior to deep disposal. The reprocessed plutonium and uranium are resources and the minor actinides are placed in a pool for cooling while a decision is made on either their transmutation or their conditioning for deep disposal;

- With MOX PWRs continuing to operate, the processing of their fuel produces a maximum of 3.5 tonnes of plutonium per year; it is therefore necessary to add one FNR every 6 years to use the plutonium produced in this way, which would mean a dozen units in 2080.

By 2080, we could then use the plutonium and depleted uranium as a resource to generate electricity for several centuries without resorting to uranium imports and enrichment. If instead the decision were made to use FNRs to put an end to nuclear powered electricity generation, then the FNRs would likely operate as sub-generators with a Capra-type fuel[11] in order to consume plutonium.

The Board recommends studying this possibility thoroughly.

[11] In response to the reduction in the share of nuclear power introduced in our energy mix and possibly its withdrawal by 2080, the dozen FNR units deployed at that time would, with a Capra-type operation (increased plutonium consumption in advanced reactors), make it possible to implement the progressive resorption of most of the nuclear materials accumulated until that time.

Chapter 2

DISPOSAL AND STORAGE

2.1. INTRODUCTION

For the preparation of its 2012 report, the Board worked on the basis of the scientific advances made by Andra in its 2009 Report and until mid-2012 while considering the new elements and questions raised by the publication of the STI project by the producers and by the first review of the Cigeo project carried out in 2011.

For the end of 2012, Andra is preparing the report for the public debate prior to the application for authorisation to construct a disposal facility. It has demonstrated the long-term containment qualities of the Callovo-Oxfordian geological layer. Concerns now focus on the design options for the disposal facility and the technological responses to future issues relating to the construction and operation of phase 1 of the Cigeo project.

The Board was unable to take into account the concepts resulting from the draft phase of the Cigeo project as no definitive information was available on the subject at the time of this report.

The results of its assessment in this regard are presented in this chapter as follows: Cigeo project inventory, characterisation of the ZIRA, scientific work (underground laboratory experiments, knowledge of the geological environment, hydrogeological modelling, long-term mechanical behaviour, release of gas) and technological advances (HL waste cavities, seals).

Moreover, the Board has analysed, in terms of impact on the implementation of reversibility, the feedback of the StocaMine situation, a disposal site for hazardous industrial waste in a salt layer, whose closure is under review *(see Appendix V)*.

Finally, the Board has expressed its views, in response to questions raised by the CLIS of Meuse/Haute-Marne, on the IEER's assessment report[12] on the research conducted by Andra *(see Appendix IV).*

2.2. CIGEO PROJECT INVENTORY

To date, 2700 m^3 of vitrified LLHL waste[13] and 41000 m^3 of LLIL waste[14] have been produced. Assuming a useful life of 40 years for the existing PWR fleet, these figures will increase to 8000 m^3 of vitrified LLHL waste and 65000 m3 of LLIL waste needing to be managed

The waste package inventory to be taken into account for sizing the Cigeo disposal facility was developed jointly by Andra, Areva, the CEA and EDF. It is on this basis that the application for authorisation to create a disposal facility (DAC) will be submitted in 2015.

12 American Institute for Energy and Environmental Research.
13 Long-lived high-level waste.
14 Long-lived intermediate-level waste.

This inventory lists the waste produced and yet to be produced by facilities within the nuclear industry, the waste generated by research activities and the waste to be produced by reactors currently under construction (EPR at Flamanville and ITER). It is calculated for operating periods taken conventionally at 50 years. The waste produced by a potential new fleet of reactors is not taken into account. The inventory has been prepared on the assumption that the spent fuel from PWRs is reprocessed. Should reprocessing be stopped, all spent fuels would become LLHL waste to be placed, as the situation currently stands, in deep disposal.

Waste producers have set margins designed to cover the uncertainties in the volume of legacy waste to be conditioned or reclaimed, in industrial strategies and in particular in the conditioning of various categories of waste.

2.2.1. Case of spent fuels

For the DAC 2015, all spent fuels are assumed to be processed, except those of the Brennilis EL4 reactor.

However, according to the PNGMDR 2010-2012, Andra, in partnership with the CEA and EDF, is updating studies on the long-term behaviour of spent fuels that would potentially be disposed of in the future without prior reprocessing[15]. Moreover, Andra is checking that the dimensions of the drift, shafts and tunnels are compatible with the underground transport of the spent fuels. The design of the cavities and the decision on their spacing require additional detailed studies. Given the considerable heat released by spent fuels, they would only be placed in the disposal facility after decades of storage once unloaded from the reactors. Andra thinks that the Cigeo project may evolve towards the creation of modules for storing spent fuels. Their management would then have to be addressed by a public investigation prior to any amendment to the authorisation decree.

2.2.2. Packages provided for in the first phase of the Cigeo project

Andra has developed a management chart to monitor the state of knowledge on the different families of waste packages whose disposal is provided for during the first operational phase of the Cigeo project from 2025 until 2029, defined in the Industrial Waste Management Programme (PIGD).

The Board considers that:

- *the level of information on some families of packages (such as hulls and end-caps, standard containers of compacted waste, packages of vitrified waste in Marcoule) is sufficient to consider storing them in the first phase;*

- *the uncertainty or lack of knowledge about other types of packages must be resolved within the next five years in order to be able to carry out the safety analysis prior to their disposal;*

[15] One metric tonne of spent fuel contains 940 kg of uranium, 10 kg of plutonium and 4 kg of fission products and minor actinides.

- *many specific problems exist concerning bituminised sludge packages, considered as an option for the first operating period of the Cigeo project. Given current knowledge and the uncertainties about their behaviour, especially in the short term, in case of fire, the recommended course of action is to exclude them from the first operational phase of a disposal facility.*

  In order to give a definitive ruling, the Board must be presented by December 2014 with a full-scale including a safety analysis of the behaviour of the first package and its container in the disposal facility, under the severest of conditions. The Board expressly requests that the testing protocol is presented to it beforehand. The safety analysis must be jointly conducted by the CEA and Andra.

  Should the demonstration not be convincing, the Board would recommend studying, prior to any decision, ways in which the bituminous packages could be processed in order to transform them into final waste whose behaviour is less difficult to model. The type of conditioning, which must meet the safety requirements, will be decided on the basis of the processing method adopted.

2.3. CHARACTERISATION OF THE ZIRA

Andra and its subcontractors successfully completed in 2012 the processing (stratigraphic inversion and depth conversion) and interpretation of the 3D seismic block, the field acquisition of which was performed in 2010. The preliminary results based on the first processing operations, including prestack migration, were already summarised in Report No. 5 of the CNE in 2011.

The stratigraphic inversion was performed using several geophysical data inversion techniques. The purpose of this, after converting seismic amplitudes into acoustic impedances and setting three calibration boreholes located at the periphery of the ZIRA, was to accurately and continuously assess the porosity of the horizons above (Oxfordian carbonate) and below (Dogger) the Cox. This stratigraphic inversion revealed a reef structure with a short horizontal extent (2 km x 300 m) in the Oxfordian carbonate, and also the extent of the N210-oriented reef structures already identified in the Dogger (Bajocian); these local porosity anomalies have no influence on the Cox clay layer, which appears to be devoid of such heterogeneities.

The Board considers that Andra has taken full advantage of the information provided by the 3D seismic survey on the ZIRA. The seismic survey helped to confirm the sedimentary origin of the heterogeneities existing above and below the layer: these heterogeneities, by their very nature, cannot propagate into the Cox. This information confirms the regularity of the geometry of the Cox, its very low lithological variability and, with regard to the interfaces with its overburden layers, the lack of faults able of penetrating the Cox. The Board considers that further information on the ZIRA may only be acquired during the excavation phase of the access shafts to the disposal facility, by taking advantage of the vertical boreholes planned along the axis of the access shafts. These will then be used to consolidate the 3D geological model before the final excavation stages of the horizontal tunnels.

2.4. SCIENTIFIC WORK

2.4.1. Underground laboratory experimentation

The experimental programme in the Meuse/Haute-Marne underground laboratory continued in 2011-2012 with an emphasis on technological tests; these have been designed to acquire useful data for preparing the DAC in 2014.

Experiments on the construction of the tunnels are in progress. A first type of test is designed to test the behaviour of rigidly designed tunnels (GCR experiments) by monitoring the structure sections equipped with different types of support: shotcrete with compressible shims or shotcrete without compressible shims. Sensors are embedded into the coating at the time of construction to monitor its loading and deformation. A second test of the same type, but conducted in a flexibly designed tunnel (GCS) is scheduled and will make it possible, through comparison with the first, to understand the relationship between ground deformation and the loading of the support.

A 40-metre HL waste cavity has successfully been excavated in the GAN tunnel and fitted with an instrumented, waterproof lining. The aims are to obtain data on the evolution of the argillite/lining interface (convergence of the rock mass, the speed at which the annular space fills with water) and to test monitoring methods, in particular by means of fibre optic sensors. An attempt to embed a 10-metre-long insert into the cavity head as planned was unsuccessful (stopped at 7.5 m) due to an inadequate drilling machine.

The TSS1 test in the GET tunnel involved testing the feasibility and behaviour of a 30-cm-wide, 2.5-m-deep radial trench, which is one of the components of the tunnel sealing facilities. Deformation measurements taken during and after the excavation show that the walls are stable.

As regards the characterisation of the Cox argillite, the experiments involved performing loading tests on a small-diameter casing (~140 mm) under the effect of the closure of the annular space of a borehole in the direction of the major horizontal stress. The results show a radial load within 50 to 100 days without impact on the deformation of the casing. A test of the same kind is in progress but with a heating casing in order to study the thermomechanical behaviour at 90°C, the temperature likely to prevail in the rock in the presence of exothermic waste packages.

The POX experiment in Bure and the HT experiment in Mont Terri have begun to produce results after a period, beginning in 2009, of stabilisation and observation of the water and gases released by the rock. The POX experiment aims to test the loss of oxygen content in the atmosphere in contact with the argillite. The first results show that this effect is obtained within a few days and is accompanied by an increase in the concentration of sulphate in the pore water, which can be attributed to pyrite oxidation. The high kinetic energy of the oxygen depletion suggests, however, that other phenomena come into play. The HT experiment focuses on the fate of the hydrogen; the results show that the consumption of this gas far exceeds the levels suggested by its distribution and dissolution in the pore water; tests are underway to examine the possible involvement of micro-organisms.

The experimental programme until 2014 provides for the continuation of technological tests with the excavation of a large-diameter tunnel (tunnelling machine assembly chamber) and an 80 m tunnel excavated with the tunnelling machine in order to test the installation of the segments. These tests will initially be carried out in the direction of the major principal stress and then be reproduced in 2015 in the direction of the minor principal stress. The feasibility of an 80-metre-long HL waste cavity will also be tested; the structure will then be set up to reproduce the hydro-thermo-mechanical behaviour of a full-scale waste cavity within the framework of the European project LUCOEX.

As regards research on seals, only separate component tests (swelling clay core, wet trenches) are envisaged for the underground laboratory; the full seal test is scheduled to take place elsewhere because of the limited diameter of the structures within the laboratory.

The CDZ mechanical compression experiment conducted on the EDZ will examine the behaviour of the EDZ after the fractured zone's imbibition with water. New diffusion experiments aimed at studying transfers over distances of several tens of metres are being reviewed for their feasibility and require the development of in-situ tracer detection methods. These experiments will last longer (10 years) than the DIR experiments already conducted.

The Board commends that Andra has already established a research programme that aims to consolidate the scientific achievements made over the past fifteen years. It notes with satisfaction that the tests in the Meuse/Haute-Marne underground laboratory are beginning to produce useful results for the DAC; it recommends the continuation of such experiments aiming towards full-scale conditions. It is also aware of the scheduling of long-term experiments, which will not be able to be performed in the disposal facility itself.

2.4.2. Long term behaviour

The long term behaviour of the rock mass must be properly assessed as the structures to be excavated in it will remain open for at least 100 years. In particular, the lining of the LLHL waste cavities, the concrete supports of the LLIL waste cavities and the connecting tunnels, must be, from the outset, properly sized to tolerate the stresses that will ultimately be applied to them and to allow reversibility.

Studying the long term behaviour is difficult because argillite is a complex material: besides the creep itself, desaturation due to the ventilation air, changes in the pressure of the water contained in the pores, physico-chemical transformations and changes in temperature can play a significant role.

The identification of the mechanisms responsible for the creep, which Andra entrusted to a group of laboratories, has given rise to experimental and theoretical work using techniques at the cutting edge of research; a lot of data on the influence of the microstructure have been collected; the respective roles of the creep of the argillaceous matrix and the propagation of micro-cracks still appear poorly prioritised. The Board encourages the continuation of this work.

Drained, unconfined compression laboratory tests, with loads of between 5 and 18 MPa, which covers much of the range of stresses that might occur in a disposal facility, show an initial decrease in the deformation rates, which tend towards values from 10-11 s-1 to 10-10s-1 (if this trend were to persist in the long term, the cumulative deformation would respectively be from 3% to 30% within a century and the coating would have to support a large part of the weight of the ground). Beyond a load of 12-13 MPa, the damage would probably be coupled with the long term behaviour of the rock mass. The issues of the presence of a viscoplastic threshold, the influence of the average stress, the temperature and the existence of a secondary creep at a constant speed remain unresolved. An important additional experimental programme is in progress.

The observations and measures in place in the underground laboratory are an impressive combination. Andra has shown that the excavation technique, digging speed, stiffness and the moment the support is applied (so-called BPE experiment) all influence the delayed deformations.

Late application of the support results in a slower loading rate. This is an argument in the discussion about the best moment for applying the support.

The long term behaviour of the tunnels opened in the directions of the major principal stress and the minor principal stress are very distinct from each other. Andra believes that this difference must be linked to the particular geometrical shape of the fractured and damaged zones in each of the two cases. The behaviour of these areas appears largely responsible for the delayed deformation observed at the wall. The difference between the horizontal and vertical convergence, much larger than would be expected from the anisotropy of the natural stresses, could have the same origin. The overall mechanical properties of the fractured zone are also studied by applying a point load on the wall. Remarkable sets of data are therefore available.

The LLHL waste cavities seem to deform at least as fast as the tunnels, despite a much smaller diameter; as a result, careful consideration must be given to the sizing of the steel liners designed to facilitate the insertion and possible removal of packages.

Andra (with its partner INERIS) and EDF have formed a working group to compare their argillite mechanical behaviour models in view of sizing the structures. The results of the predictive calculations made using INERIS' and EDF's software still show differences that are linked to the variations in the behaviour models. An additional difficulty is that the concept of a reasonable upper bound model, which allows other areas to compensate for the residual uncertainties, is more difficult to define here.

To conclude, the Board considers that the sizing of the structures' support must be based on strong scientific evidence. It greatly appreciates the experimental work conducted by Andra, the collaboration established with EDF, and the desire to draw a conclusion. However, due to the complex nature of the long term behaviour, we must actively pursue observations and their modelling in order to progress as quickly as possible, before the DAC, because of the role the model must play in supporting the engineering.

2.4.3. Hydrogen and heat output

The deep disposal facility's existence over the very long term (hundreds of thousands of years) will lead to the release of radionuclides beyond the Callovian-Oxfordian host layer. Andra has shown that the quantity will be very low. Two other far-reaching consequences of the existence of the disposal facility are the increase in temperature of the geological formation and the diffusion of hydrogen in the host layer.

The calculation of the temperature rise in the underground structures and their surroundings is now more accurate. The increase is particularly significant in the first few hundred years. The maximum temperature criterion of the argillite at the interface with the packages (90°C) remains unchanged. The maximum temperature of 30°C for the asphalt packages does not leave much margin should they be put in deep storage. The uncertainties and margins, in view of the safety analysis, are now clearer. The Board noted a possible trend in extending the storage period of the hottest packages.

Andra also provided details on the analysis of the thermomechanical effects up to the ground surface, as requested by the Board in its Report No. 4. The heat produced is essentially attributed (98%) to LLHL waste. The calculation model, made on the assumption of a linear poro-elastic behaviour, shows minor amounts of uplift of the ground surface due to the low thermal expansion of the argillites (0.2 m after 600 years), shear stresses not exceeding 3 MPa and therefore unlikely to cause disturbances to the vertical edges of the hottest areas, but excess pore pressures (due to the thermal expansion of the water contained in the pores and the low permeability of the medium) of about 5 MPa. Overall, these results are consistent with what one would expect; Andra is continuing to improve the model in order to reduce the uncertainties.

Hydrogen is generated by some LLIL packages and by the corrosion of steel in the disposal facility and in particular in the LLHL waste cavities. Andra has calculated the "large-scale" movement of fluids and radionuclides across the geological environment for up to 1 million years by means of a detailed description of the physical phenomena that influence these movements. The hydrogen pressures in the disposal cavities reach relatively high levels. After 1 million years, 80% of the hydrogen produced (in the region of 6.109 moles) remains, in dissolved form, in the water of the Callovian-Oxfordian and 1% will have reached the surface after dilution in the aquifer levels above the Callovian-Oxfordian.

2.4.4. Hydrogeological modelling

Hydrogeological modelling has evolved considerably since the 2005 report. In 2008, Andra entrusted the University of Neuchâtel in Switzerland with the task of constructing a mathematical model of the groundwater flow in the aquifer of the Paris Basin which also takes into account fluid transfers on a regional scale throughout the entire basin and across a smaller area centred on the transposition zone. Significant advances were presented to the Board in 2012.

Following the recommendations of the assessors, the model now includes in a single simulation tool both the regional model and the limited area model. It takes into account all the lithostratigraphic data gathered by IFP for the 2005 report and also incorporates the most detailed information available to date on the transposition zone, especially with regard to permeable levels within the Upper Oxfordian. The model also includes faults with a very high level of detail on this zone and can simulate their hydraulic role by distinguishing the faults parallel to the main horizontal stress, thought to be hydraulically conductive, and the closed faults orthogonal to this stress, which can play the role of a hydraulic screen for lateral flows. The modelling tool built uses a finite-element-based numerical method and comprises 27 layers discretised by a mesh of more than 6 million elements, most triangular, whose sizes range between 150 m at the limited area level and 5000 m at the regional level. Together, the calculation code and its database form the most developed hydrogeological simulation tool ever applied to the Paris Basin.

Referring to the current piezometric situation, the University of Neuchâtel conducted a careful recalibration of the steady-state model until it obtained a base-line adjustment returning, with an accuracy of a few metres, the groundwater levels across the control points available, over the transposition zone and in the aquifers of the Dogger and Oxfordian framing the Callovian-Oxfordian. This resulted in substantial differences in the flow structure compared to the 2005 report. This difference is only modestly visible in the Oxfordian, for which the magnitude of the transfer speeds of dissolved elements from the ZIRA remains unchanged (1 km over 100,000 years), but for which the position of the outlets is shifted from the west to the north, thereby affecting the valley of the Ornain. The differences are more significant for the Dogger, for which the consideration of new measurement points and lithological heterogeneity has led to the flows converging southwards towards an outlet located in the valley of the Marne. The flow rates increased at the same time by a factor of 10 (a few km over 100,000 years compared to the 1 km over 1 million years estimated in 2005).

After being adjusted, the model was applied to test sensitivity to the role of faults in the flow structure, which revealed that its role is limited to the structures' surroundings, without a significant effect on the flow direction and the hydraulic gradients.

The model was then used to predict the changes in flow after 1 million years based on the geomorphological evolution of the basin. The simulations show that the directions and rates of flow should change very little over this period.

Andra also explored the influence of climate cycles on the flow, including the appearance of a permafrost using a limited area model developed by Golder Associates, which is based on the boundary conditions extracted from the regional model. The results show minor changes in flow directions and changes of the order of 20% in the transfer time to the outlet (reduction for the Oxfordian and an increase for the Dogger).

Andra draws from these simulations that there is no adverse effect from a hydrogeological point of view in constructing a disposal facility in the ZIRA, and that the molar flow rate of a very mobile element such as iodine-129, calculated at the top of the Cox with the updated model in 2012, is close to that calculated in the 2005 report, with even a slight decrease.

The Board considers that, in its current form in 2012, the hydrogeological model has reached a very high level of maturity. The results of the flow simulations in the Oxfordian and Dogger are able to be used to refine the findings of the 2005 report without fundamentally challenging them. The Board recommends that this model be developed in order to examine the possible migration of natural tracers, with a view to checking the transfer speeds currently predicted within the surrounding aquifers of the Cox. The Board recommends that the concepts and results of this model be fully used for the Cigeo safety analysis.

2.4.5. Deep drilling results

In 2008, Andra drilled the EST-433 borehole at the heart of the transposition zone; its purpose was to provide a better understanding of the role of deep formations in transfers (current fluid and paleofluid transfers, chemical and thermal transfers) and to assess the geothermal potential of the Triassic.

The Board reported on the observations made in this borehole in its previous reports. Since then, the accompanying work conducted by various French research teams (CNRS and universities) on samples from this deep borehole have made it possible to better describe the lithostratigraphic column of the transposition zone, from the surface to the base of the Triassic; previous boreholes did not get deeper than the Dogger.

Some of the topics addressed have no direct relationship with the characterisation of the disposal site in terms of transfers and safety, but nevertheless have a scientific and cultural value that complements the information already available on the local geology presented in an educational manner in the Bure laboratory's visitor centre.

The contributions of the Forpro and Trasse national research groups (GNR) in terms of paleothermicity and paleoburial are, however, fundamental for understanding the site. The teams from Paris XI University and the University of Lorraine have therefore deployed a wide range of advanced techniques (fluid inclusions, Tmax of pyrolysis, fission tracks, etc.) to assess the maximum temperature reached by the different horizons cored and the maximum burial age. All of these paleo-thermometers coincide and suggest that the Triassic, currently at 65°C, recorded higher temperatures in the past, with a thermal peak in the region of 90°C. These deep data are consistent with the observations at a shallower depth, implying that it is the whole sedimentary column, and not only the Triassic, that has experienced temperatures higher than those of today. This therefore allows experts to rule out a hydrothermal hypothesis, in which hot exotic fluids would have filled the Triassic reservoirs at some point. The explanation given for this difference of 25-30°C between ancient and current temperatures is erosion during the Tertiary period of a thick series of upper Cretaceous chalk, the thickness of which would in fact have reached several hundred metres in this part of the Paris Basin.

The total organic carbon (TOC) content of the Toarcian formation is between 5% and 15%, giving it the characteristics of an excellent source rock; however, it is still immature for the generation of hydrocarbons (the depth at which the oil window starts has been located at a depth of around 1400 m according to the values of the maximum pyrolysis temperature). Traces of methane under the salt of the Keuper however indicate the existence of a deeper flow of hydrocarbons, probably associated with the strong maturity of the underlying Carboniferous series.

The IRSN team was also able to show the existence of two separate fluid systems on both sides of the Triassic salt. At some time or other, all of the aquifers were fed by meteoric waters: fifteen million years ago for the deepest, compared to six million years ago for those nearest to the surface. This age difference may possibly be explained by the oldest disappearance of the Cretaceous cover on the edge of the basin, where the Triassic came into contact at an earlier stage with the meteoric waters, at a time when the Cretaceous cover was still present ats centre. According to geochemical analyses, most of the basic vertical transfers are therefore controlled, in this area located at the centre of the transposition zone, by diffusion and not by convection.

The Board stresses that, as well as their undeniable scientific value, the interpretation of the observations taken from the deep borehole up to the base of the Triassic helps to demonstrate the absence of vertical fluid transfer over the transposition zone over several million years, which is an argument in favour of the containment properties of the Cox.

2.5. TECHNOLOGICAL ADVANCES

2.5.1. LLHL waste cavities

Each cavity designed for the disposal of LLHL packages is a horizontal blind hole, measuring 70 cm in diameter and several tens of metres in length. From access tunnel side, the hole has a non-alloy steel insert, measuring about ten metres in length and slightly less than the hole itself in diameter. Once the waste cavity is closed, the insert will contain a 3-m-long swelling-clay plug, put in place 6 years after the disposal of the packages and which will have a sealing function. From the tunnel side, the clay plug will rest against a concrete plug sealed in turn by an embankment created within the tunnel; the purpose of this concrete-embankment combination is to take the pressure generated by the swelling. On the other side, fitted into the insert, a metal lining will keep the hole open, allowing packages to be inserted and possibly removed. Between its junction with the insert and the end of the disposal cavity, the lining will first contain a metal plug, in contact with the clay plug, then the packages with the appropriate spacers to better distribute the heat, and finally, at the end of the cavity, a metal plug.

The design of the waste cavities is still being discussed and since 2005 it has undergone several important changes:

- The insert, which initially was to be removed, will now remain after closing, which has some advantages (it is not attached to the lining, which makes the lining's thermomechanical behaviour more autonomous; the initial interplay between the insert and the ground is less significant than the interplay between the lining and the ground, which limits the development of the EDZ above the waste cavity) and some possible disadvantages (the insert is a metal interface between the ground and the clay plug, which could delay the saturation of the plug or cause a chemical disturbance that could reduce its effectiveness).

- The reference length of the waste cavities has been increased from 40 m to 80 m following the Cigeo project review conducted after the publication, in late 2011, of the STI project, an alternative to that of Andra. This extension, the feasibility of which is still untested, carries a higher risk of loss of alignment, which would make any attempt to remove the packages more difficult. This risk must be analysed.

- The primary role of the alloy steel lining, currently 25 mm thick, is to facilitate the placement (or removal) of the skid-mounted packages. Andra has examined the possibility of giving it additional functions, as explained below:

Andra first explored the idea of giving it a sealing function, at least for the duration of the operational phase, in order to delay water coming into contact with the outer containers and the start of their anoxic corrosion. As the initial corrosion, in the presence of oxygen, happens quickly, the Board suggests considering inerting the waste cavity's atmosphere before closing it. Furthermore, it was found that long-term waterproofing is not easy to achieve. A perfect seal would have the disadvantage of creating a possible pressure difference between the upper and lower surface of the lining, which would then require increased mechanical strength. Andra decided to discard this function.

However, Andra is considering giving a greater mechanical function to the lining which, in the new design, should be sized so that a continuous interplay between the lining and outer container lasts for the entire useful length of the waste cavity over a long period, similar to that of the duration of the thermal event (approximately 2000 years). All metal to metal contact between the lining and outer container would thus be avoided and the outer container would only bear gas or water pressure. This change would remove certain restrictions, in particular with regard to seals, which weigh on the design of the outer containers. However, any argument for reducing the thickness of the carbon steel of the outer containers could not be considered without further study.

For Andra, the risk of rupture of the metal lining mainly depends on the forces exerted on the upper surface by the ground. In fact, the phenomena that affect the waste cavity are complex. The temperature remains high for a thousand years. Recent tests show that the initial interplay between the ground and lining could quickly cease to exist. In this context, the discharge of water from the rock mass to the waste cavity is complicated to describe, particularly as the pressure of the hydrogen produced by anoxic corrosion may reach high valuesand oppose the arrival of the water. Even if it is slow, the corrosion of the lining, occurring faster on the upper surface, must be considered. The load applied to the lining is therefore marked by uncertainty. Andra has examined whether this load could result in the lining losing stability (buckling). The calculation of the onset of buckling depends heavily on the assumptions made with regard to fluid pressures (or stresses exerted by the rock mass) on the upper and lower surfaces. The primary anti-buckling design with regard to sizing relies on standard rules but it should be more clearly defined, particularly as lessons can be learned from experiences within the oil industry where this is a common problem.

The Board notes that the design of the LLHL waste cavities has not yet been finalised. It believes that it is normal at this stage of the project that discussions continue, especially as the first waste cavities are not likely to be operational for several decades. It reiterates its opposition to certain ideas, such as opening the waste cavity on both sides. Because of their impact on safety and reversibility, the Board will carefully consider the design options presented in the draft phase. It believes that the programme of theoretical work should continue, but that full-scale tests, such as the one started under the European LUCOEX project, will be necessary to fully understand the phenomena.

2.5.2. Seals

The safety of a geological disposal facility relies on three nested barriers: the geological barrier, the engineered barrier and the package with its outer container. The engineered barrier uses swelling clay, which slows the flow of water and effectively retains many radionuclides, including all actinides. In some designs, swelling clay is placed around the packages and also forms the core of the plugs placed in the access shafts (or drifts), in the tunnels and around the edges of the waste cavities. In the 2005 French project, as in the Belgian project, no clay is placed around the packages as the rock mass itself is composed of clay.

The engineered barrier thus comprises, in the Cigeo project, on the one hand, 3-metre-long swelling-clay plugs placed in the LLHL cavity head inserts between a metal plug (on the side of the packages) and a concrete plug (on the tunnel side) and 50-m-long expanding-clay plugs placed at either end of the LLIL waste cavities between two embankments. On the other hand, for the vertical shafts, the drift and the connecting tunnels, the engineered barrier consists of 40-m-long swelling-clay plugs (seals), undoubtedly with a larger diameter than considered in 2005, blocked by concrete and an embankment. For the latter group, the seals are placed so as to isolate in particular the LLIL disposal subzones and the around twenty LLHL exploitation modules. In order to leave the Cox layer via the network of tunnels and shafts, a radionuclide would have to go through several seals. For these seals, an overall permeability equivalent to 10^{-18} m^2 is sought (the permeability of the intact rock mass is still two to three orders of magnitude smaller).

Most of these seals, with the exception of the waste cavity plugs, will not be put in place for a hundred years, leaving time to perfect them. The design of the plug and the type of materials it must be made of are known. Many countries are studying them and contributing to the knowledge base. Finally, the safety calculations made in 2005 showed that, even under the very pessimistic hypothesis of the seals' widespread failure, the dissemination of radionuclides through the Callovian-Oxfordian rock mass remained the prevailing cause of transfer for radionuclides outside the host layer.

The plugs provide a degree of redundancy from the point of view of the disposal facility's safety. Yet, various changes to the design presented in 2005 and certain observations made in the laboratory – an increase in the diameter of the connecting tunnels, abandonment of the design of a LLIL blind waste cavity, possible separation of certain shafts, choice of a drift as well as access shafts, presence of a wider EDZ than expected – mean that the structures' potential contribution to the transfer of radionuclides may be higher, while remaining at a level below that of transfer through the Callovian-Oxfordian.

A wide range of physical phenomena[16] are potentially important for the effective operation of a seal. It is therefore essential that, in addition to calculations and modelling, tests be conducted under as close as possible to full-scale conditions. These tests take a long time because the resaturation time of the swelling clay is in the region of ten years. In addition, the underground laboratory does not allow for half-scale tests to be conducted because of the limited diameter of the tunnels (5 m instead of 8 to 9 m for the LLIL waste cavities, for example). Tests in a dedicated area within the disposal facility itself will be necessary.

The Board requested a seal design and sizing note including the problem statement, the objectives, the expected performance, initial modelling efforts and indications for an optimisation strategy – a first draft stage, a standard procedure in the manufacturing and civil engineering industries for structures of this magnitude. Partial technological tests were conducted by Andra in the underground laboratory; some results (resaturation during the KEY test) provided valuable lessons but alone fall short of the amount of information desired.

A more consistent experimental programme is now being prepared:

- The so-called SET test, conducted in a surface facility in 2012, aims to analyse methods for filling a trench (half-scale); it will be followed by TSS2, starting in mid-2013 and expected to last several years; performed in the underground laboratory, TSS2 aims to study the filling of a full-size trench with artificial resaturation;

- The so-called NSC experiment for assessing the performance of part of a sealing core (half-scale), conducted in a dedicated tunnel within the laboratory, will begin at the end of 2012; it is likely to last until 2020 and aims to monitor the resaturation of swelling clay and ultimately estimate the equivalent permeability of the whole plug;

- The so-called FSS test, starting in 2013 for a period of 18 months, focuses on the methods for implementing a full seal under near-industrial conditions and at full scale in terms of diameter; it will be conducted above ground or underground, but outside the Meuse/Haute-Marne laboratory. It is part of the European DOPAS programme;

- The so-called USC test for the removal of lining segments (removal of the support in line with the future plug) will be conducted in the first half of 2014 in the tunnel at -445 m.

All of this signals Andra's willingness to move forward with the issue of seals, which until now has been an area of weakness in the project. A complete, full-scale test such as the one originally wanted by the assessors may only be completed in Cigeo, and therefore only after completion of the first phase of work, after 2025. The review of the DAC will make it possible to assess whether, in 2015, sufficient evidence has been provided in terms of the feasibility and performance of the seals. In any event, any uncertainties about the effectiveness of the seals, which will still inevitably remain, will have to be taken into account in the calculations of the safety analysis.

[16] Existence of the EDZ; possible presence of fluid pressures; chemical interactions, including alkaline disruption between the clay, steel and concrete; high-temperature in the case of LLHL waste cavities; long saturation time for the swelling clay; need to remove several metres of the coating, or at least in those areas where the isolation trenches of the EDZ are to be built.

2.6. COST OF THE DISPOSAL FACILITY

In its report of July 2012, the CNEF[17] notes that Andra sent to the producers in 2009 its latest valuation of the disposal site: 35.9 billion euros. The producers contested Andra's valuation; they presented the case of the STI project, which is based on a different approach and the cost of which is estimated at 14.4 billion euros. The difference between the two values is a question of investment costs, operating costs and "other" items (taxes, R&D, insurance). Some differences can be explained by tax or economic considerations, others by technical considerations; the Board requests further clarification, with each explaining and justifying its numbers. The CNEF therefore makes no decision between the two estimates but wonders whether the producers should not, as a precaution, revise their provisions upwards. The DGEC should, in March 2013, complete the costing of the draft chosen by Andra.

Even if, as a percentage, the cost of the disposal facility is only a very small proportion of the cost price of the nuclear kWh, it is important that the figures are reliably known at the time of the public debate because it is a very sensitive issue for the general public.

> *The Board wishes to have details of the fees that will be put in place to recover these costs: fees at the time of capacity reservation? Fees at the time of disposal? Dual-component fee (capacity reservation and use of the subscribed capacity)?*
>
> *The Board wishes to have accurate information about the cost allocation formula between the different waste producers and the cost of a package removal operation, should the reversibility of the storage facility be necessary.*

2.7. LONG-TERM ENVIRONMENTAL MONITORING

The long-term environmental research monitoring and testing system that Andra has gradually been putting into place for several years in and around the transposition zone has three objectives: to collect the environmental data that must be taken into account in the design of the disposal facility, to conduct an initial review of the environment in order to assess the impact of the industrial project, and to prepare the site's long-term environmental monitoring plan. The resulting database will be an essential reference for detecting any disturbance but also for validating models of how the biosphere functions.

The work carried out within the framework of this monitoring and testing system already includes monitoring the region's ecosystems and climatic context; analysing the anthropogenic pressure over waterways, soils and biodiversity; the development of several experimental sites in which the studies are conducted in collaboration with scientific and community-based teams; and the creation of an "ecolibrary" ensuring the conservation of samples under controlled conditions.

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17 Commission nationale d'évaluation du financement des charges de démantèlement des installations nucléaires de base et de gestion des combustibles usés et des déchets radioactifs [National Assessment Committee for the Financing of the Dismantling Charges of Basic Nuclear Facilities and of Management Facilities for Spent Fuel and Radioactive Waste] (Article 20 of the law of 28 June 2006).

The Board approves of and follows with interest the implementation of this monitoring and testing initiative. It hopes that this remarkable research effort will be enhanced by a sustained effort of modelling and publications, particularly in the fields of atmospheric circulation and biogeochemical cycles. The Board issues a very strong recommendation for the Government to support Andra's efforts in carrying out two essential actions: the epidemiological surveillance of the region and of the environmental reference site outside the impact zone of the disposal facility.

2.8. STORAGE AND SURFACE FACILITIES

Even though research on the disposal methods for different radioactive wastes in the deep geological formation has reached, thanks to the Meuse/Haute-Marne underground laboratory in particular, a high degree of sophistication, studies on the design and siting of the surface facilities and connections to different networks remain largely in their embryonic stages.

The surface facilities, however, are not a mere adjunct to the underground disposal facility; they are very much part of the Cigeo project, both in terms of the technical design and the acceptability of the project by the populations concerned.

In a sparsely populated rural environment, they will be the visible part of this project, which will now have to coexist alongside industrial facilities that are unusually large for the region and with network connection requirements (water, electricity, sanitation, roads, railways, etc.) comparable to those of a town of several thousand inhabitants.

In the specifications defining the tasks entrusted to the System Integrator, in July 2011, the System Integrator was asked to submit, at the end of the draft phase, "a comprehensive solution" for the disposal facility by the beginning of 2013. It therefore looks promising that by then a comprehensive "surface" solution will be known, with precise details, not only about the siting of the surface installations, but also the technical risk assessment and design principles.

Some ambiguities, however, remain.

This is why, in the second stage of the draft studies, submitted by the System Integrator, in September 2012, it is stated that a siting area for the drift had been defined "following the analysis of environmental constraints".

Even though it is only a proposal, it is unclear how the public debate could lead to the facilities being sited outside an area that would have been defined according to objective criteria. Yet, logically, the location of the surface facilities should have been one of the options left open to public debate. It should also be noted that in 2009, a High-Level Committee asked Andra to site the drift in an interdepartmental area between Meuse and Haute-Marne, which further reduces the choices for the populations concerned.

Another problem that may arise during the public debate is that the principles of waste and radiological zoning will only be defined when the draft architecture solutions for the surface facilities are available.

At the moment, the general architecture of these facilities has not yet been defined and three scenarios coexist:

- a "shafts" scenario in which the surface facilities are located on the site of the access shafts;
- a "drift" scenario in which these facilities are located at the entrance to the drift(s);
- a "balanced" scenario in which these facilities are distributed between both sites.

These three scenarios will be presented during the public debate, but the location must be approved by the Government during 2013.

The storage and handling techniques to be used are standard, already well known and tried and tested by all nuclear operators; they therefore require little specific research. It is therefore perhaps regrettable that these aspects of the project were not submitted by Andra in an abstract model defining the general outlines, prior to entrusting the project to the System Integrator.

Thinking could then have been focused on the adaptations necessary for serving an underground storage facility such as:

- the operations and features of "buffer" storage, making it possible to regulate the arrival of packages according to availability within the underground storage facility (at the hearing on 8 March 2012, Andra clearly indicated that it was not considering thermal decay storage for the Cigeo project);
- a facility for receiving, checking and, if necessary, reconditioning packages. Also, this facility, or a similar one, must be designed to be able to recover defective packages;
- preserving the possibility of implementing, when appropriate, the handling and disposal operations for packages that have to be retrieved from the underground disposal facility in order to meet the requirements of reversibility or retrievability;
- the compatibility of the facilities for transferring packages and lowering them into the repository with a possible direct disposal solution for spent fuels.

The Board asks to be informed about studies relating to the impact and costs of the surface facilities, including expenses related to water and electricity supply, and the adaptation of road and rail infrastructure.

2.9. FOR AN OVERVIEW OF THE CIGEO PROJECT

In order to implement the geological disposal facility, a coherent and systematic project is needed.

To ensure the protection of citizens, workers and the environment, it is essential to clarify the hierarchy among different issues, equally for storage, transport and disposal during the reversibility period, as for definitive disposal of radioactive waste. The same requirement applies for the transmutation of actinides, which would no longer be final waste.

The issues to consider are the following:

- The use of deep geological disposal was decided under the law of 2006; long-term safety is ensured by the triple barrier: "packages / engineered barriers / geological layers". An understanding of the issues concerning the transport of radionuclides through the three barriers is essential. This understanding is ultimately what will allow the safety analysis, including the calculation of the dose at the outlet, ensuring that the disposal site is safe for the public;

- An explanation of the implications of choosing a reversibility period of at least a hundred years, in terms of safety, engineering and costs, is essential;

- Protection and safety must also be ensured during the storage and transport phases. They call for a reasoned consideration of the associated logistical requirements;

- It is important to assess the benefits and risks associated with any decision to defer all or part of the Cigeo project.

This overall vision is essential for understanding the coherence of the Cigeo programme and the realism of the schedule. This programme has several areas of action that must be treated with the same attention:

- *Industrial project:* all the work necessary for the design choices and the construction of the facilities required on the disposal site, both above and below ground;

- *Technological development:* the work involving the industrialisation of the technology necessary for building and preparing the cavities for storing the waste packages, for ensuring the lowering and positioning of the packages, and, when the time comes, for closing the waste cavities, tunnels and access structures. Under the law, plans must also be made with regard to the package recovery techniques to be implemented during the required reversibility period;

- *Scientific support:* the acquisition, development and maintenance of scientific competence to ensure that, in the long term, waste will not pose a problem. This approach must not be limited to academic research; it must closely accompany the industrial project. Moreover, they must integrate the feedback from the Meuse/Haute-Marne laboratory experiments, the construction work on the disposal facility and international studies.

These three areas of the Cigeo project (industrial project, technological development, scientific support) must be clarified and harmonised in terms of needs, priorities, and costs, in order to address the issues identified above (long-term safety, reversibility, storage and transport, and schedule). For the Cigeo project to succeed, it is imperative that these three areas are integrated into a coherent operational plan.

The Board regrets not having had an abstract model, however brief, before the project was entrusted to a System Integrator responsible for the design of the future industrial disposal facility[18].

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[18] See Andra note: "Cigeo – Specifications for the project management of the system" – Cigeo.CC.ASMO.11.0008 – 1/7/2011.

The Board requests that Andra provide it with a document laying out the groundwork for an operational plan that combines the conclusions from all the studies carried out (including those of the System Integrator) with the requirements that the four issues identified impose on the three areas of action.

Chapter 3

INTERNATIONAL OVERVIEW

This chapter only describes in 3.1 and 3.2 the latest data since publication of the Board's previous report (Report No. 5). An overview of the international R&D in progress regarding geological disposal, new technologies for partitioning and transmutation and education, is given in Appendix VI.

3.1. INTERNATIONAL LEGAL CONTEXT

Radioactive waste management and, by extension, R&D on waste management, takes place within a national and international legal context. At European level, the publication of the Council Directive 2011/70/Euratom of 19 July 2011, establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste, is certainly the major event since the last report.

The directive aims to establish a legal framework for the management of spent fuel and radioactive waste, from generation to disposal, when resulting from civilian activities. This directive indicates that geological disposal is the preferred solution for the management of long-lived high-level waste.

Member States are ultimately responsible for the management of spent fuel and radioactive waste. They must establish, implement and maintain a national programme for the management of spent fuel and radioactive waste, covering all stages of management from generation to disposal. These programmes must be reviewed and updated regularly. Member States are responsible for putting in place national policies which:

- keep the generation of radioactive waste to the minimum practicable level;
- ensure the interdependence of the different steps in spent fuel and radioactive waste generation and management;
- safely manage spent fuel and radioactive waste, including in the long term;
- implement appropriate measures following a graded approach;
- govern all stages of the management of spent fuel and radioactive waste.

States shall be required to dispose of their waste within their own territory unless they have entered into agreements with other Member States for the use of their disposal facilities. However, the responsibility remains with the State of origin.

They must establish a national legislative, regulatory and organisational framework; they shall establish and maintain a competent regulatory authority responsible for spent fuel and radioactive waste management.

A safety demonstration must be prepared as part of the licence application for a facility or activity. The safety demonstration shall cover:

- the development and operation of an activity;
- the development, operation and decommissioning of a facility;
- the closure of a disposal facility;
- the post-closure phase of a disposal facility.

3.2. RESEARCH LABORATORIES AND UNDERGROUND DISPOSAL SITES

Depending on the local geological characteristics, R&D on the host rock focuses on clay, granite or salt. In Europe, the main research concerning geological disposal is being conducted in Belgium (Mol, GIE Euridice, in clay), Finland (Olkiluoto, Posiva Oy, in granite), France (Meuse/Haute-Marne site, Andra, in clay), Sweden (Äspö, SKB, in granite) and Switzerland (Mont Terri and Grimsel sites, Nagra, in clay and granite). Lithuania, the Netherlands, Slovakia, Slovenia/Croatia, Czech Republic, and several other European countries have geological disposal projects, either individually or in collaboration with others.

- **Germany**

The final disposal of high-level waste (exothermic) is planned in Gorleben in a salt dome at a depth of 800 m. Despite satisfactory deep drilling results, the Government considers, with the consent of the Länder (German states), assessing alternative sites. Following the decision to abandon nuclear power, the Government intends to propose a new law on nuclear waste management and the siting of disposal facilities. Pending the emergence of solutions accepted by the political and safety authorities, high-level waste is stored in various sites (including reactor sites) spread across the country. The glass packages produced by reprocessing are stored above ground at Gorleben.

The final disposal of long-lived, intermediate-level waste (not exothermic) is planned in the Konrad mine (an old iron mine) at a depth of 800 to 1300 m. With the political disputes and litigation now resolved, work is underway to make the site operational for receiving waste in 2019.

- **Belgium**

The ONDRAF, National organisation for radioactive waste and enriched fissile material, has finalised its "Waste Plan". The organisation has submitted the report on the environmental effects, the report from the social responsibility conference and the comments received during social and legal consultation. With this Waste Plan, ONDRAF provides the Government with the elements necessary to make an informed policy decision on the long-term management of waste, including spent fuel declared as waste.

Valuable and high-quality research, development and demonstration (R&D&D) work regarding the long-term management of LLIL and LLHL waste was initiated in 1974 by the Centre d’étude de l’énergie nucléaire (SCK•CEN); it has been upheld several times since 1976 by various committees and working groups responsible for commenting on ongoing studies. The preferred solution proposed by ONDRAF is geological disposal within poorly-indurated clay (i.e. Boom clay and Ypresian clays, for Belgium).

- **Canada**

The Nuclear Waste Management Organization (SGDN-NWMO) has initiated discussions with interested organisations and individuals in order to identify the principles of a fair process for finding a community positively disposed to hosting irradiated nuclear fuel management facilities. The Canadian Government has approved this approach. To date, twenty municipalities are willing to help select a site within their territories.

The project of a LLLL and LLIL waste disposal facility set in a deep (680 m) limestone host medium is in progress in the Bruce Peninsula (Tiverton, municipality of Kincardine, Ontario). The authorisation request procedure is ongoing; the application for an operating licence is to be filed in 2015.

- **China**

The Chinese geological disposal project involves the China Atomic Energy Agency (CAEA) and the China National Nuclear Corporation (CNNC) with four subsidiaries: the Beijing Research Institute of Uranium Geology (BRIUG), the China Institute of Atomic Energy (CIAE), the China Institute for Radiation Protection (CIRP) and the China Nuclear Power Engineering Company (CNPE). The BRIUG is responsible for research on a high-level waste disposal facility, including the search for a suitable site.

Three potential disposal sites have been identified. The "host" medium is granite. The site being studied, without the location of the future disposal facility having been decided, is the Beishan region in the Gobi desert. Studies prior to the siting of an underground laboratory are underway with its opening planned before 2020. The disposal site is expected to be operational by 2050.

- **United States**

The "Blue Ribbon Commission on America's Nuclear Future", established under President Obama, has issued a list of recommendations to the Government as alternatives to the Yucca Mountain project in Nevada. Here are some of them:

- Deep geological disposal is affirmed as an essential component of the management system of long-lived high-level radioactive waste;
- The search for sites must be based on a consent-based approach between stakeholders;
- A new organisation dedicated solely to the implementation of the waste management programme must be created and have access to funds collected for this purpose;
- Care must be taken in developing one or more interim storage and geological disposal facilities.

The cleanup of 22 storage sites for transuranic waste of military origin, spread across the United States, allowed, over a period of 13 years, without incident, 83,000 m^3 of waste to be disposed of at the Waste Isolation Pilot Plant (WIPP). The WIPP is located in the Chihuahuan Desert in New Mexico. The waste is disposed of there at a depth of 650 m in a salt layer dating back 250 million years and with an average thickness of 1,000 m. The Department of Energy (DOE) is studying the possibility of also disposing of high-level military waste there.

Finland

Posiva Oy, which manages Finnish radioactive waste, undertook the construction of a research laboratory in 2004. The site chosen for this was Olkiluoto, where an EPR is under construction. The application for the construction of the disposal site, including the laboratory, is scheduled for late 2012. The site will receive spent fuels from the reactors currently in service, as well as those from two reactors to be built in the future. Operations are expected to begin in 2020.

France

For the record: R&D is proceeding at a rapid pace in the Meuse/Haute-Marne laboratory.

Japan

The tsunami, followed by the Fukushima incident, gave rise to an in-depth reconsideration, which is still not stabilised, of Japan's nuclear policy. The Fukushima disaster remediation and cleanup activities, in both the surrounding areas and the contaminated nuclear sites, highlighted the problems inherent to the processing and management of large quantities of waste.

For the record, two research laboratories are currently under construction, one in Mizunami in crystalline rock, and one in Horonobe in sedimentary rock. At the Mizunami laboratory, a depth of 500 m has been reached, the ultimate goal being a depth of 1000 m. Studies concerning the hydrology and mechanics of the rock are continuing. At the Horonobe laboratory, hydrological tests and hydrochemical measurements are continuing. A depth of 250 m has been reached, out of the planned 500 m. The projects face strong public opposition.

Netherlands

The Netherlands have decided to store radioactive waste for a century. However, a research programme, Opera, must study the conditions that will allow the waste to be disposed of safely in a clay or salt medium after this period. The research will focus not only on the scientific and technological aspects, but also the social aspects.

United Kingdom

The Nuclear Decommissioning Authority (NDA) has published a report outlining a framework for the identification and assessment of candidate disposal sites based on the voluntary participation of local communities. A candidate region is West Cumbria, where a decision is expected in early 2013. The Shipway District (Kent) recently decided to withdraw its application.

Russia

The Russian Duma passed a law on the management of radioactive waste in 2011. The law determines limits for the quantities intended for storage, and for its duration. It also sets out the conditioning of waste for disposal, the transfer of waste to the newly created operator (NORAO) and the funding mechanisms. The Nizhnekansky granite massif near Krasnoyarsk could host an underground laboratory. The construction of a disposal site could be decided in around 2025.

- **Sweden**

SKB has submitted an authorisation request for the construction of the deep disposal facility in Fonsmark and for the encapsulation plant, in line with the so-called KBS-3 concept, under the Swedish environmental code and the Swedish act on nuclear activities. The Nuclear Energy Agency of the OECD has assessed the disposal authorisation application and concluded that it is sufficiently substantiated for the authorities to make a final decision. This process will last three years. The disposal facility is expected to be operational in 2025.

- **Switzerland**

The Federal Energy Office (OFEN) has designated six potential locations for a disposal site; these will now be studied in great detail: Südranden, Zürich Nordost, North of Lägern, Jura Ost, Jura-Südfuss and Wellenberg. The studies are in progress and will last for four years. For the record, Switzerland has two research laboratories: the Grimsel laboratory is located in granite on one side of the Aar mountain. The Mont Terri laboratory is located along a highway tunnel in an opaline clay layer. Andra participates in a large number of experiments there, due to the similarity between the clay at Mont Terri and that at the Bure laboratory.

3.3. SOURCES OF FAST IRRADIATION

The number of reactors that offer the ability to irradiate using fast neutrons is extremely limited on the global level. In Europe, the reactors that produce fast neutron fluxes locally are limited to very small sample irradiations. The absence of European FNR reactors heavily compromises the development of new technologies and transmutation experiments.

- **Germany**

The 20-MWt FRM-II reactor in Garching (2004-...) can irradiate materials in a fast neutron spectrum (± 1.9 MeV) with a pair of uranium converters positioned in a beam of thermal neutrons.

- **Belgium**

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

- **China**

The sodium-cooled 65-MWt (20MWe) CEFR research reactor was put into operation in July 2010.

- **France.** For the record: Osiris and RJH (under construction).

Since the Phénix shut down, there is no longer any fast reactor available.

- **India**

Since 1985, India has had the 40-MWt Fast Breeder Test Reactor (FBTR) in Kalpakkam. One of the aims is to demonstrate the thorium cycle.

- **Japon**

The Joyo reactor appears to be permanently stopped and, after the incident at Fukushima, the Government decided to stop the Monju project. It is very unlikely that the two reactors will be restarted.

- **Pays-Bas**

The HFR in Petten allows limited irradiation.

- **Russie**

The Bor-60 (1969-2015) is a 60-MWt sodium-cooled research reactor.

3.4. PRINCIPAL INTERNATIONAL INITIATIVES ON ADS

- **Germany**

The Karlsruhe Institute of Technology (KIT), the Institute for Applied Physics of the University of Frankfurt (IPA-FU) and the Helmholtz Zentrum Dresden Rossendorf (HZDR) research laboratory are involved in the Belgian projects MYRRHA and GUINEVERE. The Jülich research centre (FZJ) offers a gas-cooled ADS concept (AGATE).

- **Belarus**

For about ten years, Belarus has been developing an experimental ADS programme by building the subcritical assemblies Yalina (low power and thermal spectrum) and Yalina Booster (moderate power with a fast spectrum booster zone in the centre), used in international programmes for assessing the physics of ADS cores.

- **Belgium**

In 2010, SCK•CEN inaugurated GUINEVERE, a very-low-power test reactor to support the MYRRHA project. To achieve this, SCK•CEN worked in close collaboration with the CNRS, which built the accelerator, and the CEA, which provided the fuel. GUINEVERE, driven by an accelerator, can operate in both critical mode and subcritical mode. The MYRRHA project, a source of flexible, very-high-flux fast spectrum irradiation, has entered the front-end engineering design phase (FEED).

- **China**

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

- **South Korea**

An ambitious nuclear waste management programme (transmutation of minor actinides using ADS and pyrochemical reprocessing methods) is being developed at the Nuclear Transmutation Energy Research Centre of Korea (NUTRECK) and at Seoul National University (SNU).

- **United States**

Since the 1990s, several ADS transmutation projects have been proposed. The shutdown of the Yucca Mountain project has renewed the interest of the Department of Energy (DOE) and national laboratories (LANL, ANL, Jefferson Lab, Fermi Lab, etc.) in ADS.

- **France**

For the record: the CNRS, Areva and the CEA are working on the Belgian GUINEVERE and MYRRHA projects.

- **India**

The ADS programme, launched in 2000, aims to accelerate the establishment of the thorium cycle by producing fissile uranium-233 from non-fissile thorium-232.

- **Italy**

Several research centres (ENEA, INFN, CRS4, etc.), universities (CIRTEN) and industries (Ansaldo Nucleare) are participating in European projects concerning ADS. In Italy, an experimental, low-power (100-200 kW) ADS is being developed at the Legnaro INFN Laboratory.

- **Japon**

The aim of the Omega project, launched in 1988, is to conduct R&D on partitioning and transmutation in order to reduce the area of a disposal site. It involves the construction of ADS. The current road map provides for the TEF-P with a low-power spallation target and a subcritical MOX-burning core; the TEF-T with a high-power target but without a subcritical core; an approximately 100-MWt experimental ADS (national or international collaboration); and an 800-MWt industrial ADS.

3.5. CONCLUSION

By supporting, in 2012, more than 60 projects devoted to optimising technical solutions or training in the field of long-lived waste or that of new reactor concepts, Europe has shown the great importance it attaches to these areas. France is involved in 53 projects (see Appendix VI), which shows its role as a European leader in nuclear R&D. This strong involvement is primarily through the CEA and the CNRS, involved respectively in 34 and 20 projects, followed by Areva and EDF, each with 12 projects, and Andra and the IRSN with 10 projects.

Andra logically focuses on projects that relate to waste management and disposal. The organisation is present in the major European forums and often plays a leading role. Albeit to a lesser extent, the CNRS, the CEA, the IRSN, Areva and EDF are also highly present in waste-related projects.

The CEA conducts research on new reactor concepts. It mainly participates in projects concerning the design of fast sodium reactors and innovative fuels or those dedicated to the transmutation of minor actinides.

The CNRS is particularly active in research on lead-cooled subcritical systems and the design of the accelerator that drives them.

The lack of French participation in European projects relating to societal aspects or the involvement of stakeholders is regrettable.

Appendix I

MEMBERS OF THE NATIONAL ASSESSMENT BOARD
NOVEMBER 2012

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

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

Adolf BIRKHOFER* – Emeritus Professor at the Technical University of Munich.

Pierre BÉREST – Research Director at the Ecole Polytechnique.

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

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

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

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

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

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

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

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

Claes THEGERSTRÖM – President of SKB (Swedish company responsible for the management of nuclear waste and fuel) – Member of the Linnaeus University Board (Sweden), Member of the Swedish Royal Academy of Engineering Sciences.

* Guest expert.
** Did not take part in the drafting of this report.

II

Appendix II

BODIES HEARD BY CNE2

1 December 2011:	CEA – R&D of the CEA under the law of 28 June 2006.
19 January 2012:	CEA – Multi-recycling of Pu: innovating to generate less waste and materials (fabrication and processing).
16 February 2012:	Andra – Management strategy and R&D for graphite waste and organic waste.
22 & 23 February 2012:	Andra – Engineering topics: excavation, ventilation, sealing, reversibility.
07 March 2012:	CEA – ASTRID: the cycle of ASTRID's materials: manufacturing workshop, reprocessing pilot (morning).
08 March 2012:	ANDRA – Storage.
04 April 2012:	CEA – Effluents and waste from facilities: what R&D to optimise them? Radiotoxicology programme – A management example: water decontamination in Fukushima.
05 April 2012:	CEA – Studies of scenarios: short-term reprocessing; deployment of FNRs; End of life: main principles; ADS fleets; HTRs.
11 & 12 April 2012:	Andra – Visit to Bure – environmental monitoring site.
13 June 2012:	Andra – Source terms.
14 June 2012:	ANDRA – Compliance strategy – monitoring – Sensor technology.
27 & 28 June 2012:	CEA – ADS – 2006-2012 Report on partitioning and transmutation R&D.

* * *

19 October 2011:	Meeting with the President of the IEER and a delegation of the CLIS.
09 November 2011:	Meeting with the KNS.
18 January 2012:	Andra – Restricted hearing – Follow-up to Report No. 5.
15 February 2012:	CEA – Restricted hearing – ASTRID: what concrete innovations?
07 March 2012:	CEA – Work meeting on the material reports.
11 May 2012:	EDF/CNE meeting.
21 September 2012:	EDF/CNE meeting

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Visits by cne2

11 & 12 April 2012:	Visit to Bure – Environmental monitoring site.
18 to 20 September 2012:	Visit to the Mol Laboratory (Belgium).

Appendix III

LIST OF DOCUMENTS PROVIDED TO CNE2
2011-2012

Andra

- Note "problématique liées au stockage des colis de boues bitumées dès 2025" (Réf. DP:11-0228) – novembre 2011.
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Appendix IV

ANALYSIS OF THE IEER REPORT

The American Institute for Energy and Environmental Research (IEER) conducted, at the request of the local information and monitoring council of the Bure laboratory (CLIS), a critical review of the research carried out by Andra in the underground laboratory and on the transposition zone. In preparation for its annual meeting with the CLIS on 13 March 2012, the Board read the IEER's final report and met with its Director in October 2011. This gave the IEER the opportunity to present its assessment process, highlight the important findings and answer the CNE's questions. The Board then asked the IEER a number of additional questions that were to be answered in writing – these written responses have still not been received. At the meeting on 13 March 2012 with the CLIS, the Board therefore proposed postponing in this report its comments on the IEER's study.

The Board appreciated the IEER's views, which provide an external perspective of Andra's work by placing it in a different methodological framework from that defined by the French doctrine. The Board lists the key points of the IEER's assessment by commenting on them below.

Too tight a schedule

The IEER found that "given the research and characterisations that remain to be done", the current schedule was "too tight" (p.13).

The schedule determined by the acts of 1991 and 2006 on the sustainable management of radioactive waste has been followed to the letter so far; as a result, the French programme is making progress comparable to that of Sweden and Finland. Compliance with the schedule is consistent with France's environmental protection policy, which prohibits passing on undue burdens to future generations.

A substantive review, however, should be conducted to examine whether the established objectives have been met so far.

The Callovo-Oxfordian geological formation has been meticulously surveyed by Andra. It has a set of favourable characteristics, including geological stability over more than 100 million years, extremely slow water circulation, chemical properties that ensure the retention of all minor actinides and most other radionuclides. To date, investigations have brought to light no evidence of any kind whatsoever that raises concerns of an unacceptable risk regarding the safety of the disposal facility.

The Board also finds that Andra has considered all the important issues in terms of the disposal facility's safety. Some questions inevitably remain. The examination of the application for authorisation to create a deep disposal facility, to be submitted in 2015, will provide an opportunity to check whether satisfactory answers have been provided. If this were not the case, the CNE would advise taking the time to further the necessary studies.

Also, some questions will only have a more comprehensive answer when the excavation work reaches the Callovian-Oxfordian levels under the ZIRA, in around 2025. This will include:

- checking if the properties observed in the laboratory are fully transferrable to the ZIRA, which seems very likely but must be confirmed through direct observation,
- performing certain full-scale tests, which is not possible in the underground laboratory.

The creation of the disposal facility will be punctuated by stages during which the knowledge acquired will be assessed, in accordance with the concept of a reversible disposal facility. The 2015 stage is only one milestone; it will not imply definitive approval of the design and creation of the disposal facility. The Board therefore sees no reason right now, rather the opposite, to modify the schedule established by the law.

On the disposal of spent fuel

The IEER recalls that Andra falls under the law of 2006, which does not provide for the direct storage of spent fuels – except for very small volumes of "historical" fuels. The IEER is right to note that changes in the law may lead to changes in the design and creation of the disposal facility - and also in the safety assessment.

Andra, in its 2005 report, considered the disposal of spent UOX and MOX fuels and showed its feasibility. Andra has confirmed that the Cigeo draft phase would take into account infrastructure (wells, drifts and tunnels) adapted to the handling of spent fuel packages and would produce plans describing possible changes to the surface and underground facilities making their disposal possible. Any change to the current inventory, which does not provide for, contrary to what happens in the USA, the disposal of these spent fuels, must be addressed by a new comprehensive procedure including in particular a public investigation.

On the seismic risk

While the eastern part of the Paris Basin is located away from the clearly identified seismic zones of the Rhine Graben and the Alpine Arc, the IEER devotes a large part of its analysis to seismic risk, while ultimately recognising that the seismic threat in the area around the site was very low. The Board shares this view and will ensure that, in addition to historical archives, all methods helping to define the maximum spectrum will be properly implemented in order to ensure that the disposal site's infrastructure is designed to withstand the strongest possible earthquakes that could one day affect this part of France.

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On the existence of faults and fractures in the Cox

The IEER appears convinced of the absence of large-offset faults in the ZIRA and shares Andra's view that the faults observed above the Trias do not spread beyond the Dogger; it has more reservations about the possible role of fracturation reported in the more carbonated upper part of the Cox.

Andra's investigations in the underground laboratory and in the boreholes show that these fractures, if indeed they are present, are systematically sealed by calcite and very rare at depth (hectometric horizontal frequency); they bear witness to ancient fluid flows. Each of the hydraulic tests performed in an inclined borehole in line with these fractures have shown that they were not permeable. The issue therefore seems resolved on the basis of current knowledge and may only evolve as new observations are made during the excavation of the disposal facility's shafts and tunnels. If hydraulically conductive fractures were found during the excavation, Andra would study their properties and evaluate their role and impact on the safety of the disposal facility. This presupposes the excavation sites being accompanied by meticulous geological and hydrogeological studies.

On the characterisation of the transfer processes within the Callovian-Oxfordian

Over the very long term, the radionuclides in a geological layer with very low permeability can migrate under the influence of convection – they are then transported with the movement of the water – or under the influence of diffusion – they then move in the water even if the water is stationary. The relative importance of these two mechanisms can be assessed using a "Péclet" number. In the case of the Cox, Andra believes that the diffusive mechanism is predominant, i.e. the least slow of the two. The IEER contests this conclusion by taking into account the range of values that the Péclet number could be when all the local measurements taken by Andra are used. For the Board, using the extreme values that the Péclet number could be locally is ill-suited to a global characterisation of transfers within a geological formation.

The heterogeneity or local anisotropy of a local vertical transport parameter will only have a limited role in the calculation of overall safety – the only one that counts – while its influence on the distribution of the values of the Péclet number is likely to be considerable. It is therefore not a matter of conducting a sensitivity analysis on the Péclet number in order to judge performance but of assessing the transfers by means of an overall calculation that takes into account both diffusive and convective mechanisms and assessing the consequences of the variability of the parameters of this calculation. This is the method adopted by the safety analysis, based on a probabilistic or deterministic approach. The important thing here is that Andra carefully examines the consequences of the extreme values of the parameters in non-optimistic conditions, something the Board will pay attention to.

On the assessment of the performance of the Oxfordian-Callovian vis-à-vis thetransport of radionuclides

The IEER notes that Andra successfully characterised the heterogeneity and anisotropy of the properties of the Cox but believes it did not then take this sufficiently into account in the safety calculations. This remark concerns how these values were used rather than the experimental approach taken to obtain them.

The American doctrine attaches great importance to performing safety calculations using probabilistic methods consisting of choosing the parameters of a calculation by drawing lots through mathematical functions representing the probability distribution for the values of these parameters. The result is a large number of calculations that do not rule out unrealistic combinations of values. The French approach is different; it involves determining reference values, based on expert opinions, representing a normal evolution scenario, then completing the assessment with calculations that use extreme values, but that are consistent with each other, for the parameters, representing degraded scenarios. In doing so, it follows the Safety Guide published by the ASN, which recommends seeking the most punitive scenarios.

Both of these approaches have their supporters. They appear to the Board to be the result of historical habits. They are both relevant as long as the logic and underlying assumptions are clearly known to the assessors and the results of the calculations are analysed critically.

The IEER used a probabilistic approach based on Andra's data. The variability of the total doses calculated is much greater than that obtained by Andra (factor 100,000 compared to factor 10) but the upper envelope corresponding to a probability of very low occurrence remains below 1 mSv/year after 1 million years. However, the IEER states that its calculation is not intended to obtain a realistic estimate of the dose but to assess the uncertainty over its estimate, in the spirit of the American approach. This is reassuring in the eyes of the Board, with regard to the consistency of the results of the two approaches, probabilistic and deterministic.

Very-long-term mechanical behaviour

The IEER points to an "excessive and widespread optimism" from Andra and gives as a "striking example" the assumption that, over the very long term, the rock mass will behave as an ideal fluid, the gaps being closed and sealed (p.13).

The issue of the long-term recovery of the initial properties of the rock affected by the underground structures is still unresolved. The experiment conducted by Andra in the underground laboratory involving applying pressure on the tunnel walls, simulating their long-term evolution after closure, helped to demonstrate a fairly quick partial healing, but this result is still insufficient for it to be included in the safety analyses. They also indicate that any transfer of radionuclides is principally through the healthy rock mass, rather than the underground structures and their possibly damaged surroundings. In this sense, as important as it is, the issue of healing over the very long term does not currently seem likely to be unacceptable from the point of view of safety.

Role of the engineered barrier

The IEER suggests adopting a structure design in which the engineered barriers (probably swelling clay placed around the disposal packages) would perform a redundant isolation function (p.17).

A certain level of redundancy must obviously be sought. In fact, a geological disposal facility involves three barriers: the disposal packages; the engineered barriers, often consisting of swelling clay placed around the packages but also in the access structures; and the geological barrier. The nature of the geological barrier largely determines the design of the other two barriers.

The French concept, designed for a different rock from those used by the Americans and Scandinavians, includes a thick steel outer container which acts as a long-standing barrier to prevent water contact with the primary package of vitrified high-level waste. Beyond the lifetime of the outer container, the slow dissolution of the glass and reducing chemical conditions make it difficult for several large radionuclides to dissolve, including actinides. Over an even longer term, the clay geological barrier, like the swelling clay, considerably slows down the movement of water and retains some of the radionuclides that could migrate by diffusion. Andra has therefore decided not to place swelling clay in contact with the packages: the benefit in terms of safety would be reduced, while introducing the clay in the horizontal structures would be complicated. However, swelling-clay plugs will be placed in the tunnels, shafts and cavity heads; the IEER noted that their number was sufficient to provide redundancy. In Belgium, ONDRAF also plans to dispose of its waste in a clay rock mass and does not intend to place swelling clay around the waste packages either. The Board considers that the contribution of such devices to the necessary redundancy of the barriers would be small.

Appendix V

STOCAMINE

Introduction

An industrial-waste disposal facility was opened in 1997 at a depth of 500 m in tunnels specially excavated for this purpose in layers of rock salt located some twenty metres below the potash mine of Mines de Potasse d'Alsace. On 10 September 2002, some waste that should not have been disposed of in the facility, given its physico-chemical nature, caught fire. The operation of the disposal facility and the use of MDPA's last potash mine, which hosted it, ceased after the fire. Complete removal of the waste, the possibility of which was required by regulations, is being called for by part of the general public. After several expert assessments, it seems that this removal operation would be very difficult. The CNE has visited the StocaMine facility and examined various reports dedicated to it in an attempt to draw valuable lessons for the design and implementation of reversibility in a deep geological facility.

Legislation on the reversibility of disposal facilities for hazardous products (excluding radioactive waste)

The law of 19 July 1976 on facilities classified for environmental protection, amended several times, in its current version[19], stipulates that:

> *"The underground disposal in deep geological layers of hazardous products, irrespective of their nature, shall require government authorisation. This authorisation may only be granted or extended for a limited time and may therefore set out the conditions for the disposal facility's reversibility. The products must be removed upon expiry of the authorisation.*
>
> *After an authorised period of operation of at least twenty-five years, or if waste input has ceased for at least one year, the permit may be extended for an indefinite period, on the basis of an ecological assessment including an impact study and the presentation of alternatives to the continued use of the disposal facility and of their consequences..."*

The intention of the legislature was very clearly that reversibility remain physically and financially possible for a sufficient time and in any case during the period of operation.

The fire at StocaMine in 2002

In 1997, StocaMine was authorised to operate an underground disposal facility - the only one to date affected by this law - for class C0 and C1 industrial waste, containing in particular mercury, antimony, lead, arsenic and asbestos waste. The disposal of radioactive substances was ruled out. The products were disposed of at a depth of 500 m in underground tunnels excavated for this purpose in a salt layer from the infrastructure of the Amélie potash mine, operated near Mulhouse by Mines de Potasse d'Alsace (MDPA). On 10 September 2002, when 44,000 tonnes of waste had been placed in the disposal facility, a fire broke out in the last block being used for disposal. The immediate cause of the fire was the presence of non-compliant packages that had been placed in the facility a few weeks earlier despite several warnings, including those expressed by workers. A deeper cause behind this non-compliance could have been the economic pressure due to competition from German (non-radioactive) waste disposal facilities in salt mines, even though the privatisation of StocaMine had already been committed. These German disposal facilities, which currently contain millions of tonnes of waste in total, are not subject to the requirement of reversibility or to the requirement of the corresponding financial reserves.

[19] Légifrance. Article L515-7 of the Environmental Code, as amended by law no. 2006-739 of 28 June 2006.

Although the unused waste disposal cavities are still accessible, all disposal and excavation of new cavities ceased after the fire. However, monitoring and maintenance operations have been carried out by the operator to this day.
The disposal project, which offered the prospect of maintaining some level of activity in the potassium basin, was rather well received, but the fire created a feeling of distrust. Part of the general public is calling for the disposal operation to be reversed and the waste retrieved.

The matter of implementing reversibility at StocaMine

After several years of expert assessments following the fire, the examination of the disposal facility in its 2011 state showed that, even if retrieval was possible, it had become very difficult and potentially dangerous. This was obvious for the block containing the waste that had burned: the packages and mining tunnels there are highly degraded. But many experts felt that it was the same for the entire disposal facility: the tunnels for receiving the waste were closed quicker than originally expected. Also, some packages, metal drums and big-bags already showed signs of degradation that might make handling them dangerous, unless extensive precautions were taken.

By mid-2012, no decision had been taken.

It does not fall within the Board's remit to evaluate the design, implementation or current situation of StocaMine. However, this project is an example of the problems involved in implementing the principle of reversibility. For information purposes, the Board therefore visited the site in early 2011, at the kind invitation of the current managers of StocaMine. The Board also examined various documents, including the report[20] written for the Local Information and Monitoring Council (CLIS), prepared in 2011 by a panel of experts known as COPIL (Steering Committee).

XIV The steering committee notes that [for this type of disposal] *"the texts do not clearly define the concept of reversibility"*. It proposes that a "reversible" disposal facility be defined as a site where the cost of retrieval and its risks (in particular for those responsible for the retrieval) are comparable to those accepted during the disposal of the waste. It proposes a list of technical prerequisites that facilitate the implementation of reversibility:

> *"Labelling and the location of the waste must leave no doubt. Access routes must be kept in a satisfactory state. There must be sufficient space between the walls, the roof and the packages [...] so that the packages can easily be retrieved by handling equipment. This space must have been calculated with a margin to ensure it is preserved despite the inevitable movement of the ground during the reversibility period. The packaging of the waste, big-bags or drums, must have, during this same period, maintained the qualities necessary for safe and easy handling. If a large number of packages need to be removed, waste packages of the same nature must, to the extent possible, be placed in the same location; otherwise, a provisional storage location is necessary above or below ground for sorting the packages prior to transit. Finally, when large numbers of packages are to be retrieved with no intention to relocate them on-site, another disposal solution must exist for the retrieved packages. (p.19)"*

and the report of the COPIL concludes that:

> *"The general impression of the COPIL is that StocaMine was managed with unlimited disposal in mind. The COPIL must recognise that, even beyond the particular case of block 15 [the block affected by the fire], over time the actions of the disposal facility have become increasingly difficult to reverse due to, in particular, movements of ground but also the degradation of the waste packaging, slightly visible at the entrance to the tunnels of the disposal facility, but the extent of which remains to be assessed.* (p.20)"

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20 StocaMine Steering Committee. Expert report. July 2011. This report is available on the website of the Alsace Regional Directorate for Environment, Development and Housing (DREAL).

Lessons to be learned from the StocaMine example

From the point of view of implementing reversibility in a disposal facility, the StocaMine example highlights serious dysfunctions but also some positive elements, such as the response of workers to the emergencies caused by the fire. Although it is a very different site to Cigeo, not only in terms of the nature of the "host" medium but also with respect to the products disposed of there and the design of the waste cavities, lessons can be drawn from the StocaMine example that complement the views already presented by the Board:

1. The analysis of scenarios enabling the implementation of reversibility to be considered, must cover a wide range of possibilities, including normal and abnormal operations within the disposal facility. During the design of StocaMine, the possibility of a fire caused by equipment had been considered, but the idea of a fire breaking out in the package disposal area had been ignored. The incident was only made possible by a flagrant violation of the rules in terms of the nature of the products to be disposed of.
2. Concerning the geological disposal of radioactive waste, the quality of the waste package receipt and acceptance procedure is an essential element of the disposal facility's safety. This procedure, independent of that of waste producers, must be ensured by drastic material and organisational measures.
3. The notions of reversibility and retrievability must first have been fully considered by the person responsible for the disposal facility prior to the creation of the site. The contribution of contradictory and independent assessments during this consideration period is invaluable. The StocaMine[21] project definition document comprised 162 pages supplemented by appendices and external studies. Only a few tens of lines (p.11, p.62 and p.30 for the matter of financial guarantees) were devoted to reversibility.
4. The material requirements for reversibility must have been planned and the design of the site must make it easy. Utmost attention must be given to the safety of the workers who will retrieve the waste. The Board outlined in its Report No. 5[22] a list of these requirements, similar to the one provided by the COPIL and recalled above.
5. The same applies to the financial conditions for implementing reversibility; they must not hinder this implementation if the principle were adopted, in particular if the decision was due to safety considerations.
6. The ease at which reversibility can be implemented changes over the lifetime of a deep radioactive waste facility and must be rigorously assessed at its various stages. Conditions for institutional monitoring (by safety authorities) and democratic monitoring (in particular by local monitoring bodies) of the state of reversibility must have been put in place. This monitoring must be effectively implemented throughout the disposal facility's entire lifetime.
7. Safety must be the priority of those in charge of the disposal facility, who must have the necessary financial means and authority. Creating conditions centred on cost efficiency must not be at the top of their concerns.
8. An essential element of a deep radioactive waste disposal facility is the involvement at all levels of skilled, competent and experienced workers, who are able to present any views they may have on the safety and operation of the site..
9. All of these concerns must be addressed by a suitably solemn commitment to the national community. The law on reversibility, which is to be discussed by national representatives in 2016, should be a major milestone in this direction.

[21] Groupe EMC. Projet de stockage en mine de déchets industriels [Industrial waste disposal project in a mine], February 1996.

[22] CNE. Assessment Report No. 5, Volume 2, P. 41.

Appendix VI

INTERNATIONAL R&D

DEEP GEOLOGICAL DISPOSAL

The nature of the "host" medium requires specific techniques for the industrial excavation, operation, and sealing of the disposal tunnels. Additionally, the characteristics of the waste or spent fuel affect the choice of structural barriers, which, in combination with the "host" medium, will influence the performance of the disposal facility.

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

Public participation in decision-making processes and access to justice in the environmental field have become a right. This means not only transparency in the choices and decisions to be made, but also prior access to knowledge and a willingness by authorities to adopt new good governance rules.

An overview of ongoing projects in 2012 is presented.

BELBAR[23] Recent assessments of the safety of disposal facilities have shown that the formation and stability of colloids may have an impact on the disposal facility's overall behaviour. The main goal of the project is to increase knowledge of the processes that control the genesis and stability of colloids and their ability to transport radionuclides.

BIOPROTA[24] The goals of Bioprota, launched by Andra in 2002, is to identify biosphere models, determine the surface environment data acquisition protocols and analyse the state of knowledge about the processes and specific parameters of the transfer into the biosphere of priority radionuclides such as chlorine 36, selenium 79, carbon 14, iodine 129 etc.

CARBOWASTE[25] The graphite-moderator reactors are representative of the first generation of reactors being dismantled. Irradiated graphite contains carbon 14 and chlorine 36 in varying concentrations. These two radionuclides are highly mobile and prone to absorption by living matter. The aim of the project is to develop optimal techniques for processing this waste.

CATCLAY[26] Following the results of the FUNMIG project, CatClay should resolve the problem of migration of cations in densely compacted clay. For certain cations, the experiments have shown deeper diffusion than expected. A scientific explanation is essential for the safety studies on the concepts of disposal in clay.

CROCK[27] This project aims to develop a method for reducing the uncertainties in long-term predictions of the migration of radionuclides in crystalline rock. Variation in current data about retention in this rock cannot yet be linked to material properties or mechanisms. As a result, very conservative valuesare used in safety assessments. The project follows on from the FUNMIG project and Swedish siting studies.

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23 Bentonite Erosion: effects on the Long term performance of the engineered Barrier and Radionuclide Transport, 2012-2016, FP7, 7 countries, 14 partners.

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

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

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

27 Crystalline Rock Retention Processes, 2011-2013, FP7, 6 countries, 10 partners.

ERDO[28] Following the success of the SAPIERR projects, a multinational workgroup was appointed by the participating governmental organisations to study the possibility of creating a non-commercial association that could establish one or more European disposal centres 10 to 15 years from now

FEBEX 11[29] In the Grimsel underground laboratory, the Febex I experiment simulated the heating of a bentonite barrier and measured the consequences. As most of the sensors are still operational, Febex II continues the observation phase of the experiment in order to improve and validate the data and codes for the study of the geochemical processes, the generation and transport of gas, and the corrosion and performance of the measuring instruments.

FIRST-NUCLIDES[30] The aim of this project is to improve understanding of the quick release mechanisms of certain radionuclides in irradiated, high-burnup, disposed of fuel. The IGD-TP has given high priority to this issue.

FORGE[31] The objective of the project, which combines experimentation and modelling, is to improve knowledge of the gas transfer processes in the main materials present in the various radioactive waste disposal concepts currently being studied in Europe.

IGD-TP[32] The IGD-TP European technological platform for the geological disposal of nuclear waste is the culmination of work that began during the 6th Framework Programme, pursued by radioactive waste management organisations in Sweden, Finland and France, in collaboration with the German Federal Ministry of the Economy and Technology. A policy document describes the platform's mission, objectives, services and organisation. It also summarises the technical measures to be applied during the next 10-15 years in order for the Member States to implement the geological disposal of nuclear waste. The IGD-TP has defined and implemented a strategic research agenda that will help coordinate the efforts needed to address the scientific, technological and socio-political challenges regarding the geological disposal of nuclear waste while maintaining the highest levels of safety and environmental protection.

INSOTEC[33] Insotec will identify the major socio-political challenges involved in siting a geological disposal facility as well as their interplay with the technological challenges, such as adapting a general disposal concept to the social and natural reality of a chosen site.

IPPA[34] IPPA focuses on the creation, mainly in Central and Eastern Europe, of structures that allow different individuals or groups concerned to improve their understanding of geological disposal and discuss their views.

LUCOEX[35] The aim of this project is to conduct field demonstration tests of different concepts for HL waste disposal facilities: the horizontal concept at Mont Terri and Bure; the horizontal concept in granite at Aspö and the vertical concept in granite at Onkalo. Andra will also perform a heating test on a HL waste cavity.

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

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

30 Fast / Instant Release of Safety Relevant Radionuclides from Spent Nuclear Fuel, 2012-2014, FP7, 7 countries, 9 partners, including the CNRS.

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

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

33 International Socio-Technical Challenges for implementing geological disposal, 2011-2014, FP7, 11 countries, 14 partners, including the CNRS.

34 Implementing Public Participation Approaches in Radioactive Waste Disposal, 2011-2013, FP7, 12 countries, 17 partners, including Mutadis consultants.

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

MODERN[36] This project aims to provide a reference describing the technical objectives, resources and methods for designing a system for surveying and involving stakeholders during the different disposal phases, while respecting the needs and constraints specific to each country.

NEA-MESA[37] In most countries, the disposal of radioactive waste in geological repositories is the standard solution. Decision-making and social acceptance concerning these facilities rests on the degree of confidence in the safety assessments. The project examined and documented these assessment methods, deduced the similarities and differences, and identified the work yet to be done.

NWD[38] The aim of this action is to provide both experimental data and calculation results that help to develop an overall understanding of the long-term behaviour of high-level waste from current and future fuel cycles.

PEBS[39] Using a global approach, integrating experiments, models and studies of the impact on long-term safety functions, PEBS will assess the performance of machined barriers. The experiments and models will cover the complete spectrum of conditions, from the start (high temperature, resaturation of the barrier) up to the thermal balance and the resaturation with the "host" medium.

RADIOECOLOGY AND WASTE TASK GROUP[40] In 2002, Andra and the International Union of Radioecology launched an international working group in a bid to promote scientific collaboration between radioecologists in the field of radioactive waste.

RECOSY[41] The goal is to understand the redox phenomena that govern the fixation and release of radionuclides during the underground disposal of spent fuel. The aim is to provide tools for assessing the performance of the different methods of disposal and the safety record.

REDUPP[42] This project aims to reduce the uncertainties in the dissolution rate measurements of spent fuel. This is to increase the credibility of safety studies. A second objective is to organise training for young researchers who will ensure the future of research concerning geological disposal.

SITEX[43] This project identifies the approaches to be developed through the creation of a sustainable European network to improve understanding, harmonisation and cooperation between regulatory bodies, technical and safety organisations and waste management agencies.

SKIN[44] Studying the processes involving very slow movements of water in geological layers should enable the development of robust long-term assessment methods.

SORPTION II[45] The goal of this AEN project is to demonstrate the possibility of using several thermodynamic modelling techniques as part of the safety assessment for radioactive waste disposal in deep geological formations. In order to be able to assess the respective benefits and limitations of different thermodynamic sorption models, the project has taken the form of a comparative modelling exercise applied to a series of data sets on the sorption of radionuclides by materials.

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

37 Methods for Safety Assessment of Geological Disposal Facilities for Radioactive Waste, 2008-2012, Nuclear Energy Agency (NEA) of the OECD.

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

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

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

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

42 Reducing Uncertainty in Performance Prediction, 2011-2014, FP7, 3 countries, 5 partners.

43 Sustainable network of independent technical expertise for radioactive waste disposal, 2011-2014, FP7, 10 countries, 15 partners, including the IRSN (coordinator), the European Nuclear Safety Training and Tutoring Institute, Mutadis Consultants and the French Ministry of Ecology, Sustainable Development, Transport and Housing.

44 Slow processes in close-to-equilibrium conditions for radionuclides in water/solid systems of relevance to nuclear waste management, 2011-2013, FP7, 7 countries, 10 partners, including ARMINE/SUBATECH (coordinator).

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

NEW TECHNOLOGIES FOR PARTITIONING AND TRANSMUTATION

Transmutation strategies primarily rely upon fast neutrons, whether in critical or subcritical systems (ADS). The Generation IV initiative and the Sustainable Nuclear Energy Technological Platform (SNE-TP) aim to develop new types of reactors which include fast neutron reactors that recycle a maximum amount of fuel. They will require the development of new materials and innovative fuels that incorporate radionuclides derived from new partitioning techniques.

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

The development of a new technology must take into account all costs, both internal and external, positive and negative, as well as geopolitical elements so that the safety of supplies is optimally guaranteed.

An overview of ongoing projects in 2012 is presented.

ACSEPT[46] This project is the successor of Europart and Pyropep. Its goal is to select and optimise actinide partitioning and recycling processes compatible with the advanced fuel cycle options. The scientific feasibility of hydrochemical processes (selective and grouped extraction and back-extraction of actinides) and preliminary pyrochemical assessments (electrolysis and liquid-liquid extraction) must be demonstrated, taking into account the criteria and constraints of the industry.

ACTINET-I3[47] The goal of the project is to enable the European scientific community to benefit from laboratory infrastructures for research concerning actinides.

ANFC[48] Alternative fuel cycles based on partitioning and transmutation will be studied and assessed. Methods for the recovery of long half-life radionuclides, the optimisation of technologies for the production of innovative fuels based on inert matrices, and the characterisation of fuel properties before and after irradiation will also be examined.

ARCAS[49] A technico-economic study of the performance of critical and subcritical systems, such as machines dedicated to the transmutation of radioactive waste, will be conducted in a dual-layer approach.

ASGARD[50] Cross-sectional studies will be carried out in synergy with European programmes on fuel and waste, such as Acsept or Fairfuels. They will also further research on new reactor concepts, such as ASTRID and MYRRHA. Asgard will provide a research framework for the development of dissolution, reprocessing and fabrication techniques for a new generation of fuels.

ASTRID[51] For the record, the 600-MWe, sodium-cooled fast reactor prototype is planned for 2020. ASTRID should be built at the Marcoule nuclear site.

CDT[52] The project picks up where Eurotrans left off. CDT aims to obtain an advanced engineering design for MYRRHA using an integrated European team of experts and engineers. CDT should make it possible to give component suppliers and engineering firms the necessary specifications for the construction of the infrastructure. The team will also study the facility's operation in critical mode.

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46 Actinide recycling by separation and transmutation; 2008-2012, FP7, 12 countries, 34 partners including the CEA, EDF, the Compagnie Générale des Matières Nucléaires, Alcan Voreppe Research Centre, Louis Pasteur University, the CNRS, and Pierre and Marie Curie University.

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

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

49 ADS and fast reactor comparison study in support of SRA of SNETP; 2010-2012, FP7, 8 countries and 14 partners, including the CNRS

50 Advanced Fuels for Generation IV Reactors: Reprocessing and Dissolution, 2012-2015, FP7, 9 countries, 16 partners, including the CEA.

51 ASTRID, a prototype sodium-cooled fast neutron reactor, a project led by the CEA.

52 Central Design Team for a Fast Spectrum Transmutation Experimental Facility; 2009-2011, FP7, 8 countries, 19 partners including the CEA, the CNRS and Areva.

CP-ESFR[53] The project will address key problems linked to the development of the European sodium-cooled fast reactor (ESFR). The goal is to optimise safety levels, vis-à-vis existing reactors, the guarantee of a comparable financial risk, and flexible but robust management of nuclear materials. Optimisation studies will be conducted on the cores with an oxide fuel or carbide. The production and determination of the physical properties of minor actinide-bearing fuels will be studied.

EUFRAT[54] The CCR-IRMM neutron physics unit has a unique infrastructure for the highly accurate measurement of cross sections covering a wide energy spectrum. This project is continuing the work carried out during the Nudame project.

EVOL[55] The CNRS has been developing an innovative molten-salt fast reactor concept since 2004. Based on the use of liquid fuel, the concept is inspired by the molten-salt reactors of the 1960s. The aim is to propose a project in 2012.

ERINDA[56] In order to study their ability to transmute, various concepts of critical and subcritical reactors (ADS) will be studied. Precise knowledge of the nuclear reactions induced by neutrons or protons in the energy range from 1 keV to 500 MeV is critical for predicting the reduction in the inventory of plutonium, minor actinides and long-lived fission products..

FAIRFUELS[57] This project should provide a path towards more efficient use of fissile material in reactors, in order to reduce the volume and potential danger of LLHL waste. Fairfuels is concentrating on minor actinides. Dedicated fuel will be produced and a sufficiently complete irradiation programme will be established to study transmutation capabilities. In parallel, the programme includes post-irradiation analyses on certain older fuels to develop models. An education training programme is also planned.

FAR[58] This measure will make basic and applied knowledge available in the field of nuclear materials and fuels, and will be an "academic window" and a reference centre for the activities of CCRs (Joint Research Centres) in these domains.

F-BRIDGE[59] The empirical method used until now for the development and qualification of conventional fuel, is not suitable for the development and qualification of fuel for Generation IV reactors. The aim of the project is to build a bridge between theoretical research on ‘ceramic’-type fuel and cladding materials on the one hand, and technologies for the reactor fuels of the future on the other.

FREYA[60] Building on the results of the Muse and Eurotrans projects, Freya will further the study of subcritical configurations in order to validate the methodology for on-line reactivity monitoring of ADS systems.

GACID[61] The experimental programme, established through a collaboration between the CEA, the DOE (USA) and the JAEA (Japan), provides for the production of a fuel assembly with a high minor-actinide content, from reprocessed MOX, and its irradiation in a sodium-cooled FNR. It will be conducted over the long term with irradiations due to take place between 2015 and 2025, as the project requires the construction of a pilot workshop for the manufacture of the assembly and sufficient operating feedback after irradiation in Monju.

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53 Collaborative project on the European sodium fast reactor; 2009-2012, FP7, 10 countries, 25 partners, including the CEA, Areva NP, IRSN and EDF.
54 European facility for innovative reactor and transmutation neutron data; 2008-2012, FP7, CE-CCR.
55 Evaluation and Viability of Liquid Fuel Fast Reactor System, 2010-2013, FP7, 8 countries, 11 partners, including the CNRS, Inopro and Aubert & Duval.
56 European Research Infrastructures for Nuclear Data Applications, 2010-2013, FP7, 10 countries, 14 partners, including the CEA and the CNRS.
57 Fabrication, irradiation and reprocessing of fuels and targets for transmutation; 2009-2013, FP7, 6 countries, 10 partners, including the CEA and Lagrange-LCI.
58 Fundamental and Applied Actinide Research; CCR (Joint Research Centre) action, 12 countries, 26 partners.
59 Basic research for innovative fuels design for GEN IV systems; 2008-2012, FP7, 8 countries, 18 partners including the CEA, the CNRS, Areva, Materials design, Nathalie Dupin and Lagrange-LCI Consulting.
60 Fast reactor experiments for hybrid applications, 2011-2015, FP7, 10 countries, 16 partners, including the CNRS and the CEA.
61 Global Actinide Cycle International Demonstration; DOE, JAEA, CEA.

GETMAT[62] The aim of this collaborative project is to integrate in a common effort the R&D of expert European research laboratories on materials for future reactors and transmutation systems, including Generation IV and fusion reactors.

GIF/GEN-IV[63] The Generation-IV forum initiative aims to develop new types of reactors, including fast reactors producing minimal waste. Two technological avenues are being explored in Europe in order to be able to make a choice and to limit the risks related to development and the research agenda: a sodium-cooled fast reactor (SFR) is the first technological avenue based on European experience, the second is alternative gas- or lead-cooled fast reactor technology. The aim is to be able to commercially exploit fast reactor technology by 2040. In a sustainable development perspective, these two technologies can help to minimise the generation of radioactive waste and the risks of proliferation.

GOFASTER[64] In order to develop a more sustainable version of a very-high-temperature reactor, this project focuses on a gas-cooled fast reactor (GFR). The design of the GFR aims for a core outlet temperature of 850°C, a power density of 100 MWt/m3 and a core containing little plutonium. It must also not generate plutonium in order to be considered non-proliferating.

GUINEVERE[65] In March 2010, the "GUINEVERE" reactor was opened at SCK•CEN (Mol). GUINEVERE is a fast research reactor, driven by a very low powered accelerator (ADS) of only a few hundred Watts, and a precursor to MYRRHA. The reactor is the fruit of an excellent collaboration between the SCK•CEN, CEA and CNRS, within the framework of the EUROTRANS PROJECT. The Génépi-C accelerator was built by the CNRS in Grenoble, and the fuel was supplied by the CEA.

JASMIN[66] The goal of this project is to develop a new European simulation code, ASTEC-Na, in order to incorporate the feedback from severe incidents concerning sodium-cooled reactors. This will help design a Generation IV European SFR.

JHR-CP[67] For the record, the Jules Horowitz Reactor (JHR) is a 100-MWt research reactor, currently under construction in Cadarache. It is designed to offer, throughout much of the 21st century, a high-performance experimental irradiation capacity for studying the behaviour of irradiated fuels and materials, in response to the industrial and public needs for Generation II, III and IV power reactors (pressurised-water reactors, boiling-water reactors, gas reactors, sodium reactors, etc.) and the associated technologies. JHR-CP organises the international networks collaborating on the Jules Horowitz reactor, prepares the irradiation systems needed for these programmes and defines the training that will be useful to the future operators of these systems.

LEADER[68] This is the follow-up to the ELSY project. This project proposes to refine the technological design choices for a lead-cooled prototype reactor with a power of 600 MWe, and to design an LFR demonstrator.

MAX[69] Following the recommendations of the strategic research agenda of the SNE-TP for ADS development in Europe, the project addresses the design of a high-power accelerator for the MYRRHA project. Particular attention is being paid to the reliability and availability of the accelerator.

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62 Gen IV and transmutation materials; 2008-2013, FP7, 11 countries, 24 partners including the CEA, the CNRS and EDF.
63 Generation IV International Forum; 2001-?, Euratom + 12 countries, including France.
64 European Gas Cooled Fast Reactor, 2010-2013, 2010-2013, FP7, 10 countries, 22 organisations including the IRSN, Areva and the CEA.
65 GUINEVERE: Generator of Uninterrupted Intense Neutrons at the lead Venus Reactor; 2006-..., collaboration with the CEA and CNRS.
66 Joint Advanced Severe Accidents Modelling and Integration for Na-cooled fast neutron reactors, 2011-2015, FP7, 5 countries, 9 organisations including the IRSN (coordinator), Areva and EDF.
67 Jules Horowitz reactor collaborative project: contribution to the design and construction of a new research infrastructure of pan-European interest, the JHR material testing reactor; 2009-?, FP7, 5 countries and 6 partners including the CEA, which is managing the project.
68 Lead-cooled European Advanced Demonstration Reactor; 2010-2012; FP7, 12 countries and 17 partners including the CEA.
69 MYRRHA accelerator experiment, research and development programme, 2011-2014, FP7, 6 countries, 11 partners, including the CNRS (coordinator), Thales Electron Devises, Accelerators and cryogenic systems and the CEA.

MYRRHA[70] This project involves the construction of a 60-100-MWt subcritical, lead-bismuth-cooled, fast neutron ADS, which will demonstrate the feasibility of an accelerator - spallation source - subcritical reactor coupling in a pre-industrial installation. The reactor is designed to also be able to operate in critical mode. As a flexible, fast spectrum irradiation tool, this will offer the fast reactor communities (SFRs, LFRs and GFRs) a machine for testing materials and fuels, which will be essential to their development. Currently, the project is in the front-end engineering design phase.

ND-MINWASTE[71] This project aims to generate results from experiments for assessing the safety of current and future reactors, spent fuel and radioactive waste management.

NURISP[72] This project is part of the follow-up to the FP6 NURESIM project. Its aim is to integrate the digital and physical state of the art into a European simulation software platform in the domain of nuclear reactors.

PELGRIMM[73] In order to support the strategic research agenda of the SNE-TP, this project addresses the development of fuels containing minor actinides for fast react ors. Both options, homogeneous recycling within the core and heterogeneous recycling at the periphery of the core, are considered.

SARGEN-IV[74] This project brings together safety experts from technical bodies, design offices and industries as well as research centres and universities, in order to:

- develop and make available a common methodology for the safety assessment;
- provide a roadmap for new directions in safety-related R&D, including an estimation of their cost.

SEARCH[75] This project aims to help the licensing process by investigating the safety aspects concerning the chemical behaviour of the fuel and liquid metal coolant in the MYRRHA reactor. The areas investigated in further detail are the control of oxygen content and impurities in the liquid metal.

SILER[76] The aim of this project is to investigate the risk associated with seismic-initiated events in Gen IV reactors cooled by liquid heavy metals. Special attention is given to earthquakes and tsunamis beyond design limits as well as mitigation strategies, such as identifying solutions that prevent radioactive leaks from the core and spent fuel storage pools.

SNE-TP[77] The European technology platform for sustainable nuclear energy offers a short-, medium- and long-term view of the development of nuclear fission technologies. It encourages the development and implementation of potentially sustainable nuclear technologies, including the management of all kinds of waste. The platform also proposes extending the use of nuclear energy beyond electricity production, notably to hydrogen production, heat generation and seawater desalination. The platform has prepared a European industrial initiative, the European Sustainable Nuclear Industrial Initiative (ESNII), worth between 6 and 10 billion euros, and includes both the ASTRID and MYRRHA projects.

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

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

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

73 PELlets versus GRanulates: Irradiation, Manufacturing & Modelling, 2012-2015, FP7, 9 countries, 10 partners, including the CEA (coordinator), EDF, Areva, Lagrange and the European network for training in the nuclear sciences.

74 Harmonized European methodology for the Safety Assessment of innovative GEN-IV reactors, 2011-2013, FP7, 12 countries, 22 partners, including the IRSN (coordinator), Areva and the CEA.

75 Safe Exploitation Related Chemistry for HLM reactors and Lead-cooled Advanced Fast Reactors, 2011-2014, FP7, 7 countries, 12 partners, including the IRSN (coordinator), Areva and EDF.

76 Seismic-initiated events risk mitigation in lead-cooled reactors, 2011-2014, FP7, 8 countries, 18 partners, including the CEA, Nuvia Travaux Speciaux and Areva.

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

TDB[78] The goal of this project concerning a thermodynamic database (TDB) on chemical species, launched by the AEN, is to meet the specific modelling needs of safety evaluations of sites for the disposal of radioactive waste.

THINS[79] This project provides for the design and performance of thermo-hydraulic experiments in support of different innovative liquid metal-based systems.

EDUCATION, TRAINING AND KNOWLEDGE MANAGEMENT

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

ALICE[80] This project is a coordinated action between European and Chinese partners with a view to developing transnational access to large material test infrastructures, with the emphasis on irradiation facilities.

ENEN-III[81] The project covers the structuring, organisation, coordination and implementation of training schemes in cooperation with local, national and international training organisations, to provide training to professionals active in the nuclear industry or their (sub)contractors. The training schemes provide a portfolio of courses, sessions, seminars and workshops for life-long learning, upgrading knowledge and developing skills.

HeLiMnet[82] The goal of this project, which follows on from the Vella project, is to enable the exchange of researchers between laboratories that have an infrastructure for studying liquid metals such as sodium and lead.

PETRUS II[83] This project enables European professionals, active in the field of radioactive waste management, irrespective of their initial studies, to undergo a training course on geological disposal, which would be widely recognised in Europe.

78 Thermochemical Database project; AEN.
79 Thermal-Hydraulic research for Innovative Nuclear Systems; 2010-2014, FP7, 11 countries, 24 partners, including the CEA and IRSN.
80 Access to Large Infrastructures in China and Europa, 2012-2016, FP7, 5 countries, 5 partners, including the CEA
81 European nuclear education network training schemes, 2009-2013, FP7, 11 countries, 20 partners, including the European network for training in the nuclear sciences and the CEA.
82 Heavy Liquid Metal network; 2010-..., FP7, 9 countries and 13 partners, including the CEA
83 Towards a European training market and professional qualification in Geological Disposal; 2009-2012, FP7, 10 countries, 14 partners including the European network for training in the nuclear sciences, ANDRA and the Institut National Polytechnique de Lorraine.

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