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°7

NOVEMBER 2013

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SUMMARY

SUMMARY AND CONCLUSIONS

According to the provisions of the law of 2006, there are two aspects to the long-term management of long-lived high-level (LLHL) waste: the geological disposal of long-lived high- and intermediate-level waste from current reactors and the partitioning-transmutation of the actinides that would be present in the spent fuel from future reactors.

PARTITIONING AND TRANSMUTATION

The strategic and technological strategy of legislators is paving the way for the future by exploring the potentials of fast neutron reactors (FNR) and subcritical accelerator-driven reactors (ADS).

The highly innovative project involving the technology demonstrator Astrid absolutely must be completed to enable a full assessment of the capabilities of sodium-cooled FNRs and, in particular, their safety. There are interesting prospects in gas-cooled FNRs and molten-salt reactors using thorium, but only far in the future; it is advisable to continue the exploratory studies undertaken with our European partners in the hope of resolving the numerous scientific and technical stumbling blocks.

Studies of accelerator-driven systems are led by the French National Centre for Scientific Research (CNRS), which is partnered with the Myrrha project of the Belgian Nuclear Research Centre (SCK-CEN); these must be continued so as to later enable the creation of a pre-industrial system.

Major advances have been achieved in the field of partitioning in recent years. These involved the development of procedures to extract uranium and plutonium from spent fuel to recycle them, as well as the selective partitioning of minor actinides for potential transmutation purposes. To train the high-level personnel capable of running the future facilities under optimal safety conditions, it is essential for studies and research in partitioning and process engineering to be maintained at a level of excellence.

The exploration of possible avenues in the transmutation of americium, particularly with a view to lowering the costs of this process, still needs to be the subject of extensive research.

In a tense economic climate, the Board feels that the completion of the Astrid industrial demonstrator and the workshop for manufacturing its fuel must be made a top priority. Subsequently, a workshop for the reprocessing of the irradiated MOX fuel in Astrid must be implemented to demonstrate this reactor's ability to run on the plutonium from its spent fuel and the simple addition of depleted uranium. This will validate its functioning in isochronous generator mode with a high level of safety at least equal to that achieved by EPRs. The industrial transmutation of americium in heterogeneous mode must then be tested. To enable the final stock of plutonium to be reduced, Astrid's functioning in sub-generator mode, with the same level of safety, absolutely must be demonstrated.

CIGÉO GEOLOGICAL DISPOSAL FACILITY

More than 15 years of studies of the Meuse/Haute-Marne site have demonstrated the excellent containment properties of the argillite layer (COx), over 130 m in thickness and located at a depth of 500 m over an expanse large enough to accommodate the waste disposal facility of the Industrial Waste Management Programme (Programme Industriel de Gestion des Déchets - PIGD). No notable progress in the knowledge of this zone's properties will be made until direct access to the argillite is achieved via the shafts and tunnels that will need to be excavated to complete phase 1 of Cigéo. Andra will therefore need to define a scientific and technical support programme to be carried out during the conduct of work in this phase.

Backed by an international research framework, Andra launched an ambitious programme to study the seals and, in particular, the concretes that will contain the swelling clay cores within the rock mass. Given the considerable length of time required for a full-scale test, which can only be carried out in the disposal facility itself, modelling is essential. This has progressed more in the field of physical chemistry than in hydromechanics. The issue of the seals, which are responsible for providing radioactivity containment redundancy, will not therefore be fully addressed in the application (Demande d'Autorisation de Création - DAC) for authorisation to create Cigéo in 2014. This is not crippling at this stage, provided that Andra actively continues its research programme while integrating the experience feedback from other countries.

Significant progress has been made on modelling the hydraulic and solute transportation processes in the presence or otherwise of gas. Andra currently has very advanced tools for understanding and predicting the phenomena caused by the transfer of fluids within the COx. These models will be used to assess the disposal facility's performance and fine-tune the safety analysis that will accompany the DAC.

A review of the Cigéo design drafts, with the participation of the waste producers, was conducted at the start of 2013. It confirmed Andra's choices, which take safety requirements into account, notably in terms of fire; it also proposed increasing the length of the LLIL cavities to 500 m instead of 400 to reduce costs. Andra must now stipulate the avenues for optimising the Cigéo project and the scientific and technical issues to be addressed during and after the excavation. This programme will need to be accompanied by a schedule and must be available before the DAC is submitted. Cigéo must be sufficiently flexible to handle the wide variety of LLIL waste and adapt to possible developments in energy policy. Extensive studies are still required to plan the packaging and method of disposal of materials containing pyrophoric metals or organic products. As with bitumen matrix, Andra and the producers will need to create a complete knowledge file on this waste that details the studies on its behaviour under normal and incidental conditions.

The Board has made a recommendation on numerous occasions that, to comply with Andra's prerogatives, the project should benefit from the producers' experience throughout its execution. It stresses that the review of the project at the start of 2013 was completed just a few days before the launch of the public debate. This method of operation is not satisfactory. The Board would like to think that in future, the necessary consultation between the stakeholders will be carried out further in advance of any submission of files, particularly the DAC.

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The expected cost of Cigéo must be determined at the end of 2013 by the Minister by drawing on the conclusions of the working group headed by the DGEC and in which the waste producers participate alongside Andra. This cost will be revised upwards compared with the 2005 estimates. It is important for Andra to quickly provide a detailed assessment of the cost of the first phase of the project. It would be preferable to carry out comparisons using the methodologies, costs and financing methods chosen by the countries that have disposal projects, notably Belgium, Finland and Sweden.

Cigéo will have a major socio-economic impact on the host region. The consequences, both positive and negative, brought about by the construction and subsequent operation of Cigéo must be identified, analysed and taken into account in consultation with the populations concerned.

INTERNATIONAL DIMENSION

Most countries using nuclear power have a disposal centre that is operational or under construction for short-lived low-level (SLLL) or intermediate-level (SLIL) waste. In the case of long-lived low-level (LLLL) or intermediate-level (LLIL) waste, few sites are operational or even under construction. In the US, the WIPP (Waste Isolation Pilot Plant, excavated at a depth of ~600 m within salt beds in New Mexico) has been operational since 1999; it stores transuranium waste from the military programme.

The IAEA and the European Union specify that geological disposal is the benchmark solution for guaranteeing long-term safety in the management of LLHL radioactive waste and spent fuels in countries where they are considered as waste. Three basic options are envisaged for managing the irradiated fuel.

Direct geological disposal after cooling storage (Finland, Sweden, Canada, etc.).
The complete or partial recycling of the fuel; reprocessing enables the extraction of uranium and plutonium. The LLHL waste resulting from this reprocessing and the non-recycled fuels are temporarily stored prior to geological disposal (France, Belgium). The future of reprocessing is strongly linked to the policy chosen for managing plutonium.
Interim storage for countries that do not yet have an identified site (US, South Korea, Netherlands, etc.).

For the disposal of long-lived high-level waste, several countries have study and research programmes being conducted in underground laboratories (Germany, Belgium, France, Sweden, Switzerland, etc.). Finland, France and Sweden are the most advanced countries, as the start of construction on a disposal facility is planned in these countries within three to five years, with service activation coming around 2025/2030.

PREAMBULE

The Board lists in full the opinions that were presented in the preamble of its previous report dated November 2012, as reiterated below. Its opinions were prepared in compliance with the law of 2006 and the energy policy in place until that time, which recommended in particular:

- the continuation of nuclear power production;
- the reprocessing of all spent fuel;
- the manufacture and use of MOX fuel;
- the continuation of research into fourth-generation fast neutron reactors.

If some of the principles that guided its process of consideration had to be questioned, there would be major consequences for the entire nuclear power cycle, particularly the reprocessing of spent fuel. The Board would then have to reconsider its conclusions while taking into account the new system for materials and waste management that would be required by the new scenarios envisaged.

As it did in 2012, the Board feels justified in stating that:

- 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 poses a problem for people living above the disposal facility;
- the Meuse/Haute-Marne geological site was selected for detailed studies because a clay layer over 130 m thick and at a depth of 500 m demonstrated excellent containment qualities: stability over at least 100 million years, very slow water circulation and a high storage capacity;
- 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 have 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;
- 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. This 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 has already validated 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.

CNE2 ACTIVITIES

The period from November 2012 to October 2013 is the sixth full fiscal year for CNE2, and is the subject of this Report No. 7. Since the publication of its previous report in December 2012, the Board has presented its Report No. 6 to various bodies including the OPECST and ministerial departments. A Board delegation also visited Bar-le-Duc on 4 & 5 April 2013 to present its report to the members of the CLIS (local information and monitoring council) of Meuse/Haute-Marne.

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The Board (see Appendix I) followed the same working method as used in previous years. It held 14 hearings (see Appendix II) - five full-day sessions and seven half days 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 92 individuals 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.

To prepare this report, the Board held a two-day pre-seminar session during its visit to Marcoule, as well as internal meetings, one of which was a five-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.

The Board travelled to China and South Korea from 3 to 14 November 2013, visiting the disposal site in Beishan, the CEFR and the LILW Disposal Center (see Appendix IV).

This year, the Board has met the CNS/ESK[1] and visited the Mont-Terri laboratory in Switzerland.

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This report is organised to reflect the two complementary aspects of studies and research on the management of radioactive waste and materials: partitioning and transmutation in Chapter 1, and the storage and disposal of long-lived high-level (LLHL) and long-lived intermediate-level (LLIL) waste in Chapter 2. The management of long-lived low-level (LLLL) waste is addressed in Chapter 3.

Consistent with its mission, the Board continues to observe the overall international situation. The main elements are reported in Chapter 4.

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Lastly, with the public debate in mind, Ms Delphine Batho, the French Minister for Ecology, Sustainable Development and Energy, sent a letter to the President of the National Assessment Board on 3 December 2012 asking for the Board to assess the progress of research, and examine and formulate an opinion on files concerning partitioning-transmutation, the storage of long-lived high- and intermediate-level waste (LLHL-LLIL), the Cigéo design draft and reversibility. On 25 March 2013, the Board sent the following opinions to the Minister for Ecology, Sustainable Development and Energy:

- Opinion of the Board on the 2012 CEA report: partitioning-transmutation

[1] Eidgenössische Kommission für nukleare Sicherheit/Commission fédérale de sécurité nucléaire.

- Opinion of the Board on Andra's proposals: reversibility
- Opinion of the Board on Andra's proposals: the storage of long-lived high- and intermediate-level waste (LLHL-LLIL)
- Opinion of the Board on Andra's proposals: the Cigéo design draft

These opinions appear in Appendix V of this report and were made public. They can also be viewed on the website of the National Assessment Board at www.cne2.fr.

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Chapter 1

PARTITIONING-TRANSMUTATION

1.1 INTRODUCTION

1.1.1 Inventory and prospects

France has chosen to process spent nuclear fuel, which means separating the associated fission products and the minor actinides from uranium and plutonium. Fission products and actinides are currently vitrified, then packaged for geological disposal purposes. Plutonium is recycled to make the MOX fuel used in 900 MWe PWRs. A total of 22 PWR reactors, out of the 58 that currently make up the French nuclear fleet, use MOX. Meanwhile, uranium is used in so-called ERU fuels made from Enriched Reprocessed Uranium. Currently, spent MOX and ERU fuels are not reprocessed but stored. The decision to reprocess them is contingent on the deployment of fast neutron reactors (FNRs). This is because, due to the modification of the isotopic composition of MOX plutonium when it passes through a reactor, it is impossible in practical terms to envisage recycling it in a pressurised water reactor. However, this plutonium combined with depleted uranium could serve as a fuel for fast neutron reactors. In theory, the ability to reprocess it, once spent, in an FNR would allow it to be indefinitely recycled in this type of reactor. This property justifies the studies and research into generation IV FNRs around the world. In France, the CEA, in partnership with Areva, EDF and other industrial groups, is leading the industrial demonstrator project called Astrid, which aims to ensure that it is possible to construct and run an FNR that meets safety standards superior or equal to those of current third-generation reactors and could potentially recycle its own plutonium at competitive costs.

1.1.2 Fast neuron reactors: various implementation methodologies

By 2040, France will have over 450,000 tonnes of depleted uranium (DU) and enriched reprocessed uranium (ERU) provided by plants for the enrichment or reprocessing of materials (uranium and plutonium). These materials could be used for the deployment of a series of FNRs, which would complement or replace PWRs in the current fleet. A fleet of 60 GWe FNRs (power equivalent to the current nuclear power fleet) would consume during steady-state operations less than 50 tonnes of DU per year. This would guarantee France independence of supply for centuries, given that the importation of natural uranium and 235U enrichment would no longer be necessary.

Spent MOX fuel contains around 6% plutonium (1% in spent UOX fuel). As such, 7 tonnes of plutonium are produced every year and added to the stock already accumulated (around 300 tonnes in 2013). In 2030, the reprocessing of stored MOX and OUX would therefore yield the plutonium needed for the deployment of several 1,500 MWe FNRs.

One of the scenarios envisaged by the CEA, in partnership with EDF and Areva, involves implementing a sodium-cooled FNR around every four years, once the Astrid industrial demonstrator has enabled the technology to be validated. Such a deployment would stabilise the inventory of stored MOX. Subsequently, the implementation of FNRs would enable the transmutation of certain minor actinides into shorter-lived elements. In keeping with the law of 2006, the CEA has undertaken studies and research on the industrial implementation of partitioning and transmutation. The development of the Astrid industrial demonstrator is part of this approach. The study of ADS (Accelerator-Driven Systems), an alternative to the use of FNRs for the transmutation of minor actinides, is being carried out in a European framework with the Myrrha project. In addition, France is involved in the European gas-cooled FNR project "Allegro". What's more, the CNRS is conducting studies of molten-salt reactors, concentrating on the fast neutron spectra and the ability to use a thorium-based fuel.

The Board believes that the scientific and technology strategy of legislators lays a good foundation for upcoming decisions, notably by exploring potential options in the field of FNRs. The opinion that the Board submitted to the Government concerning partitioning-transmutation appears in the appendix to this document.

1.2 PARTITIONING

The CEA and Areva are fully proficient in the process of reprocessing spent UOX fuel from PWRs in the nuclear power fleet. Developments in partitioning in recent years have involved the development of procedures for co-extracting uranium and plutonium from spent UOX and MOX fuels with a view to recycling them, and the selective partitioning of minor actinides for possible transmutation purposes. The advances concern new substances with extractant properties tested on real spent fuel solutions at the CEA's Atalante facility. The selected substances meet the requirements for industrial implementation – in particular, resistance to radiolysis, solubility and selectiveness.

Several approaches have been developed, corresponding to the various options for the transmutation of actinides:

- The SANEX process, which separates americium associated with curium downstream of the PUREX process separating uranium and plutonium.
- The EXAm process, which isolates americium downstream of the PUREX process.
- The GANEX process, which can separate plutonium associated with minor actinides, as well as uranium and fission products.

The Board recommends maintaining R&D in the field of partitioning and process engineering at a level of excellence. More specifically, the focus must be placed on the chemistry and physical chemistry of the solutions and the materials containing actinides. In addition, although the effluents from partitioning operations are now well characterised, the processing and packaging of the waste generated still needs to be studied and researched. The Board asks that studies and research be conducted into the development of stable matrices for the disposal of iodine.

The programme concerning the chemistry and physical chemistry of radionuclides, particularly actinides, is essential for the success of the Astrid project and can only be conducted in the long term by maintaining high-level personnel capable of innovating and carrying out developments of current and future fleets under optimal safety conditions.

1.3 TRANSMUTATION

1.3.1 Managing materials and tools

With a view to best utilising the energy resources of depleted uranium and plutonium (obtained after the processing of spent MOX fuels), France is conducting studies and research on sodium-cooled fast neutron reactors and gas-cooled fast neutron reactors, currently focusing its efforts on sodium-cooled fast neutron reactors. This choice, confirmed by the French government in 2005, is justified by:

- the ability of FNRs to combine electricity production in the multi-recycling of plutonium; this, combined with 238U (an essential component of depleted uranium) in a specific fuel, enhances the energy potential of uranium, which would therefore become the leading fossil fuel resource that France would have in abundance;
- the experience gained worldwide, and more specifically in France, from the creation and operation of the Phénix and Superphénix reactors;
- the potential of FNRs to industrially transmute all or part of minor actinides.

1.3.2 Astrid (Advanced Sodium Technological Reactor for Industrial Demonstration)

The Astrid project aims to demonstrate the technical and industrial possibility of producing electricity with a sodium-cooled FNR functioning with a ^{238}U-Pu fuel and guaranteeing an equivalent or higher level of safety compared with an EPR

The project is carried out as part of extensive collaborations:

- at an international level, as part of the Generation IV Forum, in which France is partnered with the European Union, Japan, Russia, the US, South Korea and China for the development of sodium-cooled FNRs;
- at a national level, the Astrid project is conducted by the CEA in partnership with Areva, EDF, Alstom, Bouygues, Comex, etc.

The Astrid reactor is designed to have a power of 600 MWe, corresponding, for safety, to core dimensions that enable subsequent extrapolation to 1,500 MWe reactors. The use of sodium as a coolant fluid is justified by:

- its thermal inertia, which maintains an excellent behaviour of the reactor in the event of the loss of cold source;
- its high boiling point, which ensures a difference of 300°C between the temperature under operating conditions and the boiling temperature of sodium;
- its low corrosivity compared with that of lead which, combined with bismuth, is used as a coolant in certain FNRs.

By contrast, sodium's very high reactivity to air and water and the increased risks of a reaction in the event of sodium voiding require adaptations and innovations to achieve the targeted level of safety. In addition, a power of 600 MWe corresponds to the electricity production capacity that, with Astrid connected to the network, would cover the running costs of this reactor thanks to the sale of electricity.

a) Astrid's innovations

In association with its partners, the CEA is proposing a series of innovations aimed at compensating for the known drawbacks of sodium-cooled FNRs, including the significant increase in reactivity in the event of the disappearance of sodium in large cores. These include:

- the design of a benchmark core called CFV (from the French acronym for low void effect core) to prevent an increase in the reaction in the event of the local voiding of sodium; the innovations consist of a reduction of the volume proportion of sodium in the core and the addition of a sodium-filled cavity above the beam of pins (sodium plenum);
- heterogeneous geometry of the core, due to the presence of a plate fertile in depleted uranium oxide mid-way and the differentiation of internal and external fissile zones (pot-shaped core);

  - ✓ These first two innovations enable a warning about the increase in reactivity caused by sodium voiding, by significantly increasing the release of neutrons outside the core's fissile zones. These advances, which promise favourable core behaviour in the event of cooling loss, still need to be validated at an international level. A French-US independent verification and simulation programme is being carried out. A French-Russian neutron physics programme (Genesis) using the critical models BFS (Russia) and MASURCA (Cadarache) is planned.

- the draining of the residual power of the fuel in the event that the chain reaction is halted (control rods down) requires continuous cooling of the core. The Astrid project includes systems that optimise natural convection within the primary circuit, with exchangers as close as possible to the heat source to ensure cooling even if the electric power to the pumps is cut off;
- the development of a sodium-sodium-gas cooling system (benchmark system) using pressurised nitrogen (18 MPa) at an operating temperature of 300 to 500°C to power gas turbines would be a major innovation from a safety viewpoint; alternatively, a tertiary gas circuit, combined with the primary and secondary sodium circuits to convert the heat into water vapour (sodium-sodium-gas-water), would also prevent any accidental water-sodium contact;
- studies and research are also under way to define the architecture of a corium collector so as to maintain its subcriticality and long-term cooling and limit corium-collector interactions;
- significant advances have been made for in-service inspection thanks to experience feedback from Phénix.

The Board takes a favourable view of the safety improvement effort from which Astrid would benefit compared with current FNRs. It recommends continuing on this path, while at the same time expanding on inspection and repair techniques in the presence of liquid sodium. International collaborations (US and Russia) play a major role, notably by providing access to irradiation capabilities. The Board therefore recommends that it be presented with the results of the international programme to validate the neutron physics and elements constituting the core of Astrid.

b) The materials

The choice of the mixed oxide $(U\text{-}Pu)O_2$ as a benchmark fuel for the core of Astrid draws on experience feedback spanning more than 40 years collected thanks to the experience gained from Rapsodie, Phénix and Superphénix. Technical proficiency has been achieved in the technical facilities that allow this fuel to be produced (Melox plant). The industrial feasibility of producing MOX at 25% Pu now needs to be demonstrated..

As far as the cladding materials and hexagonal tube are concerned, the initial choice is an austenitic steel, for which experience feedback from Phénix has demonstrated excellent resistance under operating conditions. The studies and research, primarily based on the analysis of irradiated nuances in this steel, are under way and are expected to enable the production and qualification of the first Astrid core within the time frames set by law. One major studies and research programme concerns ODS martensitic and ferritic steels. Indeed, the material chosen must have a very low rate of swelling under irradiation to meet the requirements of a very tight fuel network with high burnup rates (>150 MWd/t). The studies and research also concern SiC-SiC materials and vanadium-based materials, which would allow very high reactor operating temperatures.

Such materials, which are capable of functioning at high temperature, would enable a higher performance and a significant improvement in safety. The Board recommends that the industries able to manufacture the components using ODS or SiC-SiC be identified as soon as possible and involved in the project's conduct over the long term.

c) Implementation of Astrid

The detailed preliminary design was initially due to be presented in 2017 and, if followed by a construction decision, would have begun in 2018 and been completed around 2023. The CEA has now submitted a revised timetable at the Government's request; this has resulted in a detailed preliminary design in 2019 and a possible postponement until 2026. Five hundred people, half from the CEA and half personnel from French and foreign industries, are now contributing to the project.

Astrid needs to be extremely flexible, as it must both act as a precursor to an industrial nuclear power reactor (safety and operating modes) and cater for experiments on innovative fuels and the transmutation of minor actinides.

The facility must also demonstrate that, after operating with a core whose plutonium will come from the reprocessing of MOX, Astrid will be capable of reusing its own Pu to manufacture a new fuel. A complete programme therefore requires attaching to the reactor:

- a UPuO2 fuel production workshop;
- a spent fuel processing workshop for recycling uranium and plutonium.

The Board recommends that the studies and research continue and that the schedule include the construction of the fuel production workshop and spent fuel processing workshop facilities. In particular, using the experience gained from the Phénix Reactor, it is necessary to size and design the radiological protection of personnel during various operations.

1.3.3 The transmutation of minor actinides

Subsequently, the transmutation of actinides in an FNR could be tested using two methodologies:

- homogeneous, by incorporating into the fuel the minor actinides mixed with the plutonium resulting from the GANEX process;
- heterogeneous, by placing blanket fuels containing the actinides on the edge of the core; two types of blankets could be envisaged:
    - ✓ CCAM, for minor actinide-rich blanket fuels: these contain americium and curium obtained via the SANEX process;
    - ✓ CCAm, for americium-rich blanket fuels obtained via the EXAm process.

Transmutation in homogeneous mode requires the presence of minor actinides at significant levels in the fuel, which may have a negative effect on safety. The reprocessing of this fuel will require specific studies on criticality and radiation protection.

The Board agrees with the CEA regarding the choices presented to it for the transmutation of actinides and feels that the studies and research must address the heterogeneous transmutation of americium alone in blanket fuels (CCAm) as a priority.

Whereas homogeneous transmutation would require numerous technological breakthroughs (a core containing U, Pu and Am), the choice of blanket fuels would allow the gradual implementation of transmutation in Astrid. This is because the CCAm will only be deployed after the reactor starts up and all operation and safety parameters have been validated. This choice also allows a separation between the manufacture of the fuel (uranium and plutonium) and that of the blanket fuels (americium and uranium) and avoids the presence of actinides in all stages of the fuel cycle..

The Board stresses that the presence of americium in the blanket fuels will require specific radiation protection measures for the personnel and facilities.

The CEA's studies and research programme concerning americium-rich blanket fuels is comprised of several important stages:

- The acquisition of all physical data enabling the definition of the geometry of the blanket fuels, their americium content and their positioning to ensure the degree of safety required for the reactor's implementation.
- The complete laboratory trialling of the EXAm process to test it, from the dissolution of the fuel through to the production of the solution containing the americium, and to manage all of the flows and effluents.
- The large-scale implementation of the EXAm process.
- The synthesis of $UAmO_2$ pellets at a laboratory level for upstream irradiation studies.
- The large-scale synthesis of $UAmO_2$ pellets.

1.4 THE BENEFIT OF AMERICIUM TRANSMUTATION

The Board reiterates that the transmutation of actinides does not concern LLHL (Long-Lived High-Level) waste produced or to be produced by the current fleet of reactors. This waste is irreversibly vitrified. After packaging, it is sent to a deep geological disposal facility. The studies carried out by Andra have shown that the actinides present in these packages migrate so slowly into the clay that they cannot contribute to radioactivity detectable at the outlet.

In the event of a 2040-2050 schedule for a fleet containing FNRs, the actinides could be partitioned before vitrification. This would reduce the size of the LLHL waste storage cavities and significantly reduce the potential radiotoxicity. However, it would cause additional difficulties in terms of radiation protection within the facilities of the nuclear cycle. The dedicated studies and research have so far been envisaging the transmutation of americium alone, as the benefit of curium transmutation remains to be demonstrated.

The benefit of the transmutation of americium lies in its important contribution to the emission of heat by the vitrified packages. The studies have shown that extracting americium from LLHL waste would reduce the size of the dedicated cavities by a factor of 7, which, for the current inventory, would lead to a factor 3 reduction for the entire disposal facility. However, this extraction would not eliminate the need for either the storage of vitrified packages for the 120 years necessary for the decrease in fission products or the geological disposal of residual LLHL waste.

Financially speaking, this space gain would have to be weighed against the significant increase in the cost of electricity production. According to the CEA's estimates, this would be 5% to 9% if the transmutation was carried out in FNRs and around 25% if it used ADS.

It is currently difficult to draw up a definitive appraisal of the advantages and disadvantages of the implementation of transmutation. Even limited to americium alone, it would significantly reduce the radiotoxicity of the waste disposed but, for a waste disposal facility in a layer of clay, which contains actinides over the long term, this advantage is primarily valid in specific scenarios such as that of human intrusion.

Nevertheless, scientific and technological breakthroughs could significantly improve the design of transmutation. The Board therefore strongly recommends the continuation of research requested by the laws of 1991 and 2006. It believes that this research constitutes an important objective of the Astrid programme.

1.5 SCENARIOS FOR THE DEPLOYMENT OF SODIUM-COOLED FNR IN THE FRENCH NUCLEAR POWER FLEET

In the event that Astrid is postponed until 2026, it is likely that this technological demonstrator will have achieved its industrial objective around 2040 and that a first series of sodium-cooled FNRs could then be introduced into the nuclear power fleet. This commissioning of a few FNRs at the rate of one every four years would achieve experience in the industrial operation of this type of reactor, maintain and strengthen expertise in the implementation and safety of FNRs, stabilise the stock of plutonium and minimise the accumulation of 241Am originating from 241Pu during storage.

The flexibility of sodium-cooled FNRs enables the efficient management of materials, as these reactors can operate in:

- iso breeder mode: the reactor produces as much fissile material as it consumes and only the addition of uranium is needed to reconstitute a new core;
- breeder generator mode: the reactor produces more plutonium than it consumes, thereby enabling new FNRs to start up;
- sub-generator mode: the reactor consumes more plutonium than it produces.

Within the framework of an energy transition and the scheduled abandonment of nuclear power, FNRs operating in sub-generator mode would consume plutonium while at the same time producing electrical power. Theoretical calculations and initial experimental results show that the plutonium inventory could be reduced by two thirds in 60 years.

The isochronous and breeder generator modes for the operation of a FNR have been the subject of studies with the Phénix and Superphénix reactors. Concerning the sub-generator mode, the CEA has tested, in the Phénix reactor, a sub-generator of the CAPRA type (from the French acronym for Increased Plutonium Consumption in Fast Reactors).

This experience in sub-generation and plutonium consumption must be expanded, as it is essential for the proficient management of plutonium. The research programme under way, using Masurca and the irradiation systems available in France or abroad, must be very actively sustained. Once Astrid has demonstrated its ability to operate in isochronous generator mode, the Board recommends that this FNR be used to test operation in sub-generator mode on an industrial scale.

1.6 ALTERNATIVES TO SODIUM-COOLED FNR

1.6.1 For electricity production and the transmutation of minor actinides

a) Gas-cooled FNR: ALLEGRO

The development of this project is based on the scientific and technical collaboration of four European countries: Hungary, Slovakia, Czech Republic and Poland. Its implementation, within the Generation IV Forum, involves the creation of a centre of excellence that would host the prototype. Support from the European cohesion funds will be requested for the 2014-2020 period.

The Allegro project will require numerous technological stumbling blocks to be resolved. The Board is planning to monitor its conduct and will attentively examine the initial achievements in its next report.

b) Molten-salt reactors (MSR)

◆ **The concept**

The use of liquid fuel (molten salt) would be a major breakthrough in the design of reactors. Indeed, this type of so-called homogeneous reactor has intrinsic safety properties thanks to the liquid fuel's coefficient of thermal expansion. If the temperature rises, this liquid expands and exits the core, thereby ensuring a drop in neutron reactivity. Management of the fuel is potentially simplified compared with that of a solid fuel, as all operations would be continuously carried out via the simple transfer of fluid between the core, the reprocessing unit and the voiding areas. Unlike solid-fuel reactors, these operations would not require the reactor to be shut down.

Experience in the running of FNRs has been gained in the US in particular, with the MSBR industrial reactor (Molten Salt Breeder Reactor). Given the experience feedback from the MSBR, the CNRS proposed a new concept in 2006: the MSFR (Molten Salt Fast Reactor), which was selected by the Generation IV Forum in 2008. Today, countries such as India and Brazil are interested in this technology.

The potential advantages of the MSFR are:

- a fast neutron spectrum and therefore an optimal use of the energy capacity of the thorium-based fuel;
- the possible transmutation of minor actinides;
- continuous reprocessing in situ of the fuel, which, limited to ~0.1% of the total volume per day, would not affect either the stability or operation of the reactor.

The characteristics of the MSFR during a project would be:

- a benchmark liquid fuel comprised of a mix of 75.5 mole % 7LiF – 22.5 mole % ThF4, with part of the thorium being able to be replaced by 235U, depleted U, Pu and minor actinides;
- geometry enabling a fast neutron spectrum associated with high power thanks to the stability of the fluoride salts;
- an absence of control rods compensated by a passive or active voiding system.

◆ **Difficulties to overcome and obstacles to resolve**

Studies and research concerning molten salt have not been very active in recent decades, so much so that the expertise and skills required for the implementation of an MSFR project are currently limited. The challenges to face include:

- the development of materials resistant to corrosion in molten salt at a temperature of 700°C;
- the absence of cladding, which constitutes the first barrier in a standard reactor, requires a totally new approach to safety;
- the impact on the safety of the coupling between the reactor and the fuel processing system;
- the demonstration of the effectiveness of waste processing and the operation of heat exchangers over the very long term;
- comprehensive control over corrosion and erosion;
- the introduction of an industrial technology for the waste.

The Board stresses the need to acquire national expertise in the thorium cycle. It encourages the CNRS to assemble a community with skills and expertise in molten salt and materials, applied to an industrial project to develop a prototype in the second half of the 21st century.

1.6.2 For the transmutation of minor actinides: ADS (Accelerator Driven Systems)

In France, studies of accelerator driven systems are led by the CNRS, which is associated with the Myrrha project of Belgium's SCK-CEN. Myrrha is a sub-critical, 100 MWth fast neutron spectrum ADS cooled using lead-bismuth. The test reactor Guinevere, designed as part of the Myrrha project, was unveiled at the SCK-CEN site in 2010. This low-power, accelerator-driven reactor can operate in critical and sub-critical mode. Numerous developments of components - accelerator, spallation target, fuel - will need to be tested and validated with the help of Myrrha to be able to achieve a pre-industrial system.

ADS will enable the transmutation of minor actinides, but cannot achieve the transmutation of plutonium in the necessary quantities. In the European ADS development scenarios, the transmutation of large amounts of plutonium remains confined to FNRs.

The Board analysed ADS in its previous report. It will closely follow this project, which has entered into the front-end engineering design phase.

1.7 CONCLUSIONS AND RECOMMANDATIONS

The programme of studies on the partitioning and transmutation of actinides addresses key problems in proficiency, safety and evolution in a context of electricity production using FNRs. It is preparing a technology demonstrator project in keeping with the law, while at the same time leaving innovative scientific options open.

The Board recommends the continuation of the Astrid project; it absolutely must be completed to enable a complete assessment of the potentials of sodium FNRs.

The Board believes that gas and molten salt FNRs open up interesting prospects for far in the future; it is therefore advisable to continue the exploratory studies undertaken with our European partners.

Although the transmutation of minor actinides was chosen, the Board is of the opinion that the solutions considered by ADS should be taken into account and compared to those of FNRs.

Because the partitioning-transmutation of americium and the operation of FNRs in sub-generator mode present substantial advantages, the Board urges active research to continue into these subjects.

Lastly, the Board would like the full appraisal of waste produced by FNR technology to continue to be refined.

In a tense economic climate, the Board feels that the completion of the Astrid industrial demonstrator and the workshop for manufacturing the fuel must be made a top priority.

Subsequently, a workshop for the reprocessing of the spent MOX fuel in Astrid must be implemented to test the possibility of powering this FNR on the Pu it has produced itself and available depleted uranium.

When the operation of the Astrid FNR in iso breeder mode has been validated on an industrial scale, the heterogeneous transmutation of americium on an industrial scale must be demonstrated. The Board asks the CEA to conduct active monitoring of scientific advances that could open up new transmutation possibilities. It also asks it to develop studies and research on the operation of Astrid in sub-generator mode and propose a plan for the management of actinides (U, Pu, Minor Actinides) in case of a scheduled shutdown of a nuclear power fleet including FNRs.

The first industrial trials of transmutation and sub-generation in Astrid will only be able to be carried out in 20 years' time at best. The Board would like to know the outlines, milestones and resources of the scientific programme for preparing these trials.

Chapter 2

DISPOSAL IN CIGÉO

For the preparation of its 2013 report, the Board took into account the elements notified to it from December 2012 concerning the conclusions of the design draft phase carried out by Andra with the support of its systems integrator Gaiya. It was also informed about the debates between Andra and the waste producers that took place regarding the design draft, during the project review held between November 2012 and February 2013. On 21 May 2013, Andra presented an analysis and a justification of its choices. In addition, the Board spoke about Andra's design draft proposal at the request of the French Minister for Ecology, Sustainable Development and Energy. This opinion was made public and attached to the document file of the public debate required by law prior to the submission of the DAC (request for authorization of construction).

In this report, the Board also mentions recent progress on the assessment of disposal costs and speaks about the socio-economic impact of the Cigéo project.

2.1 GEOLOGICAL KNOWLEDGE ABOUT THE ZIRA (from the French acronym for zones of Interest for further investigation)

Andra has implemented the best proven technologies for the further investigation of the ZIRA from ground level. Andra considers that the high-resolution 3D seismic study confirmed that the identifiable discontinuities at the base of the Callovo-Oxfordian (COx) claystone would not spread into the COx. These heterogeneities have been interpreted as having a sedimentary origin (reef facies) or an early structural origin prior to the deposit of COx, with dissolutions into the Triassic saliferous mass possibly having caused deformations in the underlying layers now sealed by the COx.

None of the data collected by these investigations suggests the presence of geological anomalies of an extent above the resolution threshold of the seismic study (no faults with vertical offsets larger than a few meters), which could have altered the consistency of the COx and its ability to contain waste over the long term.

The main uncertainty concerns the precise geometry of the COx at its top and results from the major heterogeneity of seismic speeds in the overlying formations, which are therefore not fully understood. Undulations of a few metres in amplitude and large wavelengths in the argillite layer dedicated to the disposal facility therefore cannot be ruled out. It will be sufficient to take this into account in the overall architecture of the site to ensure the required thicknesses of argillite above and below the disposal areas.

The Board believes that no notable progress in the knowledge of the ZIRA's properties will be made until direct access to the COx is achieved via the shafts and tunnels in phase 1 of Cigéo. This excavation will provide an opportunity to confirm the geological model for the ZIRA.

The Board recommends that Andra defines the scientific and technical support programme planned to take place during the conduct of work in phase 1. This programme will aim to fine-tune the values of the COx parameters for the ZIRA. Andra will need to define the resources put in place to identify any geological inconsistencies during the excavation. It will also need to indicate the strategy it is considering adopting to take into account any new results that may emerge.

2.2 STUDIES IN UNDERGROUND AND SURFACE LABORATORIES

The innovative studies that have been submitted to the Board concern the seals on which it placed great importance in its previous reports.

Three successive barriers are placed between the radionuclides and the biosphere: the disposal packages, the engineered barriers built during the construction of the site, and the natural geological barrier made up of the overburden. In the Cigéo project, the engineered barriers are comprised of three-metre-long swelling clay plugs placed into the inserts of the LLHL cavities and much longer seals placed between two concrete supporting embankments in the access tunnels, shafts and drifts. The latter are placed in such a way that a radionuclide must breach several plugs in order to exit from the argillite layer.

To limit the flow of water across the seals, Andra is aiming for a permeability of the clay core of less than 10^{-18} m^2. In addition, the clay comprising the core of the seals contains over the long term some of the radionuclides dissolved in water, particularly the actinides, as carried out by the natural surrounding geological environment made up of argillite.

It is likely that the overall permeability of the plug will play an important role at the core-argillite interface, the EDZ (Excavation Damaged Zone) and the sections of coating left in place. The Board observes that the hydraulic cuts envisaged in the 2005 Report, which aimed to reduce this role, no longer appear to be included as an option.

2.3 RESEARCH PROGRAMME

A programme of research in this field can draw on the experience feedback of numerous countries that have chosen similar technical solutions for the creation of structural barriers. Andra has wisely utilised this international collaborative research dynamic, particularly through the European programmes.

The difficulty of such a programme is due to several factors:

- As with all seals in underground structures with high effectiveness targets, small-scale prototypes can provide a useful contribution to the design. However, a convincing result can only be completely achieved through full-scale tests carried out under real-life conditions, as these structures are too large to be placed in the underground laboratory. In addition, in the case of the bentonite plugs considered, put in place in a dry state, the natural hydration and swelling necessary for them to effectively play their role in the disposal facility are very long processes spread out over hundreds of years.
- The implementation of swelling clay poses intricate technological problems, as a high dry density that guarantees strong swelling pressure after hydration needs to be obtained on the scale of the whole structure. It is therefore necessary to leave gaps as weak as possible within the clay core and in contact with the walls of the tunnels, given that, after the at least partial removal of the coverings, the tunnels will undoubtedly contain profile form deviations that will make compact placement more difficult.
- The concrete intended for the supporting embankments, the role of which is to contain the core after swelling, must be taken to the tunnels from the surface; its installation is accompanied by a transitional thermomechanical phase (heating-cooling-cracking) that must not diminish its later performances.

[2] 10^{-18} m^2 corresponds to a water flow of 150 litres per year through a plug 50 m long in a tunnel 50 m^2 across and with a pressure differential of 5 MPa between the two ends of the seals.

As such, although the research programme must concentrate on the choice of materials (concrete and swelling clay) and the analysis of performance in the very long term, it must also demonstrate the industrial feasibility of their placement under basic conditions.

2.3.1 Tests under way or in preparation

The FSS (Full Scale Sealing) test forms part of the European programme DOPAS. In a surface workshop, it uses a horizontal model 7.6 m in diameter containing a swelling clay core 13.5 m in length placed between two low-pH concrete embankments 5 m in length, respectively poured concrete and shotcrete. The test, which does not include hydration or, therefore, verification of the barrier's effectiveness, is significantly orientated towards industrial feasibility: the creation of a high average dry density in the presence of unplanned anomalies in the walls, the placement of large volumes of low-pH concrete under conditions intentionally similar to those in the facility, with instrumentation that can verify that the objectives have been achieved, notably in terms of average density. The experimental protocol is gradually refined; the dismantling of this model, at the end of 2015, will be a particularly important measurement phase.

The FSS test is complemented by a metric scale hydratation test that will begin at the end of 2013 and provide an order of magnitude of the resaturation durations.

The so-called NSC test, carried out in a blind tunnel of the underground laboratory (a seal 4.6 m in diameter and 5 m in length), uses clay bricks in the form of stacked 0.3 x 0.2 x 0.1 m^3 parallelepipeds. It contains forced hydration and aims to evaluate the barrier's performances, particularly the overall permeability (clay core plus interface plus EDZ plus concrete left in place) of the structure, but only partial results will be available at the end of 2014.

2.3.2 Sealing materials

The CEA has examined, for Andra, the nature, shaping and placement of swelling clay for the tests envisaged. For the NSC test, the material chosen is a mixture of Wyoming bentonite and quartz sand. The presence of the latter illustrates the difficulty of developing an ideal mixture, which needs to swell - to ensure close contact with the walls of tunnels -, but not too much - to avoid longitudinal movements and excessive forces on the supporting embankments; it must also present low permeability in its final stage, while at the same time enabling faster hydration in the initial phase. For the FSS test, the swelling clay will take the form of pellets (pellets 32 mm in diameter) accompanied by dry powder or crushed pellets.

Concrete is extensively used in the disposal facility as a containment matrix for certain packages, for supporting tunnels and for the embankments supporting the seals. Its mineralogical composition and high pH make it a significantly exogenous material within the clay rock mass with which it is in contact, the latter being characterised by strong CO_2 partial pressure, the presence of chloride and a high sulphate content. The long-term behaviour of the concrete-argillite-core interfaces must therefore be carefully assessed.

Taking international research into account, Andra has endeavoured to formulate concretes subject to multiple forces (pumpable, low pH, low hydration heat, low free alkaline content, etc.) and the components of which will need to meet a set of properties dictated by the disposal conditions.

The Board notes the importance of the research work conducted by Andra regarding the sealing materials. This has resulted in innovative concretes that are suited to a complex set of constraints and the long-term properties of which, currently being studied, must be the subject of a long-term characterisation effort.

2.3.3 Modelling the behaviour of seals

There are specific difficulties in modelling the behaviour of seals. The hydromechanical final equilibrium of the core will not be attained for at least a thousand years, meaning that the long-term extrapolation of the evolutions of the materials will play an important role. The packaging conditions (presence or otherwise of pressurised hydrogen, nature of the hydraulic loading) and the behaviour of the materials (recently designed low-pH concrete, bentonite-sand mixture), the high-volume assemblies of these materials and their interfaces (between each other and the rock mass) still present uncertainties, as is normal for any innovative procedure.

Knowledge has nevertheless advanced sufficiently for Andra to be able to calibrate calculation models. Its calculations over 100,000 years show, in comparison with a traditional concrete, an increase in the porosity of the concretes and a reduction in the spread of damage from the interface, both in the concrete and the argillite.

The Board notes that a major effort to model the chemical behaviour and its physical consequences has begun. It hopes that the mechanical and hydraulic aspects still described in general terms will be presented more comprehensively.

More generally, the Board observed, in its previous reports, that the matter of seals could not be addressed comprehensively in the 2014 report. Several arguments have led the Board to determine that this time frame was acceptable. Firstly, in principle, the use of swelling clays has been chosen by nearly all of the countries concerned, which attests to its credibility and provides the benefit of extensive experience feedback. Secondly, the engineered barrier provides redundancy, as the safety studies conducted so far show that in the event of the widespread failure of the seals, diffusion through the geological barrier would remain the preferred way of radionuclide transfer. Lastly, the question of putting the seals in place will mainly come during the closure of the disposal facility, in over a century, so comprehensive experimental results are not yet essential at this stage.

The Board will carefully examine how the DAC answers the questions that still remain about the seals. In any event, this question will remain partially open. It strongly recommends that the recent attention paid to the quality of the seals be maintained. The FSS test will only be able to establish technological feasibility, while the NSC test will provide very valuable findings but will only serve as an initial component of a longer-term demonstration in a disposal situation, on which a major priority will need to be placed. Particular attention will need to be paid to the interfaces between the swelling clay, the concrete and the COx.

2.4 DIGITAL SIMULATION CAPABILITIES

Since the publication of its 2005 report, Andra has made a considerable effort in digital simulation. The general strategy is based on a partnership with the academic world for upstream research and with services and engineering companies for developments and certain studies, with Andra retaining responsibility for the physical conceptualisation of the systems and the choices of models. Andra carries out simulations itself in the phenomenological domains that are central to the issues it faces, such as hydraulics and the transportation of solutes, water-gas two-phase transport and reactive transport. It mostly entrusts external parties with thermal, mechanical and air processing simulations, taking care to maintain an internal level of expertise enabling proficiency in the interpretation of the results.

For its internal work, Andra has selected the best calculation codes available on the market, leaving itself the option of having the designers make any upgrades it deems necessary. As such, digital simulation toolboxes are available for each of Andra's three favoured themes mentioned above. Each toolbox contains a reference code, into which is gradually integrated all of the specific necessary developments, verifier codes and an academic code on which current developments are tested.

Concerning the practical implementation of simulation resources, Andra has abandoned the Alliances platform developed for the 2005 report in favour of a new, more ergonomic platform called Cassandra (from the French acronym for Codes Applied to the Simulation of Andra's Disposal Facilities). The objective is to have a single interface for managing all of the digital codes. This allows codes to be easily combined for the simulation of multiphysical phenomena, as well as easy intercomparison while minimising the risks of human error in their management.

> *The Board reminds Andra that outsourcing digital simulation skills could be detrimental in the long term. It is therefore advisable to maintain an internal capability for intervention at the three levels of codes: reference, qualification and academic.*

This simulation capability was put to use during compared assessments of solutions in the draft phase. This enabled all of the engineered components (cavities, tunnels, shafts and seals) in the storage facility to be taken into account at a detailed architectural level during a single simulation that includes a realistic hydrogeological description of the COx. These calculations enabled the quantification, in the various draft scenarios, of the transfers of iodine 129 within the disposal facility; they required the meshing of over 12 million elements to be able to distinguish between the solutions, which represents a considerable digital technological leap compared with the 2005 situation.

Progress was also made in simulating the multicomponent two-phase migration of gases, which is now completely handled from the gas-generating packages through to the structures linking the surface to the facility. Once again, considerable progress has been made here in the methods for analysing disposal situations.

Efforts have also been made on modelling the chemicals-transport coupled processes. Complete proficiency has now been achieved in this area, enabling 2D and 3D simulations of chemical interactions in multiple components, as may occur at the concrete-clay interfaces for example, in keeping with realistic timescales that are representative of the duration of containment of the radionuclides.

This simulation work has been made possible thanks to partnership research work, with Andra acting either as a research prescriber or playing an active role. As such, the collaboration with Inria primarily concerned adaptive meshing techniques and high-performance digital methods that enable coupled systems to be handled. Questions arising further upstream, aimed in particular at quantifying the uncertainties present in the simulations, are taken into account within the Momas GNR (French Research Group, Momas = Mathematical Modelling and Digital Simulations dedicated to Nuclear Waste Management), although no practical responses have yet been provided in cases of realistic simulations. Several European projects (PAMINA for performance and safety analysis, FORGE for gas transfers) have been utilised for carrying out code intercomparison exercises.

The Board notes with satisfaction that significant and rapid progress has been made in modelling hydraulic processes and the transport of solutes at multi-scale and multi-physical levels. Andra currently has very advanced tools for understanding and predicting the phenomena caused by the transfer of fluids within the COx, while taking into account the details of the disposal facility's architecture. Among other things, this allows optimisation options to be sought out and justified in order to improve the disposal facility's performances.

Useful work still needs to be carried out on combining recent progress, which appears to mostly involve near fields and intermediate field, with the advances made in 2012 in regional hydrogeological modelling. Indeed, the regional model built by the University of Neuchâtel draws on a very large collective knowledge base concerning the geology and hydrogeology of the Paris basin, complemented by Andra's own results. It therefore provides a quantified and validated scientific understanding of the local and regional hydrogeology, as it combines within a single simulation tool a model of the entire Paris Basin and a sector model that takes into account all of the data acquired in the transposition zone. This tool allows visualisation, through to their surface outlets, of the radionuclide transfer channels that would have diffused through the COx to the over or underlying aquifers. It also provides the ability to assess how long it takes a substance dissolved in water to travel the length of these transfer channels.

The Board advises Andra to assess all of the developments and improvements made to the hydrogeological model at all levels during the conduct of the safety analysis that will be provided in the DAC. This safety analysis will need to be gradually refined as new information emerges during the excavation of phase 1 of Cigéo.

2.5 CONDUCT OF THE DRAFT PHASE

In its role as project owner, Andra defined in 2011 the requirements applicable to the Cigéo project. These requirements were stated in the specifications for the systems integrator chosen to conduct the draft study. Following an initial project review in May 2011, during which the viewpoints of Andra and the producers could be compared, project contractorship was entrusted in January 2012 to the Gaiya group (Technip/Ingerop) after examination of a European call for tenders.

The objective of the draft study was to:

- state the project's technical and environmental constraints;
- verify its technical feasibility;
- present technical solutions combined with a scheduled programme of work and a cost estimate.

In December 2012, Andra presented three comprehensive solutions developed by Gaiya for the underground facilities. These took into account the disposal of waste packages according to the hypotheses defined by the producers in the Industrial Waste Management Programme (PIGD). In this framework, the LLIL packages, which are highly diverse in nature, would be disposed of from 2025. Meanwhile, high-level packages that are highly exothermic but more consistent in nature would be disposed of from 2075.

The three solutions chosen meet the requirements of the specifications. Their overall architecture varies little and in each case includes separate disposal zones for LLIL waste, HL0 waste and HL (h) waste, all of which can be inserted in the ZIRA. Solutions 1 and 3 enable greater use of the tunnelling machine than solution 2, which favours the selective heading machine, the result being that the latter solution presents a more compact surface area footprint than the other two.

Andra undertook a comparative analysis of the solutions, examining:

- operating safety;
- a phenomenological analysis of the disposal solutions;
- the long-term safety performances after closure.

Concerning operating safety, Andra concludes that there are no significant differences between the three solutions concerning the exposure of personnel to ionising radiation, the possibility of releasing radiolytic gases and risks inherent to the handling of the packages. Regarding the fire risk and the risk of co-activity between work zones and operating zones, solution 2 proves to be less successful.

The phenomenological analysis of the three solutions was carried out in terms of the thermal behaviour of the disposal facility and transient mechanisms concerning hydraulics and gases after closure. The causes of variability are primarily linked to the geometry of the COx over the extent of the ZIRA (dip, thickness), with the rock's physical properties remaining identical. Solution 2, which is more compact, gives rise to temperatures several degrees higher in the COx 500 years after deployment. As such, it results in a temperature around 15 degrees higher in the air return ventilation shafts in the HL areas after 100 years of operation. The thermohydraulic behaviour of the water and gases after sealing seems similar, although there is higher gas pressure (by 0.5 MPa) in solution 2 due to a more pronounced thermal regime.

Long-term safety is examined by Andra by taking into account the performances of engineered components and the position of disposal zones in the ZIRA in view of the hydraulic gradient in the COx and the directions of flow in the aquifers situated above and below the COx. The conclusions are based on the transport of iodine (129I), a radionuclide that emerged during previous studies as being the most disadvantageous. They are on the whole identical for the three solutions; a slight difference emerged in solution 2, in which the releases of iodine come later.

A multi-criteria analysis lead Andra to choose solution 1 for the underground facilities, arguing that it is the most favourable in terms of responding to industrial questions, particularly as far as the organisation of co-activity is concerned. It includes:

- a surface-facility link provided by two drifts excavated by the tunnelling machine and by five shafts;
- LLIL and HL zones whose access tunnels are excavated by the tunnelling machine and a HL0 zone excavated by the selective heading machine;
- a procedure for transferring the baskets containing the packages by the funicular in the drifts, then by rail to the disposal zones.

Andra also presented three solutions for the surface architectures, these differing primarily by the greater or lesser extent of the burial of the facilities and by the respective locations of the work activity zone and disposal activity zone. The analysis of the associated risks and the optimisation of the use of space point to a choice comprising a work activity centred around shafts and a disposal activity established in the drift zone in semi-buried structures. These measures appear to be the most favourable in terms of outside hazards such as aircraft crashes and adverse weather (protection against flooding being thoroughly assured).

At the request of the Minister for Ecology, Sustainable Development and Energy, the Board addressed Andra's proposals in an opinion submitted on 25 March 2013. Its conclusions are that Andra's choice takes into account the safety requirements, both over the long term and the short term, in such a way that there are no scientific or technical reasons to postpone the continuation of the process of preparing the DAC.

2.6 PROJECT REVIEW

The Directorate General for Energy and Climate at the Ministry of Ecology, Sustainable Development and Energy held, between November 2012 and February 2013, a draft-purpose project review of the Cigéo project. This review's report found that it was not possible, as things currently stand, to move on to the basic preliminary design phase. It requested an in-depth assessment of several technical design choices deemed decisive for the project's continuation.

The Board was invited to attend a debriefing on 21 May 2013 during which Andra presented an analysis of the diverse variants and a justification of those it had chosen, namely:

- the transportation of packages in the drift by funicular;
- the doubling, where possible, of the link and access tunnels according to a so-called "dual tube" design;
- the option of the basket as a second containment barrier for the transportation to the facility of the majority of LLIL waste.

Their examination led to confirmation of Andra's choices, which are superior from a safety viewpoint, notably in terms of fire hazards. In addition, there is no significant difference in the costs involved.

Andra also proposed modifying the architecture for the disposal of LLIL packages by lengthening the cavities by 400 to 500 m and reducing their number proportionally, thus reaping cost savings.

The Board feels that the consequences of this latest development must be analysed, particularly from the viewpoint of the implementation of reversibility, as well as the questions raised by co-disposal.

More generally, in its Report No. 5, the Board recommended that the producers be included in discussions throughout the conduct of the industrial project and that their contribution be put to use through a process that remained to be implemented and in which Andra would need to maintain all its prerogatives as project owner, in keeping with the law.

The Board observes that the debriefing of 21 May 2013 aimed to give a verdict on fundamental choices for the Cigéo industrial project, even though its design draft had already been submitted to the government, and this just a few days before the launch of a debate aimed at gathering the public's observations. It feels that this method of operation is not satisfactory. In future, the necessary consultation with producers, carried out in compliance with the prerogatives of the various stakeholders, should be carried out sufficiently in advance of any submission files and in particular that of the application for authorisation to create the disposal facility, scheduled for the end of 2014.

2.7 CIGÉO FINAL DESIGN

The Cigéo concept initially proposed by Andra, adapted by taking into account elements that emerged from the project review, now appears credible from an industrial viewpoint. At this stage, the design draft is compliant overall with rules aimed at ensuring the disposal facility's safety in keeping with the ALARA principal[3]. Optimisation possibilities have been identified and will need to be explored by Andra. A timetable for the conduct of work in phase 1 of the disposal facility is proposed.

Following the project review and the public debate, the Board feels that Andra must now present an updated version of the Cigéo project. It will need to stipulate the possibilities for optimising the concepts chosen and the scientific and technical questions that need to be addressed during and after the excavation work. This will need to be accompanied by a timetable that absolutely must be available before the submission of the DAC, scheduled for the end of 2014.

2.8 NECESSARY FLEXIBILITY OF CIGÉO

In the Board's view, various questions to which the responses could change over time require flexibility in the Cigéo concept starting with the conduct of phase 1.

2.8.1 Knowledge of LLIL waste

The state of knowledge concerning LLIL waste is currently being advanced and Andra has established, at the Board's request, a dashboard that provides an overview of this knowledge. This dashboard identifies five categories:

- Vitrified LLIL waste (975 m^3).

[3] As low as reasonably achieavable

- Hulls and end-caps (11,130 m^3) and waste from decommissioning (10,356 m^3).
- Waste containing pyrophoric metals (2,157 m^3).
- Waste containing organic matter (20,793 m^3) and bitumen matrix (13,598 m^3).
- Miscellaneous waste (7,996 m^3).

Pyrophoric metals such as sodium, aluminium and magnesium have the property of spontaneous inflammation upon contact with air. While aluminium and to a lesser extent magnesium can form layers of oxidation that protect them from direct contact with air, sodium "burns" entirely. The disposal of materials containing pyrophoric metals must therefore be the subject of special attention and advanced studies into the reactions they are liable to generate. Given sodium's very high reactivity to water, its presence in Cigéo must also be limited as much as possible; sodium waste is already processed so that it is partially decontaminated of its sodium, although it remains to be verified whether this decontamination is sufficient to ensure the disposal facility's long-term safety. As far as other pyrophoric metals such as aluminium and magnesium are concerned, Andra and the producers must endeavour to demonstrate that this waste is present in bulk form (no highly explosive powders), protected by an isolating layer making them passive, and that no physicochemical phenomenon is liable to cause their inflammation.

The Board emphasised bitumen matrix in its Report No. 6, although these are not the only organic wastes. Generally speaking, this waste releases from hydrogen and other gases such as alkanes and hydrochloric acid. In addition, the radiolysis of organic matter is liable to produce complex chemical species that promote the mobility of radioactive material.

In the case of vitrified LLIL waste, the state of knowledge is satisfactory on the whole and the programmes under way will enable various uncertainties to be resolved.

Similarly, Andra and the producers have gained a very good level of knowledge about the packaging of hulls and end-caps. It is nevertheless advisable to stipulate their fissile material content and verify their very low mobility under disposal conditions so as to guarantee an absence of criticality risk. As for waste produced by decommissioning, studies can be envisaged over the medium/long term.

The Board reiterates its request for an additional study of bitumen matrix, which must be submitted to it by the end of 2014.

It recommends adding to the knowledge file on pyrophoric waste and organic waste. It would like to have studies on their behaviour under normal and incidental disposal conditions, particularly in the event of fire.

Waste classified as miscellaneous by the PIGD must quickly be the subject of detailed studies to define its final method of disposal.

2.8.2 Optimisation of the disposal facility and chemical compatibility

Andra is considering extending the HL and LLIL cavities. Unlike HL waste, which is consistent from the viewpoint of the design and dimension of the packages and which therefore all has very similar characteristics, LLIL waste is very diverse and extremely variable in terms of the volume of packages and chemical composition within the same family. As such, the extension of the HL cavities will not pose chemical compatibility problems, whereas the extension of the LLIL cavities risks resulting in the joint disposal of different families and sub-families of waste. It is therefore advisable to study the compatibility of these different families so as to ensure that the joint disposal of their packages does not create additional risks.

Joined disposal facilities will need to be tested under the severest of conditions with non-radioactive chemical equivalents in order to experimentally verify that they do not create additional risks. From this viewpoint, the approach proposed by the producers to validate the possibility of the disposal of bitumen matrix must be applied to all joint disposal facilities.

The Board would like to receive the knowledge file on waste families that Andra is considering disposing of together and the studies on their chemical compatibility under normal and incidental conditions.

The Board would like to receive as quickly as possible a workload plan for the LLIL cavities, indicating the families of waste planned per cavity, the joint disposal facilities planned and the studies justifying these facilities.

2.8.3 The case of spent fuels (SF)

As things currently stand, SFs, excluding SF0, are not final waste intended for deep geological disposal, as they are intended for reprocessing; they must not appear in the inventory submitted for the DAC. Changes in energy policy could alter this choice. There are multiple scenarios that depend on decisions yet to be made: whether or not to vitrify all HL waste in the PIGD, obtain waste from PWRs without waiting for FNRs, etc. Andra envisaged this eventuality by introducing, in the design of Cigéo, infrastructures (drifts, access tunnels, tunnel crossroads) capable of catering for the transfer of SF packages. A safety analysis of the disposal of SFs was presented in the 2005 report. Current uncertainties regarding the national energy strategy encourage flexibility. Cigéo must not turn into a rigid programme that prevents the disposal facility from being adapted to new directions.

The Board believes that Andra should specify the scientific and technological elements that would need to be developed to adapt Cigéo to the disposal of SFs in various scenarios with a view to a new safety analysis prior to a new DAC.

2.9 COST OF CIGÉO

Studies on the Cigéo project are financed by a "research" tax (tax on Basic Nuclear Facilities). The plan is to maintain these studies and research efforts, and the tax is a good mechanism to keep in place going forward.

The financing of the construction and operation of Cigéo will be borne by the waste producers (EDF, CEA and Areva) and will be provided through agreements between Andra and the producers. The cost allocation formula chosen is currently as follows: 78% for EDF, 17% for the CEA and 5% for Areva. By law, the producers must make the necessary provisions and secure these provisions through so-called "dedicated" assets. The cost of the disposal facility must be decided on during 2013 by the Ministry, although discussions are still under way and no decision has yet been made. This cost will be significantly higher than the initial estimates in 2005; this is in no way surprising for a "prototype", particularly because the volume of the packages for disposal has increased since the first project. The fact that the lifespan of power stations has been increased will also have an impact on the volume of LLIL and LLHL waste for disposal. Creating a tax to finance this spending does not appear judicious: this would detract from the waste producers' responsibility and place the role of payer of "last resort" on the taxpayer's shoulders. The law is clear on this matter: waste producers are responsible for paying for the disposal facility.

The first phase of Cigéo involves creating the necessary infrastructures to implement the start-up of the facility. This involves the surface buildings (conventional facilities and nuclear facilities), excavating the first tunnels and various cavities, and an initial storage facility. In 2012, the DGEC set up a working group that, under the Ministry's guidance, brings together the waste producers (EDF, CEA, Areva) and Andra. The Board participates in this "costs WG" as an observer. Experience has shown that this WG's periodic meetings were useful for explaining the differences concerning costs between the stakeholders and sharing their experience feedback. Certain reconciliations were observed, although differences remain (particularly regarding the cost of the concrete). Discussions within the "costs WG" are specifically aimed at explaining the discrepancies observed in terms of the figures put forward by Andra on the one hand and the producers on the other. Two observations can be made.

- By nature, it is currently difficult to predict the cost of facilities whose lifespan is more than a century. This cost is also highly sensitive to the waste delivery schedule provided by the producers. Furthermore, it is sensitive to changes in the techniques that will be used. Calculations currently draw on the waste schedule provided in January 2012. This may change. Certain cost discrepancies compared with the 2005 estimates are due to the different scope of the facilities. Two surface facilities are planned (EP1 for IL waste and EP2 for HL waste), compared with just one in the 2005 project. By the end of 2013, Andra should be in a position to provide the construction costs for the surface facilities and the first underground facilities. An accurate picture also needs to be provided of the operating costs, upgrade costs (it is currently difficult to predict the cost of replacement equipment that will be necessary in the future), insurance costs, and in particular the amount of taxes that will be charged to these facilities. Uncertainties remain regarding the amount of taxes; these should be resolved when negotiations between the Ministry of Industry and the Ministry of Finance come to an end.
- A distinction needs to be made between gross expenditure and discounted expenditure. Expenditure will be staggered over the long term and its positioning over time does not mean that comprehensive financing plans need to be made at present. According to the January 2012 estimate by the Court of Auditors, the cost of disposing of this waste will amount to a very low percentage, put at 1% to 2%, of the price per KWh paid by consumers. Discounted expenditure is by nature significantly lower than gross expenditure and varies depending on the discount rate applied. For example, at a discounted cost of 3%, a 50-year time frame corresponds to a cost reduction of 77%.

While advocating the continued analysis of the disposal facility's total cost, the Board would like to quickly receive an estimate of the completion costs for phase 1. Estimates of the disposal facility's cost will need to be refined as the packages are deposited, based on experience feedback.

It recommends carrying out international comparisons concerning costs registered for an underground disposal facility. A comparative analysis regarding the cases of Belgium, the UK, Finland and Sweden would be useful in shedding light on this debate.

The project contains fixed costs and variable costs. Some of these costs can be attributed either to LLIL waste or LLHL waste, while others are difficult to attribute (shared costs). This is true both for fixed costs and variable costs (operation). How are they to be financed? Can a two-way tariff be devised? In this case, reservation costs would be paid based on the volume of waste to be disposed and operating costs, will be recovered when waste is disposed. It is necessary to bear in mind that there can be a long period of time between the reservation of capacities and the disposal of waste. To finance the initial facility costs, a "work advance" agreement needs to be made with the producers. Charging EDF and Areva ultimately means charging electricity consumers, as the cost will obviously be reflected in the price of electricity. Charging the CEA (which mainly produces LLIL waste) means charging taxpayers, as the government will ultimately have to provide the necessary loans. The financing method's impacts on the cost of electricity and on public finances must be stated. The rules will also need to be adjustable over time.

The Board feels that a process of reflection now needs to be undertaken on how to finance the various stages of the project.

2.10 SOCIO-ECONOMIC IMPACTS OF THE CIGÉO PROJECT

Due to its scope and duration, the Cigéo project will have an undoubted impact on the living conditions of the inhabitants of Meuse and Haute Marne affected.

Claiming that the project is in the community's best interest cannot in and of itself legitimise the negatively perceived impacts. Indeed, the construction and operation of a radioactive waste disposal centre will cause disruptions. However, the economic knock-on effects and the support measures envisaged are expected to create an opportunity for the development of a region hit by deindustrialisation and depopulation.

The consequences of a project comparable in scope to Cigéo are the subject of in-depth studies in several countries. A social science research programme in Sweden has since 2004 been looking at the long-term socio-economic impact of the construction of a storage facility on the communities concerned.

The Board feels that the scientific studies and those on the industrial facilities must be complemented by studies on economic and social integration in order to make Cigéo a cohesive and balanced project.

Although some parties are already experiencing the project's positive effects, others will only see them in the long term. Those who will experience the disruptions will not always be the direct beneficiaries of the economic and social knock-on effects. The imbalance between perceptions of the negative externalities and the positive compensating factors partially explains the concerns expressed during the public debate.

The consequences, both positive and negative, brought about by the construction and subsequent operation of Cigéo must be identified, analysed and taken into account in consultation with the populations concerned.

Chapter 3

LONG-LIVE LOW-LEVEL

Long-live low-level (LLLL) waste includes graphite from "natural uranium-graphite-gas" technology, radium-contaminated waste, including waste from the processing of rare earth minerals, drums of bitumen matrix and, lastly, processing residue from the conversion of uranium, produced at the Comurhex plant in Malvési.

In its Report No. 2 dated June 2008, the Board said that radium-bearing waste could be disposed of under reconstituted or intact coverings. However, the 23,000 tonnes of graphite, the total ^{36}Cl content of which, of a period of 300,000 years, was roughly estimated at 21,000 TBq, required disposal under an intact covering to isolate from the biosphere the ^{36}Cl, which is labile and very mobile in the environment. No study had been presented for the disposal of other categories of LLLL waste.

Since 2008, the producers have been developing a research programme concerning graphites in order to achieve a more accurate assessment of the ^{36}Cl content; the initial results indicate that the initial content had been overestimated. Meanwhile, the European project Carbowaste is examining decontamination methods. The Board is not familiar with the conclusions of this project. In addition, studies are under way into the possibility of converting certain types of LLLL waste into LLIL waste via the concentration of their radionuclides. These would then be intended for disposal in Cigéo.

The Board feels that the management of LLLL waste has thus far been too chaotic. In many respects, the results of studies and research still seem preliminary.

The Board will be keeping a close eye on the conclusions that Andra and the producers draw from the studies and research under way. The disposal of the diverse varieties of LLLL waste will require the definition of dedicated disposal systems. The radionuclide concentration procedures will need to include effective disposal matrices.

In preparation for its next report, the Board will hear from Andra and the producers regarding their strategies concerning all LLLL waste.

The Board reiterates that, in cases where waste cannot be disposed of at the surface due to its radioactivity, it must be isolated from the biosphere. This isolation must be maintained throughout the period during which this waste poses a threat. A safety analysis of the disposal site must demonstrate this.

The current silence regarding the search for a potential disposal site under an intact covering is worrying.

Chapter 4

INTERNATIONAL OVERVIEW 2007-2013

4.1 DIFFERENT OPTIONS IN THE MANAGEMENT OF LONG-LIVED LL, IL AND HL WASTE

Most countries using nuclear power have a disposal centre that is operational or under construction for short-lived low-level (SLLL) or intermediate-level (SLIL) waste. Because of this, there are no longer major challenges to be met with regard to the management of this type of waste. The most important efforts remain those concerning demonstrating the safety, quality assurance and guarantee that the scheduled capacities fully take into account future production.

For long-lived low-level (LLLL) and intermediate-level (LLIL) waste (transuranium elements, chlorine 36, etc.), processing and management technologies still partially need to be developed. There are few sites in operation, under construction or even under development. In the USA, the WIPP (Waste Isolation Pilot Plant, located at a depth of 650 m in the salt layer in Carlsbad, New Mexico) has been operational since 1999 and is used for the final disposal of transuranium waste from the military programme.

For the disposal of long-lived high-level waste (LLHL), several countries have study and research programmes being conducted in underground laboratories (Belgium, France, Germany, Sweden, Switzerland, etc.). In Europe, in terms of concrete projects to install geological disposal facilities for irradiated fuel or LLHL waste, Finland, France and Sweden are the most advanced countries, each with a similar schedule. Construction is set to begin in three to five years, with service activation coming around 2025.

In all countries that use nuclear power, the most important strategic choice concerns the management of irradiated fuel. There are three basic options:

- Direct disposal: the fuel is stored for a few decades, then disposed of in a geological formation (Finland, Sweden, Canada, etc.).
- Complete or partial recycling: the fuel is reprocessed, uranium and plutonium are (mono) recycled in pressurised water reactors; LLHL waste from this reprocessing and MOX or non-recycled fuels are temporarily stored (France, Belgium: moratorium on reprocessing etc.).
- Wait and see: long-term storage (for a few decades) is planned pending the emergence of a clear vision of the future of nuclear energy and/or the time required to develop processing, disposal and site selection techniques (US, South Korea, etc.), potentially shared between several countries (Netherlands, Romania, Italy, Croatia-Slovenia, etc.).

The IAEA and the European Union specify that geological disposal is the benchmark solution for guaranteeing long-term safety in the management of LLHL radioactive waste and spent fuels, if the latter are considered as waste.

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

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

4.2 INTERNATIONAL LEGAL CONTEXT

Radioactive waste management and, by extension, research into waste management, takes place within a national and international legal context. A reminder of these national and international conventions and treaties is provided in Appendix VI.

4.3 RESEARCH LABORATORIES AND UNDERGROUND DISPOSAL SITES

Depending on the local geological characteristics, studies and research on the host medium 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). Italy, Lithuania, the Netherlands, Romania, Slovakia, Slovenia/Croatia, the Czech Republic and several other European countries have geological disposal projects, either individually or in collaboration with others. Countries' efforts in the area of disposal are presented in Appendix VII.

4.4 SOURCES OF FAST-SPECTRUM IRRADIATION

The number of reactors that offer the ability to irradiate using fast-spectrum neutrons is extremely limited at a global level. In Europe, these are thermal-neutron reactors that produce fast neutron fluxes locally, limited to very small sample irradiations. The absence of European FNR reactors heavily compromises the development of new technologies and transmutation experiments. Sources of fast irradiation are presented country by country in Appendix VIII.

4.5 PRINCIPAL INTERNATIONAL INITIATIVES ON ADS

ADS (Accelerator Driven Systems) are, among other options, proposed as alternatives to critical fast reactors for eliminating the minor actinides present in waste from the reprocessing of spent fuel.

Unlike fast neutron reactors, which are electrogenic, the core of an ADS reactor is sub-critical. To maintain the chain reaction, an external input of neutrons is required. To achieve this, the beam of a high-power (around a few dozen MW) particle accelerator (protons) is aimed on a "spallation source" (a liquid or solid metal target such as lead, lead-bismuth, tantalum or tungsten). The interaction between the proton beam and the metal spallation target creates a very intense source of fast neutrons that triggers the chain reaction in the core.

Unlike critical reactors, in which the chain reaction needs to be constantly controlled using neutron absorbing elements, sub-critical ADS can only operate when there is an external input of neutrons. They therefore have inherent passive safety, as they stop running when the accelerator is cut off.

If the intention is to significantly charge (40% to 50%) the core of a reactor dedicated to transmutation, subcriticality is necessary. This is because controlling a critical reactor using absorbants is made possible thanks to the presence of a small fraction of delayed neutrons. However, the heavier the core to fission becomes, the weaker this fraction becomes. As such, the fraction of minor actinides such as americium or curium that could be charged in a critical core is limited to just a few %.

The majority of ADS projects include a liquid metal coolant, typically Pb-Bi eutectic or pure Pb. An alternative project proposes gas cooling. The choice of Pb-Bi is primarily dictated by the absence of an exothermic chemical reaction in contact with air or water (unlike sodium) and by the relatively low melting point of the eutectic (123°C).

Compared with a fourth-generation electrogenic critical reactor, the fast neutron flow can be significantly higher in the core of an ADS depending on the intensity of the proton beam. However, the neutron flux level and the total power of the core are dictated by the capacity of the cooling system. For comparable total powers, it is possible to have higher neutron flux levels for the ADS than for a critical reactor.

The accelerator-Pb-Bi spallation source was studied in the international framework of the Mégapie experiment (Megawatt Pilot Target Experiment) at the Paul Scherrer Institute (PSI - Switzerland). The Mégapie experiment, which took place in 2006 and the results of which are currently being analysed, is the fruit of a collaborative effort between 17 partners, including the CEA and the CNRS. The goal is to demonstrate the feasibility of a Pb-Bi target as a high-intensity spallation source.

The accelerator-subcritical reactor pairing was studied as part of the Muse-4 experiment in Cadarache, at the Masurca experimental Reactor, over the 2000-2004 period. To this end, the CNRS developed an accelerator-pulsed neutron source, called Genepi.

Guinevere, installed in the Venus reactor at SCK•CEN (Centre d'Etudes de l'Energie Nucléaire in Mol, Belgium) is a lower-powered model of a first ADS with a fully-lead core. The project is a collaboration between the SCK•CEN, which modified the Venus water reactor into a fast lead reactor (solid, given the low power), the CEA, which made the fuel available, and the CNRS, which delivered Genepi-3C, the continuous or pulsed beam accelerator. The experiments conducted on Guinevere, which began in 2010, will provide an understanding of the specific behaviour of an ADS. One of their main aims is to determine a methodology that allows monitoring, during operation, of the continual measurement of the subcriticality level, a parameter that characterises the safety of the accelerator-reactor combined system. Since March 2011, the Freya project (Fast Reactor Experiments for hYbrid Applications) has continued the studies initiated on Guinevere. The CEA and the CNRS are partners of this FP7 project.

Pb-Bi is used as a coolant in Russian reactors. Visualisation in liquid metal and the interactions between the eutectic and the materials in contact with the Pb-Bi are currently being studied as part of the Myrrha project and by other partners in Europe (KIT, CIEMAT, ENEA, KTH, NRG, NRI), Russia (IPPE), Japan (JAEA), South Korea (NUTRECK/SNU), India (BARC) and the US (LANL, MIT).

The studies initiated in the Eurotrans project resulted in the CDT project (Central Design Team), as part of which the design of the "Myrrha – Fastef" system was developed. This will be used to study the transmutation of actinides in very intense fast neutron beams. The CNRS and Areva are partners of the CDT project.

As part of Gedepeon, various scenarios for transmutation in FNRs and/or ADS have been collaboratively studied by the CEA, CNRS, EDF and Areva. The scenarios, which are specific to the French context, compared single- or double-strata approaches in an electrogenic or dedicated reactor. As the scenarios are studied based on data that has not yet been experimentally verified, as well as based on technologies that are still virtual, the results must nevertheless be viewed with caution.

At present, as part of FP7, the Arcas project is enabling the study of transmutation scenarios in heterogeneous mode (i.e. with dedicated transmutation fuels) and the economic comparison of transmutation by critical FNRs and by ADS. The project is coordinated by the SCK•CEN with the participation of 11 partners, including the CNRS.

The various obstacles that need to be overcome before the construction of an ADS industrial prototype for transmutation are:

- the reliability of the high-powered accelerator (very promising research at the CNRS, the CEA and abroad);
- continuing the demonstration of the spallation source (Mégapie) for operating periods of at least one year;
- confirmation of the choice of materials while generating a base of experimental data;
- the manufacture of a fuel with a high minor actinide content (preliminary research at the CEA and the ITU in Europe, as well as in Japan and the US);
- the robotics for inspection and maintenance technologies under liquid metal, in a highly radioactive environment;
- the study of optimised scenarios in a specific national context, as well as the consolidation of the economic aspect.

It should be noted that, alongside the use of ADS for transmutation, these systems offer very promising prospects as high-flux fast neutron sources for the study and qualification of materials and fuels for FNRs and other new reactor concepts. With this in mind, the Myrrha project has been chosen as part of the ESNII (European Sustainable Nuclear Industrial Initiative) as a support facility for the development of sodium (Astrid), gas (Allegro) and lead (Alfred) fast reactors. Myrrha also forms part of the roadmap of the ESFRI (European Strategy Forum on Research Infrastructures) for major energy research infrastructures.

An overview of national initiatives is presented in Appendix IX.

4.6 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 the projects is presented in Appendix X.

4.7 NEW TECHNOLOGIES FOR PARTITIONING-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, including 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 supply is optimally guaranteed.

An overview of the projects is presented in Appendix XI.

4.8 EDUCATION, TRAINING AND KNOWLEDGE MANAGEMENT

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

An overview of the projects is presented in Appendix XII.

Appendix I

MEMBERS OF THE NATIONAL ASSESSMENT BOARD NOVEMBER 2013

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

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

Adolf BIRKHOFER – Guest expert on the National Assessment Board - Emeritus Professor at the Technical University of Munich.

Pierre BÉREST – Research Director at the Ecole Polytechnique.

Frank DECONINCK – Professor at Vrije Universiteit Brussel - President of the 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 – Honorary 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).

Gilles PIJAUDIER-CABOT** – Civil Engineering Professor, ISA-BTP, LFC-R – Senior member of the Institut Universitaire de France.

François ROURE – Professor and scientific expert at the IFP-Energie Nouvelles – Extraordinary Professor 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.

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

** Appointed on 13 August 2013 as the replacement for Mr Yves Bréchet.

Appendix II

BODIES HEARD BY THE CNE2

12 december 2012 :	Andra - Presentation and analysis of draft solutions – Presentation of the submission of the public debate.
16 january 2013 :	CEA - Restricted hearing – 2012 report.
17 january 2013 :	CEA – CEA programmes on the downstream part of the cycle for future nuclear systems.
13 february 2013 :	CNRS – Thorium technology.
14 february 2013 :	ANDRA – Concrete.
6 march 2013 :	CEA – Low doses.
7 march 2013 :	Andra – Digital simulation.
24 april 2013 :	CEA - Review of nuclear power scenarios.
25 april 2013 :	Andra – Gas – Hydraulic gas transient processes – Rejections – Results of the Forge programme.
15 may 2013 :	Andra - Waste containing organic components.
16 may 2013 – morning :	CEA – Astrid.
16 may 2013 – afternoon :	Andra – Other LLIL waste and graphites.
19 june 2013 :	Andra – Cigéo progress report.
20 june 2013 :	Andra – Seals.

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11 january 2013 :	DGEC – Technical meeting on the costs of the Cigéo radioactive waste disposal centre.
16 january 2013 afternoon :	Meeting between CNE2/Claude Bernet – President of the Public Debate Committee responsible for the Cigéo project.
17 january 2013 :	DGEC – Cigéo public debate preparatory meeting.
7 february 2013 :	HCTSIN – Cigéo public debate preparatory meeting.
13 february 2013 :	Andra – Cigéo review meeting.
28 february 2013 :	OPECST – round tables on partitioning-transmutation and development prospects in waste management and decommissioning in view of upcoming decisions connected with the energy transition.
4 & 5 april 2013 :	Presentation of Report 6 to the CLIS in Bar-le-Duc (Meuse).
22 april 2013 :	DGEC – Cigéo public debate preparatory meeting.
14 may 2013 :	ASN – Discussion meeting with the CNE2.
21 may 2013 :	Andra/DGEC – Debriefing – project review.
12 june 2013 :	CEA – Proliferation.

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VISITES DE LA CNE2

3 to 14 november 2012 :	Study trip to China and South Korea.
17 & 19 april 2013 :	CNE2/CNS/ESK meeting - Visit to the laboratory in Mont-Terri (Switzerland).
18 to 20 september 2013 :	Visit to the Melox plant in Marcoule (Gard).

Appendix III

LIST OF DOCUMENTS SUBMITTED TO THE CNE2 2012-2013

Andra

- Appraisal of studies and research into the storage of long-lived high-level and intermediate-level radioactive waste – December 2012.
- Andra proposals concerning the reversibility of the Cigéo project – December 2012.
- Summary of microbial activity and its consequences in an HL cavity – 28 February 2013.
- Summary of draft studies of the Cigéo project – March 2013.
- Radioactive waste: monitoring report – International monitoring of projects for the geological disposal of long-lived high-level waste and the management of radioactive waste – February 2013.
- Summary of the single-tube – twin-tube study – 7 May 2013.
- Summary of basket transfer studies: electric railcar/funicular comparison – 7 May 2013.
- Andra Cigéo report - The second containment system during operations to transfer LLIL waste packages to the Cigéo underground facility – May 2013.
- Objectives contract – State-Andra – 2013-2016 – May 2013.
- Summary of microbial activity and its consequences in an HL cavity – February 2013.
- Dashboard of knowledge on all LLIL packages planned for Cigéo – 12 July 2013.
- Technical document – Waste taken into account in the Cigéo design studies – July 2013.
- Annual progress report on work carried out the underground research laboratory in 2012 – 17 June 2013.

CEA

- Report on the long-term management of radioactive waste with fourth-generation reactors – December 2012.
- Report on the partitioning-transmutation of long-lived radioactive elements – December 2012.
- Report on fourth-generation sodium-cooled fast neutron reactors – the Astrid demonstrator – December 2012.
- Report on fourth-generation gas-cooled fast neutron reactors – the Allegro experimental Reactor - Other fourth-generation fast neutron technologies – December 2012.
- Summary and recommendations.
- Technical memo – Programme of research on partitioning-transmutation – 2013-2020 period – 5 March 2013.
- Monograph of the Nuclear Power Department – Neutronics – 2013.

Appendix IV

STUDY TRIP TO CHINA AND SOUTH KOREA FROM 3 TO 14 NOVEMBER 2012

The Board undertook a study trip to China and Korea from 3 to 14 November 2012.

CHINA

The Nuclear Department of the French Embassy in Beijing has provided an updated and highly in-depth overview of nuclear activities in China. This information enabled the CNE to analyse and assess the current developments presented by the Chinese nuclear authorities.

Meetings with the CAEA (China Atomic Energy Authority), CNNC (China National Nuclear Corporation), BRIUG (Beijing Research Institute for Uranium Geology) and CIAE (China Institute of Atomic Energy) have determined the outlines of the nuclear power policy put in place in China.

In 2011, electricity production of a nuclear origin (12.5 GWe) represented 2% of total production. The table below compares the figures on total electricity production for France, the US and China. It shows China's low electricity consumption relative to its population and indicates rapid growth in the future.

2011	CHINA	US	FRANCE
TWh	3,450	4,110	536
Population in millions	1,337	313	65

The CNNC and the CAEA have confirmed a plan to construct 19 units for 20 GWe by 2020 and seven units for 7 GWe in 2030. Electricity production of a nuclear origin is expected to total 240 GWh in 2050. The analysis of global uranium resources and anticipated tensions in the future are leading China to opt for the reprocessing of spent fuel to recycle plutonium and uranium in a future fleet of FNRs. Studies and research concerning FNRs are primarily developed at the CIAE (China Institute of Atomic Energy); the CEFR (China Experimental Fast Reactor) was presented to the CNE. This 20 MWe prototype was connected to the network for 48 hours in 2012 and updates are continuing to achieve an industrial connection in the future. This sodium-cooled prototype has the characteristics of second-generation Russian reactors.

As far as ADS are concerned, a study and research programme less advanced than that in FNRs is under way.

Having opted to reprocess spent fuels (except those from a CANDU reactor), the fission products and most likely the minor actinides will be vitrified and sent for deep geological disposal.

As is standard internationally, the concept of geological disposal relies on three barriers: the containers, the engineered barrier, for which the Chinese teams are studying the use of bentonite, and a deep geological disposal facility. Five regions are studied, the north-west of China with the Beishan site, Inner Mongolia, the south and south-west of China, and the East of China not far from the heavily industrialised coastal areas. The priority post-rock is granite, although clay has not been ruled out. Twelve sites will be initially selected, then this figure will be reduced to three sites considered of an equivalent quality for the establishment of a geological disposal facility.

The development plan includes a site search launched in 1985, the creation of an underground laboratory in 2020 and the deployment of a geological disposal facility in 2050.

The Board visited the Beishan site, where studies are most advanced. 19 boreholes have already been dug to study the quality of the rock, its cracking and the hydrogeology. This site, situated in the Gobi Desert, is currently considered as having the best potential due to the low population density, the absence of mineral resources, a favourable geological context in hydrological terms and very low precipitation. An already very advanced network of communication routes is being constructed, even before the underground laboratory is established.

All this results in a highly favourable assessment of the coherency of the Chinese strategy.

SOUTH KOREA

The Board was greeted by the French Embassy in South Korea, which provided it with detailed information enabling a better understanding of how the country addresses scientific and technical research in the field of nuclear power and what economic challenges it faces.

The meeting with actors from the nuclear industry in Korea took place on Monday 12 and Tuesday 13 November 2012. The KAERI (Korean Atomic Energy Research Institute) is conducting research concerning pyrometallurgical treatment, based on the high-temperature electrochemical partitioning of the constituents of spent fuel. This technology aims to reduce the volume of waste and to recycle uranium and plutonium in future FNRs. Research concerning the development of fast neutron reactors is under way and a sodium loop prototype is being tested. Also in the field of innovations, the KAERI is conducting research concerning the fuel cycle for CANDU reactors by developing a DUPIC fuel (Direct Use of Pressurised Water Reactor Spent Fuel). This approach enables Korea to abide by the non-proliferation treaty, which bans it from partitioning elements contained in spent fuel. The DUPIC fuel is remanufactured from uranium, plutonium, minor actinides and fission products.

So far, low- and intermediate-level waste and spent fuel have been stored on-site in the wait for a complete solution for the downstream part of the cycle. Spent fuels are stored in a swimming pool in the case of PWRs and in dry conditions in the case of CANDUs. This situation cannot continue for the long term due to the upcoming saturation of the storage facilities.

A site for the disposal of low- and intermediate-level radioactive waste, managed by the KRMC (Korean Radioactive waste Management Corporation), is in the construction phase on a site located nearby the city of Gyeongju (east coast). The Board visited this site, the design of which is based on silos bored into an underground granite cave; it is therefore similar to the Swedish model. Its deployment was scheduled for 2013, postponed by four years compared with the initial project. It was recently postponed until June 2014.

The Board was surprised by the size of the tunnels, which seem oversized for the waste envisaged, while the problem of high-level waste remains completely unresolved. What's more, the strengthening of the granite walls with a concrete layer indicates the possibility of a cracked environment in the future.

APPENDIX V

OPINION OF THE CNE2 SUBMITTED ON 28 MARCH 2013 TO THE MINISTER FOR ECOLOGY, SUSTAINABLE DEVELOPMENT AND ENERGY

OPINION OF THE BOARD ON THE 2012 CEA REPORT: PARTITIONING-TRANSMUTATION

This opinion was prepared based on the CEA 2012 report, volumes 1 to 5 (law no. 2006-739 of 28 June 2006)

The deployment of a fleet of fast neutron reactors (FNR) would ensure France complete independence in its electricity production for several centuries and would place its nuclear industry in a prime global position. Technical and technological challenges still remain, although the French nuclear industry should be capable of solving them. The biggest challenge will be to ensure a safety level or superior to that of the most recent reactors and to foster in the general public a sense of trust in the safety level achieved.

The Board notes the following from its hearings:

1. France is involved in three fast neutron reactor projects: the Astrid project (sodium), the Allégro project (gas) and the molten salt liquid reactor project. In addition, it is participating in the accelerator driven reactor (ADS) project Myrrha, which might to burn the minor actinides. Only the sodium technology has reached preindustrial maturity. The Astrid project is currently the only one of its kind in the world to propose innovations commensurate with the safety requirements brought about by Fukushima.

2. FNR technology would consume the plutonium produced both by these reactors and by current reactors. A fleet of FNRs producing, like the current fleet, 430 TWh per year would in 2150 have a stabilised inventory of 900 tonnes of plutonium, or three times the quantity already produced to date. In the event of a fleet of reactors of the current type and an equivalent power, the inventory would be 1,300 to 1,900 tonnes in 2150 and would continue to grow.

3. What would become of these 900 tonnes of plutonium after the discontinuation of FNR technology? One solution would be to place the spent fuel directly in the deep disposal facility, as occurs in other countries. However, this would require dedicated studies, as the 25% plutonium content in the fuels would require specific solutions. Decisive progress, put forward by the CEA, would consist of consuming the plutonium in the RNRs running in sub-generator mode, while at the same time continuing to produce electricity. The stock of plutonium included in the cycle would thereby be reduced by 65% every 60 years. This solution, the technical and industrial feasibility of which remains to be demonstrated, requires a long term stable energy strategy.

4. Considerable progress has been made in the partitioning of elements contained in the spent fuel. Minor actinides can now be specifically isolated, which paves the way for their transmutation. In practical terms, this would apply in particular to americium. Its transmutation would reduce the size of the long-lived high-level (LLHL) waste disposal facility. The radiotoxicity of the disposed inventory would also be reduced. However, due to the low mobility of americium in clay, this advantage would above all be sensitive in a scenario such as unintended human intrusion into the deep disposal facility. The advantages of transmutation would be offset by an approximate doubling in the total cost of the management of LLHL waste. A more accurate costing should draw on a close comparison between a disposal facility with transmutation and another without.

5. The advantages of transmutation would be offset by an approximate doubling in the total cost of the management of LLHL waste. A more accurate costing should draw on a close comparison between a disposal facility with transmutation and another without.

Recommendations of the Board:

- The Board recommends the continuation of the Astrid project (reactor and fuel manufacturing and processing workshops); it absolutely must be completed to enable a complete assessment of the potentials of sodium FNRs.
- The Board believes that gas and molten salt FNRs open up interesting prospects for far in the future; it is therefore advisable to continue the exploratory studies undertaken with our European partners.
- If transmutation of minor actinides is considered, the Board is of the opinion that the solutions considered by the ADS should be taken into account and compared to those of FNRs.
- Because the partitioning-transmutation of americium and the operation in sub-generator mode of FNRs present substantial advantages, the Board urges that they continue to be the subject of active research.
- Lastly, the Board would like the full appraisal of waste produced by FNR technology to continue to be refined.

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OPINION OF THE BOARD ON ANDRA'S PROPOSALS: THE STORAGE OF LONG-LIVED HIGH- AND INTERMEDIATE-LEVEL WASTE (LLHL-LLIL).

This opinion was prepared using all of the documents provided by Andra prior to 7 March 2013.

The storage of LLHL-LLIL radioactive waste must ensure the completely secure preservation of waste packages while they wait to be repackaged or placed into a disposal facility. It must be fully reversible and temporary; it must not act as a substitute for the disposal facility itself, which must be permanent. Storage and disposal are therefore complementary tools, which must be designed and operated in a coordinated manner.

Storage performs several functions:

- It ensures flexible management of the construction and operation of the deep geological disposal facility.
- It cools the packages (this applies primarily to HL waste) by radioactive decay to ensure optimal disposal.
- It plays a part in any operations to retrieve disposed packages by accommodating those brought up to the surface.
- It allows the packages to be monitored and changes in certain packages to be better ascertained.

A storage facility can therefore not operate in a passive mode and must instead remain in active operation until its permanent closure and decommissioning.

To fulfil its purpose, the storage facility must be designed to:

- protect, during the necessary time duration, the packages from external hazards (adverse weather, flooding, etc.) and internal hazards (release of heat, gases, etc.) to ensure their integrity;
- protect workers, populations and the environment from radioactivity;
- guarantee the maintenance of the facility;

- enable monitoring of the packages;
- allow packages to be withdrawn if necessary;
- adapt, as much as possible, to changes in the nature of the packages.

The research conducted by Andra in collaboration with the producers initially considered a comprehensive approach based on the concepts in the 2009 report. The industrial waste management programme (PIGD) identified optimisation options that ensure coordination with the development of the Cigéo project. This research resulted in the following conclusions:

- Plan the storage facilities for a 100-year period, particularly in the case of LLHL waste, for which the PIGD favours a storage period of 85 years.
- Design optimised facilities that take into account the heat emissions of LLHL waste and the gas emissions of LLIL waste.
- Allow the storage of primary packages and disposal packages.
- Favour surface or slightly buried facilities, which are less complex to construct than deep facilities.
- Construct the storage facilities on the production sites.
- Do not establish a storage facility on the Cigéo site, except for the facilities required for the flexible management of the flows of packages for disposal.

Opinion of the Board

The Board feels that the discussions and research concerning storage, carried out in close collaboration with the producers, have reached maturity. The results obtained allow for the design of a storage development programme that is in line with the needs of producers and developments concerning the deep geological disposal facility. It approves Andra's scientific programme aimed at optimising the facilities in terms of the durability of the structures, of the simulation of their hydro-thermo-aeraulic operations and of the monitoring resources.

The Board recommends that all historic waste be provided with storage conditions that comply with the concepts resulting from current research.

The Board urges Andra and the producers to continue their fruitful dialogue with local populations beyond their legal obligations in relation to any operations concerning the storage facilities (creation, modification and decommissioning).

* * *

OPINION OF THE BOARD ON ANDRA'S PROPOSALS : THE CIGÉO DESIGN DRAFT.

This opinion was prepared using all of the documents provided by Andra prior to 7 March 2013.

Andra has demonstrated the ability of the argillite layer of the ZIRA[4] to contain over the long term the radionuclides contained in the LLHL[5] and LLIL[6] waste. As a result, it asked the Gaiya group, which is tasked with being the project manager of the Cigéo project, to provide it with a design draft containing three separate solutions for underground as well as surface structures. To define these solutions, Andra first established a hierarchised set of criteria, at the top of which was long-term safety and operating safety.

Safety of the disposal facility

The concept adopted for the disposal facility must make it possible to keep the radiological impact at the lowest reasonably achievable level, in light of the scientific knowledge available, the state of the art, and social and economic factors. The Board believes that Andra has adopted an approach that complies with this principle.

In particular, it was essential for the search for solutions to form part of a series of measures promoting safety: the grouping together of access shafts; the choice of orientating the cavities so as to reduce the damage caused to the rock; the simplicity of the packages' journey, from their receipt at the surface to their permanent location in the deep disposal cavities; and a strict separation between activities of a nuclear nature and activities involving the creation of underground structures.

As a result, from a long-term safety viewpoint, there are no differences in the solutions proposed by the group that allow them to be distinguished from each other to any significant degree. Although in light of the preliminary safety calculations it is slightly inferior to solution 2, which is more compact, the underground solution chosen by Andra, known as solution 1, presents significant advantages in terms of simplicity of creation and operating safety, notably due to the particularly clear division between nuclear activities and civil engineering activities.

Solution 1 favours the use of the tunnelling machine rather than the selective heading machine successfully tested in the underground laboratory. The tunnelling machine, which is less flexible in terms of the geometry of the disposal facility's tunnels and architecture, presents certain advantages in terms of the safety of work and reduces damage to the rock. Implementation tests are under way in the underground laboratory to validate this option.

Coating – fire – sealing

The coating of the tunnels and cavities must ensure the good performance of the structures and therefore enable any required retrieval of the packages for at least a century. The question of sizing is clearly adressed in the design draft; the knowledge accumulated until 2025 must be used to resolve any remaining uncertainties.

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[4] From the French acronym for zone of interest for further investigation.

[5] Long-lived high-level.

[6] Long-lived intermediate-level.

The prevention of fire and the limitation of its effects are key concerns in the design of an underground structure. Particular efforts must be made concerning the reduction of the quantities of flammable materials, alert mechanisms, the fire resistance of the civil engineering structures and the management of a fire. Evacuation of personnel in the event of fire in the LLIL tunnels is made easier in the solution 1 chosen by Andra due to the presence of parallel tunnels whose functions are completely separate.

The creation of seals primarily concerns the end of the disposal facility's lifespan. The study of these seals must be continued, although the design draft has provided clarifications. Level 1 tests are planned in Cigéo.

LLHL and LLIL cavities

The choices made regarding the disposal of exothermic LLHL waste still leave room for optimisations. This waste is not scheduled for disposal until 2075. Andra has demonstrated that it has a credible technological solution.

The basket principle seems the most robust choice as a second barrier to contain LLIL waste during its surface-facility transfer.

A small number of packages require large-diameter structures that cannot be qualified in the underground laboratory. If the creation of these structures proves impossible, the producers will need to resize these packages.

Optimisation

Certain measures in the discarded solutions, such as the position of the structures within the ZIRA and the distance between the LLIL, LLHL and HL0 areas, may have advantages from the viewpoint of long-term safety. It will be important to verify whether, as part of an optimisation approach, they can be integrated into solution 1.

Surface facilities

Andra has studied several solutions for the surface facilities, including the safety aspect as well as requests by elected officials and the architectural and landscaped quality. It prefers the subsurface creation of the buildings for the receipt, checking and packaging of the waste packages and entry into the drifts, with the work support activities being located in the vicinity of the shafts. The report is still at a preliminary stage. The final choices will take into account the requests that will have been made during the public debate.

Opinion of the Board

The Board feels that the choice of solution 1 by Andra, which is responsible for designing the storage facility under the law, takes into account the operating safety and long-term safety concerns sufficiently. The remaining industrial uncertainties (tunnelling machine, large diameter) are reduced.

In the Board's view, the design draft is at this stage credible from an industrial viewpoint and complies, on the whole, with the principles aimed at ensuring the maximum safety of the disposal facility. The improvement options have been clearly identified and will definitely need to be explored.

Given the proposed design draft, the Board sees no scientific or technical reason to postpone the continued process to examine the application for authorisation to create a deep disposal facility.

* * *

[7] Moderately exothermic vitrified high-level waste packages.

OPINION OF THE BOARD ON ANDRA'S PROPOSALS: REVERSIBILITY

This opinion was prepared using all of the documents provided by Andra prior to 7 March 2013.

The CNE's position on reversibility

Reversibility encompasses the principle that the disposal facility is may to evolve throughout its operation, therefore requiring that all necessary interventions can be carried out. In addition to ensured and verified quality, its implementation requires recoverability and flexibility.

Recoverability means the ability to extract all waste packages from their disposal location; it implies the ability to mobilise, if necessary, the required necessary technical and economic resources throughout the period of reversibility established by law.

Flexibility requires the combination of a variety of capabilities:

- Consideration of scientific and technical advances, as well as experience feedback, throughout the century-long period of operation.
- The disposal facility's adaptation to changes in the nature of the waste and packages.
- The monitoring of the various components of the structure so as to apply any reversibility actions that may be required.

The Board is in favour of the disposal facility's reversibility designed and implemented in this manner. Reversibility establishes constraints that must be planned in advance and practices that must be complied with. As a contrary example, the Board observes that changes to the disposal rooms in the Asse mine would have probably been easier to control if the structures had been designed from the outset to be reversible, and that the retrieval of certain Stocamine packages was seriously compromised by the omission of reversibility during the disposal facility's operation.

However, the Board reiterates that, in the long term, a radioactive waste disposal facility is intended for closure and operation in passive mode, without its monitoring being necessary. Consequently, measures fostering reversibility must not compromise the disposal facility's safety during the operating phase until after closure.

Opinion of the Board on Andra's report

In the operation and closure master plan proposed by Andra, the Board takes a favourable view on:

- the construction of the facilities in phases as part of a modular design; the integration, from the design phase of the facilities, of elements that facilitate the retrieval of packages without questioning the objective of permanent disposal;
- the implementation of control structures: the Board recommends that these correspond to the various levels of closure and therefore the various levels of retrieval difficulty;
- the organisation of project reviews every ten years to benefit from experience feedback and update the reversibility conditions: the Board would like the conclusions of the project reviews to be made public;
- the implementation, from the Cigéo design phase, of mechanisms to monitor the disposal facility;
- the creation of the Permanent Environmental Monitoring Station, which is designed to remain in place after the disposal facility's closure.

The Board considers that:

- the safety of workers and the safety of the disposal facility in the long term are priority matters;
- in addition, the closure of a cavity on time to guarantee optimal evolution must be preferred over extending its opening for retrieval purposes;
- the master plan must stipulate the maintenance and repair operations that can be performed in both normal and accident conditions;
- package retrieval exercises in compliance with radiation protection rules must be planned; these will provide an opportunity to sound out the disposal environment.

Appendix VI

INTERNATIONAL LEGAL FRAMEWORK

EURATOM TREATY, ARTICLE 37 (1957)

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

ESPOO CONVENTION (1991)

The Convention on Environmental Impact Assessment (EIA) in a Transboundary Context stipulates the obligations of the Parties to assess the impact of certain activities on the environment as soon as planning for them has begun. It further stipulates that the States have a general obligation to give notice and consult regarding any major project being studied that may have a major harmful transboundary impact on the environment. The Convention entered into force on 10 September 1997 and was ratified by France in 2001.

INTERNATIONAL OSPAR CONVENTION (1992)

Following the London and Oslo conventions for the Prevention of Marine Pollution by Dumping from Ships and Aircraft, and the Paris Convention for the Prevention of Marine Pollution from Land-Based Sources, European countries ceased disposing of radioactive waste in the Atlantic Ocean in 1982. In 1992, the conventions were combined into the International OSPAR Convention, ratified by France in 1997 and officially entering into force in 1998.

For any hazard resulting from the disposal of waste into the sea, the convention requires that the precautionary principle be applied, with the polluter paying, and that the best environmental techniques and practices available always be chosen.

CONVENTION ON NUCLEAR SAFETY (1994)

The goals of the convention are as follows:

- To achieve and maintain a high level of nuclear safety worldwide through the enhancement of national measures and international cooperation including, where appropriate, safety-related technical cooperation.
- To establish and maintain effective defences in nuclear facilities against potential radiological hazards in order to protect individuals, society and the environment from harmful effects of ionising radiation from such facilities.
- To prevent accidents with radiological consequences and to mitigate such consequences should they occur.

Adopted in 1994 by the IAEA, the convention was approved by France in 1995. Since 2005, all countries operating nuclear power reactors have ratified it.

DIRECTIVE EC/97/11 (1997)

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

JOINT CONVENTION ON THE SAFETY OF SPENT FUEL MANAGEMENT AND ON THE SAFETY OF RADIOACTIVE WASTE MANAGEMENT (1997)

The purposes of the convention, negotiated under the auspices of the IAEA, are:

- to achieve and maintain a high level of safety worldwide in spent fuel and radioactive waste management, through the enhancement of national measures and international cooperation;
- to ensure that during all stages of spent fuel and radioactive waste management there are effective defences against potential hazards so that individuals, society and the environment are protected from the harmful effects of ionising radiation.

To date, 42 States have ratified the Joint Convention, including France in 2001.

ÅARHUS CONVENTION (1998)

The Aarhus Convention governs public participation in decision-making processes and environmental justice. The Convention entered into force in 2001 and was ratified by France in 2002. The right to access information can be exercised with all authorities and public operators. The convention also stipulates that public participation in decision-making processes must be permitted whenever all options and solutions are still possible. The results of the participation must be duly taken into account. Finally, access to justice must provide for sufficient measures, without prohibitive costs.

EUROPEAN UNION COUNCIL DIRECTIVE ON THE MANAGEMENT OF SPENT FUEL AND RADIOACTIVE WASTE (2011/70/EURATOM)

On 19 July 2011, the Board adopted the directive concerning the management of spent fuel and radioactive waste. In order to continuously improve the safety of radioactive waste management within the European Union, the directive requires:

- the establishment, by each Member State, of a national plan for the management of spent fuel and radioactive waste that is accessible to the public and must include an inventory of financial arrangements or a regulatory framework;
- the implementation of waste management policies in a transparent way and the involvement of the public, particularly concerning decisions on the construction of a disposal facility;
- the enhanced use of peer reviews.

Member States are obliged to submit the first report on the implementation of their respective national programme in 2015.

The directive aims to establish a legal framework for the management of spent fuel and radioactive waste, from generation to permanent 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 that:

- 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.

Because the text of the directive is subject to interpretation, the ENEF (European Nuclear Energy Forum) has said what, in its opinion, should be understood by 'national programmes'. The ENSREG (European Nuclear Safety Regulators Group) has published instructions concerning the reports to produce. The IAEA, AEN and WANO (World Association of Nuclear Operators) will do the same for other articles of the directive, such as those concerning the peer review.

Appendix VII

RESEARCH LABORATORY OR UNDERGROUND DISPOSAL SITE

BELGIUM

Since 1982, Belgium has had the Hades laboratory -225 m deep, located in a layer of clay below the Belgian Nuclear Centre in Mol (SCK•CEN); the laboratory is operated by the EIG Euridice. The laboratory is currently more than 200 m long and houses several dozen experiments. The research and experiments, some of which have been going on for 30 years, primarily deal with construction techniques, corrosion, radionuclide migration, waste behaviour and instrumentation. Most of the research projects are performed in an international framework. Andra participates in them regularly.

A large-scale thermo-hydro-mechanical and chemical experiment, Praclay, is installed there. It simulates the temperature field around a tunnel for burying high-level waste. To that end, a gallery whose dimensions correspond to the Belgian disposal concept will be heated for 10 years at 80°C over a length of 30 m. As part of the Forge project, an experimental device 40 cm in diameter has been installed there in order to study the effect of on-site constraints on the flow of gases. This experiment and others are complemented by a major surface-level laboratory research programme, involving modelling.

For more than ten years, two experiments have been under way as part of the Coralus programme intended to study the influence of different boundary conditions (chemistry, temperature and radiation) on the leaching and migration of actinides incorporated into nuclear glass. In these experiments, glass plates with representative concentrations of uranium, plutonium, americium and neptunium isotopes (order of magnitude: 10^{10-11} Bq/g), prepared by the CEA, were placed in contact with various porous materials. The gamma radiation field is being simulated using sources of cobalt 60 (order of magnitude: 10^{13} Bq). The Hades laboratory is currently the only one that has a licence to operate at such levels of activity.

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. The preferred solution proposed by ONDRAF is geological disposal within poorly-indurated clay (i.e. Boom clay and Ypresian clays, for Belgium).

CANADA

Canada has an underground research laboratory located near the laboratories in Pinawa-Whiteshell, Manitoba. It was created in 1982 to study the feasibility of safely disposing of nuclear fuel waste in granite rock. The laboratory is no longer operational; it is in the initial stages of decommissioning.

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. The NWMO has indicated that the disposal site will probably be located in the provinces of Ontario, Quebec, New Brunswick or Saskatchewan. To date, 21 municipalities are willing to help select a site within their territories. The site will be operational in 2035.

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 creation of an underground laboratory are under way, with the start of construction scheduled for 2016 and opening in 2020. The disposal site is expected to be operational by 2050.

FINLAND

In 2003, Posiva Oy, which manages Finnish radioactive waste, began construction work on a research laboratory in granite at a depth of 400 m. The site chosen for this was Onkalo in Olkiluoto, where an EPR is under construction. The application for the construction of the disposal facility and the encapsulation plant was introduced in December 2012 on the same site. The construction of the tunnels for accessing the laboratory, and therefore also the future disposal centre, is complete. The site will receive the 9,000 tonnes of spent fuels from the reactors currently in service, as well as those from two reactors to be built in the future. Following the KBS3 Swedish concept, operation is scheduled from 2022.

FRANCE

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

GERMANY

From 1967 to 1978, the former salt mine in Asse received SLLL and SLIL waste as part of a disposal project. Afterwards, the mine was used as an underground research laboratory, mainly for studying the effects of heat on the salt surrounding heated containers used to simulate LLHL waste.

This disposal site is currently experiencing difficulties due to brine seepage (around 12 m3 per day). An amendment of the law that, among other items, governs waste management (AtG – Atomgesetz) states that the Asse site must be cleaned and declassified as quickly as possible. This operation is considered risky and technically difficult.

The former salt mine in Morsleben (formerly in the GDR) received the first radioactive waste in 1971. In 1981, a temporary licence for the disposal facility was obtained, then this license became permanent in 1986. The mine continued to accept waste packages until 1998. It is experiencing severe stability problems that have required the injection of more than 4,000,000 m3 of ballast materials.

The permanent storage of high-level (exothermic) waste was planned at Gorleben in a salt dome at a depth of 800 m. The Gorleben site has been studied for 30 years regarding the possibility of using it for the disposal of all categories of waste, as well as spent fuel. The laboratory 840 m deep was operational between 1998 and 2000, when a political moratorium interrupted the studies and research. Despite the satisfactory results of boreholes at depth, the replacement government conducted an assessment of alternative sites with the consent of the Länder. Following the nuclear withdrawal decision and the primarily political difficulties regarding the choice of a disposal site, the government consulted the Länder and, in 2013, announced a new law concerning the management of nuclear waste and the choice of disposal sites. The law, which is a federal law, will be applied by the Länder under the guidance of the federal government. It stipulates a study of all regions that may contain a suitable host rock: salt, clay or crystalline rock. The Gorleben site has not been ruled out in theory, but will be assessed alongside the other potential regions. Before any site selection process takes place, the government will task a multidisciplined committee with studying matters connected to the disposal facility, including the relevance of a geological disposal facility. The conclusions will be transcribed in the form of a law submitted to parliament. A site will be chosen in 2031, ahead of the beginning of construction in 2040. The waste producers will be required to pay for the studies and the exploration of new sites, which they are contesting given that the study of the Gorleben site has not been officially abandoned.

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 permanent disposal of long-lived intermediate-level waste (non-exothermic) is planned in the Konrad mine (a former iron mine) at a depth of 800 to 1,300 m below a very thick layer of clay. In 2002, the German government authorised the disposal of LLLL and LLIL waste there. Following legal challenges, the operation of the disposal facility was postponed. The final green light for operation was obtained in 2008. Following the resolution of political disagreements and legal proceedings, work is continuing to get the site operational to receive waste in 2019.

HUNGARY

The Bataapati site has been under construction since 2008 in granite caves surrounded by layers of clay at a depth of 200 to 250 m. It is intended to hold all of the low- and intermediate-level waste from the Paks power plant.

INDIA

For eight years, India has studied, through experimentation, the reaction of the host rock to a thermal load in an old gold mine 1,000 m underground. Other experiments are planned in abandoned mines. Currently, potential sites have been identified in granite, among which a 4 km2 area will be chosen. A site is scheduled to be operational in 30 to 40 years.

JAPAN

The tsunami, followed by the Fukushima disaster, highlighted the problems inherent to the processing and management of large quantities of waste following the remediation and clean-up activities, in both the surrounding areas and the contaminated nuclear sites.

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 1,000 m. Studies concerning the hydrology and mechanics of the rock are continuing. At the Horonobe laboratory, hydrological tests and hydrochemical measurements are continuing. The EDZ is being studied there around a tunnel at a depth of 140 m. A depth of 300 m out of 500 has been achieved.

The Japanese organisation for the management of radioactive waste, NUMO, is responsible for developing a disposal site for LLHL waste. A site will be selected in three phases: preliminary investigation, detailed investigation zones and construction zone. Operation is set to begin in 2035. NUMO invited applications in 2002, but to date, its request has been unsuccessful. If any proposals are received, NUMO will conduct a bibliographic study on the volcanic activity, faults and other geological characteristics. In the meantime, NUMO is continuing to approach various municipalities likely to volunteer for these preliminary studies. The projects face strong public opposition.

NETHERLANDS

The Netherlands has 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. The Netherlands is also advocating a regional solution shared by several countries, including Italy, so as to optimise the management of different waste and share the costs.

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 packaging of waste for disposal, the transfer of waste to the newly created operator (NORAO) and the funding mechanisms. No geological disposal site is currently available, although the Nizhnekansky granite massif near Krasnoyarsk could host an underground laboratory. A decision on the construction of a disposal site could be made around 2025. The first phase of the facility involves the transfer of 20,000 tonnes of LLIL and LLHL waste, ensuring its recoverability.

SWEDEN

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

Since 1995, SKB has had the Äspö laboratory near the city of Oskarshamn, which is dug into granite at a depth of 460 m. Unlike the Finnish approach, the laboratory will not be a part of the final disposal site, but rather will serve to approve the selected concepts. Research at the site is primarily focused on construction techniques, the positioning of the containers and concrete in their disposal site positions, hydrogeology, the migration of radionuclides and modelling.

The "Bentonite Laboratory" entered service in the spring of 2007; it is located at the surface above the Äspö laboratory. This laboratory examines whether bentonite - which forms a buffer around the containers and serves as a filler material for the tunnels - is fulfilling its role in different groundwater flow patterns. It complements the underground activities and enables the large-scale testing of various operating methods under varied conditions. Machines and robots are also developed and tested there.

The "Canister Laboratory" in Oskarshamn is SKB's centre for developing canisters. There, SKB develops the technology for welding the lids and bottoms of the canisters intended for spent nuclear fuels. Methods are also being developed for inspecting the welds and materials. Another major field of research consists of verifying that the machines and equipment that will be used in the encapsulation plant function adequately. This laboratory will also serve as a training centre for the corresponding plant's future staff.

SKB has submitted an authorisation request for the construction of the deep disposal facility in Forsmark 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 take three years. The disposal facility is expected to be operational around 2025.

SWITZERLAND

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. A few hundred meters long in total, it includes dozens of international experiments into the geological, hydrogeological, geochemical and geotechnical characteristics of opaline clay. The experiments are both methodological and aimed at selecting opaline clay as the host medium for a disposal site. The Federal Energy Office (OFEN) has designated six potential locations for a disposal site for LL and IL waste. They will be the subject of in-depth studies: Südranden, Northeast Zürich, North of Lägern, Eastern Jura, Southern Piedmont and Wellenberg. The studies are in progress and will take four years. Three of these regions (Zürcher Weinland, North of Lägern and Bözberg) will also be the subject of studies for the disposal of HL waste.

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. Although two towns in the county of West Cumbria, Allendale and Copeland, have confirmed that they want to continue the process of evaluating a disposal site in their area, the county has decided to withdraw from the project. The district of Shepway (Kent - clay) has also decided to withdraw its application. No site is currently being studied and no timetable has been set. In September 2013, the government launched a consultation to request opinions on a new working approach with potentially interested local authorities. The new proposal includes a veto right for districts and the consultation of counties.

UNITED STATES

For more than two decades, Yucca Mountain in Nevada has been the main site studied for the disposal of LLHL waste in the United States. In 2002, the Yucca Mountain Development Act was approved by US Congress and signed by President Bush. Yucca Mountain therefore became the site officially proposed for a disposal facility. In June 2008, the Department of Energy (US-DOE) submitted a licence request for the site to the competent authorities (Nuclear Regulatory Commission, NRC). Following a drastic reduction in the budget allocated to the project under President Obama - which has effectively undone all progress made on the waste problem – the NRC has not reviewed the licence request and the American government has created a top-level commission, the "Blue Ribbon Commission on America's Nuclear Future" (BRC), in order to propose alternatives to the project. The commission has published a list of recommendations for the government in order to propose alternatives to the Yucca Mountain project in Nevada. Following are some of these recommendations:

- 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 clean-up of 22 storage sites for transuranium waste of military origin, spread across the United States, has since 1999 enabled 83,000 m^3 of waste to be disposed of at the Waste Isolation Pilot Plant (WIPP) without incident. 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.

The US Court of Appeal ruled that the NRC acted illegally by abandoning the review of the licence request by the DOE. The NRC is therefore obliged to process the licence request. The producers also noted the fact that they contributed around $35 billion to the management of spent fuel.

Following the conclusions of the "Blue Ribbon Commission", the government published a document entitled "Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste". This document describes the framework for achieving a long-term and integrated solution for the transportation, storage and disposal of spent fuel and high-level waste resulting from electricity production, as well as activities related to defence, national security and other activities. The document is the response to the BRC report, the guiding principles of which it adopted.

The government hopes that Congress will approve a ten-year plan that stipulates a pilot storage centre in 2021, progress towards a larger storage facility around 2025 and a disposal centre around 2048.

The 2013 budget plan for R&D concerning the geological disposal site is $60 million.

Appendix VIII

SOURCES OF FAST-SPECTRUM IRRADIATION

BELGIUM

The 120 MWt BR2 research reactor (1963-2026?) is designed to accommodate both small (diameter of 1.5 to 3 cm x h=80 cm) and large volumes (diameter of 8 to 22 cm x h=80 cm) to irradiate samples under a fast-spectrum high flux, simulating an FNR fuel sub-assembly.

CHINA

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

FRANCE

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

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.

INDIA

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

JAPAN

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

NETHERLANDS

The HFR (1961-2015) in Petten allows limited irradiation.

RUSSIA

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

Appendix IX

MAIN INTERNATIONAL INITIATIVES CONCERNING ADS

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.

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

FRANCE

For the record: the CNRS, Areva and the CEA are working on the Belgian Guinevere and Myrrha projects.

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) is proposing a gas-cooled ADS concept (AGATE).

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 kWt) ADS is being developed at the Legnaro INFN Laboratory.

JAPAN

The aim of the Omega project, launched in 1988, is to conduct R&D on partitioning and transmutation in order to reduce the footprint 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 an MOX-based subcritical core; an approximately 100 MWt experimental ADS (national or international collaboration); and an 800 MWt industrial ADS.

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). Kaeri is evaluating different options for changing the nature and reducing the volume of the waste to be disposed of.

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.

Annexe X

DEEP GEOLOGICAL DISPOSAL

ARGONA[8] ARGONA examines the questions of transparency and participation and to what extent they relate to each other. It also assesses the connection to the political system, which will ultimately take the decisions with regard to the final disposal of nuclear waste. Lastly, the project examines the role of mediators to involve the public in the issue of nuclear waste.

BELBAR[9] 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[10] The goal of BIOPROTA, launched by Andra in 2002, is to identify biosphere models, determine the surface environment data acquisition protocols and analyse the state of knowledge about 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[11] Graphite-moderator reactors are representative of the first generation of reactors being decommissioned. 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[12] 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 a discrepancy compared with the expected diffusion. A scientific explanation is essential for the safety studies on the concepts of disposal in clay.

CIP[13] The main aim of the CIP programme, which follows on from Cowam-2, is to contribute to good governance in radioactive waste management in Europe. For each country (France, Romania, Slovenia, Spain and the UK), a national group works on the processes by which the interest groups are involved in making decisions concerning radioactive waste management.

CROCK[14] 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 values are used in safety assessments. The project follows on from the FUNMIG project and Swedish siting studies.

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8 Arenas for Risk Governance, 2006-2009, FP6, 7 countries, 14 partners.

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

10 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.

11 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.

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

13 COWAM In Practice; 2007-2009, FP6, 6 countries, 11 partners, including the IRSN; the Syndicat de l'Enseignement de la Productique, de la Mécanique et des Matériaux; the Centre d'Étude sur l'Évaluation de la Protection dans le Domaine Nucléaire, the Symlog Institute and Mutadis Consultants.

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

DOPAS[15] The aim of this project is to improve the industrial feasibility and performance of plugs and seals to be used in the disposal facilities situated in the host rocks studied (clay, crystalline and salt). Five experiments will be set up. These will serve as a demonstration and their characteristics will be studied.

EBSSYN[16] EBSSYN is a joint project between the European Commission and the Nuclear Energy Agency that aims to prepare a summary report on the barrier systems and the safety of LLHL disposal sites.

EMRAS[17] The EMRAS programme, launched within the framework of the IAEA, focuses on radioecological modelling, particularly the consequences of the release of radionuclides into the environment.

ERDO[18] Following the success of the SAPIERR projects, a multinational working group 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.

ESDRED[19] The objective of this programme is to demonstrate the industrial feasibility of the developments and technologies needed to build, operate and close a deep geological disposal site that meets long-term safety requirements. The programme takes into account various European concepts and includes education and training activities.

FEBEX II[20] 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 is continuing the observation phase of the experiment in order to improve and validate the data and codes for the study of the geochemical processes, the generation and transport of gas, and the corrosion and performance of the measuring instruments.

FIRST-NUCLIDES[21] The aim of this project is to achieve an improved understanding of the quick release mechanisms of certain radionuclides in irradiated, high-burnup, disposed fuel. The IGD-TP has given high priority to this issue.

FORGE[22] The objective of this 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.

FUNMIG[23] The central objective of FUNMIG is to understand and model the process in the migration of radionuclides through the geological layers and the geosphere. The host rocks considered are clay, granite and salt.

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15 Full-scale Demonstration Of Plugs And Seals; 2012-2016, 8 countries, 14 partners, including Andra.

16 A joint EC/NEA EBS project synthesis report; 2008-2009, FP7 and NEA.

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

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

19 Engineering Studies and Demonstrations of Repository Designs, 2004-2009, FP6, 9 countries, 14 partners, including Andra.

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

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

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

23 Fundamental processes of radionuclide migration; 2005-2008, FP6, 15 countries, 53 partners, including Andra, the CEA, the BRGM, the Joseph Fourier University Grenoble 1, the University of Maine, the Association pour la Recherche et le Développement des Méthodes et Processus Industriels, Études-Recherches-Matériaux, the École Nationale Supérieure de Chimie at Mulhouse, the Alpine Institute for Environmental Dynamics and UJF-Filiale.

IGD-TP[24] 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 implemented during the next 10-15 years in order for 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[25] 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[26] 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[27] 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.

MICADO[28] This FP6 programme aims to assess uncertainty in the modelling of mechanisms for the dissolution of spent nuclear fuel in a disposal site.

MODERN[29] The project aims to provide a benchmark describing the technical objectives, resources and methods for designing a monitoring system. The project also aims to enhance the understanding and trust of stakeholders during the various disposal phases by complying with the specific needs and constraints of each country.

NEA-MESA[30] In most countries, the disposal of radioactive waste in geological repositories is the standard solution. Decision-making and social acceptance concerning these facilities relies 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.

[24] 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). IGD-TP currently has 107 members.

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

[26] Implementing Public Participation Approaches in Radioactive Waste Disposal, 2011-2013, FP7, 12 countries, 17 partners, including Mutadis Consultants.

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

[28] Model uncertainty for the mechanism of dissolution of spent fuel in a nuclear waste repository; 2006-2009, FP6, 6 countries, 19 partners, including Andra, the CEA, the IRSN and the Association pour la Recherche et le Développement des Méthodes et Processus Industriels at the Ecole Nationale Supérieure des Techniques Industrielles des Mines in Nantes.

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

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

NWD[31] 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.

OBRA[32] The OBRA programme aims to implement mechanisms by which interest groups can access knowledge generated by European research programmes on the management of waste and spent fuel, regarding both the scientific and social sciences aspects.

PAMINA[33] The goal of this project is to improve and harmonise the assessment methods and tools used to demonstrate the safety of the various disposal concepts for LLHL waste and spent fuel in the various host rocks considered in Europe.

PEBS[34] Using a global approach including experiments, models and studies of the impact on long-term safety functions, PEBS will assess the performance of structural barriers. The experiments and models will cover the complete spectrum of conditions, from the start (high temperature, resaturation of the barrier) to the thermal balance and resaturation with the "host" medium.

RADIOECOLOGY AND WASTE TASK GROUP[35] In 2002, Andra and the International Union of Radioecology launched an international working group in order to promote scientific collaboration between radioecologists in the field of radioactive waste.

RECOSY[36] 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[37] This project aims to reduce uncertainties in measuring the dissolution speeds of spent fuels in order to enhance 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.

SAPIERR II[38] During the period from 2003 to 2005, the SAPIERR project was devoted to pilot studies on the feasibility and conditions of shared regional disposal facilities for the use of European countries. The objective of the second phase of the programme, SAPIERR II, is to develop potential implementation strategies as well as organisational structures.

SITEX[39] 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.

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

32 European observatory for long-term governance on radioactive waste management; 2006-2008, FP6, 7 countries,10 partners.

33 Performance assessment methodologies in application to guide the development of the safety case; 2006-2009, FP6, 10 countries, 25 partners, including Andra, the CEA, the Université Claude Bernard Lyon 1 and the IRSN.

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

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

36 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 at Armines.

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

38 Strategy action plan for implementation of European regional repository - stage 2; 2006-2009, FP6, 8 countries and 8 partners.

39 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.

SKIN[40] Studying the processes involving very slow movements of water in geological layers should enable the development of robust long-term assessment methods.

SORPTION II[41] The goal of this NEA 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.

THERESA[42] The THERESA programme aims to develop a methodology for assessing the mathematical models and codes used for assessing the performances of a disposal facility. These models and codes are used for design, construction, operation, safety and performance analysis, and for the monitoring of geological disposal sites for nuclear waste after their closure. This methodology is based on a microscopic representation of the chemical and thermo-hydro-mechanical processes and mechanisms in geological materials and systems.

TIMODAZ[43] This project aims to study the thermal impact on the damaged zone of "host" clay around a radioactive waste disposal facility. To this end, three clays are studied, Boom clay from the Mol site, opaline clay from Mont-Terri and Callovo-Oxfordian clay from Bure.

[40] 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).
[41] Sorption II project; 2000-?, AEN, 11 countries, 20 partners, including Andra.
[42] Coupled thermal-hydrological-mechanical-chemical processes for application in repository safety assessment; 2007-2009, FP6, 7 countries, 16 partners, including the IRSN.
[43] Thermal Impact on the Damaged Zone Around a Radioactive Waste Disposal in Clay Host Rocks; 2006-2010, FP7, 8 countries, 15 partners, including Joseph Fourier University Grenoble 1, École Nationale des Ponts et Chaussées and ITASCA Consultants.

Appendix XI

NEW TECHNOLOGIES FOR PARTITIONING-TRANSMUTATION

ACSEPT[44] 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 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[45] The goal of the project is to enable the European scientific community to benefit from laboratory infrastructures for research concerning actinides.

ANFC[46] Alternative fuel cycles based on partitioning and transmutation will be studied and assessed. Methods for the recovery of long-lived 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 studied.

ARCAS[47] 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[48] 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[49] For the record, the 600 MWe, sodium-cooled fast reactor prototype is planned for 2020. ASTRID is set to be built at the Marcoule nuclear site.

CANDIDE[50] As part of this action, a network coordinates the nuclear data measurement efforts necessary to minimise the flow of waste through transmutation in fast neutron reactors or ADS.

CDT[51] 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 scenario of the facility's operation in critical mode.

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

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

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

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

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

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

50 Coordination action on nuclear data for industrial development in Europe; 2007-2008, FP6, 11 countries, 14 partners, including Areva, EDF and the CEA.

51 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[52] 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 the 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.

EFNUDAT[53] The aim of the project is to create a European network of research infrastructures capable, if necessary, of generating the necessary data for the study of critical or subcritical reactors using a spallation source. The education and training aspects will be developed in collaboration with universities, research centres and industry.

EISOFAR[54] This action aims to define the specific research objectives concerning sodium-cooled fast reactors. It forms part of the SNE-TP and GenIV approach.

ELSY[55] The ELSY project of FP6 aims to design a lead-cooled reactor with a power of 600 MWe. Design simplifications are being sought based on the characteristics of the lead coolant. These simplifications will pave the way for a fast reactor that could be economically competitive from the viewpoint of investment costs and operating costs, in a deregulated electricity market.

EUFRAT[56] 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 as part of the Nudame project.

EVOL[57] 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.

ERINDA[58] 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.

EUROTRANS[59] - Studies and research on ADS is currently being carried out as part of the European programme EUROTRANS. This integrated programme studies the design, cost and safety aspects of an ADS system, the reliability of the accelerator, the connection between the various elements, materials and technologies of the coolant, the fuels and targets, and the base nuclear data. It also includes an education and training to mention.

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52 Collaborative project on European sodium fast reactor ; 2009-2012, 7ème PCRD, 10 pays, 25 partenaires dont le CEA, Areva NP, IRSN et EDF.

53 European Facilities for Nuclear Data Measurements, 2006-2010, FP6, 7 countries, 10 partners, including the CEA and the CNRS.

54 Sodium cooled Fast Reactor; 2007-2008, FP6, 9 countries, 13 partners, including the CEA, Areva and EDF.

55 European Lead-cooled System; 2006-2009, FP6, 15 countries, 20 partners, including the CNRS and EDF.

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

57 Evaluation and Viability of Liquid Fuel Fast Reactor System, 2010-2013, FP7, 8 countries, 11 partners, including the CNRS, Inopro and Aubert & Duval.

58 European Research Infrastructures for Nuclear Data Applications, 2010-2013, FP7, 10 countries, 14 partners, including the CEA and the CNRS.

59 European research Programme for the transmutation of high level nuclear waste in an accelerator driven system; 2005-2010, FP6, 14 countries, 29 partners, including the CNRS, the CEA, Areva, Advanced Accelerator Applications and the European Nuclear Education Network (ENEN).

FAIRFUELS[60] This project aims to pave the way for the 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[61] 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[62] 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[63] 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 online reactivity monitoring of ADS systems.

GACID[64] The experimental programme, established through a collaboration between the CEA, the DOE (USA) and the JAEA (Japan), aims to produce 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 experience feedback after irradiation in Monju.

GETMAT[65] The aim of this collaborative project is to integrate the R&D activities of European laboratories that have expertise in research on materials for future reactors, including Generation IV reactors, transmutation systems and fusion reactors.

GIF/GEN-IV[66] 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 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. As part of a sustainable development approach, these two technologies can help to minimise the generation of radioactive waste and the risks of proliferation.

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60 Fabrication, irradiation and reprocessing of fuels and targets for transmutation; 2009-2013, FP7, 6 countries, 10 partners, including the CEA and Lagrange-LCI.
61 Fundamental and Applied Actinide Research; CCR (Joint Research Centre) action, 12 countries, 26 partners.
62 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.
63 Fast reactor experiments for hybrid applications, 2011-2015, FP7, 10 countries, 16 partners, including the CNRS and the CEA.
64 Global Actinide Cycle International Demonstration; DOE, JAEA, CEA.
65 Gen IV and transmutation materials; 2008-2013, FP7, 11 countries, 24 partners, including the CEA, the CNRS and EDF.
66 Generation IV International Forum; 2001-?, Euratom + 12 countries, including France.

GOFASTER[67] 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[68] In March 2010, the "GUINEVERE" reactor was opened at SCK•CEN (Mol). Guinevere is a fast research reactor, driven by a very low-power accelerator (ADS) of only a few hundred watts, and a precursor to MYRRHA. The reactor is the fruit of an excellent collaboration between the SCK•CEN, CEA and CNRS as part of the EUROTRANS PROJECT. The Génépi-C accelerator was built by the CNRS in Grenoble and the fuel was supplied by the CEA.

JASMIN[69] The goal of this project is to develop a new European simulation code, ASTEC-Na, to incorporate the feedback from severe incidents concerning sodium-cooled reactors. This will help design a Generation IV European SFR.

JHR-CP[70] 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[71] 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.

LWR-DEPUTY[72] This project is studying the possibility that the current pressurised-water reactors (PWR) may generate less waste by burning fuel based on inert matrices. It aims to eliminate plutonium from reactors by seeking new fuel types.

MARISA[73] This project aims to bring to the MYRRHA project the degree of maturity necessary to begin construction. In particular, the project supports the engineering of MYRRHA, the coordination of the R&D programme, the creation of the international consortium, operating management and the preparation of the authorisation process. A roadmap will be developed, identifying MYRRHA's contribution as a European fast neutron research facility at the closure of the fuel cycle.

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67 European Gas Cooled Fast Reactor, 2010-2013, 2010-2013, FP7, 10 countries, 22 partners, including the IRSN, Areva and the CEA.

68 GUINEVERE: Generator of Uninterrupted Intense Neutrons at the lead Venus Reactor; 2006-..., collaboration with the CEA and CNRS.

69 Joint Advanced Severe Accidents Modelling and Integration for Na-cooled fast neutron reactors, 2011-2015, FP7, 5 countries, 9 partners, including the IRSN (coordinator), Areva and EDF.

70 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.

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

72 Light Water Reactor fuels for Deep Burning of Pu in Thermal Systems; 2006-2011; FP7, 6 countries and 9 partners.

73 Myrrha Research Infrastructure Support Action; 2013-2016, FP7, 9 countries, 15 partners, including the CEA, the CNRS, Areva and ACS.

MATISSE[74] This project brings together several R&D organisations that established, as part of the European Energy Research Alliance (EERA) initiative, a programme called Joint Programme on Nuclear Materials (JPNM) for the improved coordination of national initiatives, European programmes and potential public-private or transnational collaborations. The project's work programme includes actions, coordination activities and priority R&D activities in support of the JPNM.

MAX[75] 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.

MAXSIMA[76] Following the recommendations of the SRA of SNETP concerning the development of ADS in Europe and more specifically the Myrrha project, this project addresses safety studies under normal conditions and under incidental and accidental conditions useful for licensing. Analyses of severe accidents that can result in tearing of the fuel cladding will be carried out. Problems connected with an accident involving the rupture of a heat exchanger tube and the spread of the consequences of such an accident will be studied. Temporary safety experiments on MOX fuel segments are planned in an experimental reactor in Romania.

MYRRHA[77] 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[78] This project aims to generate results from experiments for assessing the safety of current and future reactors, spent fuel and radioactive waste management.

NURISP[79] 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.

PATEROS[80] This action aims to implement, on a reduced scale, all of the steps and components necessary for partitioning and transmutation technology.

[74] Materials innovation for safe and sustainable nuclear energy, 2013-2017; FP7, 13 countries and 28 partners, including the CEA, the CNRS, EDF and LGI Consulting.

[75] 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.

[76] Methodology, Analysis and eXperiments for the Safety In Myrrha Assessment, 2012-2018, FP7, 8 countries and 13 partners.

[77] Multipurpose Hybrid Research Reactor for High-tech Applications; 1998-2024, collaboration with the Eurotrans partners, including the CNRS, the CEA, Areva, Advanced Accelerator Applications and ENEN.

[78] 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.

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

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

PELGRIMM[81] In order to support the strategic research agenda of the SNE-TP, this project studies the development of fuels containing minor actinides for fast reactors. Both transmutation in homogeneous mode in the reactor core and transmutation in heterogeneous mode at the periphery of the core are studied.

PUMA[82] This project will provide the key elements for the transmutation of plutonium and minor actinides in future gas-cooled reactors.

SANF[83] This project studies fuel safety aspects for the fast neutron reactors (GFR, SFR, LFR) and very high temperature reactors (VHTR) developed as part of Gen-IV. The goal is to establish safety limits for the manufacture and behaviour of these fuels under the constraint of high combustion levels, very high doses and very high temperatures. The project brings together the US, Japan, Korea, the European Union, the OECD and the IAEA.

SARGEN-IV[84] 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 estimate of their cost.

SACSESS[85] In keeping with the SRA strategic agenda of SNE-TP, SACSESS will create a structured framework in order to optimise the fuel cycle associated with the S&T. Safety studies will need to identify the current weak points. An education and training programme is associated with the project.

SEARCH[86] 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[87] 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.

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[81] PELlets versus GRanulates: Irradiation, Manufacturing & Modelling, 2012-2015, FP7, 9 countries, 10 partners, including the CEA (coordinator), EDF, Areva, Lagrange and the European Nuclear Education Network.

[82] Plutonium and Minor Actinides Management by Gas-Cooled Reactors; 2006-2009, FP6, 9 countries, 16 partners, including Areva, EDF and Lagrange.

[83] Safety of Advanced Nuclear Fuels; concerted action, in 14 countries, 33 partners, including the CEA and Areva.

[84] 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.

[85] Safety of actinide separation processes, 2013-2016, FP7, 13 countries, 26, partners, including the CEA, the IRSN, the CNRS, the University of Strasbourg and Lagrange SARL.

[86] 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.

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

SNE-TP[88] The Sustainable Nuclear Energy Technology Platform 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 billion and €10 billion euros, and includes both the ASTRID and MYRRHA projects.

TDB[89] 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[90] This project aims to design and conduct thermo-hydraulic experiments in support of different innovative liquid metal-based systems.

VELLA[91] The initiative aims to create a virtual European laboratory to study heavy metal technologies, primarily lead and its alloys.

88 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.

89 Thermochemical Database project; AEN.

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

91 Virtual European Lead Laboratory; 2006-2009, FP6, 9 countries, 13 partners, including the CNRS and the CEA.

Appendix XII

EDUCATION, TRAINING AND KNOWLEDGE MANAGEMENT

ALICE[92] 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.

CINCH-II[93] This project follows on from the CINCH-I project, which finalised a long-term strategy for the teaching of nuclear chemistry, as well as a roadmap for its implementation. Among other factors, CINCH-II aims to develop and implement a EuroMaster and a European training passport for nuclear chemistry.

ENEN-III[94] This 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[95] 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.

KTE[96] Archiving, maintaining and deepening knowledge in nuclear research are the aims of this project. High-level training will be offered to young students and researchers through courses and internships in laboratories participating in the project.

PETRUS II[97] This project enables European professionals, active in the field of radioactive waste management, irrespective of their initial studies, to take a training course on geological disposal that would be widely recognised in Europe.

92 Access to Large Infrastructures in China and Europa, 2012-2016, FP7, 5 countries, 5 partners, including the CEA.
93 Cooperation in education and training In Nuclear Chemistry; 2013-2016, FP7, 7 countries, 11 partners, including the CEA.
94 European nuclear education network training schemes, 2009-2013, FP7, 11 countries, 20 partners, including the European Nuclear Education Network and the CEA.
95 Heavy Liquid Metal network; 2010-..., FP7, 9 countries and 13 partners, including the CEA.
96 Knowledge Management, Training and Education; 2007-..., FP7, Karlsruhe CCR (Joint Research Centre).
97 Towards a European training market and professional qualification in Geological Disposal; 2009-2012, FP7, 10 countries, 14 partners, including the European Nuclear Education Network, Andra and the Institut National Polytechnique de Lorraine.

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