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°10

MAY 2016

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SUMMARY AND CONCLUSIONS

According to the provisions of the 2006 law, only ultimate waste is intended to be disposed off. Spent fuel elements are excluded as they contain reusable materials. The law provides for the disposal of long-lived high and intermediate level waste (LL-HLW & LL-ILW) from the current fleet in geological repositories, in accordance with the principle of reversibility, and for the study of partitioning-transmutation of actinides found in the spent fuel of nuclear reactors. Nuclear facilities in operation, dismantling of decommissioned nuclear facilities and certain industries produce long-lived low level waste (LL-LLW), very low level waste (VLLW) or waste with augmented natural radioactivity (Tenorm). These types of waste require specific management schemes due to the very large quantities produced.

CIGÉO GEOLOGICAL REPOSITORY

The aim of the Cigéo project is to build and operate a geological repository for LL-HLW and LL-ILW included in the French industrial programme for waste management (Programme industriel de gestion des déchets – PIGD), which covers all of the waste from the current fleet. This repository must be created at a depth of 500 m in the 130 m-thick Callovo-Oxfordian (COx) argilite formation at the location of the site in the Meuse-Haute Marne.

The Board notes that the Andra plans to submit a construction application (demande d'autorisation de création – DAC) mid-2018. It should be examined until mid-2021 and the decree authorising the construction could be published end 2021. Excavation of the first section of the project could then begin in order to start the industrial pilot phase (IPP) in 2025. This would take place over around ten years. The Board considers that the IPP will be an essential step in demonstrating Cigéo's industrial mastership, and quality of the work. The Board recommends, throughout the excavation phase and the IPP, that the Andra provide public feedback along with a yearly progress report. In order to establish, in due time, the robust industrial design essential for submission of the DAC, it recommends that the Andra fix the technical options of the first Cigéo section as soon as possible, with a large robustness margin to allow for flexibility and to set aside optimisations, which still need to be studied, for the later sections.

The Board considers that understanding of thermo-hydro-mechanical (THM) phenomena needs to progress before submission of the DAC, in order to conceive the architecture of the HL1 and 2 areas. In any case, the Andra should submit a benchmark solution including any uncertainties remaining at that date. As these areas should only be created in several decades, the Board recommends that the Andra, with flexibility in mind, put forward an experiment for testing THM - interaction at a relevant scale.

The Andra, over the last ten years, has conducted a remarkable set of measurements and tests in the tunnels of the underground laboratory. Despite all that, the Andra has not yet succeeded in developing a relevant model able to take all mechanical observations into account. The Board considers that the main features of the mechanical behaviour of the rock over a century should be established first, given the centennial time scale of operation of the repository.

Concerning the seals, which could not be validated at scale 1 at the time of the DAC, the Board recommends that the Andra make good use of the tests in the underground laboratory; that it submit, to support the design options, a general sealing operational model at the various repository service life phases, and that it establish the deadline for scale 1 testing planned in Cigéo from the IPP.

Waste to go to Cigéo will be transported in primary packages. How it should be controlled is being determined by the Andra and producers. The Board considers it essential that the package specification and inspection process be clearly defined in due time for submission of the construction application.

By Ministerial decree of January 2016, the Ministry for Energy estimated the cost of Cigéo to be 25 billion Euros. The Board wonders how the reduction in the cost, with respect to that which the Andra has estimated, will be reflected. It recalls its recommendation for the technical options for the first section, selected by mutual agreement between the Andra and the producers, to be maintained and not to be affected by budget constraints.

VLL, LL-LLW OR WASTE WITH AUGMENTED NATURAL RADIOACTIVITY

VLL waste is currently stored in a special centre in Morvilliers, the Cires. Authorised storage capacity there is 650,000 m^3 and it should be full by 2030. VLL waste storage capacity requirements have been evaluated up to 2080. They are considerable. In addition to extension of storage capacity at the Cires, another high-capacity centre should also be opened to cope with the VLL waste from fleet dismantling. The Board encourages research organisations, industrialists and the authorities to continue their studies on innovative methods for the management of dismantling-derived materials also classified as waste, although they contain little or no added radioactivity. It reiterates its recommendation to develop methods for measuring very low levels of radioactivity in large batches of materials, which should be finalised for supporting any innovative VLL waste management strategies.

Technologically-enhanced naturally occurring radioactive materials, known by the English acronym Tenorm, are produced by various industrial activities, during which the natural radioactivity of the materials becomes concentrated. Transposition of Directive 2013/59/Euratom covering radioprotection in human activities will lead us to consider this waste as if it resulted from nuclear activities. The Board asks the Andra to assess the repercussions of this transposition on waste management.

The site in Malvési, near Narbonne, contains uranium mill tailings (see reports 8 & 9). The studies for the long-term management of the waste from Malvési by on-site storage are only in the early stages. The Board recommends undertaking, in addition to studies in areas near to repositories, modelling of groundwater flow at regional scale, taking the presence of faults, karsts and aquifers into account.

Andra has begun exploratory research on characterising a potential LL-LLW storage site in Soulaines, in the Aube region, where clay series formations could allow for the construction of a sub-surface repository. The Board considers that the inventories for the radionuclides in LL-LLW should be consolidated and more accurately estimated. The results obtained on the behaviour of these radionuclides in the planned repository are as yet insufficient to be able to conduct a realistic safety assessment including all of the site's geological parameters. As it is, it seems to the Board that LL-LLW should be managed via several disposal routes.

PARTITIONING AND TRANSMUTATION

To meet the objectives laid down by the law of 2006, the CEA is developing the Astrid project, an industrial demonstrator of a generation IV fast-neutron reactor. This highly innovative project is an essential step to introducing these reactors to the electricity-generating fleet. Astrid will allow to assess the industrial feasibility of multiple recycling of its own fuel.

The construction application will only be submitted in 2020 due to the reduction in human and financial resources allocated to the CEA, and the wish to bring studies on the gas-based energy conversion system to the same level as those reached with the water-steam-based energy conversion system.

The recent change in the agenda, which maybe makes it more realistic, does not essentially bring the Astrid project into question but the delay should be managed and used to maintain and further develop expertise and skills by continuing R&D.

Manufacturing of the elements for the fuel assemblies is mastered and R&D for moving onto the industrial scale is under way. The Board recommends ensuring the long-term maintenance of the industrial sectors essential to the project. Given the scope of the scientific and technological challenges, the Board recommends launching now a long-term R&D programme to ensure industrial reprocessing of FNR fuel. To prepare the study of americium transmutation in Astrid, projects to manufacture fuel with high americium content should receive continued, unfailing support, due to the tests that are very lengthy to carry out.

INTERNATIONAL OVERVIEW

France, Finland and Sweden are today the three countries in which significant progress has been made in the process to obtain permission to create a deep geological, high-level waste repository. The decision by the Finnish government to issue a building permit for a repository in granite, of an initial capacity of 6,500 tonnes of spent fuel came in November 2015. Construction, starting from the existing facility in Olkiluoto, is due to begin in 2016. In Sweden, early 2016, the environmental court announced its decision to consider SKB's application for 12,000 tonnes of spent fuel as admissible for the public hearing, planned early 2017.

A significant European effort, in which Belgium plays a leading role, covers ADS (Accelerator Driven Systems) which are facilities proposed as fast-neutron reactors for actinide transmutation. The core of the reactor in an ADS facility is subcritical. External neutron supply is required to maintain the chain reaction, which is an advantage in terms of safety. The neutrons are provided by a high-intensity proton accelerator bombarding a spallation target. The first section of the accelerator (100 MeV, 4 mA) is planned for 2024.

The Allegro fast-neutron reactor project with gas coolant was launched in 2002 in the frame of the Generation IV international forum. Until 2009, the CEA invested significant resources, which enabled it to define the initial characteristics of the experimental Allegro reactor. In 2010, following the proposal by the CEA, three institutes signed a MoU (Memorandum of Understanding) to study together the development and conditions of installation of Allegro: MTA-EK for Hungary, VUJE for Slovakia and UJV for the Czech Republic. The Polish institute NCBJ joined the consortium in 2012. Following its visit to Eastern Europe, the Board sees that the Allegro project is still in a design phase; safety issues and technological obstacles have been identified. The Board has realised the immense R&D effort that is now necessary to reach the ambitious objectives set for Allegro. The Allegro project will only be the very first step. Gas coolant FNR will not be available for industrial use for a long time.

INTRODUCTION

The National Assessment Board has been analysing the state of progress of research and studies relating to the management of radioactive materials and waste for more than twenty years. The period from September 2015 to April 2016 was the Board's 9th full year in operation as CNE2. This report (Report no. 10) consists of an evaluation of the research that has been presented to the Board during this period. As in previous years, a large proportion of this report is devoted to examining the management of nuclear materials and waste, on monitoring the Cigéo repository project which concerns waste registered on the French industrial programme for waste management (plan industriel de gestion des déchets – PIGD) and on monitoring the Astrid programme, which aims to build a highly innovative Generation IV fast-neutron reactor (FNR) and which alone, will make testing of the transmutation of americium at an industrial scale possible.

Chapter 1 discusses Cigéo. The Board notes that the Cigéo construction application will only be submitted in 2018. In this chapter, the Board looks at the specific features of such a nuclear facility, taking its deep geological location into account. Following this analysis, the Board lists any pending scientific issues that need to be resolved in order to compile the application, which should be based on a robust safety demonstration.

However, underground storage of LL-HLW and LL-ILW is only one of the problems posed by management of waste downstream of the nuclear fuel cycle. Indeed, regardless of the time line for the application of the 2015 law on the energy transition and that of the new regulations currently in preparation, their consequences on nuclear waste and material management should be taken into account. These new elements strengthen the vigilance of the Board. In Chapter 2, it reviewed waste recycling and packaging and management of LL-LLW, VLL waste and technologically enhanced naturally occurring radioactive waste, less active but present in large quantities. The management of it requires the construction of new storage infrastructures, the locations of which must be analysed with great care. The future dismantling of nuclear facilities will generate a significant amount of VLL waste, for which storage solutions and, where applicable, processes for reducing their volume remain to be developed.

Before presenting the highlights of the international overview, and the report of its visit to Eastern European countries (chapter 5), the Board review the Astrid industrial demonstrator project, Generation-IV reactor in chapter 3, and the progress of the fundamental research effort conducted by the national scientific community in chapter 4. Construction of the Astrid demonstrator is a major challenge, which will enable France to verify its ability to use plutonium, depleted uranium and reprocessed uranium to produce electricity.

* * *

Since the publication of its previous report in June 2015, the Board presented its Report no. 9 to OPECST and to the relevant ministerial departments. A delegation from the Board visited Joinville on 29 October 2015 to present its report to members of the CLIS (local information and monitoring committee) at the Bure laboratory.

The Board (see Appendix I) followed the same working methodology as in previous years. It conducted 10 day-long hearings (see Appendix II), and 8 other shorter half-day hearings, all held in Paris, in addition to a certain number of additional meetings with concerned parties. The Board members, all volunteers, heard 88 people from the Andra and the CEA, as well as from French and foreign academic institutions and industrial organisations (see Appendix III). These hearings brought together around sixty people on average and were also attended by representatives of the French Nuclear Safety Authority, Areva, EDF, the French Radioprotection and Nuclear Safety Institute and the central administration.

The Board spent a day visiting the EDF plant in Chooz.

The Board also went on a study tour of Eastern European countries from 21 to 30 September 2015.

To prepare this report, the Board held a 2-day pre-seminar during its visit to the Iter site and the CEA centre in Cadarache. It also held numerous internal meetings, including a five-day residential seminar. A list of the Board's hearings and visits can be found in Appendix II of this report. The persons heard are listed in Appendix III. A list of documents received from the organisations that participated in the hearings is provided in Appendix IV.

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CHAPTER 1: CIGÉO

TOWARDS CONSTRUCTION APPLICATION SUBMISSION

The Cigéo project, in application of the law of June 2006, aims to design, build and operate a reversible geological repository for LL-HLW and LL-ILW radioactive waste from the French industrial waste management programme (Programme industriel de gestion des déchets – PIGD). This repository must be created at a depth of 500 m, in the approximately 130 m-thick Callovo-Oxfordian (COx) argillite formation found in the area of interest for in-depth exploration (Zira), identified in 2009 by Andra in the Meuse-Haute Marne area. This project has emerged from studies and research carried out over a period of more than twenty years, which demonstrated the excellent ability of the COx formation to confine the radionuclides found within the waste.

Assisted by their system project manager Gaya, Andra, as project owner, completed the basic preliminary design ("APS") in June 2015. The design was examined in a project review mandated by the DGEC (Direction générale de l'énergie et du climat), known as preliminary review, which issued 35 recommendations for R&D, engineering and governance; the recommendations cover:

- problems relating to the long-term thermo-hydro-mechanical (THM) changes in the geological formation;
- dimensioning of the tunnel linings;
- LL-HLW cell extension;
- LL-ILW cell geometry;
- package specifications;
- infrastructure construction time frame;
- safety;
- management and Andra-producer relations.

The recommendations from the project review on R&D are the same as those from the CNE. As a result of the project review, Andra reviewed its schedule and gradually launched into the basic design phase (avant-projet détaillé – APD).

1.1 NEW PRE-CONSTRUCTION CIGÉO SCHEDULE

The basic design phase will take place over 2016-2017 in anticipation of the construction application submission (DAC) mid-2018. During this period, in view of preparing processing of the DAC, Andra submitted the following documents to the ASN, and to the Board in April 2016:

- safety options dossier (DOS),
- technical recoverability options dossier (DORec),
- draft master operating plan (PDE).

Also, the environmental impact study document is expected to be ready for end 2016.

The first three documents will be examined by the ASN, which will issue an opinion; the Board will do the same. The results of the basic design phase, available end 2017, will then be examined by a project review (detailed design review). All of these assessments will be taken into account in the construction application and in an update to the master operating plan in the first half 2018.

Andra currently has almost full management of the land required for the Cigéo facilities; it is already conducting preventive archaeology investigations.

The Board notes the adjustments to Andra's schedule for gradually preparing the elements of the construction application.

The law of 2006 provides for the Parliament to set the conditions for reversibility. Pending this, the Board will analyse the DOS, the DOREC and the PDE in the light of the definition of reversibility that it put forward in its report no. 8.

1.2 POST-CONSTRUCTION CIGÉO SCHEDULE

The construction application should be examined until mid-2021; the processing phase could lead to the construction authorisation being published end 2021. A first works section could then start and allow an industrial pilot phase (IPP) to be launched in 2025.

The industrial pilot phase would take place over around ten years, between 2025 and 2035, with an initial five year-long phase, during which repository operational tests would be carried out with inactive packages. The first active packages would be taken down from 2030, after commissioning authorisation has been granted. Storage would then be accelerated in the aim of demonstrating that it is possible to achieve operating conditions compatible with the maximum delivery rate of 3,000 primary packages per year, as provided for by the PIGD, at the end of the IPP. The experience acquired during this industrial pilot phase would be used to update the master operating plan.

The DAC should include robust solutions for the entire Cigéo project, the implementation of which will be approved during the industrial pilot phase. The IPP will also be a time during which areas for optimisation will be qualified. It will thus prefigure the flexibility required for design of an installation intended to be operated for a century.

The Board notes that the schedule for establishing the robust industrial design essential to submission of the construction application remains very tight. The Board recommends that Andra fix the technical options of the first Cigéo section as soon as possible, with a large robustness margin and to set aside optimisations, which still need to be studied, for the later sections.

The industrial pilot phase will be an essential step in demonstrating industrial-scale mastership of Cigéo, the quality of the works and flexibility of its operation. During the industrial pilot phase, Andra should guarantee that it is possible to recover the packages. The Board recommends, throughout the excavation phase and the industrial pilot phase, that Andra provide public feedback along with a yearly progress report.

1.3 WASTE TO GO TO CIGÉO

In its 2015 inventory of radioactive materials and waste, Andra presents a prospective vision of the waste which would be produced at the end of a facility's service life, such waste being included in the PIGD. Two contrasting scenarios, both based on the hypothesis of a 50-year service life of the facilities, are put forward:

- the first scenario takes into consideration electronuclear production and maintenance of the current spent fuel processing strategy, which implies that the uranium and plutonium from these fuels are materials which can be used in the current fleet or which will be used in a future fleet. In these circumstances, the LL-HLW resulting from processing is all vitrified into final waste to go to Cigéo, and all LL-ILW is packaged for disposal there.

- The second scenario takes into consideration the non-renewal of the existing fleet, which involves stopping processing of spent fuels at the right time so as not to stockpile separated plutonium. In these circumstances, LL-HLW will include vitrified waste and spent UOx and MOx fuels and LL-ILW will be that produced when processing is stopped.

The Board notes that the two scenarios represent contrasting but plausible scenarios for management of electronuclear fleet waste, in relation to the potential changes in the French energy policy. Andra fulfils its legal obligations by presenting the two scenarios.

The waste to go to Cigéo is that included in the PIGD. It includes waste from nuclear facilities in operation or authorised end 2013. It should be ultimate waste according to the terms of article L542 of the environment code. Spent fuels from electricity-generating reactors are not ultimate waste.

However, on the request of the PNGMDR, Andra ensured there were no unacceptable obstacles to handling them in Cigéo facilities.

In order to prepare the construction permit application, Andra is currently referring to the reference inventory (PIGD) along with a back-up inventory in the event where the ongoing studies would lead LL-LLW to be stored in Cigéo provided other storage facilities are unavailable.

The Board considers that the construction application for Cigéo should take a standardised configuration into account for which the inventory should be set, covering ultimate waste according to the terms of article L542 of the Environment Code.

1.4 SPECIFICATIONS AND ACCEPTANCE OF PRIMARY PACKAGES IN CIGÉO AND PACKAGE INSPECTION

In report no. 9 (Appendix VIII) the Board described the iterative process undertaken by Andra and waste producers since 2012, to draw up specifications for acceptance of primary waste packages, and for defining monitoring of compliance with the specifications for the packages certified by Andra. Indeed, the packages already meeting the specifications, and those to come, should have been first approved by Andra at the producers before they are handled by Andra.

At the end of the preliminary design phase, preliminary specifications were drawn up for all primary packages, whether they are to be placed in reference packages or reinforced packages for containment, or be disposed of as they are. However this version of the specifications is still being discussed. The ASN shall come to a decision on the version presented by Andra in the DOS. The dialogue engaged between Andra and the producers shall continue during the basic design phase on the basis of furthering knowledge of packages and their behaviour, along with technical and economical optimisation. Andra shall therefore provide a consolidated version of the preliminary specifications in the construction application. The final specifications shall be ratified by the French nuclear safety authority (ASN) only on commissioning of the repository.

Procedures for inspection of primary packages, outlined in 2015, are currently being defined by Andra and the producers. They will be suited to the package categories and shall include final inspection by Andra in the Cigéo surface nuclear facilities. Andra is planning an initial version of the inspection procedure for the construction application. For the time being, an Andra-producers working group has been set up in the aim of defining a strategy for managing package quality, according to the milestones based on those of the basic design phase. This strategy should distribute responsibilities specific to Andra and to the producers among them as set out by the ASN:

- the producers should characterise the waste and packages and demonstrate that they are compliant with the specifications;
- Andra should have a programme for monitoring manufacture of the primary packages at the producers.

Andra plans to continue working on waste inspection procedures along with the producers, until commissioning of Cigéo.

The Board notes the progress of the studies in view of the acceptance of primary waste packages in Cigéo. It requests Andra to clearly explain, in full transparency, how any uncertainty in terms of knowledge can be made up for with more extensive safety systems.

The Board hence considers it essential that the package specification and inspection process be clearly defined in time for submission of the construction application. As a result, the Board recommends accelerating the studies and the R&D still necessary.

It would like to know how a "package accepted for disposal" label is allocated by Andra's agents to each of the primary packages arriving at the Cigéo site.

1.5 TWO SPECIFIC ISSUES

1.5.1 Hydrogen production

Hydrogen production in the repository is a phenomenon, which is taken into account in the repository safety demonstration. It comes from radiolysis in LL-ILW packages and over the long-term from corrosion of the metal materials. According to package type, several codes for calculating radiolysis-derived hydrogen production are used by Areva and CEA. R&D in the laboratory and on package storage facilities (Appendix V) allows to confirm the codes. Radiolysis also leads to degradation of the organic matter, which produces chemical species that, in the long-term, can affect radionuclide containment following damage to the packages.

The Board considers that the consequences of the effects of radiolysis on the operating conditions of LL-ILW disposal cell in Cigéo are such that R&D on the subject should be stepped up. Andra should therefore have consolidated and consistent data on the production of radiolytic species in time for the construction application.

The Board would also like to receive the general hydrogen production model in the repository as a whole after its closure.

1.5.2 Co-disposal

There are 176,000 LL-ILW primary packages to be disposed of. Andra has managed to reduce the number of storage container models to seven. Andra is looking at disposing them in around fifty disposal cells.

Therefore, in order to optimise disposal by reducing the number of LL-ILW cells, the idea of co-disposal of LL-ILW packages with different physico-chemical and radiochemical structures in the same cell has been studied for several years. The Board mentioned the process for selecting packages that can be disposed together in its report no. 9 along with the relevant R&D. At the end of the preliminary design phase, Andra consolidated classification of the 79 LL-ILW package families into 7 categories, LL-ILW1 to 7, which are differentiated by their physico-chemical content.

Category	Number of families	Number of primary packages	Volume (m^3)	Type of waste
LL-ILW1	11.	20878.	6494.	Significant quantity of salts / non bituminous
LL-ILW2	6.	41071.	13673.	Bituminous
LL-ILW3	40.	40683.	27957.	Organic matter
LL-ILW4	6.	21720.	16155.	Cemented, weakly exothermic, not containing salt or organic matter
LL-ILW5	11.	50274.	9074.	Non-cemented, weakly exothermic, not containing salt or organic matter
LL-ILW6	3.	1347.	242.	Vitrified, weakly exothermic
LL-ILW7	2.	8.	13.	Sodium-containing

By construction, packages from the same physico-chemical category can be stored together. Andra is continuing studies on the consequences of physico-chemical interactions between packages, to determine the possibilities for disposing of packages belonging to different categories together. The feasibility of co-disposal is based on Andra's knowledge of hydrogen production, radionuclide release/transfer and degradation of package materials (organic, concrete, metal) in the repositories thermal and hydric conditions. Andra has conducted qualitative cross analyses of interactions between all waste package families, on the basis of data files provided by the producers, and on its own research into the behaviour in disposal conditions, of radionuclides with complexing agents from radiolysis of organic matter. The consequences of inter-package interactions are looked at conservatively, any significant uncertainty leading to rejection from co-disposal.

All of this data will be taken into account in the basic design phase, for defining the optimal method for filling the relevant LL-ILW disposal cells.

Andra can already confirm that LL-ILW4 and LL-ILW5, whether cemented or not, can be disposed together, as it does not contain any organic compounds or salts.

In the current state of the evaluations, all LL-ILW packages can be disposed in 50 cells.

The Board supports Andra in its reasonable choice to only dispose waste from categories LL-ILW4 and LL-ILW5 together.

1.6 CIGÉO CONSTRUCTION APPLICATION DETAILS

The law of 28 June 2006, on the management of radioactive materials and waste, specifies that radioactive waste disposal sites in deep geological formations are basic nuclear facilities (installations nucléaires de base - INB).

The construction of Cigéo should therefore be authorised by a decree of the Council of State issued following opinion from the French nuclear safety authority (ASN) and after a public enquiry. Moreover, according to the terms of this law, the construction application should also be submitted with a report from a public debate and report from the CNE.

After evaluation of the application by the French parliamentary office for the evaluation of scientific and technological options (Office parlementaire d'évaluation des choix scientifiques et technologiques – OPECST), the Government should submit a draft law setting out the conditions for storage reversibility to the Parliament. This provision, provided for in the law of 2006, will also provide the Parliament with the occasion to examine the application and conclude on reversibility.

This special procedure has the advantage of making elements of the dossier available to the public through parliamentary works and debates, but what if one of the requirements of the law setting out the conditions for reversibility was not compatible with the provisions set out in the construction application which will already have been submitted?

The Cigéo project includes a certain number of specific features to which the construction application should be adapted:

- Cigéo will be a special INB due to the fact it is both located at the surface and at a great depth;
- Cigéo is expected to operate for a period of more than one hundred years;
- Cigéo should take the principle of reversibility into account in conditions which are not yet determined by law;
- the underground part of Cigéo is not expected to be dismantled at the end of its service life but to be closed and to operate in passive mode.

Such requirements imply the construction and operating process should be flexible enough so as to be able to include feedback from the different stages of the operating life of the installation and from progress by R&D.

The ASN is expecting to see information which will prefigure that which should be found in the construction application in the documents (DOS, DORec and PDE). At the same time as its own analysis, the ASN will request an additional analysis of the safety case documentation by a group of international experts. The ASN will issue an opinion and recommendation on these documents, which should be taken into account in the construction application.

The safety options file (DOS) will be a way of preparing drafting of the construction application, in compliance with the iterative approach defined in the ASN safety guide. In the same way, the technical recoverability options dossier (DORec) could provide technical elements in preparation of the law on reversibility.

Therefore rearrangement of the schedule submitted by Andra (see 1.1) should enable the Parliament to have all the elements needed for the debate on reversibility.

In its Cigéo construction application, Andra should be able to demonstrate that the technical provisions for the construction, operation, closure and dismantling of surface facilities are likely to prevent or at least minimize the risks and disadvantages the facility could carry for populations and the environment.

The combination of the general requirements for the construction of INB and of the specific provisions for the storage of radioactive waste, makes preparation of the construction application especially complex. The evaluation of the construction application, a first in France, will be the subject of in-depth analysis.

During construction of Cigéo and throughout its operation, the operator will be subject to the very specific rules of the decree of 2 November 2007 on INB's. The operator can request, during the INB service life, an amending decree to change the type, increase the capacity or make essential changes.

> *For any major changes to Cigéo, the Board insists that all guarantees be met and that the public be widely informed.*

1.7 CONSTRUCTION APPLICATION SCIENTIFIC REQUIREMENTS

The work by Andra has demonstrated the excellent ability of the Callovo-Oxfordian (COx) argilite to contain radionuclides. This is due to the specific qualities of the rock at various levels:

- its stability on a geological time scale;
- the low porosity of the argilite and its very low permeability which minimise water circulation to the extreme;
- clay retention capacity which considerably slows migration of a large number of radionuclides by diffusion;
- the homogeneity of the layer over at least 130 m thickness and over the entire Zira;
- the absence of cracks and fractures which may bring homogeneity into question.

Safety of the repository is therefore ensured first and foremost by the geological barrier. The disposal packages and the engineered barriers (seals) are additional and non-superfluous containment factors which reinforce safety in accordance with the principle of defence in depth.

It is therefore essential to be able to guarantee that the properties of the host layer at various levels will be preserved throughout the necessary duration of containment.

In its previous reports, the Board drew attention to the scientific questions that were important to be mastered at the time of submission of the construction application, in order to ensure that Cigéo operates safely in the long-term. These questions, which have not yet all been thoroughly thought out, are listed below.

1.7.1 Rock thermo-hydro-mechanical behaviour

In its report no. 9, the Board noted that Andra had improved its argilite massif behaviour model given the effect of the heat given off by the exothermic HL waste. This change was driven by a revision of the hydro-mechanical parameters and by modification of the architecture in the HL storage areas aiming to reduce the length of the cell service tunnels. Recent studies led to the reduction of the permeability of the argilite of almost one order of magnitude and to an increase in rock stiffness. This results in the criterion for rock fracture under the effect of the increase in interstitial pressure taking precedence over the criterion for the temperature reached in the clay in contact with the disposal cells, taken into account in previous studies. Even if Andra seems to have adopted careful hypotheses in its thermo-hydro-mechanical (THM) calculation for evaluating this criterion, the uncertainty which still prevails as to certain parameters such as Young's modulus, incite the greatest care to be taken when evaluating the consequences of this criterion being overtaken.

Given that the question of THM behaviour is of utmost importance when it comes to ensuring the sustainability of the essential containment characteristics of the COx, the Board request:

- *Andra to state which are the respective parts of the change in the parameters and in architecture having led to the fracture criterion taking precedence over the thermal criterion;*
- *Andra to use all existing results and interpretations of the thermal tests carried out in the underground laboratory for validating the THM model used;*
- *Andra to carry out studies for evaluating the consequences of possible hydraulic fracture on the COx containment properties and on their subsequent effects on safety.*

In the current context, the Board considers that the THM model still needs to be worked on further before submission of the construction application. In any case, for the benchmark solution to be selected, Andra should submit an architecture for the HLW areas which is compatible with the THM criterion, while including any uncertainty which may subsist at that time.

Concerning the flexibility in the construction of the Cigéo LL-HL area, which will only come into operation in several decades, the Board recommends that Andra put forward an experiment for testing the THM model at a relevant scale.

1.7.2 Massif desaturation-resaturation and gas migration

Andra studied the desaturation-resaturation transients of the massif during the repository's service life for its 2009 application. According to Andra, it would appear that ventilation causes desaturation which develops at least up to the boundaries of the excavation damaged zone, and that this phenomenon is not prevented by the concrete lining. However, stopping ventilation does not lead to as rapid water back flow as to begin with, so resaturation takes a lot longer than desaturation. This mechanism is due to the fact that the conditions at the boundary of the hydric problem are very dissimilar in both cases. Low humidity is required when ventilation is active, whereas humidity is free to come back up to hydric balance in the opposite case.

Water content inside the argilite plays a role in at least two levels, affecting the near field.

1. The first level is swelling of the argilite during resaturation, a confirmed phenomenon which can have mechanical consequences on the lining as mentioned below;
2. A second level involves migration of the hydrogen into the pores or microcracking in the near field and into structural materials. Low water content encourages gas migration and dissipation of pressure, whereas the resaturated argilite constitutes a barrier which can cause an increase in gas pressure with risk of fracture.

The Board recommends that Andra ensure that all transients involving desaturation-resaturation and hydrogen release mechanisms have effectively been taken into account, given the uncertainty as to the thermal regime and hydraulic coupling between the various repository areas.

1.7.3 Tunnel and disposal cell lining dimensioning

Andra, over the last ten years, has conducted a remarkable set of measurements and mechanical tests in the tunnels of the underground laboratory. This is the highest level of that which has been carried out in similar facilities in the world. It concerns both description of fractures in the damaged area and observation of the intrinsic thermo-hydro-mechanical behaviour of the argilite, and more technological tests comparing various excavation methods, various choices of lining and time for applying linings.

For all that, the Andra has not yet succeeded in developing a mechanical behaviour model able to take all observations into account. Several models appear to coexist, that is to say those of the producers, the Ineris, the project managers', academic partners', which are not fully compatible among them. The absence of a unified and shared vision can be explained by the complexity of the problem, the behaviour of the material as it is viscoplastic and hydromechanical, affected as much by variations in temperature as by the level of saturation. The very marked difference between the forms taken on by the damaged area (referred to here by the English acronym *excavation damaged zone* EDZ) according to the orientation of the tunnels/cells is very well described but difficult to explain, the difference between the main horizontal stresses not being highly significant.

We therefore have a lot of data, which provide for good empirical knowledge of the behaviour, significantly superior to that which we have in general when building a tunnel for instance, but which concern time scales even shorter than around ten years. However we are lacking a model and a set of mathematical relations for a well-founded extrapolation to longer time scales, of around a century or longer.

a) Specific features of deep disposal

The repository tunnels and cells are not excavation works that can be fully compared to a tunnel, the service life of which can be just as long. Indeed, even if it will undoubtedly be possible to carry out monitoring, it will become extremely difficult after a certain amount of time to access certain waste-filled disposal cells and therefore to carry out repairs or improvements there. It is more important in the case of Cigéo than in that of an ordinary tunnel for initial proportioning of the linings to be carried out, taking account of the loads actually borne in the long-term (resulting from the delayed deformation in the lining and the host rock). The knowledge acquired should therefore be extrapolated to much longer time scales. The absence of a robust and approved model is then obvious.

b) Characterising the main features of long-term behaviour (longer than a century)

Several hypotheses can be put forward; they do not depend on the details of the rock's behaviour in actual operating conditions, but rather on some main features of the behaviour of the massif (and of the EDZ) which determine lining proportioning (concrete thickness and/or grade).

In the most straightforward of hypotheses, argilite behaves as a viscous fluid over a century, the lining supporting in the long-term all the natural stresses which appear to be slightly anisotropic but close to the weight of the superincumbent land, therefore 11 to 13 MPa. The lining should be calculated accordingly with the necessary margins.

In the most favourable of hypotheses, the argilite has a sufficiently high threshold below which no viscoplastic deformation occurs; or even, given the viscosity of the argilite, the stiffness and time it takes to place the lining, the final balance is only achieved after time scales a lot longer than a century. The discussion is complicated by the following observation, according to which delayed deformation is above all active in the micro-cracked area. The lining would only support a certain fraction of the land weight in the long-term. The lining could therefore be less thick than in the first hypothesis.

The third hypothesis, a lot more unfavourable and undoubtedly pessimistic, is that in which in the long-term the massif would make the lining bear more than the weight of the superincumbent land. It would not be impossible if the argilite swells with water, a phenomenon which has been confirmed, before a century has passed. In effect, we cannot immediately rule out the hypothesis that at least locally, resaturation, although very slow, is faster than expected and leads to swelling, the effects of which would add to those of the weight of the land. In this case the lining should be especially thick.

The Board considers that the point to be handled as a priority is the exact nature of the mechanical behaviour of the rock over a century, which is that required for the active operation of the installation.

The Board notes that Andra appears to prefer one model, the Ineris/Andra model, which provides for a viscoplastic threshold and decrease in deformation rate under constant load over time, two rather optimistic hypotheses which mean a thinner lining can be selected.

The Board considers it essential that the main features of the model of the long-term mechanical behaviour of the massif be backed by very solid arguments.

The Board would like to receive a comparative study of the various models of the delayed behaviour of the host rock as soon as possible.

1.7.4 Excavation damaged zone concerns (EDZ)

20 The influence on safety from the effects of the excavation damaged zone (EDZ) at the tunnel walls is a concern common to all repository projects, regardless of the host rock. We may fear that such a zone, between the intact massif and the packed or sealed tunnels, form a more permeable shaft, which can enable water to flow through, possibly loaded with radionuclides, to the access tunnels, thus constituting a short circuit to the geological barrier. Such a mechanism requires however, in addition to the increased permeability, hydraulic gradients to drive the flow. In the case of clay rock, the consequences of this mechanism are probably greatly attenuated by the ability of the clay to absorb certain radionuclides, which likely delays their effective circulation.

a) The EDZ in Cigéo

Andra has acquired a clear picture of the damaged zones, the form of which largely depends on tunnel orientation, and has a number of ways for measuring local permeability which is (micro)fracture permeability. However, it does not have permeability measurements on a larger scale (decametric to get an idea) in the direction parallel to the tunnel axis. Such a measurement could be used to assess the potential role of an eventual hydraulic short circuit in the shaft, but it is difficult to do by construction. In the current context, the permeability of the EDZ on a wide scale can only be determined by modelling.

b) EDZ repair

Andra considers that the artificial permeability of the EDZ could decrease over time (over a century) under the effect of two mechanisms:

- the first, convergence of the massif to the lined tunnels would at least partly reconstitute the natural stresses of the massif, which would help close the (micro) fractures and restore low permeability. Rock punching tests, inspired by those carried out on Mont-Terri, effectively highlighted this phenomenon. However, Andra has qualitative results that are not general in the form of behaviour equations, which reduces their scope. Also, the hypothesis put forward by Andra that argilite is viscoplastic, also implies that restoration of the initial stress condition is not complete, and therefore that natural permeability will not be restored.

– also, Andra considers that water tightness will be restored to the damaged material under the effect of resaturation which will lead to swelling of part of the clay fraction of the rocky material. This phenomenon has also been confirmed; but it appears that resaturation is a slow phenomenon, regulated by the permeability of the intact massif, which is low. The time line should be described and swelling kinetics should be described via behavioural relationships.

The Board doubts that the two mechanisms lead to rapid return to low permeability in the EDZ in the case of flexible linings, and this especially as a highly porous and permeable layer remains between the coating and the rock, to withhold application of high stresses on the lining. This point will be discussed in the next section.

The Board would like to know how Andra plans to handle the issue of the EDZ in the construction application. It would especially like to be informed of the models used and the global scenario developed. It recommends that the case of potential migration of radionuclides subject to low absorption by the clay be examined.

1.7.5 Hydraulic role of materials at the outside of the linings

Other than the question of the EDZ in the near field mentioned above, the Board wonders what role the materials placed at the back-end of the tunnels and disposal cells will have on fluid displacement.

Recent design developments by Andra propose that compressible and therefore porous and permeable materials be placed between the lining and the rock, to withhold application of part of the load while enabling early placement of the final lining. The permeability will gradually decrease in these zones during convergence of the massif, but will probably remain highly permeable for a long time, compared to sound argilite and even damaged argilite, the cracks in which will be eventually sealed. The question of their effect on fluid circulation in the area near to the cells and tunnels is therefore raised. It may concern hydrogen from radiolysis or anoxic corrosion but also water during the resaturation phase. This situation complicates the modelling of the various transient phenomena and their coupling.

The Board asks Andra to ensure that use of compressible materials at the back-end of the tunnels and disposal cells does not lead to circulation of fluid likely to prevent the repository operating properly throughout the various stages of its service life.

1.7.6 Tunnel and surface-underground access sealing

The Board, on several occasions, insisted on the need to have a credible tunnel sealing design by 2018, from submission of the construction application. It notes that the elements required will not all have been validated at level 1 at this stage of the procedure. Andra will at that time however have collected a significant body of results from tests and modelling on the behaviour of the various seal components, and on ways of using them.

Concerning the seals, the Board therefore recommends the following to Andra concerning the construction application:

- *that it make good use of the surface or underground experiments;*
- *that it submit, to support the design options, a general seal operational model at the various repository service life stages;*
- *that it provide details of the level 1 tests provided for in Cigéo from the industrial pilot phase and that it define the most important objectives of the tests and their time scale.*

1.7.7 Monitoring

Monitoring will be necessary throughout the repository's active phase. The pilot industrial phase will serve to test the monitoring equipment and use in actual conditions of package delivery provided for in the PIGD. This should be based on a programme specially designed to evaluate the behaviour of the various components.

The monitoring methods over the repository service life will differ according to the intended use of the works; they include:

- infrastructure and service works which should remain operational throughout the operating phase through to final closure of the repository. The works will be accessible and maintainable; it will be useful to monitor them in order to collect information over the long-term and anticipate incidents;
- inactive demonstration disposal cells foreseen for during the pilot industrial phase, which may provide enhanced monitoring without the risk of compromising the safety of long-term operation;
- disposal cells in actual conditions, to be closed and operated in passive mode within a time frame to be determined. Monitoring should be designed so as not to compromise safety in the long-term; it should be adapted to levels of recoverability reached.

The Board recommends that, for the construction application, Andra define the monitoring programme and the resources to be used to conduct it, by specifying the various types of works and their function during the repository's service life.

1.8 THE COST OF CIGÉO

In 2014, Andra estimated the total cost at around 33 billion Euros, a figure contested by producers who at the time had estimated it at around 20 billion. The cost structure was the following according to Andra at the time: 19.8 billion in investment, 8.8 billion for operation up to 2144 and 4.1 billion in taxes and other charges. After discussion with the producers and convergences on certain items, during an optimisation process by a working group set up by the DGEC, the cost was estimated at a little under 30 billion in 2015. The figures did not however take account of certain "additional optimisations" requested by the producers. On this basis, the cost of the first section appeared to be around 5 and 6 billion, that of the other sections between 8 and 9.5 billion; the costs of closure were around 1 billion and the renovation costs were estimated at 4.2 billion. Total investment therefore seemed to amount to 20 billion. To that are added operating costs over the period during which the repository is supposed to stay open, then estimated at 9.4 billion, coming to a total of 29.4 billion for this project.

The Board considers that it is not surprising to see that today it is difficult to estimate such a cost over such a long period and that many uncertainties prevail. What is important in the Board's opinion is that it be regularly reassessed and that an agreement be reached on the cost of the first section, which is the closest in time and therefore easier to estimate.

As the revenue court highlighted in its 2013 and 2014 reports, the cost of waste disposal only represents between 1 and 2% of the cost of production of the nuclear kWh. It is therefore a lot less than 1% of the price of the kWh paid by a domestic consumer in France, which includes the cost of production, the network cost and taxes.

The Board saw there was agreement on the overall project design, at least on section 1 (excavation and IPP), between Andra and producers, which it is pleased about. The Board recommended however exploring the LL-ILW area via an exploration tunnel behind the zone concerned by the pilot industrial phase, over the entire area for the later phases. This option has not been included in the cost estimate.

The Board also recommended developing R&D to explore the debated cost reducing opportunities. It should be noted that expenditure by the laboratory in Bure is not counted here, which is usual since it is financed today by a special INB tax. There should be a clarification of how the situation will evolve in the future, especially if there is a desire to continue the R&D studies, as the Board has already requested.

One of the key issues of the controversies between waste producers and Andra resides in the fact that establishing the global cost of the project has a direct and immediate impact on the total amount of provisions that the producers must set aside. An revised reassessment of the cost will automatically lead to a significant increase in the provisions, which could have a big impact on the liquidity position of the companies and, indirectly, on their share price where applicable. For this reason the Board had recommended updating cost estimates for Cigéo every 3 to 5 years, so the waste producers do not find themselves up against a cliff effect due to a too long lapse of time between two reassessments.

By a decree of January 2016, the Ministry for Energy has just estimated the project to cost 25 billion Euros. It is on this basis that the producers should today adjust their provisions. It is therefore slightly less than the last figure that Andra had seemingly put forward.

The Board notes this official figure but wonders how the reduction in the cost will be reflected by Andra and which items the adjustments will concern.

The Board recommends that the technical options for the first section, selected by mutual agreement between Andra and the producers, be maintained and not subjected to budget constraints.

Concerning the subsequent sections, the Board is concerned to see the first signs of reductions on redundant elements and margins (such as filling in areas instead of using seals). On this matter the Board recalls that the law of 2006 states "When examining the construction application, the safety of the site is assessed with regard to the various stages of its management, including final closure".

CHAPTER 2: WASTE MANAGEMENT, INTERMEDIATE STORAGE, LL-LLW AND VLL WASTE

2.1 WASTE MANAGEMENT

On 21 April 2015, the ASN issued a decision (DC-0508) concerning the management of radioactive and conventional waste produced in INB throughout their service life. It resumes, in a consistent manner, previous provisions and covers the principle of INB zoning, the contents and methods of studies required by various decrees and content of waste reports that should be drawn up by producers. All aspects of waste management should be examined: re-use, recycling and reuse before disposal in operational or planned disposal pathways.

Intermediate storage comes before disposal. This applies to most long-lived waste. However there are numerous types of waste waiting to be picked up for packaging, and dismantling waste is still to come. The first is especially LL-ILW, the second especially VLL waste.

All waste going to a repository has to be packaged to meet acceptance specifications (see report no.9). Packaging processes are already up and running for most waste from INBs in operation. For the others, new packaging needs to be developed according to a standard which has been submitted to the ASN for production authorisation. The authorisations confirm that packages can be placed in disposal at a later date. Also, the PNGMDR is closely monitoring management of various types of nuclear waste and materials, and imposes a number of milestones for waste producers as well as that they compile inventories. The ASN issued several opinions at the beginning of 2016 concerning their management.

The types of waste package families to be stored are highly varied. It would be useful if the quality of the primary packages could be assessed with regard to their cost and performances based on straightforward criteria. To this effect, Areva uses a rational approach to qualify its packages, by examining all of the performances expected in intermediate storage, during repository operation and after closure of the repository.

Areva therefore defined 6 parameters: 2 economic (bulk waste incorporation rate, packaging process savings) and 4 concerning integrity (matrix, container, radiolysis, component release). During design of the package the values of each parameter need to be assessed under various bounding conditions. It is the purpose served by R&D on packages. We can therefore allocate a qualitative score. The ideal package is that for which the scores each have the maximum value. The methodology can be extended to all packages.

The Board encourages all producers to submit the characteristics of the primary waste packages in a homogeneous manner. Areva approach can be extended to all packages.

2.2 DISMANTLING OPERATIONS

Areva, EDF and CEA have already conducted considerable clean-up and dismantling (C&D) operations and have several operations ongoing, described in Appendix VI. These operations are monitored by the ASN which is waiting for several Areva and CEA documentation packages on the dismantling and the management of waste produced (ten-year update expected for June 2016). Early dismantling of EDF's UNGG reactors is linked to the commissioning of Iceda. C&D of the Chooz reactor is EDF's first experience in dismantling of a PWR.

The challenges of the C&D are shared by Andra and the producers:

- as accurate as possible inventory of the waste,
- package specifications for acceptance in disposal,
- reduction of the volumes to be stored given the limited VLL waste disposal capacities,
- VLL waste recycling and economic optimisation

Andra's forecast for the waste shows that the main problems with management will occur from VLL waste.

The R&D behind these aspects is managed by the CEA on behalf of the producers:

- characterisation of facilities and waste,
- effluent treatment,
- solid waste treatment and packaging,
- operating tools and management systems.

The CEA is working with a number of industrialists. The international dismantling market is already large and is set to grow.

Andra and the national research agency (ANR) launched a call for tenders end 2014 for backing for dismantling. It targeted all R&D stakeholders from academic and industrial circles. The second call for tenders has just been launched (December 2015 – March 2016).

The Board approves the synergy that exists between the producers and Andra to ensure consistent management of dismantling waste and launch of Andra's first call for tenders for optimised management of this waste.

2.3 WASTE RECOVERY AND PACKAGING

Several waste recovery and packaging operations (RCD) are continuing (Appendix V). They mainly concern old LL-ILW in intermediate storage at Marcoule and la Hague of highly varied types. Difficulties with recovery require large-scale operations which will take tens of years still to complete.

All of these operations involve at least characterisation of the waste prior to packaging (radionuclide and chemical composition inventory) and primary package characterisation. R&D often also involves development of new containment materials compatible with the physico-chemical nature of the waste. The incidence of radiolysis should be assessed in each case.

RCD operations by the CEA and Areva are scheduled according to a time frame compatible with the Cigéo PIGD time frame and opening of a LL-LLW repository. Areva plans to draw up specification sheets for the new primary packages at la Hague (SWP-C HL0 and FRP-HL0) for 2016. For the others, R&D has to progress in order to arrive at this stage. The Cigéo preliminary acceptance specifications are being discussed between the producers and Andra (see report no. 9 and chapter 1). For the time being nothing concerns LL-LLW packages.

Later packaging has more constraints than in-line packaging, not to mention waste recovery, and where it is possible, sorting. It often concerns very heterogeneous waste batches, each component having its own characteristics, and the packaging should take that into account. The batches are often low tonnage also.

The Board is attentive to the developments in the recovery and packaging of waste in intermediate storage for decades. It underlines the need to produce robust primary packages ready for disposal.

The Board recommends stepping up R&D on packaging of waste to be recovered from the CEA's and Areva's sites. It considers that a better coordination between R&D participants should be envisaged and would like to receive a synthetic progress report on this work.

2.4 WASTE PACKAGE INTERMEDIATE STORAGE

Waste package intermediate storage is a necessary part of standard waste management, but, if it lasts a long time, becomes complementary to disposal (flexibility pending commissioning of repositories, waste decay before storage, package monitoring). Intermediate storage would be necessary once again if it was decided that the packages should be recovered from Cigéo.

Today, 60% of the LL-ILW packages and 30% of the HL packages on the PIGD are already produced. They are in intermediate storage pending dispatch to Cigéo. The first LL-ILW packages are expected in Cigéo's alveoli in the second phase of the IPP (by 2030) along with the first HL0 packages. The first HL1 packages should arrive in 2075.

Feedback on package industrial intermediate storage has been collected for more than 50 years. Recent intermediate storage facilities are suited to the package dose rate, to the expected intermediate storage time (between 50 and 100 years) and to producers' requirements. However, construction of intermediate storage facilities takes a long time and the forecasts should be assessed a decade before they are required.

The CEA has been storing its LL-ILW packages since 2006 (non-bituminous) in Cedra (Cadarache) and its bituminous LL-ILW and LL-LLW packages since 2000 in EIP (Marcoule). HL0 packages are in the SEV repository in Marcoule. The Diadem repository in Cadarache for SL-LILW and dismantling alpha LL-ILW waste will be commissioned in 2018. Areva has been storing HL packages in la Hague in several facilities since 1989 and regularly builds new ones. The same applies to the LL-ILW packages since 1987. EDF is building Iceda on the site in Bugey to store plant operating and dismantling waste from 2018 on.

According to the PIGD (version D of 2014) all HL1 and 2 waste packages (51,886 packages) which need to cool for at least 75 years, will be stored in la Hague before being sent to Cigéo (between 2075 and 2140).

Storage at the Cigéo site will only concern package flow management.

Intermediate storage of LL-LLW intended for LL-LLW disposal or waiting to be recovered for temporary or final packaging, is discussed in section 2.8 and Appendix VII.

2.5 TRANSPORT TO CIGÉO

All HL1 and HL2 packages will stay at la Hague until 2075 and there is no particular rush for deciding how they will be transported to Cigéo. For the other packages, the time line for transport as per the PIGD provides for transfer as of 2030 from la Hague (21% of HL0 U-SWP, 51% of LL-ILW packages) and from intermediate storage with the CEA (Marcoule and Cadarache) and EDF (Bugey).

This requires certified transport packaging and adequate fleet. Areva has considerable experience in these fields as much in the design, manufacture and operation of packaging as in transport logistics. Areva has already returned V-SWP and C-SWP to its foreign customers and frequently transports UP assemblies and nuclear materials from the cycle.

Most packaging that could be used for transporting LL-ILW and HL0 packages is already available. However, for most, the internal structure needs to be rearranged to adapt them to the shape and weight of the packages to be transported, and they need to be certified by the ASN for the intended uses. This means that R&D is required (materials, radiolysis, etc.) at least for all packages that are not standard packages such as V-SWP and C-SWP. Only the packaging for these packages is certified (TN843 and TN28).

The certified packages will be available or will be able to be made in sufficient quantities to meet Areva's needs throughout Cigéo's service life. Areva suggest coordinating programmes for transport studies by the various participants. Areva will present an update of the issue of package transport to Cigéo in 2016.

The Board notes Areva's studies and proposals as to the transport of waste packages to Cigéo. It will involve many journeys and transport will be a visible demonstration of Cigéo's operational status. The Board would like to be informed of the progress of the dossier in relation to the time frame for delivery of the PIGD and of previsions relating to secondary waste from packaging use.

2.6 VLLW

2.6.1 VLLW management

The Cires (classified facility) in Morvilliers is a VLL waste disposal facility with cells or trenches in the Aptian clay. It has compacting waste treatment facilities (metallic and plastic waste) and several buildings for non-nuclear radioactive waste (and sorting from 2016) and for storage during decay (clean-up waste from polluted sites). The authorised disposal capacity is 650,000 m^3. Where a trench has been filled and covered it immediately receives a permanent blanket.

The Cires filling ratio exceeds 40%. The flow rate is 25 to 30,000 m^3/year, almost half of the VLLW of which is almost inactive (radioactivity estimated to be lower than a Bq/g). It will be full towards 2030.

Waste acceptance specifications cover the radioactivity of the waste packages (specific activity and quantities), their physico-chemical content and their packaging. They enable flexible continuous management of VLL waste. In addition to conventional packages (big-bags, barrels, baskets and cement-injected cases) the Cires takes large single units (between 12 and 24 tonnes). For larger objects (oversized), a cell is currently being built to accommodate them using heavy-duty handling equipment (loading frame).

VLL waste disposal capacity requirements have been evaluated up to 2080. They are considerable. The first way of ensuring continuous VLLW disposal is to extend the capacity of the Cires from 2030. It can be extended to 900,000 m^3 without increasing site coverage and without compromising radionuclide containment after closure, which depends on the clay barrier (7 m) under the trenches. Andra should submit an extension application.

In addition to extension of the Cires disposal capacity, a new disposal site able to receive 30,000 m^3/year with a capacity of 0.6 to 1.2 million m^3 to cope with the VLLW from dismantling of the fleet by the end of the century should be opened. The range depends on the metal and rubble recycling possibilities. In particular, VLLW volume flows could be reduced by metal fusion (12,000 m^3/year), incineration (2000 m^3/year) and compacting (2,000 m^3/year) of the materials (Appendix VIII).

Andra has drawn up an industrial VLLW management programme in agreement with VLLW producers comprising several scenarios in keeping with the current French energy strategy, but which in all cases maintains service continuity. The programme needs to be optimised and consolidated. Andra plans to store simplified VLLW on sites (i.e. dismantling sites) which could be the alternative to "release" practised abroad for saving disposal capacity. Indeed, in France, current legislation on waste produced in nuclear facilities leads to the management via dedicated channels of contaminated or activated waste, but also of waste possibly not contaminated or activated.

2.6.2 VLLW reuse

Currently only a very small volume of steel is reused in the form of radiological protection in radioactive waste packages.

Many technical and economic discussions on reuse of VLLW, based on actual projects, have taken place within the PNGMDR (Appendix VIII). In this respect, the Board heard the DGEC on the work of the PNGMDR on 9 December 2015 and attended the hearing of the IRSN on 17 February 2016 by the French parliamentary office for the evaluation of scientific and technological options.

a) The PNGMDR's work

The working group set up as part of the PNGMDR looked to define favourable ways of reusing contaminated or activated materials or likely to take that status, produced in nuclear facilities.

It looked closely at the conditions of reuse of ferrous metal materials qualified has having very low level activity. It compiles recommendations and puts forward areas for work in terms of:

- technical aspects, with especially identification of material types and processes for determining favourable physico-chemical and radiological processes for reuse;
- reuse channels, with identification of suitable facilities in accordance with health, environmental, societal and radioprotection concerns posed by the type of substances at each of the treatment steps and related traceability procedures;
- foreseeable prospects, by proposing hierarchisation of the latter in order to ensure traceability of the reused materials as far as possible;
- analysis of management options, overall analysis (service life) for comparing the advantages and disadvantages of the various solutions planned;
- methods for informing stakeholders and encouraging them to participate locally and nationally;
- content of exemption applications provided for by legislation in the event of reuse outside the nuclear industry.

The working group has issued 14 recommendations on waste reuse (Appendix IX).

b) The IRSN's work

The IRSN considers that "identical renewal of current management methods is not necessarily the optimal solution, and that diversification of management solutions is preferable where it minimizes and allows for a fair share of risks and difficulties of all kinds brought by the planned management methods, and where it promotes use of the resources in a more suitable proportion to the actual risk presented by the waste."

The IRSN considers "that the choice to change doctrine can only actually be made if civil society fully partakes. It is therefore necessary to create conditions for debating the challenges and avenues to be explored."

To this effect, the IRSN considers "that all aspects of the subject should be discussed, whether it is a question of technical methods to be implemented for characterising both radiological and conventional risks relating to management methods, or ethical questions possibly resulting for instance from definition of radiological management thresholds and a dose level below which management methods likely to deliver it, today or in the future, could be considered to be "optimised" and "fair."

c) ASN's standpoint

In opinion 2016-AV-0258, the ASN rules out any notion of release threshold for INB VLLW (except rare exceptions). This opinion is substantiated by public health concerns and the need to ensure, as for the other waste, the traceability of the VLLW in the specific channels, the last point being subject to regulatory considerations. The ASN endorses the PNGMDR's recommendations for metal waste and rubble, and in this respect, it is waiting to receive proposals from Areva (Eurodif diffusers) and from EDF (steam generators) to answer to them. It also expects producers to reduce the volumes to be disposed (sorting, incineration, densification) and proposals for a new VLLW disposal site and specific local storage facilities.

d) Conclusion and recommendation

In its report no. 9, the Board analysed waste management at international level. It noted the difference in the solutions used. It was concerned about the scheduled and future dismantling operations generating large quantities of VLL waste and about the fact that the Cires' capacity would be insufficient to be able to take it. It also drew attention to the uncertainties as to the inventory.

The Board encourages research organisations, industrialists and the authorities to continue their studies on innovative methods for the management of dismantling-derived materials classified as waste although it contains little or no added radioactivity.

The Board reiterates its recommendation on the subject of the measurement of very low levels of radioactivity in large batches of materials: this should be finalised for supporting any innovative VLL waste management strategies.

2.7 TECHNOLOGICALLY ENHANCED NATURALLY OCCURRING RADIOACTIVE WASTE

This waste is also known by the English acronym Tenorm, Technologically Enhanced Naturally Occurring Radioactive Materials. It comes from processing of ore or materials (known as Norm) which, due to the ubiquitousness of the natural radioactivity, concentrate ^{40}K and radioelements from natural decay chains. Unlike certain potentially radioactive VLL waste from INB, there is no ambiguity as to the origin of the radioactivity in the Tenorm.

Tenorm are produced in large quantities by highly numerous and officially listed industrial activities. Their specific activity (1 to 100 Bq/g) can reach (or even exceed) the limits of that of VLLW. Some are reused (ash in cement, backfill, construction products, etc.) but most are stored *in situ* or in facilities authorised to store hazardous conventional waste (4 HWSF in France have received 120,000 t of Tenorm over the last ten years) or again with the VLLW at the Cires (2,100 m^3 stored end 2013) and some should even go to LL-LLW repositories (rare earths and zircon industries, 21,000 m^3 planned).

2.7.1 Legal framework

Tenorm-VLL and Tenorm-LL-LL waste, clearly identified in Andra's inventory, take two names, which create confusion in ordinary usage. A lot of Tenorm waste is stored on production sites before it is treated.

The circular of 25 July 2006 provides the framework for management of Tenorm. Directive 2013/59/Euratom on radioprotection in human activities is currently being transposed. It will refer to this waste as waste resulting from nuclear activities. This change of status complicates how it will be managed. It poses general problems with consistency in the management of very low specific activity waste with regard to its radiological impact: exemption (little radioactive Norm) and release (Tenorm*).* Tenorm waste is not governed by the same regulatory bodies as VLL waste but public health considerations remain. Below the release thresholds (some Bq/g) it would go to the various HWSF depending on its chemical nature and to VLLW and LL-LLW tracks above the thresholds. The new status also poses specific problems for waste in large quantities: inventories, disposal *in situ*, centralised disposal, transport and that of the potential recovery of Tenorm already stored in the HWSF. The new way of referring to Tenorm in legislation calls for clarification in the classification of waste with very low radioactivity according to the tracks.

Concerning R&D, the new provisions refer to radiological characterisation of Tenorm which is just as, or even more difficult than for VLLW, which comes in addition to their characterisation from a chemical toxicity point of view. The list of incriminated non-nuclear industries, already a long one, is currently being extended to industries that until now were not affected by the legislation.

The Board asks Andra to assess the consequences of transposition of Directive 2013/59/Euratom, in the absence of reuse/exemption, for the VLLW volume to be processed.

2.7.2 Conversion process waste (AREVA site in Malvési)

In its reports 8 and 9, the Board discussed the existence of uranium mill tailings (UMT) on the Malvési site near to Narbonne. They result from the production of UF_4 by the Comurhex I factory. Some old waste produced from reprocessed uranium contains traces of fission products and alpha emitters, which led to the creation of the Ecrin INB in order to manage them. The other waste produced from natural uranium is Tenorm and is managed in a classified facility for environmental protection..

The decree of 12 July 2015 authorises Areva to construct and operate the Ecrin intermediate storage INB for 30 years. It will group UMT waste deposited in basins B1 and B2, the waste from basins B5 and B6 and possibly waste produced over the next 30 years (see below). It will take 5 years for Ecrin to be commissioned. Authorisation has been issued for 400,000 m^3 and 120 TBq in Ecrin. The remainder of the 690,000 m^3 on the 2015 inventory will be managed in the classified facility. Waste deposits in Ecrin will be covered by a multilayer bituminous blanket over 6 hectares for the duration of the INB service life.

In the mid-term, the Comhurex II factory, which is ready to start up, should benefit from a number of innovations aiming to reduce effluent volume, and therefore that of new waste produced up to the end of the service life of the two factories. Given, especially, significant changes in the future uranium purification process, 90% of the future operating waste can be managed via VLLW channels. The remaining 10% (dehydrated sludge from nitrate and gypsum treatment) pose process problems (reduction of their nitrate content) and management problems (LL-LLW storage on site or nearby). Their storage in Ecrin appears to be ruled out.

At the end of Ecrin's service life, Areva is planning final disposal, on-site or nearby, of old waste (Comhurex I) and of a fraction of future waste (Comhurex II). Its feasibility has been examined for several years. R&D is managed by a group of international experts and is set to continue to end 2017, time at which a disposal scenario could be selected.

The waste inventory is known. The radionuclides in the various waste to be contained include uranium, thorium and ^{226}Ra, in variable proportions, as well as their daughter products. They are more or less leachable from the minerals they are contained in and retained more or less by the geological materials. The ongoing measurements to characterise their behaviour show that the sulphur mine tailings used for the basin foundations are good uranium captors, the only really leachable element.

The Board considers that the studies for the long-term management of the waste from Malvési by in situ disposal are only in the early stages. It will closely follow R&D upstream of qualification of the repository concept, that is the R&D which is both generic (waste characterisation, source term) and specific (geology, hydrogeology of the site).

The feasibility of 3 different repository designs, presented to the Board in November 2015, is currently being assessed and will be finalised in 2017:

1. The first avenue involves a backfilled and covered surface repository. Undoubtedly the easiest to implement since it is the least dependent on the underlying geological environment, this solution is very similar to that adopted by Andra at the Cires. The fact remains that such a solution should ensure containment of radionuclides and other toxic products in the long-term, and should be sufficiently robust to resist erosion, and have very little permeability to prevent dilution and diffusion of the radioactivity and of chemical pollutants to aquifers and the biosphere.
2. The second also plans a covered repository, but at a short depth in the old sulphur mine adjacent to the Malvési site, taking advantage of an existing cavity. This 40 m-deep pit, dug out of the very little permeable and reducing layers of the lower oligocene marl, is currently filled with water, probably from surface run-off. It will nevertheless be necessary to ensure the permeability of the future repository here, as much with respect to the said surface water as to that likely to be exchanged with the adjacent intra-oligocene aquafers, or with the karstic aquafers of the underlying jurassic limestone, the normal oligocene faults may just as well be used as preferred water drain.
3. The third, also aiming for disposal at a short depth in the little permeable but rather oxidant series of the upper oligocene, under a reworked cover, requires however excavation of a new hole. The first geological explorations (2 exploratory boreholes) and geophysical explorations (3 reflection experiment profiles) were able to control the lateral variations in oligocene layer thickness, of between 100 and 300 m in this part of the basin, and of which the low permeabilities were to constitute a natural barrier for chemical transfers. The existence of several normal faults obviously controlled the geometry of the centre of the basin and the compartmentalisation of the sedimentary series. It will therefore be necessary to consolidate the geological model at regional scale, in order to take account of the deep geometry of the fractures and potential exchanges between the Triassic salt layers, the mesozoic carbonate karstic reservoirs, the silico-clastic aquifers of the cenozoic series, and hydraulic recharge areas (La Clape and Corbières mountain) or resurgence areas (Montlaurès massif).

In addition to the modelling under way on the behaviour of the covers and fluids in the neighbouring area to the future repository, the Board recommends modelling of groundwater flow at a more regional scale, taking account of fault compartmentalization (drains or conducts), the mesozoic karsts and cenozoic aquifers.

2.8 LL-LLW

The June 2015 progress report by Andra covering the period 2012 to 2015 updates the inventory and the characteristics of LL-LLW, without making any major amendments to the types and quantities reported in the Board's reports 8 and 9. It also provides the first elements of the simplified calculations used to assess the safety of LL-LLW disposal under a reworked cover

(SCR) in the tile clay of the geological site currently being investigated. Two repository designs are planned, one as a tunnel and the other levelled from the surface down.

The radiological inventory of the LL-LLW (Appendix VII) is consolidated as waste producers continue measures. The difficulties establishing it evidently come from the low specific activity of the LL-LLW or low radiation energy emitted (20 Bq/g in ^{238}U or ^{232}Th, 60 Bq/g in ^{226}Ra on average).

Andra will have consolidated data in 2018 (graphite from the CEA, EDF sheathing). At that time a new, more accurate inventory of the radionuclides should be drawn up.

The reduction in radionuclide inventories, a consequence of the accurate measurements made and not the use of bounding values, is rather favourable to an SCR repository, or even to sending certain types of waste to other tracks. Other than the reduction in the waste radiotoxicity inventory, the effects of radiolysis are reduced, especially for asphalts (no hydrogen production) and only their long-term swelling under water remains a constraint.

For all that, R&D on waste processing and on characteristics should continue by focussing on the type of species they are likely to release in the long-term during disposal. In effect, it is the radioactivity-carrying species that need to be contained in near field conditions that are not yet properly defined. Interactions between waste salts (radiferous and asphalt nitrates and sulphates), cement and clay may affect migration of radioactivity-carrying species (Appendix VII). All of these studies are common with those conducted by Andra, for instance on the influence of salt released by packages on radionuclide migration in the clay, conducted on behalf of Cigéo.

The Board considers that the inventories for the radionuclides in LL-LLW should be consolidated and more accurately estimated. It would like to receive a summary table of long-lived radionuclide specific activities and total radionuclide activity of the various types of waste.

Andra carried out preliminary calculations of the molar radionuclide flow rates at the boundaries of the tile clay layer of the geological site currently under investigation for each type of waste. It considered a straightforward repository and put forward conservative hypotheses: carbon released at the rate of $5\ 10^{-6}$ to $5\ 10^{-3}$ per year is 30% in organic form and all the other radionuclides are labile and released immediately from the packages. The source term is either constant over a long period (20,000 years for ^{14}C) or decays over time in the other cases. The packages are 20 m from the clay roof (levelled repository) or 2 m (tunnel repository) and the lower clay barrier is 25 or 35 m for a layer of 55 m thick.

The chemical species transfer methods include diffusion in the cells (disposal packages, filling concrete, platform slab, tunnel arches) then to the surface and convection to the aquifer. The physico-chemical conditions in the cells and in the cover are oxidant and in the cells the cement materials are broken down. The undisturbed clay remains reducing. The values for the clay's permeability, diffusion coefficients and hydraulic gradient parameters are measured or estimated. Erosion of the clay surface, 10 m maximum, is taken into account up to 50,000 years, time compatible, according to Andra, with the necessary containment of radionuclides and prevision of the geological behaviour of the site.

The calculations produce orders of magnitude for release of radionuclides from the repository (^{36}Cl, ^{14}C, ^{99}Tc and ^{129}I) still below 10^{-3} mol/year, to the time it reaches the roof, and in the lower clay boundary (maximum at around 20,000 years) and the time after which they are all in the environment (50,000 years). These calculations show that the choice of disposal method, trenches or tunnels, is not really different. They also show the sensitivity of migration at the parameters used in the calculations (permeability, diffusion coefficients etc.) and in the disposal provisions (clay barrier thickness, waste grouping on platforms, role of the concrete etc.). The more the repository is reducing the more it will be containing. Finally they show what remains to be specified or otherwise studied: chlorine and graphite carbon release (block or powder), gas diffusion (radon, chlorine, CO_2) in the blanket, modification of the clay by salts, management of the redox potential in the cells etc.

On the basis of these results, Andra assessed the radiological impacts for the conventional scenarios of the safety analyses for geological repositories (see Appendix VII).

The results acquired on the behaviour of the radionuclides from this waste in sub-surface disposal in tile clay are as yet insufficient to support the calculations of the radiological impacts of a realistic safety analysis. The physico-chemical conditions which govern migration of the radionuclides should be specified and behavioural studies should be conducted in as similar conditions as possible. The Board strongly recommends that these studies be made more realistic.

In its opinion 2016-AV-264, the ASN agrees with the concerns the Board has been expressing for some years. It asks waste producers and Andra to take management measures and to set deadlines. The situation should become clearer in 2019.

The Board considers that the management of the various types of LL-LLW is far from being clear. The inventories and characteristics should be specified and a full list of existing waste and foreseen waste should be drawn up. Evaluation of the possibilities for processing the various LL-LLW should be fully carried out.

As it is, the Board believes LL-LLW should be managed by several tracks. The Board recommends that they be specified. In particular, the Cigéo reserve inventory should be defined for the construction application.

CHAPTER 3: PARTITIONING AND TRANSMUTATION

This chapter concerns the radioactive material and waste management programme as it is defined by the law of 28 June 2006. Article 3, paragraph 1, defines research on "partitioning and transmutation of long-lived radioactive elements". In this context, the CEA is developing the Astrid project, an industrial generation IV fast-neutron demonstrator. It plays upon the unique expertise acquired thanks to feedback from operation of the fast-neutron reactors (FNR) Rapsodie, Phénix and Superphénix.

Also, research bodies (CNRS, French universities and SCK-CEN in Belgium) are investigating the opportunities that could be offered by a thorium cycle and by coupling accelerators to reactors (ADS) in order to produce energy and transmute the long-lived radioactive elements (see Chapter 4: Fundamental research).

3.1 ASTRID: REACTOR AND FUEL PRODUCTION WORKSHOP (FPW)

3.1.1 Astrid project background

The Astrid project aims to reinforce the national independence strategy by opening the way to sustainable electricity production through an FNR electronuclear fleet. Indeed, irradiated nuclear fuel contains considerable quantities of uranium and plutonium, which are considered to be nuclear materials and not waste. In the case of uranium, the depleted uranium resulting from enrichment during production of UOx fuel covers largely the needs for a future FNR fuel fabrication. As for plutonium, plutonium oxide is added to uranium oxide to produce MOx fuel, the use of which was authorised in 22 reactors in the fleet by the ASN. Depleted uranium and plutonium would be used to produce FNR fuel. France has the necessary materials for the sustainable supply of a FNR fleet. Operation of such a fleet would no longer depend on importation of natural uranium nor enrichment in ^{235}U to produce the fuel.

The Astrid reactor (Appendix X) should meet a certain number of objectives to enable, at the right time, the decision to install a sodium-cooled FNR (FNR-Na) in the French fleet to be taken. Thus:

1. Astrid should reach a level of safety equivalent to that of the EPR and include elements from the analysis of the Fukushima accident.
2. Astrid should be able to use fuel combining depleted uranium and a high content of plutonium from treatment of spent UOx and MOx fuel. It should also demonstrate its ability to operate with its own multi-recycled plutonium (closed cycle).
3. Astrid should make it possible to study transmutation of actinides until the industrial process is eventually validated.
4. Astrid should demonstrate its ability to operate in sub-generator mode, that is to use plutonium to be able to consume the stock of plutonium when necessary.

The CEA, project owner, set up the project with the collaboration of fourteen French and foreign industrial partners: EDF, Areva, Alstom, Rolls-Royce, Bouygues, SEIV, CNIM, Airbus, Comex, Jacobs, Technetics, Velan, Toshiba, Mitsubishi group.

Following the reduction in planning, human and financial resources, allocated to the CEA/DEN and due to the necessity to develop test facilities, the CEA, in agreement with the authorities, changed the Astrid project schedule. This is why construction of the reactor is now scheduled to begin end 2022 / beginning 2023. The new deadline will especially enable the development of the Cheops platform, which will be used to develop and qualify the gas-based energy conversion system (ECS).

A new schedule was outlined in 2015. It is currently based on the following steps:

1. **End 2015**: synthetic dossier (specifications, cost estimate, project process), DOS (with sodium-water steam ECS) submission to the ASN, decision to go on to the detailed project phase (2016 – 2019) which becomes the reactor's "Basic Design" phase.
2. **From 2016 to 2017**: continuing studies on the gas ECS to bring them to the same level as those with the water-steam system end 2017.
3. **End 2019**: official set up of a construction consortium bringing together the Astrid project partners. The construction application (DAC) would be submitted in 2020. It is on this basis that the decision to go on to the "Detailed design" phase may be taken.
4. **End 2022**: after the ASN's assessment after processing of the DAC over two to three years (2020 to end 2022), construction authorisation decree and beginning of construction of Astrid which should last 7 years.
5. **2029**: divergence of Astrid.

Postponement of the provisional date of construction of Astrid appears to be mainly related to a temporary precarious financial situation for the Astrid programme that the Board has already indicated. The schedule is subject to further changes.

The Board recalls that Astrid is an essential step to introduction of the fourth generation FNR in France. It underlines that throughout the first half of the 21st century, no type of reactor other than a FNR-Na can be used to evaluate the industrial feasibility of the use of nuclear materials represented on the one hand by depleted uranium and on the other hand the plutonium and uranium contained in the spent fuel.

The change in the schedule does not fundamentally bring into question the Astrid project but is a new time-shift from the deadlines set out in the law of 2006. The Board draws attention to the fact that the delay should be managed and used to build on expertise and skills by continuing R&D.

The Board asks the CEA to present the new consolidated schedule and pluriannual financing plan for the Astrid programme.

3.1.2 Astrid technical features and options

The synthetic dossier compiled end 2015 by the CEA, for the end of the preliminary design phase, includes a full description of the Astrid plant with a safety file on water-steam energy conversion. It brings together all organisational, technical and scientific aspects of the Astrid project before going on to the preliminary design phase.

Choice of option reviews and "risks and performance" reviews backed the dossier which received contributions from three groups of experts from the CEA, Areva, EDF and Alstom. The main choices concern the nuclear boiler comprising highly innovative aspects and the Astrid FNR as defined today has no equivalent anywhere in the world.

At the end of the preliminary design phase, the main areas, which will be refined in the basic design phase, were studied in-depth; they are:

- development of the site planned in Marcoule and study of its constructability over 17 ha;
- reactor building structure;
- structure of the assembly handling halls;
- systems for preventing sodium-water-air reactions.

R&D will be developed during the basic design phase. As it is a gas Energy Conversion System (gas ECS), the DEN Scientific Council decided, on the basis of the results already seen, to continue studies on gas ECS until end 2017.

3.1.3 Gas ECS

This energy conversion system replaces heat exchange between sodium and water by heat exchange between sodium and gas, the gas chosen for Astrid being nitrogen. This system, if it is possible to use it at industrial scale, would prevent the risk of a sodium-water chemical reaction. Astrid would thus be a doubly innovative FNR. The main technological obstacle to be removed is the development of the sodium-nitrogen heat exchanger. Qualification of the components would begin during the basic design phase. Current R&D on Diademo should continue in Cheops. The other changes brought by the introduction of a gas ECS in Astrid's design can be made in the current state of technology.

3.1.4 Fuel

All phases of preparation of Astrid's fuel need to be managed on an industrial scale. Areva has been producing MOx for many years and the CEA has studied and succeeded in developing manufacture of Astrid fuel pellets containing 25% plutonium.

Today R&D covers the fuel cycle facilities and primarily concerns production of the first core and its recharges for the first decades of operation of Astrid. The fuel production workshop (FPW) should come into operation early enough to produce the first Astrid core in due time. The first core will be manufactured with plutonium from UOx spent fuel processing. Astrid's fuel has specific characteristics and an R&D programme has been ongoing for several years to optimise manufacture of the uranium oxide and plutonium-based ceramic.

The CEA and Areva have joined forces to be able to produce 61 experimental MOx pins containing 4,000 pellets between 2018 and 2019 (20 kg oxide of which 5 kg of Pu). In the absence of appropriate irradiation tools in France, an agreement with Russia provides for the first fuel assembly which should be qualified in the BN 600 reactor. The irradiated pins will be examined in Cadarache in 2024. Pellet manufacture feasibility is confirmed (300 pellets produced with 25% Pu). The Astrid core will require 25 t of U and 5 t of Pu.

Today it would appear that existing facilities could be adapted to allow for the production of fuel and their processing during the first operations in Astrid's industrial demonstration phases. This involves validation and implementation of large number of processes.

This strategy can be used to manage production of the first Astrid cores. Use of a closed cycle involving treatment of FNR spent fuel and production of new fuel will require significant R&D to be able to design and implement the new processes needed (see 3.2.1 and Appendix X).

The Board recommends unfailing support for all actions in order to ensure the simultaneous implementation of numerous operations such as those provided for in the "Basic Design". It considers R&D on the gas energy conversion system as a priority as it is a major innovation.

3.1.5 Structural materials and elements

R&D covers structural elements such as the cladding and hexagonal tubes for making the assemblies. This is how the first hundreds of cladding tubes, adapted to Astrid in austenite steel 15-15Ti, grade AIM1, were produced. In the same way, industrial manufacture of the hexagonal tubes, structural elements specific to this type of reactor and to the unprecedented dimensions is being studied not only to qualify manufacture, but also, from now, to identify and motivate industrial companies able to manufacture these objects in the future.

The CEA is looking into the possibilities of additive production (3D printing) of metal components in the nuclear field, which requires significant skills in modelling/scanning and engineering. The first applications of this technology led to the production of parts with complicated geometry planned for Astrid. A platform for developing R&D in this specific field has been set up.

The Board notes that manufacture of the elements necessary for the fuel assemblies is managed and that R&D for qualifying the assembly procedures at industrial scale is under way. It recommends securing industrial sectors.

3.2 RESEARCH AND DEVELOPMENT

3.2.1 Partitioning

a) Optimisation and extension of the current cycle

The CEA has optimised the Purex Process and has studied a set of molecules that can be used to partition all actinides in the spent fuel of thermal neutron reactors. Emphasis has been placed on partitioning of minor actinides after those of U and Pu. Today hydro-metallurgical processes can be used to separate each actinide for its forming in view of producing fuel for reactors or for transmutation where applicable.

These processes were developed as part of wide scale international collaboration during various Euratom joint programmes. This approach, which is mobilising a community of European researchers, has the double advantage of maintaining high level expertise and making it possible to validate the CEA's experience acquired by the same community.

Current projects developed at the CEA and in the frame of Euratom (Sacsess FP7) aim to identify the various parameters for conduct of the processes along with chemical processes such as radiolysis, hydrolysis, 3rd phase formation, likely to affect the safety of the facilities. Active experiences are conducted in Atalante (Marcoule) and in the Institute for TransUranium elements (Karlsruhe).

b) Future cycle design

The fuel cycle of a fleet containing FNR-Na will require scientific and technological breakthroughs concerning the treatment and recycling of U and Pu materials. The high plutonium content in the spent fuel, along with minor platinoids and actinides, will require the use of new processes to ensure a high industrial Pu recovery yield and safety of the reprocessing facilities. In the same way, partitioning and recycling of large quantities of americium, essential for ensuring its transmutation, will require the development of industrially-qualified processes. Adaptations to develop the processes of tomorrow should aim to streamline and reduce the number of operations, to get around oxidoreduction reactions and remove fine particles.

R&D should lead to a new reprocessing process.

The Board considers, given the extent of the challenges to be met as much fundamentally as technologically, that it is essential to launch a long-term R&D programme from today, to ensure industrial processing of FNR fuel assemblies.

3.2.2 Transmutation

In order to prepare the transmutation study in the Astrid reactor, a number of projects on preparation of high americium content fuel have been set up. It is essential for research to be conducted from today as manufacture of a pin, its transport authorisation, irradiation (currently in the HFR reactor in Petten – Netherlands), and post-irradiation examination take a considerable amount of time.

Building on its mastership of americium partitioning, the CEA is managing a European project, Pelgrimm, for the manufacture and irradiation of Am transmutation fuel in FNR-Na. Two types of actinide oxide fuel are being studied for homogeneous ($(U,Pu,Am)O_2$) and heterogeneous radiation on UO_2 medium ($(U,Am)O_2$).

Next to conventional fuels in pellet form, the project also concerns the study of fuels in microsphere forms. They would make it possible to streamline the production process by direct filling of the pin by the microspheres, and by improving behaviour under irradiation thanks to better accommodation of fuel swelling.

Specific programmes are supporting Pelgrimm.

- Marios for studying gas release and swelling of a $U_{0.85}\,Am_{0.15}O_{2-x}$ fuel at 2 irradiation temperatures (1000 and 1200°C) and 2 microstructures (porous and dense).
- Sphere for implementation of irradiation conditions for a $U_{0.75}\,Pu_{0.22}\,Am_{0.03}O_{2-x}$ fuel in the HFR reactor as close as possible to those planned in FNR-Na.
- Marine for studying a $(U, Am)O_{2-x}$ fuel in the same conditions as those in the Sphere project.

The various post-irradiation tests will be carried out in the Leca/Star facility in Cadarache.

The CEA is also developing bilateral partnerships for partitioning – transmutation:

- with the United States (DOE) for extractant selectivity, preparation and irradiation of fuel samples for transmutation (Futurix and AmBB in ATR),
- with Japan (JAEA) for the feasibility of pin preparation and irradiation, or even of a fuel assembly for Astrid,
- with the CCR-ITU for the production of samples for homogeneous and heterogeneous transmutation.

3.2.3 Conclusion and recommendation

R&D for americium transmutation is being developed at the CEA and also, for about ten years, in Euratom programmes mainly managed by the CEA, or even with bilateral national/international partnerships. The R&D supports that on FNR fuel. The pace is set by the availability of irradiation resources and facilities for examining irradiated samples.

The Board encourages R&D conducted by the CEA in the field of fuels for transmutation of americium in FNR.

This R&D imposes a long time scale, which may mask the logic of progression of experience. The Board asks the CEA to present a yearly dashboard showing the progress in the various experiments undertaken and the resulting programmes in the field of FNR fuels and transmutation fuels.

CHAPTER 4: FUNDAMENTAL RESEARCH

Upstream research in relation to the directions of the 2006 law on "the sustainable management of radioactive materials and waste" is essentially developed by the CEA, the CNRS, schools and universities, Andra, EDF and Areva, with or without partnerships. National partnerships are bi or multipartite and are set up as part of several framework agreements between organisations. In addition to these are European or International partnerships. The two main upstream research players remain however the CNRS and the CEA, the other organisations mentioned being supporting entities. Finally, other organisations such as the BRGM and the IRSN provide their support for this research.

All in all a wide academic community of French researchers (750 full time equivalent) is working in the field of electronuclear energy and especially on the partitioning and transmutation of long-lived radioactive elements and on disposal of high to intermediate level waste in deep geological formations.

4.1 CNRS UPSTREAM RESEARCH

The NEEDS challenge aims to improve the visibility and consistency of the various types of research undertaken at the CNRS, including in human and social sciences. Its ambition is to contribute to the creation of scientific programmes concerning nuclear energy and related environmental and societal questions. It is conducted in collaboration with the CEA, Andra, Areva, EDF, the BRGM and the IRSN. After its launch, Needs saw a restructuring phase. A collaborative council is arbitrating the budget and the scientific council directs and assesses research. The visibility of Needs was clearly affirmed in each of its 7 federating projects (see report no. 8, Appendix IX). The CNRS is a member of the Alliance Ancre, of the European platform SNE-TP and of the I2EN which brings together education and training to support the nuclear industry.

Each year Needs sets up open or predetermined projects on the basis of calls for tenders and has done since 2015. Between 2013 and 2015, the budget decreased by 40%. The yearly budget by federating project amounts to between 100 and 500 k€, half coming from the CNRS and the other half from its partners. It can only be used to launch start-up operations. It is also the CNRS's will to be upstream with R&D in the nuclear field.

Appendix XI describes in detail the research conducted by Needs in federating projects and those concerning two nuclear systems, the ADS and molten salt FNR.

Needs is in place until end 2017. Its future mainly depends on the financial backing it will receive. On the clear decrease, it runs the risk of reaching a budgetary limit below which it will be impossible to mobilise teams.

The CNRS is conducting research in keeping with the main national nuclear energy projects. The academic research laboratories involved in Needs constitute an important pool of researchers and university lecturers and researchers, essential to the training of future technicians, engineers and nuclear industry researchers. Needs is now structured to start and lead fundamental research projects in addition to the action by the other actors of the law of 2006.

The Board encourages the development of Needs actions and recommends that national research bodies and companies from the sector support them. Without this support, fundamental research in the nuclear field will decline, just at the time it needs to be reactivated to meet the challenges of the next decades.

4.2 CEA UPSTREAM RESEARCH

The CEA's upstream research for nuclear energy, in the broad sense of the term, covers a large part of the science in support of maintaining French nuclear power and if possible, its evolution towards a new generation of reactors and fuel cycle plants (see Appendix XI). It covers the main areas. It is conducted as part of a number of partnerships, between the CEA's divisions, with schools, universities, Areva and EDF; some are conducted as part of Needs. The CEA is contributing to European Euratom projects, often as a coordinator. The guiding and unifying line of the research supported on several platforms bringing together unique means, resides in the complementarity between multiscale experimentation and modelling. It enables the nuclear energy directorate (DEN) to develop highly innovative R&D for Astrid and future GenIV FNR, and to assert its expertise for the benefit of the many national and international partnerships.

However, the CEA had to make certain choices due to budgetary considerations. Therefore, certain areas of research have seen their resources significantly reduced (metal materials, fundamental actinide chemistry etc.) whereas the CEA has in France most of the appropriate facilities for working on nuclear materials and highly radioactive solutions.

Considering the ambitious future nuclear programmes stipulated in the law and entrusted to the CEA, the Board recommends strong upstream support for research essential to its implementation.

4.3 ICSM UPSTREAM RESEARCH

The separative chemistry institute in Marcoule (ICSM) is a four-party joint research unit (unité mixte de recherche – UMR) (Appendix XI) which occupies an additional research space to that of the CEA-DEN in Marcoule. Research covers immiscible solid/solution and solution/solution interface exchange dynamics upstream and downstream of the electronuclear cycle. It is at molecular mechanism level, well upstream of the processes, and opens the way to new areas as much in dissolution of refractory materials as in partitioning by liquid-liquid extraction widely used downstream of the cycle. The activity of the ICSM is compliant with the mission that was assigned to it when it was set up.

CHAPTER 5: INTERNATIONAL OVERVIEW

5.1 INTRODUCTION

This chapter describes the recent developments that occurred since the chapters on the international overview in previous reports were written. To this effect, we should recall that report no. 7 included an international overview which described the situation through to 2013 in detail. Report no. 8 especially focussed on the organisation of the management, financing and estimated cost for a geological repository and on the international approach to reversibility/recoverability. Report no. 9 analysed in more detail approaches concerning the cost of a geological repository and the problem of the decommissioning or release of dismantling materials.

Also, section 5.4 covers the conclusions of the Board's study tour to Poland, the Czech Republic and Hungary.

5.2 INTERNATIONAL SITUATION

5.2.1 International legal framework

Management of radioactive waste, and by extension the related E&R, come under both a national and international legal framework. The framework mainly includes:

- the Euratom Treaty, Article 37 (1957) which obliges each Member State to provide the [European] Commission with general data on any radioactive waste treatment projects;
- the Espoo Convention (1991) on evaluation of the impact on the environment (EIE) in a cross-border context;
- the international Ospar Convention (1992) on the prevention of marine pollution;
- the nuclear safety convention (1994), in order to reach and maintain a high level of nuclear safety;
- Directive CE/97/11 (1997) concerning the evaluation of the effects of certain public and private projects on the environment;
- the joint convention on the safety of management of spent fuel and radioactive waste (1997);
- the Åarhus Convention (1998) which governs public participation in decision-making processes and access to environmental justice;
- Directive 2011/70/Euratom on the management of spent fuel and radioactive waste;
- Directive 2013/59/Euratom setting out the basic requirements for health protection from hazards resulting from exposure to ionising radiation.

5.2.2 Research laboratories or geological disposal sites

a) Germany

The BfS (Bundesamt für Strahlenschutz) is in charge of the disposal of German radioactive waste, but The ultimate responsibility lies with the German federal government. Any progress in this area is however significantly perturbed by the opposition of the local 'Länder' governments and by a significant part of public opinion. A multidisciplinary commission on the disposal of highly radioactive materials, created as part of the 2013 law which regulates the methodology for choosing sites, suggested merging the parties concerned from the BfS, DBE (Deutsche Gesellschaft zum Bau und Betrieb von Endlagern für Abfallstoffe) and Asse-GmbH (which manages the Asse mine) into a new federal company, BfkEG (Bundes Gesellschaft für kerntechnische Entsorgung). BfkEG will be in charge of managing waste disposal, choosing the site and operating the repository, and of assuming the technical and financial responsibility.

To date, the programme plans to use the old iron mine in Konrad for storing low and intermediate level waste (non-thermal waste) and a site, as of now not yet selected, for the disposal of high level waste. Although the Gorleben salt dome site is not officially abandoned, it seems highly unlikely that it be selected due to strong local opposition and the accident which occurred in the Asse mine following inflow of brine which weakened the salt dome repository. A policy decision provides for the recovery of 120,000 barrels stored in the Asse mine. Recovery is contested as it is often considered as unrealistic. The analyses show that it would be in any case impossible to do before 2033. Pending an operational disposal site, reprocessing HL waste already in Germany is stored mainly in Gorleben. Packages remaining to be expatriated will be stored in different places. Spent fuel (SF) assemblies will be stored on site.

The cost of dismantling reactors and storing waste and spent fuel is estimated to be at least 36 billion Euros.

b) Belgium

To date there is still no approved political decision as to the geological disposal of long-lived high or intermediate level waste.

In order to study the thermo-hydro-mechanical impact of high-level waste on the properties of clay, the Praclay test has begun in a special scale 1 disposal cell, in the Hades underground laboratory in Mol. The clay of the test tunnel wall in 2015 reached a temperature of 80 °C. The temperature will be maintained for ten years, during which the properties of the clay will be measured i*n situ*, before dismantling and laboratory analysis.

c) Canada

The Nuclear Waste Management Organization (NWMO) is responsible for the long-term management of spent nuclear fuel. End 2015, SGDN chose four towns in the north of Ontario (Elliot Lake-town, Blind River-village and Manitouwadge and White River districts) where in-depth investigations will be carried out. SGDN considers that the site could be chosen in 2023 at the earliest and commissioned as of 2035. A construction application for a LILW waste repository in the deep geological formation in Kincardine was submitted by Ontario Hydro and it is currently being evaluated by the public authorities. The Ministry of the Environment has recently requested additional studies.

d) China

An underground laboratory is expected to be set up in granite in Beishan, in the Gobi desert, in around 2020. It will be operated for 20 years. Another research site is planned in clay. A disposal site should be constructed by 2050.

e) United States

Pending selection of one or several final disposal sites, the regulator (NRC) decided that the long-term and dry intermediate storage of spent fuel, for several decades, was a reliable and safe solution. This is the interim option that will be implemented in the USA. Therefore, Waste Control Specialists (WCS), a Texan firm processing and storing radioactive or hazardous waste, has signed an agreement with Areva for the design, construction, operation and maintenance of a temporary spent fuel storage facility (CISF) in Texas. Areva would also transport the fuel to the facility. The CISF capacity is believed to be 40,000 tonnes.

In 2015, the Chairman authorised the DOE to plan a specific disposal site for military high level waste. The DOE's approach will be based on a societal consensus, as proposed by the "Blue Ribbon Commission".

The DOE also indicated that the disposal of certain specific waste in deep boreholes (5,000 m) could offer an alternative to disposal in tunnels, even if this approach is not foreseen for most of the spent civil fuel. A site (Rugby in North Dakota) for experimental excavation is currently being selected.

Before the accident in the Wipp in 2014, where a barrel opened following an exothermic reaction caused by chemical incompatibility between the radioactive materials and organic absorbents, the Wipp was planned to close in 2030. The new plan is to reopen the Wipp end 2016 for an estimated cost of $500 million. Its closure is planned by 2055.

f) Finland

As a reminder, after review of the construction application submitted by Posiva in 2012, the Stuk safety authority informed the government in 2015 that the "plant for encapsulation and installation of a repository for spent fuels, as proposed by Posiva, can be built in ensured safety conditions ". The formal decision by the Finnish government to issue a building permit for an initial capacity of 6,500 tonnes of spent fuel (SF) came in November 2015. Construction, based on the existing facility in Olkiluoto, is due to start in 2016. The operating licence application is expected end 2020 in order to begin operation for around a one-hundred year period. The total cost is estimated at €3 billion. As a reminder, the SF repository design is the same in Finland as it is in Sweden. A reinforced cooperation agreement was concluded beginning 2016 between Posiva and SKB (Sweden). The agreement provides for the possibility of developing, building and delivering container components and bentonite as part of a partnership.

g) France

As a reminder, studies and research are continuing in the underground laboratory in Bure. A fatal accident, when the wall of a tunnel under construction collapsed, sent the community into mourning. The DAC is to be submitted in 2018.

h) India

No site has been selected to date. The Bhabha Atomic Research Centre (BARC) is continuing research.

i) Japan

Two 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 out of the 1,000 m expected has been reached. In the Horonobe laboratory, an experiment for studying THM properties at scale 1/1 is planned at -350m.

Numo also introduced the Care concept (Cavern Retrievable), including two phases: intermediate storage of HL barrels, fully retrievable from a ventilated cavern, followed by final sealing after 300 years. The first phase makes it possible to reduce the thermal load and to significantly increase waste filling density in the final repository.

The Government recently decided to preselect areas potentially suitable for a repository, before beginning discussions with the local communities concerned.

j) Netherlands

The country has two potential host rocks, salt and clay. Disposal is planned after 100-years intermediate storage. A policy decision on a choice of site is expected shortly.

k) United Kingdom

The United Kingdom's programme is based on the government's document, "Implementing Geological Disposal", dated 2014. It includes three actions to be taken before the site selection process:

- national inventory of potentially-appropriate geological areas;

- decision to accord the status of national infrastructure to the geological disposal facility;
- development of the framework enabling communities to be represented and to participate in site selection.

The Radioactive Waste Management Directorate (RWMD), subsidiary of the Nuclear Decommissioning Authority (NDA) will be selecting the site and managing subsequent steps.

l) Russia

NO RAO, national operator for the management of radioactive waste (Национальный оператор по обращению с радиоактивными отходами, НО РАО), manages Russian waste and SF. It plans to build an underground laboratory (- 500 m) in Yeniseysky, region of Krasnoyarsk, in the Nizhnekansky granite massif. A decision concerning construction of a deposit is expected in around 2025. At the same time, Russia is still planning the possibility of injecting certain waste solutions in the subsoil.

m) Sweden

The authorisation process for a deep geological disposal facility in Forsmark is ongoing since 2011. The SSM safety authority has just issued a first favourable opinion for the choice of a site in Forsmark and for the encapsulation facility to be built in Oskarshamn. SSM, and the environmental court, will submit their final opinions to the government in 2017. The final decisions by political bodies, the communities concerned and the government will ensue. Early 2016, the environmental court announced its decision to consider SKB's application for 12,000 tonnes of spent fuel as eligible, for the public hearing planned early 2017.

n) Switzerland

Nagra is continuing studies in two regions: East Jura and North East Zurich. The two sites appear to be able to house both disposal facilities for LILW, HL and SF, along with the required surface facilities. The sites are going to be studied in more detail and in around 2020, Nagra will make a preliminary selection for an implantation site. The dossier for the final site selection by the federal council is expected by 2027. It should be approved by the Parliament and will be subject to an optional referendum in around 2029. The deep deposit for low and intermediate level waste will probably be commissioned in around 2050 and that for high level waste in around 2060.

5.2.3 Fast spectrum sources

a) Germany

The FRM II reactor in Garching (2004 - …), 20 MWth, enables fast spectrum irradiation.

b) Belgium

The BR2 (1963-2036?), 120 MWth, test reactor can be used to irradiate small (diameter 1.5 to 3 cm x h=80 cm) and large samples (diameter 8 to 22 cm x h=80 cm) in fast neutron spectrum, such as for a FNR fuel sub-assembly.

c) China

The sodium cooled CEFR 65 MWth (20MWe) test reactor was commissioned in July 2010. Since it has been stopped over long periods. In December 2014, the CEFR operated at full rating for three days.

d) United States

The United States does not have any available fast spectrum sources.

e) France

Since Phénix was stopped, there are no more fast spectrum reactors in France. The Jules Horowitz test reactor, in construction, will be used to irradiate a small volume at high flux in a fast spectrum. It is due to be commissioned in 2019.

f) India

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

g) Japan

The Jōyō reactor appears to have stopped indefinitely and following incidents and the consequences of the Fukushima accident, the government decided to stop the Monju project. Following failure of certain tests, the Japanese regulator, NRA, asked the Government to find a new operator for this reactor. It is very little likely that the two reactors will be able to start again one day.

h) Netherlands

The HFR (1961-2024) in Petten allows limited fast spectrum irradiation.

i) Russia

The Bor-60 (1969-2020) of 60 MWth is a sodium-cooled test reactor. The characteristics of the fast spectrum power reactor BN-600 (600 MWe) would be suitable for qualifying the Astrid reactor fuel.

5.2.4 Main activities on the ADS

ADS (Accelerator Driven Systems) are offered as alternatives to fast critical reactors for the transmutation of actinides found in the waste deriving from spent fuel reprocessing.

Unlike electricity-generating fast neutron reactors, the core of an ADS reactor is subcritical. In order to maintain the chain reaction, external neutron supply is required. To this end, the beam of a high power proton accelerator is directed to 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 nuclei of the target create a high intensity fast neutron source, able to maintain and manage the chain reaction in the core.

a) Germany

The Karlsruhe Technology Institute (KIT), the Institute of Applied Physics at Frankfurt University (IAP-FU) and the Helmholtz Zentrum Dresden Rossendorf (HZDR) are participating in the Belgian Myrrha project.

b) Belarus

Belarus has developed an experimental ADS programme by building the Yalina (low power and thermal spectrum) and Yalina-Booster (moderate power with central fast spectrum zone) subcritical assemblies, used since 2005 in international physics validation programmes for ADS cores.

c) Belgium

The Belgian Nuclear Research Centre, SCK•CEN, has been developing the Myrrha (Multi-purpose hYbrid Research Reactor for High-tech Applications) project since 1998. Myrrha will be a hybrid multifunctional test facility using a liquid metal-cooled (lead, bismuth), subcritical fast neutron reactor controlled by a proton accelerator.

The project will take place in three phases:

1) a linear accelerator of 100 MeV and 4 mA and related scientific facilities for 2024;
2) increase in accelerated proton energy up to 600 MeV;
3) reactor construction, including the spallation source.

The Guinevere project for a very low power test reactor based on the accelerator-controlled Venus reactor was completed successfully. The accelerator was built by the CNRS and the CEA provided the fuel. Guinevere operated both in critical and subcritical mode with fast neutrons.

d) China

The Chinese Academy of Sciences (CAS) has decided to build an ADS for transmutation research. To this end, a partnership agreement was signed in 2016 by the CAS with the China General Nuclear Power Corporation (CGN, formerly China Guangdong Nuclear Power Holding Group), partner with EDF for the EPR reactors being built in Taishan. The road map plans a test facility followed by a 80-100 MWth ADS and a 1000 MWth demonstration facility. The proton accelerator will be combined with a molten salt-cooled subcritical fast neutron reactor.

e) South Korea

The Nutreck Institute (Nuclear Transmutation Energy Research Center of Korea) and the Seoul National University (SNU) are developing a programme based on the transmutation of minor actinides by ADS and reprocessing by pyrochemistry.

f) United States

The Department Of Energy (DOE) and national laboratories (Oak Ridge, LANL, ANL, Jefferson Lab, Fermi Lab …) are interested in ADS.

g) France

As a reminder: the CNRS and, to a lesser extent Areva and the CEA, are working together on the Belgian Myrrha project.

h) India

The ADS programme, started in 2000, was intended to fast-track setting up of the thorium cycle by the production of fissile uranium 233, from non-fissile thorium 232. More recently, the Bhabha Atomic Research Centre (BARC) placed the emphasis on the potential role of ADS for burning minor actinides from reprocessing as subcritical fast reactors are believed to be more effective than critical FNRs.

i) Italy

Several research centres (ENEA, INFN, CRS4, etc.), universities (Cirten) and industries (Ansaldo Nucleare) are participating or have participated in European projects on ADS. The Legnaro INFN is proposing to build an ADS based on a cyclotron producing a 70 MeV and 0.75 mA proton beam. The spallation source would be a beryllium target, the ensemble being helium-cooled. The 150-200 kWth subcritical reactor fuel is believed to be UO_2 enriched to 20% in a lead matrix.

j) Japan

The Omega project, started in 1988, concerns E&R in minor actinide separation-transmutation, in order to reduce the footprint of a disposal site. It includes construction of ADS. The current road map provides for TEF-P with a subcritical low power spallation target burning MOx; TEF-T with a high power target but no subcritical MOx core; a test ADS of around a hundred MWth (national or in international partnership); an 800 MWth industrial ADS.

5.3 EUROPEAN PROJECTS FROM THE 7TH FRAMEWORK PROGRAMME AND H2020

5.3.1 Geological repository

An overview of projects ongoing in 2015 or 2016 is presented.

- Cebama[1] As the cement is used to immobilise waste in barrels, as container, tunnel structural elements, plugs and other things, the transport properties in the cement and at the cement interfaces, host rock or bentonite, should be studied and modelled.
- Dopas[2] The project aims to improve the industrial feasibility and performance of the plugs and seals to be used in disposal facilities in the host rock studied (clay, crystalline and salt). Five tests have been set up in France, Sweden, Finland, Germany and the Czech Republic. They are used as demonstration and their characteristics are studied.
- IGD-TP[3] The European technology platform IGD-TP on the geological disposal of nuclear waste is the result of the work started during the 6th Framework Programme. A guide describes the mission, objectives, services provided by and organisation of the platform. It also summarizes the technical measures to be implemented over the next 10-15 years to apply the geological disposal of nuclear waste by the Member States.
- Joprad[4] The purpose of Joprad is to establish a joint schedule for work at national level on the disposal of radioactive waste, there where synergies have been identified.
- Mind[5] The project aims to quantify the impact of microbial activity on geological repository safety.
- Modern 2020[6] The project aims to design and implement a monitoring programme in disposal facilities, based on safety requirements. The project will take account of national specificities (inventory, host rock, designs, legislation etc.). Special attention will be paid to understanding of the expectations of stakeholders, especially those of local populations.
- SIT EX-II[7] The project aims to develop a sustainable European network to improve the understanding, the harmonisation and collaboration between regulation bodies, technical safety organisations and waste management agencies.

5.3.2 New partitioning – transmutation channels

Transmutation strategies mainly rely on fast neutrons, either in critical systems or in subcritical systems (ADS).

An overview of projects ongoing in 2015 or 2016 is presented.

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[1] Cement-based materials, properties, evolution, barrier functions, 2015-2019, Horizon 2020, 11 pays, 27 participants including the BRGM, the Association for the research and development of industrial methods and processes, University of Lille, Andra and the RSN.

[2] Full-scale Demonstration Of Plugs And Seals; 2012-2016, 8 countries, 14 partners including the Andra.

[3] European technology platform IGD-TP on the geological storage of nuclear waste, founder members: waste management organisations in Belgium (ONDRAF), Finland (Posiva), France (Andra), Spain (ENRESA), Sweden (SKB), Switzerland (Nagra), UK (CND) and the German federal ministry for the economy and technology (BMWi). IGD-TP currently counts 107 members in 24 countries.

[4] Joint Programming on Radioactive Waste Disposal, 2014-2018, Horizon 2020, 5 countries + EC, 10 partners including the Andra (coordinator), IRSN, CNRS and Mutadis.

[5] Development of the safety case knowledge base about the influence of microbial processes on geological disposal of radioactive wastes, 2015-2019, Horizon 2020, 9 countries, 15 partners.

[6] Monitoring Developments for safe Repository operation and staged closure, 2015-2019, Horizon 2020, 12 countries, 28 partners, including the Andra (coordinator), IRSN, Areva, EDF-DTG and XLIM.

[7] Sustainable network of independent technical expertise for radioactive waste disposal, 2015-2017, Horizon 2020, 10 countries, 17 partners, of which the IRSN (coordinator), the European nuclear safety training and tutoring institute, Mutadis consultants, ASN and the Symlog Institute.

As a reminder:

- Alfred is a lead-cooled fast reactor prototype project.
- Allegro is the gas coolant fast reactor prototype project, described in more detail in the relevant section.
- Astrid is the sodium coolant fast reactor prototype project, of a power of 600 MWe, managed by the CEA.
- Esnii concerns technology demonstration requirements for fast reactors defined in Gen-IV. Esnii also concerns research infrastructures, fuel production and any research required for that purpose.
- Esnii Plus[8] The aim of the transversal project is to develop a strategic approach to support the sustainable industrial European initiative (Esnii).
- GIF/GEN-IV[9] The initiative by the Generation-IV forum aims for the development of new types of reactors, among which fast reactors producing a minimum of waste. In a sustainable development perspective, new technologies should also help minimize the risks of proliferation. Australia has just joined the forum.
- Marisa[10] The project aims to provide the Myrrha project with the necessary level of maturity for starting construction. In particular, the project supports the engineering for Myrrha, coordination of the R&D programme, setting up of the international consortium, operational management and preparation of the construction application process. A road map will be developed, identifying Myrrha's contribution as European fast neutron research facility contributing to closure of the fuel cycle.
- Matisse[11] The project brings together several R&D organisations having established, as part of the "European Energy Research Alliance" (EERA) initiative, a programme called the "Joint Programme on Nuclear Materials (JPNM)" for better coordination of national initiatives, European programmes and any private-public or transnational partnerships. The project work programme includes actions, coordination activities and priority R&D actions to support the JPNM.
- Maxsima[12] Further to the recommendations of the SNETP SRA concerning the development of the ADS in Europe, and especially the Myrrha project, the project concerns safety studies in normal conditions and incidental and accidental conditions useful for licensing. Analysis of serious accidents likely to lead to fuel cladding rupture will be carried out. The problems with heat exchanger tube rupture and propagation of the consequences of such an accident will be studied. Safety transient tests on MOx fuel segments are planned in the test reactor in Romania.
- Myrrha[13] The project aims to build a hybrid multifunctional research facility based on a subcritical fast reactor driven by a particle accelerator and cooled with liquid metal (lead-bismuth). Myrrha should demonstrate the feasibility of the coupling between the accelerator, spallation source and subcritical reactor in a pre-industrial facility. The fast spectrum flexible irradiation tool will offer fast reactor communities (SFR, LFR, GFR) a machine for testing materials and fuels.
- Myrte[14] The project concerns the research necessary for the development of Myrrha in order to demonstrate the industrial feasibility of minor actinide transmutation in HL waste.

[8] Preparing ESNII for HORIZON 2020, 2013-2017, 7th RDFP, 14 countries, 36 partners including the CEA (coordinator), Areva, EDF, Lagrange and Nuvia Structure.
[9] Generation IV International Forum; 2001- ?, Euratom + 12 countries including France.
[10] Myrrha Research Infrastructure Support Action, 2013-2016; 7th RDFP, 9 countries and 15 partners including the CEA, the CNRS, Areva and ACS.
[11] Materials innovation for safe and sustainable nuclear energy, 2013-2017; 7th RDFP, 13 countries and 28 partners including the CEA, the CNRS, EDF and LGI Consulting.
[12] Methodology, Analysis and eXperiments for the "Safety In MYRRHA Assessment, 2012-2018, 7th RDFP, 8 countries and 13 partners.
[13] Multi-purpose Hybrid Research Reactor for High-tech Applications; 1998-2024, collaboration with Eurotrans partners including the CNRS, the CEA, Areva, Advanced Accelerator Applications and ENEN.
[14] MYRRHA Research and Transmutation Endeavour, 2015-2019, Horizon 2020, 9 pays, 27 partners including ACS, CNRS, Thales and the CEA.

– Pelgrimm[15] In order to support the strategic agenda of the SNE-TP, the project concerns the development of fuels containing minor actinides for fast reactors. As well homogeneous recycling in the core itself as heterogeneous recycling in the blanket are studied.
– Sacsess[16] In accordance with the SRA strategic agenda of SNE-TP, Sacsess will provide a structured framework in order to optimise the fuel cycle related to the S&T. Safety studies should identify any currently weak points. A teaching and training section is included in the project.
– Samofar[17] The aim of the project is to demonstrate the excellent safety characteristics of molten salt reactors and to ensure that a suitable consortium can build it.
– Sesame[18] The project attempts to improve metal liquid coolant reactor safety (Astrid, Alfred, Myrrha, etc.) by providing new safety test data and by improving digital approaches. It should enable the development of systems which meet more appropriate standards, while improving safety culture.
– SNE-TP[19] The European technology platform on sustainable nuclear energy proposes a vision of the development of nuclear fission energy technologies in the short, mid and long-term. It proposes the development and implementation of potentially sustainable nuclear technologies, including the management of all types of waste. The platform also proposes extending the use of nuclear energy beyond electricity production, especially for hydrogen production, heat generation and seawater desalination. The platform prepared the European industrial initiative "European Sustainable Nuclear Industrial Initiative" (Esnii), including the two Astrid and Myrrha, as well as the Alfred and Allegro projects.

5.3.3 Low doses, radioprotection

– Melodi[20] The platform is dedicated to research on low dose risk. The purpose of Melodi is to propose research priorities for 2020, to inform parties concerned on the progress in research and to disseminate knowledge.
– Operra[21] The project aims to set up a legal and logistic coordination structure for managing future European calls for tenders in radioprotection.

5.3.4 Teaching training, knowledge management and societal aspects

– Alice[22] The project is a coordinated effort between European and Chinese partners to develop transnational access to large material research infrastructures, in particular irradiation facilities.
– CINCH-II[23] The project is the continuation of the CINCH-I project, which finalised a long-term sustainable strategy for chemistry teaching in the nuclear sector and a road map for its implementation. Among other things, CINCH-II aims to develop and implement a EuroMaster and European training passport in chemistry for the nuclear sector.

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[15] PELlets versus GRanulates: Irradiation, Manufacturing & Modelling, 2012-2015, 7th RDFP, 9 countries, 10 partners, including the CEA (coordinator), EDF, Areva, Lagrange and the European network for teaching of nuclear sciences.
[16] Safety of actinide separation processes, 2013-2016, 7th RDFP, 13 countries, 26 partners, including the CEA, the IRSN, the CNRS, the University of Strasbourg and Lagrange SARL.
[17] A Paradigm Shift in Reactor Safety with the Molten Salt Fast Reactor, 2015-2019, Horizon 2020, 7 countries, 11 partners including the CNRS, IRSN, Areva, CEA and EDF.
[18] Thermal hydraulics Simulations and Experiments for the Safety Assessment of Metal cooled reactors, 2015-2019, Horizon 2020, 9 countries, 23 partners including the CEA, LGI Consulting and IRSN.
[19] The European Technology Platform on Sustainable Nuclear Energy; 2007- ?, ≥19 countries, > 60 members including the CEA, the IRSN, the CNRS, Areva, EDF Research and Transmutation Endeavour, 2015-2019, Horizon 2020, 9 countries, 27 partners including ACS, CNRS, Thales and CEA.
[20] Multidisciplinary European Low-Dose Initiative, 17 countries, 30 partners including the CEA and IRSN.
[21] Open Project for European Radiation Research Area, 2013-2017, x countries, 66 partners including the IRSN (coordinator), Melodi, CEA, Université Paris Descartes, Mutadis Consultants, CEPN, CIRC, InVS and NERIS.
[22] Access to Large Infrastructures in China and Europa , 2012-2016, 7th RDFP, 5 countries, 5 partners, including the CEA.
[23] Cooperation in education and training In Nuclear Chemistry; 2013-2016, 7th RDFP, 7 countries, 11 partners including the CEA

– Eagle[24] The project will help to better define and disseminate good objective information and communication practices concerning the risk of ionizing radiation.

5.4 STUDY TOUR

The Board went on a study tour to Poland, the Czech Republic and Hungary from 21 to 30 September 2015. The tour aimed to:

1) appreciate the progress of the Allegro project lead by the countries from the Višegrad group (Poland, Hungary, Czech Republic, Slovakian Republic);
2) to assess the dynamics of research conducted by Poland, the Czech Republic and Hungary in view of disposal of their nuclear waste.

5.4.1 Allegro

a) FNR-G experience

In 2002, fast neutron reactors (FNR) with gas coolant (FNR-G) showed promising potential for reaching Generation IV FNR objectives according to the Generation IV International Forum (GIF). The GIF believed that FNR-G could be developed by 2020. In the SNE-TP's (Sustainable Nuclear Energy Technical Platform) 2009 *Vision Report*, FNR-G like lead-bismuth cooled FNR (RNR-Pb) were alternatives to sodium-cooled FNR (RNR-Na) that needs to be looked into. In 2010, the Esnii (European Sustainable Nuclear Industrial Initiative) initiative by the SNE-TP brought together industrialists and research bodies around an action plan for the construction of technological demonstrators: Astrid for FNR-Na, Allegro for FNR-G and Alfred, along with Myrrha, for FNR-Pb. However in its last agenda (Strategic Research and Innovation Agenda, February 2013), the SNETP redefined Esnii's objectives which should focus on studies relating to the Astrid (FNR-Na) and Myrrha projects so they can be operational by 2025. In the latter strategic agenda, FNR-Pb are seen as an alternative to FNR-Na, credible in the relatively short-term, whereas FNR-G are only foreseeable in the long-term.

b) FNR-G objectives

FNR-G aim to produce electricity and provide high temperature fluids, at around 850 °C. The preferred gas coolant is helium (He). Helium is chemically inert, transparent in light, regardless of temperature and pressure. Helium cannot be activated by neutrons. However this gas is a poor coolant due to its low density and low heat capacity. To ensure the safety of FNR-He in all circumstances, the best compromise between the density of the core power (which depends on the fuel), the pressure of the primary circuit helium (several tens of bars) and core and structure materials needs to be found. As the heat capacity of gaseous helium is clearly lower than that of liquid sodium, the fuel needs to be as dense as possible. This is why U/Pu carbide is planned to be used as fuel in the long-term. In effect, uranium and plutonium oxide blends (MOx) would only bring helium to a maximum temperature of 560 °C.

Also, to ensure the production of high temperature fluids (850 °C), the fuel cladding has to resist up to 1,100 °C in normal operation and, in the event of the loss of the primary circuit, make up for the reactor's lack of heat inertia, which may bring the temperature to 1,600 °C. The two major obstacles to be removed are therefore demonstration of safety according to the power and design of the fuel and assembly elements.

[24] Enhancing educAtion, traininG and communication processes for informed behaviours and decision-making reLatEd to ionizing radiation risks, 2013-2016, 8 countries, 11 partners including the IRSN and the Symlog Institute.

c) The CEA's Allegro design

In France, the atomic energy committee recommended in 2005 that priority in R&D be given to FNR-Na and to FNR-G. The CEA had already conducted studies on FNR-G as part of the GIF, studies that it continued as part of European programmes (5th and 6th RDFP, GoFastR programme etc.). Until 2008/2009, the CEA invested significant means which enabled it to define the initial characteristics of the experimental Allegro reactor. The CEA's main results are gathered in its 2012 report submitted to the Government as part of the 2006 law. The figures presented below derive from this report.

FIGURE 7 : VUES DU CIRCUIT PRIMAIRE ET DE SON INTÉGRATION DANS L'ENCEINTE RAPPROCHÉE

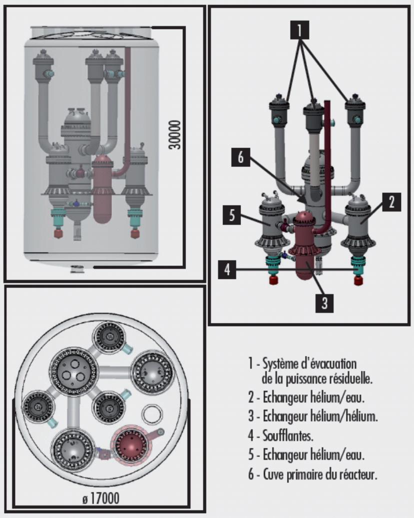
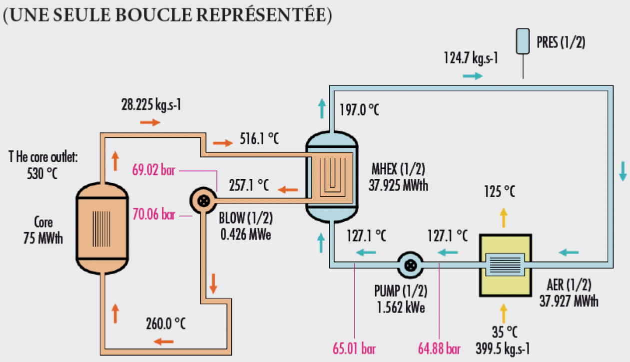


FIGURE 9 : PRINCIPAUX PARAMÈTRES DES CIRCUITS PRINCIPAUX DE REFROIDISSEMENT DU CŒUR ALLEGRO (UNE SEULE BOUCLE REPRÉSENTÉE)



As in the reactor planned for the industrial sector (2,400 MWth), the entire primary circuit is contained in a leak tight metal closed enclosure. Its function is to ensure fold pressure in the event of leakage from the primary circuit, which may be combined with nitrogen injection.

The MOx start-up core is believed to have a 30% plutonium content. In the long-term, it was planned to set up a UPuC carbide core with 30% plutonium content. The CEA 2012 report presents the advantages in terms of fuel assembly for ensuring the safety of a FNR-G and Allegro design, which would be the demonstrator. If a MOx core ($UPuO_2$/Ti 15-15 stainless steel cladded pins) is easy to see implemented, it is not the same when applied to a UPuC core with SiC/SiC cladded pins, essential however to bring the helium to 850 °C.

d) The V4G4 project

In 2010, following the proposal by the CEA, three central European institutes signed a MoU (Memorandum of Understanding) to study together the development and conditions of installation of Allegro: MTA-EK for Hungary (fuel), VUJE for Slovakia (design and safety) and UJV for the Czech Republic (reactor physics, He technology). The Polish institute NCBJ joined this consortium in 2012 (industrial applications for high temperature nuclear heat). An Allegro project Steering Committee (ST) was thus set up with representatives of the bodies. The CEA belonged to it as promoter of the FNR-G design in the GIF and of the Allegro design and ensured technical support of the project by transferring its knowledge to the consortium. This set-up enabled the members of the consortium to receive financial backing from European cohesion funds. The European Alliance programme (Preparation of Allegro - Implementing advanced nuclear fuel cycle in central Europe – FP7 Euratom -2012-2015) started on that date with the ambition of continuing the CEA's work until the technical and administrative formalities have been accomplished for starting Allegro. Six institutions from 4 countries in central Europe participated in it in addition to the CEA and the IRSN for France and the INBK for Germany.

In 2013 the CEA gave priority to R&D on FNR to Astrid. The Allegro Steering Committee created a centre of excellence for research on Allegro, called V4G4 (4 Višegrad countries) and R&D responsibilities were specified. Therefore MTA-EK in Hungary is in charge of R&D on the fuel and its qualification, VUJE in Slovakia R&D on the safety design, UJV in the Czech Republic R&D on He technology and NCBJ in Poland R&D on materials. The objective of V4G4 (2014-2020) is, in addition to advancing R&D on the difficult points of the FNR-G and on Allegro, to compile dossiers for obtaining European financial backing but above all for increasing national financing and appointing the country which will accommodate the reactor prototype. In this perspective V4G4 is working as part of the regional Vinco (Višegrad Initiative for Nuclear Cooperation, 2015-2018) project which succeeded Alliance. Concerning the financial backing, Allegro is only eligible for European funds if Allegro is on ESFRI's (European Strategy Forum on Research Infrastructure) road map.

e) Outlook

Several working groups have been set up to discuss the various R&D themes, one of which is in charge of preparing a new Road Map. In 2015 V4G4 defined highly detailed phases of progression for the Allegro project and the action to be carried out by each partner, according to its skills, and gave a new direction for the first core: low power, highly enriched uranium core. 2015/2016 covered the preliminary phase for the technical specifications and safety objectives. The schedule of tasks identified stretches to 2025, date at which it will be time to choose the main options and perform a preliminary safety analysis. The project will only be in the preliminary design phase in 2025.

The Board understands that the Allegro project is still in a design phase; safety issues and technological obstacles have been identified. The Board is aware of the immense R&D effort that is now necessary to attain the ambitious Allegro objectives assigned to it by V4G4.

These reactors were intended to be built in a far off future on a market open to electric and high temperature thermal energy.

The Allegro reactor will only be the first step to FNR-G. FNR-G will not be available for industrial use for a long time.

5.4.2 Waste intermediate storage and disposal in geological repositories

a) Poland

Following an agreement between Russians and Americans to fight nuclear proliferation, the spent fuels from the Maria test reactor are sent to Russia.

- **LL-LLW intermediate storage & disposal**

LL-LLW is currently stored in Rozan, over 3 ha, in an old fort, closed in containers placed in sealed tunnels. Short-lived waste is buried in trenches with concrete base and sides, with cement and bentonite between the barrels and cement and asphalt at the top.

The Rozan site has been in activity since 1961, but should close between 2024 and 2029. It will then be monitored for 300 years. As the Rozan site capacity is almost full, a new site is being studied.

♦ **Site selection for long-lived waste**

Exploration work for a deep geological repository does not really appear to have begun, as construction of an underground laboratory is planned for 2035, with the site actually coming into operation from 2070.

Several types of geological environment appear to be studied, without any obvious priority at this stage between the layers or domes of the Permian salt (3 potential identified sites), granites from the NE of the country like in Finland or in Sweden, or clays (layers 300 m thick already identified).

b) Czech Republic

♦ **LL-LLW intermediate disposal**

LL-LLW is currently stored in Litomèřice, on the hillside in underground tunnels dug into a layer of limestone 4 to 5 m thick between the impermeable clay layers, in a sediment basin North of Prague. The Richard quarry, which accommodates the repository already under way, was operated from 1864, then used from 1937 and also during the German occupation as war material construction factory, before being operated by Lafarge cements until 1957.

The tunnels were converted into a disposal site between 1962 and 1964, the LL-LLW repository being operational since 1965. The average temperature is 10°C, with hygrometry of 75 to 95%. The three quarters of the volume available for the repository are already occupied.

♦ **Site selection for LL-HLW**

Spent fuel is currently in dry storage near to plants.

The Czechs are looking for a deep disposal site (around 500 m from the surface) in granite. After contacting the towns concerned, 5 sites have already been preselected out of the 7 initially proposed. The purpose of the on-going exploration work is to only have 2 in 2020, and to be able to choose the final site from 2025.

Before starting excavation work on the actual site, an underground laboratory is first due to be built in 2030. Construction of the repository should begin in 2050.

c) Hungary

♦ **LL-LLW and intermediates**

The site in Bátaapáti, in the south of the country, 190 km from Budapest, is already up and running.

Dug in granite, it has 2 service tunnels leading to large diameter disposal tunnels and chambers dug 200-250 m under the ground surface. The initial plans provided for 17 tunnels, but hydrology studies in progress (especially thanks to 4 horizontal exploration wells), meant certain sectors of the granite massif had to be abandoned as having a too high fracture permeability.

The 6 chambers currently available or being finalised are hundreds of metres long, and would appear to suffice for disposal of all LL-LLW. The site has areas into which it can be extended further.

The surface facilities are in a woody small valley and are barely visible, the site as a whole being remarkably set into the landscape.

- **Site selection for LL-HLW**

Spent fuel is currently in intermediate dry storage in 5 modules on the Paks plant site. Four other modules are being built. Intermediate storage should last around fifty years, and be followed by disposal in a deep geological site, the construction of which should begin in 2055 for commissioning in 2064.

Site selection and characterisation has begun and will continue until 2030. It concerns the clay formation in Boda, which crops out of the surface near this area, and which has already been crossed by mine boreholes 1 km deep in the south-west of the country. This formation already has high natural radioactivity, and depths of around 300 and 1000 m. Seismic profiling is already available and other profiles will be produced to demarcate the main area of interest (sector in which the clay is found at depths of between 500 and 900 m).

Regional studies should also be conducted to study the vertical and lateral variability of this formation, distribution of active faults (neotectonic studies), and thermicity (high geothermal gradient expected over the entire area, with temperatures of 50 °C 1 km underground).

d) Board's standpoint

The Board has taken note with much interest of the nuclear waste management and geological repository projects in Poland, the Czech Republic and Hungary.

5.4.3 Conclusion

The three countries have a strong background in the field of nuclear sciences. Moreover, they have gained experience in the field of nuclear energy production and radio-isotope production in medicine. It is worthwhile to step-up European partnerships with these countries in the field of Generation IV and geological disposal as this would reinforce the nuclear sciences community by encouraging exchanges and mutual participation in major reactor (Astrid, Myrrha, Allegro, etc.) and deep geological disposal (France, Finland, Sweden etc.) projects.

APPENDIX I:
NATIONAL ASSESSMENT BOARD MEMBERS
MAY 2016

Jean-Claude DUPLESSY – Chairman of the National Assessment Board, Member of the French Academy of Sciences, CNRS Project leader emeritus.

Pierre BEREST – Expert invited by the National Assessment Board, Project leader at Ecole Polytechnique.

Adolf BIRKHOFER – Expert invited by the National Assessment Board, Professor emeritus at Munich Technical University.

Frank DECONINCK – Professor emeritus at Vrije Universiteit Brussel, Honorary chairman of the Belgian Nuclear Research Centre in Mol, Belgium.

Pierre DEMEULENAERE – Professor of Sociology, University of Paris-Sorbonne (Paris IV).

Robert GUILLAUMONT – Member of the French Academy of Sciences, Member of the French Academy of Technologies, Honorary Professor at the University of Paris XI Orsay.

Maurice LAURENT – Honorary director of the Parliamentary office for evaluating scientific and technological choices.

Emmanuel LEDOUX – Vice-chairman of the National Assessment Board, Honorary project leader at the Paris Ecole des mines, Mines-Paristech.

Maurice LEROY – Vice-chairman of the National Assessment Board, Associate member of the French national academy of pharmacy, Professor emeritus at the University of Strasbourg.

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

Gilles PIJAUDIER-CABOT – Civil Engineering Professor, Director of the SA-BTP, Senior member of the Institut Universitaire de France.

François ROURE – Professor and scientific expert at IFP-Energie Nouvelles, Adjunct professor, University of Utrecht.

Claes THEGERSTRÖM –Former President of SKB (Swedish company in charge of managing nuclear fuel and waste), Member of the Royal Swedish academy of engineering science.

APPENDIX II:

ORGANISATIONS HEARD BY THE BOARD

25 November 2015:	Andra – Progress on site selection for LL-LLW – Option for extension of capacities for VLLW – Which channels for technologically enhanced naturally occurring radioactive waste?
26 November 2015:	CEA – International overview
09 December 2015:	Andra – Dismantling – waste processing – What options, what sectors?
10 December 2015:	CEA – progress report on waste recovery and research projects on waste chemical stability
20 January 2016:	Andra (morning) – Cigéo: master plan, key stages of the basic design phase, project support, related projects, major project approval
21 January 2016:	CEA – ASTRID programme
17 February 2016:	Andra – Cigéo: cell and utility tunnel structure, industrial process for waste deposit in cells – package acceptability
18 February 2016:	CNRS/CEA – Fundamental research and upstream research as part of the 2006 law – Projects relating to ADS in the ALLEGRO thorium cycle – Progress of projects from the CNRS interdisciplinary mission
30 March 2016:	Andra – Cigéo THM and hydraulic gas behaviours and behaviour of the surrounding geological environment
31 March 2016:	CEA – ASTRID – gas ECS

RESTRICTED HEARINGS

03 June 2015:	CEA – Astrid and CES's 2015 report
07 October 2015:	Andra – morning – Cigéo project
07 October 2015:	EDF – afternoon – Feedback on report no. 9
08 October 2015:	CEA – morning – Overview of research conducted at the CEA/DEN for sustainable radioactive material and waste management (2006 law)
08 October 2015:	Areva – afternoon - 2015-2016 outlook – Feedback on report no. 9
26 October 2015:	CNE/IRSN meeting
20 January 2016:	Andra – Cigéo territorial role
14 April 2016:	Andra – Cigéo 2015 project deliverables

BOARD HEARINGS

29 October 2015: Hearing of the Board by the CLIS.

CNE2 VISITS

04 June 2015: EDF Chooz plant visit

07 April 2016: Iter site and CEA centre visit in Cadarache

APPENDIX III:

PERSONS HEARD BY THE BOARD

ANDRA

ABADIE Pierre-Marie
ALAVOINE Olivier
ARMAND Gilles
BONNEVILLE Alain
BOSGIRAUD Jean-Michel
CALSYN Laurent
DUTZER Michel
FARIN Sébastien
GERARD Fanny
GIFFAUT Eric
HOORELBEKE Jean-Michel
HURET Emilia
KRIEGUER Jean-Marie
LABALETTE Thibaud
LAUNEAU Frédéric
LAVILLE Arnaud
LEVERD Pascal
L'HONNEUR Frédéric
MENANTEAU Jean-Michel
MICHEL-DIT-LABOELLE Nicolas
OZANAM Odile
PEPIN Guillaume
PETIT Laurence
PLAS Frédéric
ROUX-NEDELEC Pascale
SEYEDI Darius
SCHUMACHER Stephan
TALANDIER Jean
TALLEC Michèle
TEXTIER-MANDOKI Nathalie
THABET Soraya
TORRES Patrice
VOINIS Sylvie
WENDLING Jacques
YVEN Béatrice

AREVA

DREVON Caroline
FORBES Pierre-Lionel
GAGNER Laurent
LAMOUROUX Christine
LEBAILLIF Daniel
LEBRUN Marc
ROMARY Jean-Michel
VIDEAU Gérard

CEA

ADVOCAT Thierry
BEHAR Christophe
BERTRAND Frédéric
BOURG Stéphane
BOULLIS Bernard
CACHON Lionel
CHAIX Pascal
DELAGE Fabienne
DEVICTOR Nicolas
GAUCHE François
GAILLARD-GROLEAS Geneviève
GARNIER Jean-Claude
GEORGES Christine
IRACANE Daniel
LADIRAT Christian
LAMOTTE Hervé
MARTIN Philippe
MAUGER Gédéon
MUNIER Isabelle
NICOLAS Laetitia
PARET Laurent
PIVET Sylvestre
PLANCQ David
PRENE Philippe
ROUAULT Jacques
TOURON Emmanuel
VALOT Carole
VARAINE Frédéric
WAHIDE Carole

CNRS - IN2P3

BARTHE Marie-France
BIARROTTE Jean-Luc
DAVID Sylvain
FUCHS Alain

NUCLEAR ADVISERS FOR FRENCH EMBASSIES

GORBATCHEV Alexandre (MOSCOW)
PINEL Cyril (LONDON)

ECOLE DES MINES DE NANTES

BRETESCHE Sophie

DGEC (GENERAL DIRECTORATE OF ENERGY AND CLIMATE)

GARD Louis-Marie

EDF

BENOIT Géraldine
DUMORTIER François
ISNARD Luc
LAUGIER Frédéric

ESK

SAAS Arsène

ICSM

MEYER Daniel

LPSC GRENOBLE

RUBIOLO Pablo

ONDRAF (BELGIUM)

BRAECKEVELDT Marnix

APPENDIX IV:

DOCUMENTS SUBMITTED TO THE BOARD IN 2015-2016

ANDRA

- Mémo de présentation des colis de déchets vitrifiés HA portés à l'inventaire de Cigéo – 30 juin 2015.
- Le journal de l'Andra – n°20 – printemps 2015 – Edition Meuse/Haute Marne.
- Le journal de l'Andra – n°20 – printemps 2015 – Edition Nationale.
- Rapport de la revue de projet Cigéo réalisée du 23 mars au 25 juin 2015 - 13 juillet 2015.
- Document technique – Projet FAVL – Evaluation géologique des sites accueillant des installations nucléaires de base – juillet 2015.
- Document technique – PNGMDR 2013-2015 – Projet de stockage de déchets radioactifs de faible activité massique à vie longue (FAVL) – Rapport d'étape 2015 – juillet 2015.
- Inventaire nationale 2015 – juillet 2015.
- Note de positionnement sur la réversibilité – Cigéo – 5 octobre 2015.
- Mémo sur les valeurs des paramètres retenues à ce jour pour les évaluations de la réponse THM de la couche du Callovo-Oxfordien à la charge thermique des quartiers HA – novembre 2015.
- Document technique – Règles de co-stockage des familles de colis MA-VL sur la base de catégories physico-chimiques – données d'entrées pour l'APD – Septembre 2015.
- Règles de co-stockage des familles de colis MAVL sur la base de catégories physico-chimiques, données d'entrées pour l'APD – Septembre 2015.
- Note de positionnement sur la réversibilité – janvier 2016.
- Présentation du modèle de comportement mécanique des argilites du Callovo-Oxfordien dit INERIS/ANDRA.
- Note sur le dimensionnement thermique des quartiers HA – 8 avril 2016.
- Dossier d'options de sûreté – Partie après fermeture (DOS-AF) – 8 avril 2016.
- Dossier d'options de sûreté – Partie exploitation (DOS-Expl) – 8 avril 2016.
- Dossier d'options techniques de récupérabilité (DORec) – 8 avril 2016.
- Cigéo – Proposition de plan directeur pour l'exploitation (PDE) – 8 avril 2016.
- Glossaire des livrables CIGÉO 2015 – 8 avril 2016.
- Projet Cigéo : Evaluation du transitoire hydraulique-gaz en post-fermeture – 30 mars 2016.

CEA

- Rapport d'activité technico-économie au CEA – Année 2014.
- Rapport PNGMDR – CEA – Avancées des recherches sur la séparation-transmutation et le multi-recyclage du plutonium

APPENDIX V:

WASTE RECYCLING-PACKAGING OPERATIONS AND RELATED R&D

Cadarache-CEA.

All alpha contaminated technological waste from the CEA, more or less irradiating, is treated in Cadarache by compaction and cementation. The producers' 50 L bins or 100 L barrels are compacted and placed in 500 or 870 L containers into which cement is injected. The packaging line enables radiological data records to be produced. The packages are then transported to the Cedra, irradiating 500 L packages are stored in wells (25 packages/year) and the others (150 packages/year) at the surface.

Waste recovery and packaging operations for alpha waste stored in Pegase-Cascad are complete. Between 2006 and 2013, 2,700 100 L barrels were repackaged in 619 870 L containers and deposited at the Cedra. Before carrying out this operation, the CEA and Areva used the Pegase warehouse to validate the hydrogen production code by alpha radiolysis in technological waste (see below).

Marcoule-CEA

A cementation and packaging unit was set up in Marcoule in 2012 (on the model of that of Cadarache) to package old alpha contaminated technological waste waiting to be processed on this site. The 870 L containers are transported to the Cedra. The recovery operation should end in around 2017.

The waste recovery and packaging operations for asphalt barrels from Marcoule began in 2000 with the recovery of LL-LLW barrels. Reconditioning enables archiving of the radiological characteristics of the new packages which are stored in EPI intermediate storage. Destructive analyses on 5% of the packages recovered, used for the chemical and radiochemical characterisation of asphalt coatings, did not detect any out of range packages with respect to that which is expected according to the coating process. Concerning coatings, the CEA continued examining the calorimetric data collected last year see report no. 9) for identifying the potential role of minor components on their stability according to temperature. These additional results do not bring existing results into question. Any local warming due to exothermic reactions between nitrates and other salts remains very low and is only triggered above 100 °C. Runaway is not possible. The stability of the asphalt remains to be demonstrated with respect to the slow chemical or physical modifications over around a hundred years during disposal in LL-ILW cells, and therefore that primary packages effectively conserve the characteristics they had when they were placed in the disposal packages.

In intermediate storage in Marcoule, there is UNGG fuel structure metal waste: magnesium, aluminium or stainless steel cladding and powdery process waste: sludge, graphite dust, fines, resins. It is the same as that stored at the Hague (see below). The CEA examines the packaging before recovering it. R&D here is well ahead of recovery operations.

Magnesian waste packaging has been chosen (see report no. 9). Inactive cladding compacting tests are under way to achieve maximum density. In the same way, gamma radiolysis of the geopolymer (a silico- aluminate zeolite of fluorine-doped hydrated sodium) as coating matrix is being studied. Hydrogen production is comparable to that of cement radiolysis. The CEA is planning the complete characterisation of the primary package for end 2020.

Powdery waste will be packaged by homogeneous cementing in 380 L stainless steel containers. Scale 1 inactive feasibility tests have been carried out with 10% weight incorporation. No schedule has been issued by the CEA for this package.

Preliminary waste recovery and packaging studies for other waste from Marcoule are ongoing. The Board has not had any information this year.

La Hague-Areva

Waste recovery and packaging from the UP2 400 plant (known as RCD) of which the 6 INB are situated on the site in la Hague is ongoing since 2014. It requires significant civil engineering and development building work to create access to the waste and to recover it, along with installation of special equipment for sorting and packaging it. The various technological waste (non alpha contaminated) is currently being cemented according to the C2 and C'2 package specifications, the UMo FP are being vitrified at high temperature (100 SWP-U already done, HL0) status, the STE2 sludge will be placed in C5 packages (authorisation pending, see report no. 9, appendix IX), the hulls and tips and shear fines will be compacted and placed in SWP-C HL0 packages (1,500 packages expected) and the dissolution fines and resins will be cemented in CFR-HL0 packages (120 packages expected). SWP-C HL0 and CFR-HL0 packages are being developed. UNGG (SOD) structure waste and graphite-magnesian waste will be cemented. Finally, technological alpha waste will be processed, like other waste of the same type, by the PIVIC process (incineration, fusion, vitrification in the waste container) in development. The PIVIC package should be developed in around ten years (2025).

R&D on the C5 package has passed all the necessary steps for estimating and optimising the 6 parameters of the Areva mapping.

The type of waste from the HL0 and SOC silos has led Areva to compact all bulk waste together (hulls, tips, metal technological waste, organics and oxides) using technology already applied for creating SWP-C packaged, and to mix small particle size waste in cement (shear and dissolution fines, and resins) using conventional homogeneous cementing technology for CFR-HL0 packages. It is obviously better to separate the two types of waste on recovery from the silos. Due to the waste's high alpha (TBq/t) and beta (tens to hundreds of TBq/t) radioactivity, the phenomenon feared for the packages is significant hydrogen production, essentially by radiolysis of the water in the packages. For SWP-C HL0 there is little residual water in the waste and production is low (0.2 L/year). For the CFR-HL0 package, Areva has developed a cement formulation compatible with the type of metal fines and organic resins (30/70 ratio) ensuring even distribution up to 11% of waste. However in these conditions, average hydrogen production from cement and resin pore water is estimated at 120 L/year/package, a value significantly above the maximum acceptable value for Cigéo (40 L/year). It is the dissolution fines (very small particle size and rich in alpha emitters) to shear fines ratio which governs hydrogen production. The ratio will be high for some packages and low for others. Areva and Andra are looking to see if the quantities of hydrogen released by the CFR-HL0 packages are manageable during operation and after closure of Cigéo.

Alpha technological waste (building 119) is the same type as other alpha waste (ATPu and Melox plant, la Hague reprocessing plants): varied organic waste and metals. To package them the CEA is developing the PIVIC process with Andra and Areva (PIA agreement). It will consist of incinerating waste organic material in a plasma and then melting together the incineration ash, glass frit and non-incinerated metals in a crucible by induction. The cylindrical crucible (known as the CAN,110 kg) made up of two hulls, one stainless steel the other ceramic, will ultimately contain a vitrified part including ash and most of the alpha radioactivity and a metal part. A crucible can process 10 120 L waste barrels. The incineration chamber and crucible are combined. The combustion gases are processed. The PIVIC primary package will comprise two crucibles in a metal container. Inactive metal/frit fusion tests have been carried out successfully.

The 1,100 tonnes of mixed waste of graphite sheaths (90%) and magnesium cladding (10 %), with traces of uranium, and of aluminium stored in silos 115 and 130 have specific ^{14}C and ^{36}Cl activity of around 12,000 and 250 Bq/g respectively. These activities are of the same order of magnitude as the activities of some of EDF's LL-LLW graphite waste and would make them eligible for LL-LLW disposal but their alpha Pu and Am level is high (36 TBq); it should be taken into account. Also, their packaging by cementing is complicated as it should prevent carbon magnesium contact to prevent the formation of radioactive methane and to reduce as far as possible the formation of hydrogen by reaction between Mg, U and Al with water. R&D is ongoing.

There are also 50 t (600 TBq alpha) of powder graphite and various mineral and organic materials in the UP2 400 decanters at the decanning workshop. This waste is similar to that of Marcoule for which the CEA is studying cementing.

There is other waste to be recovered and packaged on the site at la Hague, but the tonnages are lower than those for which Areva is currently developing a packaging. If the worst comes to the worst they will be placed in intermediate storage until R&D designs a definite packaging.

RCD operations by the CEA and la Hague are scheduled according to a time frame compatible with the Cigéo PIGD time frame and opening of a LLLLW repository. Areva is planning the SPW-C HL0 and CFR-HL0 package specifications for 2016. For the others, R&D has to progress in order to arrive at this stage.

RCD operations enabled waste producers to measure radiolysis-induced hydrogen production in actual conditions in LL-ILW packages rich in organic matter. Radiolysis in these packages is inevitable. It is therefore important, in general, to be able to estimate hydrogen production if it cannot be measured. According to the type of primary package, several codes are used by Areva and the CEA, and any data that can be used to validate the codes is important.

The test was conducted on the alpha technological waste intermediate storage facility in Pegase, before the barrels containing them were repackaged. The ventilated intermediate storage room was ideal for measuring the hydrogen flow emitted by the 2,714 barrels in which PuO_2 (UNGG) and $PuUO_2$ (PWR) oxides irradiated the organic matter (cotton, latex, PVC, cellulose, etc.) where they were deposited in the form of micrometric grain aggregates. Several hydrogen tests were conducted. They showed that average hydrogen production, on the 619 870 L packages after barrel reconditioning, was 8.6 L H_2/package/year. This value was compared to that from the direct measurements on 29 870 L packages representative of barrels more or less rich in alpha emitters. It resulted in 8.1 L/packages/year). The statistical analysis of the number of packages according to the flow rate shows that 90% of the packages emit less than 22 LH_2/package/year. The OPM used in the calculations of flow rates by alpha radiolysis applied to the situation studied results in an average of 33 LH_2/package/year. It is highly upper bound.

Radiolysis produces hydrogen and degrades the organic matter. Break down leads to the production of chemical species (water soluble degradation products, PDH) which, in the long-term, can affect radionuclide containment during damage to the packages. In report no.9 the Board gave some indications on the R&D conducted by Andra to take account of these phenomena in radionuclide migration. PDH are organic acids or molecules carrying this chemical function. They diffuse into the clay and cement materials but they are also partly retained there. They are more or less complexing for actinides, among others, which modifies solubility, sorption and diffusion of the elements. Due to these multiple interactions it is very difficult to foresee all effects on radionuclide confinement. This is why Andra is conducting an extensive R&D and development programme on this subject, which should be completed in 2018, to correct the values of the related geochemical parameters which govern radionuclide migration.

APPENDIX VI:

DISMANTLING AND RELATED R&D

Clean-up and dismantling (C&D) of nuclear facilities (reactors, fuel cycle plants and research), generally of INB, leads to complex radiological characterisation of buildings, facilities and equipment and nuclear engineering operations for their demolition. It often poses, like during RCD operations, the problem of packaging of new radioactive waste for producers, which means it needs to be characterised first. In addition to site operations paid for by the producers, Andra must manage waste which cannot be recycled. The challenges of C&D are therefore shared by Andra and producers: detailed inventory of waste, package specifications for disposal, reduction of the volumes to be stored in view of the limited disposal capacities for VLLW, VLLW recycling and economic optimisation.

Waste from ongoing dismantling operations from EDF is identified, without its management being decided on. The graphite stacks should go to SCR disposal directly or after decontamination treatment (incineration being ruled out). In effect the ^{36}Cl inventory represents 75% of the CSA's radiological capacity. Reactor deconstruction will lead to secondary waste.

Underwater dismantling of UNGG stacks from Chinon will produce ion exchange resins loaded in ^{36}Cl and some thousands of tonnes of rubble (contaminated concrete) and to sludge (10 cm concrete removed from the walls of the cases). The SLA1 and A2 (2000 t) graphite sheaths will go to Cigéo. Resumption of the dismantling operations by EDF is linked to the commissioning of Iceda for intermediate storage of the first waste from UNGG and from the other reactors.

The C&D of the PWR reactor in Chooz (350 MWe) is, for EDF, the first experience with dismantling of such reactors. Removal of large components (pressuriser, exchangers) required large scale preparation sites, additional buildings, tool qualification and waste management. Tank deconstruction is being prepared. The 4 exchangers were stored in the Cires. The waste is expected to amount to 20 t (0.1%) of LL-LLW, 2300 t (6.4%) of FMA-VC, 7900 t (21.3%) of VLLW and 26 530 t (72.2%) of conventional waste.

For the other PWR the C&D deadlines are far off, although 'EDF confirms that its strategy on the subject is dismantling in as short a time frame as possible according to intermediate storage and waste channel possibilities. This stance is in keeping with the national strategy. According to a reasonable estimation based on the series effect, the quantities of waste and future of the waste from the EDF PWR fleet are believed to be the following:

- conventional waste, 880 000 t with 90% recycling and 10% in ISD,
- LL-ILW, 300 t with intermediate storage in Iceda followed by disposal in Cigéo,
- SL-ILW, 53 000 t with 98% in the CSA and 2% at Socodei/Centraco for incineration then disposal at the CSA and for fusion then recycling in containers for the CSA or the Cires,
- VLLW, 11 5000 t, at the Cires (or recycling, on-site disposal, or specific disposal).

Areva and the CEA have already conducted considerable clean-up and dismantling (C&D) operations and have several sites ongoing. The diversity of the facilities, one of a kind, cannot systematically establish the proportions of categories of dismantling waste. Nevertheless, in any case, it is VLLW which is predominant.

Generally it is the CEA which ensures, on behalf of producers, the R&D behind C&D: characterisation of facilities and waste, effluent and solid waste treatment and waste packaging, intervention and management systems. It is working with a number of industrialists. The international dismantling market is already large and is set to grow.

C&D operations are monitored by the ASN which is waiting for several of Areva's dossier on the management of waste and dismantling (ten-year update expected for June 2016) and from the CEA.

Andra's forecast for waste by end 2030 shows that 500 000 m^3 of VLLW and 100 000 m^3 of FMA-VC is expected from dismantling and a lot less LL-ILW and LL-LLW. In the long term, in around 2080, dismantling should produce at least 65 000 m^3 of LL-ILW, 180 000 m^3 of LL-LLW, 1.8 million m^3 of FMA-VC and 2.1 million m^3 of VLLW. If the CSA can collect dismantling FMA-VC waste, the same does not apply to the Cires for VLLW (see below). Andra underlines however that the CSA was built for operating FMA-VC waste and not dismantling waste, this is why it is drawing up new specifications with producers for acceptance of this waste at the CSA.

Andra and the ANR launched at the end of 2014 a call for innovative projects to support dismantling, financed on the PIA to the amount of 45 M€. It targeted all R&D stakeholders from academic and industrial circles. Seven projects were selected for the characterisation of facilities to be dismantled or dismantling waste and 5 for waste sorting and treatment. The "Profusion" project for studying the fusion/decontamination of metals from Eurodif directly concerns VLLW recycling (see below). The other projects concern all waste. Areva and the CEA are participating in most of the 12 projects. The Dem & Melt project aims to develop the PIVIC project for incineration, fusion and vitrification directly in LL-ILW containers from MOX preparation (organic and metallic) but also of technological waste containing incineratable organic matter.

The second call for tenders has just been launched (December 2015 – March 2016).

C&D relies on, throughout the operations chain, from initial radiological characterisation of facilities to final characterisation of the sites that will accommodate them (and the environment), on tried and tested techniques and processes adapted the radioactive media. The radionuclides to be taken into account, notably long-lived, are known. Waste from the various operations has been identified. For the main part it will go to operational industrial management channels. The studies cover economic optimisation by playing on the recycling of the less radioactive materials (VLLW) and best use of disposal capacities. The related R&D mainly concerns the reduction of uncertainty on waste radiological inventory, the possibilities of decontaminating certain waste and its packaging. In addition to R&D is that of the behaviour of waste packages during disposal.

APPENDIX VII:

LL-LLW AND RELATED R&D

The current inventory of LL-LLW is given in the June 2015 update report by Andra. There are no major changes to the types and quantities reported in the Board's report no. 8 and 9.

The repository should accommodate radiferous waste (45 000 m^3) and Tenorm (38 000 m^3), technological waste from la Hague that can't go to the CSA (16 000 m^3), from sealed sources (2000 m^3), graphite waste (23 000 tonnes around 90 000 m^3 with resins) and 32 000 asphalt barrels (42 000 m^3). These volumes are those of waste packaged according to the current hypotheses and packaged in disposal packages if necessary. The primary and disposal packages will be in concrete, except for the radiferous waste. That will go to disposal in barrels or metal containers. LL-LLW therefore represents around 230 000 m^3 to date. It may be necessary to add 86,000 m^3 of waste from Malvesi (gypsum and dehydrated sludge) if it wasn't possible to store it on the Malvési site. This point is being discussed between Andra and Areva.

Long-lived radionuclides to be taken into account in the management of LL-LLW mainly include: ^{36}Cl (3 10^5 a) and ^{14}C (5,7 10^3 a) for graphite stacks, ^{226}Ra (1,6 10^3 a) and ^{230}Th (7,5 10^4 a) and their daughter products for radiferous waste, ^{63}Ni (100 a), ^{241}Am (430 a), ^{240}Pu (6,5 10^3 a), ^{79}Se (7 10^4 a), ^{99}Tc (2 10^5 a), ^{129}I (1,6 10^7 a) for graphite sheathing, asphalts and technological waste from la Hague (CBF C'2) to which the possible presence of ^{41}Ca (1,010^5 a), ^{93}Mo (3,5 10^3 a), ^{238}Pu (88 a) and short-lived radionuclides, ^{137}Cs (30 a), ^{90}Sr (28 a) and ^{241}Pu (14 a) should be added for the 3 waste categories. All artificial radionuclides are activation products or fission products. LL-LLW also contains chemical toxics, the main one being uranium, in radiferous waste (tens of tonnes).

The specific activity of the various radionuclides, is, for instance, around the tenth of that of LL-LLW in C-SWP (except for iodine), however the quantities of waste coming into play lead to total levels significantly higher than those that can be accepted at the CSA. The CSA's ^{36}Cl carrying capacity is at 90% of the repository's capacity, which will be mainly taken up by UNGG graphite sheathing from the Bugey (not contaminated by fission products or actinides). Although their level appears to be overestimated for the time being, the CSA no longer appears to be legally able to receive other graphite LL-LLW.

Radiferous waste from Solvay is in intermediate storage in Cadarache (barrels) and in La Rochelle (bulk), that from Areva in Jarrie (barrels) and that from the CEA in Itteville (consignor). Non-nuclear LL-LLW only containing natural radionuclides is in a special building at the Cires.

No graphite waste has been packaged as yet. Around 80% of the graphite waste (stacks) is still inside the UNGG reactors, 6 for EDF (Chinon A1, 2 and 3, Bugey 1, Saint Laurent A1 and 2) and 6 for the CEA (G 1,2 and 3 in Marcoule, EL 1 and 2 in Saclay, Rapsodie in Cadarache) and 20% (sheathing and miscellaneous) is in intermediate storage in La Hague, Saint Laurent and Marcoule. There are 23,000 tonnes in total. The total ^{36}Cl inventory is estimated at 2 TBq.

The latest results of characterisation of EDF's graphite waste can be used to set their ^{36}Cl activity at 0.9 TBq (0.3 for stacks and 0.6 for sheathing). The 15,000 tonnes of stacks contain 30 kg of chlorine and 250 g of ^{36}Cl. ^{36}Cl activity could be reduced by thermal treatment. EDF is optimising (via studies with the CEA) thermal treatment of the graphite to remove ^{14}C from it, its destruction by gasification being ruled out at this time. ^{36}Cl activity of the graphite LL-LLW from the CEA and Areva is therefore estimated by difference at 1.1 TBq.

The CEA's asphalt packages are in Marcoule: part in casemates in the STEL (barrels) and part in the EIP (barrels after reconditioning. The ^{36}Cl and ^{129}I activity of the asphalt LL-LLW barrels from Marcoule, at the limit of detection, is estimated at 0.06 TBq. That of ^{99}Tc needs to be better assessed. The CEA considers that possible processing of asphalt by incineration/vitrification is not economically viable. However a final decision has not been taken on this matter.

The concrete-fibre packages of FCC-C'2 technological waste in intermediate storage at la Hague and classed as LL-LLW has a radiological inventory at the upper limit of LLW classification and a lot of it is irradiating.

The physico-chemical behaviour of most of the species the radionuclides in LL-LLW can theoretically form, in clay and cement media, is more or less foreseeable according to the databases of studies conducted on LL-LLW of the same chemical type. However, even in the best-case scenarios, the behaviour, especially for radionuclides with high total activity, needs to be confirmed (^{14}C, 1000 TBq), as they are known to be mobile in the environment (^{14}C in organic form, ^{36}Cl, ^{99}Tc, ^{129}I) or the radiological impact of which is significant (^{129}I, DPUI ingestion 1,1 10^{-7} Sv/Bq therefore 100 times more than ^{36}Cl and 1000 more than ^{14}C and ^{99}Tc).

The latest results (Andra, CEA, EDF) show that the leachability of ^{36}Cl by water from EDF graphite stacks can reach 60% depending on their origin (with two types of kinetics, one rapid, labile fraction; the other slow), that ^{36}Cl retention by cement materials decreases with the salinity of the medium at steady state (Kd from 1 to 50) and that it migrates slightly like water in tile clay (5 10^{-11} m^2/s). The 10 to 90% labile fraction is released in a few days, the other is released at the rate of 5 to 20%/year. Variability depends on the samples. The chemical behaviour of chlorine is reasonable well-known in the graphite environment in disposal conditions.

^{14}C leachability from the graphite remains low (less than 1% with release rates of 5 10^{-6} to 5 10^{-3}/year). It is highly sensitive to experimental conditions, the pH of aqueous solutions, the more or less divided state of the graphite and origin of the samples. Around 30% of the ^{14}C is in unidentified organic form little reactive with cement materials and tile clay (low retention). Only the behaviour of ^{4}C released in the form of carbonate ions (70%) is well known, it is rapidly incorporated in carbonate environments (clay cement and rock) by isotopic exchange. EDF is studying the influence of thermal treatments on leaching of ^{14}C (quantities and species released, including organic species). ^{14}C can also be contained in gaseous species (CO_2) but which are believed to be trapped by cement materials. The behaviour of ^{14}C LL-LLW disposal is far from being understood. Numerous studies on this subject are ongoing with waste producers and in European programmes. The same applies for ^{41}Ca behaviour (in theory it is exchangeable with the calcium in the minerals from the geosphere) or with tritium (environmental labelling).

In radiferous waste, ^{226}Ra is contained in insoluble barium sulphate (atomic content of 10^{-7}). However, in the presence of water the radium is split between solid and solution depending on the pH. 2% of the Ra can be found in solution at pH 12-13 (cement water). In this pH range Ra is highly sorbed on cement materials (Kd from 100 to 700). Uranium is found in the form of poorly identified and little soluble hydroxides, the leachability of which through water releases hydrolysed forms retained in the cement materials. Ra is also highly sorbed on tile clay, regardless of the conditions. It is also the case of ^{230}Th but not that of uranium, the sorption of which is sensitive to local physico-chemical conditions.

The mechanisms of release of radionuclides from asphalt-coated salts are known. Radionuclides are above all released at the same time as highly soluble sodium nitrate. All cationic species will be retained on cement degradation materials and by clay. The fate of anionic species, i.e. technetium (TcO_4^-) and iodine (I^-), known to be mobile in the environment, is more difficult to estimate, especially as nitrate and sulphate release can considerably alter local physico-chemical conditions.

The first consequence is the increase in the ionic force of aqueous solutions. Sulphate anion content, and to a lesser extent, nitrate content, play a role on degradation of the cement by modifying the nature and distribution of the mineral phases in the degradation material (from silicate phases to sulphate phases). Also, secondary mixed, sulphate and nitrate based phases may precipitate. Nitrate anions, in the presence of steel or bacteria can be reduced, which changes the redox conditions. However, ionic force, phases present and the oxidant or reducing properties of the medium play a role in species retention. It is the case for Ra and U(VI) the sorption of which decreases with the increase in the ionic force, and for Tc and U which are very little mobile when in Tc(IV) and U(IV) form. Only the actinides found in LL-LLW are effectively retained in the clay in the reducing medium.

Prevision of the behaviour of ^{226}Ra, ^{99}Tc and U in a LL-LLW repository partly refers to the study of the change/stabilisation in the redox potential in the cells.

From radionuclide migration calculations in the conditions described in the body of this report, Andra has evaluated the radiological impacts related to conventional safety analysis scenarios for geological repositories. No dose commitment related to the various return of radionuclides to the biosphere is really unacceptable (doses << 1 mSv/year). However, exposure, inhalation and ingestion scenarios from involuntary human intrusion, which only concern radionuclides in place in the repository, show that asphalt waste and waste containing alpha emitters (graphite from the silos and technological packages from la Hague with ^{239}Pu and ^{240}Pu, ^{241}Am), can lead to situations posing a problem with respect to radioprotection (dose >> 1 mSv/year).

The Board would like migration calculations to be continued by Andra, and adjusted as the values of the radionuclide diffusion and retention parameters and the parameters characterising the site as a whole, intact and reworked tile clay and cells, are fined down. The safety analysis will only be all the more realistic.

APPENDIX VIII:

VLLW TECHNICO-ECONOMICS AND RELATED R&D

The quantities of VLLW to be stored are estimated by Andra. They still depend significantly on a lot of hypotheses on what the final VLLW will be, resulting from its sorting, according to INB zoning, its processing, aiming to reduce volumes (densification, incineration, fusion), its use in the nuclear field or its strictly supervised recycling in the public domain.

In this context many technico-economic discussions are taking place in the PNGMDR WG on the possibilities of recycling metals and other very little radioactive materials or non-radioactive materials from non-conventional INB areas. For metals this represents considerable deposits, 900,000 tonnes after dismantling (150,000 t of GB 1 diffusers, 100 000 SG, other waste such as transport packaging). The current fleet includes 198 SG, 182 have been replaced or are due to be, and there will be 370 in total. It cannot be stored at the Cires. The recycling working group issued recommendations, especially for large homogeneous lots (BG and SG) and concrete rubble. Waste producers are looking at tangible projects for large scale fusion (thousands of tonnes/year) on the basis of the feedback from the small fusion facilities already commissioned for radioactive metal materials (Centraco in France, Studsvik abroad).

Thus Areva and the CEA undertook with Eurodif and Studsvik to conduct the "Profusion" project (4 years) which aims to qualify a steel fusion/decontamination process (tests on 150 t of SG1 metals), in order to be able to recycle steel processed in conventional "steel" channels. They are many constraints. Level 8 qualification on the TRL scale is targeted. An industrial facility can therefore be set up in Pierrelatte for SG1 steel. The project is accompanied by economic studies on the steel market.

Tests have already been carried out on the steel in Studsvik, with UO_2F_2 surface contamination only They present 99% uranium contamination. For all that, numerous parameters need to be looked into: optimal composition of the slag for decontamination, characterisation of the gases, redox condition control (to prevent uranium oxide reduction), secondary waste management etc. . The case of activate steel is more complicated as it is the behaviour of several elements that needs to be studied in the partitioning process between slag, steel and gas.

Discussions on the release of very low level waste are closed for the time being, which comes back, in a sense, to limiting production of such waste or any other operations for reducing the volume to make it easier to manage.

In its report no.9, the Board underlined that release of radioactive materials could not go without highly sensitive radioactivity measurement to ensure a low radiological impact in all circumstances of use. Germany is practising unrestricted and restricted waste release, for waste having to be processed before it becomes standard materials (steel from dismantling of nuclear plants). Release radioactivity thresholds to ensure a dose of 10 µS/year for the population are extremely restrictive: lower than the Bq/g for unrestricted release and less than or equal to 10 Bq/g for restricted release. In addition are limits on surface contamination and restrictions on releasable quantities per year (under 1,000 tonnes). The total quantities released are very low. A lot of restricted release waste is released to conventional dumps or to incineration, which is not without acceptance problems. Release in Germany is not a great success although the price of release is competitive with that of disposal.

APPENDIX IX:

PNGMDR WG RECOMMENDATIONS

R1-The working group recommends that the study of recycling channels be conducted first on large homogeneous lots, the characteristics of which are known and verifiable, to be able to envisage the development of an industrial-scale process, to make controls reliable at the various stages of the process and to provide guarantees on the quality of the finished products.

R2-The working group recommends that the performance of the treatment processed be justified on the basis of several lines of independent and successive arguments, especially including knowledge of materials and treatment processes, and the definition of a controls and measurements programme.

R3-The working group, at this stage, considers that fusion is an essential step to recycling metal materials as it can be used to make characterisation reliable and produce homogeneous batches. Also, it can be used to determine the favourable aspects of metal material recycling in certain cases by decontamination.

R4-The working group recalls that favourable radiological characteristics should not be obtained by dilution.

R5-The working group recommends that the processing channels comprise facilities only processing fluxes from nuclear facilities, as far as possible. Where processing has to be carried out in a facility also processing conventional material flows, the working group recommends that:

- specific provisions be set out concerning material traceability, waste produced, scrap and rejects in particular etc.,
- radiological criteria be defined and controlled in order to minimize constraints relating to the management of materials from nuclear facilities,
- the potential impact of processing of materials from nuclear facilities on the activity of the industrial partner be assessed and controlled,
- employees have sufficient knowledge of health and safety at work.

R6-The working group recommends that the methods for tracing materials, waste, scrap, trimmings, by-products, be determined for each stage of the recycling channels. Conditions for exempting substances from traceability should be specified, where appropriate.

R7-The working group considers that reuse outside areas in which the waste produced is likely to be contaminated or activated, should only be envisaged for materials for which their use is not likely to affect health and protection of the environment, while taking account of the worst case scenarios, even in the event of loss of traceability.

R8-The working group recommends that for each of the solutions identified, the quantities of substances likely to be recycled and an economic model be assessed in order to confirm the relevance of the potential channels.

R9-The working group recommends that the preferential criteria for the choice of solutions include guaranteed long-term product traceability.

R10-The working group recommends that the opportunity for setting up recycling tracks be clarified by analysis of the service life contributing to compilation of a technical, economical, financial, societal, sanitary, environmental and energy assessment of the various solutions planned. The working group considers that recycling of VLLW can only be envisaged if the analysis is positive and demonstrates the general benefits.

R11-The working group recommends the highest level of transparency for the study and for the implementation of treatment and recycling tracks:

- within companies (including subcontractors): information and participation of employees, staff representative bodies, trade unions, occupational medicine etc.
- locally, especially at the processing and conversion site (and reuse site if possible) and where applicable initial material site: information within bodies such as local information committees, information committees, site monitoring committees etc.
- nationally (PNGMDR, ANCCLI, HCTISN working group).

R12-In the case of solutions outside the nuclear industry, the working group recommends that suitable information resources be set up.

R13-The working group considers that the provisions set out in article R.1333-4 of the French code of public health could be implemented to enable the use of materials likely to be contaminated by radioactive substances in consumer and construction goods, but that the procedure should be adapted.

R14-The working group considers that the dossier submitted in application of the order of 5 May 2009 should be based on the following elements:

- a health and environmental impact analysis;
- quantities of materials concerned;
- an overall assessment including service life analysis;
- conditions of traceability and radioprotection and, where applicable, the time at which they are no longer essential;
- public information and participation.

APPENDIX X:

ASTRID PROGRAMME PROGRESS

The Astrid project R&D programme has several lengthy phases: reactor design as industrial FNR-Na demonstrator and transmutator, setting up of the Astrid fuel production workshop, implementation of processing workshops for fuel dumped from the reactor. The latter are necessary to the industrial demonstration of plutonium multirecycling and minor actinide transmutation.

Only the fuel production workshop is necessary for Astrid start-up, the others should be commissioned as required in the decades following Astrid start-up.

Astrid's design should take account of safety requirements. A major guide is the feedback on the construction, operation and deconstruction of FNR-Na. It therefore covers innovative provisions for the management of neutronic reactivity, cooling in all circumstances and to enable inspection/repair during service.

The Astrid fuel cycle facility design is based on:

- for the production workshop, new FNR MOx fuel assemblies, on the feedback from production of new MOx fuel assemblies in the ATPu-plutonium technology workshop (for FNR) and Melox (for PWR)
- for the spent FNR MOx fuel, on the feedback from reprocessing of spent UOx and MOx fuel assemblies at la Hague. It will benefit from the ongoing improvements (TCP-La Hague, extension Melox). It covers the provisions necessary for taking account of Pu isotopies and the high proportion of Pu in the irradiated FNR MOx.

The design of the facilities for demonstration Am transmutation, is seen as an extension of fuel production workshops and the fuel-processing workshop. The Atalante facility is sufficient for the first tests at pin scale.

Planning and governance

The Astrid programme is continuing but the schedule deadlines and governance changed over 2015.

In the June 2015 report (handed to the authorities by virtue of the PNGMDR decree of 27 December 2013) the CEA planned, at the end of the basic design phase (APD – Avant Projet Détaillé), which was to last from beginning 2016 to end 2019, for a decision to build reactor to be taken and for its construction to begin end 2020/beginning 2021. Due to uncertain planning and development resources for the test facilities required to qualify certain reactor components, Astrid's construction date has been set back by 2 years. This decision was taken by the CEA authorities.

In October 2015 the provisional schedule deadlines were:

- End 2015: preliminary design phase (preliminary design phase divided into 2 phases, AVP1 and AVP2) providing the specifications, estimated costs and project layout, submission of the SOF to the ASN, decision by the authorities to go onto the reactor basic design phase from 2016 to 2019 (also known as the "Basic Design").
- End 2019: official set up of a consortium bringing together partners of the Astrid project (CEA, EDF, Areva, other French and foreign industrial partners etc.). The consortium should carry the project and submit the DAC in 2020 containing the Preliminary Safety Report (PSR), decision to go onto the "Detailed Design" phase.
- End 2022: building permit issued by the ASN, which will have processed the DAC for two to three years (2020 to end 2022).

Construction of Astrid should last 7 years and its divergence should take place in 2029.

This schedule included reviews with the authorities, end 2017, end 2019, end 2022, essential appointments for passing the project milestones. The authorities were to control and ensure the project is being conducted properly, especially end 2019 to go on to the "Detailed Design" phase.

The schedule for construction of the fuel production workshop, which should be ready to operate three years before Astrid's divergence (2029), that is to say in 2026 in this schedule, was based on that of the reactor. The fuel production workshop included extension of Melox.

The objectives of Astrid (FNR-Na safety and operations demonstrator, Pu multirecycling demonstrator, Am transmutation demonstrator and increased Pu consumption demonstrator, reference for investment cost estimation etc.) and the reactor's technological options remained unchanged. In particular the choice of a gas ECS was confirmed by the CEA and R&D on this subject was becoming a priority for the coming years.

End 2015, the CEA had finalised the APS dossier with a water steam ECS (see below) and the decision to go on to the APD was taken by the authorities. The CEA decided to bring knowledge of gas ECS to the same level as that of steam water ECS by end 2017, at the end of the APS. This important decision results from a project review by the DEN on the gas ECS in which EDF, Areva, Alstom and other industrialists participated. It is therefore a joint decision by nuclear stakeholders.

The project's schedule and governance were also changed slightly end 2015, such as submission of the SOF to the ASN in Spring 2016. The Astrid programme has slackened with respect to the voluntarist programme of October 2015 by clearly centring it on the technical aspects to be developed during the basic design phase. A particularly important meeting with the authorities end 2017, should prepare the post-2019 phases. For all that the "Detailed Design" phase (2020 – 2022) and regulatory formalities for construction of the reactor and the fuel production workshop are essential. The other provisions from the previous schedule remain to be confirmed in late 2015.

The general project organisation remains in place: strategic management by the CEA as project manager and the Astrid Project Unit (APU) which is up and running since 2010, R&D ensured by the CEA by collaborations and partnerships, assistance and design ensured by the CEA and 14 industrialists (to date). The CPA is reinforced. The R&D phase is extended by two years, which will make it possible to support final choices for Astrid on the bases of reinforced techniques.

The Astrid project, even though supported by Areva and EDF, is seeing some disagreement as to the rate of implementation. EDF believes that Astrid and its cycle should enter into the uncertain prospect of gradual commissioning of FNR-Na in France. The objective to be reached for transition to level B is of course the demonstration of the safety of FNR-Na over their entire spectrum of operation, but FNR and related cycle performances should be consistent with fleet renewal requirements, with cycle plants and with market economic conditions.

Report on R&D conducted during the preliminary design phase

R&D on the reactor conducted by the CPA during the preliminary design phase was constantly directed by option choice reviews. It had to cover the design and qualification of components, reactor operating conditions, materials, scientific calculation tools (SCT) and risks and performances. The summary dossier at the end of the preliminary design phase provides a full description of a preliminary reactor version with the conventional steam water ECS option. The APS dossier includes all documents edited during the preliminary design phase (around 2,300). The summary dossier at the end of the preliminary design phase discusses the organisation of the Astrid project and cost estimation, description of the components, industrial architecture, safety and regulatory aspects, reasons for the options and R&D progress on gas ECS (see below).

The Board assessed some of these elements in its previous reports (materials, components etc.). The preliminary design dossier describes the structure and function of the components in detail and places them in a consistent overview of how Astrid will be. The assembly handling chain is especially delicate and its design is still being determined, whereas for the other components the design has already been decided. The dossier for the end of the preliminary design phase is the material used to improve the design of the reactor in the basic design phase.

Astrid's passive safety is a central design element and it essentially concerns prevention of serious accidents (core fusion) and management of the corium if ever a major accident occurred. Other than the fact that the core is intrinsically safe (discharge coefficient near to zero) the objective of non-fusion of the core is ultimately ensured by two passively activated reactor shut-down systems, either in the case of loss of sodium flow rate or in the event of a sodium temperature rise above 600 °C (sodium boils at 900 °C). In each case there are 3 devices for stopping reactor power still: pneumatic shut-down rods or electromagnetic shut-down rods per Curie point. Mitigation of fusion where there is any is ensured by guided corium flow and its collection and cooling. It is the final solution among all active and passive safety systems. The two prevention and mitigation systems are studied in simulation/experimentation programmes conducted by the CEA and Japan as part of the CEA-Japan agreements.

The preliminary design phase R&D which led to the definition of Astrid is based on the feedback from past constructions, new technological developments and tests, but above all on new OCS to support simulations. For example, Astrid's neutronics and behaviour of the heterogeneous core could not be covered by applicable codes having been tested on previous FNR-Na. Also OCS are essential for simulating the behaviour of the reactor in incidental or accidental situations, on which the safety demonstration, object of the PSR (end 2019) is based. The CEA (and its partners, especially Japan) has improved and developed more than ten codes for simulating the performances of the Astrid core. The OCS need to be checked and approved to simulate the behaviour of components and ultimately qualified in the legal sense of the term for the safety demonstration. Validation/qualification is based on comparisons with known and documented situations or with the results of new tests, some of which are only possible, today, abroad (Japan, Russia, Kazakhstan). The OCS are up and running to consolidate Astrid's design during the basic design phase, or will be in time for preparing the PSR.

R&D on facilities for the Astrid fuel cycle essentially involved the manufacture of the first core and its recharges for the first decades of operation of the reactor. The heterogeneous CFV 4 core comprises pins filled with $UPuO_2$ and UO_2 pellets but differently according to their location in the internal or external core (only made up of $UPuO_2$ pellets). At cruising speed, Astrid will consume 5 t of UPuO2/year and 3 t of UO2/year (Uapp). Around 8 t of spent fuel (MOx RNR) at a mean combustion rate of 90 GWj/t will be reserved each year. However, before arriving at this balance, 15-20 years' operation will be required with a start-up core and recharges.

The Pu from the new fuel of the first core, around 5 t (for 25 t of MOx $UPuO_2$) will come from UOx spent fuel in stock at la Hague. It will gradually be replaced for a quarter by recharges requiring around 1 to 1.6 t of UOx Pu/year then 1 t of PWR MOx Pu/year also in stock at la Hague, the percentage of Pu in the new MOx fuel being adjusted according to the isotopy. 22 recharges will be required over 20 years. 15 t of UO_2 depleted uranium for the core and a few tonnes per year for the recharges (5 to 3 t UO_2/year) is also in stock. The gradual power build-up of the core means that the rate of combustion of the FNR MOx spent fuel removed from the first core will be around 45 GWj/t. The irradiated FNR MOx, regardless of its rate of combustion, will be placed in stock for recycling later in in Astrid.

The fuel production workshop should manage fuel production (first core ready in 2026) by taking account of Pu isotopy (^{238}Pu, neutron emissions) and the plant in la Hague should manage reprocessing of the spent PWR UOx and PWR MOx fuel required to produce Pu, which does not pose a problem. It is only later when Astrid will recycle its own Pu that la Hague will need to be renovated to process FNR MOx. The CEA and Areva are looking at setting up the fuel production workshop in Marcoule.

The process for the production of dense $UPuO_2$ pellets (25% of Pu, 0.97% of the theoretical density, near stoichiometric mixed oxide) is developed. More than 300 pellets have been produced at Melox, the objective being to produce thousands between October 2018 and August 2019 with an optimised production/inspection process (20 kg of oxide, 5 kg of Pu). Indeed, 61 experimental MOx pins containing 4000 pellets are required to qualify Astrid's fuel by irradiation in BN 6OO in Russia. The irradiated pins are to be examined in Cadarache.

Significant progress has been made in the manufacture of the fuel pins (AMI1, 2.2 m stainless steel), of the hexagonal assemblies (EM10, 4.5m steel) and boron carbide (B_4C) for the numerous neutronic protections, which require more than 50 tonnes. Astrid's assemblies are complicated objects containing, in addition to the pin bundle, a removable pin bundle filled with B_4C pellets (natural B and enriched in ^{10}B , 0.94 m), a leg (0.75 m) and an empty part (0.4 m) filled with sodium (formation of the Na plenum).

R&D to be conducted during the Basic Design Phase and beyond

The next two years will be devoted to the in-depth study of gas ECS, consolidation of preliminary design choices and optimisation as a whole. For the gas ECS, it involves bringing the dossier to the same level of knowledge as that of the steam water ECS in the current design. It is an ambitious objective. Certain choices from the preliminary design deserve to be looked at again, in the two energy conversion options. The hypotheses on the upstream and downstream aspects of the fuel cycle will also be consolidated. End 2017 the CEA has announced that it will have several important dossiers: reworked design, cost, and schedule. End 2019 the basic design dossier can be used to decide whether to continue the Astrid project or not.

The R&D to be conducted on gas ECS will be significant during the basic design phase. It first requires the design and qualification of a powerful $Na-N_2$ exchanger (190 MWth), key element for moving on from the reactor's secondary Na-Na circuit to the $Na-N_2$ tertiary circuit running on a Brayton thermodynamic cycle. The other major component of the tertiary circuit is the turbomachine. It involves adapting a model to Astrid's requirements (N_2, thermal power). Astrid would be fitted with 4 exchangers (2 per secondary loop) and 2 turbomachines. Finally, R&D should develop other minor but nevertheless essential gas ECS (tight seals, heaters, coolers, compressors, cold traps for purifying N_2 etc.) and study setting up of the other components in civil engineering. At the same time, the safety of Astrid coupled with the gas ECS needs to be demonstrated which means new codes have to be used. There is no feedback on coupling of a FNR with a gas ECS. R&D will be coordinated by the CEA and conducted by the CEA, Areva and Alstom (and their partners).

The characteristics of the Brayton were defined during the preliminary design phase (N_2 at 180 bars, theoretical yield 37/38%, Na temperature ranges -345/530 °C- and those of N_2 -310/515 °C, fluid flow rates) as was the general gas ECS design, following multicriteria optimisation of the system, taking account of the industrial materials on the market. The metal materials have also been chosen. An initial safety analysis has been conducted.

R&D conducted by the CEA concerns the exchanger. Heat exchange takes place at basic level by a plate contactor 1 mm thick (316L(N) steel used for Astrid) which places the Na circuit (6 bars) and the N_2 circuit (180 bars) in thermal contact, each made up of the appropriate cornered square tubes. The plates are welded together under pressure at 1000 °C to form an exchange module (23 MWth) which looks like a block of steel pierced with tubes. The diffusion welding process was developed by the CEA. The modules (8 in total coupled in pairs) are assembled in parallel in a chamber (10.5 m, diameter of around 5 m) under pressure to form the exchanger. Distribution of contraflow fluids (9000 tubes for Na and 18 000 for N_2) has successive branches for supplying each tube. The welding technology was developed by the CEA. It has an effect on the quality of the steel which influences heat exchange. The formation of large grains should be avoided. The steel microstructure is characterised by metallography. Fluid injection and recovery are ensured by specific distributors. Exchangers are of rare complexity and the first challenge is to construct and qualify a pair of modules.

The CEA has constructed several experimental modules (in DB-316 steel similar to 316L(N) steel) in plaque assembly conditions. Currently the CEA is testing their behaviour in Diademo at 40 KWth with N_2 pressure of 80 bars (thermo-hydraulics, fatigue, corrosion, etc.).

The CEA has established a gradual qualification schedule for exchanger materials and elements (plates, module, mock-up etc.) in Diademo until end 2019. The 1/20 scale exchanger can only be qualified when Cheops will be up and running.

The turbomachine will be qualified by Alstom.

The safety studies require modelling of the influence of any events on controlling fuel reactivity and cooling and containment. For this the CEA needs to develop the Cathare2 calculation code.

The gas ECS is a major innovation. The R&D remaining to be conducted remains considerable. If Astrid has one (beyond GenIV FNR-Na) it will be a doubly innovative reactor.

Partnerships

The CEA is continuing and stepping up national and industrial partnerships beyond R&D. These partnerships are essential for the validation and qualification of the reactor's innovative components, fuel cycle-related processes and safety aspects. Development of the components requires, among other things, significant experimental resources and new OCS and the development of the MOx fuel requires FNR for irradiation, which France does not have.

At international level the Astrid reactor project and the developments it gives rise to, such as the gas ECS or increased Pu consumption, interest several countries (USA, Russia, Japan, India, United Kingdom, China) and the Generation IV Forum. There are tangible projects with Japan and Russia and India (reactor components and codes with Japan, irradiation with Russia, safety with India). For the time being only Japan can invest in the design of the reactor and in its construction.

Europe is contributing indirectly to the Astrid reactor by its Euratom programmes to supper FNR and several countries: Switzerland, Italy, Germany and Sweden are in the ARDECO organisations network set up to conduct specific R&D as part of bilateral agreements under intellectual property protection.

Partitioning and transmutation

Technico-economic studies of the scenarios confirm that the introduction of a FNR-Na fleet would gradually reduce production of HL waste (nuclear glass) and SF assemblies in intermediate storage, these brought to become obsolete with a 100% MOXed FNR fleet. For all that, the hold of glass disposal between level A and levels B and D is believed to be almost the same since the quantity of FP and MA only basically depends on the fleet's power. Only MA transmutation would reduce hold from 150/170 to 20 m^2/TWhe.

Regardless of the interest of the ST in the MA management strategy and the foreseeable difficulty of its implementation in a FNR-Na fleet, it is fitting to continue partitioning and irradiation tests. The comprehensive EXAm conducted in Marcoule (see report no. 9) is ongoing. The 30 L of Coex raffinate have been decontaminated of U and Fe and concentrated at 5 L to meet the conditions required by the EXAm process.

The stage which R&D has reached in minor actinide partitioning (following that of Pu and U from spent fuel dissolution solutions) by hydrometallurgy results from studies which began more than 20 years ago. They were conducted by the CEA alone or in collaboration in 7 consecutive Euratom programmes from 1994 to 2015. The last one was Sacsess (7th RDFP) which brings together 26 partners and which aims to optimise Sanex, Ganex and EXAm. For all that R&D in this field is at the experimental demonstration stage of the processes (scale TRL 5 - 6). To move towards potential industrialisation TRL 8 - 9 needs to be reached which implies that the safety of the processes has been analysed. Sacsses is mainly used for that. An EXAm test on a Purex raffinate is to be carried out at the ITU in 2016 to test the effectiveness of a new complexing agent for more effective separation of Am from Cm and from lanthanides (Euro-EXAm process). In this test it is above all the United Kingdom (NNL), France (CEA) and Germany (KIT, Juelich, ITU) which are involved.

U, Pu and minor actinide partitioning by pyrochemical processes is a lot less advanced. Three of the 7 Euratom programmes are working on it. In Sacsses the pyrochemistry partnership has been extended to the USA and Russia. The two areas for spent fuel processing, electrorefining on aluminium in molten chloride media for metal fuels, and liquid-liquid extraction by a reducing metal liquid from molten fluoride media for the oxide fuel are being studied. The objective is to optimise processes but above all to maintain skills in pyrochemistry in Europe.

At the same time as the R&D conducted in Sacsses, the CEA is working directly in as ST with the USA, (DOE): extractant selectivity, preparation and irradiation of fuel samples for transmutation (Futurix and AmBB tests in ATR), Japan (JAEA): feasibility of pin preparation and irradiation, even of an assembly, fuel for Astrid, JCR-ITU: manufacture of samples for transmutation in homogeneous and heterogeneous mode and post-irradiation tests, and some other countries (Poland, United Kingdom, Israel): essentially fundamental studies on Am complexation.

For oxide sample preparation/irradiation $(U,Pu,Am)O_2$ (homogeneous mode, Am content < 3%) or $(U, Am)O_2$ (heterogeneous mode, Am 15 content 20%) the CEA actively collaborated with the 9 other bodies and the 2 industrialists (EDF and Areva) from the Pelgrimm Euratom Programme (2012-2017). Pelgrimm aims to compare the performances of pellet and oxide microspheres under neutron flows (spherepac fuel) in various temperature, density and fission rate conditions (mechanical hold, helium production, interaction with the cladding). A spherpac fuel would have advantages. Pelgrimm follows on from 3 other programmes on these mixed oxides (F-Bridge, CS-ESFR and Fairfuels). The Board has issued a R&D update and results from these programmes (see reports 8 and 9). Several methods for the preparation and characterisation (stoichiometries) of oxides in pellet or microsphere form have been developed in Pelgrimm including all previous R&D. They are power sol-gel-metallurgy or ion exchange resin impregnation-calcination methods (WAR process). $U_{0,87}Am_{0,13}O_{2-x}$ was synthesised at ITU (sol-gel, pellets and microspheres of 60 and 80 microns) and $U_{0,9}Am_{0,1}O_{2\pm x,}$ at the CEA (WAR process, 300-micron microspheres) for future irradiation from semi-comprehensive tests Marine 1 and 2 and that of Sphère, in the HFR. Sphère also uses $U_{0,75}Pu_{0,22}\ Am_{0,03}O_{2-x}$ oxides prepared in the Fairfuels programme, as does the Marios experiment ($U_{0,85}Am_{0,15}O_{2-x}$). Some non-destructive post-irradiation analyses (gamma spectrometry, visual aspect) were carried out in situ: discs from Marios, mini pin pellets and microspheres. They should continue and be completed by measurements of the gases produced in the irradiated samples (destructive tests) in the CEA's facilities. The results that have come out until now are preliminary.

Conclusion

In ongoing and future R&D for the Astrid programme, the following need to be differentiated:

- R&D which still needs to be conducted by 2019 (APD or Basic Design) so the results available at that date (presented in the PRS) can be used to back the decision to go onto the detailed design phase (2020 -2022) and launch construction of Astrid (in 2022) according to the design that takes account of the experiments the reactor will need to accommodate throughout its service life;
- R&D which needs to be conducted in view of testing in Astrid (after 2029), innovations aiming to equip future FNR-Na to improve safety and make their operation easier. This involves for instance new steel for cladding (ODS steel to reach 150 dpa), additional systems for preventing serious accidents (to be studied and qualified in Cheops after 2019), additional residual power evacuation systems (oil heat exchanger as near as possible to the safety tank in addition to EPuR), systems for the mitigation of serious accidents (minimizing the consequences of core fusion);

- R&D which needs to be continued in view of testing, including in Astrid (after 2029), technological innovations and processes for equipping workshops/plants for U and Pu multirecycling and Am transmutation. We can already see now that FNR spent fuel reprocessing will pose serious problems, mainly due to the increase in Pu content (from 1 to 20%) and ^{238}Pu and ^{241}Am content, fission products and high radioactivity. If the Purex process has to be replaced the challenges are considerable.

R&D generally requires:

- increasing the capacities of the scientific calculation tools and developing modelling codes on all scales;
- developing test platforms for validating and qualifying components.

A preliminary cost assessment is conducted as the project progresses.

APPENDIX XI:
FUNDAMENTAL RESEARCH

Fundamental research in relation to the 2006 law is multidisciplinary and multipartite. Generally it supports the R&D for the Astrid or Cigéo programmes or is prospective towards new concepts and/or process for these programmes. It also concerns two nuclear systems: ADS and molten salt FNR. Scientific publication in open literature is significant. Cross-partnerships only make it possible to identify the organisation coordinating the research, that we refer to in what follows as the CNRS or the CEA.

Research coordinated by the CNRS

The Board was informed of the research conducted in two federating programmes in detail: Needs-Materials and Needs-Waste.

The Needs-Materials projects concern the development and characterisation of materials for GenIV FNR and ADS (oxides and ceramics for cores, boron carbide B_4C, metal cladding). It involves methodological studies of the morphology of the oxides resulting from fritting at around 1100 °C according to those of precursors or damage due to Fe-Cr alloy irradiation (10 to 15%) by ions, electrons and neutrons or their fragilisation by sodium. The project on B_4C brings together researchers from 12 partner organisations including the CEA. Astrid and heterogeneous core FNR-Na use 10 times more boron carbide than Super-Phénix. Neutron absorption by the boron produces lithium (10% and more) and defects. The programme includes complete characterisation of carbide (fritting, structure by RX, NMR and modelling before and after irradiation, thermo-mechanical properties, B_4C-cladding interaction, B_4C-Na and B/C/Fe/Ni/Cr function diagram), characterisation which was only partial until now. The project programme aims to understand why B_4C has very good structural stability in FNR.

The Needs-Waste Noumeha project (6 partners bringing together all nuclear stakeholders and the IRSN, consortium of 9 laboratories and 3 SMB) aims to identify and use non-ferrous materials for SWP-V disposal packages and HL cell sheathing. This would notably reduce hydrogen production in the repository. A ½ scale ceramic package prototype exists (alumina silicate 4 cm thick). Since 2014 Needs is financing the Scellmo project in this programme for validating a sealing process for both parts of the disposal package with microwave heated glass. A glass composition was created, ceramic parts sealed at around 700 °C and it is now necessary to adjust the scale of the process. The sheathing tube being studied is a glass-ceramic fibre composite which could be formed by additive manufacturing. It is clear that here it is a case of original prospective upstream research breaking with the benchmark solution for SWP-V disposal. The Noumeha flow chart includes 5 WP for covering all sealing studies (temperature, microwave frequency, welding characterisation, mechanical properties, sheathing).

The 4 Needs SHS projects are included in the "Risks and societies" federating programme and are led by around twenty researchers. They aim for social understanding of nuclear in its diversity, based on field surveys (post-Fukushima situations) or archives on the nuclear sector from 1970 to 2010. The federating programme produces interesting seminars bringing together stakeholders from the nuclear sector and researchers in social sciences.

In the European Myrrha project France is mainly represented by the CNRS/Needs since 2005 (report no. 9, Appendix X). Myrrha has strong backing from Belgium. The CNRS's contribution was decisive in basic nuclear data, development of the accelerator components, construction and determination of the subcriticality of the Guinevere system. It is currently the WP leader for the H2020 Myrte project (2015-19) for the design and construction of the first stage of the final accelerator in Myrrha (Linac ADS of 100 MeV) and of the supra-conductive accelerating cavities. The decision to build the first part of Myrrha may be taken end 2017.

The CNRS has been developing a liquid coolant fuel reactor design alone for 20 years, made up of molten thorium salts. The MSFR (Molten Salt Fast Reactor) design which is a GenIV FNR is in the safety analysis stage. This analysis is very different from that of the other FNR due to the specific characteristics of the MSFR: fluoride salts, controlling reactivity without rods to regulate the neutron flux, partial and continuous reprocessing of the salt-fuel, emergency shut-down by core emptying. This is the aim of the H2020 Samofar programme (2015-19, 11 European partners including IRSN, EDF, Areva, CEA and 3 non-European: China, Russia, United States). In this vast programme, the CNRS is responsible for management and is 3 WP leader in thermo-hydraulics and neutronics, salt draining and salt treatment facilities. A test molten salt draining loop will be built to complete the thermo-hydraulic loop (Swath facility in Grenoble, France)

Research conducted by the CEA

The CEA-DEN's upstream research is pluridisciplinary. It is organised to clarify and support the R&D that the DEN is developing on the reactors (Gen II, III and IV, RJH, etc.) and fuel cycles. There is no clear line between fundamental research activities and R&D. The Board's yearly assessments on the CEA-DEN's activities often cover them. However we can say that the directing and unifying line that characterises the DEN's upstream research is multiscale and multitemporal modelling. In this doubly multidimensional framework, the CEA looks at the properties of materials, and reactor neutronics, fuel condition, component irradiation, that is to say general reactor simulation. It develops and uses theoretical modelling systems (Monte Carlo method with billions of draws), uses the most powerful calculators and experimental platforms for validating codes. Evidently the DEN works with other divisions from the CEA, Needs, EDF and Areva and participates in European programmes as mentioned above.

The CEA presented the latest developments in simulation/validation of the behaviour of the pellets and of the UOx or MOx fuel rod, covering the mechanical, thermal and physico-chemical aspects. The CEA is able to predict O, U, Pu and fission product diffusion, fission gas bubble development, chemical restructuring of oxides in the oxide grains and grain seals and oxide-cladding interactions. All of the codes are contained in the Pléiades platform (CEA, EDF Areva) which is a remarkable tool, also used for Astrid. Pléiades also capitalises on experimental data to validate the codes.

A field in which upstream research is very important is that of development of AmBB fuel, uranium and americium mixed oxide (see report no. 8 Appendix VIII and no. 9 Appendix XII). Here the Board has noted the difficulties identifying the phases of the U/Am/O system and their stability domains, especially during Am transmutation. The CEA is currently managing the production of $U_{1-x}Am_xO_{2\pm\delta}$ oxides with 0.75<x<0.5 and pellets with the high densities sought (> 95% of theoretical density). Hold in reactors in situ is being tested (Marios, Diamino and AmBB-1 preliminary tests). It remains to be demonstrated that these oxides, once prepared are stable before being placed in a reactor.

Alpha self-irradiation of oxides prepared with ^{241}Am first of all leads to oxidation (proven by DRX, O/U+Am increases, array parameter decreases) followed by swelling (lower than 1%) due to accumulation of helium and local defects around the Am (proven by SAX) but without general amorphisation of the structure (proven by DRX). The latest tests by XANES show that Am^{3+} exists regardless of x and only if 0.75<x<0.3, δ=0 and there is as much U^{5+} as Am^{3+} ($U^{4+}_{(1-2x)}U^{5+}_xAm_xO_2$). In the other cases U can be at degree of oxidation 5 and 6 and the oxides are substoichiometric in oxygen (δ = 0.03). This data was used, by modelling, to determine the domain of definition of the compounds $U_{1-x}Am_xO_{2\pm\delta}$ in the U/Am/O ternary. For all that studies on AmBB fuel oxide are not complete.

If France decides to introduce GenIV FNR reactors, upstream research will be necessary: recycling of PWR MOx (^{241}Am found in large quantities), rapid recycling of FNR MOx (presence of ^{238}Pu, new FP spectrum), potential recycling of AmBB. The processes will probably need to be changed and streamlined. The challenges are enormous but within reach of French teams if only they were provided with the resources.

Separative Chemistry Institute – Marcoule (CEA – CNRS – Montpelier University – ENSCM)

The ICSM (UMR 5257) occupies a joint research space with the CNRS (11 people), the CEA (22 people) and UM/ENSCM (11 people) devoted for 75% to the nuclear sector upstream of the DEN's activities. Research covers materials/nanomaterials (fuel dissolution and production, containment matrix) and partitioning (upstream and downstream of the cycle). Essential progress is made on the dynamics of the molecular mechanisms at the solid-liquid interface and/or supramolecular mechanisms at the liquid-liquid interface, respectively studied by high resolution microscopy and X ray and neutron reflectivity. The ICSM is studying the conventional dissolution of spent fuel components containing Pu (monitoring *in operando*) or sonochemical-assisted dissolution. Redox phenomena are highly important. Actinide oxide properties depend on the morphology of the precursors, in turn dependent on the original compound (inorganic or organic). The relationships have been clearly demonstrated. The ICSM has radically changed the way in which we saw liquid-liquid partitioning of metal elements by dissecting the effects of complexation, self-organisation and organic phase dispersion. This offers additional combinations of molecules and diluents for varying extraction selectivity. Everything is modelled from the microscopic to the mesoscopic. Finally, several prospective avenues are open in partitioning by using unusual phases: ionic liquids, foams, in additional to traditional phases by directly collecting metals, extracted from the organic phase. The ICSM opens perspectives in accordance with its mission.

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