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° 12

JUNE 2018

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FOREWORD: SETTING A DIRECTION

There is no coherent management of nuclear materials and radioactive waste without a clearly defined energy strategy.

As the Board writes its report, the National Commission for Public Debate is organising a debate on the Multi-annual Energy Programme in accordance with the law of 17 August 2015 on energy transition for green growth. In the framework of the National Plan for the Management of Radioactive Waste and Materials (PNGMDR), several scenarios have been considered for the future of the nuclear sector. In the framework of the National Inventory of Radioactive Waste and Materials (INMDR), Andra assesses the quantity of waste that these scenarios could produce. As recalled by the Board on 23 November 2017 in its hearing before the Parliamentary Office for the Evaluation of Scientific and Technological Options (OPECST), strategic choices in the field of energy have a direct impact on the design of radioactive waste storage. Indeed, these choices are liable to transform into waste significant quantities of nuclear material currently deemed recoverable.

France must choose between three strategic options for its nuclear power program.

- Option 1: continuation of the program with the objective, in the medium-long term, of establishing a fleet of fast neutron reactors (FNRs).
- Option 2: continuation of the program without the prospect of establishing a fleet of fast neutron reactors.
- Option 3: abandonment of the nuclear power program, by not renewing current reactors at the end of their life.

Each of these three options has very different consequences for the definition of nuclear materials as well as the volume and nature of waste to be disposed of in Cigéo.

Option 1, in accordance with the provisions of the 2006 law, aims to reuse fissile material (uranium and plutonium) from the existing fleet to produce energy in a future fleet of FNRs. It will stabilise plutonium stocks and could allow for transmutation of minor actinides from future nuclear power plants.

Options 2 and 3 imply direct storage of spent fuel. The absence of FNRs will allow neither the reduction of plutonium stocks nor the transmutation of minor actinides. In addition, prior to the dismantling of reprocessing facilities that would no longer be of any use, option 3 requires the processing of materials that will have become useless and have no dedicated channels. These options would entail a substantial modification to the technical specifications of the Cigéo project, in order to take on new types of waste.

Current uncertainties over strategy jeopardise France's ability to study and prepare the use of nuclear materials for the future. These uncertainties introduce instability into the Cigéo technical specifications.

The Board recommends that, after the public debate on the multi-annual energy programme, France should define a medium- to long-term nuclear energy strategy that is clear and understandable to all.

Given the volume of waste already produced (48 000 m^3) and the strength of scientific and technical knowledge already acquired, the Board also recommends that the process of filing the DAC (construction authorisation request) in the current legislative framework should not be slowed down.

SUMMARY – CONCLUSION

The nuclear industry generates radioactive waste. Some of it is especially dangerous for the public because of its high activity and long life. According to the provisions of the 2006 law, the long-term management of this waste has three components: its industrial storage, its disposal in geological repositories and the separation-transmutation of long-lived radioactive elements. In addition, the nuclear industry and the dismantling of decommissioned facilities also produce waste of lower activity which requires specific management, in particular because of the large quantities produced. This report assesses the state of progress of studies and research on these topics and reviews the approach to these issues in different countries with a nuclear industry.

CIGÉO GEOLOGICAL REPOSITORY

The purpose of the Cigéo project is the design, construction and operation of a reversible geological repository for long-lived high- and intermediate-level radioactive waste (LLHLW and LLILW). This repository should be created at a depth of 500 m in the approximately 130 m-thick Callovo-Oxfordian (COx) argillite formation in Meuse-Haute Marne. It has benefited from more than twenty years of studies and research carried out by Andra and the scientific community, notably in the underground laboratory at Bure. In contrast to storage, which is inherently temporary, a repository built on solid scientific and technical principles is a long-term solution because it relies on stable properties of nature.

The construction authorisation request (DAC) for the Cigéo repository should be filed during 2019, and then reviewed under the aegis of the Nuclear Safety Authority (ASN). In addition, the 2006 law stipulates that the DAC also gives rise to a report from the Board. Andra is currently preparing the DAC. The Board requests that the Cigéo safety assessment should cover the entire inventory identified for the DAC. The Board notes that, in the preliminary design phase, changes in the design of Cigéo move in the direction of a simplified architecture and increased use of more secure mechanical digging equipment, with a corresponding cut in costs.

Andra has updated the financial evaluation of the entire Cigéo project. The Board requests that it should clarify the impact of uncertainties and implementation risks on the overall cost of the project.

The Board appreciates Andra's extensive programme of consolidation and structuring of the knowledge it has acquired. This effort provides a robust foundation of knowledge in support of Andra's sizing calculations for Cigéo. This foundation is assessed and used by the authorities in charge of verification. Andra has set up a complementary research programme to improve evaluation of the performance of Cigéo seals and provide a better description of the transient behaviour of the repository after closure. The Board recommends that the estimate of the impact of spatial variability and change over the lifetime of the repository of the key parameters of the simulations should thus be refined. The Board considers that the knowledge base on radionuclide migration is sufficient to estimate their transfer over the very long-term to the COx boundaries.

It has recently emerged that the acceptability of the LLILW bitumen packages in Cigéo has been questioned. The question debated by the various stakeholders is *ultimately* to establish whether there can be (1) self-ignition of a bitumen package within an LLILW cell and (2) a spread to the whole of the cell if that were to happen. The body of knowledge is subject to differing interpretations. Additional studies are under way. At its hearing before OPECST, the Board requested an international scientific expert commission, and its creation was announced by the High Level Committee of the Cigéo project. The Board will follow with interest the progress of this international expert commission and will analyse the body of documents presented with the greatest attention.

Andra’s studies guarantee the feasibility of Cigéo. The Board draws the attention of the public authorities to the risks of indefinitely postponing the creation decision by preferring short-term solutions to the long-term solution. The Board strongly recommends that the public authorities mobilise all stakeholders to ensure that the DAC is submitted on time. It considers that the knowledge base acquired by Andra is sufficient for this. The decision-making process must not be slowed down, and our generation must take responsibility for the waste it has produced.

SEPARATION AND TRANSMUTATION

The 2006 law stipulates that transmutation research should be carried out within the framework of research on Generation IV reactors. This is why the CEA, in conjunction with industrialists, launched the Astrid programme to design and build an industrial demonstrator of a 600 MWe fast neutron reactor (FNR) that stands out from previous projects through an increased level of safety. The Board has followed the development of this project in accordance with the law and considers that the Astrid reactor concept represents highly significant progress compared with the world's other existing or planned FNRs.

The Board stresses the strategic importance of studies and research on separation and transmutation. These are essential for the controlled management of materials and waste from the nuclear power cycle; transmutation in particular would minimise the quantities of actinides to be disposed. For this reason, the Board wishes that the CEA maintains and develops its expertise and skills in actinide physics and chemistry.

Given the low cost of uranium, the expected deployment by EdF of a fleet of EPRs with a life expectancy of 60 years and the call into question by the supervisory authorities of the power level of the Astrid FNR, the CEA is now considering a research programme based on the implementation of a low-power FNR. This programme would take advantage of all the current achievements of Astrid and rely heavily on simulation. The Board awaits a presentation of this programme.

The Board regrets that a comprehensive and coherent medium- to long-term strategy for the nuclear power sector is still not clearly defined for the FNRs. The resulting uncertainties also have serious consequences for the necessarily multi-year programming of the research required to give France the means to achieve its ambitions. This research must now be mobilised to avoid jeopardising internationally acclaimed know-how.

At the request of the PNGMDR, industry has resumed studies into the multi-recycling of uranium and plutonium in PWRs. The Board notes that this multi-recycling allows only a limited reduction in the consumption of natural uranium at the cost of a significant increase in the production of minor actinides. Furthermore, compared to an FNR fleet, this approach to managing materials does not correspond with the objectives of the 2006 law.

DISMANTLING AND WASTE MANAGEMENT

All basic nuclear facilities must be decontaminated and dismantled after they are shut down. This produces significant quantities of very low-level waste (VLLW). Some of this waste could be recycled, as is the case in other European countries. However, recycling of VLLW requires a change in French legislation to recognise a release threshold. The Board notes that at this stage of the studies in progress, no clear conclusion has emerged.

The Board also questions the availability of reliable analysis tools and protocols for measuring radioactivity at levels of the order of Bq/g, for very large volumes of waste. It requests that it should be presented with the state-of-the-art on this issue. The Board recalls that the VLLW management policy must be based on studies assessing their harmfulness and thus meeting societal expectations.

The Board recalls that dismantling will produce significant quantities of LLLW in addition to those resulting from the processes implemented in the fuel cycle. To date, there is still no outlet for this waste. The Board recommends detailed consultation between producers and Andra to suggest LLLW management strategies to the ASN, taking into account the specific features of the waste.

At a time when several countries are involved in dismantling nuclear facilities, the Board encourages the implementation of an industrial strategy and a dismantling school in order to better exploit this know-how.

INTERNATIONAL PANORAMA

All countries using nuclear energy consider that geological disposal of LLHLW-LLILW is the reference solution. The implementation of such disposal is most advanced in Finland and Sweden. It was subject to a democratic process of consultation which led to wide acceptance by the communities concerned.

In Finland, where 4 sites were examined in terms of geological criteria, the final choice focused on the municipality of Eurajoki (Olkiluoto peninsula), which decided in favour of the repository. Construction of the repository started in 2017.

In Sweden, the application procedure for authorisation to build a deep geological repository for spent fuel started in March 2011. From 2011 to 2017, a formal analysis was carried out with independent expert advice. The safety authority (SSM) gave a favourable opinion in January 2018. The Environmental Court approved the Forsmark site, the host rock (granite), the engineered barriers and the environmental impact studies. It also gave a favourable opinion on the encapsulation plant and the spent fuel storage site (Clab). However, it wanted SKB, the project manager, to complete its dossier on the container and for the government to clarify responsibilities after closure of the repository, thus meeting demands from the municipality.

Municipalities with nuclear sites wrote to the Government and to Parliament to draw their attention to the need for a geological repository. They asked the Government to ensure that the authorisation process is not unnecessarily prolonged.

INTRODUCTION

In 1991, in a first law in France on the management of radioactive waste, Parliament, conscious of the specific character and novelty of the problems posed, entrusted a 15-year assessment of the state of advancement of research in this field to a National Assessment Board (CNE) made up of twelve independent and voluntary individuals. Under this law, CNE assessments give rise to an annual report to Parliament, submitted to the Parliamentary Office for Evaluation of Scientific and Technological Options (OPECST). This first Board (CNE 1) generated a total of 13 reports between 1991 and 2006.

In June 2006, a second law on the management of radioactive materials and waste confirmed the existence and role of the Board, which became the current CNE 2, and this document constitutes its 12th report to Parliament.

The Board evaluates current research and makes recommendations to aid decision-making by public authorities.

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This year, the Board held 9 one-day hearings, generally bringing together around sixty people representing all sector stakeholders. It also held 5 closed hearings and made several visits (see appendices I to VI). For this 12th report, it has taken account of documents submitted up to 1 May 2018.

As in previous years, the Board (*see* appendix VI) has devoted a large part of its work to the analysis and evaluation of research and studies on Andra's Cigéo project. Application of the 2006 law provides expressly that long-lived high-level and intermediate-level waste should be disposed in "deep geological strata". Andra is thus currently preparing the construction authorisation request (DAC) for an underground repository at a depth of 500 m in a clay formation that is more than 100 m thick and is located at the district border of the Meuse and Haute Marne.

The 1991 and 2006 laws also recommend that research be conducted on the separation and then transmutation of long-lived radioactive elements present in the nuclear waste in order to reduce long-term radiotoxicity. This report reviews the highly innovative results obtained from the Astrid fast neutron reactor (FNR) project, which was supervised by the CEA. The Board has noted that the CEA cannot continue this project and is considering a future FNR project suitable for research, coupled with an ambitious simulation programme. The Board points out the importance of transmutation research and hopes that a detailed analysis of this project will be presented.

The Board also assesses issues related to the management of nuclear waste, regardless of its activity. It stresses that the dismantling of many nuclear facilities will produce very large quantities of low and very low radioactivity waste in France and that its long-term management must be planned. To this end, it analyses the strategy adopted in several countries for its optimal management.

In all countries confronted with management of waste downstream of the nuclear power cycle, the deep geological repository is considered the reference solution, as pointed out in the 2014 OPECST report. The Board, benefiting from input from its foreign members, provides a review of progress in research carried out in the main countries with a nuclear industry for the disposal of high- and intermediate-level waste.

CHAPTER I: CIGÉO

The purpose of the Cigéo project, by application of the law of June 2006, is to design and build a reversible geological repository for LLHLW and LLILW radioactive waste as part of the French industrial waste management programme (PIGD). This repository should be created at a depth of 500 m in the approximately 130 m-thick Callovo-Oxfordian (COx) argillite formation in Meuse-Haute Marne districts. This project has emerged from studies and research carried out over a period of more than twenty years, especially in the underground laboratory at Bure, which demonstrated the excellent ability of the COx formation to isolate the waste and then sustainably confine the radionuclides it contains. Some descriptive elements of the environment surrounding the repository site are highlighted in Appendix VII.

Assisted by the system project manager, namely the Gaiya group (Technip-Ingérop), Andra, as prime contractor, carried out the initial preliminary design of Cigéo up until June 2015. After a project review commissioned by the Directorate-General for Energy and Climate (DGEC), the project entered the detailed preliminary design phase, which is expected to close with the submission of the construction authorisation request (DAC) scheduled for 2019. To prepare for filing of the DAC, Andra has developed a safety options dossier (DOS) which was under review by the ASN/IRSN until October 2017.

This chapter presents the Board's reflections on the progress made with the Cigéo project since this date.

1.1 CIGÉO LICENSING PROCEDURE

The licensing procedure for the Cigéo project is governed by strict provisions stemming from the laws on regulated nuclear facilities (INBs) and the Environmental Code. The main stages of this procedure are highlighted in Appendix VIII. In accordance with the legislation in force, Cigéo, as an INB, will be subject to ten-year inspections by the ASN. In addition, the 2016 law on reversibility provides the public involvement in the management of Cigéo.

1.1.1 Specific characteristics of Cigéo

Cigéo differs technically from any other INBs in its centuries-long operating life and the coexistence of surface and underground facilities.

This operating life implies construction in successive stages as well as staggered closure of the structures. It is reasonable to assume that components of the repository to be built in the distant future will be made in a different way from that provided for in the DAC. Indeed, the flexibility of Cigéo must allow it to adapt to incorporate feedback and scientific and technological progress.

The underground nature of the facility implies the design and qualification of specific equipment. To this end, Andra is planning an industrial pilot phase (Phipil) early in the life of Cigéo, during which the performance of the equipment, the design of the structures and demonstration of safety will be confirmed. It is during the Phipil, expected to last around a decade, that the first commissioning will take place to allow the reception of radioactive packages, in around 2030 according to Andra. This will be authorised after taking account of feedback and demonstrations carried out with inactive packages. Andra plans to produce, after sufficient experimentation, a report to initiate the process for authorisation of industrial commissioning as from 2036.

Cigéo's flexibility requires scientific and technical support throughout the life of the facility. Andra proposes to define an R&D programme in the form of a disposal facility development plan (PDIS), which designates the intermediate period between the DAC and the Phipil, the Phipil *per se* and then the operational phase. This document is currently the subject of discussions with the ASN.

The Board recalls that Andra must prove that the creation of Cigéo is possible with the techniques currently available and that the industrial pilot phase must take as long as necessary to validate the technical options and achieve the planned regular operational mode. In addition, it considers that continuing R&D is essential so that new technical solutions can be implemented in the future under optimal safety conditions.

1.1.2 Impact of the safety options dossier on preparation of the DAC

The safety options dossier (DOS) filed with the ASN in April 2016 was under review between July 2016 and May 2017. The IRSN recommendations were reviewed by the Permanent Group of Experts in May 2017, which issued an opinion with 3 recommendations and taking note of 66 commitments by Andra. ASN's final opinion was published in January 2018.

An analysis of the DOS was also produced by an international group of experts under the auspices of the IAEA, which met in November 2016. The Board also submitted an analysis of the dossier in November 2016, and its conclusions were set out in its report No. 11. A citizens' initiative was finally carried out by IRSN in association with Andra.

The conclusions of these different analyses agree in highlighting:

- the documentary nature of the dossier;
- a scientific and technical maturity that is generally satisfactory at this stage;
- the positive aspect of the principle of gradual development of the facility supported by the operational master plan.

The recommendations generally addressed the need to justify, at the time of the DAC, the repository architecture to ensure optimum safety. Andra reacted positively to the recommendations and requests and has made commitments to ASN/IRSN in particular on the following scientific issues:

- control of the behaviour and performance of closure structures;
- control of large-scale disposal behaviours, including long-term hydro-thermo-mechanical transients;
- monitoring mechanisms.

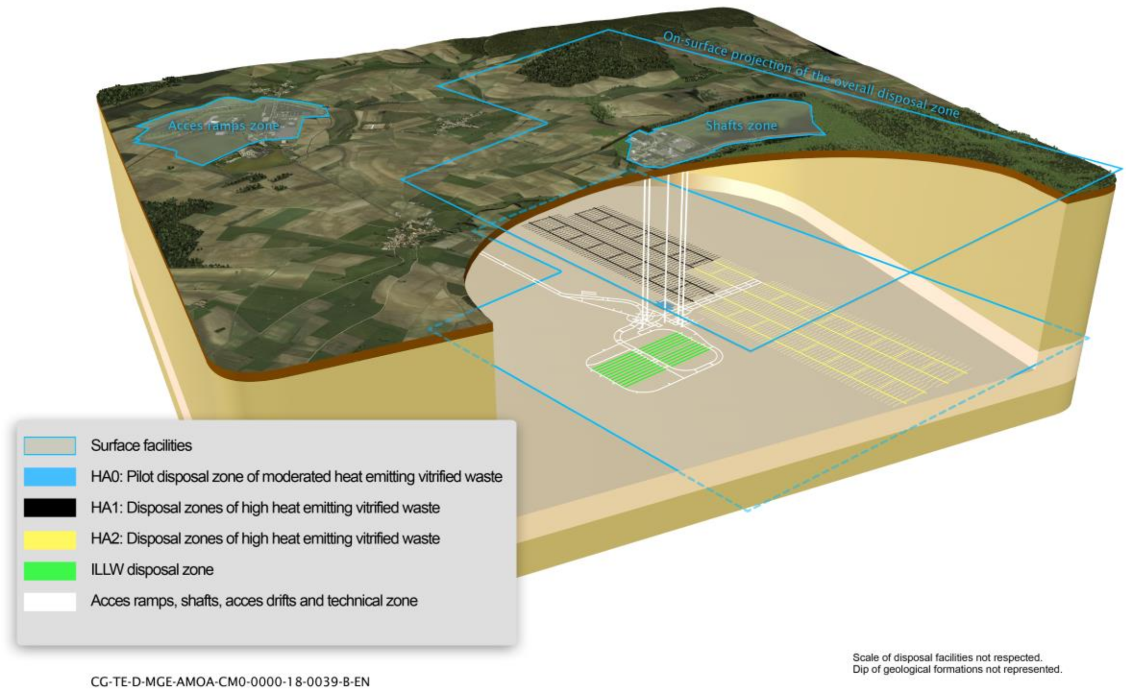
The main lines of scientific consolidation on which Andra has structured its R&D programme for the DAC are included in section 1.4 of this report.

An important reservation was expressed regarding the capacity of Cigéo to take in bitumen sludge packages. This point is the subject of section 1.5 of this report.

1.2 CURRENT STATE OF THE PROJECT

With the current detailed preliminary design (APD), Andra has developed the design proposed in the initial preliminary design (APS) used for the DOS. This has been made possible by consolidating optimisations considered during previous studies. It comes in the context of the safety requirements for the repository and the wish to move closer to the objective cost of the repository fixed by the Ministry.

In its reflections, Andra has made a distinction between subjects that could be taken into account in the APD to fix the reference configuration and those that would be mentioned only in the DAC as being possible future developments, not yet demonstrated (See Appendix IX).



Layout of the Cigéo project at the detailed preliminary design stage

The major changes taken into account in the APD impact on the ground plan. They concern the repository construction methods, the lengthening of the high-level cells and the design of the LLILW section (*See* Appendix IX and X).

The Board notes that changes in the design of Cigéo are based on simplified architecture and increased use of more secure mechanical digging equipment, with a corresponding reduction in costs. It appreciates that Andra has implemented its recommendation to explore, as from the industrial pilot phase, the entire perimeter of the LLILW area.

1.3 INVENTORY OF CIGÉO WASTE

The Cigéo reference and reserve inventories are used to design the facility (article D 542 of the Environmental Code). The first is made up of packages of LLHLW and LLILW from the PIGD (version E of 2016). It corresponds to the production of waste according to the current strategy for the management of spent nuclear fuel, regardless of source (civilian, military). It is used to develop the APD to design Cigéo and file the DAC. The second consists of waste packages liable to be received at Cigéo if this strategy is modified and if new management channels for other long-lived waste cannot be put in place. It is used to develop so-called adaptability studies for the design of Cigéo. These studies, included in the APD, consist in showing that the technical choices made for the configuration of Cigéo corresponding to the reference inventory are not prohibitive in relation to other waste.

The reference inventory is known (10 000 m^3 LLHLW, 73 000 m^3 LLILW) of which 48 000 m^3 has already been produced.

Andra has made proposals for the reserve inventory: spent fuel (civilian, non-reprocessed military, quantities depending on the reprocessing shutdown scenario), surplus LLHLW and LLILW if the electric power reactors were to run for 60 years instead of 50 years (2 000 m^3 of each category) and LLLW in the absence of outlets (Marcoule bitumen packages – 40 000 m^3, graphite jacket –

10 000 m^3, UNGG reprocessing waste from La Hague - 7 000 m^3). These quantities, accounted for in the 2015 national inventory, will be revised in the 2018 national inventory.

For the design of Cigéo, Andra is relying on the knowledge base of the primary LLHLW and LLILW packages, based on the information files about these packages sent by the producers. The reference inventory packages are grouped into 19 families for LLHLW packages and 80 families for LLILW packages referenced in the PIGD and collected in the Andra Oscar database. No such knowledge base exists for the reserve inventory packages. For the adaptability studies, the packaging of new potential waste is estimated from the preliminary acceptance specifications for disposal. The APD is based on current knowledge and can take into account any changes.

R&D in support of the DAC is organised according to the safety functions that each Cigéo component must fulfil. R&D on knowledge of the primary packages is not concerned.

The Board requests that the Cigéo safety assessment should cover the entire inventory identified for the construction authorisation request.

The knowledge acquired on the behaviour of spent fuel in Cigéo is not sufficient to support a safety analysis. Therefore, the Board notes that spent fuel cannot be included in the inventory of the construction authorisation request that will be filed in 2019.

1.4 THE KNOWLEDGE BASE

1.4.1 A knowledge base to support the sizing of Cigéo

The Cigéo project benefits from more than twenty-five years of studies and research carried out by Andra and the French and international scientific community.

Andra has embarked on a vast programme of consolidation and structuring of the acquired know-how in the form of a scientific and technical knowledge base. This helps to rank knowledge and identify operational implications, especially development needs. It also makes it possible to identify remaining uncertainties, in particular in response to requests from assessors (CNE, ASN, etc.). Finally, it should constitute the benchmark technical knowledge for the DAC.

The knowledge base is built from various sources. The raw data on the characteristics and properties of Cigéo components is listed in *scientific and technological knowledge repositories*; they include uncertainties and variability of parameters. The data is organised in *databases* that ensure aggregation and traceability from different sources (sensors, analyses). The base is complemented by *concept notes* on the evolution of components of the repository throughout its life.

Review sheets summarise scientific and technical topics at the heart of the design and safety issues. These sheets are fundamental to the sizing of Cigéo. This consists in showing that the guaranteed loads for the structure remain below admissible thresholds (deformability, maximum constraints, temperature, diffusive flow, etc.). Together, these inequalities constitute the “sizing criteria”.

By detailing the scientific bases, the hypotheses and choices underlying the simulations, the review sheets form an essential reference for the operator who calculates the loads and determines the sizing thresholds. They are equally useful for the auditor who can challenge the relevance and validity of the basic assumptions and verify the sizing approach in its entirety. These sheets are being prepared and will be gradually submitted to the assessors.

The Board welcomes the effort to structure all the data and models that will support Andra's sizing calculations.

Appendix XI shows, as an example, what are the thermal sizing criteria, derived from the knowledge base, conditioning the arrangement of packages in moderately exothermic LLILW cells (CSD-C), and how the sizing of the LLILW cells based on an innovative design interacts with the enrichment of the knowledge base through an R&D programme.

1) All the thermal simulations carried out show that the requirement of 65°C in the concrete elements, in normal operation, is the envelope criterion for sizing.
2) In terms of mechanical sizing, the studies show Andra’s capacity for innovation, with the proposal to combine mechanical tunnelling using a tunnel-boring machine with the installation of compressible lining segments as it advances.

The Board recommends that Andra applies this approach more generally, making it possible to better assess the relevance of the research efforts undertaken and the validity of the sizing criteria.

1.4.2 The research themes planned for the DAC

The additional R&D effort planned by Andra for the DAC or to be planned beyond that are organised into four themes:

- design of the HLW cells;
- control of the thermo-hydro-mechanical (THM) mechanisms in the HLW area;
- characterisation of the hydraulic water/gas performance in the EDZ (excavation damaged zone) and the sealing materials;
- analysis of the major multi-physical transitories.

Depending on needs, these developments will be carried out in the surface laboratory, the underground laboratory or in the Cigéo structure during the industrial pilot phase.

These research themes are detailed below. A more in-depth description is presented in Appendix XII.

a) Theme 1: HLW design

The HLW cells are blind micro-tunnels, oriented along the main horizontal stress, 100 m long for the HA0 area and 150 m for the HA1 and HA2 areas. As support, they are equipped with a steel lining intended to allow the placement of packages during the operational phase and their removal for possible recovery. A filler material (bentonite cement) is injected on top of the lining. The purpose of this material is to increase the mechanical strength over time by limiting voids and deterioration of materials.

For the DAC, Andra plans to increase research on the influence of the filling material on corrosion. Later, the cell excavation technique will be consolidated in the underground laboratory where a demonstrator campaign is planned from 2019 to 2024.

Finally, it should be remembered that the effective commissioning of the HA1/2 area will not take place before 2070. Major changes are highly likely, taking into account the progress made in the fields of construction and materials. They will be part of the changes made possible by the flexibility that guides the construction of Cigéo.

b) Theme 2: thermo-hydro-mechanical impact of the HLW area

The HLW areas give off a significant amount of heat during the thermal phase of disposal. The rise in temperature changes the hydraulic (overpressure) and mechanical (extension or sheer stress) behaviour of the host rock. These mechanisms are strongly coupled. Studies have enabled the development, qualification and validation of numerical models coupling thermal, hydraulic and mechanical processes. These models reproduce the near-field and far-field behaviour observed during underground laboratory experiments.

To achieve the dual objective of maintaining monophasic conditions and preventing fracturing of the rock, the characterisations and calculations define a maximum temperature criterion of 90°C. This temperature is compatible with the extension and sheer rupture thresholds.

Given the importance of certain parameters (Young's modulus, permeability) on the calculation results, the study of the impact of the spatial variability (inherent to the geological uncertainty) on the dispersion of the THM response must be detailed in order to determine an optimised envelope configuration of the HLW area.

c) Theme 3: hydraulic water-gas performance in the EDZ and the cement sealing materials

The sealing structures planned by Andra are based on a core of reworked clay materials contained by concrete support structures. Gallery coatings at each sealing core of clay should be removed. For the surface-to-bottom connections, sealing is achieved in the silt-carbonate unit (USC). For the seals of horizontal galleries, one option being considered is to kerf the argillite, to a depth corresponding to the connected fractured zone, then to fill it with swelling clay materials to constitute a hydraulic block.

The support structures will be made of low-pH concrete. Their main function is to provide mechanical strength and confinement of the clay core. The chemical change at the interface with the clays continues to be studied, especially with regard to the determination of the secondary magnesian mineral phases that are produced there. These results, expected after the DAC, do not constitute a safety issue, since the confinement function is not carried by the concrete support mass but by the clay core.

Andra has planned to continue its work on the sealing elements. Additional tests are scheduled in the underground laboratory to test backfilling galleries with argillite tailings, kerfing and removal of the lining segments. The characterisation of the hydro-mechanical behaviour of the clay mixtures should continue. The tests carried out by Andra will make it possible to define and justify, with a sufficient level of confidence for the DAC, the choice of components and strategies for making the seals. The overall performance of the sealing structures can thus be evaluated thanks to modelling, which is able to integrate the operating modes of these components during the different phases of the repository’s life.

d) Theme 4: the major multi-physical transients and the final equilibrium

Cigéo is destined to function for more than a century in operational mode; this will cause significant disturbances of the surrounding environment in thermo-hydro-mechanical and chemical terms. Some of these disturbances will still be active for long periods of time after closure. They will gradually fade away until a new stabilised state is achieved. The complexity of the elementary mechanisms involved and their coupling create transient situations with time constants that can be very different (see Appendix XII). Mindful of assessing the consequences on safety, Andra has focused on characterising and modelling the different areas of operation of the structure at different periods of its life.

Andra identifies the main factors capable of exerting demands on the environment by classifying them according to their importance. They primarily concern the relationship between water and gas in the structure’s components and in the surrounding argillite.

The hydraulic-gas transient simulations can be made highly representative by distinguishing the detailed architecture of the repository, its multiple components (COx, EDZ, concretes, clay and metal components) and taking into account the major multi-physical couplings (release of hydrogen, two-phase water/gas coupling, thermo-hydraulic coupling, gas diffusion/dissolution). The simulations provide a prediction of changes in gas pressure and water saturation in the repository components, over several hundred thousand years, as well as an assessment of gas leakages through identified transfer routes.

Once the hydraulic-gas transient has resorbed, the gas phase given off will have disappeared. Andra is carrying out three-dimensional hydraulic simulations in steady-state disposal, by individualising all the cells, galleries and surface-to-bottom connections and taking into account the permeabilities of the different components. The completely resaturated structure will evolve according to the regional hydrogeological boundary conditions, but also the local hydrodynamic properties of the repository components.

A more precise consideration of the transient hydraulic-gas regime should not fundamentally change the long-term safety of Cigéo, i.e. modify the maximum value of the radionuclide flow at the COx boundaries. It should, however, be carried out.

e) Recommendations

The Board appreciates the additional 4-theme research programme put in place by Andra.

Since Andra has shown that the sealing performance is strongly influenced by the water-gas transient, particularly within the EDZ, the Board considers that the demonstration would be even more robust if a test allowed evaluation of the behaviour of the EDZ during rehydration.

The Board approves Andra's provision of a hydromechanical behaviour test of a surface-to-bottom connection in the USC at a scale close to 1 and under conditions representative of re-saturation after closure of the repository.

The Board recommends that spatial variability and temporal variations of the key parameters of the simulations should be taken into account. Particular attention should be paid to the hydraulic-gas transient and the thermo-hydro-mechanical criteria as they can influence the properties of the COx. The role of natural hydraulic gradients in the COx and surrounding aquifers, and gradients disturbed by operations, must be clarified as they could affect long-term safety.

1.5 BITUMENS

The essential information concerning the disposal of bitumen sludge packages is summarised below. The presentation of the technical details and the various evaluations can be consulted in Appendix XIII.

1.5.1 Brief history

The disposal, in Cigéo, of 42 000 packages of LLILW bitumen mixes is included in the PIGD version E reference inventory (25% of the LLILW packages). Around 30 000 packages produced at the STEL (liquid effluent treatment station) in Marcoule are stored at this site. The others (12 000), produced at STE2 and STE3 (effluent treatment stations) are stored at La Hague.

R&D on the behaviour of the bitumen packages has been carried out by the CEA and other producers/holders of these packages (Orano and EdF) over many years. CNEs 1 and 2 have evaluated the results as they became informed about them.

From the first safety option studies on the Cigéo APS (initial preliminary design), the behaviour of the bitumen packages with respect to a rise in temperature has been questioned. In fact, these packages are not inert. The chemical compounds embedded in the bitumen matrix can, in principle, react with each other, or even with the bitumen; the reactions would be exothermic and temperature-sensitive. Furthermore, the bitumen, subjected to a rise in the external or internal temperature, may, depending on the circumstances, pyrolyze and even ignite in the air. These reactions could result in dispersal of the radioactivity trapped in the bitumen.

At the Board's request (reports 3 and 6), the CEA, Andra, EdF and Orano have undertaken studies on the temperature and fire behaviour of the bitumen packages. The CEA submitted a report to the Board at the end of 2014. The Board noted the good fire resistance of bitumen disposal packages and drew attention to the possible effects due to ageing of radioactive bituminous mixes (*See* Appendix XIII).

1.5.2 Studies and research under way

Following requests from the ASN, Andra, CEA, Orano and EdF have implemented an action plan. This means being able to decide between a suitable disposal concept and processing of the packages. The choice is as follows: Andra must demonstrate in the DAC the safety of the disposal of the bitumen packages as they are, as envisaged or according to new provisions, or the holders of the packages must be able to develop, on an industrial scale, a process for processing the bitumen packages.

The decision must be based on scientific, technical, economic and safety issues. The plan provides for the establishment of working groups and an external review.

Regardless of the outcome of the plan, Andra is now reviewing developments to strengthen the concept of disposal of bitumen packages with respect to the fire risk and bearing in mind the reversibility of Cigéo.

1.5.3 Conclusions and recommendations

The safe management of LLILW bitumen packages is a long-standing issue. These waste packages are not inert in the sense that the compounds they contain in the form of micro-inclusions dispersed in the bitumen (bituminous mixes) could lead to exothermic reactions with a rise in temperature.

The question debated by the various stakeholders is *ultimately* to establish whether there can be (1) self-ignition of a bitumen package within an LLILW cell and (2) a spread to the whole of the cell if that were to happen. Since Cigéo will operate for centuries and some bitumen packages are already 50 years old, the time factor must be taken into account in the evaluations It should be noted that no combustion of any of the 70 000 or so packages stored in France over the past 50 years has been reported.

The body of knowledge of the behaviour of bitumen packages with respect to heat energy input, acquired mainly by the CEA from 2013, is incomplete. Experts differ on the interpretation of this data. As regards physico-chemical processing of bitumen, only a few tests were carried out a decade ago. The body of knowledge established by the CEA is limited.

The Board asked during its hearing before the OPECST in November 2017 for a scientific and international expert assessment to be carried out. The OPECST made this request to the State on 25 January 2018. The High Level Committee for the Cigéo project, at its meeting on 7 March 2018, announced the creation of an *international expert commission on bitumen packages, under the shared control of the State and the ASN*. This expert commission should be launched in 2018.

> *The Board will follow with interest the progress of this international expert commission and will analyse the body of documents presented to the international expert commission with the greatest attention.*

1.6 LONG-TERM SAFETY OF CIGÉO

In the very long term, after the waste packages have been degraded, the passive safety of Cigéo will be ensured by the ability of the COx to curb the migration of radioactive or toxic species. This migration is essentially by diffusion. Convection could only occur in the near-field of the repository (EDZ) (*see* Appendix VII).

Andra has presented the knowledge base relating to the values of all the parameters taken into account in the migration models. In its previous reports, the Board has had the opportunity to evaluate the studies and R&D that have been required.

Andra considers that the values of all the parameters are sufficiently well supported to conduct its safety analyses. Indeed, the issue with safety analyses is not to rely on a complete and exhaustive description of the evolution of Cigéo, but to demonstrate that radiological protection thresholds will not be exceeded by estimating the maximum values of radionuclide flows at the COx boundaries and then the doses at the repository outlets.

> *The Board considers that Andra's knowledge base on the parameters controlling the migration of long-lived radionuclides in the sound COx, the main and ultimate barrier to containment of radioactivity, is sufficient to estimate radionuclide migration by modelling, up to the COx boundaries.*

1.7 SURVEILLANCE OF CIGÉO IN OPERATION

The term surveillance refers generally to the monitoring of a change to ensure thorough understanding and anticipation of the overall behaviour of the subject under consideration, to detect deviations, if any, and to identify their causes so that they can be quickly remedied. Surveillance of Cigéo focuses on the structural components that will be used for centuries, but also the geological formation that houses them. In addition, surveillance allows, in the context of reversibility reviews, verification of the ability of the operator to retrieve packages.

The Cigéo surveillance programme will be described in the DAC. It will start with the construction of Cigéo, and will continue during the operational phase and after closure. It will have to be able to evolve according to feedback and technological progress. Andra will have to ensure that this programme does not disrupt the operation of Cigéo in the passive mode.

This programme will build on the experience gained by Andra since the early 2000s in the Bure underground laboratory and on the results obtained from participation in international research consortia. Various sensors and monitoring devices have been placed in the underground laboratory to collect a whole set of measurements.

Some sensors were directly installed in the underground laboratory when they became available on the market, while others required special development. The devices tested are functional, with very good feedback on sensor failure. Progress is being considered in terms of resolution, energy, wireless transmission, robotic automation and finally digitisation as outlined in the following section. They are being explored through European projects, Investments for the Future projects and groups of academic and industrial laboratories.

In the underground laboratory, sensor monitoring and data logging are guaranteed by a scientific data management system developed by Andra over more than 20 years. Continually acquired data is geo-referenced and integrated into the Data Acquisition and Management System (SAGD). At the same time, manually collected data such as sample measurements are geo-referenced and integrated via a database called GEO. This data management system prefigures the one that will be put in place in Cigéo.

The Board notes the quality of the work carried out by Andra over the past 20 years in connection with surveillance in the underground laboratory. The Board points out that preservation of collected data for the future is essential.

With the consolidation of the project, the Board would like Andra to present its surveillance strategy for Cigéo, the sensor devices, the provisions for quality assurance of the measurements carried out and their integration into decision-making processes.

1.8 THE DIGITAL MODEL OF CIGÉO

Within three years, Andra wishes to develop a digital model which will have multiple uses. In the project phase, it facilitates virtual testing of operations and verifies the relationship between the objects and the geometry of the structure. During construction, it will allow for integration of the construction phases and improved flow of communication between workers on the site. During operation, it will provide support for operator training and a method for testing new procedures or handling unusual situations. The Cigéo model will be linked to the data management system mentioned above in the context of repository surveillance. The model will therefore evolve throughout the life of the project while always ensuring the traceability of any modifications. The consistency of the model with the object is crucial to the role it must play, so version tracking must also be preserved.

Andra has developed an operational prototype for handling operations in the LLILW galleries. This demonstrator allows immersive monitoring of the arrival of the package from the galleries, docking operations, transfer of the package to the handling area and then to the disposal cell.

The Board considers that the virtual package handling demonstrator is performing well and strongly encourages Andra to continue to digitize all of Cigéo's operational components, which should be completed by the time of filing the construction authorisation request.

1.9 CIGÉO COSTS AND FINANCIAL ENGINEERING

The target reference cost of Cigéo was set by a ministerial order in January 2016, for the period 2016-2156. The cost estimate is €25bn (2011), whereas the initial cost estimate was around €34bn. Andra believes that it can achieve this objective cost through a set of actions: technical opportunities, reduction of purchasing costs, and even longer-term gains. This target cost of Cigéo is covered by provisions made by the producers.

This cost-saving approach is important because it indicates how Andra could comply with the objective cost set by the State, while respecting the requirements of safety, security and reversibility. In managing technical opportunities with unchanged security and reversibility constraints, organisation of project management and the allotment strategy allow a balance to be struck in terms of defining contracts and the time scale for their implementation.

1.9.1 Contract engineering

The scheme adopted is based on the public procurement procedure and a consultation between Andra and the producers, based on the principle that the polluter pays. Particular attention will be paid to the ability of local companies to respond to calls for tender for these contracts, alone or with the help of more specialised companies.

Two different procedures are envisaged.

1) The so-called "design-build contract" involves a dialogue between several proposers and the contracting authority, usually leading to a firm price for the work to be carried out by the chosen lead contractor. This procedure would be considered mainly for surface works. For these, Andra and the producers benefit from feedback guaranteeing the quality of the work to be carried out.
2) The "call for applications" procedure consists in first choosing a lead contractor, then making allocations to carry out the work. In this case, when choosing the lead contractor, the price of the work to be carried out is provisional, because it depends on the individual contract for each lot. Andra says it prefers to use this procedure for underground work, because of the greater financial risk associated with carrying it out.

The Board notes that the contract engineering choices do not optimise management of the financial risk portfolio. This is assumed by Andra, almost unilaterally.

1.9.2 Provisions made by waste producers

Orano is covering the expenses associated with Cigéo, though the source of this cover has not been the subject of a presentation to the Board. The CEA has presented a schedule of provisions covering the contributions due, following an envelope approach (creation of an additional envelope for contingencies and a claim from the State).

EdF is using financial markets to ensure provisions based on the calculation of current and committed expenses for dedicated assets[1]. Asset management (essentially a portfolio divided equally into equities, bonds and unlisted assets) allows for coverage of future charges at 108.5%. Current regulations impose a coverage rate of 110%. As a result, EdF will increase its provisions.

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[1] Spent fuel management, long-term management of radioactive waste, recovery and conditioning of old waste, dismantling the fleet in operation, dismantling of first-generation and last-generation power stations.

For EdF, the discount rate for future charges (4.1% in 2017) is significantly lower than the rate of return on dedicated assets (6.6% in 2017). The discount rate calculated according to a method specific to the company and validated by its auditors is framed by the ceiling rate set by the administration (4.16% in 2017). On average, since 2004, EdF notes that the performance rate of its dedicated assets (6.3%) is significantly higher than that of the discounting of its future charges (4.8%). However, the downward trend in the discount rate (4.2% in 2016, 4.1% in 2017) will automatically increase the weight of future expenses and therefore the EdF's debt. The consequence is an increase in provisions in order to maintain sufficient coverage. Indeed, the difference of 2.5% recorded in 2017 between the performance and discount rates only covers half of the increase in provisions due to a 0.1% decrease in the discount rate.

The Board notes that the overall management of dedicated assets ensures profitability that is significantly higher than the discount rate. This observation shows, in hindsight, the prudent nature of the choice of discount rate.

In addition, to meet regulatory obligations, EdF will increase its provisions due to the decrease in the discount rate.

Finally, the Board requests Orano to present the composition of its provisions.

It should be noted, nevertheless, that there are significant uncertainties as to the cost of Cigéo, which could change the amount of the provisions dedicated to its creation.

On the occasion of the cost update that Andra is currently preparing, the Board asks Andra to clarify the impact of uncertainties and implementation risks on costs.

1.10 THE NEED TO DECIDE

Regardless of the strategy for the nuclear power sector, France already has 48 000 m^3 of LLILW and LLHLW currently stored by the producers and intended, according to the 2006 law, for geological disposal. This accounts for more than half of the estimated waste stock generated by the current fleet during its life time.

1.10.1 Storage or disposal?

The nuclear industry generates long-lived intermediate and high-level waste. This waste is dangerous to the public in the event of exposure to radiation. It ceases to be if it is effectively isolated. There are two solutions to this: a short-term solution, which is storage, and a long-term solution, which is geological disposal.

Storage is an effective solution, since waste is effectively excluded from interaction with the population as part of ongoing active surveillance. However, this can only be a short-term solution: we must be able to ensure and guarantee this surveillance throughout the period that this waste remains dangerous. This is estimated to be tens of thousands of years for much of it. Regular repackaging would also be inevitable, with a cost constraint, but also maintenance of technology, particularly in the handling of highly radioactive materials. This long time frame inevitably entails risks, since there is no guarantee, in an unknown and probably unstable future, that surveillance will be appropriate and effective. Finally, since it seems unlikely that this type of storage would be continuous over such a long period of time, it would necessarily have to lead to another solution.

Yet there is no evidence to suggest that a new technical solution can help reduce the harmfulness of waste in the foreseeable future and thus solve the problem.

In contrast, deep geological disposal provides a solution to isolate this long-lived waste through passive safety, enabled by deep burial in a layer of clay. This solution has the considerable advantage of solving the problem by choosing a site with geological stability over a very long time frame. It removes the uncertainty over future surveillance and ensures safety, provided not by unreliable human means but by the thickness of the natural geological layer.

It also removes the burden on future generations of extremely long active surveillance of this waste. The costs of such surveillance over a very long period of time would be charged by the current beneficiaries of electricity generation to a large number of future generations, who would inherit this burden of our making. Moreover, disposal is necessarily less expensive than storage in the long term. Admittedly, building the structure over the scheduled period is more expensive than the corresponding storage over the same period. But what should be compared is the cost of storage over a very long period with the limited cost of building a repository over one hundred to one hundred and fifty years. This calculation cannot be done with precision, but the immeasurable nature of the time periods shows that storage would necessarily be more expensive.

1.10.2 The risk of putting off the decision

Given the fact that studies have made good progress in ensuring project feasibility, and given that the regulatory framework now allows for the filing of a DAC, French society is faced with what looks like a dilemma leading to a significant risk, that of perpetually putting off the decision to build the geological repository.

- On the one hand, the repository, if it is well designed and well made within the framework of the principle of reversibility, represents a durable, safe, ethical, complete and economic solution.
- On the other hand, the existing storage is in fact an effective and satisfactory solution in the short term. There is no immediate danger in continuing storage.

Reasoning is tending then to emerge spontaneously: there is no urgency to start the construction of the repository structure since, in view of the persistence of the dangerous nature of the waste, a few years more or less do not make a difference It is tempting therefore to wait, and put off the decision. We can always ask for additional studies and consider that, given the thousands of years necessary for the radioactive decay of waste, the case has not yet reached a sufficient degree of maturity. But since uncertainties are inevitably and structurally linked to building such a structure, the risk is that we will never consider that we are ready. In reality, we can only be ready if we start work and, in the context of the principle of reversibility, try to remove uncertainties through feedback.

1.10.3 The institutional context of decision-making

The general context of the French institutional situation, marked by mistrust of institutions by the public, encourages the temptation to postpone the decision indefinitely.

- Producers, who are obliged by law to make provisions for the financing of the repository, have no short-term interest in committing themselves to something which, from a financial point of view, can be put off (see § 1.9). By contrast, in Finland and Sweden, the decision-making process went a long way because the law provided an incentive for producers to move towards such a repository, without which they could not start up new reactors.
- From the point of view of the safety authorities, the legitimate concern to protect concerned populations naturally leads them to wait for a convincing safety approach before authorising the commissioning of the structure. When making the construction authorisation request, the supporting evidence must be sufficiently detailed to give reasonable assurance that this demonstration of nuclear safety is confirmed. The

definition of what is reasonable can lead to very different approaches across countries and cultures to achieve the same end result.

- On the side of the operator, subject to the opinions of the supervisory authorities and dependent on the public authorities, it has to provide legitimate answers to renewed requests in terms of safety demonstrations and expectations resulting from public debates.
- In northern countries, the State's only political contacts are municipalities familiar with the nuclear industry, which have broad administrative competences, and which took the responsibility to agree to the repository, taking into account the economic benefits. In France, by contrast, municipalities and local authorities do not have administrative powers to support and promote the decision-making process even if they wanted to, and it is therefore the State alone that makes the decision.

There is therefore a real risk of stagnation due to this temptation to put the decision off indefinitely, on the basis that there is no urgency since we have the efficient storage solution. But this real risk of stagnation could lead to the gradual and indifferent abandonment of the project and therefore to the highly questionable choice of perpetuating a short-term solution to the detriment of a long-term solution, thus favouring present generations to the detriment of future generations.

The Board strongly recommends that the public authorities mobilise all stakeholders to ensure that the DAC is submitted on time. It considers that the knowledge base acquired by Andra is sufficient for this. The decision-making process must not be slowed down, and our generation must take responsibility for the waste it has produced.

CHAPTER II: SEPARATION AND TRANSMUTATION

2.1 MATERIAL AND WASTE MANAGEMENT

The 2006 law stipulates that transmutation research should be carried out within the framework of research on Generation IV reactors. This is why the CEA, associated with industrialists, launched the Astrid programme to design and build an industrial demonstrator of a 600 MWe fast neutron reactor (FNR) that stands out from previous projects through an increased level of safety thanks to its many innovations.

The Board has followed the development of this project in accordance with the law and appreciates the work carried out in the framework of the detailed preliminary design.

Given the low cost of uranium, the expected deployment by EdF, of a fleet of EPRs with a life expectancy of 60 years and the questioning by its supervisory authorities of the power level of the 600 MWe Astrid FNR, the CEA is now considering a research programme based on the implementation of a lower power FNR. This new reactor would take advantage of all the current achievements of Astrid and would feed into a simulation programme.

The Board reviews below the achievements of the Astrid programme, the outline of the new programme envisaged by the CEA and the studies carried out by the CEA and industry to respond to the PNGMDR's request to analyse various scenarios for the management of nuclear material and plutonium (Appendices XIV and XV).

2.2 ASTRID

Following the 2006 law, in response to the Government's request, the CEA launched the Astrid programme in 2010. With the Rapsodie, Phénix and Superphénix reactors, the CEA has a very high level of expertise in FNRs. In previous reports, the Board has highlighted the potential contribution of FNRs for the management of material and waste from the fuel cycle. Here it reviews the main results obtained over the past eight years.

For the development of an industrial and technological demonstrator, joint studies by CEA, EdF and Orano converged very quickly on the design of a 600 MWe sodium FNR and associated facilities. The technical specifications stipulate that this reactor must satisfy a series of criteria:

- Have the safety and operability of an industrial and commercial reactor that would be superior to those of the EPR. This reactor, planned for a life of 60 years, would be iso-generating for plutonium
- To allow multi-recycling of plutonium by using a fuel combining depleted uranium (or reprocessed uranium) with plutonium resulting from the reprocessing of spent UOx and MOx. This implies adapting uranium and plutonium separation processes for the treatment of spent PWR MOx fuels and the development of a manufacturing facility for a plutonium-rich MOx FNR fuel.
- Allow the transmutation of minor actinides, especially americium and neptunium. This implies separation of these elements, on an industrial scale, from the spent fuel and the manufacture of fuels charged with americium or neptunium for irradiation at the periphery of the core.
- Demonstrate an increased capacity to consume plutonium, in order to remove the plutonium involved in the cycle.

2.2.1 Design of the reactor

At the end of 2017, a progress report on the design of the Astrid 600 MWe sodium FNR was submitted to the supervisory authorities. At the end of the APD planned for 2019, the CEA will provide definition studies including a complete file with construction plans. Financing of the CEA-State contract for the Astrid 600 MWe ends with this deadline.

Studies carried out by the end of 2017 allowed definition of the major components of Astrid including the core, the fuel handling and storage devices, the residual power evacuation systems (active and passive), energy conversion system (ECS) as well as on-site implementation with civil engineering and associated infrastructure. Thanks to the studies and experiments carried out in 2016-2017, development of gas ECS has progressed and now allows a sound choice to be made between steam ECS and gas ECS.

The overall assembly of Astrid in gas ECS or steam ECS configuration is now available thanks to a 3D digital model of the entire reactor and ancillary facilities. Digital modelling is being extended to include complete project management.

The Board considers that the Astrid reactor concept represents highly significant progress compared with the world's other existing or planned FNRs.

2.2.2 Cycle facilities

Significant innovations have been made in the manufacture of assemblies, involving many materials such as $UPuO_2$, B_4C, MgO and steels of various types. Finally, the CEA has undertaken the reconstruction of the industrial base for the manufacture of the hexagonal tubes and other parts of the FNR MOx assemblies.

Studies on the facilities for the Astrid material cycle are continuing, to clarify their location and configuration.

As for the facilities used today for the study of the transmutation of americium (Atalante), they only allow the manipulation of a few grams of americium (rod scale) and new specific facilities will be necessary for the industrial implementation of a process.

2.2.3 Increased consumption of plutonium

The CEA is also studying the increased consumption of plutonium from the Astrid core with several approaches: a fuel without uranium, a specific assembly (inert, moderating or neutron-absorbing rods) while maintaining a low void effect, the Doppler effect and the delayed neutron fraction ensuring control.

2.2.4 Separation and Transmutation

a) Separation

In order to enable the study of the changes necessary for the transition to a fleet comprising FNRs while preserving the operation of the current fuel reprocessing and fabrication plants, the CEA is pursuing R&D on the enhanced separation of uranium, plutonium and fission products Since 2016, the CEA has been revisiting all the operations related to this separation in which it has acquired unique world expertise:

- dismantling of the rods,
- oxide-sheath separation (laser cutting, voloxidation),
- dissolution of the oxides (continuously),

- U/Pu separation in a single cycle without a reducing agent (asymmetric monoamides),
- synthesis of mixed oxide (syn-crystallization U(VI) and plutonium (IV), co-denitration), manufacture of pellets (granulation, paste),
- online packaging of waste (decontaminating fusion of shells, incorporation of fines, new glasses),
- continuous on-line control.

Given the complexity of the Exam process for the separation of americium with a view to its transmutation, since the beginning of 2017, the CEA has participated in the Geniors programme (GenIV Integrated Oxide Fuels Reprocessing Strategies - 24 partners from 11 countries) aimed at simplifying the Euro-Ganex, I-Sanex and Euro-Exam processes, all based on CEA processes.

b) Transmutation

The CEA has acquired good control of the preparation of rods consisting of mixed oxide of uranium and americium ($UAmO_2$) or metallic uranium-americium (UAm).

The irradiations for the Diamino programme were carried out in the HFR and Osiris reactors and the post-irradiation examinations have been carried out or are under way. Other programmes (Marios, Marine and americiumBB-1) plan for new irradiations for which the CEA expects that the examinations will be carried out in the framework of international collaborations.

The CEA is thus continuing the study of the transmutation of americium, which once removed from vitrified waste, would significantly reduce the thermal contribution.

The Board stresses the strategic importance of studies and research on separation and transmutation. These are essential for the controlled management of materials and waste from the nuclear power cycle; transmutation in particular would minimise the quantities of actinides to be stored. For this reason, the Board hopes that the CEA will maintain and develop its expertise and skills in actinide physics and chemistry.

2.3 PROPOSED EVOLUTION OF THE ASTRID PROJECT

As the need for an FNR industrial prototype has become less urgent for the development of a fleet of FNRs, the CEA is now considering an FNR project suitable for research. This project, dedicated to the knowledge transfer and development of French expertise on fourth-generation FNRs, would make extensive use of simulation, an area of excellence for the CEA.

This research FNR should, like Astrid, be able to:

- operate with a fuel that combines depleted uranium (250 000 tonnes from the enrichment process are available) and plutonium (from the processing of spent UOx and MOx);
- continue studies on transmutation of minor actinides;
- recycle its own plutonium;
- study ways to increase consumption of plutonium.

In 2018, the CEA should prepare a presentation file for the “Sodium FNR simulation” programme, which will specify in particular the reactor power, simulation tools and experimental platforms.

This preparatory phase would also redefine national and international partnerships, starting with the special relationship with Japan established under the Astrid programme.

This reactor would be designed not as an industrial demonstrator but as a research tool dedicated to experiments on sodium-FNR physics, structural components and materials, energy conversion devices as well as fuels adapted to iso-, over- or sub-generator operating modes. Its design would benefit from all the studies and advances made with Astrid, as they are compatible with this reduction in power.

The idea put forward by the CEA contains the essential elements of the 2006 law, namely the transmutation of minor actinides and the consumption of plutonium with a view to closing the cycle.

The Board regrets that a comprehensive and coherent medium- to long-term strategy for the nuclear power sector is still not clearly defined for the FNRs. The resulting uncertainties have serious consequences for the necessarily multi-year programming of the research needed to give France the means to achieve its ambitions. This research must now be mobilised to avoid jeopardising internationally recognized know-how of France.

2.4 SCENARIOS AND PLUTONIUM RECOVERY

2.4.1 Scenarios for deploying a fleet of FNRs and their consequences

Since 2013, the CEA, Orano and EdF have been studying industrial scenarios for possible developments in the nuclear power plant fleet. The approach consists in developing software to establish the material balance of the cycles to estimate the nature and quantities of the corresponding waste. The results of the calculations indicate modifications to cycle facilities that would be required; they are compared with industrial and economic realities (*see* Appendix XIV).

2.4.2 Multi-recycling of plutonium in PWRs

In the absence of an FNR and at the request of the PNGMDR, the CEA, Orano and EdF have resumed studies on multi-recycling uranium and plutonium in PWRs, with Corail and Mix assemblies (*see* Appendix XV). While EDF had demonstrated that PWR plutonium multi-recycling was impossible for combustion rates close to 70 GWd/t, a combustion rate limited to 45-50 GWd/t makes multi-recycling possible. The consumption of natural uranium is thus reduced (by about 10%) compared to that of the current fleet, but the production of americium and other minor actinides is significantly increased (by about 30%). This increase in waste volume would require an increase in the size of the HLW area in the geological repository. Regarding the plutonium, this multi-recycling stabilises the stock but does not increase its consumption.

The Board notes that this multi-recycling of plutonium in PWRs allows only a limited reduction in the consumption of natural uranium at the cost of a significant increase in the production of minor actinides. Furthermore, compared to a FNR program, this material management approach does not correspond with the objectives of the 2006 law: transmutation of minor actinides and increased plutonium consumption.

CHAPTER III: WASTE MANAGEMENT

The management of radioactive waste is regulated by the PNGMDR and orders from decree 2017-23 of 23 February 2017. It has many facets. In this chapter, the Board assesses progress in a few areas with a focus on waste from dismantling. It develops these points in Appendices XVI and XVII.

3.1 VERY LOW TO VERY VERY LOW LEVEL WASTE

In 2016 the Board highlighted the lack of planned outlets for this waste and therefore the need for a new management approach in order to take into account the very large volumes in the future. They will be generated by the dismantling of nuclear power plant facilities and historic nuclear installations already shut down (or even already dismantled). In addition, the geographical location of the reactors and facilities throughout the country will give rise to widespread production.

Current thinking would associate Andra and the waste producers in setting up a new management approach for very low level (VLLW) and very very low level (VVLLW) wastes. The IRSN is also studying these developments at the scientific, technical and also societal level.

Several important points motivate this thinking:

- the creation of dedicated disposal centres in anticipation of the saturation of the VLLW disposal centre, Cires located at Morvilliers, by 2030;
- the technical and economic evaluation of the recycling of metallic VLLW and rubble from concrete;
- the conditions for creating a release threshold for VVLLW waste.

VLLW recycling requires changes in French legislation over the problem of a release threshold; this threshold would obviously be linked to the absence of health impact of the waste thus released. The introduction of a release threshold must, of course, be accompanied by control measures.

A recent study by Andra shows that, on average, 70% of VLLW (in particular metal and rubble) stored since 2003 at Cires has a specific activity lower than that declared by the producers and less than 1 Bq/g. The activity of the other VLLW never exceeds the producers' declarations, which are therefore, in all cases, conservative. In countries where there is a release threshold (see Chapter IV), this waste would have been declassified for recycling or sent for conventional disposal. This approach, applied in France, would have delayed by several decades the saturation date for Cires.

Studies on the recovery of VLLW are continuing. EdF has recently acquired Cyclife (see Chapter IV and Appendix XXI). This company located in Studsvik, Sweden, has 30 years of expertise in the field of recycling activated or even contaminated metals. EdF acquired Cyclife to gain experience in the field of metal recycling. EdF wants to recover large homogeneous batches of metallic materials (80 000 t of steam generators). EdF will soon carry out an experiment at Cyclife by recycling two steam generators from France.

VLLW, unlike other types of waste, is not included in an industrial waste management plan (PIGD) which manages future flows in consultation with producers and Andra. Such a plan appears indispensable. In this respect, ASN wishes to set up an overall industrial plan for VLLW management by 2020.

The Board notes that studies so far have not led to any innovative solution capable of developing changes in methods for VLLW management.

The Board recalls that the VLLW management policy must be based on studies assessing their harmfulness and thus meeting societal expectations. It requests that it should be presented with the state-of-the-art on these issues.

3.2 TENORM WASTE

The procedures for storing Tenorm (*See* Chapter IV and Appendix XVI) from the non-nuclear industry and managed by the directorate-general for risk prevention (DGPR) will be amended as from July 2018. The decree is imminent. Any Tenorm with an activity in uranium (U), thorium (Th) or potassium (^{40}K) greater than 20 Bq/g will be stored in Cires like VLLW from INBs. Only Tenorm of very low activity (less than 1 Bq/g in U or Th and 10 Bq/g in K) will be able to go into authorised conventional disposal or be recovered. It will be up to the operators who produce Tenorm to characterise it according to future regulations. Depending on its type, it will be sent for recycling, conventional disposal or radioactive waste disposal.

The Board has questions regarding the protocols that will allow the characterisation of natural radioactivity at levels close to Bq/g for industrial waste. It requests that it should be presented with the state-of-the-art on this issue.

3.3 LLLW

With regard to long-lived low-level waste (LLLW), Andra is continuing to characterise the Vendeuvre-Soulaines site. It is assessing the capacity of the site to receive, isolate and then confine the radionuclides according to the two shallow disposal concepts. The DOS for a preliminary design for disposal of LLLW should be provided to ASN by 2021.

The disposal of LLLW is a significant and complex problem to which the Board has been drawing the attention of producers and public authorities for many years. The absence of disposal leads in particular to prolonged storage or delayed dismantling. It has an impact on the Cigéo reserve inventory. The varied nature of waste grouped under the LLLW designation makes it difficult to design a single disposal facility.

The Board recalls that dismantling will produce significant quantities of LLLW in addition to those resulting from the processes implemented in the fuel cycle. To date, there is still no outlet for this waste. The Board recommends detailed consultation between producers and Andra to suggest LLLW management strategies to the ASN, taking into account the specific features of the waste.

3.4 WASTE MANAGEMENT

3.4.1 Storage

The waste packages from the nuclear power fleet and the cycle facilities reach the LILW-SL and VLLW waste disposal sites or, depending on their nature, are kept in storage pending: decrease in their activity (tritium waste), decrease in their thermal power (LLHLW) or the commissioning of a geological repository (LLLW, LLILW and LLHLW).

All the industrial storage facilities have received good feedback in terms of both performance and operation. Their modular construction provides flexibility in the management of waste intended for Cigéo or other repositories (*See* Appendix XVII). However, extending the storage of waste packages beyond the technical requirements for their acceptance in storage is not a responsible management solution. It requires active safety, using resources with a cost that needs to be quantified. It contributes to immobility.

The Board considers that only an authorised repository is able to provide a safe and also ethical solution to the problem.

Although current or planned storage capacities are sufficient to cope with a delay in commissioning appropriate disposal facilities until around 2040, the Board stresses that the extension of storage should not be a strategy to defer the implementation of repositories.

3.4.2 Clean-up & dismantling

The Board has addressed this vast subject in previous reports and details of the latest R&D results are given in Appendix XVII.

Those conducted by EdF mainly concern various reactors (Chooz, Brennilis, UNGG, etc.) while those from Orano and the CEA relate more to nuclear fuel cycle facilities, UP2 400 and GB1 for Orano and UP1 for the CEA. Waste stored and accumulated during operation of the facilities, for which recovery is often very difficult, is added to the waste resulting from the dismantling process.

The CEA is in charge of dismantling the Marcoule G1, G2 and G3 reactors, which have been at IAEA level 2 (*see* Appendix XVII) for decades. Ongoing actions will allow development of methods to characterise and analyse graphite activity that can be applied to the dismantling of all UNGG reactors. In addition, the CEA is continuing R&D on magnesium waste, which is difficult to manage because of its reactivity with water. The matrix adopted meets the rheological criteria for casting and mechanical strength which are required for implementation on an industrial scale. The first full-scale tests of this matrix have been carried out.

Orano is continuing its research on the recovery and packaging of waste, stored in several silos at La Hague (*see* Appendix XVII).

EdF has been involved for the past ten years in the dismantling of the 6 UNGG-EdF nuclear power reactors (*see* Appendix XVII). EdF's strategy was to start with the dismantling of Chinon A2 as top-of-the-line, and to put the other 5 reactors in safety configuration. Currently, Chinon A2 is almost at IAEA level 2. The most difficult part of dismantling a UNGG reactor is the caisson (reactor core closed in a metallic sphere). Dismantling of the Chinon A2 caisson (2030-2055), under air, will be preceded by the construction of an industrial demonstrator to test the tools and obtain feedback. This demonstrator will include scale models of representative parts of the caisson, physical simulators for testing robotic tools and digital simulation platforms. EdF plans approximately 25 years for dismantling a UNGG caisson, including that at Chinon A2. Dismantling of the 5 caisson of the other reactors is programmed for after 2060.

Evacuation of the Chinon A2 graphite stacks to the CSA is planned for 2045. This solution is possible because of improved evaluation of the ^{36}Cl activity of the graphite stacks. EdF will build a storage facility around 2023 at the Saint-Laurent site to accommodate the graphite sleeves currently stored in silos. This will allow their removal as from 2028. The removal of the graphite stacks from the 5 other caissons and the graphite sleeves from Saint-Laurent A to LLLW disposal is planned beyond 2070.

EdF is preparing the final shutdown of the irradiated materials examination workshop on the Chinon site. The schedule is about 10 years.

For all dismantling operations, the operators are developing very important strategic and technological R&D combined with the search for optimum economics, while observing nuclear safety constraints.

Dismantling is the subject of the European INSIDER project (insider-h2020.eu) launched in June 2017 for a period of 4 years (18 European partners). Its purpose is to offer a methodology for the characterisation of dismantling materials, evaluation of the performance of measurement methods and evaluation of financial costs and radiological impacts.

The Board notes that decommissioning projects commit the industry for very long periods of time, with the risk of drifting schedules. It wants to see the planned deadlines observed.

3.5 DISMANTLING STRATEGY

The LLILW and LLLW resulting from the dismantling of reactors and cycle facilities are taken into account in the current management of this waste. Future VLLW after saturation of Cires will be managed according to new provisions.

Many facilities have already been dismantled by the CEA, Orano and EdF over a few decades. More than 30 INBs and INBSs are in the process of being cleaned up and dismantled, with or without recovery and packaging of waste. These operations will probably extend through to the end of the century.

French dismantling operators have internationally recognised expertise. At present , each operator acquires this expertise when dismantling its nuclear facilities according to its own strategy. There are, however, common actions, if only in terms of site and facility characterisation methods, the use of robotic tools and means for digital archiving of data.

At a time when dismantling nuclear facilities is becoming an international activity, the Board encourages the implementation of an industrial strategy and a dismantling school within the French Nuclear Platform in order to better exploit this know-how.

CHAPTER IV: INTERNATIONAL PANORAMA

4.1 EXCLUSION, EXEMPTION, RELEASE, NORM, TENORM – INTERNATIONAL APPROACH.

4.1.1 Introduction

The dismantling of nuclear facilities, the disposal of sterile mining tailings or the control of foodstuffs following the Fukushima disaster have generated a growing interest in the problems associated with the release of very low-level radioactive materials considered as waste, and naturally occurring radioactive materials (Norm), materials with natural radioactivity enhanced by an industrial process (Tenorm), or the release of premises or sites after clean-up and decontamination.

The concepts and regulations that govern the different issues sometimes lead to confusion. The following paragraphs provide an overview of major international approaches.

First of all, it should be remembered that any material that constitutes or surrounds us has a natural radioactivity and that the cosmic rays that bombard the earth permanently produce new radioactive nuclei that enter bio-geo-chemical cycles. These natural radioactive sources expose us to an effective dose of a few milliSieverts a year (mSv/year).

The fact that a material is radioactive does not imply that it is dangerous. A regulation, based on scientific and medical data, is necessary to differentiate material that is without real danger for the individual or the environment and therefore does not require regulation, and that which requires radiation protection measures and therefore specific regulations.

4.1.2 Some internationally accepted definitions

Radioactive material: Material which, because of its radioactivity, is subject to regulatory radiological control for its use.

Norm (Naturally Occurring Radioactive Materials): Raw materials that are naturally radioactive because of the radionuclides they contain, and not containing significant quantities of artificial radionuclides.

Tenorm (Technologically Enhanced Naturally Occurring Radioactive Materials): Raw materials whose concentration in natural radionuclides has been significantly enhanced by treatment, the purpose of which is not to use the radioactive properties.

Exclusion: Decision to remove materials, facilities or practices from regulatory control.

Exemption: A generic decision taken initially to exempt materials, installations or practices from regulatory radiological control, since their nature is such that the danger to health is non-existent and any control is therefore superfluous.

Release (or declassification): A decision subsequently made by the inspection body to release from control any materials, installations or practices resulting from a human activity, itself under control. This decision is taken when their radiological characteristics or impacts are below predefined thresholds.

Remarks

- A “trivial” dose is currently defined as one-hundredth of the limit dose of 1 mSv/year (i.e. 10 µSv/year) for exposures other than exposure due to natural exposure or to public medical examinations. For comparison, the dose due to natural sources is 2-3 mSv/year in France.
- The release criteria are related to the dose received by the public.
- Dilution or dispersion of material, in order to get below a release threshold, is not allowed, unless specifically decided by the inspection body. This is the case for authorised discharges at sea or in the atmosphere.
- Release may be unconditional, in which case the materials or sites may be used without restrictions, or conditional for use for a specific purpose. This is the case in some countries such as Germany, Belgium or Sweden for the melting of very very low level (VVLLW) metal waste issued from dismantling. After decontaminating melting, these metals are released “conditionally” with an additional dilution of a factor of ten.
- The exemption thresholds used by countries that authorise release are logically lower than release thresholds.
- The Tenorm definition is not adopted by the IAEA.
- The ASN defines decommissioning as all the administrative and regulatory operations intended either to reclassify a nuclear installation in a lower category or to eliminate its initial classification. It does not define release.
- The DGPR prescribes the management of VLLW containing only enhanced natural radioactivity, Norm and Tenorm, following transposition of Directive 2013/59/EURATOM.

In France, materials leaving the nuclear area of an INB are considered as radioactive material, subject to control, even if their additional activity is not measurable. This equates to a release threshold of 0 Bq/g. The exemption thresholds for Norm materials are therefore by definition above the release thresholds, while the exemption thresholds should logically be equal to or lower than the release thresholds. This means that an identical material may be considered either as radioactive waste, or as a non-radioactive material, solely on the basis of its location as opposed to its activity.

4.1.3 International approaches

The international approaches of particular interest to the Board are those concerning the exemption and release of wastes with radioactivity that is very low or not measurable (*see* Appendix XVIII).

The IAEA publishes safety guides that represent the international reference for nuclear safety and radiation protection. Guide RS-G-1.7 deals with the application of the concepts of exclusion, exemption and release. The IAEA guidelines do not apply to food, drinking water, radon or ^{40}K exposure in the body, nor to transport activities. Other regulations, such as those of the World Health Organization (WHO), the United Nations Food and Agriculture Organization (FAO) or the Nuclear Energy Agency (NEA-OECD) partially govern these matters.

Directive 2013/59/EURATOM sets out the basic standards for health protection against the dangers arising from the exposure of the public or workers to ionising radiation. It is largely based on the work of the International Commission on Radiological Protection (ICRP) and the recommendations of the IAEA, WHO, FAO and NEA.

The exemption and release thresholds specified by the IAEA and Euratom are identical.

In Appendix XVIII, we have reviewed the practices of some OECD member countries on the management of nuclear waste (Belgium, Canada, Finland, Germany, Italy, Netherlands, Sweden, Spain, Switzerland, United Kingdom, United States).

The Board notes that France and the United States are alone in the international community in not practising the release of nuclear waste.

4.2 THE REPOSITORY PROJECT IN SWEDEN

4.2.1 Introduction

The procedure to apply for authorisation for a deep geological repository for spent fuel started in March 2011 when the Swedish company in charge of radioactive waste and spent fuel (SKB) submitted its application to the Swedish government. This application consists of three files:

- a request in the context of the regulation of nuclear activities for Clab (storage for spent fuel) and for the encapsulation plant at Oskarshamn;
- a request in the context of the regulation of nuclear activities for a deep geological repository for spent fuel at Forsmark in the municipality of Östhammar according to the KBS design (*See* section 4.3.2);
- a request under the environmental code covering the entire concept (Clab, encapsulation plant and geological repository).

Requests under the code of nuclear activities are analysed by the Swedish Radiation Safety Authority (SSM) and the application under the environmental code is analysed by the Environmental Court. Both these authorities forward their opinions to the government which makes the final decision. However, municipalities have a right of veto on the establishment of any nuclear installation planned on their territory.

During 2011-2017, a formal process of analysis was carried out including independent expert assessments on the key points, additional information provided by SKB and exchanges in the form of questions/answers between the stakeholders and SKB. Over 5 weeks, the Court held public hearings in Stockholm, Oskarshamn and Östhammar where authorities, stakeholders and SKB were able to present their cases for and against the project. At the end of 2017, the Court and SSM completed their analyses and in January 2018, their opinions were sent to the government.

4.2.2 Opinion of the Radiation Safety Authority (SSM)

SSM (See Appendix XIX) has recommended that the projects submitted by SKB to build a deep geological repository for spent fuel at Forsmark and the encapsulation plant in Oskarshamn should be approved by the government.

SSM gave a favourable opinion on SKB's request for creation of the repository and made it subject to a series of safety analyses before each of the main phases of the project (construction, test operations, industrial operation).

4.2.3 Opinion of the Environmental Court

The opinion of the Environmental Court (See Appendix XX) is also positive on several important points. The Court approved the proposals for the choice of the Forsmark site, host rock (granite) and engineered barriers. It also approves the conclusions of the environmental impact studies. The Court gave a favourable opinion on the encapsulation plant and the spent fuel storage site (Clab).

However, the Court wants SKB to complete its file on the copper container and its impact on long-term safety. In addition, the Court wants the government to determine who will assume long-term responsibility for the repository after its closure, thus meeting the demands of the municipality.

4.2.4 Next step

It is now up to the government to take control of the authorisation process, taking into account the advice received. The municipality of Östhammar has cancelled the referendum it had planned on the issue of the deep geological repository, pending insight into how the government would manage these two partially divergent opinions. This divergence results from the fact that the Safety Authority comments on the project throughout its progress while the Environmental court comments only once on the initial project.

The management of the file is now in the hands of the ministries in charge of energy and the environment. SKB is preparing the report that the Environmental court requested. This is actually a document that SKB had already committed to submit to the safety authority for the safety analysis review prior to the start of work. SKB expects that all additional studies will be finalised by the end of 2018.

The consequence of the Environmental Court's request for further information is that the authorisation process for the deep geological repository has been delayed by one year. Municipalities in Sweden with nuclear sites have written to the Government and Parliament to draw attention to the need for a deep geological repository and to ask the Government to ensure that the authorisation process is not unnecessarily slowed down.

4.3 STUDY MISSION TO SWEDEN AND FINLAND

The main objective of the mission was to meet the different stakeholders in the nuclear sectors as well as the elected representatives of the municipalities concerned by the disposal of radioactive waste in order to explore the two following points:

1) the process of societal acceptance of the construction of deep geological disposal sites for high-level nuclear waste
2) recycling of activated or even contaminated metals.

4.3.1 Energy systems

There is an interesting contrast between the two countries, since one, Finland, is engaged in active development of the nuclear industry, while the other, Sweden, has declared a gradual withdrawal. It is in this very different context that both have nevertheless embarked on a very advanced waste disposal policy.

This waste results from the operation of the following reactor fleets. For more details see Appendix XXI.

a) Finland

Finland has two nuclear power plants, one operated by TVO, located in Olkiluoto in the municipality of Eurajoki (reactors OL1 and OL2, BWR ABB of 880 MW which entered into service in 1979 and 1982 for 60 years and OL3 EPR of 1600 MWe under construction) and the other by Fortum at Hashtolmen in the municipality of Loviisa (reactors LO1 and LO2, PWR VVER of 488 MWe which entered into service in 1977 and 1981 for 50 years). Fennovoima; a third company created in 2007, has applied for permission to build 1 GenIII PWR of 1200 MW in Hannhikivi in the municipality of Pyhäjoki. Nuclear produces 25% of electrical energy and 18% of the energy consumed. Finland targets 50% nuclear power in 10 years.

b) Sweden

Sweden has three nuclear power plants run by three different operators (RAB, OKG, FKA), located in Ringhals (1 BWR ABB of 875 MW, 3 PWR WH of 800, 900 and 1000 MW), in Oskarshamn (3 BWR ABB of 500 , 600 and 1400 MW) and Forsmark (3 BWR 900, 1100 and

1200 MW). They entered service between 1974 and 1985. Today 4 reactors are in operation in Ringhals, 3 in Forsmark and 1 in Oskarshamn. Reactors 1 and 2 at Ringhals will close in 2019 and 2024. Nuclear produces 40% of electricity and 20-25% of the energy consumed. Sweden should eventually become nuclear-free (declared position, but as yet unclear).

c) The NordPool market

Finland and Sweden are part of Europe's largest electricity market, NordPool, which includes Norway and Denmark, but also Germany and the United Kingdom. The Nordic market is one of the most integrated in Europe: 80% of the electricity consumed in the region is sold on the spot market (intraday and overnight markets).

Finland imports almost 20% of its electricity, mainly from Norway. Hydropower production, although high in the Finnish mix (24%), is down sharply (24% in 2016, compared to a historic peak of 80% in the 1960s). Although this decline is partially offset by other renewable sources, production remains low in the face of electricity consumption, which has steadily increased in the last 20 years and is still forecast to rise. The interconnections with the other countries of NordPool, Sweden, Estonia and Norway, are often saturated, causing price rises in Finland compared to other NordPool countries. Gas supply is provided by a single point of import from Russia. Overall, it is a country at risk with respect to security of supply and the continuity of electricity supply in the coming years. In this context, nuclear power generation will play a key role in the development of Finland's energy mix and its integration into NordPool.

The situation in Sweden is similar to Finland with regard to the decline in hydroelectric production in the last twenty years, but with a less pronounced tendency (today the share of hydropower amounts to more than 40%). Several factors will enable Sweden to avoid the tension between supply and demand for electricity: electricity consumption has been falling since 2001, thanks mainly to ambitious energy efficiency programmes; the share of renewable energies excluding hydroelectricity is very high; gas is not used very much in electricity generation. In addition, the new interconnection with Lithuania (NordBalt, operational since 2016) facilitates trade with NordPool, allowing the price of electricity to remain in line with average costs in the Nordic and Baltic countries.

4.3.2 Waste management

Finland and Sweden have adopted an open nuclear fuel cycle, i.e. spent fuel assemblies from reactors are considered to be final LLHLW. They cannot be exported to a third country for disposal. Reciprocally, legislation does not allow the import of LLHLW nuclear waste for disposal. To manage it, both countries have chosen deep geological disposal in granite. The operation of the reactors leads to LILW-SL technological waste. Dismantling will also lead to similar waste and LLLW. Both countries have chosen to store the waste in silos or galleries excavated at shallow depths in the granite. Exporting and importing this waste for disposal is prohibited, as for LLHLW. All transport of waste is by sea.

It should be noted that in both countries, the producers are responsible for waste management and not, as in France, a public national agency. They have created specific companies (Posiva and SKB) for this purpose.

a) The KBS 3 disposal concept for spent fuel

Sweden (SKB) with the help of Finland (Posiva) has developed the so-called KBS3 disposal concept for spent fuel assemblies from BWR and/or PWR reactors. Galleries are excavated to a depth of about 450 m in the granite. In these galleries, separated by at least 6 m, vertical wells are excavated to a depth of about 8 m, to position the canisters that contain the assemblies. The canisters are copper cylinders 5 m high and 1 m in diameter, and their walls have a thickness of 5 cm. They are hermetically sealed. A canister can hold 12 BWR assemblies or 4 PWR assemblies arranged in a steel case, adapted to the characteristics of the assemblies, a case that fits into the canister and becomes one with it. The copper is almost indestructible, and the steel case ensures the rigidity of the package. In the wells, the canisters are surrounded by rings of bentonite. The well access shafts will be filled with bentonite blocks before the closure of the repository. The galleries are accessible from the surface by an access tunnel..

Implementation of the KBS3 concept requires approximately 30 years of storage time to allow the assemblies time to cool and an encapsulation plant that includes sealing the lids.

All repository sites are on the coast. However, the rise in water levels is not considered a problem because these areas benefit from a significant isostatic rebound following the melting of the ice caps (almost 1 cm/year).

b) The technological waste disposal concept

Among the LILW-SL waste disposed in silos and tunnels 60 m deep in granite are ion exchange resin packages embedded in bitumen. The possibilities of fire have been evaluated. The conclusion is that the risk is very low and therefore acceptable.

c) Finnish waste

The company Posiva Oy (about 80 people) manages waste, under the control of the STUK safety authority. LLHLW will be disposed of at Onkalo, municipality of Eurajoki. The Onkalo site was chosen by the government in 2000 to install a repository of 6500 tU. The construction of a site characterisation laboratory began in 2004 with a research laboratory. In 2015, Stuk authorised disposal.

Low- and intermediate-level waste is stored in Olkiluoto and Loviisa in silos 60 m deep in the granite.

There is no CEA equivalent in Finland. Nuclear research is carried out by VTT and the universities.

d) Swedish waste

The company SKB (500 people) manages waste, under the control of the safety authority, SSM. LLHLW will be stored in Forsmark, municipality of Osthammar. The Forsmark site was selected by SKB in 2009 for a 12 000 tU repository facility. The spent fuel assemblies are stored in the Clab located at Simpevarp, municipality of Oskarshamn. The encapsulation plant will be located near the Clab. There are also plans to set up the canister preparation plant in this location. The applications for authorisation for the repository and encapsulation plant date from 2011. The LILW-SL waste is stored in the SFR at Forsmark in silos at 60 m depth in the granite. SKB has requested the extension of the SFR. It is expected that LLLW will also be stored at depth in Forsmark.

SKB has been operating the Äspö laboratory in Oskarshamn since 1996 at a depth of 480 m, where the KBS3 concept was tested and the encapsulation (1998) and bentonite (2007) laboratories.

In addition to the safety authority, Sweden has the National Council of Sweden (SNC) which comprises 11 members from various fields of expertise (6 women and 5 men). It produces a report every year that evaluates the current state of nuclear waste management. It organises seminars with various sector and government stakeholders, as well as other larger ones in which local inhabitants participate. It is in some respects the equivalent of the CNE.

There is no CEA equivalent in Sweden. Nuclear research is carried out by the universities.

4.3.3 The process of societal acceptance

The representation of citizens in the governance of the two countries is fundamentally at two levels: that of the government and that of the municipalities, which are relatively few in number and much larger than in France. The municipalities have very broad powers, they levy very high taxes and are responsible for missions which, in France, are dealt with at national level. There is also a regional level in Sweden, but it is of little importance in the decision-making process.

Municipalities are managed by a council whose members are renewed every 4 years. The election of the members by strictly proportional representation means that the municipalities represent the views of the population (70% of voters). Public life (finances, social services, location of industries, etc.) is managed with the focus on information, openness and transparency, especially with regard to nuclear power. There are various municipal commissions that investigate each case.

The roles and responsibilities at each level are clearly defined: SKB initiates the site selection process; it turns to the municipalities concerned which must express their interest and then have the final responsibility to accept or reject (right of veto in Finland and Sweden) the establishment of any nuclear facility, including the construction of a repository. All decisions are put into effect.

The fact that the municipality is ultimately responsible for the decision to install a facility has led to the possibility of organising a referendum in Sweden, in the municipality concerned, which would take place in 2018. The result will however be consultative, and the decision is taken by the municipal council.

a) Finland

- **The municipalities concerned**

The Board visited the municipality of Eurajoki, which has 9400 inhabitants (17 inhabitants/km^2); it has a very broad remit, in the sense that it collects and spends taxes. Since 1978, it has had a long practice of decision-making with regard to nuclear power, with several facilities already present on its territory (reactors, LLLW disposal, etc.).

The representatives met expressed strong confidence in the companies and institutions in charge of the nuclear industry. On the one hand, they found that TVO and Posiva have extensive experience in technology and safety, and on the other hand that the opinions of the STUK safety authority are entirely credible. This is based on close cooperation since 1995 between these organisations and the municipality (information, seminars, audits, etc.). The municipality fought to obtain the Onkalo repository site. As early as 1999, an opinion poll indicated that 60% of the population was in favour of a repository, which the municipality accepted a year later (20 votes in favour, 7 against).

It believes that the implementation and management of the repository represent a development opportunity for the municipality (jobs, taxes). The President of the Council of the Municipality thinks that the votes are based on personal convictions and not on those of political parties. Finally, the municipality has initiated cooperation in the form of visits and information sharing with several European countries.

The Board also met with the municipality of Loviisa. It manages the municipality of 15 000 inhabitants (18 inhabitants/km^2). It was not selected in the end for the construction of the repository, and the representatives met expressed their disappointment in this respect (especially in terms of employment prospects).

- **Selection process for the deep geological repository site.**

The selection process began in 1983 with screening of the entire Finnish territory. Four sites were examined more specifically later. At the next stage, the municipalities of Eurajoki and Loviisa, which had shown interest in these projects, were selected. It was in terms of geological criteria that Eurajoki had the final say, which then decided in favour of the repository.

b) Sweden

- **The municipalities concerned**

The Board met the municipality of Östhammar (22 000 inhabitants for 2 800 km^2). The unemployment rate is below 2%. The municipality (chairman of the council and mayor) has been very involved since 1995 in discussions with SKB and with the inhabitants to explain the reasons why it seems appropriate to host a deep geological repository. It also seeks to spread the approach developed in the municipality internationally. This municipality was chosen for the disposal of LLHLW nuclear waste because the granite in this region is of very good quality (1 fracture every 100 m against 1 every 2.5 m for the Äspö laboratory).

The Board met the Mayor of Oskarshamn, the municipality where spent fuel assemblies stored in the Clab will be encapsulated.

- **Site selection process**

SKB initially selected 2 sites in northern Sweden, but as the municipalities refused, SKB preferred to choose municipalities with pre-existing nuclear knowledge through the presence of reactors. It therefore selected two municipalities, Oskarshamn and Östhammar. Östhammar won.

c) Some features that promote societal acceptance of nuclear waste repositories

The decision-making process for the creation of nuclear waste repositories is very advanced in both countries.

- **Some are common to both countries**

From a general social point of view, these two countries are characterised, in opinion polls, by a high level of confidence in institutions. During meetings with the Board, the various stakeholders presented opinion polls which revealed in particular that the nuclear safety authorities of both countries enjoy a high level of confidence. These safety authorities have clearly come out in favour of repositories, and their opinion has therefore met with a favourable response in the population, although there is, of course, opposition. Moreover, these countries are used to important, in-depth democratic debate close to the ground, which favours the legitimacy of the decisions taken. At the end of the debate on nuclear waste, the idea of safer disposal at depth rather than on the surface proved to be the majority decision, especially at local level, for the populations directly concerned. National results were, however, lower.

From an institutional point of view, the clarity of the division of roles at governmental and local levels is very high, thereby promoting the speed of the decision-making process. Indeed, while the initiative was taken at government level to make the decision to prepare a repository and search for relevant sites to then submit for the approval of the municipalities, the latter were able to apply for the repository or to refuse it. They therefore have ultimate responsibility for accepting or refusing the repository, so that the decision-making process enjoys greater legitimacy, particularly because of its greater institutional and democratic clarity.

From an organisational point of view, the number of stakeholders involved is relatively small: it is the producers who are in charge of waste management, not a separate dedicated organisation. In both countries, there is only one regulator giving public opinions, which limits the risk of discrepancies in the opinions produced. Further, Stuk took its decision in principle on the basis of a still relatively general project, emphasising that it would be inefficient at that stage to go into more detail. It will have to decide again on these details, in view of repository authorisation, once studies have been carried out in more depth.

From an economic point of view, the decision-making process has been favoured by two complementary aspects. All of the municipalities selected already had nuclear installations on their territory. Populations are therefore familiar with these issues, and obviously have economic interests associated with setting up these sites. Then, the repository facility may appear as a source of additional employment and income through the new taxes it will collect. From the point when the municipalities ultimately decide on the establishment and gain directly from the economic benefits (employment, taxes and various compensations), they have a greater economic incentive to accept these projects.

Finally, from an environmental point of view, it can be assumed that the fact that the selected municipalities already have nuclear installations reduces the feeling of a strong environmental impact that radically modifies nature and landscapes. The impact has already happened, and the prospect of the repository prompts action for additional protection of the landscape.

- **Specific to Finland**

The Onkalo repository was accepted in 2001 by the municipality. TVO is the largest employer in the municipality and nuclear taxes contribute 30% of the budget of around €60m. Posiva has consistently helped the municipality in its real estate projects. Both organisations have always kept the population well informed. All of these factors have greatly helped the process. Onkalo is intended to receive the waste from current plants. The disposal of waste from the planned reactor at Hannhikivi (municipality of Pyhäjoki) is excluded. Their disposal problem has yet to materialise.

The construction of the Onkalo repository, which precedes that of Forsmark (Sweden), is a full-scale demonstration of the selection of granite blocks for digging the canister disposal wells.

- **Specific to Sweden**

The acceptance process for the Forsmark repository has long since been prepared through the operation of Äspö, where the KBS 3 concept was developed.

4.3.4 Recycling of metallic waste

In accordance with the provisions of several regulations published by the Safety Authority (SSM) in 2011, waste producers can release certain metal waste without (SSMFS 2011/EC RP122) or with conditions (EC RP89). The conditions relate to information that manufacturers of products made with the released metals must attach to products for conventional uses by the public. In Sweden, for example, metal from nuclear facilities, whether intact or decontaminated, is used to produce consumer products. Obtaining a “release” certificate involves a long process. In this process, Sweden applies IAEA requirements.

a) Conditions for the release of waste in Sweden

Sweden classifies radioactive (or supposedly radioactive) materials of very low activity according to their radiological risk based on IAEA criteria. For dismantling waste from nuclear reactors, for example, only that with ^{60}Co activity greater than 0.1 Bq/g and less than 1000 Bq/g is considered to be more or less risky. Below 0.1 Bq/g it is conventional waste for which the risk is extremely low (undetectable activity) and waste for which the risk is low (dubious activity). All materials beyond “low risk” are candidates for release (and also those that fall outside the classification). For the dismantling of a BWR, 150 000 t of waste is conventional, 30 000 t is low risk and 10 000 t is at risk. Of this 10 000 t, about 70% is metallic (half at less than 0.1 Bq/g), 25% is building material and less than 5% can be incinerated. In the release process, the metals are characterised - one part is released without processing and the other is processed.

b) Recycling of metals in the nuclear industry in Sweden

EdF bought a small business in Studsvik, municipality of Nyköping, which it has called Cyclife. It provides work for about 90 people. This company has great expertise and experience in recycling activated and even contaminated metals, acquired since it started out in 1987. EdF acquired Cyclife to gain experience in the field of metal recycling. EdF has also observed that the societal acceptability of the VLLW disposal site is decreasing and that disposal costs are increasing. EdF sees a market opening for the dismantling of a large number of reactors. Cyclife works with many customers (11 European countries).

Cyclife is located in Studsvik in an industrial complex served by a port. It includes a large waste cutting unit (reactor exchangers, for example) with a capacity of 200 t/year adjacent to an induction melting unit (iron, copper, aluminium, lead) with a capacity of 5 000 t/year and a unit for pyrolysis and incineration of organic waste. Melting is done in batches of 3.5 t for steel (2 t for aluminium). Metallic waste is sorted and characterised. The non-releasable part is cut, decontaminated by sanding and melted into ingots. These are characterised (15 to 20 radionuclides measured) and sent to customers. Secondary waste (non-processable waste, sanding waste, melt waste), approximately 5% by weight of the waste, is also characterised, packaged and returned to customers in their countries of origin (every 3 years). The process reduces the volume of metal waste from dismantling by 90%.

The release of metals is valid if the cost of storing this waste is high enough to justify the cost of recycling. Recycled steel from Cyclife is worth around 3 euros/kg.

The work in this company is very manual and could benefit from automation.

EdF will soon carry out an experiment by recycling a steam generator from France. EdF wants to recycle activated and contaminated metals in France by adding large uniform batches of metallic materials (80 000 t of steam generators and 13 000 t of Eurodif diffusers). This project requires a change in French legislation on the issue of release thresholds.

The Board visited Cyclife. Once again, trust between the public, customers and the industry was highlighted. Cyclife displays its transparency. This company reports annually to the SSM through a report accessible to all. It also has discussions with a nuclear safety/security committee representing the Nyköping municipality. This committee is composed of politicians without technical experts. The exchanges are based on trust.

Cyclife says that the customers for the recycled metals are fully aware of the origin of the said metals and that traceability is guaranteed. This is true if their customers are the industries that buy recycled metals. It is less so if we consider the end user of the manufactured product, for example the person who buys a car. At no point is this person told they are buying a car that may contain recycled metals. Metals recycled in Sweden can therefore be found everywhere, including in France.

APPENDIX I: BOARD ACTIVITY

Since the publication of its previous report in May 2017, the Board presented its report No. 11 to OPECST and to the relevant ministerial departments. A delegation from the Board visited Joinville on 29 March 2018 to present its report to members of the CLIS (local information and monitoring committee) at the Bure laboratory (*See* Appendix II).

The Board adopted the same working method as in previous years. It conducted 9 day-long hearings (*See* Appendix III) and 5 closed half-day hearings, all held in Paris, in addition to a certain number of supplementary meetings with legal stakeholders. The Board members, all volunteers, heard 84 people from Andra and the CEA, as well as from French and foreign academic institutions and industrial organisations (*See* Appendix IV). These hearings brought together around sixty people on average, in particular representatives of the Nuclear Safety Authority, Orano, EdF, the Institute for Radiological Protection and Nuclear Safety and the central administration.

The Board devoted two half-days to a visit to the Brennilis plant and the Chinon site, AMI visit - visit to Chinon 2 and visit to the Museum of the Atom (*See* Appendix II). It also made a study trip to Sweden and Finland.

To prepare this report, the Board held a pre-seminar of 2 days, on the occasion of the visit to the Chinon site. It also held numerous internal meetings, including a five-day residential seminar. The list of Board hearings and visits is given in appendix III to this report. The list of documents that it received from the organisations attending hearings is provided in Appendix V.

APPENDIX II: BOARD PRESENTATIONS AND VISITS

Board hearings

23 November 2017:	Presentation of report No. 11 to OPECST
29 March 2017:	Presentation of report No. 11 to the Clis

Board visits

12 December 2017:	EdF – Visit to the Brennilis plant
5 April 2018:	EdF – Visit to the Chinon site – Visit to AMI – Visit to Chinon A2 – Visit to the Museum of the Atom

Board study trip

03 to 13 October 2017:	Study trip by the National Assessment Board to Sweden and Finland

APPENDIX III: HEARINGS HELD BY THE BOARD

PUBLIC HEARINGS

20 September 2017:	CEA & Producers –Disposal and R&D programmes for the RCD
21 September 2017:	Andra – DAC file – Inventory presented in the DAC file – R&D activities
22 November 2017:	Andra – Area of operation, surveillance programme and digital model of Cigéo
6 December 2017:	Andra – Scientific and technological knowledge base and R&D work for the Cigéo DAC: The geological environment and the LLHLW and LLILW areas
7 December 2017:	CEA – Health and environmental impacts of radioactivity
10 January 2018:	CEA – Orano – EdF – Strategy and technico-economics of fuel reprocessing
11 January 2018:	Andra – Scientific and technological knowledge base and R&D work for the Cigéo DAC: Closure structures, surface-to-bottom connections and the repository in general
14 February 2018:	CEA – ASTRID scientific and technological roadmap
15 February 2018:	Andra – LLLW, VLLW & Tenorm: Towards a global and coherent industrial plan

CLOSED HEARINGS

18 October 2017 – morning:	Andra
18 October 2017 – afternoon:	EdF
19 October 2017 – morning:	High Commissioner for Atomic Energy
19 October – morning:	Orano
14 February 2018 – morning:	General Administrator of the CEA
15 March 2018:	Andra – Cost and financing of Cigéo

APPENDIX IV: LIST OF PEOPLE HEARD BY THE BOARD

ANDRA

ABADIE Pierre-Marie
ARMAND Gilles
BENABDERRAHMANE Hakim
BOSGIRAUD Jean-Michel
BOURBON Xavier
BUMBIELER Frédéric
CALSYN Laurent
CAMPS Guillaume
CHABIRON Aliouka
COCHEPIN Benoit
CRUSSET Didier
DELAROQUE Philippe
DELRIEU Nicolas
DE LA VAISSIERE Rémi
FARHOUD Radwan
FOIN Régis
HURET Emilia
LASSABATERE Thierry
LAUNEAU Frédéric
LEMAITRE Elsa
LEVERD Pascal
LIEBARD Florence
MICHAU Nicolas
MUNIER Isabelle
PEPIN Guillaume
PLAS Frédéric
PRIN Coralie
RENAULD Valérie
RIGAL Jean-Pierre
ROBINET Jean-Charles
SCHUMACHER Stephan
SEYEDI Darius
TABANI Philippe
TALANDIER Jean
TALLEC Michèle
THABET Soraya
VOINIS Sylvie
WENDLING Jacques
YVEN Béatrice

Orano

FORBES Pierre-Lionel
GAGNER Laurent
LAMOUROUX Christine
ROMARY Jean-Michel

CEA

ABONNEAU Eric
ADNET Jean-Marc
ADVOCAT Thierry
CHABERT Christine
DEFFAIN Jean-Paul
DELEUIL Stéphane
DEVICTOR Nicolas
DUBUISSON Philippe
FERRY Cécile
FILLION Eric
FIRON Muriel
GARNIER Jean-Claude
GORGUE Vincent
JOURDA Paul
MAGNIN Magalie
MARTIN Guillaume
MENETRIER Florence
MIRGUIRDITCHIAN Manuel
MONFORT Margot
PIKETTY Laurence
PLANCQ David
ROMEO Paul-Henri
ROUDIL Danielle
SARRADE Stéphane
SATURNIN Anne
TOURON Emmanuel
VARAINE Frédéric

CNRS - IN2P3

DAVID Sylvain

DGEC

DEPROIT Laurent

EdF

BENOIT Géraldine
DUVIVIER Remi
FERNANDES Roméo
GIRAUD Olivier
ISNARD Luc
LAUGIER Frédéric

HC

BRECHET Yves

POSIVA

AALTONEN Isma

IRSN

LEURAUD Klervi
RENAUD Philippe

VIANOVA SYSTEM

MARC Cédric
RIVES Michel

APPENDIX V: LIST OF DOCUMENTS SUBMITTED TO THE BOARD IN 2017-2018

ANDRA

- Summary and review of the work of the Verre-Fer-Argiles Group of Laboratories (2006-2014) – 20 June 2017.
- 2016 R&D activity report – Andra – 2016.
- Andra activity report – 2016.
- International Watch report on radioactive waste management and geological disposal projects for high-level and long-lived waste - February 2018.
- Radioactive waste: watch report - International Watch report on radioactive waste management and geological disposal projects for high-level and long-lived waste - February 2018.

CEA

- Annual report – The CEA at the heart of major future challenges – 2016.
- DEN monograph - Clean-up and dismantling of nuclear facilities.

HC

- Expert report on the Andra R&D programme for the Cigéo project – March 2017.

APPENDIX VI: COMPOSITION OF THE NATIONAL ASSESSMENT BOARD

Jean-Claude Duplessy – Chairman of the National Assessment Board – Member of the French Academy of Sciences – Emeritus Research Director at the CNRS.

Anna CRETI – University Professor, Université Paris Dauphine, Senior Research Fellow, Department of Economics, Ecole Polytechnique External Affiliate, University of California Environment, Energy and Economics, Berkeley and Santa Barbara.

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

Pierre DEMEULENAERE – Professor of Sociology, Sorbonne University.

Robert GUILLAUMONT – Member of the French Academy of Sciences – Member of the French Academy of Technologies – Honorary Professor at the Université Paris Sud Orsay.

Vincent LAGNEAU – Professor of Hydrogeology and Geochemistry at the Institut Mines Télécom - Deputy Director of the Geosciences Centre at MINES Paris Tech.

Maurice LAURENT – Honorary Director of the Parliamentary Office for Evaluation of Scientific and Technological Options.

Mickaele LE RAVALEC – Head of the Georesources department, Geosciences Division, at IFPEN.

Emmanuel LEDOUX – Invited expert on the National Assessment Board – Honorary Research Director at the Paris School of Mines.

Maurice LEROY – Vice-chairman of the National Assessment Board – Associate Member of the French National Academy of Pharmacy – Honorary professor - European School of Chemistry, Polymers and Materials in Strasbourg.

José Luis MARTINEZ - . Research Professor at the CSIC (Institute of Materials Science, Madrid, Spain). Official representative of Spain on the European Strategy Forum on Research Infrastructures (ESFRI, European Commission), responsible for the strategic group in Physics and Engineering.

Gilles PIJAUDIER-CABOT – Vice-Chairman of the National Assessment Board, Professor of Civil Engineering, Executive Director of E2S, Université de Pau et des Pays de l'Adour – Senior Member of the Institut Universitaire de France.

Claes THEGERSTRÖM – Emeritus President of SKB (Swedish company in charge of managing nuclear fuel and waste) – Member of the Royal Swedish Academy of Engineering Sciences.

APPENDIX VII: THE GEOLOGICAL, HYDROGEOLOGICAL AND HYDROGEOCHEMICAL ENVIRONMENT

THE GEOLOGICAL ENVIRONMENT

The site selected for the Cigéo structure, located within the Area of interest for deep reconnaissance (ZIRA), is of excellent quality in geological terms. In general, the Paris Basin is hardly affected by tectonics. The selected area is remarkably stable, almost aseismic. It is distinguished by the absence of faults in the Callovo-Oxfordian (COx).

The COx, in the area of interest, is 490 m deep, 130 m thick and is slightly inclined. It is surrounded by 2 layers of limestone: the Dogger below and the Oxfordian above. The COx's clay sediments were deposited 155 million years ago, in an open and calm marine environment, far from the sources of supply (hence very fine particles). There are 3 sedimentary sequences due to sea level variations: from top to bottom,

- the silt-carbonated unit (USC), 20 to 30 m thick, more heterogeneous;
- the transition unit, not very thick, passing between the clayey rocks of the underlying clay unit and the rocks of the overlying silt-carbonate unit;
- the clay unit (UA), 100 to 120 m thick, the richest in clay minerals, very uniform.

The maximum proportion of clay minerals increases from 25% at the top to 60% in the middle of the layer. The proportion of carbonates varies from 80% maximum in the upper part to 15%. There is also pyrite (iron sulphide), with a maximum proportion of about 2% in the middle of the layer.

The presence of carbonates ensures a good mechanical resistance of the rock while the high proportion of clay minerals drastically limits the flow of fluids.

All the data collected allowed the development of a 3D model representative of the geological environment. This model serves as a basis for simulations to evaluate the performance of the repository system.

THE HYDROGEOLOGICAL MODEL OF THE SITE

The hydrogeological model aims to numerically evaluate the impact of Cigéo on its environment at the scale of the Paris Basin and on a time scale of up to one million years. It takes into account the geology of the environment and the flow of fluids in this environment at present and in the future. This modelling must make it possible to identify the groundwater outlets that can come into contact with the constituents of the repository and to quantify the transfer times to reach these outfalls from the repository. These elements will then be taken into account in calculating the doses received via the groundwater transfer route, integrated into the safety analysis.

The reliability of the hydrogeological model is based on the fact that a whole set of regional, sectoral and local data and knowledge is included: geological observations, hydrological, hydrochemical measurements, etc.

The design of the model has progressively evolved since the 2005 file, benefiting from new recognition campaigns, and in the choice of computing tools. It currently includes a regional model extended to the entire Paris Basin and a sectoral model extracted from it. This model is built with the GROUNDWATER finite element calculation code from the University of Neuchâtel in Switzerland, which constitutes a benchmark. Improvements have allowed a better calibration of the Dogger's piezometry thanks to a more developed representation of the role of the faults.

Hydrogeological evolution modelling over the next million years is carried out with the GEOAN calculation tool (Golder Associates); it requires taking into account different interrelated processes such as tectonic uplift, erosion and sedimentation, climate. Natural climatic changes have been postulated to date.

HYDROGEOCHEMISTRY OF THE SITE

The excellent hydraulic and geochemical properties of the Callovo-Oxfordian formation, combined with its thickness, make it the major safety element of the repository. These properties have been extensively studied for more than twenty years, at different scales, by French, European and international laboratories and consortia. Andra thus has a very large and robust knowledge base.

The mineralogy and pore structure of the rock are now well known. The diffusion properties have been well characterised in the laboratory and have low spatial variability. The effect of anion exclusion and the (reversible) effect of a rise in temperature have been studied. *In-situ* tracer tests have already confirmed the results obtained with samples.

The geochemistry of Callovo-Oxfordian waters is well understood: it is based on a body of samples and analyses and geochemical speciation calculations. The changes associated with a rise in temperature are also well understood, largely controlled by the solubility of the carbonates; it has also been shown to be reversible.

The retention of many radionuclides has also been extensively studied. Andra benefits from the results of the research programmes it has undertaken, and from the results of the work of many international teams working in similar environments. Sorption on clay surfaces is the dominant mechanism and appears to be little affected by the spatial variability of the mineralogy. Dependence on geochemical conditions (pH, Eh, competing ions) is also well understood.

Andra continues to support the development of thermodynamic databases, including the consolidation of all constants up to 80°C.

MIGRATION OF RADIONUCLIDES

To model the diffusion in the various porous media of the repository (degraded anthropogenic materials, altered COx, healthy COx) Andra uses, in principle, three experimental parameters for each species and media, the effective diffusion coefficient De, the apparent porosity and the coefficient Kd (except for caesium), a coefficient that reflects the sorption of a species regardless of its concentration (in the case of Cs it is taken into account). This is the classic approach for evaluating the displacement distances of the elements in a saturated medium and the times taken to go through them. The concentration of the elements remains very low in the COx and in the near field because it is limited by the solubility of a compound ($C < C_{sat}$) or the low rate of relaxation of packages. The migration of an element being governed by that of the chemical species that it forms in the porous water of the solid media crossed, the composition (presence of complexing agents such as carbonates, sulphates, chlorides, silicates, of organic species, content of natural cations, etc.), the pH and the Eh of this water as well as the value of C play important roles. Effectively, they define the speciation of the element. All parameters and distribution of the species are sensitive to temperature.

The values selected by Andra for healthy COx and for long-lived radionuclides classified according to their anionic or cationic nature in the pore water of the COx have been measured (lab, *in situ*) for monocharged species (Cs^+, Na^+ , I^-, Cl^-) and often estimated for others. Andra has based this on several methods (incomplete series of known values, analogies, calculations according to the thermochemical data base, effect of temperature, natural profiles, etc.). They have reported on the behaviour of certain elements over the entire spatial scale ranging from nanometres (laboratory experiments on clay mineral slips) to hundreds of meters (*in-situ* experiments in the LSMHM and natural tracer in the thickness of the COx). All values are conservative.

The same applies for the values used for altered environments. These environments are well characterised whether it be the EDZ, COx in contact with concrete and vice versa, COx in contact with metallic materials and glass and the corresponding corrosion products, COx in contact with air, etc. In fact, the composition of the interstitial water of healthy COx depends on the mineralogy of argillite, which is satisfactorily known in three dimensions. Its main characteristics, measured in the 30-80°C range, make it possible to understand: 1) the corrosion of concretes and metallic materials as well as the subsequent alterations of the clay materials on contact with them, 2) the alteration of the confinement matrices, 3) the diffusion of the elements and their sorption, phenomena that have been widely studied and described in the scientific literature.

Andra can hence estimate the possible corrections to be made to the parameters of the healthy COx to represent the alteration, if they cannot be measured directly. Note that in the end it is the barrier of healthy COx that forms the ultimate defence, an environment for which the values of the parameters are best known.

APPENDIX VIII: CIGÉO APPRAISAL PROCEDURE

The Cigéo project is in the first place subject to the administrative rules for the creation of a regulated nuclear facility (INB) which comprises three stages.

- The first optional step involves the filing of a security options dossier (DOS). The Andra Board of Directors decided in 2014 to carry out this step and the DOS was sent to ASN in April 2016 marking the start of the procedure for the future Cigéo INB. The appraisal of this dossier under the aegis of the ASN took place from July 2016 to October 2017.
- A second step leads to the submission of the construction authorisation request (DAC), expected in 2019 followed by an appraisal period of an average duration of three years which can be extended to five years if the complexity of the DAC requires it. The instruction is carried out by the IRSN under the guidance of the ASN. The DAC gives rise to a report from the Board.
- A third step is finalised by the publication of the creation authorisation decree which includes the ASN requirements, and this normally completes the appraisal of the DAC.

The general INB regulation (decree 2007-1557 of 2 November 2017) specifies the documents and the contents of the documents that make up the DAC. Two important documents are the preliminary safety report, which must cover, in the case of disposal, the operational and long-term after-closure phases and, secondly, the dismantling plan which must take into account that part of the facility will not be dismantled. An impact study must also be provided.

Once the authorisation decree has been published, the project passes successively through the construction, operation and closure phases, which are governed by the “procedure” decree.

The commissioning of the INB is authorised on the basis of additions to the file.

- The safety report is based on the updating of the preliminary safety report intended to include feedback from construction and to verify the compliance of the facility with the construction requirements defined by the ASN. This report should provide a detailed demonstration of nuclear safety. It must also describe the conditions under which the start-up tests and the control procedures will be carried out.
- The update of the impact study.
- The supply of additional documents setting out the general operating rules (RGE), the waste management method of the facility and the internal emergency plan (PUI).

When the INB is authorised to operate, the “procedure” decree contains the following provisions. Design changes are possible and framed by the regulations. An update of the safety report constitutes the end of start-up file. ASN's control continues through regular inspections.

These general provisions applicable to INBs must be adapted and supplemented to take into account the specificities of Cigéo.

Thus, in terms of regulation, the DAC must take several factors into account.

- *Temporality:* it is expressed by the different phases of life that Cigéo goes through from construction/operation up to the post-closure period where the facility, once dismantled, operates in passive mode.
- *Governance:* it must ensure the participation of citizens throughout the life of the facility; this is the role of the operational master plan. A first version has been provided with the DOS; a revised version will accompany the DAC. It is provided by law that this document must be updated every five years during the operating period, with citizen participation.
- *Reversibility:* it must make it possible to re-evaluate the choices in the course of operation and to make changes to management solutions. A “reversibility report” will be attached to the DAC.
- *Package acceptance:* their specifications are currently being revised and will be attached to the DAC.

For this purpose and taking into account the specificities of Cigéo, the following additional documents are awaited on filing the DAC:

- the operational master plan (PDE);
- preliminary specifications for package acceptance;
- the development plan for the repository facility;
- the reversibility report.

APPENDIX IX: TECHNOLOGICAL EVOLUTION OF THE DESIGN OF THE LLILW CELLS AND GALLERIES

The technological concepts of the repository are still evolving. Andra is gradually including optimisations after their validation. These changes are made possible by enhancing the knowledge of the site and the processes. They are generally in the direction of reducing costs, while maintaining the same level of safety.

The LLILW cells and the galleries built in Cigéo will have excavated diameters of the order of 10 m. They fall into the category of large underground structures. A major feasibility programme has been carried out by Andra in the Bure underground laboratory over the past 15 years. Galleries of increasing diameter, up to 9 m, have been excavated; different methods of lining/support have been studied. These experiments demonstrated the principle of the constructability of the LLILW cells.

The main results concerning the fracturing induced by the construction of the galleries are summarised below.

- A damaged zone (EDZ) appeared around the gallery, it includes 2 zones: a fractured zone where the fractures are connected and beyond that, an area with few fractures which are, moreover, not connected. The permeability of the connected zone is high; it is linked to the network of fractures induced by excavation, not to the matrix. Beyond the fractured zone, the permeability decreases rapidly. The extent of the disturbed zone is approximately equal to the radius of the gallery.
- Only the orientation of the gallery with respect to the main horizontal stress acts on the disturbed zone, it influences the preferred direction of extension.
- Hydraulic healing of fractures was observed in the UA.
- The fracturing is anisotropic. The sizing of the structure takes into account the impact of this anisotropy on the mechanical behaviour of the structure, notably by aligning the direction of the structures with the main directions.
- The stresses on the support depend on the rock/structure interaction (respective rigidity and time for implementation).
- Convergence is at two speeds: a fast convergence followed by a much slower relaxation. Several types of linings have been tested to minimise the long-term stresses affecting them.
- The introduction of compressible elements (compressible segments) significantly reduces the long-term deformations/stresses in the linings.

BEHAVIOUR OF THE MATERIALS (LLHLW AND LLILW) AND INTERACTIONS WITH THE CALLOVO-OXFORDIAN

LLILW areas

Cement materials will be very widely present in Cigéo: their volume is of the order of half of the volume excavated. They will be used in particular for the linings/supports, filling material (space between the lining of the LLHLW cell and the host rock), but also as conditioning matrices for the LLILW waste. These cements will have to fulfil two functions:

- a mechanical function, i.e. to ensure the physical stability of the structural elements (structures and containers) in the operation phase;
- a chemical function, i.e. to ensure the maintenance of a physico-chemical environment limiting the migration of radionuclides in the long term after closure, in particular due to pH.

Andra has studied, alone or in collaboration with other groups in the world, the impact of various disturbances that could change the performance of the concretes. It has a solid foundation of knowledge on this subject. Changes in cement components are described from:

- delayed mechanical behaviour (shrinkage, creep) as a function of water and thermal conditions. The integration of delayed deformations in behaviour patterns is and will be the subject of research up to the DAC;
- carbonation in a saturated or non-saturated medium;
- corrosion of steel reinforcements;
- the impact of radiation on mechanical behaviour and corrosion;
- chemical degradation in a saturated environment in relation to the physicochemical conditions imposed by the COx or certain waste.

More generally, the chemical processes that will develop in the cement materials during the different phases of the repository are known. It is the boundary conditions imposed by the waste or the COx that will control the characteristic times and extensions.

A research theme that remains important for Andra before the DAC is the description of coupled phenomena.

In the presence of cement materials, it is necessary to examine not only their behaviour, but also their interactions with the surrounding environment. Andra has conducted, through numerous research programmes internally or collaboratively, studies on alkaline disturbance, i.e., of all the phenomena that affect the COx due to the presence of cement.

Andra’s excellent subject knowledge is again apparent in this area. The development of alkaline disturbance is well understood. The results obtained show limited effects (extension of the alkaline plume of a few metres in the fractured zone). The intensity and extension of the transformations are lower in bentonite-based materials. The expected changes in the clays are related to their swelling potential. At the interface between clay and cement materials, alkaline disturbance can lead to a decrease in porosity, and thus to a reduction in the flow of fluids.

APPENDIX X: ASSUMPTIONS INFLUENCING THE CIGÉO GROUND PLAN

ASSUMPTIONS

The reference (target) configuration of Cigéo for the DAC file is based in particular on the following assumptions.

- The reference inventory includes waste produced and to be produced by existing facilities and those already selected (Flamanville EPR).
- All used fuels are reprocessed and the life of the reactors is 50 years (Assumption SR1 of the National inventory of Radioactive Materials and Waste 2018).
- The LLILW cells are built in a single excavated section of 85 m² (22 cells in all).
- The cells are multi-purpose and the interior is adapted to different forms of storage packages or primary LLILW packages.
- The pilot HA0 area includes the high-level UMo waste from La Hague (about 800 packages, 19 cells) and the cells have a length of 100 m.
- The length of the HA1/2 cells is 150 m.
- The thermal design guarantees preservation of the beneficial properties of the Callovo-Oxfordian: less than 90°C maximum in the Callovo-Oxfordian and verification of the absence of fracturing by THM loading with a prudent fracturing criterion for the pilot HA0 area.
- The direct disposal of certain LLILW waste is taken into account (5 cells).

CASE OF THE BITUMEN SLUDGES

If it is decided to place it in Cigéo, the assumption is that bitumen sludge will be disposed in the same way as described in the Cigéo safety orientation file.

CONTINGENCY EVALUATION

If the direct disposal of certain waste were not allowed, 2 more cells would be required.

If the bitumen sludge were to be disposed in reinforced cells, 2 additional cells would be required.

In an extreme case, Andra estimates that the number of cells would increase from 22 to 26, which would increase the LLILW area footprint from (1 km × 1.3 km) to (1.1 km × 1.3 km).

MAJOR CHANGES TO CIGÉO

As a consequence of the assumptions about the reference configuration, the major changes that are taken into account in the APD relate to the following points.

- *The ground plan and the repository construction methods:* the general layout in three blind storage areas ensuring consolidation in a central area away from the arrival of the surface-to-bottom connections is maintained. The complete structure comprises an HA0 area of 19 cells 100 m long, an LLILW area including 22 cells 500 m long, a logistics support area (ZSL), and an HA1/2 area grouping 916 cells 150 m long. In order to maximise the safety of the construction sites, the mineshafts and access galleries in the LLILW will be excavated with a tunnelling machine in a single phase and the LLILW cells as well as the access galleries to the HA areas will be made with a road header tunnelling machine. Only the structures concerning the ZSL, HA0, LLILW and of course the surface-to-bottom connections will be built in the first tranche. The construction of the HA1/2 area will be postponed to a later tranche in order to receive the first packages by 2070.

- *The HA area to the north of the Zira:* the main innovation is the extension of the cells to 150 m, which reduces the length of the access galleries without changing the criterion of thermo-hydro-mechanical sizing and favours transfers by diffusion via the COx, limiting the transfers by the structures of the repository. The feasibility of such an extension has been demonstrated in the underground laboratory. The HA1/2 area will receive LLILW vitrified waste and some of the HA0 packages, which are not very exothermic, which will serve as dividers between HA1/2 waste in order to limit the thermal load. At the same time, the extension of the HA0 area to be carried out in the first tranche will be reduced.
- *The LLILW area:* this zone has been subject to a major change. The excavated section of the cells changes to 85 m^2 which has the effect of reducing their number from around fifty to twenty-two and halving the total area of the zone. The consequences of this optimisation are important: a single type of cell excavated by the road header tunnelling machine for all LLILW packages, digging the access galleries in a single loop, allowing recognition, as from the Phipil, of the total perimeter of the LLILZ area. Finally, Andra now accepts the possibility of direct storage of certain primary packages. This affects about 30% of LLILW waste that will be disposed in 6 cells out of a total of 22.

APPENDIX XI: EXAMPLE OF SIZING CIGÉO STRUCTURES

The structuring approach associating innovative design and the enrichment of the knowledge base is illustrated by the following examples concerning the LLILW cells.

THERMAL SIZING OF AN LLILW CELL

The thermal sizing of a moderately exothermic LLILW package storage cell (CSD-C) is subject to several design constraints. Thus, the arrangement of the waste packages is constrained by several requirements to respect the functional limits of the materials, such as temperature thresholds:

- 90°C within the rock, justified by the need to maintain the favourable properties of the Callovo-Oxfordian;
- 70°C at the time water reaches the waste, justified by the need to remain within the range where the behaviour of radionuclides in the water is well characterised;
- 65°C in the operating phase, within the concrete elements, justified by the need to avoid heat damage or physicochemical changes likely to alter the containment and mechanical strength of the concrete;
- 80°C in case of an incident within structural or containment concretes (packages), admissible for a duration of up to ten days.

Added to these specific requirements is verification by the contractors of the rules of the art of civil engineering, i.e. the acceptable nature, within the structure, of the mechanical constraints that produce the thermal gradients in particular. Andra finally prefers passive dissipation of the thermal power of the packages, in normal storage configuration, without resorting to ventilation.

All the thermal simulations carried out show that the requirement of 65°C in the concrete elements, in normal operation, is the envelope criterion for sizing.

MECHANICAL SIZING OF THE LLILW CELL LININGS

With regard to mechanical sizing, the design objective covers different requirements:

- for all structures, the first requirement is for a sizing objective giving a service life of about 120 years, covering the operating period of Cigéo;
- for structures involved in long-term safety performance, such as LLILW cells and LLILW gallery segments to accommodate seals, there are additional requirements for limiting and controlling the connected fractured area(EDZ)overtime.

These two requirements are characterised by different criteria: for the first, they are structural dimensions in accordance with industrial feasibility standards, as well as states of stresses and deformations to be maintained in the expected operating range; for the second, these are the characteristics for the EDZ not to degrade, such as the extent of the EDZ or its increase in permeability, because of its importance for safety after closure of the repository.

The sizing approach consists in finding the right compromise between two opposing strategies that contribute to the achievement of these requirements:

- one consists in blocking ground convergences to limit the EDZ;
- the other favours the formation by convergence of a plastic zone absorbing the stresses and allowing an operation below the rupture limits of supports/linings of reasonable thickness.

The reference configuration of Cigéo retains, for all of the LLILW mineshafts and connection galleries, mechanised excavation by tunnelling machine accompanied by the installation of segments as it advances. These include an outside layer of compressible material allowing a controlled decompression of the solid mass. This innovative solution was developed by Andra.

Andra first motivated this choice of construction provisions using several arguments, including the improvement of site safety and greater speed of construction. The interest of such a construction solution was also, according to Andra, to accommodate some of the convergence of excavated solids, with better management of uncertainties and sizing margins. This choice therefore had to be confirmed by a research programme that led to new results:

- in the first place, the monitoring of the structures in the Underground Laboratory and the creation of a new gallery with a road header tunnelling machine, with installation of compressible segments as it advances, have confirmed the feasibility of this innovative construction method;
- digital simulations have made it possible to specify the sizing margins, i.e. the margins separating the nominal operating range of the structure from its critical range (at breakage).

This research has therefore demonstrated the positive role of compressible linings (reduction in the anisotropy of initial stresses in the rock, limitation of the concentration of deformations in the segments and in the EDZ because of creep sensitivity).

They also carried out an additional evaluation of the sizing margins: the calibration of the models on the data resulting from the convergences measured in the short-term overestimates by 15 to 20% the expected behaviour over the service life of Cigéo compared to a calibration on the convergences measured in a more “established” regime (i.e. between 40 and 100 days). It is therefore the most restrictive for sizing.

By characterising changes in the structures and the EDZ, taking advantage of Phipil feedback, these studies should ultimately confirm the operating range of the retaining structures, improve surveillance strategies and, for the LLILW cells, check that retrievability of the packages remains possible during the operation phase.

APPENDIX XII: R&D THEMES FOR THE DAC

THEME 1: HLW DESIGN

The HLW cells are blind rising micro-tunnels (slope of 1 to 2%), directed along the main horizontal stress, 100 m long for the HA0 area and 150 m for the HA1 and HA2 areas. As supports, they are equipped with a steel lining intended to facilitate the placement of HLW packages during the operational phase and their removal for possible recovery.

A filler material (bentonite cement) is injected on top of the lining, in principle from the bottom of the cell. This material is intended to enhance the mechanical strength by limiting corrosion through the neutralisation effect of transient acidic disturbance related to the oxidation of argillite pyrites.

The experiments carried out in the Meuse-Haute Marne underground laboratory made it possible to consolidate the technique for excavating the HLW cells. An HLW cell demonstrator campaign is planned from 2019 to 2024 on the future site of zone 4 of the underground laboratory.

Andra has carried out both experimental and computer modelling analyses of cell deformation. An original device for measuring deformation using fibre optics has been used. Experiments carried out under certain conditions, for example with 60 m cells or 8-pad packages, contribute to the demonstration of package retrievability.

Numerous studies have also been carried out on the corrosion of the metal components of the HLW cell (container and lining) over 15 years. The results were as follows:

- The kinetics of corrosion decrease in an anoxic environment, hence the achievement of low corrosion rates.
- A bentonite cement has been added to the upper surface to avoid gaps and to protect the steel by limiting corrosion rates.
- The influence of certain factors (radiation, oxygen, chemistry, mechanical stresses) has been minimised through the design choices.

It should be recalled that these studies are essential in the DAC to demonstrate the feasibility of storage of HLW, using current techniques. However, effective implementation should not take place before 2070. According to the flexibility concept that guides the construction of Cigéo, major changes are highly likely, to take into account the availability of materials on the one hand, but also progress made in the fields of construction and materials on the other hand.

THEME 2: THM IMPACT OF THE HLW AREA

The HLW areas give off a significant amount of heat during the thermal phase of storage. The rise in temperature changes the hydraulic (overpressure) and mechanical (extension or sheer stress) behaviour of the host rock. These mechanisms are strongly coupled. Studies and research must provide justification for the thermal sizing of the area, so that the confinement properties of the rock are preserved.

Current results integrate the determination of properties from measurements on laboratory samples, underground laboratory tests, and large-scale analysis of clay formations on geological analogues. These results have enabled the development, qualification and validation of numerical models coupling thermal, hydraulic and mechanical processes. Thus, experiments were conducted in the underground laboratory to simulate near-field and far-field behaviours; the model correctly reproduces the pressure and temperature behaviour. Moreover, the analysis shows that a complete mechanical constitutive law (poro-elastoplastic) is essential to represent the role of the damaged zone in the vicinity of the cell, whereas a simpler law (poroelastic) is sufficient to simulate the far-off field.

To achieve the dual objective of preventing the boiling of pore water and rock fracturing, the characterisations and calculations define a maximum temperature criterion of 90°C. This temperature is compatible with the extension and sheer rupture thresholds.

The calculations also make it possible to prioritise the importance of the value of rock properties on the results. Thus, Young's modulus first of all followed by permeability are the two main parameters of the models. Depending on the value of the Young's modulus, opposing effects can be observed: a low value (low elasticity of the rock) limits the convergence around the cells, whereas a high value absorbs the stresses more effectively and limits the damage.

These parameters are determined at different scales: centimetre for samples, decimetres in laboratory experiments, metres for *in-situ* experiments. On a larger scale, the spatial variability of these parameters is evaluated indirectly by geophysical methods. Thus, the analysis of high-resolution 3D seismic data gives access to the dynamic Young's modulus and its variability in space. This variability is then applied to the static Young modulus involved in the THM calculations.

The work planned by Andra seeks primarily to reduce residual uncertainties, by acquiring new data, and by analysing the response of models in different configurations. A new drilling campaign will aim to reduce uncertainty on THM parameters, including the Young's modulus, at the ZIRA scale. A high-volume THM loading test will be conducted in the underground laboratory to achieve fracturing and evaluate the impact on hydromechanical properties.

THEME 3: HYDRAULIC WATER-GAS PERFORMANCE IN THE EDZ AND THE CEMENT SEALING MATERIALS

The sealing structures planned by Andra are based on a core of reworked clay materials contained by concrete support structures. Coatings at the clay filling level must be laid. For the surface-to-bottom connections, sealing is achieved in the silt-carbonate unit (USC). For the seals of horizontal galleries, one option being considered is to bleed the argillite, to a depth corresponding to the connected fractured zone; filling it with swelling clay materials should then constitute a hydraulic block.

The support structures will be made of concrete. Their main function is the mechanical strength and confinement of the clay core, on which the sealing function depends. The data on the behaviour of concretes is vast: it comes from works initiated by Andra and other institutions in the context of research on the storage of radioactive waste, but also from a highly developed scientific community on the subject of cements and concretes.

At this stage, Andra is considering the use of low-pH concretes: low alkalinity limiting the alkaline disturbance of the clay core, and low hydration temperature limiting heat in the heart of the mass and the problems of concrete fracturing by internal sulphate attack. Low-pH concretes are used more recently than the more traditional formulations; they still benefit from about fifteen years of international studies on their rheology, mechanical properties and interfaces with other materials.

The chemical change at the interface with the clays continues to be studied, especially with regard to determination of the secondary magnesian mineral phases produced at this interface. The use of low-pH concretes in the repository remains very marginal (limited to the support mass only in current Andra designs): residual uncertainties surrounding the behaviour of the interfaces do not have a large impact on the safety functions required of these masses.

Andra has demonstrated its ability to handle large quantities of low-pH concrete under conditions representative of gallery installation. The methods are based on classical civil engineering technologies. The residual uncertainties on the behaviour of the interfaces have no impact on the safety functions, since the sealing function does not depend on the support mass but on the clay core.

The methods for putting clay cores in place have been the subject of dedicated study programmes. Technological choices and adjustments, qualified at full scale on a surface model, aim to obtain the most uniform core filling possible, and to avoid technological voids. Different options have been studied. Conveyor deposition of a mixture of pellets and bentonite powder is well suited to filling the core. The installation of bentonite bricks, possibly by robot, with the addition of powder and pellets, is more suitable for filling hydraulic blocks. Finally, the projection of shotclay (similar to shotcrete, but with a clay material) can be used in addition to start or finish the filling.

Andra has studied the behaviour of these filler materials. The re-saturation phase is decisive: the arrival of water causes the clays to swell, which has the effect of first blocking the technological voids and ensuring good contact with the rock, and then creating a swelling pressure that adds to the stresses in the system. Andra has carried out a very large number of laboratory experiments in order to determine the relationships between material composition, dry density of the deposit, swelling pressure and permeability, effect of the composition of the re-saturation water (in particular water in equilibrium with the Callovo-Oxfordian or different concrete formulations). Over a wide range of material and dry density, the permeabilities obtained are very low, less than 10^{-11} m/s.

Moreover, the saturation of the clay in the rock in the vicinity of the seal is also accompanied by swelling of the clay minerals: this swelling leads to closure of the fractures. Associated with the swelling pressure generated by the re-saturation of the core, this mechanism greatly reduces the transmissivity of the fracture network in the damaged zone.

Andra has a large and robust knowledge base on the hydromechanical behaviour of bentonites and reworked argillites during the re-saturation phase.

Andra has planned to continue its work on the sealing elements. Additional tests are planned in the underground laboratory to test backfilling galleries with argillite tailings, bleeding and removal of the lining segments. The characterisation of the hydro-mechanical behaviour of the clay mixtures should continue: influence of the shape or of some percolation waters. Long-term trials are still underway in the underground laboratory. Their results will obviously contribute to the knowledge base.

THEME 4: THE MAJOR MULTI-PHYSICAL TRANSIENTS AND THE FINAL EQUILIBRIUM

Cigéo is destined to function for more than a century in operational mode; this will cause significant disturbances in the surrounding environment in thermo-hydro-mechanical and chemical terms. Some of these disturbances will still be active for long periods of time after closure. They will gradually fade away over time until a new state of equilibrium is achieved. The complexity of the elementary mechanisms involved and their coupling create multi-physical and multi-scale transient situations with time constants that can be very different. Mindful of assessing the consequences on safety, Andra has focused on characterising and modelling the different areas of operation of the structure at different periods of its life. Understanding the various processes involved relies on a complex database of phenomena that Andra has progressively enriched for more than twenty years thanks to experiments in the surface laboratory, underground laboratory and cooperation with the national and international scientific community. The exercise is very difficult because it is necessary to understand the basic physical mechanisms, take into account the relevant couplings, identify the parameters and have the right computing tools.

Andra has identified the main factors capable of exerting demands on the environment by classifying them according to their importance. They primarily concern the relationship between water and gas in the structure’s components and in the surrounding argillite.

In terms of basic mechanisms, Andra identifies the following factors as having a predominant influence.

- The production of gas, mainly hydrogen, occurs mainly after closure of the repository under the effect of anoxic corrosion of metals but also as from the operating phase through radiolysis in the LLILW cells. This production could reach a cumulative quantity of

several tens of billions of moles spread over several hundreds of thousands of years, which represents an average flow of about 5 m^3 of gas per day at normal temperature and pressure.
- The very strong gas inlet pressure (5 to 6 MPa) in the healthy argillites saturated with water makes the undamaged COx almost impervious to gas and consequently favours transfers by the constituents of the structure with less accentuated capillary properties.
- The very weak diffusion of the dissolved gas in the argillite limits the evacuation capacities of the gas via the COx.
- The special properties of the interfaces between materials and the damaged zone make them preferred transfer routes for the gas.

The hydraulic-gas transient at the scale of the repository has been modelled with the aim of establishing a history of gas pressure and water saturation evolution in the storage components as well as an assessment of gas leakage through the identified transfer routes.

The simulations can be made highly representative using Though-MP software by distinguishing the detailed architecture of the repository, its multiple components (COx, EDZ, concretes, clay and metal components) and taking into account the major multi-physical couplings (release of hydrogen, two-phase water/gas coupling, thermo-hydraulic coupling, gas diffusion/dissolution). The simulations are based on a large body of knowledge about the properties of the materials making up the repository, from laboratory and *in-situ* experiments.

The lessons from the modelling are as follows.

- There is a strong coupling between the production of hydrogen and the circulation of water that tends to re-saturate the repository, with the pressure of the gas opposing the arrival of water. The total re-saturation time is thus several hundred thousand years. The maximum durations are found in the LLILW area where the release of hydrogen is most persistent.
- Re-saturation takes place primarily in the bentonite sealing cores where the strongest suction is exerted.
- Re-saturation is fastest in the seals of the surface-to-bottom connections that are in contact with the water of the Oxfordian limestone aquifer, as from closure of the repository.
- Inside the structure, gas migration takes place essentially via the connected fracturing zone (ZFC) of the EDZ.
- Gas pressure is at a maximum in the repository after a few thousand years. It varies between 3.5 and 12 MPa depending on the set of parameters adopted for the gas production flow and the properties of the ZFC. It is around 5 to 6 MPa for the median values of the parameters.
- When the gas phase has disappeared, approximately 30% of the gas will have migrated by two-phase transfer to the upper aquifer via surface-to-bottom connections and 70% by diffusion in dissolved form equally between the upper and lower clay casing.

Once the hydraulic-gas transient has resorbed, the gas phase expressed will have disappeared and the completely re-saturated structure will evolve according to the regional hydrogeological boundary conditions and the local hydrodynamic properties of the repository components. The convective movements of water that can be drained through the repository and diffusion are the processes that result in a long-term transfer of radionuclides to the aquifer environment. This mode of operation is reached only after a few hundred thousand years, the time necessary for complete re-saturation.

Andra points out the elements influencing the movement of water in this final state:

- the very weak permeability of the COx (10^{-14} to 10^{-13} m/s), uniform over the Zira;
- the low vertical hydraulic load gradient generated by the surrounding aquifers on both sides of the COx;
- the existence of a hydraulic overload in the COx, about fifty meters in the middle of the layer, whose origin (and thus role) has not been identified with certainty;

- the higher permeability by two to three orders of magnitude of the internal repository components compared with the COx promotes drainage through the surface-to-bottom connections;
- the global architecture of the repository in blind areas associated with a centralised grouping of the base of the surface-to-bottom connections.

Andra is carrying out three-dimensional hydraulic simulations in steady-state storage, by individualising all the cells, galleries and surface-to-bottom connections and taking into account the permeabilities of the different components. These simulations show:

- water flow drained by surface-to-bottom connections ranging from a few litres to a few tens of litres per year with a hydraulic contribution coming mainly from the LLILW area;
- very low water speeds (a few tenths of mm per year) within the repository components. These speeds are increased by two orders of magnitude in case of seal failure. The consequence is that the transfer of solutes from the repository is carried out essentially by diffusion through the COx.

APPENDIX XIII: BITUMEN: HEATING OF BITUMEN PACKAGES – CURRENT DATA

SCIENTIFIC DATA ON BITUMEN

Andra's data on bitumen and bitumen mixes is that known in 2013 (chemical and microstructural characteristics, radiolysis, rheology, degradation under water) [Référentiel des colis HA-MAVL, tome 3, CG.RP.ASCM.12.0026]. The 70/100 bitumen used to produce bitumen mixes softens around 40°C, becomes fluid around 100°C and very fluid around 140°C. Pyrolysis, which is a slow transformation of bitumen into gas, with or without air, begins around 200°C. Self-ignition of bitumen requires a temperature above 300°C in the presence of air but the flashpoint is around 230°C. It has been established that bitumen has a low heat capacity, a low thermal conductivity and a low thermal diffusivity which slow down the propagation of heat within it.

This data is valid for freshly prepared bitumen mixes with an average concentration in salts of 50%, but there are very large variations which must be taken into account.

For the Cigéo safety demonstration, Andra selected 180°C as the temperature not to be exceeded to avoid accidental pyrolysis and ignition of bituminous mixes. Normally the packages will be at 30°C. In case of an incident, Andra sets the temperature limit of the packages at 50°C.

SCIENTIFIC DATA ON THE BEHAVIOUR OF MIXES SUBJECT TO AN INCREASE IN TEMPERATURE

At the end of 2014, the CEA produced a set of 15 technical notes referenced in a summary note [CEA/DEN/DADN DO 103 (23/3/2013) - CEA-Andra-Orano-EdF R&D Programme on the behaviour of bitumen sludge] reporting studies undertaken following the request by CNE2 in 2012.

These notes describe the experiments and contain all the open data on the behaviour of bitumen mixes subjected to various thermal stresses.

If there are other additional documents from the CEA, the Board is not aware of them.

The CEA has established models giving the characteristics of the thermal episodes (released energy, start, maximum and end-of-episode temperatures, power output) experienced by bitumen mixes subjected to heat flows according to the chemical composition of mixes as well as a model for heat transfer in the mixes.

In short, the differential microcalorimetry experiments on 500 mg samples showed the existence of exothermic reactions, often involving nitrates, which generally start around 120°C and are more intense around 180°C and beyond. At most they release about 0.5 mW/g. This data results from statistical interpretations of the characteristics of numerous thermograms. Some show the start of exothermic reactions below 100°C. Heat transfer experiments on batches of 2 kg up to 400°C showed that the heat propagates by conduction as long as the imposed temperature does not exceed 150°C, and then by convection thereafter. The energy released locally by the exothermic reactions does not lead to general self-heating.

On the basis of its models, the CEA extrapolated the behaviour of a 200-kg bitumen package in response to an external temperature increase.

Conventional fire resistance experiments (Iso curve R834, oven 945°C, exposure 1 h) or real (1.3 MW power, 1 h) on full-scale storage packages (4 primary packages and storage packages) showed that the wall temperature of the primary bitumen packages did not exceed 150°C and that the bitumen was not degraded.

As the Board pointed out in its Report No. 11 (page 39 and Annex IX, page 97) all quantitative data on the behaviour of bitumen mixes in response to a rise in temperature, whether due to self-heating or to an external heat supply or to their combined effects, concern inactive synthetic mixes freshly prepared and therefore not containing radiolysis gas.

The Board was informed in 2017 of ongoing work by SCK-CEN on the ignition of samples of fresh, aged and radiolysis gas-saturated Eurobitumes and radioactive Eurobitume samples taken from 13-year-old bitumen parcels. These are measurements of flash points and self-ignition. The Board looks forward with interest to the results of these studies.

DATA ON BITUMEN PACKAGES ALREADY PRODUCED

There is a lot of data on real waste packages, i.e. those containing radioactive mixes. It comes from package preparation records, which made it possible to define the ranges of chemical compositions of the inactive bitumen mixes used for the experiments. The other data is obtained when the barrels are taken back to Marcoule for reconditioning before storage in the EIP. These are non-destructive radiological measurements and, for 5% of the packages, measurements on samples of the mixes, giving chemical and radiochemical compositions.

Their composition is in line with the forecasts made according to the preparation records and, according to the CEA, the examination of the packages analysed does not show any sedimentation of salts from the mixes.

The majority of the data is actually on LLLW bitumen packages, the first ones to be taken back for reconditioning and stored in the EIP (about 11 000 to date). The recovery of LLILW packages destined for Cigéo is scheduled for later.

The Board is not aware of any CEA reports on this data.

REMINDER OF CNE2 ASSESSMENT OF THIS DATA

In its report No. 9 (2015, appendix IX, page 97), the Board analysed the results presented by the CEA at the end of 2014 and considered that they demonstrated the robustness of the bitumen packages in the face of a one-hour fire and the inert character of bitumen mixes under realistic conditions of fire-resistance experiments.

In its report No. 10 (2016, appendix V, page 69) following some additions made by the CEA on the interpretation of thermograms of bitumen mixes, it drew attention to possible modifications of their chemical and physical properties over the long duration of Cigéo's operation.

In its report No. 11 (2017, appendix XIII, page 94), following studies by the CEA on the rheology of irradiated aged mixes (viscosity and dynamics of hydrogen bubbles), the Board recommended, in the absence of experiments on real samples of radioactive waste, experiments on simulated mixes to check whether the exothermic reactions are decoupled from the presence of hydrogen during a rise in temperature and to what extent an uneven distribution of the salts would accelerate the exothermic reactions (page 39). Such a distribution could come from the release of hydrogen or sedimentation during a viscosity decrease of the mixes related to their history.

POSITIONS OF VARIOUS STAKEHOLDERS ON THE DOS

Andra's position in the DOS

For the Cigéo safety demonstration, Andra selected 180°C as the temperature not to be exceeded to avoid accidental pyrolysis and ignition of bituminous mixes. Normally the packages will be at 30°C. In case of an incident, Andra sets the temperature limit of the packages at 50°C.

These choices are based on the scientific data relating to bitumen and bitumen mixes available at the end of the studies and research undertaken up to 2014 mentioned above.

CNE analysis of the DOS

In Report No. 11 and in its analysis of the DOS, the Board considered that the studies conducted by the CEA jointly with the producers and Andra provided important and credible information regarding the storage of bitumen. The tests also showed that very high temperatures did not affect the integrity of the packages for at least one hour according to the ISO 834 standard. Under these experimental conditions, the temperatures observed in the primary packages rule out the possibility of their ignition due to an external heat source. However, the Board does not have any information enabling it to evaluate the spread of a fire to an entire cell, under conditions representative of the repository, if a package were to catch fire.

Position of the CEA

On the basis of behaviour models of mixes in the face of a temperature rise (see above), the CEA concludes that no ignition of packages can occur, and that no fire can propagate under the conditions of package handling and storage, as planned by Andra. For the CEA, any heating of the package from the outside leads only very slowly (one to several days) to a rise in temperature in the core of the bitumen mix, at most equal to that imposed on the wall. This can be adjusted by the storage package to well below 180°C. To reach 180°C by internal heating would require the exothermic reactions to release amounts of heat with powers not commensurate with those measured. The accumulation of both heat sources, external and internal, can be modelled. The CEA is studying several scenarios in the presence or absence of oxygen (necessary to feed a bitumen fire) by considering exothermic reactions starting at 50°C. For the moment, the CEA considers that there is no risk of any risk of loss of confinement.

A dossier was to be ready by the end of 2017 to confirm this position.

IRSN position in its analysis of the DOS

IRSN has made known its position with regard to the reactivity of bitumen mixes and the behaviour of a bitumen package during a rise in temperature until the outbreak of fire in IRSN report No. 2017-00013. This has been provided to the Board. IRSN also gave an opinion on these subjects on holding a CSLUD (Laboratory Safety and Defence Plant Commission) on Marcoule bitumen packages in 2016. This opinion is not directly known to the Board, and nor are the documents on which it relies.

IRSN has reservations about the results of the 2014 CEA study on several points: representativity of the bitumen used for the tests, statistical processing of the data of micro-calorimetry experiments which lead to not considering the possibility of exothermic reactions at low temperature, not taking into account the variability of the package properties due to radiolysis phenomena (rising bubbles, microstructural modifications possible). Consequently, according to the IRSN, the CEA models are debatable as well as the conclusions that can be drawn from them.

IRSN also notes that the Marcoule bitumen packages before 1990 were produced under unreliable quality assurance conditions and that the initial heterogeneity of the mix may have increased over time (radiolysis sedimentation). IRSN considers that it is impossible to rule out a rise in temperature due to self-sustaining exothermic reactions at temperatures well below the threshold of 180°C, for example of the order of 40/50°C.

Finally, beyond critical considerations on the means of fire prevention and fire-fighting indicated by Andra, the IRSN does not rule out, in case a bitumen package is the seat of a thermal runaway, propagation from the thermal wave of a storage package to adjacent packages. In this respect, IRSN has carried out preliminary calculations (appendix T13 of the above-mentioned IRSN report) which show that propagation delays could be of a few days' duration depending on the scenarios and that a fire in Cigéo could take a package of bitumen in its storage package to a critical temperature with loss of containment in a few hours.

These considerations lead IRSN to recommend examining the possibilities of neutralising the chemical reactivity of bitumen packages, thus meeting the requirements of the PNGMDR (decree of 23 February 2017) or modifying the concept of package storage.

The IRSN sets the filing date of the DAC as the limit for making a decision (mid-2019), with the PNGMDR setting late 2019 for having a complete file on the subject (article 48 of the PNGMDR decree).

Position of the permanent expert groups (GPs) on the DOS analysis

In May 2017, the GPU and GPD issued an opinion incorporating IRSN's considerations. This opinion indicates a risk of runaway by exothermic reactions which could lead to a significant release of activity into the environment. The two suggestions indicated by the IRSN were retained: development on an industrial scale of a process ensuring the neutralisation of the chemical reactivity of the mix or changes in the project design making it possible to exclude the risk of exothermic runaway in the event of fire or temperature rise.

The current status of the file does not allow for a choice between them, and the GPs believe that a process must be put in place to reach a decision.

Position of the ASN

ASN issued its final opinion on 15 January 2018.

This is based on IRSN's analysis and the opinion of the GPs. It describes the uncertainties on the physicochemical, thermal and microstructural behaviour of bitumen packages in storage, which can lead to a rise in temperature (incidental or accidental situation) and considers that the current design of the repository makes it impossible to prevent or limit the risks to an acceptable level in the event of an exothermic reaction inside a bitumen package.

For the management of bitumen packages already conditioned, the opinion recalls the alternative: development on an industrial scale of a process ensuring the neutralisation of the chemical reactivity of packages or substantial changes in design options to exclude the risk of runaway exothermic reactions in case of fire or a rise in temperature.

Finally, it recalls that bitumen packages were the subject of requests for studies covered by the order of 23 February 2017, in particular articles 46, 47 and 48.

The conclusion of the ASN opinion is as follows: “The ASN considers that the search for the neutralisation of the chemical reactivity of the bitumen waste packages should be preferred. In any case, the characterisation of these packages by their producers as soon as possible is a prerequisite.”

TREATMENT OF BITUMEN PACKAGES

The path that was explored by the CEA and which the Board learnt about at the hearing on 22 January 2015 is the incineration of bitumen packages by plasma torch followed by vitrification of the residues.

IRSN issued an opinion (opinion No. 2016-00245 of 20 July 2016) on the PNGMDR 2013-2015 report “Technical-economic evaluation of a process for the treatment of bitumen sludge mixes by incineration/vitrification” which is the only open document containing scientific and technical data on the subject.

IRSN notes the numerous difficulties raised by the CEA in this report for the industrialisation of a process that seemed to be satisfactory at the laboratory scale. According to the CEA, many years of R&D would be needed to remove the barriers and it believes that the cost of an industrial facility would be prohibitive. It is the presence of salts that complicates implementation of the process. IRSN nevertheless considers that studies relating to the industrialisation of such a process should be continued, incorporating chemical pre-treatments if necessary.

The CEA has not conducted studies in this respect. Only a few attempts to extract salts after dissolution of bitumen mixes in an organic solvent were conducted by the Belgian SCK/CEN.

The PNGMDR 2016-2018 draft decree (article 48) repeats IRSN's request to continue studies and sets a deadline of late 2019 for a “technical, economic and safety evaluation comparing the different methods of processing and conditioning envisaged for bitumen waste”. This study should include all stages of waste management as well as the impact of the various choices on the design and sizing of Cigéo: “transport, safety in storage and operation phase, environmental impacts, long-term radiological impact”.

In its report No. 11 (appendix XIII page 94) the Board noted that the few tests by the CEA, carried out essentially between 2003 and the end of 2005, show that the essential difficulty of the process is due to the presence of the refractory salts, carriers of the radioactivity, which cannot be completely thermally decomposed except at very high temperature. The process would be very difficult to control. Maintaining the material balance of the numerous operations necessary to ensure control of the process seems very difficult.

APPENDIX XIV: ASTRID PROGRAMME AND MULTI-RECYCLING IN FNRS

In its previous reports, the Board has monitored and evaluated the R&D that the CEA and industry has carried out since 2010. As indicated in the body of the report, the Astrid project is being revised/redefined in the strategic framework of the closure of the nuclear fuel cycle with the priority of recycling U and Pu, the transmutation of Am being considered as a pillar of progress.

The latest advances in the Astrid-600 MWe programme are described below.

ASTRID 600 MWE

Reactor design

The design of the Astrid reactor at the end of 2017 includes: gas ECS, the latest fuel handling systems, fuel storage, residual power evacuation (active and passive), core and site infrastructure and civil engineering. The CEA essentially worked in 2016-2017 on the gas ECS to put it at the same level of development as steam ECS. The choice of heat exchangers (2 exchangers of 187 MWth with 8 exchange modules on each of the 4 secondary circuits) and the thermodynamic cycle (2 lines each comprising 1 turbine of 300 MWe, 3 compressors and 3 coolers) was made. This leads to an optimised calculated yield of 37.8%.

The CEA continued, in parallel with these studies, experimental tests in order to continue the qualification of components or sub-assemblies of the real scale or reduced scale reactor. This R&D aims to qualify the components (transition to TRL scale 5 to 6), to consolidate the design choices and to provide the calculation tools that accompany the experiment. It covers, for example:

1) on core components: tests on hydraulic levitation stopping bars, examination of MOx rods already irradiated in Phénix. Samples of B_4C that enters the composition of Astrid rods will be irradiated for several years in Bor 60 (two mini rods are ready) and,
2) on equipment: endurance and thermal shock resistance tests of the model of the sodium-gas heat exchanger on Diademo, flow and control in voltage and frequency of the electromagnetic sodium pump on the Pemdyn loop. The complete qualification of an assembly will require longer irradiation experiments.

The CEA has also advanced on the manufacture of assemblies that involve many materials $UPuO_2$, B_4C MgO and steels of several grades. More than 600 MOx pellets have been prepared at Melox in 3 campaigns since 2015 according to the conventional process of mixing UO_2 and PuO_2 powders; at the laboratory scale, new processes are being studied. The microscopic structures (size and mass fraction of Pu clusters) have been characterised. The preparation of B_4C and MgO pellets has also been mastered. Some hundreds of sheaths equipped with their spacer wire (15-15 AIM1 steel) have been made under industrial conditions. Finally, the CEA has undertaken the reconstruction of the industrial base for the manufacture of the hexagonal tubes and other parts of the assemblies. An automatic assembly station for rods at the foot of the assembly and platforms for thermal studies exist in Marcoule and Cadarache.

The overall assembly of Astrid in gas ECS or steam ECS configuration is now available through a 3D digital model of the entire reactor, the machine room and ancillary facilities. Digital modelling is being extended to include complete project management.

The studies on facilities for Astrid's material cycle have continued. In 2016, the option of implementing the AFC for the manufacture of Astrid MOx assemblies (start-up and boosting cores) was taken. The options are under evaluation (adaptations of facilities or new facilities) and equipment sizing studies are in progress.

The current processing and recycling facilities could, subject to certain adaptations, meet the early phases of industrial demonstration of the cycle: reprocessing and fabrication of some plutonium assemblies from spent PWR and FNR MOx fuel. As for the facilities for transmutation of americium (Atalante), they can only be used for a few grams of Am (rod scale). To move to kilogram scale would require new facilities.

SEPARATION & TRANSMUTATION

The Board gave an update on R&D concerning S&T in its report No. 11 (2017). The latest experiments concern the Exam programme and irradiation of samples of the oxide series UAmO2 (U(1-x) AmxO2 $_{\pm\delta}$). For now, it is a question of validating and qualifying the CCAm concept up to the scale of an experimental rod. The other steps to move towards the qualification of a fuel are to be defined.

Examination of irradiated samples

In the Marios experiment, 4 mini-needles of $UAmO_2$ at 15% Am with pellet densities of 92 and 87% (theoretical density) and porosities of 8 and 12% were irradiated at 1000 and 120°C in the HFR (2011-2012) at 300 JEPP. The first non-destructive examinations of the samples (LECA/Cadarache) show a strong fragmentation of the dense pellets, fission rates of Am as calculated (50%) and a good diffusion of He out of the oxides (no swelling, hardly any dissolved He).

In the Diamino experiment, 6 mini-discs of $UAmO_2$ at 7, 14 and 15% in Am with pellet densities of 97 and 85% (theoretical density) and porosities of 0.2, 1.6, 11 and 13% were irradiated at 800°C in Osiris (2041-2015) at 134 and 240 JEPP. Only a few examinations have been carried out confirming the fragmentation of dense oxide discs.

All examinations of the Marios and Diamino samples should be completed by the end of 2018.

Regarding the Marine experiment, which concerns the behaviour of $UAmO_2$ oxide at 13% Am in the form of a pellet or spherule, the irradiation is complete.

The AmBB-1 experiment, which aims at irradiating UAmO2 mini-oxide rods and metallic UAm in ATR is still being prepared. The CEA should prepare the oxide samples with the Am extracted in the ExAm experiment.

For these two experiments, CEA plans to continue post-irradiation examinations in international collaborations.

ExAm experiment and more

At the end of 2017, the CEA had 8.3 g of AmO_2 at 15% in Am (58.4% of ^{241}Am and 40.9% of ^{243}Am) obtained by co-conversion of oxalate U(IV)-Am(III) (calcination of oxalate under nitrogen at 750°C). This is the culmination of the “ExAm intégrale” experiment that started in 2010. The ExAm process was piloted to obtain very pure americium (95.5%) to the detriment of the Am recovery factor and Am/Cm and Am/lanthanide decontamination factors.

The CEA must now prepare between 16 and 28 pellets of Am oxides (^{241}Am or Am from the ExAm process) for the AmBB-1 experiment. These pellets, placed in 4 rods, will be irradiated in the USA in ATR at 800°C. Two rods will contain the oxide prepared by the CRMP (Calcined Resin Microsphere Pelletising) process.

The feedback from these years of R&D concludes that the process of separation of americium is too complex. This is why the CEA and 4 other partners have developed the Euro-Exam process, with new reagents, in the framework of the European Sacsess project. The Geniors programme (GenIV Integrated Oxide fuels Reprocessing Strategies - 24 partners from 11 countries) succeeded it in early 2017, with the ambition to develop the Euro-Ganex, I-Sanex and Euro-Exam processes over 5 years, all based on CEA processes.

FNR Pu consumption mode

The CEA is studying the possibilities of increased consumption of Pu from a 1500 MWe Pu iso-generator CFV core. Such a core is heterogeneous with a low drainage coefficient. This is the core planned for Astrid. A Capra type approach is followed. It consists in decreasing the regeneration of Pu. There are several possibilities by acting on the fuel (no U), the assembly (inert, moderating or absorbing neutron rods) and the core (diluent or absorbent assemblies) while maintaining a low draining effect, Doppler effect and delayed neutron fraction. The CEA is opting for the simplest approach by introducing moderator rods or a neutron absorber such as $^{11}B_4C$ (MgO replacing UO_2) in assemblies and diluent assemblies in the core (in steel). This essentially changes the lengths of cycles. The consumption of Pu could reach 50 kg/TWhe.

SCENARIOS FOR DEPLOYING A FLEET OF FNRS

Since 2013, the CEA, Orano and EdF have been studying industrial scenarios relating to possible developments in the nuclear fleet; the Board has reported on this in its previous reports. The approach consists in developing software to establish the qualitative and quantitative material balance of the cycles to estimate the nature and quantities of the waste. The results of the calculations indicate the modified or new cycle facilities that would be required to implement the scenarios. The latter are then compared with industrial and economic realities.

The central scenario studied until 2015 mainly concerned the use of Pu and U from spent fuel assemblies UOx and MOx to gradually build a fleet of FNRs from 2040. This fleet would ensure, towards the end of the century, an independence with respect to the import of natural uranium (stage D), while stabilising the Pu inventory (stage C). At stage D the transmutation of Am is possible if all the FNRs are loaded with CCAm fuel. In this vision, the construction of Astrid is completed around 2040. The other scenarios examined related to deciding whether or not to stop reprocessing in PWR and EPR, according to the assumptions and the current strategy of mono-recycling.

Since 2015, the CEA and the waste producers have studied a variant of the central scenario, considering the Astrid reactor as a 600 MWe FNR and the deployment of EPR, possibly 30% moxable. In this scenario, two 1 GWe FNRs would be loaded with Pu from PWR MOx around 2080 and stage D would be deployed in the XXIInd century. In this variant, Astrid is no longer a demonstrator of the recycling of Pu from FNR MOx and the transmutation of Am is not envisaged. The predictions in terms of waste to be managed until the end of the century for the Astrid + 2 FNR scenario and the PWR and EPR mono-recycling scenario do not fundamentally change from one option to the other: more LLWM (20%) and LLHLW (10-40% depending on PF and AM packaging) with the FNRs.

The implementation of the FNR scenarios would imply important transformations/innovations in fuel cycles both in reprocessing and in the manufacture of FNR MOx (new plants). The deployment of a fleet of FNRs with the same power as the current fleet cannot be envisaged before the next century.

APPENDIX XV: MULTI-RECYCLING IN PWR

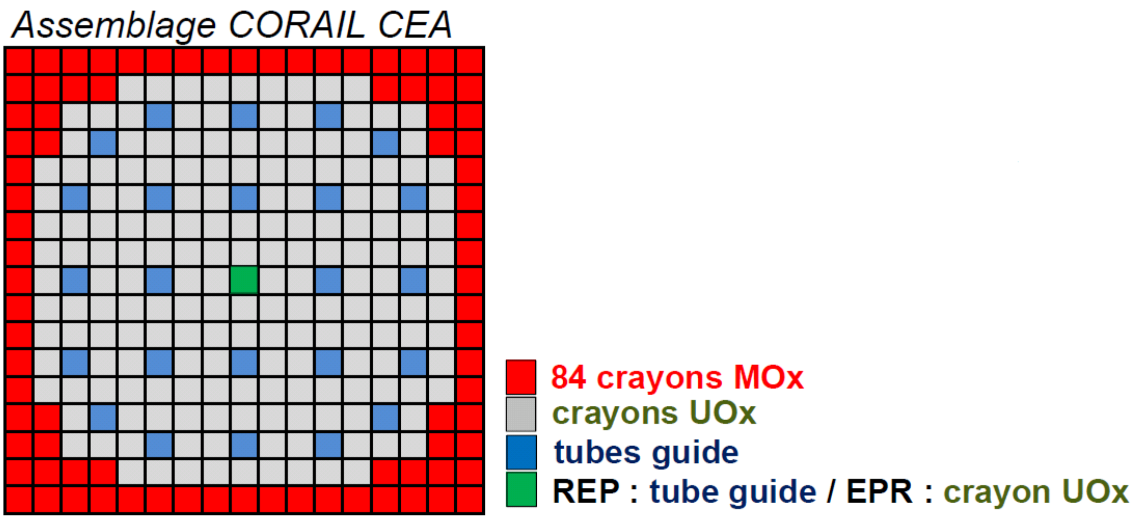
CORAIL AND MIX ASSEMBLIES

The CEA, Orano and EdF have resumed studies on the possibility of multi-recycling U and Pu in PWR and EPR, an option that was studied for PWRs in the current fleet with so-called Corail assemblies (MOx rods % Pu variable - U depleted and enriched UOx rods ^{235}U fixed at 5%) and Mix (MOx rods - % Pu fixed - U enriched - ^{235}U variable), but that had been abandoned, before the 2006 law.

At that time, an increase in the combustion rate of UOx fuel to around 70 GWd/t was desired to consume as much Pu as possible and to transmute minor actinides. The multi-recycling of Pu in MOx (and of U in URE) appeared impossible for multiple operational reasons, mainly due to the poor isotopic quality of the Pu in spent PWR MOx after mono-recycling. It was difficult to compensate for this deterioration with enriched uranium in the Corail or Mix assemblies in order to operate the reactors safely. Since then, EdF has limited the UOx and MOx fuel combustion rates to 45-50 GWd/t and the multi-recycling of Pu and U has become technically possible.

Corail assemblies are heterogeneous assemblies that contain two types of rod: MOx rods and UOx rods. The MOx rods are placed at the periphery of the assembly and the UOx rods in the centre. The plutonium content of the MOx rods is of the order of 30%.

Mix fuel is a homogeneous MOx fuel with a plutonium content of 8 to 12%. To compensate for the degradation of the isotopic vector of plutonium, it is necessary to increase the ^{235}U content of the carrier fuel during the manufacture of the MOx. The assemblies are homogeneous.



Multi-recycling in Corail or Mix mode would imply less capital investment than that involving FNR. It would only involve building new facilities in the current plants. It would make it possible to pursue the French strategy of recycling nuclear materials and not to send Pu to waste, while putting off the commitment to the FNR sector.

SCENARIOS

The CEA, EdF, Orano have developed several scenarios for the evolution of the current fleet on the basis of the implementation of various Corail and Mix fuels from 2045. These studies correspond to article 12 of the order of 23 February 2107 associated with PNGMDR 2015-2018 (report end 2017 supported by EdF). They involve a few PWRs, many UOx and Coral or Mix

EPRs and some URE EPRs. In these scenarios, the consumption of natural uranium is reduced by about 10% compared to that required for the current fleet while the production of minor actinides increases by some 30%. The outstanding Pu can be adapted for the launch of the FNRs. All scenarios require facilities for manufacturing Corail, Mix and URE assemblies and reprocessing spent MOx and UOx spent fuel, which remain to be created.

The main objectives of these multi-recycling scenarios are rapid recycling of all spent MOx fuels from water reactors and stabilisation of the plutonium inventory as well as of all spent fuel inventories.

In addition, a MIX scenario including enriched reprocessed uranium (URE) management was also considered.

Whatever the evolution of the fleet for multi-recycling of Pu and U in FNR or EPR, it is necessary to preserve the functioning of the current reprocessing and fuel fabrication plants before changing them, if possible, to treat new fuels made from various grades of Pu and U. Similarly, the processes and technologies for Pu and U recycling must be upgraded. In this respect, the CEA has been conducting a programme since 2016 dealing with cycle operations: disassembling rods, oxide-sheath separation (laser cutting, voloxidation), oxide dissolution (continuous), U/Pu separation in a single cycle without a reducing agent (asymmetric monoamides), mixed oxide synthesis (U(VI) and Pu(IV) syncrystallisation , codenitration), manufacture of pellets (granulation, paste), online packaging of waste (decontaminating melting of the shells, incorporation of fines, new glasses), continuous controls.

APPENDIX XVI: LOW-LEVEL AND VERY LOW-LEVEL WASTE (VLLW, LLLW AND TENORM)

GENERAL INFORMATION

The Board reviewed studies on this waste in its report No. 11 of 2017 (page 41 and appendix XIV page 99). Since 2016, LLLW and VLLW studies have been conducted by Andra and the waste producers (CEA, EdF and Orano) within the framework of the orders of decree 2017-23 of 23 February 2017 following requests from PNGMDR (2016-2018). They obviously based them on all the results obtained previously that the Board has assessed. Several articles of this order set deadlines for the submission of numerous intermediate files to the ASN in preparation for two important deliverables. For 2020, the ASN is waiting for a global industrial plan for VLLW management and for 2021 the DOS for a preliminary project for storing LLLW. For the moment, the LLLW already produced is in storage and the VLLW goes to Cires. The change in status of Tenorm waste is imminent. It will meet the European directive (2013/BSS/Euratom). That to be disposed will go to conventional “non-nuclear” (ISDD) authorised facilities given their low radiological impact (1mSV/year).

To meet the demands of the PNGMDR and the European Commission's directive, Andra and the waste producers have started a wide-ranging debate to set up the new management of all low and very low-level waste, for which the Board had pointed out the lack of coherence in 2016. Andra recently coordinated (February 2018) an IAEA Workshop dedicated to this subject. IRSN is also involved in this process. It deals with the scientific and technical aspects of disposal as well as societal aspects. It covers waste containing long-lived radionuclides, which are certainly not very active compared with LLILW (around 4 orders of magnitude), but the safety of repositories must be ensured over very long periods (millennia) while deploying many fewer resources than for LLILW

The Board has assessed the progress of the studies. In what follows it deals with the results acquired since report No. 11.

LLLW

Andra is continuing characterisation of the Vendeuvre-Soulaine site with a view to storing LLLW, about 250 000 m^3 of waste (radiferous: 60 000 m^3, bitumen: 42 000m^3, Malvési II: 55 000 m^3, graphite stacks: 66 000 m^3, graphite sleeves: 9 500 m^3, Norm: 7 000 m^3, Various: 3 000 m^3) and to open a second VLLW waste disposal centre. It is assessing the capacity of the site to receive, isolate and then confine the radionuclides according to two concepts of shallow disposal, under reworked cover and under intact cover. The safety requirements for the disposal of the various waste depend on the time due to the different periods of radioactive decay and their current activity. For example, at between 1000 and 10 000 years the specific activity of graphite and bitumen (around 10^4 Bq/g) remains higher than that of uranium (10^3 Bq/g) and radiferous (10^2 to 10 Bq/g). But these differences are to be compared with uncertainties on the performance of disposal facilities which increase over time (surface erosion, hydrogeology, etc.) and the relevance of the scenarios for the calculation of the doses starting from the arrival of the radionuclides at the outlets. It is therefore necessary to best evaluate the hazard of the waste including toxic chemicals as a function of time and this is the problem facing Andra and IRSN.

TENORM

Norm and Tenorm contain radionuclides of the families of uranium or the family of thorium and 40K. Their new management will be based on an exemption value (VE) of 1 Bq/g for radionuclides in uranium families and radionuclides in the thorium family and 10 Bq/g for 40K.

From July 2018, all Norm and Tenorm with activity lower than the relevant EV will be disposed in facilities (ISDD, ISDND, ISDI according to physico-chemical nature) without radiological control. That with U and Th activity between EV and 20 EV or between EV and 2 EV for 40K will be disposed in facilities involving radiological control: ISDND, ISDD equipped for control or Cires. Any Norm and Tenorm whose activity is greater than 20 EV or 2 EV depending on the case (i.e. 20Bq/g) will be disposed at Cires, like VLLW from INBs. This implies that operators of industries that produce Tenorm (listed) must characterise them before directing them to storage. Moreover, only Norm or Tenorm of activity lower than 1Bq/g will be recoverable without restriction, unlike the others which will only be recoverable with ministerial dispensation. In practice, little Tenorm is recovered in France.

All countries producing large quantities of Tenorm have their own regulations and management practices. The only common point is the depositing of waste in monitored centres, but the exemption mass limits vary greatly. The IAEA is trying to define what would be the optimum management of “Norm and Norm residues” and encourages their use and recycling as the first options.

VLLW

The practice of storing VLLW at Cires shows that the activity of waste (especially metal and rubble) based on the declarations of the producers is higher than that measured by Andra (by survey) and that 70% of the VLLW disposed since 2003 has a specific activity much lower than 1 Bq/g. But as the radioactivity of this last waste is not necessarily natural, the regulations prohibit another mode of storage. In many countries where there is a release threshold it could have been declassified. The operation of Cires without declassification can continue until around 2030, the date of saturation at 900 000 m^3.

New avenues are being explored for the management of VLLW (CNE report No. 11). A working group of the Research Committee of IRSN's Scientific Council is studying the cost and ethical aspects of complementary streams to those in place, aspects that are as important as the measurement and control aspects of the radioactivity of waste. In fact, recycling, the creation of dedicated centres other than Cires or the release of some VLLW help to understand where the problems are. The conclusions of this WG are for the IRSN/ASN, but opinions from these bodies are expected by all producers. The HCTISN is examining the relevance of a release threshold and this issue will be raised in the upcoming public debate on VLLW management.

France practises VLLW management in accordance with the recommendations of the IAEA (GSG guide 1 published in 2009) but it is almost the only country that does not practise the release of this waste in the conventional field, release which is also the subject of the safety guide. For this waste, the IAEA recommends surface/subsurface management by trenching. Examination of the practices of different countries shows that this option is almost the rule of thumb.

RECOVERY OF VLLW

The recovery of batches of metal and concrete rubble has been under consideration for a few years (article 24 and 28 of the order of 23 February 2017). The significant deadlines are for 2018. This will see the Orano and EdF report on the possibilities of a sector based on the merger of the PWR GVs and GB1 diffusers, and an Andra report on recovery of rubble. Since last year, studies have mainly focused on the economic aspects of potential recovery. The technical aspects are not prohibitive.

APPENDIX XVII: STORAGE FACILITIES AND WASTE

STORAGE FACILITIES

Orano (New Areva) and the CEA presented the Board with the state and the storage requirements for their LLILW LLHLW waste before sending it to Cigéo in accordance with article 53 of the PNGMDR 2017 order (application of decree 2017-23 of 23 February 2017). The purpose of this demand is to assess the sensitivity of storage needs to a delay in the commissioning of Cigéo. Inventories of waste packages disposed to date and expected to be disposed until 2040 do not differ from those given in the Board's report No. 10. The Orano storage facilities are in La Hague, those of the CEA in Marcoule and Cadarache. The filling rates according to the assumptions of the waste production scenario are known (PIGD Version E of 2016, first delivery of packages in 2030, industrial operation in 2035).

For Orano, existing or planned storage facilities for high-level packages can cover requirements at least until 2030. Beyond this, their extension will be necessary until the departure of the first glass packages around 2075. The storage capacities for LLILW packages are sensitive to the opening of Cigéo. Some facilities are sufficient to accept a delay of shipments until 2040, others will have to be extended to go beyond 2030. There is no technical problem for the extensions, since all the storage facilities are modular. Storage at La Hague is in many facilities of INB116 (UP3), 117 (UP2800) and 118 (STE3).

The situation for the CEA is similar. Future expansion needs for the next 20 years in the event of a delay in the commissioning of Cigéo are manageable. Recent storage is also of modular design. In the long term, only a few storage facilities will exist: Cedra in Cadarache (low-irradiating LLILW packages), EIP in Marcoule (LLILW, LLLW bitumen packages), SEV in Marcoule (high-level glass packages), Diadem in Marcoule (irradiating LLILW packages).

Many LLHLW and LLILW packages stored at La Hague or Marcoule belong to EdF. The only package storage facility managed by EdF is Iceda at Bugey intended for LLILW, FAMA-VC and activated LLLW waste packages from the decommissioning of first and second generation reactors (UNGG, Brennilis, Chooz-A, Superphénix de Crey-Maleville) as well as the operation of the current nuclear fleet. Iceda will also ensure the packaging of waste in C1PG packages. Iceda has the capacity to accommodate all activated waste packages that are planned to be produced under the current plant operating scenario (approximately 5 000 packages). No packages will be sent to Cigéo in the next 20 years. A delay in the commissioning of Cigéo would have no impact on Iceda's packaging capacity.

Tritium is produced in the atomic state by many mechanisms in the fleet's nuclear power reactors (ternary fission, nuclear reactions on boron and lithium isotopes of control rods and water). Its production increases with the power of the reactor. It diffuses through all materials. It is found in all civil nuclear waste mainly in the form of gaseous or liquid HT and HTO, and even more so in military nuclear waste, since the military produces and uses tritium in large quantities. All so-called tritiated packages release tritium. Tritium is moderately radiotoxic. Its dosimetric impact is highest in the gaseous state. So every effort is made to convert tritium into tritiated water.

Apart from the tritiated waste from the ITER facility expected by 2030, most of the tritiated waste produced in France is waste from the operation and dismantling of facilities related to CEA military applications (98%). There are many different types of waste. Tritiated waste packages are classified into six broad categories according to the radionuclides they contain, the tritium activity and the tritium degassing rate. They are all sent to Valduc. Only the most active tritiated waste packages (10000 GBq/drum) and the highest tritium emitters (55.5 MBq/package/day) are heat-treated by melting or steam heating to recover the tritium (HT gas or tritiated HTO water), then the residues (ingots from melting, baked organic matter) are put in storage-compatible packages. Tritiated water is stored as a liquid or absorbed in a resin. It can also come from the detritiation of glove box atmospheres.

Since 2008, all categories of packages have been stored in Valduc in buildings dedicated to each category, which can be expanded according to needs (planning from 2022). They must ultimately go to the CSA after decay of the tritium. Tritium (HTO) release from storage facilities is currently around 1g/year as tritium. Iter waste will be stored on site.

CLEAN-UP & DISMANTLING

The Board has addressed this vast subject in its previous reports. The A&D and RCD programmes are supported by R&D actions that are being developed by the CEA and industry according to 7 themes: characterisation of facilities and unpackaged waste or old packages, soil characterisation, development of tools for work in radioactive environments such as sampling and recovery of bulk waste, decontamination of facilities or parts, treatment of effluents in large quantities, final waste packaging and project management methodologies. R&D efforts focus on methods of non-destructive characterisation of facilities or materials and thermal treatment of organic/inorganic waste with development of prototypes (In-Can and Pivic processes).

The strategy for packaging bulk waste into primary packages is to rely on the container and the matrix or blocking material to make the package as inert as possible, during repository operation and after its closure. Pre-treatment processes for waste sometimes impose technological constraints, for example by heat treatment and always financial constraints. This directs the R&D to either packaging or the container. Orano is thus developing a universal “all-in-one” container that would be used for both transport and storage of waste.

The A&D and RCD actions concern all nuclear countries. The European INSIDER project (insider-h2020.eu) started in June 2017 for a period of 4 years (18 European partners). Its purpose is to offer a methodology for the characterisation of dismantling materials, evaluation of the performance of measurement methods and evaluation of financial costs and radiological impacts. Management of very low-level radioactive materials should benefit.

Here, the Board examines the progress of the A&D and RCD programmes and their evolution due to changes or modifications, dictated by scientific and technical considerations, cost control, delays and the search for economic optima while respecting the nuclear safety constraints.

CEA

a) Magnesian waste

Magnesian waste has been the subject of planned RCD operations since 2010. It consists of 1620 tonnes of metal waste (pieces of Mg at 0.5% Mn, at 1.5% Zr, traces of U metal) stored dry in pits at Marcoule (70% LLILW, 30% LILW-SL). The first to be taken back and packaged will be the LILW-SL category, the physicochemical and radiological characteristics of which were established in 2016-2017. The Mg is surface-damaged with formation of magnesium hydroxide: $Mg(OH)_2$. The risk of ignition of the waste on recovery is reduced if it is done under humid air. For the waste blocking matrix, the CEA has selected a sodium alumino-silicate hydraulic binder doped with sodium fluoride (NaF) called “geopolymer”. It meets the rheological criteria for casting and, once solid, the mechanical strength required for implementation on an industrial scale. It minimises the production of hydrogen, and does not undergo mineralogical or microstructural modification up to 10 MGy. Only the sodium is leachable by cement waters. H_2 production comes from reactions between the waste and water. Ongoing R&D is in line with the R&D programme (H_2 production mechanism and optimisation of the NaF content which inhibits it). Implementation tests at full scale concern packaging of LLLW (bulk waste put in concrete containers and blocked, approximately 600 kg of Mg) or LLILW (compacted drums and blocks, approximately 150 kg of Mg).

b) UNGG reactors

The G1, G2 and G3 reactors have been at IAEA-2 dismantling level for decades. The measures taken ensure the confinement of the reactor blocks. These reactors operated for 12 years (G1, power 46 MWth) and about 25 years (G2 and G3, power 250 MWth) during which time the graphite of the stacks (respectively 1200 and 1300 t) and the materials of the structures of the reactor blocks (concretes, steels) have been activated. Before continuing dismantling, the CEA is continuing the programme of the radiological inventory of materials still in place. As far as graphite is concerned, it is based on the comparison between neutron activation calculations taking into account the origin of the graphite (different impurities that can be activated) and 3D modelling of historical neutron flows and radiochemical analyses performed on core samples taken from moderators and reflectors (G1 and G2). The activities of tritium, ^{14}C and ^{36}Cl are being evaluated/re-evaluated (as well as those of other radionuclides, ^{60}Co, ^{55}Fe, ^{63}Ni, ^{93}Mo, ^{94}Nb, ^{41}Ca, ^{10}Be).

These R&D actions make it possible to develop sophisticated graphite characterisation and activity methods that can be applied to other Marcoule reactor materials and to the dismantling of all UNGG reactors.

Orano

a) HAO silo and SOD silo (waste from shells, tips, fines)

HAO and SOD silo waste is collected simultaneously, washed and sorted by decantation. The shells and tips and some other metal debris (about 1600 tonnes) will be sent to the shell compacting workshop after radiological characterisation where they will be put in CSD-C packages according to a new production specification under examination. The shearing and dissolving fines (containing predominantly alpha-emitting radionuclides) and the resins will be cemented on site (CEM IIIC cement, 11% waste incorporation rate) to form primary CFR HAO packages. Manufacture of the package is established. This packaging coats the waste very well but, as a result, leads to a production of hydrogen by radiolysis estimated today at 120 litres/year/package. Orano is examining this problem. Orano plans to file a packaging approval application in the first quarter of 2018.

b) STE2 silos (coprecipitation sludge)

After a few years of R&D on an alternative packaging to the mixing of sludge in bitumen, Orano proposed packaging this waste in a C5 package (dehydrated pellets of sludge blocked by sand in a CSD container). However, serious manufacturing difficulties appeared at the drying stage. The C5 package has therefore been abandoned. Orano is moving towards a change of strategy. The immediate objective is the emptying of the silos. Orano produces 80 bitumen packages/year at STE3.

c) Silos 115 and 130 (graphite and magnesian waste)

The so-called UNGG waste in these silos contains mainly graphite waste (92%), MgMn and MgZr magnesium alloy waste (7.5%) and metallic uranium (0.25%), all in pieces. The magnesian waste will be treated to dissolve the Mg and oxidise the uranium, elements that react with oxygen and water. The inert residues from processing will be cemented like the graphite waste. The processes are under development. This waste comes under the LLLW category. Since there are no specifications for acceptance in storage, the waste from silo 130 will be placed in ECE drums awaiting packaging, which will take place at the same time as the waste from silo 115.

d) Packaging of elution columns and strontium titanate capsules from the ELAN IIB workshop

The Elan IIB workshop (development and use of a mineral exchanger selectively fixing cesium-137 in a nitric medium) is being dismantled. The waste consists of four exchange columns (LLILW) and fifteen capsules of strontium titanate (high level) which will be packaged for storage.

EdF

EdF is in charge of dismantling the 6 reactors of its UNGG nuclear power sector: Chinon A1 (70 MWe, 1963-1973), Chinon A2 (210 MWe, 1965-1985), Chinon A3 (365 MWe, 1966-1990), Bugey 1 (540 MWe, 1972-1994), Saint-Laurent A1 (390 MWe, 1969-1990) and Saint-Laurent A 2 (465 MWe, 1971-1992). These reactors fed with metallic natural uranium are of a complex technology, very different from that of PWRs. The cylindrical core of the Chinon A2 reactor enclosed in a 10-cm thick chamber is approximately 3 times higher than that of a 900 MWe PWR (31 m) and its diameter (25 m) is 5 times greater. The graphite stack (25 000 bricks, 2 200 t) and the chamber (2 229 t) are in total 10 times heavier (4 500 t) than the vessel of a PWR. The CO_2/steam generators are also bigger than those of a PWR (water/steam). Of the 50 reactors of this technology that are shut down, only 2 have been dismantled (Fort St Vrain in the USA, 320 MWe and Windscale in England, 33 MWe).

EdF's strategy was to start with the dismantling of Chinon A2 as top-of-the-line, and to put the other 5 reactors in safety configuration, for around 30 years for Chinon A1 and A3 for example. For these 2 reactors, this essentially means dismantling the heat exchangers by 2035. Over the next 20 years, EdF will dismantle all the nuclear facilities adjoining the chambers of Chinon A1 and A3 (notably the exchangers).

The dismantling work already carried out on Chinon A2 has almost achieved IAEA-2 level. There were 2 loading machines (each of 450 tonnes) on the slab of the reactor, which allowed replacement of fuel in operation. A swing bridge allowed them to dock on the different fuel loading wells. Their dismantling generated 1 500 t of VLLW (scrap metal, concrete). Before moving on to the essential phase of dismantling, it remains to backfill the casing of the machine room. After backfilling (volume of 7 500 m^3), the redeveloped area will be made available for continued operations.

Dismantling of the Chinon A2 chamber (2030-2055), under air, will be preceded by the construction of an industrial demonstrator to test the tools and the scenario (2019-2030). Dismantling of the 5 chambers of the other reactors is programmed for after 2060. EdF predicts it will take approximately 25 years to dismantle a chamber, passing through preliminary work (35 months), opening the top of the concrete chamber (43 months), setting up a dismantling platform (37 months), opening of the biological protection (24 months), removal of the upper metal structures from the platform (35 months), the graphite stack (85 months) and lower metal structures (27 months). Opening of the chamber is planned for 2032.

This industrial demonstrator will include full-scale models of representative parts of the chamber, physical simulators for testing remote-controlled tools and digital simulations. It could be an open platform for any organisation or company involved in the dismantling of graphite reactors. Several French and foreign manufacturers have already expressed their interest in this project.

Dismantling the Chinon A2 reactor chamber will be an extraordinary project, due to: the volume of material to be demolished, the state of the graphite stack (poorly known), the radioactivity that requires remote-controlled operations and difficult access to the parts to be dismantled successively.

Evacuation of the Chinon A2 graphite stacks (15 GBq in ^{36}Cl) to the CSA is planned in 2045. In fact, the remaining ^{36}Cl capacity of the CSA where the Bugey 1 graphite sleeves are already stored (20 GBq) is 300 GBq (if not accepted at the CSA, EdF will build a storage facility). EdF will also build a storage facility (around 2023) on the Saint-Laurent site for the sleeves currently stored in the silos and then a storage facility from 2024 for the start of graphite removal in 2028. The removal of the graphite from the 5 other chambers and the graphite from Saint-Laurent A to LLLW disposal is planned beyond 2070.

The end of characterisation of graphites in the 6 UNGG chambers is for the end of 2019.

EdF has abandoned active R&D on the heat treatment of graphite. In fact, after major R&D on Bugey 1 stacks, from the laboratory to pilot tests, the decontamination rate in ^{14}C remains limited to 30% (with mass loss at 5%) and that of ^{36}Cl is insignificant and difficult to assess. The decontamination operations lead to large releases of ^{14}C and ^{3}H gas making the prospect of installation on an industrial scale unacceptable. In addition, there are serious difficulties in packaging the secondary waste, especially tritiated water.

EdF remains active internationally as part of the IAEA's GRA-PA project. International trials have not yet demonstrated the industrial feasibility of graphite treatment.

At the Chinon site from 1963 to 2015, EdF operated the Review Workshop for Irradiated Materials coming from all its plants (AMI). AMI's activities were transferred to a new laboratory built on the Chinon site: the LIDEC. EdF is preparing the final shut-down of the AMI (expected by this year) by removing the operating waste present in the main building and the waste storage areas. This is major work, to be carried out with remote-controlled tools in place. Waste forecasts are as follows: 30 000 t, 80% conventional waste (recyclable metals and rubble), 19% VLLW (Cires), 1% LILW-SL waste (CSA) and 0.02% of waste awaiting approval (storage on the site in armoured containers before defining the reference category). Dismantling is planned over 10 years.

IAEA CLASSIFICATION

France has adopted the three dismantling levels proposed by the IAEA:

- level 1 consists of removing the nuclear material, sending it either to reprocessing or to storage centres, then sealing the building hermetically while continuing to control the radioactivity inside and in the environment;
- at level 2, the facility is partially released by removing all easily removable equipment and reducing the confined area to a minimum;
- level 3 corresponds to the total and unconditional release of the site, which must once again become usable without restriction, what English speakers call the “green field” theory.

APPENDIX XVIII: RECOMMENDATIONS AND PRACTICES ON THE RELEASE OF WASTE

The management of radioactive waste is far from uniform across all countries using nuclear energy. European Directive 2011/70/EURATOM establishes a regulatory framework for the safe and responsible management of nuclear waste and spent fuel in the European Union. The production of nuclear waste should be kept as low as possible.

INTERNATIONAL ATOMIC ENERGY AGENCY - IAEA

The IAEA publishes safety standards as a set of non-binding documents that represent the international reference for nuclear safety and radiation protection. Guide RS-G-1.7 deals with the application of the concepts of exclusion, exemption and release. A distinction is made between radionuclides of natural or artificial origin. Concentration values in specific activity (Bq/g) give indicative exemption thresholds for an exhaustive list of isotopes. Others indicate the acceptable threshold for the total activity of the volume under consideration. Even if the activity concentration is below the exemption threshold, as for some naturally radioactive materials (Norm) containing uranium or thorium, the material will become a regulated material if the total activity exceeds the corresponding threshold. However, the guide provides a graduated approach to the use of thresholds. The regulator may decide to allow exemption at higher values, for example by a factor of 10, as part of optimising a potential risk.

The values were determined on a case by case basis, taking into account an increase in an individual effective dose limited to 10 µSv/year.

The IAEA standards do not apply to food, drinking water, radon or ^{40}K exposure in the body, nor to transport. Other regulations, such as those of the World Health Organisation (WHO), the United Nations Food and Agriculture Organisation (FAO) or the Nuclear Energy Agency (NEA-OECD) partially govern these matters.

EC-EURATOM

Directive 2013/59/EURATOM sets out the basic standards for health protection against the dangers arising from the exposure of the public or workers to ionising radiation. It is largely based on the work of the International Commission on Radiological Protection (ICRP) and the recommendations of the IAEA, WHO, FAO and NEA.

The directive does not apply to exposure of members of the public or workers to natural levels of radiation, other than air or space crew members.

The Directive defines non-binding "exemption and release thresholds" as values set by the competent authority or in national legislation, and expressed in terms of specific activity, at or below which practices subject to notification or authorisation may be exempted from complying with the requirements of this directive.

The exemption and release thresholds specified in the directive are identical to those recommended by the IAEA. Since they are not binding, they can differ from one country to another, which leads to a lack of European harmonisation.

NATIONAL PRACTICES

This appendix describes the salient points of the state of the various regulations that are applied.

a) Germany

Germany considers three classes of waste management and practises decay storage for very short-lived isotopes (such as those used in nuclear medicine):

- release for very low levels;
- a geological repository, planned at Konrad, for waste that does not generate heat (low and intermediate level);
- a geological repository, the nature and location of which remains to be determined, for waste that generates heat (high level).

When a risk of contamination or activation of waste exists, the regulations on the release of radioactive waste apply. They provide for 9 release levels that distinguish between unconditional release and release for a specific use. For conditional release, the release levels are a function of the specific activity (Bq/g) or surface activity (Bq/cm^2).

If the release criteria are observed and the procedure has been followed, release may be granted by the Bundesamt für Strahlenschutz (BFS) (Federal Office for Radiation Protection).

No regulation exists for the release of a site, but when all the elements present on the site are released (floors, buildings, etc.), the nuclear license is terminated, and the site automatically becomes non-nuclear.

b) Belgium

Belgium has three management classes and practises decay storage for very short-lived isotopes:

- surface storage of short-lived low- and intermediate-level waste, “Category A”, for a surface storage facility currently under construction;
- the storage of LLLW and LLILW, “category B”, which does not generate heat and is destined for future disposal in a geological repository;
- storage of “category C” high-level waste, destined for a future geological repository.

Release threshold levels (Bq/g) for solid radioactive waste are set by the regulations, thus allowing their recycling, reuse or management as conventional waste (incineration, landfilling). Deviations from these release levels may be authorised by the Federal Agency for Nuclear Control (AFCN) provided that the operator demonstrates that the radiological protection criterion is met (individual dose less than 10 μSv/year, collective dose less than 1 man.Sv/year) and optimised.

c) Canada

One of the fundamental IAEA principles, repeated in CNS guide P-290 “Radioactive Waste Management”, is that the holder of a licence to operate must minimise the amount of waste generated as much as possible. This obligation implies the development of waste management programmes that help reduce its volume and require long-term management.

Licence holders are required to research technologies that can reduce this volume and apply them when available.

d) Spain

Spain has five management classes as well as decay storage for very short-lived isotopes:

A surface storage facility for VLLW and short-lived low-level waste is operational at El Cabril.

For LLLW, LLHLW and high-level waste, a centralised storage facility (ATC) is planned. It was approved by the Council of Ministers on 30 December 2011 and is under construction in Villar de

Cañas (Cuenca), 200 km southeast of Madrid. This project is very late due to problems with the licensing process. The intermediate solution consists in the construction of several temporary storage sites on nuclear power plant sites (today 3 sites are under construction). The final solution will be a deep geological repository, the site of which has not yet been defined.

In Spain, the release of waste is managed by decree ETU/1185/2017 of 21 November 2017 on the release of residual materials produced by nuclear facilities. This regulation partially transposes the thresholds from European Directive 2013/59/Euratom. The release thresholds are defined in appendix 1 of this decree.

e) United States

The release of radioactive waste is not allowed in the United States. Minimising waste volumes is a legal requirement.

Federal agencies such as the DOE (Department of Energy) are subject to the waste minimisation and pollution prevention programmes of Executive Order 12780, and federal environment agencies are responsible for pollution and risk prevention.

The DOE must therefore reduce its releases and the volume of waste generated by its operations that requires treatment, storage and disposal.

NRC regulations require licence holders to reduce the production of radioactive waste to as low a level as possible. The cost and availability of radioactive waste storage facilities in the United States is considered a sufficient incentive for waste producers to apply this recommendation seriously.

f) Finland

The general release rules (based on volume activities) and the conditional releases of nuclear waste are given in guide YVL 8.2. For small waste producers, the exemption levels for liquid and solid waste are defined in guide ST 6.2.

g) United Kingdom

The United Kingdom considers five classes of radioactive waste:

- waste of very low activity, disposed in conventional landfill;
- low-level in surface storage at Drigg;
- low-level not intended for Drigg;
- intermediate-level for future geological disposal;
- high-level for future geological disposal.

Uranium and plutonium are not considered as waste.

The low-level exemption order is the general framework within which applications for exemptions and exceptions for radioactive waste are processed. These requests are made in compliance with the 2010 Environmental Regulations (Wales and England) and the Radioactive Substances Act 1993 (Scotland and Northern Ireland) for substances that satisfy the exemption order.

A review and administrative simplification process is underway to facilitate the use of the exemption order while ensuring a good level of human and environmental protection.

Very low activity materials (<0.4Bq/g) are automatically released and therefore not considered as radioactive waste. The exemption of a certain number of elements is planned for activities between 0.4 and 11 Bq/g. Other materials may be released or exempted on a case-by-case basis.

Release of a site is granted when there is no longer any danger to health:

- <20 µSv without additional decontamination efforts;
- <300 µSv if all efforts have been made, restrictions on future use may apply;
- <1 mSv is the absolute acceptance limit.

h) Italy

According to technical guide No. 26 on the management of radioactive waste, all measures must be taken to reduce the production of waste in mass, volume and activity. Treatments for volume reduction and storage should be considered. It is also requested that all operations in the sector should be optimised in order to reduce the overall volume of waste.

A general criterion is applied in Italy for the unconditional release of waste. Radioactive waste may be released unconditionally if the radionuclide concerned satisfies two criteria:

- The activity must be less than 1 Bq/g,
- The half-life should be less than 75 days.

If these two conditions are not met, a specific release, reuse or recycling authorisation is required. Authorisation may be granted if:

- The effective dose is less than 10 µSv/year,
- the collective dose is less than 1 man.Sv/year or analysis shows that exemption is the optimal solution,
- the activity must be lower than the threshold set by Italian law of 1 Bq/g.

i) Netherlands

In the Netherlands the release thresholds are strictly equal to the exemption thresholds. The exemption levels are those proposed by Euratom with the exception of ^{226}Ra, ^{228}Ra and ^{60}Co. For these radionuclides, the exemption threshold in the Netherlands is fixed at 1 Bq/g while Euratom proposes 10 Bq/g.

j) Sweden

The release of radioactive waste is one of the components of waste management. Materials may be released for free use or to landfill at conventional sites. For example, in 2004, approximately 600 t was released and disposed in municipal landfills and 500 t of molten metal with an activity less than 0.5 Bq/g was released and recycled.

Apart from spent fuel, Sweden has three kinds of waste:

- **VVLLW**

The release of VVLLW is authorised in Sweden and is regulated by the Radiological Safety Authority (SSM) according to detailed criteria, specified in the release regulations for potentially contaminated materials (for example: 1 Bq/g for ^{137}Cs, ^{90}Sr and ^{36}Cl; 0.1 Bq/g for ^{239}Pu, etc.).

Another option for VVLLW, also regulated by SSM, if it cannot be released, is storage in a landfill on certain nuclear sites.

- **Short-lived low- and intermediate-level waste**

The disposal facility, SFR, is in crystalline rock about 100 m deep at Forsmark. SFR has been in operation since 1988. A request for an extension of SFR was presented to the authorities by SKB in 2014.

- **LLLW and LLILW**

The forecast of total LLLW and LLILW volumes in Sweden is about 30 000 m3, mainly composed of historical waste and waste resulting from the dismantling of reactors. This waste is in storage but a specific storage facility SFL, similar to SFR, is planned. The site and depth of SFL are not yet decided. Commissioning is planned for 2040.

k) Switzerland

The release threshold for radioactive waste is deduced from the dose that the radionuclides it contains can induce by ingestion, inhalation or contact. To allow release, this dose must be less than 10 μSv. The chosen dose factors are tabulated in a radiological protection ordinance and are in accordance with the recommendations of the IAEA (IAEA Safety Series 115). The materials thus released are either recycled or treated as conventional waste.

APPENDIX XIX: OPINION OF THE SWEDISH SAFETY AUTHORITY

The Board reproduces below the press release from the Swedish Safety Authority, available on its website.

https://www.stralsakerhetsmyndigheten.se/en/press/news/2018/swedish-radiation-safety-authority-issues-pronouncement-on-final-disposal/

SWEDISH RADIATION SAFETY AUTHORITY ISSUES PRONOUNCEMENT ON FINAL DISPOSAL

23 Jan 2018

The Swedish Radiation Safety Authority, SSM, has undertaken a regulatory review of the Swedish Nuclear Fuel and Waste Management Company's (SKB) licence applications for final disposal of spent nuclear fuel. The review found that SKB has the potential to meet the requirements of the Act on Nuclear Activities concerning safe final disposal. Today, the Authority (SSM) has submitted its formal findings to the Swedish Government.

SSM recommends approval of SKB's licence applications under the Act on Nuclear Activities for permission to construct a repository for spent nuclear fuel at Forsmark, Östhammar Municipality, as well as an encapsulation facility in Oskarshamn Municipality. Östhammar Municipality is located on the east coast of central Sweden. Oskarshamn Municipality is located on the south-east coast.

“The Swedish Radiation Safety Authority assesses that SKB has the potential to ensure safe management and final disposal of spent nuclear fuel so that human health and the environment are protected against harmful effects of radiation,” says Ansi Gerhardsson, head of section at SSM.

SSM considers that SKB, though its licence applications, has demonstrated that the facilities and associated safety analysis reports, or SARs, can be developed in accordance with the established procedure for a step-wise permitting process under the Act on Nuclear Activities. SKB is assessed as having the potential and capability to produce updated SARs covering construction, operation, and long-term nuclear safety and radiation protection, which will need to be scrutinised and approved by SSM in future steps if licences are granted by the Swedish Government.

“There are a number of prerequisites for SSM's recommendation to approve the licence applications, such as the continued development of SARs and management systems for these facilities in accordance with the step-wise permitting process under the Act on Nuclear Activities. “This means that SKB, at several stages of an ongoing process, must submit further information and analysis to be examined and approved by SSM before the company is allowed to move on to the next step of the process,” says Ms. Gerhardsson.

The Authority's recommendation for licence approval applies to the specific sites, as well as to the quantities and types of spent nuclear fuel that are specified in the licence applications. SSM's favourable judgment further presupposes that SKB, in the design, construction and operation of these facilities, continues to take into account matters of significance for radiation safety and development needs identified by SSM in its scrutiny of the licence applications.

The Authority has also proposed certain conditions to be attached to Government licences for SKB's facilities. These conditions require that the facilities should be constructed, taken into possession and operated as specified in the applications, as well as that SKB should produce SARs for examination and approval by the Swedish Radiation Safety Authority prior to construction commencing, before beginning test operation, and before a facility starts routine operation.

APPENDIX XX: OPINION OF THE ENVIRONMENTAL COURT

The Board reproduces below the summary of the opinion of the Swedish Environmental Court as translated into English by the NGO MKG (http://www.mkg.se/en). The opinion of the Court is available in Swedish on its website (www.nackatingsratt.domstol.se/Om-tingsratten/Mark--och-miljodomstolen/).

OPINION OF THE ENVIRONMENTAL AND ENVIRONMENTAL COURT

The undertaking is permissible if:

1) Svensk Kärnbränslehantering AB [SKB] produces evidence that the repository in the long term will meet the requirements of the Environmental Code, despite remaining uncertainties regarding how the protective capability of the canister may be affected by
    a. corrosion due to reactions in oxygen-free water
    b. pit corrosion due to reaction with sulphide, including the contribution of the sauna effect to pit corrosion
    c. stress corrosion due to reaction with sulphide, including the contribution of the sauna effect to stress corrosion
    d. hydrogen embrittlement
    e. radioactive radiation impact on pit corrosion, stress corrosion and hydrogen embrittlement.
2) the long-term responsibility for the final repository according to the Environmental Code has been clearly assigned.

Before permission is given, Swedish Nuclear Fuel and Waste Management Company [SKB] must also provide a comprehensive report of the plant's surface operations and indicate the siting of two possible ventilation towers.

The government should consider whether a legislative amendment is needed regarding the time limit for water management. The government should also consider giving the Radiation Safety Authority the right to plead cases under Chapter 22, Section 6 of the Environmental Code, and an opportunity to apply for re-evaluations under Chapter 24, Section 7 of the Environmental Code.

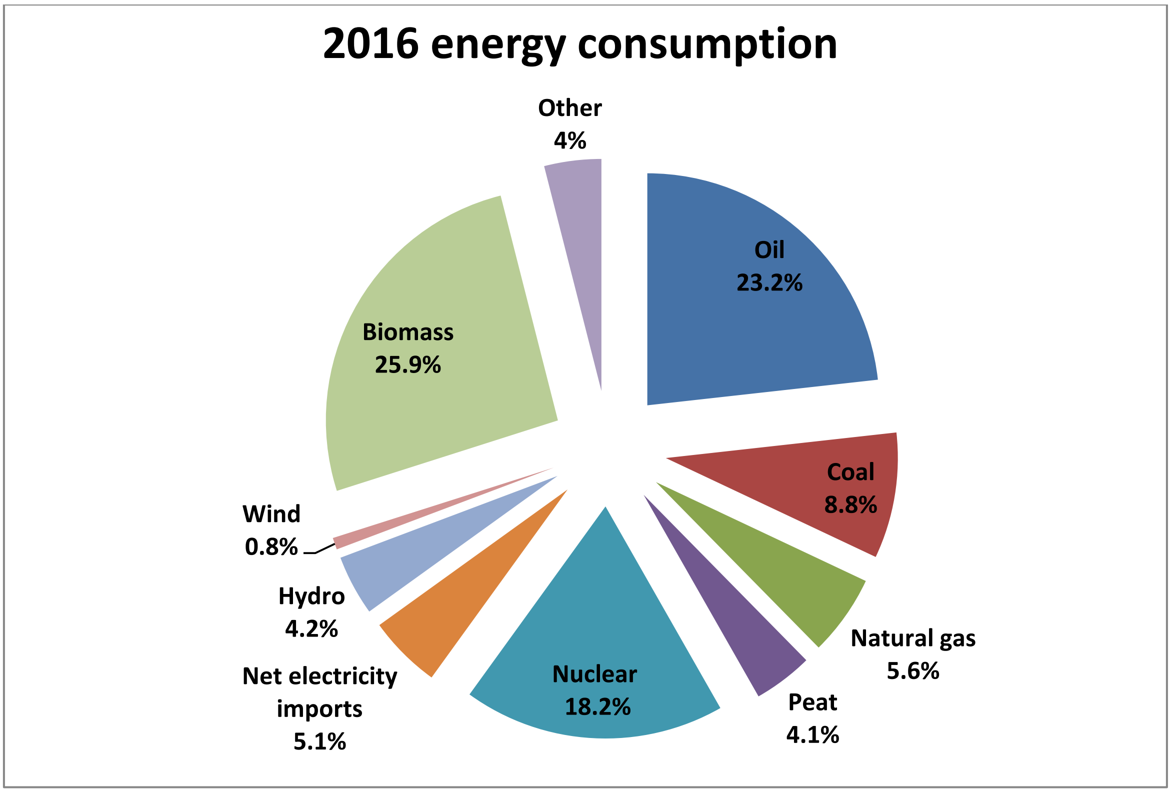
APPENDIX XXI: STUDY MISSION TO SWEDEN AND FINLAND

This appendix presents the state of play and prospects for energy systems in Finland and Sweden.

FINLAND

Energy mix

Despite its small population (5.5 million inhabitants), Finland has relatively high energy needs. This is due to the harshness of its climate (the country is located between the 60th and 70th parallels) and its energy-intensive industries: wood, paper, metallurgy, chemistry, which represent half of its energy consumption.



Energy mix in Finland in 2016. Total consumption: 1 351 PJ. (Source: Statistics Finland)

Finland is a country poor in natural resources. All fossil fuels (coal, gas, oil) are imported, along with nuclear fuel and some electricity. Ultimately, excluding nuclear power, only 39% of the energy consumed in Finland is produced from indigenous resources in the country. The majority of oil, coal, and all natural gas imports come from Russia.

Renewable energy accounted for 35% of the country's total energy consumption in 2015. Peat, although classified by Finland as "slowly renewable", has a much higher extraction rate than that of its reconstitution and use, and it is not recognised as renewable by international institutions. Finland is suspended by the European Union from the decision to endorse the renewable nature of solid biomass (wood energy), which is a pillar of Finnish energy policy but is controversial in other European countries.

The Finnish gas network is currently connected only to Russia. Several projects are underway to overcome the Russian monopoly. On the one hand, the Baltic connector pipeline between Finland

and Estonia, to connect Finland to the "continental" European gas network, is finally coming to fruition after having obtained EU funding in mid-July 2016 to cover 75% of its estimated cost of €250m. It should be completed in 2020. On the other hand, several LNG terminals (Liquefied Natural Gas transported by ship) are being built along the Finnish coast, one of which, in Hamina in south-eastern Finland, will be connected to the national network.

Finland has long since developed heating and cooling networks in urban areas and industrial sites, recovering waste heat from thermal power plants to meet the heating needs of its inhabitants and to provide steam for its industries. In 2013, cogeneration plants (CHP) provided 45% of the country's energy consumption.

Finland's 2020 climate targets are ambitious in the EU context and globally above average:

	European Union	**Finland**
Greenhouse gas reduction[2]	-20%	EU level
within the emissions trading system (ETS)[3]	-21%	EU level
outside the emissions trading system (ETS)[2]	-10%	-16%
Renewable energy share in final gross energy consumption	20%	38%
biofuel share in the transport sector	10%	20%
Improvement in energy efficiency[4]	+20%	EU level

Figure 1 – 2020 energy & climate objectives for Finland and the EU.

Finland's latest Energy & Climate Strategy dates from 2013 and includes several targets for 2020:

- Limitation of final energy consumption to 310 TWh;
- -9% in heat consumption;
- -20% in oil consumption;
- Achievement of wind-generated production of 6 TWh in 2020 and 9 TWh in 2025;
- -33% in peat consumption by 2025;
- Elimination of coal from the energy mix in 2025;
- Develop the role of forest biomass;
- 10% of biogas in national gas consumption by 2025.

Electricity mix

Finland's electricity consumption in 2016 was 85.1 TWh. The share of renewable sources in this mix was 36%. Combining various fuels, heat and power cogeneration plants supply 25% of this electricity.

Industry accounts for 47% of the country's electricity demand, half of which is for the forestry industry.

Finland has a long-standing deficit in electricity with 22% of the electricity consumed imported in 2016.

It is estimated that the country's electricity consumption will rise to 88 TWh in 2020 and 92 TWh in 2030. In view of current projections (installation of new capacity, particularly nuclear, development of renewable energies), Finland could approach self-sufficiency in electricity.

[2] Reference year: 1990.
[3] Reference year: 2005.
[4] Compared to reference scenario as estimated in 2007.

Although Finland's electricity capacity deficit (around 2 GW on average) can be compensated for, Finland still faces a real supply problem during consumption peaks. A new absolute record of electricity consumption was reached in January 2016, at 15.1 GW. Although the network has not been put at risk this year, many observers are expressing concern over the closure of domestic thermal generation capacity and the limits of the country's electricity interconnections with its neighbours. Above all, the consumption peaks correspond to very cold winter periods when production of new electrical capacity (wind and solar) is at a low, causing a real imbalance on the network from now until OL3 comes into service.

Electricity market & the Nordic network

Finland is fully integrated into the NordPool electricity market, on which it constitutes a price zone. Interconnections with its neighbours are strong (2.7 GW with Sweden, 1 GW with Estonia) but still insufficient: the connection with Sweden is often saturated, giving rise to a higher price for electricity in Finland than on the NordPool spot market.

Finland also has a connection (> 1 GW) with Russia. In 2016, 81.7% of the electricity imported into Finland was from the Nordic grid and 18.3% from Russia, where electricity became more competitive following the fall of the rouble and lower demand in Russia.

As in many other parts of Europe, the price of electricity is at a historically low level. The Nordpool spot price averaged €21/MWh in 2015, its lowest level since 2000. In Finland the average price was €30/MWh, down 18% compared to 2014. However, there was a slight improvement in prices in 2016 with an average of €27/MWh.

Low prices are also felt in Finland, where they have led to the closure of many production facilities in recent years (> 2 GW since 2013). These were mainly thermal and condensing plants that were only used during peak consumption and which became unprofitable through the erosion of electricity prices and/or their non-selection for reserve capacity. The operator of the Finnish electricity grid, Fingrid, has 1.35 GW of spare capacity and there are no current plans to expand capacity contracts.

Nuclear energy as part of the Finnish energy culture

With 4 reactors in operation, 1 under construction and 1 at project stage, Finland has a long nuclear tradition that started in the 1970s. In the wake of its Swedish neighbour, Finland opened its first reactors between 1977 and 1982.

Plant site	Municipality	Operator	Reactor	Type	Net power (MWe)	Entry in service	End of operation
Hästholmen	Loviisa	Fortum	LO1	PWR[5]	488	1977	2027
			LO2	PWR	488	1981	2030
Olkiluoto	Eurajoki	TVO	OL1	BWR[6]	880	1979	2039
			OL2	BWR	880	1982	2042
			OL3	PWR	1 600	*2018*	*2078*
Hanhikivi	Pyhäjoki	Fennovoima	HA1	PWR	1 200	*2025*	*2084*

Overview of the different Finnish nuclear projects.

15 years after the Chernobyl nuclear accident in 1986, Finland was the first western country to revive a major nuclear project by starting work on a third reactor at Olkiluoto. In 2010, the Finnish government gave its approval in principle for the construction of two new reactors. While TVO, in financial difficulty especially due to setbacks with OL3, did not follow up with the potential OL4 reactor, Fennovoima has however submitted its application for a Building Permit in June 2015 for HA1 (ROSATOM reactor). Currently being examined by the authorities, a building permit could be issued in 2019.

The FH1 project is the first of the third generation in Western Europe and thus highly strategic for Rosatom. Many French companies are interested in this project. In July 2016, Alstom-GE and RAOS Project signed the contract in Moscow for the supply of the turbo-generator unit of the plant (to be manufactured in Belfort). In June 2017, it was Rolls-Royce (whose nuclear activities are located in Isère) and Schneider Electric who were chosen respectively for the studies and the delivery of the control-command systems of the Fennovoima Hanhikivi 1 project. This project was the subject of a detailed presentation to French manufacturers on the sidelines of the Oulu Nuclear forum in May 2017.

Nuclear power enjoys quite favourable public opinion in the country, which understands its importance in achieving energy independence.

In general, the competence of the Finnish nuclear industry has strong international recognition. Finnish power plants have some of the best results in the world: since they entered service in the early 1980s, their availability rate has remained almost consistently above 90%, and often above 95% in Olkiluoto[7], compared to a world average of around 75%[8]. At the end of October 2015, TVO announced that it had broken its electricity production record with more than 14 TWh in 2014, with an availability rate of more than 96%.

Finnish operators attach particular importance to maintaining their facilities in an optimal state and have thus been able to increase the power of their reactors[7]. In fact, the reactors of Olkiluoto, in successive leaps, have gradually gained one-third additional power. In Loviisa too, the reactors now produce 9% more electricity than when they entered service.

The Finnish safety authority, STUK, also enjoys an excellent reputation. It now exports its know-how and advises the Saudi and Turkish safety authorities in their development.

[5] Pressurised Water Reactor
[6] Boiling Water Reactor
[7] Source: Finnish Ministry of Economy and Employment. *Nuclear Energy in Finland*, 2011.
[8] Source: Alternative Energies and Atomic Energy Commission. *Nuclear plants worldwide*, 2015.

The OL3 project

The Finnish EPR, for which the contract was signed in 2003 between the Finnish operator TVO and the Areva-Siemens consortium, has been under construction since 2005. The commissioning date is currently planned for the end of 2018, 9 years later than initially planned.

The latest site schedule dates from September 2014 and has a slight delay of two months. Areva, TVO and the STUK safety authority agree that the on-site working relationship is effective, resulting in some work being shared by the TVO and Areva teams.

The actual construction of the plant is nearing completion and the work currently being carried out is nearing completion. TVO thus reported the completion of fuel receipt on 9 February 2018. Started in December 2017, the hot tests are still in progress and are expected to be completed by the end of the first half of 2018. Finally, acceptance of the plant's general documentation by the Safety Authority (STUK) is planned for the second half of 2018.

On 11 March 2018, the signing of an agreement between the main project players, AREVA, SIEMENS and TVO, was announced by TVO in a press release. This agreement puts an end to all legal proceedings between the three companies, including the heavy multi-billion-euro dispute arbitrated by the International Chamber of Commerce. This agreement provides for a two-stage payment of €450m from the consortium to TVO as well as the possibility of an additional payment of up to €400m in case of further delay in the project. If the schedule is observed, an amount of €150m may be paid to the AREVA-SIEMENS consortium.

Nuclear operators

a) Fortum

Fortum is the largest energy group in Finland, half-owned by the State (50.76%). It operates the Loviisa plant and is also a shareholder in TVO (25%) and Fennovoima (6.6%). It also has a minority interest (45.5%) in the Oskarshamn nuclear power plant in Sweden. In addition to nuclear power, Fortum has invested heavily in the production of low-carbon energies. It should be noted that in 2009 Fortum submitted a new reactor project to the government, a nuclear cogenerator for electricity and heat in Loviisa (LO3) (electric & thermal cogeneration is also widely developed in Finland but has never been applied to a nuclear power plant). However, unlike TVO and Fennovoima, it did not obtain authorisation in principle.

b) TVO

TVO is a consortium of Finnish companies operating under the Mankala principle that shareholder companies share electricity produced at cost price and in proportion to their participation in the investment. It is led by the PVO group (and through it by the UPM paper company) and counts Fortum (25%) and several local energy boards among its investors.

c) Fennovoima

The Fennovoima consortium was formed in 2007 around a project to build a nuclear power plant in northern Finland. It brings together several Finnish companies, including metallurgist Outokumpu (whose facilities in Tornio on the Swedish border are particularly electro-intensive) and many local energy boards. Russia's state-owned nuclear group Rosatom, which was selected to build the plant, is a 34% Fennovoima shareholder via its Rosatom Overseas export branch. Fortum also joined the project, taking a 6.6% share.

d) STUK.

These are the Finnish safety authorities, known by the people and inspiring a lot of confidence. STUK would like France to start building deep geological repositories because it is afraid of feeling isolated and ultimately seeing the population question the value of repository sites if Finland is the only one to make this choice. The Safety Authorities, in Finland as well as in

Sweden, define the safety criteria to be observed based on the recommendations of the IAEA (International Atomic Energy Agency). They apply them without seeking to go beyond them, judging them sufficient. It is recognised that zero risk does not exist.

e) VTT.

This research centre, involved in nuclear power, works with neighbouring universities. It has now got into energy transition. Its themes are the bio-economy, low carbon economy, clean environment, digitisation, efficient production systems, health and well-being. Nuclear is included in the low carbon economy theme. This centre has about 2 500 people.

Waste storage

Storage of low- and intermediate-level radioactive waste is carried out in facilities located at the power stations and managed by the operators themselves. The waste is placed in drums in concrete silos buried at a depth of between 50 and 110 metres.

In the case of spent fuels, the Finnish legislation (Nuclear Energy Act) prohibits their import or export. Since Finland does not practice reprocessing, the fuel irradiated on Finnish soil is therefore treated as nuclear waste and is intended for direct final storage. On the other hand, concerning the research reactor Triga that was operated by VTT until 2015, an agreement was reached with the United States to return the spent fuel.

In order to manage the storage of high-level, long-lived radioactive waste, the two historic Finnish nuclear operators, TVO and Fortum, have chosen to form a joint venture, Posiva, which they own in proportion to their respective storage needs (60% and 40%). After 20 years of R&D, the deep geological disposal site developed by Posiva, on the Olkiluoto site, was the first in the world to receive its building permit, in November 2015. Work began at the end of 2016 with entry into service scheduled for 2024.

The solution adopted by Posiva is landfill, i.e. the irreversible disposal of waste. The project includes an encapsulation plant at the surface that will place spent fuel in large copper containers. These capsules will then be lowered into galleries dug to a depth of 400 to 500 meters in the Finnish granite. They will be disposed in cavities then sealed with bentonite to ensure that they are leak-proof.

The Finnish spent fuel project is relatively similar to its Swedish counterpart, a large part of the R&D being carried out in collaboration with the Swedish institution in charge of radioactive waste management, Svensk Kärnbränslehantering (SKB).

The site will be in operation for 100 years, i.e. the operating life of the current reactors (60 years), plus the cooling time of the high-level waste (in the pools adjoining the power stations), plus the dismantling of the encapsulation plant which is also expected to be buried on the Posiva site.

The future of the spent fuel from the proposed Fennovoima plant in Hanhikivi remains uncertain. The Posiva landfill was designed from the outset to accommodate only waste from the TVO and Fortum plants. In June 2016, an agreement was reached for Posiva to advise Fennovoima in the choice of its own landfill, allowing it to meet one of the conditions imposed in the authorisation in principle for the construction of the plant. From a geological point of view, most of Finland, which is based on granite, could be suitable for receiving such a site. However, the Ministry of Economy and Employment continues to hope that the two companies will reach an agreement for a single national solution for the disposal of spent fuel and does not exclude requiring them to co-operate.

Research

In the field of research (nuclear and non-nuclear) VTT and its French counterpart CEA have very good, long-established relations and collaborate closely. Both entities have a strong presence in European research programmes.

In the future, the CEA and VTT intend to continue their exchanges in the nuclear field (in particular in dismantling) and to deepen their relations in the fields of the security and nanotechnologies.

SWEDEN

A long-term historic agreement on the electric mix

On 10 June, the government concluded a historic agreement with three opposition parties on the question of maintaining the nuclear power fleet in Sweden (currently 10 reactors, providing 41% of electricity generation), which is very sensitive at the political level since the referendum of the 1980s. In a context of historically low electricity prices and a possible closure of the 10 reactors by 2020 because of profitability (see ND 2016-421177), the five parties agreed to remove the tax on the thermal effect of power plants within 2 years (with a first drop as of 2017), which could allow the 6 most recent reactors to operate until 2040.

The agreement also provides for the fee for the fleet dismantling fund (*Kärnavfallsfonden*) to be reduced by taking into account a longer reactor operating life. The fund's investment rules will also be reviewed starting in 2018 to enable better returns. The agreement specifies, however, that operators' civil liability will be increased by €0.3bn to €1.2bn per reactor, which will result in a slight increase in insurance costs. Overall, these decisions should enhance the profitability of the reactors.

The agreement also maintains the provisions of the law of June 2010 on the possibility of building new reactors to replace existing ones (up to 10 new reactors, no power limit, no direct or indirect subsidies from the State during construction). The decision to build new reactors applies to the three operators (the public energy company Vattenfall, the German E.ON and the Finnish Fortum), but they do not currently want to invest in view of the low electricity price outlook on the Nord Pool market over the medium term, and in the absence of public support measures.

While the agreement does not impose a date for closure of the nuclear fleet (thus avoiding the subject of financial compensation for the operators), it does include a goal of 100% renewable energy production in 2040. In order to reach this target, the market for green electricity certificates will be extended after 2020 and will create 18 TWh of new renewable electricity between 2020 and 2030 (about 1/3 of current nuclear generation). Marine wind generation will be particularly supported: the fee for connection to the electricity transmission network of offshore fleets will be eliminated.

With regard to hydroelectricity (43% of current electricity generation), installed capacity should only increase through modernisation of existing plants. In addition, the property tax on hydroelectric dams will be reduced progressively by 82% over a 4-year period to align with the rate of other electric power plants. The tax losses related to this decrease and the elimination of tax on the thermal effect of nuclear power plants are of the order of €1bn/year. This will be partly offset by an increase in the electricity tax of around €4.5/MWh (excluding industry).

No new nuclear reactor in Sweden and low electricity prices.

By deciding to extend the renewable electricity support scheme for 2020-2030, this agreement indirectly puts an end to plans for new reactors in Sweden. Indeed, as pointed out in ND 2016-270073, the market for green certificates generates overcapacity in the Swedish electricity market, which, in turn, maintains low prices on Nord Pool and has allowed Sweden to be an exporter for several years (new record reached in 2015 with 23 TWh exported, equivalent to 40% of its nuclear production). The decision to extend the certificate market after 2020 is the reason for the departure of the Liberals (the most pro-nuclear party of the centre-right alliance) from the three-party Energy Commission (see ND 2016-421177).

Under these conditions (selling prices on the futures markets of the order of €23/MWh, high cost of new reactors, no direct or indirect subsidies from the State), the construction of new reactors appears very unlikely.

While still pro-nuclear, Swedish industry has applauded the prospect of maintaining low electricity prices, that will enhance its competitiveness. It also welcomed the decision of the five parties to exempt it from the general rise in the electricity tax. Electro-intensive Swedish companies should, moreover, remain exempt from the obligation to purchase green renewable energy certificates for reasons of competitiveness, although they indirectly benefit from the negative impact on prices caused by the extension of the green certificate market post 2020. Finally, the agreement provides for the introduction of a new energy efficiency programme for heavy industry, inspired by the PFE programme (as a reminder, criticised by the EU for providing State aid and cancelled in 2012).

Nuclear operators

a) SKB.

SKB is a company founded by the owners of the nuclear reactors in Sweden. It manages the storage and disposal of the nuclear waste for which they are responsible. This company developed the concept of deep storage of high-level nuclear waste and studied it via the Äspö underground laboratory (started in 1986, 460 m deep). SKB also put in place the process for sealing canisters.

b) SSM.

These are the Swedish Safety Authorities.

c) SNC.

The National Council of Sweden (roughly equivalent to the CNE) comprises 11 members with various expertise, including 6 women and 5 men. It produces a report every year that takes stock of nuclear waste management. The SNC organises seminars with the various stakeholders in the sector and the government, as well as other more open ones in which the inhabitants of the municipalities participate.

There is no CEA equivalent in Sweden. Research is carried out by the universities.

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