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°8

JUNE 2014

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SUMMARY AND CONCLUSIONS

According to the provisions of the 2006 act, the long-term management of long-lived high-level waste (LLHLW) comprises two related components: separation-transmutation of actinides present in the spent fuel of future nuclear reactors and the geological disposal of long-lived high and intermediate-level (LLHLW & LLILW) waste in accordance with the principle of reversibility.

PARTITIONING AND TRANSMUTATION

The 2006 act provides for combining research on partitioning and transmutation with studies and research on the new-generation reactors (fast-neutron reactors, FNRs, and accelerator-driven sub-critical reactors, ADS[1]).

In the context of the Astrid programme, innovative options for creating an industrial demonstrator of a new-generation sodium-cooled fast-neutron reactor (FNR-Na), with a degree of safety at least equal to that of the EPR and integrating the lessons learned from the Fukushima events, were identified and have given rise to studies and research (S&R) to prepare the Detailed Preliminary Design (DPD). Main features are: a core with a low run-off coefficient that serves to prevent runaway fission reactions in the event of local drainage of the sodium coolant, of a sodium-sodium-nitrogen energy conversion system, thus preventing any contact between the sodium and the water, an in-service accessibility and inspection a design, and an internal core catcher ensuring vessel integrity in the event of a serious accident.

The Board greatly appreciates these orientations. It underlines the fact that significant resources will be required to implement the project's major innovations. In particular, the choice of core and cladding structural materials will require major research efforts, accompanied by the mobilisation of the highly specialist industries able to produce them.

The Board recommends ensuring that all the components of the Astrid programme can develop without being compromised by financial constraints.

Studies of the transition of the existing nuclear reactors and associated facilities towards FNR reactors show that this transition can be achieved under realistic industrial conditions, but requires successive configuration changes. Americium transmutation can only be achieved with FNR or ADS reactors. The Board thus requests that this give rise to active research and be taken into consideration in these scenarios.

Strong upstream chemical research must be maintained, in the context of reinforced collaborations, as it is essential to maintain the required skill levels to manage a fleet of nuclear reactors recycling all or part of their spent fuel.

The Board appreciates the deployment of pluridisciplinary nuclear energy research in the context of Needs, a programme led by CNRS. The upstream research projects must obviously be granted a large degree of freedom as it is their role to introduce innovative approaches. They must, however, remain coherent and credible. The Board recommends that the organisations' internal programmes focus on also studying the feasibility of the concepts that they propose. Finally, the Board recommends that Needs projects be designed in such a manner that the national community comes together around major nuclear electricity objectives and seed each other.

[1] Accelerator Driven System

GEOLOGICAL DISPOSAL

The aim of the Cigéo project is to build an LLHLW and LLILW repository, at a depth of 500 m, in the 130 m thick Callovo-Oxfordian (COx) argillite formation, at the location of the Meuse/Haute-Marne site.

Assisted by its contractor Gaiya, Andra proposed in 2012, concluding a so-called draft phase, several overall structure design solutions. In November 2013, the Cigéo project entered its basic preliminary design (BPD) phase. A public debate concerning the Cigéo project was held between 15 May and 15 December 2013, under the auspices of the French national public debates commission (CNDP – Commission nationale des débats publics). The conclusions of the public debate were published on 12 February 2014 and Andra presented its new schedule on 5 May 2014: the BPD shall be completed in May 2015, followed by the detailed preliminary design (DPD) to be completed by May 2017, with the building application (BA). The Board notes a 2-year slippage relative to the initial schedule.

The preliminary design S&R pertain mainly to optimising the requirements concerning the LLHLW and LLILW cells.

At its Bure underground laboratory, Andra is conducting large-scale experiments to measure variations of the physicochemical properties of COx argillite pore water according to temperature. These results will be essential for modelling the long-term behaviour of radionuclides in the near field of HLW cells and will allow temperature conditions to be better integrated into safety analyses.

The purpose of the Andra studies relating to LLILW cells is to specify their geometry and to determine the size of the clearance between the waste packages and the concrete. These studied must be intensified in light of disposal reversibility requirements. Moreover, the Board recommends amplifying Andra's collaboration with producers concerning the study of pyrophoric, saline and bituminous waste package behaviour and, more generally, concerning the study of interactions between organic chelating agents and actinides. These studies are essential in order to organise the disposal of various package types in the cells, while avoiding any incompatible co-disposal. This collaboration must urgently lead to a consensual definition of waste package specifications.

Several problems remain to be solved in order to fully control disposal operation, in particular the dimensioning of the transfer tunnels and LLILW cells coating, hydrogen release and long-term behaviour of argillite in the presence of this gas, the impact of bedrock desaturation/re-saturation, monitoring and sealing, for which the Board requests that 1:1 scale in situ tests be scheduled from phase 1 of the Cigéo project. According to the current schedule, the preliminary design studies will not be completed before 2015. Many points remain to be specified before industrial solutions that can be used for the BA are reached. The Board asks Andra to specify, before the end of the BPD, the list of points it considers must be dealt with before the BA is submitted, distinguishing structural elements from those related to an optimisation approach.

The optimisation of Cigéo phase 1 is a major BPD concern. The Board is concerned that major changes that are not simple adjustments may still be under development. Phase 1 shall represent an opportunity for industrial ramp-up of Cigéo. It must also represent an opportunity for additional scientific investigations.

The Board reiterates the need to rapidly define the cost of phase 1 of the Cigéo project, along with the distribution of amounts to be covered by producers (initial investment, operating costs and waste package depositing rate) as disposal progresses.

Finally, in order to maximise the benefits to the region hosting Cigéo, it would like to see this structure receive the "major initiative" (grand chantier) label, as was the case for the EPR.

REVERSIBILITY

The 2006 act stipulates that deep disposal must be implemented in accordance with the principle of reversibility. Different countries interpret this concept in a different manner.

Andra has initiated the debate at both the national and international levels. The OECD's Nuclear Energy Agency (NEA) has defined a reversibility scale for geological disposal: level 1 represents interim surface storage; at level 2, packages are placed in a cell; at level 3, the cell is provided with its final sealing system; at level 4, an entire zone of cells is sealed; finally at level 5, the repository is sealed and safety is ensured in a passive manner.

The Board proposes the following definition for reversibility.

> *Reversibility is a management system consisting in guaranteeing future generations the ability, at any stage in the scheduled disposal process, to decide whether to continue, suspend, or to return to the previous stage.*

To be effective, reversibility assumes retrievability, i.e. the technical and organisational ability to move the waste packages, or to return them to the surface. This implies a degree of flexibility when creating the facilities, taking into consideration scientific and technical breakthroughs and feedback.

Future generations must be given the option of changing the level of reversibility. A reasonably long phase must be used to prepare the progressive transition of filled cells from level 2 to level 3. This initial observation period, proposed by the operator, may be of between ten and twenty years. During this period, tests must be conducted on experimental cells with a view to developing and validating appropriate monitoring systems.

The Board does not, however, consider that the entirety of level 2 disposal should be imposed by our generation upon future generations. Indeed, this option may have some major drawbacks, both in terms of operating security and for long-term safety.

Consequently, the Board estimates that, after the initial observation period, the decision to switch a cell from level 2 to level 3 should be taken if its closure is deemed appropriate, particularly from a safety point of view.

INTERNATIONAL DIMENSION

The international panorama information presented in report no. 7 remains applicable.

The Board has conducted an international analysis of reversibility designs. Moreover, it presents the organisation of management and funding, along with the predicted cost of geological disposal facilities in Belgium, Finland and Sweden. Despite the broad range of approaches and regulatory provisions, these countries all apply the "polluter pays" principle, give priority to safety and provide funding the construction and operation of the facility for approximately one century.

BOARD ACTIVITIES – 2013-2014

The period of November 2013 to April 2014 corresponds to the 7th full year of operation of the Commission nationale d'évaluation des recherches et études relatives à la gestion des matières et des déchets radioactifs (CNE2 – French national Board for the assessment or research and studies into the management of radioactive waste and materials); it is covered by this report no. 8. The Board wished to resume the rhythm it had established during the initial years, drawing its report up for June, thus avoiding any overlap between the hearing and report drafting periods. Since the publication of its previous report in December 2013, the Board has presented its report no. 7 to the OPECST (Office parlementaire d'évaluation des choix scientifiques et technologiques – French parliamentary office for the evaluation of scientific and technological options).

A Board delegation travelled to Bar le Duc on 6 and 7 March 2014 to present its report to the members of the Meuse/Haute Marne CLIS (local information and monitoring committee). Moreover, at the request of the CLIS chairman, the Board (see Appendix I) drew up a note concerning the geothermal resource (see Appendix II) in the Bure region, including an analysis of the conclusions of the Geowatt AG report that the CLIS had forwarded.

* * *

The Board adopted the same working method as for previous years. It conducted 10 hearings (see Appendices III & IV), including 2 restricted hearings, both in Paris, along with a number of follow-up meetings. The Board members, all volunteers, heard 68 Andra and CEA (Commissariat à l'énergie atomique et aux énergies alternatives – French atomic energy agency) members, along with representatives of French and foreign academic institutions and industrial organisations. These hearings, bringing together some fifty people on average, were also attended by representatives of the French nuclear safety authority, Areva, EDF, the French Radioprotection and Nuclear safety Institute, the central administration and the OPECST.

To prepare this report, the Board held a 2-day pre-seminar during its visit to the EPR in Flamanville, along with a number of internal meetings, including a 5-day residential. The list of Board hearings and visits is given in Appendix II of this report. The list of documents that it received from the auditioned organisations is provided in Appendix V.

The Board was in India between 15 and 23 February 2014; the delegation met the main Indian nuclear sector organisations: the Department of Atomic Energy – DAE –, the Bhabha Atomic Research Centre – BARC –, the Indira Gandhi Centre for Atomic Research – IGCAR – and the Bharatiya Nabhikiya Vidyut Nigam Ltd –Bhavini – (Cf. § 5.4 & Appendix VI).

* * *

This report is organised according to the two complementary radioactive waste and materials S&R components: partitioning-transmutation in chapter 1, long-lived high-level waste (LLHLW) and long-lived intermediate-level waste (LLILW) storage and disposal in chapter 2. The management of long-lived low-level waste (LLLLW) is covered in chapter 3. Finally, following a question by the OPECST Chairman, the Board presents is thoughts on reversibility, in light of the work conducted by Andra and the NEA (chapter 4).

In accordance with its duties, the Board continues its observation of the international panorama. The main elements are outlined in chapter 5.

Chapter 1

PARTITIONING AND TRANSMUTATION

France's decision to opt for a closed nuclear fuel cycle provides uranium and plutonium from the processing of spent fuel assemblies, along with depleted uranium (450,000 t in 2040) resulting from uranium 235 enrichment from natural uranium. These materials allow the production of fuel used to feed a fleet of electricity-generating fast-neutron reactors.

Currently the plutonium stock is of approximately 300 t; this figure is growing at a rate of 6 t per year. A fleet of electricity-generating FNR reactors could be used to manage this plutonium. This would initially lead to the stabilisation of plutonium within the cycle (approximately 1,000 t by 2100). When the time comes, these FNRs, if required, could be used to significantly reduce the amount of plutonium.

Should France opt against an FNR technology, the plutonium will be considered as a waste requiring deep geological disposal and minor actinide transmutation will be impossible.

1.1 ASTRID (ADVANCED SODIUM TECHNOLOGICAL REACTOR FOR INDUSTRIAL DEMONSTRATION)

The knowledge and feedback acquired in France and worldwide show that the fast-neutron reactor technology is mature and could, subject to major safety innovations, enter a phase of industrial implementation by the second half of the 21st century.

A major R&D programme has been under way for several years concerning the construction of an industrial prototype, Astrid, a sodium-cooled fast-neutron reactor generating a power of 600 MWe. Currently, this project is at the preliminary design phase 2 (PD2), initiated in 2013 and set to run until 2015; this phase serves as a preparation for the detailed preliminary design (DPD) phase. The Board notes that, to date, financial support for Astrid is only guaranteed until 2016, whereas R&D activities will continue well beyond this point.

The Board recommends ensuring that all the components of the Astrid programme can develop without being compromised by financial constraints.

As of the end of 2013, ten industrial collaborations with equity participation guarantee that operational constraints will be taken into account from the Astrid design phase. Similarly, the CEA has established a number of contacts with a view to international R&D collaborations with Russia, the United States, China, India, South Korea and the United Kingdom. France recently signed an agreement with Japan defining a framework for participation in the Astrid project. The CEA is also developing an R&D network of European partners.

A number of innovative options for creating a new-generation industrial FNR-Na demonstrator (safety level at least equal to that of the EPR, integration of lessons learnt from the Fukushima events) were identified during the 2010-2012 period and have given rise to R&D efforts to prepare the DPD. These elements include :

- Low run-off coefficient (LRC) core, breakaway from known FNR technologies (CEA-Areva-EDF patent) that significantly enhances safety as it avoids runaway fission reactions in the event of local sodium coolant run-off.
- A sodium-sodium-nitrogen cooling system designed to avoid any possible contact between the sodium and the tertiary circuit water of a sodium-sodium-water system, the nitrogen being used to thermodynamically convert the heat to electricity. This highly innovative improvement is based on the progress made in the field of gas turbines. Promising tests were conducted at Cadarache in 2013; the net conversion efficiency for a sodium-sodium-nitrogen system (37%) is lower than for a sodium-sodium-water system (45%), though it remains acceptable. Alstom is currently studying the industrial feasibility.

- Accessibility and in-service inspection provided for by design, along with the development of sensors used for sodium-immersed and out-of-sodium measurements. These innovations benefit from the experience acquired with Phénix and Superphénix.
- An internal core catcher, placed in the main vessel; this core catcher ensures vessel integrity, avoiding any early or major release in the event of a serious accident.

Significant resources will be required to conduct the project's major innovations and to ensure that the Generation IV safety level of the FNRs can be achieved. The Board recommends that they be implemented in due course.

The R&D also pertains to cladding materials, that must display a very low swelling rate under irradiation for high burn-up rate, of circa 150 GWd/t. Current studies pertain to martensitic and ferritic ODS steels.

R&D also concerns the production of MOx FNR fuel for Astrid, along with materials for gas turbines and sodium-gas exchangers required to withstand pressures of 18 MPa and temperatures of between 300 and 500 °C.

The Board emphasises the point that the choice of core and fuel cladding structural materials will require major research efforts, accompanied by identification of the highly specialist industries able to produce and form them. These are long-term commitments that must be guaranteed to ensure the success of the project.

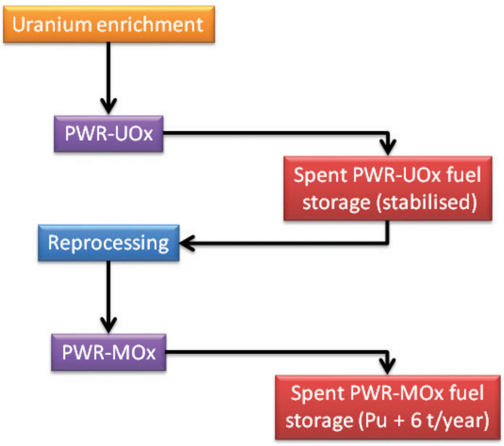
The Board would like to remind that the choice of MOx FNR fuel manufacturing process must be specified and that a fuel production workshop, whose location remains to be defined, must be commissioned 3 years before reactor start-up.

DPD development should last from 2015 to the end of 2019, date at which the request to create Astrid may have been submitted, followed by a construction phase, for divergence in 2025 and coupling to the electricity network in 2026. Astrid's preliminary safety options are currently being examined by the ASN. The decision to build the Astrid reactor should be made at the end of 2019.

1.2 FNR DEVELOPMENT SCENARIOS

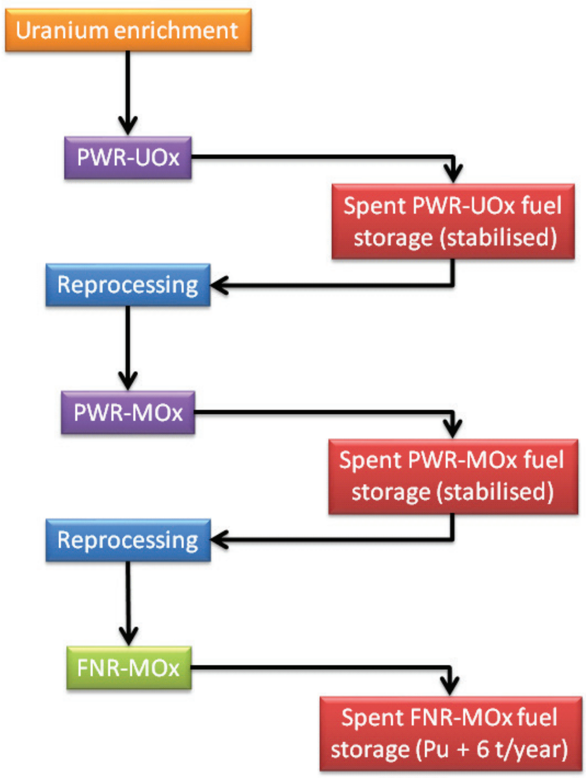
CEA, Areva and EDF have created a steering group in charge of proposing FNR-Na integration scenarios with the current fleet, based in particular on the hypothesis of a nuclear electricity production of 420 TWhr/year, along with the progressive replacement, for equal power, of the end-of-life PWRs in the current fleet with EPRs over the 2030-2060 period.

Four open-ended fleet configurations for progressive FNR introduction are proposed (see Appendix VII). They focus on optimum plutonium resource utilisation to save uranium and to stabilise the inventory of stored spent fuel. These configurations make use of the flexibility of FNRs, which can operate in iso-generator reactor mode, breeder reactor mode or sub-generator reactor mode.

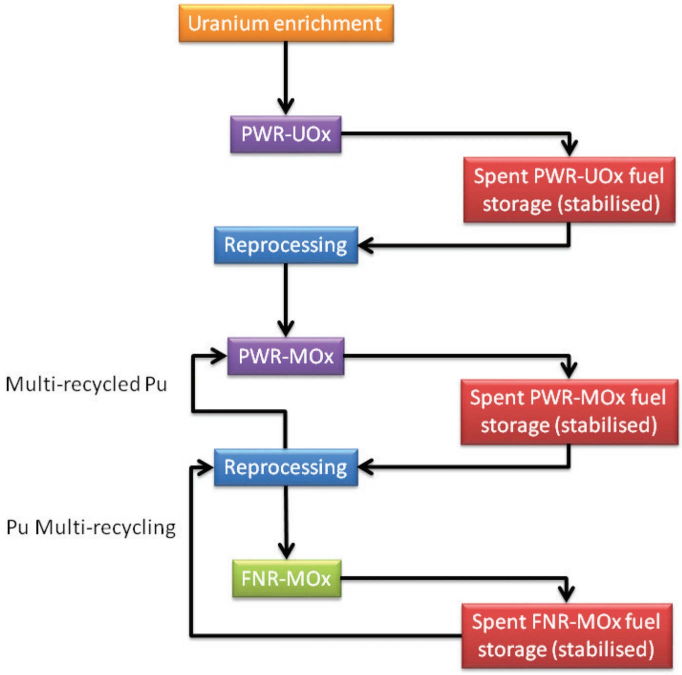


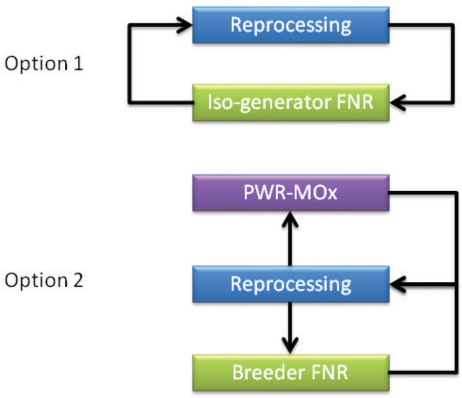
"Configuration A" (see figure opposite) corresponds to the current situation, that could lead to the implementation of 11 EPRs, 3 to 4 of which could use MOx fuel and 3 would use reprocessed and re-enriched uranium (ERepU). The fleet configuration serves to reduce and stabilise the storage of spent UOx fuel and leads to an increase in Pu inventory of 6 t/year stored with spent MOx fuel.

"Configuration B" (see figure opposite) involves the deployment of FNRs for an electrical production of 4 to 5 GWe, and aims to stabilise the spent PWR MOx fuel inventory. For this, we need to define the MOx processing strategy and hence any alterations that may need to be made to the La Hague plant, along with the optimum FNR power to implement. In this configuration, FNR MOx fuels are sent to storage, where Pu builds up at a rate of 6 t/year.



"Configuration C" (see figure opposite) aims to stabilise the Pu inventory. The FNRs would use Pu obtained from the reprocessing of spent MOx. The plutonium could also be recycled in EPRs after several passages through FNRs, in order to restore its isotopy, rendering it once more suitable for use as PWR MOx. A new reprocessing plant will need to be built.





"Configuration D" (see figure opposite) would not use natural uranium and would involve a fleet of FNR reactors, possibly associated with EPRs. The FNR fuel consists of depleted uranium combined with 30% plutonium.

Overall, the new studies of scenarios for switching the current fleet of nuclear reactors and associated facilities to a large fleet of FNRs tend to confirm the previous studies and provide additional details. This transition, at constant power and electrical energy produced, could only be achieved through successive changes in nuclear electricity fleet configuration. The operating periods of each configuration, along with the reactor construction rates, remain to be defined.

The Board notes that these scenarios only take energy production-related aspects into consideration. The Board asks that the role of the transmutation of minor actinides, in particular of americium, be analysed.

1.3 PARTITIONING AND TRANSMUTATION

1.3.1 Partitioning

The main direction of S&R in separative chemistry concerns the plutonium multi-recycling programme and, more generally, the recycling of long-lived actinide elements. The CEA has developed the molecules, processes and technologies required to separate actinides from fission products, uranium and plutonium. In order to be applied at the industrial scale to MOx fuels from PWRs, EPRs and FNRs, these partitioning processes require major R&D efforts aimed at adapting current processes. To meet this demand, the CEA has mobilised its Saclay, Cadarache and Marcoule centres, along with the ICSM and its various facilities, in particular Atalante. Research is organised around two major topics: understanding the phenomena governing partitioning and conceiving new partitioning concepts.

Moreover, this R&D should also serve to simplify uranium ore processing, which, for the production of thermal reactor fuel, involves multiple steps before uranium oxide is obtained.

Such research requires expertise and skills in fields such as radiochemistry, chemistry, physical chemistry, along with partitioning and chemical engineering.

The Board recommends that strong upstream chemical research be maintained, in the context of reinforced collaborations, as it is essential to maintain the required skill levels to ensure scientific and technological management of a fleet of nuclear reactors recycling all or part of their spent fuel.

1.3.2 Transmutation

FNRs, thanks to the flows and energy of the neutrons used, allow the transmutation of minor actinides to be envisaged. Currently the CEA is focusing on the transmutation of ^{241}Am and ^{243}Am, the most abundant americium isotopes in spent fuel and which display high levels of radio-toxicity. As they are responsible for a significant proportion of heat emissions by vitrified packages, their elimination would contribute to lowering waste radio-toxicity and would reduce by a factor of three the area covered by LLHLW disposal for a new fleet comprising a sufficient number of FNRs.

Current research focuses on the synthesis and characterisation of americium-based compounds, along with powder metallurgy for the production of fuels for high-americium blankets (HABk). These studies are accompanied by an irradiation programme, based on international collaborations aimed at defining the behaviour of these fuels, along with the optimum conditions for americium transmutation (see Appendix VIII).

The Board recommends that active and structured actinide transmutation research be maintained to ensure its possible implementation in Astrid. It will provide the missing nuclear data, but also the expertise and skills required to assess the industrial capabilities of potential transmutation systems (FNR-Na, ADS, etc.). Safety and radioprotection, during all phases involving the handling of large quantities (~ kg) of actinides, must be the subject of sustained research.

1.4 END OF CYCLE AND PLUTONIUM BURNER

FNRs, operating in iso-generator reactor mode as described in configuration D of the industrial scenarios, could serve to stabilise the plutonium stock at approximately 1,000 t.

An alternative to the deep geological disposal of plutonium is its destruction in FNRs operating in sub-generator reactor mode. This strategy would absorb the plutonium built up during operation of a 60 GWe nuclear electricity fleet at equilibrium (configuration D, see Appendix VII). This type of operation presents the advantage of remaining electricity generating. We could thus reduce the existing stock of plutonium by 50% every 50 years.

The CEA currently defines the characteristics of the R&D required to implement the adaptations to Astrid's LRC core (Pu content of circa 45%) using in particular the Capra (Consommation Accrue de Plutonium dans des RApides – increased plutonium consumption in fast reactors) design principle. The research programme will comprise a number of important steps: neutron physics, fuel manufacture, core qualification, irradiated fuel processing, safety, etc…

The Board asks that a complete research programme be implemented to ensure that the industrial operation of Astrid as a plutonium burner can be assessed once Astrid has been tested in iso-generator reactor mode.

1.5 UPSTREAM PLURIDISCIPLINARY RESEARCH

Following on from the Pacen (Programme de recherche pour l'Aval du Cycle ElectroNucléaire – Nuclear electricity cycle back-end research) programme, the CNRS implemented in 2013 an interdisciplinary research programme: "Nuclear: Environment, Energy, Waste and Society" (Nucléaire: Environnement, Énergie, Déchets et Société – Needs) in partnership with CEA, Andra, Areva, IRSN, EDF and BRGM. Half of this programme's budget is financed by CNRS, while the other half is spread amongst the other partners. It is intended to federate and structure the interdisciplinary research effort upstream of nuclear energy. This programme is detailed in Appendix IX, which also covers upstream research for the nuclear industry. Focusing on nuclear energy production and partitioning-transmutation, Needs consists of 6 lines of research:

- Resources,
- Nuclear data,
- FNR-Na and FNR-Gas reactors,
- ADS reactors,
- Molten salt reactors,
- Scenarios and modelling.

to which are added two other lines associated with downstream aspects of the nuclear electricity cycle:

- Waste characterisation,
- Processing and packaging, new materials and natural analogues,

and one major general scope line :

- The study of relationships between knowledge, society and democracy.

Needs is part of many collaborations in Europe and in many international networks. Pertaining to ADS reactors, CNRS is a major partner in the Myrrha project. It conducts S&R on thorium-based molten salt reactors and their corresponding cycle. The CEA also conducts its own upstream research.

The Board appreciates the participation of the French scientific community in the upstream research on nuclear energy, along with the intent to deploy pluridisciplinary research. Some key disciplines, such as radiochemistry, chemistry and actinide physical chemistry, partitioning sciences, neutron physics, etc., must be developed in a coherent manner to ensure that a pool of knowledge, expertise and skills is created, enabling the fleet of nuclear electricity reactors of the future to be implemented under optimum safety conditions and to manage the associated waste.

The Board underlines the importance of studies on spent fuel dissolution, fuel element separative chemistry and recycling, which represent an essential base for innovations downstream of the cycle. Similarly, research into geological and geochemical aspects are required to gain an understanding of the long-term behaviour of geological disposal.

The Board considers that it is through targeted collaborations that access to large-scale or specific nuclear equipment is possible. It recommends reinforcing, beyond Needs, those partnerships enabling academic, technological and industrial research activities to be coupled.

The upstream research projects must obviously be granted a large degree of freedom as it is their role to introduce new and beneficial approaches for the future.

The Board recommends that the research performed be coherent and credible, i.e. that the research organisations' own programmes also focus on studying concept feasibility.

For example, if the CNRS wishes to further its research into molten salt reactors, it must simultaneously initiate research into the materials required for the construction of such reactors and reinforce its research into fuel cycle control.

The Board recommends that pluridisciplinary projects be designed in such a manner as to federate communities around a major nuclear electricity objective and that they mutually seed each other.

The Board recommends that Needs be better funded, subject to supporting large-scale projects, in accordance with national priorities. These should be conducted in the context of inter-organisation collaborations, in particular between CNRS scientists, Universities and the CEA, in order to make full use of individual assets and to benefit from the opportunity represented by the ICSM as an entry point to Atalante.

Finally, in the context of multi-party research funding, the Board recommends that the ANR should place a greater emphasis on nuclear energy-related topics in its research programmes, in relation to the ANCRE (Alliance Nationale de Coordination de la Recherche pour l'Energie – French National Alliance for Energy Research Coordination) roadmap.

Chapter 2

THE CIGÉO PROJECT

The purpose of the Cigéo project, by application of the Act of July 2006, is to build an LLHLW and LLILW repository in the Area of interest, for in-depth exploration (Zira – from the French acronym for zones of interest for futher investigation) identified by Andra in the Bure region, in Meuse-Haute Marne.

This repository will be located at a depth of 500 m, in the approximately 130 m thick Callovo-Oxfordian (COx) argillite formation. It is destined to be definitively closed after an operating period ranging from 2025 to 2140, which is the period required to store the waste packages from the industrial programme for waste management (Programme Industriel de Gestion des Déchets – PIGD).

During previous studies, summarised in its Clay 2005 dossier completed in 2009, Andra demonstrated the excellent ability of the COx clay formation to contain the radionuclides present in waste. This ability is due to the homogeneity of the geological formation over the whole extent of the Zira, to its stability over the past 100 million years or so, to the very low permeability of clay and to its geochemical properties that promote radionuclide retention.

Assisted by its contractor Gaiya, Andra proposed in 2012, concluding a so-called draft phase, several overall structure design solutions. These solutions were presented during a project review attended by waste producers. The general orientations of the outline were noted during a project review in May 2013, during which the structural choices defined by Andra were confirmed.

In its report no. 7, the Board had approved these choices.

A public debate concerning the Cigéo project was held between 15 May and 15 December 2013, under the auspices of the French national public debates commission (CNDP – Commission nationale des débats publics). The public debate conclusions were published on 12 February 2014; Andra's Board of Directors meeting of 5 May 2014 presented the follow-up to be given by Andra.

Once Andra has defined the practical details for implementing the resulting orientations, the Board will analyse them and issue its pronouncement.

2.1 BUILDING APPLICATION PROCESS MILESTONES

In November 2013, following the outline phase, the Cigéo project entered its basic preliminary design (BPD) phase.

Andra's objective is currently to obtain the building authorisation for Cigéo based on the building application (BA) to be submitted to the government. During the hearing of 20 November 2013, Andra proposed observing the following schedule:

- November 2013 to May 2015: BPD definition; this is broken down into two steps, the first, until May 2014, focusing more specifically on the optimisation required after the outline studies;

- June 2015 to May 2017: drafting of the detailed preliminary design (DPD), punctuated by the submission of an initial version of the BA in November 2015;
- mid-2016: promulgation of the act establishing the terms of reversibility;
- update and filing of the final BA version in May 2017, at the end of the DPD.

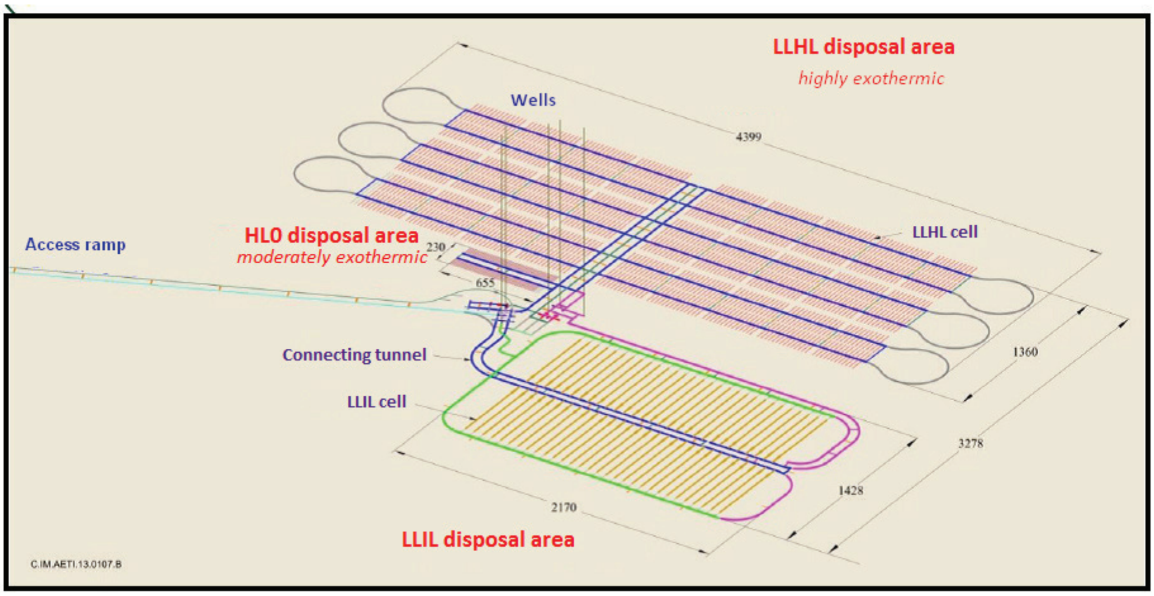
The Andra Board meeting of 5 May 2014 proposed a change to this schedule: in order to prepare for BA examination, the 2015 milestone would consists of a master plan proposal for Cigéo operation submitted to the Government, along with a safety options file and a retrievability technical options file submitted to ASN; the BA would thus be submitted only at the end of 2017.

The Board notes the schedule slide, marked in particular by BA submission in 2017, which is late according to the provisions of the 2006 act.

2.2 STRUCTURAL ELEMENTS OF THE OUTLINE

The Cigéo architecture was finalised following the project review. It is compatible with the waste inventory provided at the start of 2012 by the producers, at the launch of the outline studies.

The major components of this architecture are specified in the figure below.



Perspective view of the Cigéo outline (based on Andra document)

The underground structure project comprises three independent repositories for HLW0 waste (high-level, weakly exothermic vitrified waste), LLHLW (high-activity, highly exothermic waste) and LLILW. In their final configuration, these underground structures will comprise 85 km of access tunnels, 30 km LLILW disposal cells and 150 km of LLILW disposal cells. The reference diagram involves 100 m long LLHLW cells, with an excavated diameter of circa 85 cm and 500 m long LLILW cells, with an excavated diameter of between 8 and 12 m depending on the type of package stored. The disposal cells shall be created as and when required during the secular repository operating period. The HLW0 and LLILW areas will be created first as the disposal of HA exothermic vitrified waste will only begin in 2075. The underground structure development perspective involves a separation between the disposal and construction activities.

The phasing of work, along with the choice of a "twintube" communication route architecture (two distinct parallel tunnels) when necessary, will ensure that dual access to all points of the structure is permanently possible, allowing optimum management of fire risks by enabling the isolation of an affected area via fire doors.

The surface infrastructures consist of two discrete areas.

One area, providing access to parallel access ramp, is dedicated to receiving and inspecting the waste packages and to preparing them for disposal. It may be served by a rail connection. One area, comprising five wells, is dedicated to the digging, construction and maintenance of underground structures.

2.3 INVENTORY OF THE INDUSTRIAL PROGRAMME FOR WASTE MANAGEMENT (PIGD) IN RELATION WITH PRODUCERS

The project review underlined the need to include the package creation activities up to their disposal in the scope of the Cigéo programme. This implies that certain issues must be dealt with jointly by Andra and the producers. Thus, the PIGD inventory was updated in 2013 to take into consideration several changes to the waste management strategy by producers. The inventory will be used as the new input datum for the Cigéo preliminary design studies.

The primary LLILW and HLW0 packages stored as soon as the repository is opened for operations, then over a period of approximately sixty years, are identified and their number estimated. A disposal capacity reserve is provided to deal with certain uncertainties (industrial margins, on-going acceptance of certain disposal packages, possible disposal of certain LLLLW packages). The inventory is intended to be flexible and shall only be specified in 2015.

The PIGD also comprises a package delivery chronology, which is also essential for the PD and that may be revised before the BA is submitted, according to the decisions made by the producers and to the optimisation studies conducted by Andra.

The reference chronology for LLILW and HLW0, dated January 2014, specifies deliveries to Cigéo spread over the 2025 to 2095 period, with an average flow of 3,000 disposal packages per year at steady state. The chronology for LLHLW forecasts, between 2075 and 2140, an average flow of 860 primary packages per year.

For the moment, there are no details of the types of packages that will be transported from the production locations to Cigéo. These may be primary packages for placement in disposal packages in a Cigéo surface facility, or disposal packages prepared by the producer. Possible optimisations are under consideration, including for example the ability to use existing transport containers whose efficiency has been tried and tested. Packaging into disposal packages at the Cigéo site would be preferable as it would allow inspections prior to burial.

By 2015, Andra will study two scenarios for the direct disposal of spent fuel assemblies should its reprocessing be abandoned.

The PIGD is currently being adjusted and finalised. The state of the inventory, along with the package delivery and transport chronology, have virtually no impact on the technical development of Cigéo, nor on the research initiated by Andra, though it constitutes a major public concern. The Cigéo inventory on the other hand, could change according to the energy policy defined by the Government, particularly concerning the fate of the spent fuel. Finally, the Board asks that Andra's package acceptance specifications be determined as soon as possible.

2.4 PRELIMINARY DESIGN PHASE STUDIES AND RESEARCH

The preliminary design phase shall last from the end of 2013 to the end of 2017; it shall serve as the basis for drafting the BA and shall involve an R&D programme lasting from 2013 to 2016.

For this, at the end of 2013, Andra, acting as owner, initiated technical-economic optimisation studies aimed at making the most of the flexibility currently provided by the Cigéo project outline and of the primary waste storage facilities at the producer sites. For this same purpose, Andra is coordinating studies aimed at consolidating the demonstration of disposal robustness. These studies cover many aspects and shall be continued after submission of the BA. Indeed, Cigéo does not fit into the conventional engineering project framework and raises a number of unprecedented scientific problems.

Andra has not presented to the Board a detailed programme, structured over time, of the planned studies and research. It has, on the other hand, proposed a number of considerations that it sees as lines of optimisation that apply to the structural choices adopted after the outline phase. These considerations concern, in particular:

- changing requirements concerning LLHLW cells,
- changing requirements concerning LLILW cells, including the co-disposal problem.

2.5 LLHLW CELL OPERATION

The respective roles of the metal liner of the LLHLW cells and of the vitrified waste overpack have been specified. The overpack must protect the primary package from water for as long as possible and in any case as long as the glass core has not dropped below an acceptable temperature. The non-watertight liner, on the other hand, must be able to durably oppose a mechanical load that could prematurely damage the overpack and thus withstand the pressures generated by the argillite formation. In order to improve the liner mechanical load conditions, Andra is currently considering filling the annular space between the extrados and the rock; this arrangement would present the benefit of avoiding the effects of contact between metal and argillite. The details concerning the filling of this space, along with the consequences upon waste disposal reversibility, remain to be defined. The use of non-alloy steel is recommended for the liner and overpack as its generalised corrosion can be modelled. The rate of corrosion under radiation and/or stress depends on the steel grade used. Andra is thus studying the resistance of various grades of non-alloy steel under disposal conditions and over a broad range of temperatures and dose rates. The initial results are expected in one year.

Andra is now studying disposal configuration variants. The uncertainty concerning the time during which the overpack will protect the vitrified package from water suggests a temperature of 50 to 70 °C at the onset of leaching by COx water. This temperature is a significant parameter as it will govern the kinetics and thermodynamics of the radionuclide release and migration processes. It is therefore necessary to evaluate the changes to be made to the modelling of near-field phenomena, currently performed at 50 °C, should this temperature reach 70 °C. For this purpose, parametric nuclear glass leaching studies have been initiated, along with the update of Andra's thermochemical database. Research into glass leaching under disposal conditions focuses on the effects of water vapour and liquid water in the presence of steel corrosion products, argillite and radiolysis products, over a broad range of temperatures. The results expected within the next two years should provide an understanding of the variations of the different parameters involved in the modelling of glass leaching, allowing possible corrections to be made. Initial systematic measurements specify the trends already detected and do not show any threshold effects on temperature.

These studies must take into consideration the properties of COx argillite interstitial water according to temperature. The pH of water varies by one unit between 25 and 80 °C. Some parameters characterising aqueous solutions are temperature-sensitive (redox potential, anion and dissolved element concentrations) and may vary by several orders of magnitude, thus potentially altering element speciation in such a manner that their stability domain and mobility are affected. Since early 2012 at its Bure underground laboratory, Andra has been conducting large-scale experiments to measure variations of these parameters according to temperature (up to 85 °C) for COx argillite pore water. These data are of major importance.

Temperature influences thermodynamic constants, but also the diffusion coefficients of species in solution. Values in excess of 50 °C are very rarely reported in the scientific literature. Andra thus decided to conduct studies to obtain values around 70 °C. This solution thermodynamics research, combining an experimental approach and a critical analysis of known data, should provide us with a worst case estimation of the consequences of the main reactions governing the behaviour of radionuclides at 70 °C.

The Board considers that these studies are of great importance as they will, in fine, represent a foundation for modelling the long-term behaviour of radionuclides in the near field of LLHLW cells, thus allowing safety studies to be refined. It recommends intensifying these studies to further reduce uncertainties.

2.6 LLILW CELL OPERATION

The extension of LLILW cells to 500 m raises questions concerning the vertical height of the sound argillite barrier on either side of the structures and concerning the co-disposal of waste of varied chemical nature.

Firstly, the long-term safety requirements stipulate that the sound argillite barrier be of at least 50 m. This implies not only that the COx thickness and inclination must be precisely taken into account in the repository architecture, but also that the vertical extension of the damaged area must be reduced. The long-term limitation of the damaged area requires that the void fraction, around the cell and between the cell and the packages, be kept to the strict minimum. These voids govern the loading kinetics of the cell's concrete coating, its deformation over time and hence the near-field terrain movements. These are reduced if the voids between the COx and the concrete structure are filled during the construction process.

The gap must be kept as small as possible, while remaining sufficient to allow package retrievability during the reversibility period. This operation is further complicated by the many different container types that must adapt to the cell dimensions. For this purpose, Andra is studying the feasibility of elliptical cross-section cells, offering a greater degree of package arrangement flexibility and possibly an improved mechanical operation.

The Board considers that Andra's studied into cell geometry and gaps between the packages and the concrete are of prime importance. It recommends intensifying these studies, in light of the antagonistic requirements imposed by waste package retrievability and long-term repository safety.

Secondly, the presence of very long cells leads to amplification of co-disposal, i.e. the opportunities to store packages of different types within a single cell. Andra is considering such co-disposal, while ensuring waste compatibility, to avoid any chemical reactions that could lead to a premature loss of radionuclide containment. This could be the case, for example, for packages containing organic materials and packages containing radionuclides likely to form mobile organic metal complexes. The same problem could arise if the cells are placed too close to each other. For this Andra has performed a systematic analysis of the possible interactions between the contents of more than 70 packages, based on models of the mobility of seven organic acids and radionuclide complexes that could form.

The LLILW cells are open-ended to allow their ventilation until they are definitively sealed. The ventilation air is then vented outside after filtration. Andra has defined the nature of elements likely to be rejected and calculated the resulting doses. These would remain significantly below the maximum permissible public doses.

Andra is also considering the feasibility of shorter, blind LLILW cells for some package types. To ensure their ventilation, these structures would require an upper plenum chamber that would need to be filled upon closure in order to limit the residual void fraction.

The Board notes that the purpose of Andra's studies is to exclude incompatible co-disposals. It recommends continuing the study of pyrophoric, saline and bituminous waste package behaviour and, more generally, the study of interactions between organic chelating agents and actinides.

For this purpose, the Board recommends that Andra extends its collaboration with producers, recently initiated for bitumen packages, to all LLILW packages, in particular those containing organic or pyrophoric waste. This collaboration must urgently lead to a consensual definition of waste package specifications.

2.7 ORGANISATION OF THE STUDY AND RESEARCH PROGRAMME

The studies and research that Andra intends to conduct during the preliminary design are structured around six scientific topics.

- Waste characterisation in disposal situation aims to expand the knowledge database concerning the behaviour and transfer of radionuclides and toxic chemicals to the vicinity of the repository. This focuses mainly on organic or reactive (metallic) LLILW and bituminous sludge.
- Materials and structure behaviour: this topic covers studies on the mechanical and hydromechanical behaviour of sealing materials (concrete, swelling clay), chemical-mechanical interactions (corrosion of steel and concrete) and LLILW cell chemistry reviewed to adapt to the possible co-disposal of waste of various chemical types.
- Digital simulation, whose priorities are organised around the modelling of reactive transport and interactions with mechanical behaviour compromising the operational behaviour of the repository (damage, fracturing). Its implementation also implies developments in terms of high-performance computation and processing of large volumes of data.
- Characterisation of environmental impacts around Cigéo, with emphasis on the preparation of the environmental monitoring plan for the facility.
- Examination of structures, data acquisition and processing. This topic cover, on the one hand, the development of sensors (in particular optical fibres) for mechanical, thermal and chemical measurements, along with the definition of decision support tools for the operation and subsequent progressive closure of the repository.
- Humanities and social sciences are involved transversally to the other five topics. These studies are structured around three issues: governance, disposal circuit economy and sharing of scientific data. The aim is, in particular, to contribute to the debate on reversibility.

This study and research programme is supplemented by a programme of so-called "technology" tests intended to validate the dimensioning of the LLILW packages and cells, along with the construction processes and the various associated inspection phases. For LLHLW, the tests focus on demonstrating the feasibility, reliability and reproducibility of package manufacture, taking into account the retrievability requirements for these latter. A tunnel digging and sealing test programme (in relation with the tests already conducted in the underground laboratory) is also deployed.

To conduct this programme, Andra possesses a number of surface facilities (laboratories, demonstrators), the Long-term Environmental Research, Monitoring and Testing System (observatoire pérenne de l'environnement – OPE), the Meuse-Haute Marne underground laboratory, and a network of partners organised in laboratory groups, whose scopes have been redefined to take existing knowledge into consideration. This organisation can be distinguished from that implemented by CNRS in the context of the Needs challenge, which functions on the basis of independent calls for projects.

In connection with the Cigéo project engineering, Andra intends, beyond its own knowledge acquired during these studies, to use the experience of the industrial participants from the Gaiya consortium on the creation of underground structures. Considering the project's specific characteristics (tunnel depth, operation over a century, difficult examination conditions) and the contractual terms of the dialogue between project ownership and management, we must be vigilant considering the industrial culture differences of the participants. Indeed, the Project owner / Project manager dialogue must focus on repository safety and operation throughout the project phases.

2.8 CONCLUSION CONCERNING THE STUDY AND RESEARCH PROGRAMME AT THE PRELIMINARY DESIGN PHASE

The preliminary design studies are essential to the finalisation of the Cigéo project. Once all the design structural elements have been defined at the end of the outline phase, they will be used to draft the BA, supplementing knowledge through an S&R and technological testing programme, while continuing the project optimisation work.

In addition to the questions covered by Andra and presented to the Board during the last hearings, several other issues appear fundamental in order to fully control repository operation and to provide the necessary information in the BA.

Amongst the questions still pending, the Board places particular emphasis on the following.

The question of the dimensioning of the transfer tunnels and, more importantly, of the LLILW cells lining constitutes a major issue that must be perfectly controlled from the onset of repository construction. These structures must be able to withstand the entire operating period, in accordance with the reversibility requirements. The experience feedback from the initial structures will be put to profit when creating the subsequent ones. It will be difficult, however, to repair the first cells should they cause problems. The shape, lining type and concrete thicknesses required must thus be judiciously determined. In rheological terms, we do not yet possess a well-established model able to simulate the long-term behaviour of structures at the various concerned scales. The knowledge acquired from the numerous and high-quality underground laboratory measurements must be summarised and valued to allow the development of such a model.

The question of hydrogen release has been extensively studied by Andra, with particular emphasis on the atmospheric composition in LLILW cells during the ventilation and temporary ventilation stop phases. These studies conclude that it is possible to control the consequences relative to explosion risks and to package retrievability. One point that appears to have been less well-studied is the long-term behaviour of argillite in the presence of the gas; a number of questions remain concerning the consequences of the presence of hydrogen in pore water at the massif scale and on the effect of the pressure in the cells after closure, with the risk for near-field crack formation.

The question of desaturation/re-saturation of the rock massif has been modelled by Andra; these models appear to prove that the concrete linings and the damaged zone of the massif desaturate rapidly under the effects of air circulation, but that re-saturation is much slower once ventilation stops. The consequences of this situation, however, do not appear to have been well-studied to day and may have a significant impact, for example on the swelling clay plugs used for sealing, or on the benefits of early cell closure.

*The question of tunnel sealing i*s recurrent. It has progressed significantly since 2013, with the presentation of the studies on physicochemical interactions on sealing materials and of two large-scale tests conducted in the underground laboratory and at the surface. We are still missing a mechanical and hydraulic overview, with models justifying structural design and expected performances. It has been demonstrated that the presence of seals is redundant for long-term radionuclide containment. The analysis of repository closure conditions in the BA is required by law. This question constitutes a public concern. Full-scale studies shall be scheduled from the first Cigéo phase in order to benefit, in due course, from the necessary experience feedback.

*The question of monitoring is i*mportant for operation security, experience feedback acquisition and for the assessment of reversibility conditions. Andra is currently developing the metrics and is conducting underground laboratory experiments. It now appears essential to define a monitoring strategy, as it should be implemented in Cigéo, for all demonstrator structures and operating structures.

The Board notes that the BA shall constitute the regulatory document for the building authorisation procedure submitted to the assessors. All decisions shall be made on the basis of this document. It is thus essential that the BA provides an industrial response to all scientific and technical questions raised by the project. In the case of a structure with a secular operating time however, there must be a degree of flexibility to allow for changes to concepts and methods. It would be absurd for the BA to definitively set all the constructive provisions; it must, however, demonstrate that, for each problem, including that of closure, we have at least one satisfactory solution.

The Board notes that, according to the schedule, the preliminary design studies will not be completed before 2015. It notes that many questions remain to be addressed before industrial solutions that can be used for the BA are reached. It recommends that Andra specify, before the end of the preliminary design, the list of points it considers must be dealt with before the BA is submitted, distinguishing structural elements from those related to an optimisation approach.

2.9 OPTIMISATION OF CIGÉO CONSTRUCTION

The optimisation of Cigéo phase 1 is a major BPD concern. It is based on the new inventory data published at the start of 2014 and is being studied by Andra's project managers. It will give rise to technical orientations to be adopted for the preliminary design and to rules for their integration in the project costing that the Government requested of Andra, to be provided by the end of June 2014.

Some lines of optimisation have arisen from joint examination by Andra and the producers; they currently concern waste management upstream of Cigéo, package inspection operations and the architecture of nuclear surface facilities.

Concerning underground activities, Andra is currently working on simplifying and standardising a number of mechanical concepts and package transfer routes, on disposal cell structure and operating mode and on LLILW area deployment.

A major development in the use of LLILW cells would consist in directly storing certain primary packages (concrete C1PG and CBF-C'2 containers and CSD-C stainless steel container); this could lead to a reduction in the number of cells and to the simplification of transfer and handling means.

Andra is currently considering phasing the construction of the LLILW area structural tunnels. An initial loop, only half the length of the final project, would thus be created during phase 1, allowing the construction of approximately twenty usable cells between 2025 and 2050. The thirty following cells would then be built after extending the loop. The requirements of the operating safety standards would be met, but the changes to the layout and lengths to create during a given works sequence would be significant and could potentially influence the choice of digging mode by the tunnel-boring machine or heading machine.

The Board points out that the notion of optimisation, as presented by Andra, covers both conceptual, technical and economic aspects of structure adaptation.

The Board is concerned that changes, it considers as major and that are not simple adjustments, may still be under development.

The Board thus observes the appearance of a proposal, inspired by essentially economic motives, to create only a short LLILW area loop during phase 1. This would not enable the required geological exploration of the COx at the repository scale. Even if the geological model defined from the Zira qualification studies appears reliable, the Board recommends that the possibility of direct validation of this model via full-scale structures over the entire LLILW area be maintained.

The Board renews the recommendation of its report no. 7, in which it considered essential that the digging operations be accompanied by a continuous geological monitoring programme.

In general terms, the Board considers that phase 1 of Cigéo should be conducted in such a manner as to remove, from a scientific and technological standpoint, all industrial operating uncertainties.

2.10 COST OF CIGÉO

The Board is waiting for a new Cigéo costing, which should be finalised in 2014. The cost estimate must take into consideration the new data concerning the inventory of waste to be stored (2014 data) related to the power plant operation extension issue. This costing will involve discussions between Andra on the one hand, and the waste producers on the other hand. Lines of optimisation should enable a cost to be determined shortly, even though some uncertainties remain, in particular concerning the tax regime applied to the facility. It should be noted that, before the summer of 2014, the court of auditors should issue a report updating the nuclear kWh costs (update of its January 2012 report). This new report should include indications concerning the updated estimate of the cost of Cigéo.

The Board reminds of the need to obtain details concerning the cost of Cigéo phase 1 and concerning the predictable pricing terms applied to producers to finance the disposal of their waste as and when packages are deposited.

2.11 THE CIGÉO ISSUE

On several occasions, the Board has emphasised the exceptional nature of the scientific, technical and societal implications posed by Cigéo. The project will involve several generations of the region's inhabitants, researchers, engineers and businesses; it will have a major impact on the region's socioeconomic development. This requires that steps be taken to maximise the benefits to the populations.

The Board recommends that this aspect be taken into consideration, as was the case for the EPR, which received the "major initiative" (grand chantier) label in 2008.

Chapter 3

LONG-LIVED LOW-LEVEL WASTE (LLLLW)

3.1 INTRODUCTION

The various types of LLLLW are described in Appendix X, which also contains comments made by the Board.

The inventory of LLLLW remains uncertain. As such, it serves to define the characteristics required of a future disposal under a reworked cover (stockage sous couverture remaniée – SCR): volume and radiological capacity, particularly in terms of alpha (^{226}Ra) and beta emitters (^{14}C and ^{36}Cl) in light of the necessary containment for these radionuclides in order to meet the requirements of the safety analysis. In its 2013 report, the Board underlined the chaotic nature of LLLLW management. In light of the information it received in 2013, the Board considers that it is essential to continue:

1) the characterisation of waste likely to be directly placed in SCR storage,
2) the qualification and implementation of recoverable waste reprocessing procedures,
3) the qualification and implementation of waste processing procedures to allow their storage in an SCR,
4) the inventory of other LLLLW requiring storage under an untouched cover (stockage sous couverture intacte – SCI).

To the uncertainties concerning the inventory may be added those concerning the possibility of storing certain packages due to the lack of appropriate accreditations; these must be established for each type of LLLLW to be stored. The producers' knowledge files concerning the various LLLLW, with their associated management possibilities, to feed Andra's 2015 report, must be provided by the end of 2014.

The Board considers that all uncertainties must be lifted as soon as possible to ensure that all aspects of LLLLW management progress and that, in June 2015, Andra can submit a comprehensive report on the possibilities for managing this type of waste.

For a time, Andra studied two storage concepts, one under an untouched cover (SCI) and the other under a reworked cover (SCR), based on an inventory that had been analysed by the Board in its 2008 report. Faced with the failure of negotiations concerning the location of an SCI site, the search for a site for this waste focuses exclusively on SCR storage; any LLLLW that could not be accepted would be sent to Cigéo where a reserve will be provided. The benefits of an SCI storage will be examined once more in 2015. The inventory data presented to the Board in 2013 differ significantly from those presented in 2008. Their validity will need to be confirmed and these data must be taken into consideration in all related documents.

3.2 LLLLW RESEARCH

These research activities focus on better characterising this type of waste, on packaging waste declared as LLLLW for storage, transport and SCR storage, and in developing processes for their recovery, to reduce their volume or to ensure their compatibility in a given storage. This research has developed in a context of laws and regulations and are guided by the knowledge files that Andra demands of the producers. Characterisation is not a problem as the resources as available and industrial programmes are in place.

The nature of the storage packages on the other hand is governed by the storage site selected and by the design of the repository itself. For the moment, Andra defines a number of orientations, taking into consideration the feedback from the SCA (Centre de Stockage de l'Aube – Aube storage centre). For economic reasons, it is clear that storage packages should be stored as is. The lack of storage specifications thus generates a degree of confusion.

Research into processes for possible rework of the packaging for the waste concerned here has been under way for several years, including on significant quantities, and have either been completed or are in their final stages. The economic advantages remain to be ascertained.

The next dead-line on LLLLW management is set by decree no. 2013-0304 of 31 December 2013. This same degree stipulates that Andra must provide the following by 30 June 2015:

- a report on the feasibility of graphite and bitumen waste management scenarios, which may lead to the opportunity of relaunching the search for an SCI storage site;
- a SCR storage project feasibility file, comprising the range of waste to store and associated implementation schedule.

3.3 SEARCH FOR AN LLLLW STORAGE SITE UNDER REWORKED COVER

SCR storage is clearly a priority for Andra, as indicated in the PNGMDR (National plan for the management of radioactive materials and waste) decree of 2013. The purpose of this storage will be to receive radiferous waste and, potentially, other LLLLW. Andra is thus searching for an appropriate site.

The ability of the SCR repository to accept, beyond radiferous waste, all or part of current LLLLW, either with or without treatment, will be governed by its radiological capacity for alpha emitters, but more importantly for ^{36}Cl, or even for other radionuclides (^{14}C, ^{129}I, etc.). Andra estimates that values such as 750 TBq for alpha over 300 years and 10 TBq for ^{36}Cl would allow the majority of LLLLW to be accepted in SCR storage. The required alpha emitter performance levels are those of the CSA, though these are far from the ^{36}Cl radiological capacity of this site, which is of 0.4 TBq. This highlights predictable difficulties for the sub-surface storage of certain graphite waste containing high levels of ^{36}Cl contamination. Only the good performance levels of the host rock, of the reworked cover and of the packages, that remain to be assessed, will enable these limits to be achieved.

In this respect, the Board reiterates a recommendation it had made in its report no. 7. When radioactive waste cannot be stored aboveground due to their activity, they must be isolated from the biosphere. Radionuclide containment must be maintained as long as they remain toxic; this must be demonstrated by a safety analysis.

Geological investigations were initiated on the Soulaines community of municipalities, which volunteered for them in 2008.

The current target comprises two Cretaceous clay strata, broadly exposed in the studied sector: (1) Albian tile-making clay (Gault Formation), of up to 80 m in thickness to the west, though rapidly thinning out by erosion to the east, and (2) Aptian Plicatules clay, of between 20 and 30 m in thickness over the entire area.

These two impermeable layers are separated by an aquifer consisting of a few metres of green sand, and they surmount another aquifer, of comparable thickness, consisting of Barremian sand. Andra has initiated hydrological modelling of these aquifers at the regional scale, though it must still draw up a precise inventory of the current uses of these aquifers, that do not appear to be used for significant pumping activities. In the Soulaines sector, these clay series are partially covered with

Quaternary alluvial deposits. In this case, their valley-bottom position excludes storage under an untouched cover as the Cretaceous and post-Albian deposits are only preserved to the west of the area being prospected by geophysical measurements and boring.

As they are located close to the surface, these clay formations are very different from COx clay. Consequently, they possess very high water contents, reaching up to 40% of rock volume. Andra must continue the characterisation of their petrophysical (porosity, permeability) and geo-hydro-mechanical properties, along with the radionuclide retention capacities (diffusion into pore water and interactions with clay minerals).

The other aspect still requiring advanced research is the estimation of Aptean-Albian clay erosion rates over protracted periods of time, considering that they are currently close to the surface and that the storage of LLLLW is considered at a depth of approximately ten metres, under a reworked cover.

Thanks to the work already conducted by Andra at Bure and over the entire Paris basin and its periphery by many academic teams, the mechanisms that led to the erosion of several hundred metres of Upper Cretaceous series in Lorraine are currently interpreted as the result of the uplift of the shoulders of the Oligocene rift comprised of the Rhine graben in Alsace and of the large radius wrinkling of the West-European lithosphere in response to Alpine deformations. Even though these phenomena are old, they led to a cumulative erosion of 700 m over 60 million years, thus significant less than 10 m per 100,000 if we take the average of this erosion that started at the beginning of the Tertiary. To the west of Soulaines, the centre of the Paris Basin, on the other hand, has remained globally subsided since the end of the Cretaceous, thus escaping the peri-Alpine upheavals and still comprises several dozen metres of Tertiary marine sedimentary series.

To guarantee the safety of the SCR site, Andra has also undertaken studies focusing on much shorter timer periods, aimed at precisely quantifying the cumulative erosions over the past 100,000 years on the slopes around Soulaines, and at specifying the age of alluvial deposits at low points. The initial estimates of these erosions do not appear to exceed 10 m per 100,000 years and are partially controlled by the climatic variations of the Quaternary.

The Board recommends that Andra continue its modelling of relief and topography changes in the sector over the coming 100,000 years, considering various climatic and eustatic scenarios, in order to identify the best LLLLW disposal site.

Whatever the quality of the clay in which the waste packages are to be stored, the concept of SCR disposal requires the implementation of a cover providing a protection for the packages that is close or equal to that which would have been provided by the natural environment prior to digging. Andra possesses significant experience in manufactured covers for surface repositories, such as the Manche centre currently being monitored, as does Areva with the repository covers for uranium mine residues, also being monitored. The design of a cover for an LLLLW SCR repository as the essential component of such a repository requires further studies, independently of site research.

The Board wishes Andra to present the goals to achieve for the definitive cover of an SCR repository, along with the studies or experiments it is conducting on its design.

3.4 PROBLEM OF DATA AND PUBLIC PERCEPTION

There are several sources of information on the characteristics of radioactive waste, in particular LLLLW: type, quantities, volumes, location, storage, monitoring, etc. The national waste inventory, published on a regular basis by Andra and fed by the waste producers, is publicly available. Data are also communicated during the PNGMDR workgroup presentations. The ASN publishes values in various documents. Finally, the Board is directly informed of data searches during the hearings. It mentions them in its reports. The information that citizens may obtain and compare from these sources are not always consistent. This is detrimental to the credibility ascribed to predictive disposal inventories, which are one of the public's major concerns.

The Board recommends that these sources of information be standardised.

3.5 CONCLUSION ON LLLLW MANAGEMENT

The studies conducted on graphite and bitumen radiferous waste, along with the management options considered by the producers, provide a glimpse of LLLLW management.

- There are no major uncertainties concerning the management of radiferous waste: Approximately 50,000 t could be placed in SCR disposal, if a suitable site can be found.
- Of the approximately 80,000 m^3 of graphite waste (CEA and EDF), approximately 70,000 m^3 could be placed in SCR disposal, as their ^{36}Cl activity is low. The 10,000 m^3 of EDF and CEA liners could only be placed in this type of disposal after decontamination, while the associated waste would be sent to Cigéo. If decontamination was not selected, the waste would need to be stored either in an SCI repository, or in Cigéo. If, after decontamination, liner gasification is required, the residues would be sent to Cigéo. Areva's graphite/magnesium waste is destined for Cigéo deep geological disposal.
- With regard to bitumen waste, the Board had recommended that they be sent to an SCI repository or to Cigéo. The fate of CEA's 40,000 drums of bitumen is under consideration.

Chapter 4

REVERSIBILITY

The 1991 act mentioned reversibility as simple option for deep disposal. The 2006 act indicates that deep disposal must be performed in accordance with the principle of reversibility and that repository building authorisations must specify the duration, which must not be less than one hundred years, during which disposal reversibility must be guaranteed. It states that the Government will present a draft law defining the conditions of reversibility.

4.1 THE NATIONAL AND INTERNATIONAL DEBATE

The principle of deep geological disposal of nuclear waste has been adopted by all concerned countries, in particular the European countries, China, Japan and the United States. These countries have introduced the principle of reversibility of geological disposal to varying degrees. Indeed, the main purpose of geological disposal is long-term safety; this does not necessarily imply reversibility.

Andra has contributed to the national and international debate on reversibility, in particular by organising conferences, including the Reims conference in 2010, and has taken the debate to the Nuclear Energy Agency (NEA) of the Organisation for Economic Cooperation and Development (OECD). The OECD's Nuclear Energy Agency (NEA) has defined a reversibility scale for geological disposal: level 1 represents interim surface storage; at level 2, packages are placed in a cell; at level 3, the cell is provided with its final sealing system; at level 4, an entire zone of cells is sealed; finally at level 5, the repository is sealed and safety is ensured in a passive manner.

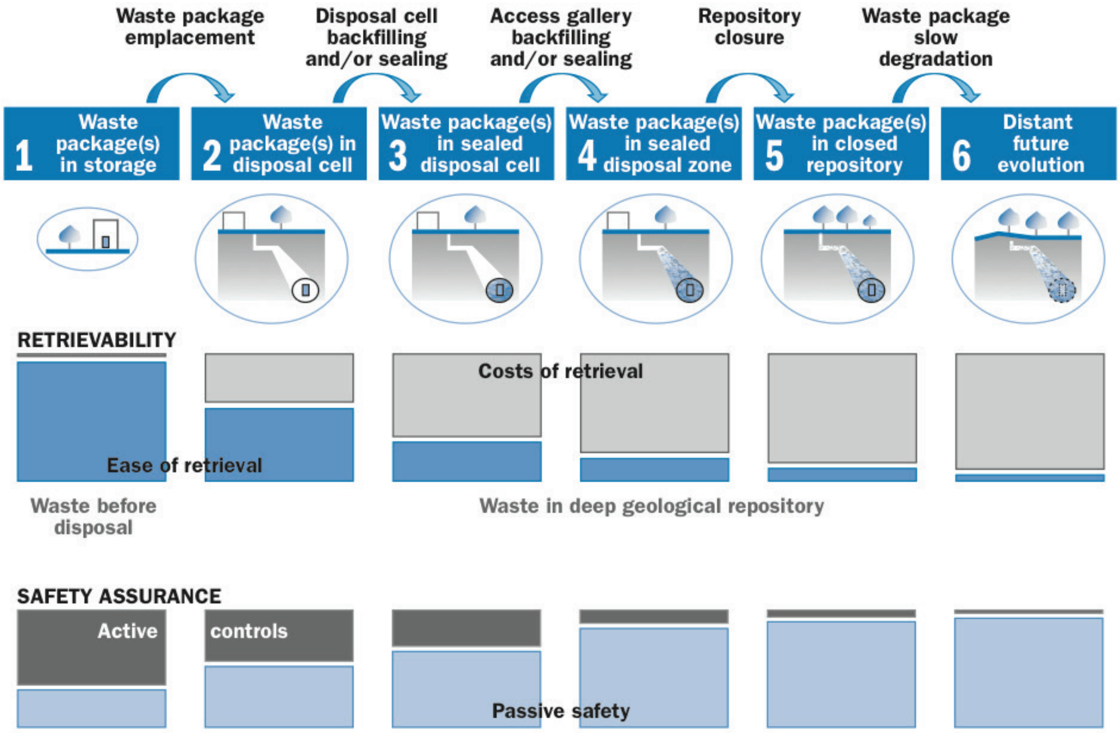


Illustration of the vision of deep geological disposal evolution according to the NEA

In this approach, there are two distinct dimensions.

- Firstly, a description of the progressive steps towards complete closure. From this point of view, there is a fundamental contrast between the initial stage of simple interim surface storage (level 1), the second stage of deep disposal (level 2) and the third closure stage limited to filled cells (level 3). Closure then becomes increasingly complete at levels 4 and 5.
- Each of these three stages can then be interpreted in terms of reversibility. Considerations of reversibility, however, must also take into consideration what would happen if each stage were maintained durably; for example we would need to examine the consequences in terms of risks of prolonged holding at stage 2. The notion of reversibility must also include a comparison of the various closure scenarios, from the standpoint of their predictable consequences. The notion, that could be suggested by the diagram on the previous page, of a constant safety level, independent of the duration of each stage, during the progressive transition from active safety to passive safety, must not be accepted out of hand.

4.2 NOTION OF REVERSIBILITY

Considerations on reversibility have led to the clarification of associated notions. The notion of reversibility itself was introduced in order to define a method of managing a waste repository. For radioactive waste, it implies three distinct dimensions:

- decision concerning the nature of acceptable waste and the terms of their disposal,
- practical structure management,
- natural evolution of the waste and barriers, both man-made and geological, used to contain the radioactivity.

It should thus be noted that the notion of reversibility involves several dimensions of different types.

- Concerning disposal decisions, the key variable is social and is determined by the various motivations and representations concerning this subject. Protection of workers and the public, along with safety, must be the main objectives.
- Practical disposal management on the other hand, requires changing technological knowledge and implies economic costs that are difficult to predict over such a long period.
- From the standpoint of changes to the waste itself and to the barriers, both man-made and geological, the issues are distinct:
    - waste evolves independently, governed by its disposal conditions,
    - the possible effects on the environment will be determined by the structure, whether partially closed or open.

The structures must conform to a principle of robustness keeping their deformation over time to a strict minimum in order to ensure that the waste can be removed and taking into consideration the variable time span between cell opening and closure.

Finally, we need to move away from a simplistic mechanistic notion of reversibility, focused on the model of a system that could simply function in reverse, with no impact on safety. Remaining at stage 2 (filled and unclosed cells) can have irreversible consequences in terms of increase in the risk of accident and of reduced disposal safety. The various dimensions of reversibility, in particular the social dimensions, thus take us away from a mechanistic model. The principles of security and reversibility require that we compare all changing variables of each scenario.

4.3 DEFINITION OF REVERSIBILITY

Reversibility is a management system consisting in guaranteeing future generations the ability, at any stage in the scheduled disposal process, to decide whether to continue, suspend, or to return to the previous stage.

A schedule of meeting points, providing the opportunity to discuss these matters and to make such a choice under conditions of complete transparency, must be defined in advance.

To be effective, reversibility assumes retrievability, i.e. the technical and organisational ability to move the waste, or to return it to the surface. This implies a degree of flexibility when creating the facilities, taking into consideration scientific and technical breakthroughs and feedback. Finally, it requires the definition and implementation of monitoring means allowing informed decisions to be made.

It is important to understand that it is never impossible, from a technical standpoint, to remove the waste from a repository; even after this latter has been definitively closed. Of course, in this latter case, extremely heavy technical means would need to be implemented, comparable to those used to build the repository. Retrievability may be more or less difficult, but, based on our current technical abilities; there is no point of non-return beyond which retrieval would be impossible.

The principle of reversibility, specified by law, thus implies practical retrievability of waste that can be adapted to the disposal stage reached. It does not, however, imply any decision concerning effective removal operations, except experimental, in view of performing the in situ validation of certain procedures. Indeed, an effective removal decision is not a goal in and of itself. Ideally therefore, the reversibility principle must make package removal possible, while considering this removal increasingly unlikely over time.

4.4 REVERSIBILITY EXPERIMENTS IN ACTUAL STRUCTURES

The Board also based its considerations on the analysis of actual situations. The Herfa Neurode, Stocamine and WIPP feddback (see Appendix XI) showed that removals were effectively performed and that waste retrieval is always possible, though it becomes increasingly difficult.

Nevertheless, these three examples, along with that of Asse, show that retrieval operations are all the easier if planned in advance. Moreover, they highlight the absolute need for strict management, excluding the insertion of non-compliant packages.

4.5 BOARD RECOMMENDATIONS

The fundamental objective of geological disposal is to ensure the passive safety of the facility after its closure. This gives rise to a natural hierarchy of concerns. These include very long-term passive safety, worker and public security during the repository operating period, along with reversibility.

The Board considers than, in the event of conflict between these concerns, priority must be given to very long-term passive safety and to worker and public security: we must not compromise safety by introducing a condition that would facilitate package removal.

Various retrievability modalities that conform to reversibility goals must be considered: at level 2, Andra plans to use the circuit used to insert the packages, in reverse, from the cell to the surface. From level 3, this simple reversal is no longer sufficient, but package removal remains technically possible.

The law stipulates that reversibility must be guaranteed for a period of no less than 100 years. In agreement with this provision, the Board considers that the repository must be designed such that the first cells to be filled can be left at level 2 for a reasonably long initial observation period, before progressively switching to level 3.

Indeed, the Board does not consider that the option of leaving entire repository at level 2 should be imposed by our generation upon future generations, as it may present major disadvantages both in terms of security and of safety.

Our generation's responsibility is to design the most secure repository possible, making the best use of current knowledge. Consequently, the progressive transition of cells from level 2 to level 3 must, from now on, be included in the design and operation of Cigéo.

Indeed, the progressive repository closure is an option that may be considered more secure than maintaining the entire repository at level 2 for 100 years, and this for four different reasons:

1) *It corresponds to the choice of long-term passive safety. It reinforces it, as it reduces risks of storage-specific accidents, or to the indefinite postponement of structure sealing and site closure.*

By leaving the LLILW cells – the first to be created and filled – open, the ventilation in these cells is maintained for longer. Ventilation air provides oxygen and bacteria, generates temperatures distinct from that of the rock and sufficiently low humidity levels to cause the desaturation of the lining concrete, followed by that of the surrounding rock massif. These disturbances delay the return to equilibrium. In the event of an accident, it is preferable that the smoke from a fire be prevented from circulating in cells left open. Andra has analysed these effects and has demonstrated that their consequences remain acceptable. The Board deems that this result is credible. Nevertheless, a prudent attitude would consist in avoiding the need to test the hypothesis.

Moreover, after filtration, the ventilation air is released to the outside. Andra has determined that the resulting doses are significantly below the maximum permissible public doses. Nevertheless, once again a prudent attitude would lead to efforts to further reduce these doses by closing certain cells to eliminate their contribution to outside releases.

2) *It reduces the social hazard: the simulations that can be performed on changes to the packages and their environment are much more precise and reliable that those performed on the social state in the distant future. The risk associated with poor subsequent social management is much higher than the risk of a burial-related accident, the knowledge of which is objectively based on known behavioural laws.*

While we are certain that our generation possesses the technical, scientific and organisational means to design, build and operate a deep repository, there is no guarantee that the future generations will possess the same skills. Allowing future generations greater freedom also imposes them greater responsibilities.

Finally, the considerations must not exclude a brutal social evolution, leading to the careless abandonment of the site, no matter how improbable it may currently appear. In this case, we would need to be as close as possible to a state of passive safety.

3) *This takes into consideration the highly improbable benefits of package retrievability.*

Various reasons could lead to the partial or complete removal of waste. The experience derived from other structures provides a few of these reasons: an unpredicted geological hazard, or non-compliant package depositing. The Board nevertheless indicates that, considering their nature and packaging, it appears highly improbable that there would be any economic benefits to retrieving the waste (see Appendix XII). This is true in particular for LLHLW, resulting from reprocessing that has removed any potentially useful substances – uranium and plutonium – from the spent nuclear fuel and which is then packaged in glass matrices chosen because they are extremely difficult to recover or break down. The hypothesis of a withdrawal dictated by the appearance of a better waste management solution cannot of course be excluded out of hand; it does, however, appear to be relatively unrealistic as deep geological disposal is the solution chosen by all concerned countries, whether they reprocess their spent fuel or not.

4) *Progressive closure avoids imposing on future generations the management of waste that it has not produced.*

Deep geological disposal assumes definitive closure after a defined period, currently set at approximately one century after the first packages are deposited. This is a fundamental choice made by law. It is inspired by the ethical principle of preventing or limiting loads to be borne by future generations, a principle stated in the opening paragraphs of the Environment Code. Its consequence, in the case of radioactive waste, is that the financial and material charges resulting from the use of nuclear energy must be borne by those generations benefiting from it.

This ethical principle leads us thus to prepare a definitive closure, but also a progressive closure, in order to provide future generations with the knowledge acquired by the intermediate generations. Our generation must prepare this progressive closure.

For all of these reasons, the Board is in favour of progressive cell closure – it will be up to the future generations to verify whether this closure is appropriate and secure.

The Board proposes that an agreement be reached that, in any case, a transition from level 2 to level 3 is excluded for a given period of time after the start of operation and filling of the first cells. This initial observation period, proposed by the operator, may be of between ten and twenty years. During this period, tests must be conducted on experimental cells with a view to developing and validating appropriate monitoring systems used to measure changes to closed cells. Once this initial observation period has expired, if cell closure is deemed appropriate, particularly from a safety standpoint, then the decision to switch the cell from level 2 to level 3 should be made.

Chapter 5

INTERNATIONAL PANORAMA

In its report no. 7, the Board published an exhaustive presentation of the 2007-2013 international panorama, including the nuclear waste management options and R&D actions. This information is still valid today and the Board has decided to focus this report on a European panorama of the financial aspects of waste management, on the international approach to reversibility, on the recent WIPP accident and on nuclear activities in India.

5.1 ORGANISATION OF MANAGEMENT, FUNDING AND PLANNED COST FOR A GEOLOGICAL REPOSITORY

Finland and Sweden have already filed an application for construction of a pository. France is finalising its documentation for an application. Other European countries, such as Belgium, have initiated studies for the creation and financing of geological repositories. France's situation is described in Appendix VIII to enable comparison at the European scale.

5.1.1 Belgium

a) Organisation in charge of radioactive waste management

In 1980 Belgian law established the National Agency for Radioactive Waste and enriched Fissile Material (Ondraf-Niras), a 100% public organisation, in order to manage radioactive waste, whatever its origin and source. Ondraf-Niras also has to draw up an inventory of all nuclear facilities and of all sites containing radioactive substances. Management includes transport, processing, packaging, storage and final disposal. Some of these tasks are performed by the industrial subsidiary of Ondraf, Belgoprocess. As a public organisation, Ondraf is required to define and implement its management policy in such a manner as to best serve the general interest. Ondraf manages the funds.

The organisation is subject to control by a supervisory authority, consisting of federal ministers with Economic affairs and Energy amongst their responsibilities, along with the regulator, the Federal agency for nuclear control (Agence Fédérale de Contrôle Nucléaire – AFCN).

Radioactive waste is defined by Ondraf as "Any material for which no use is planned and which contains radionuclides at concentrations higher than the values that the competent authorities considers as permissible in materials suitable for use or disposal without control" [2].

In Belgium, enriched fissile materials[3], mainly those produced by the nuclear fuel cycle, are "those for which no use or processing is planned by the producer or operator and which can consequently be likened to radioactive waste".

b) Financing and estimation of the cost of geological disposal

The financing of day-to-day management is based on two principles:

- The first is that all Ondraf costs are borne by the recipients of its services, the radioactive waste producers, according to the "polluter pays" principle;
- The second states that, as Ondraf has a monopoly on the management of radioactive waste in Belgium, it is required to work at cost price and to maintain financial equilibrium.

[2] NB: This definition includes the principle of exclusion below a concentration threshold.
[3] Mainly spent fuels.

Ondraf enters into contract with radioactive waste producers. These contracts define the terms according to which Ondraf performs its duties. Contractors are required by law to provide Ondraf with all necessary information for this purpose.

The financing of future management is based on various funds, the most significant being the long-term and medium-term funds.

The purpose of the long-term fund is to finance costs associated with the construction and operation of radioactive waste storage and disposal facilities via a three-part financing mechanism:

- capacity reservation, which is the contractual notification, by each producer, of its complete waste production programme;
- tariff payment, supplying the fund each time Ondraf accepts waste under its responsibility.

Electricity producers contribute to the fund via a levy on each kWh sold. The discount rate adopted by Ondraf for waste in their possession is currently of 4%. Synatom (a private company managing the entire fuel cycle for Belgian nuclear power plants) applies a rate of 4.8% for producer provisions.

The medium-term fund is intended to cover costs incurred with a view to creating and maintaining the societal base required to integrate a radioactive waste disposal facility into a municipality. The medium-term fund is maintained by integration fees paid by radioactive waste producers and calculated according to total disposal capacity and to the respective total quantities of waste by the producers that are to be stored. The obligation to contribute to the medium-term fund will start as soon as the disposal facility will have received its legal authorisations.

In 2009, Ondraf estimated the cost of geological disposal based on a number of hypotheses:

- Belgian power plants will operate for a period of 40 years;
- spent fuel will be reprocessed;
- the repository will be built at a depth of 250 m in Boom clay, a host rock studied in the Hades/Euridice underground laboratory;
- There will be two areas: one for LLLLW and LLILW ("cat. B", approximately 11,000 m^3) and one for LLHLW; the volume of this latter (cat. C) will depend upon the chosen management mode: it is estimated at approximately 600 m^3 if the spent fuel is reprocessed, or 4,500 m^3 if the spent fuel is not reprocessed and added to already vitrified waste;
- construction will start in 2032.

The estimate, which comprises a financial plan and a tariff proposal to be negotiated with the producers, was drawn up in close collaboration with Synatom and the Belgian Government (responsible for a certain volume of "historical" waste). In the context of an international assessment, Andra performed a critical reading before the estimate was finalised.

Taking into account the aforementioned hypotheses and a 0% discount rate, the total cost would be of approximately 3 billion Euros for a one-century operating period, after which the site will be in a post-closure state. Construction costs represent approximately 40% of this sum.

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  http://www.ondraf-plandechets.be/nieuw/downloads/pdf/Plan%20Déchets.pdf
- Cost estimate:
  http://www.ondraf.be/sites/default/files/NIROND%20TR%202009-15%20E%20signed.pdf
- Belgoprocess: www.belgoprocess.be

5.1.2 Finland

a) Organisation in charge of radioactive waste management

Finnish law stipulates that all radioactive waste produced in Finland must be processed, stored and disposed of in Finland and that no foreign waste will be imported into the country.

By "radioactive waste", Finland means: "radioactive materials, along with contaminated equipment and objects that are no longer of use and must be rendered harmless". Once the activity falls below a certain level, determined by the radionuclides concerned, the waste is no longer considered as radioactive waste.

The responsibility for managing radioactive waste is incumbent upon the electricity producers, Teollisuuden Voima Oyj (TVO) and Fortum Power, that have created Posiva Oy for this purpose. Posiva Oy conducts research and development into the disposal of spent fuel. Posiva Oy stocks are owned by TVO (60%) and Fortum (40%).

The Ministry of trade and industry supervises power plant operation and waste management. The regulator, Säteilyturvakeskus – Strålsäkerhetscentralen (Radiation and Nuclear Safety Authority, Stuk), which is in charge of inspections, is administered by the Ministry of health and social affairs.

The repository building application, submitted to Stuk by Posiva in December 2012, concerns 9,000 t of non-reprocessed spent fuel uranium metal, according to the KBS-3 concept, i.e. 4,500 containers, covering the needs for Loviisa 1 and 2 and Olkiluoto 1 to 4. This granite repository shall be located at a depth of between 450 and 500 m.

Once a tunnel has been filled, it is immediately and definitively closed. New tunnels are dug as and when required.

A new power plant is to be built by the company Fennovoima. Posiva does not account for the disposal of spent fuel generated by Fennovoima, though this may be imposed by the Government.

Low-and intermediate level reactor operating waste is managed individually by each producer. The annual production at Olkiluoto is of 150 to 200 m^3; that of Loviisa between 100 and 150 m^3. Waste is packaged either in bituminous or concrete form. After storage, the LL and IL waste is disposed of separately, both at Olkiluoto and at Loviisa, in silos at -60 and -100 m in granite. Once a silo is full, the access is definitively sealed. The Olkiluoto facility has been operational since 1992; that of Loviisa since 1998. Total capacity is around 8,600 m^3. Extensions are planned at both sites, amongst others for decommissioning waste.

Stuk possesses a small repository for long-lived Low or very low level waste not generated by power plants (hospital, industrial waste, etc.). This repository is located in Olkiluoto.

b) Financing and estimation of the cost of geological disposal

The electricity producers are responsible for financing the spent fuel management and disposal costs. Each year, they must submit their best estimates for the future. They have created a fund (2.270 billion Euros at the end of 2013) to cover costs currently estimated until 2120. The discount rate is 0%. The price per kWh includes a contribution to this fund.

Costs are estimated at 3.3 billion Euros (2009), including 700 million for investments, 2.4 billion for operation for 50 to 60 years and 200 million Euros for decommissioning.

The extension of the Olkiluoto site to receive spent fuel from Fennovoima would costs 200 million Euros, whereas the creation of an independent repository would cost approximately one billion Euros.

References:

- Posiva: http://www.posiva.fi/en
- Stuk : *http://www.stuk.fi/en_GB/*
- Ministry of Employment and the Economy *: www.tem.fi*

5.1.3 Sweden

a) Organisation in charge of radioactive waste management

Following the statutory provisions, the Svensk Kärnbränslehantering AB (Swedish Nuclear Fuel and Waste Management Company, SKB) was created by the electricity producers, responsible for the development of a global spent fuel and associated radioactive waste management and disposal concept. The producers are also responsible for conducting the required research and demonstrations. SKB is owned by Vattenfall (36%), Forsmark (30%), OKG (22%) and E.ON Sweden (12%).

SKB's mission is to manage the transport, packaging, storage and disposal of waste and spent fuel, ensuring the current and future protection of the population and the environment. SKB is also responsible for the disposal of waste generated by non-electricity-generating applications and by the decommissioning of research or other facilities.

The Government, via its Ministry of the environment, is in charge of supervising SKB's activities.

The regulator, Strålsäkerhetsmyndigheten (Swedish Radiation Safety Authority, SSM) monitors safety and radioprotection aspects, checks the costs calculated by SKB and proposes rates to the government, that then sets them for the coming 3 years. This procedure is repeated every 3 years, making any necessary adjustments.

The Kärnavfallsrådet (Swedish National Council for Nuclear Waste) monitors the issues of waste, decommissioning and financing and advises the government on this topics.

Waste is classified according to its dose rate and activity constraints:

- Very low dose waste, equivalent to VLL, is either released for recycling, or stored at landfills on the reactor sites;
- Short-lived low or medium activity waste is stored in silos or chambers dug into granite, at depths of less than 60 m below the Baltic Sea in Forsmark. The capacity is of 63,000 m^3. A 200,000 m^3 capacity extension is planned;
- Long-lived medium-level waste will be stored at great depth (approximately 500 m) in granite. The disposal concepts remain to be determined and the choice of site will follow on;
- The disposal concepts remain to be determined and the choice of site will follow on;
- Spent fuel is destined to be stored at Forsmark, in granite at great depth (approximately 500 m). The capacity will be of 12,000 tonnes, or 6,000 containers. The application to construct a repository was submitted to SSM in 2011, in accordance with the nuclear activities act, and another application was submitted in parallel to the "Environment court", in accordance with the Swedish environmental code. The final decision will be made by the Government following consultation with SSM and the Court. Moreover, the government must request the opinion of the hosting municipality, which possesses a right of veto. The Oskarshamn fuel encapsulation facility also requires a building application based on the same procedure.

Sweden has no high-level reprocessing waste.

The repository concept takes into consideration the various retrievability levels, as defined by the NEA.

b) Financing and estimation of the cost of geological disposal

The electricity producers are required to finance the spent fuel management and disposal costs. For this, they pay a contribution of around 0.25 Euro cents per kWh to a fund, the Kärnavfallsfonden (Swedish Nuclear Waste Fund). They must also guarantee that unexpected future costs will be covered.

The discount rate is currently of 2.3%.

The costs incurred for management, decommissioning or research are refunded progressively by the fund. The towns are refunded for the costs incurred for public information.

In 2010, SKB estimated system cost of spent fuel and waste management and decommissioning, including disposal, and this for a power plants service life of 50 years, at approximately 14 billion Euros.

References:

- SKB: *http://www.skb.se/default____24417.aspx*
- SSM: *www.stralsakerhetsmyndigheten.se/In-English/About-the-Swedish-Radiation-Safety-Authority1/*
- Swedish Nuclear Waste Fund: *http://www.karnavfallsfonden.se/informationinenglish.4.725330be11efa4b0a3f8000131.html*

5.2 INTERNATIONAL APPROACH TO REVERSIBILITY / RETRIEVABILITY

The countries with nuclear energy initiated internal discussions on the notions of reversibility/ retrievability as soon as the civil society appropriated the questions of interaction between sustainable development and the management of radioactive waste. These discussions focused on the ethical aspects of protection of humans and the environment, along with future generations.

It rapidly became apparent that the definition of the notions of reversibility/retrievability varied from one country to the next and/or from one language to the next and that is was sometimes difficult to reach a consensus on a common understanding of the two concepts. In order to reach this consensus internationally and between the most directly concerned parties, the International Atomic Energy Agency (IAEA, under the auspices of the United Nations) and the Nuclear Energy Agency (NEA, under the auspices of the Organisation for Economic Co-operation and Development, OECD), took the initiative to bring together the representatives of their respective member states.

The considerations in the context of the IAEA led to several publications, the most recent of which is that of 2009: "Geological Disposal of Radioactive Waste: Technological Implications for Retrievability". As the title suggests, the report focuses mainly on the technical implications of reversibility by emphasising retrievability. The report defines retrievability as a specific case of reversibility, i.e. the reversibility of the action consisting in placing the waste at its definitive location.

The report also clearly defines the ethical bases leading to retrievability:

- the generation that benefits from nuclear energy is responsible for managing the resulting waste; this implies that future generations must not be required to maintain repository safety and, consequently, passive safety must be guaranteed after a reasonable amount of time;
- as knowledge and values change, future generations must be able, should they so desire, to adapt the management of buried waste; we must therefore use a repository concept that does not make subsequent work inordinately difficult before closing the repository.

The report shows that ideas converged on a certain number of points, such as the fact that retrievability will become progressively more complex over time and that this may have a negative impact on security and safety.

In parallel to the work conducted in the context of the IAEA, the NEA organised several workgroups and symposia on the topic. In order to resolve the last discrepancies between the IAEA's and NEA's conclusions, the NEA sponsored, between 2007 and 2011, a project titled "Reversibility of decisions and retrievability of radioactive waste – Considerations for national geological disposal programmes" in association with experts from safety authorities, industry, R&D and public policy decision-making bodies, from NEA, IAEA and European Commission member countries.

Even though each national programme is unique, as it fits into a social, legal and technical context that varies from one country to the next, over time, a certain number of conclusions emerged as an international consensus. These are listed below.

According to NEA, reversibility refers to the ability to go back on decisions made during the progressive implementation of a disposal system, independently of the effective exercise of this ability. Going back is the concrete action of reversing or altering a decision, either by changing direction, or possibly by reinstating a previous situation. Reversibility implies taking steps to enable going back if necessary. Reversibility is thus an approach to decision-making that acknowledges that this decision-making process occurs in steps and implies that the implementation of decisions and technologies is sufficiently flexible to reverse or alter, if necessary, without undue effort, one or more decisions made previously.

According to the NEA, retrievability refers to the ability to retrieve waste packages, either alone or in transport containers, though it does not specify the conditions of their possible repackaging. The notion is presented independently of the effective exercise of this ability. Retrieval is the concrete action of retrieving waste packages. Retrievability implies taking the necessary steps to allow this retrieval.

According to the NEA, during a repository's operating phase, reversibility and retrievability are the result of the application of a precautionary principle. They are used to manage the uncertainty surrounding certain technical solutions; they provide additional safety guarantees; they help meet the general public's desire to not be the prisoners of an irreversible situation.

As long as the continuity of institutional provisions is maintained, the removal of waste packages, if necessary, would be considered as a nuclear activity, requiring authorisation from the nuclear safety authority.

Following the operating phase and upon termination of institutional monitoring of the facilities, and beyond the period during which disposal container integrity can be guaranteed, waste retrieval would still be possible, but would require increasing technological and financial resources in order to meet the safety requirements.

The fact of taking measures, enabling potential removal of waste packages, into consideration in repository design does not imply a clear intent to retrieve the waste in the future. The aim is simply to avoid causing needless removal complications should a future society decide to retrieve the waste for whatever reason. While reversibility provides a certain freedom of choice, however, it must never be achieved at the expense of current or future safety.

In the short term, the retrievability provisions may be considered as good engineering practice and contribute to safety, for example, by enabling adequate management of operating incidents or accidents. Maintaining retrievability beyond the minimum requirement for operation may have negative impacts on safety (industrial and mine-related risks, worker exposure, etc.). In the very long term, attempting to keep the repository open to promote retrievability would make it impossible to meet safety requirements.

When the notion of retrievability is included in a disposal programme, the retrieval of waste packages will obviously become increasingly difficult as the disposal facilities take on their final form and function.

A relationship has been established between waste package retrievability and the various repository evolution phases for disposal projects in the form of a "retrievability scale". This latter reflects the progression of a repository and the evolution of the ease of waste retrieval, retrieval costs, passive safety elements and active monitoring elements. This scale is currently included in various European disposal programmes.

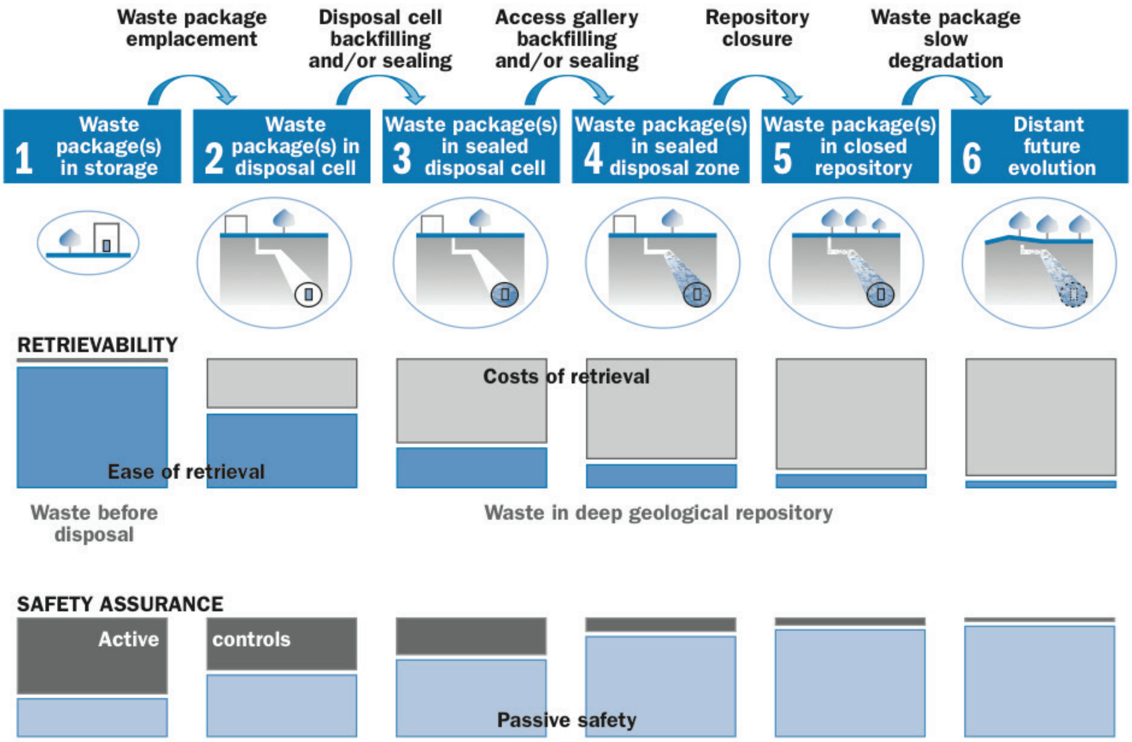

Illustration of the vision of deep geological disposal evolution according to the NEA.

The practical application of these principles is governed, amongst others, by the institutional context, cultural differences, types of waste and geological formations. Thus, in some countries, reversibility or retrievability is set out in law (France, Switzerland, USA, etc.); in others, it is not required by law, but nevertheless provided by contractors (Sweden, Finland), or by the waste management supervisory body (Belgium, Korea, etc.). In the Swedish and Finnish granite formations, tunnel backfill is performed as and when the tunnels are filled, to immobilise the spent fuel containers; this is not necessarily the choice for tunnels dug in clay formations (France, Belgium, Switzerland).

While the various countries adhere to the principles laid out, the choices pertaining to retrievability and to short or medium-term safety are thus not identical in all programmes. All, however, agree upon the priority to be given to current and future safety over all other considerations.

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- Réversibilité des décisions et récupérabilité des déchets radioactifs – Éléments de réflexion pour les programmes nationaux de stockage géologique, AEN N° 7105, ISBN 978-92-64-99170-5, 2012.

5.3 WIPP ACCIDENT

The WIPP (Waste Isolation Pilot Plant, Chihuahua Desert, New Mexico, United States) has been operational since 1999 for the definitive disposal of transuranic waste generated by the American military programme. The waste is stored at a depth of 650 m in a 1,000 m thick (average) and 250 million year-old salt formation.

On 5 February 2014, probably following a diesel oil leak, the tyres of a salt hauling truck caught fire. The fire generated large amounts of smoke and soot. The driver tried unsuccessfully to put the fire out using the extinguishers available. The alarm was raised and an evacuation order issued. At the time of the fire, there were 86 workers underground. All were evacuated. Some workers required care, but there were no injuries.

The fire shed light on a number of procedural and equipment errors. Thus, the available extinguishers were inappropriate, the evacuation order was not heard by all workers and a ventilation system started up to remove the smoke actually caused it to spread to fall-back areas.

An exhaustive list of points to analyse was drawn up and corrective measures were implemented.

The Board approves Andra's strategy aimed at reducing the underground use of vehicles powered by combustion engines and of vehicles fitted with tyres.

Moreover, on 14 February 2014, an abnormal increase in radiation levels was observed by a continuous air monitor in the mine. There were no workers underground at the time of the observation and, as a precaution, the mine was immediately closed. Over the following days, traces of Pu and Am were detected by the surface monitoring network and several workers were very slightly contaminated.

At the time of drafting this report, the reason for these emissions was unknown.

References:

- WIPP: *http://www.wipp.energy.gov/*
- DOE: *http://www.energy.gov/*

5.4 STUDY TRIP TO INDIA FROM 15 TO 23 FEBRUARY 2014

The Indian nuclear energy development program focuses on the eventual implementation of a fleet of indigenous nuclear electricity-generating reactors using thorium and uranium 233 (^{233}U) as fuel. As planned, the Indian thorium circuit requires the passage of three stages, during which several types of nuclear electricity reactors are in operation:

1) PHWR-Pressurised Heavy Water Reactors supplied with natural uranium to produce plutonium;
2) FBR – Fast Breeder Reactors supplied with the uranium and plutonium generated by the PHWRs; the FBRs will in turn produce more plutonium than they use, along with ^{233}U by thorium irradiation;
3) pressurised heavy water reactors fertilising the thorium with the plutonium and ^{233}U produced by the FBRs and, in fine, with thorium fertilised by ^{233}U that they will produce themselves once all the plutonium has been used.

Stage 1, which has reached industrial maturity, is under way and should generate a power of some ten GWe by 2020 and to an energy and plutonium production over 20 to 30 years. The service life of the PHWRs is of approximately 60 years. This energy production corresponds to the consumption of the estimated quantity of Indian uranium. The PHWR fleet, comprised of low-power units (0.2 GWe and 0.7 GWe planned), will coexist with foreign-bought nuclear electricity reactors using enriched uranium, which will generate the same amount of electrical power as the PHWR fleet (cf. Appendix XI, Indian Nuclear Organisation).

Stage 2 is just starting, with the construction of a prototype fast breeder reactor (PFBR). It should lead to the generation of considerable power: 60 GWe by 2030, then 200 GWe a few decades later.

Stage 3, the thorium circuit, is planned towards the end of the century. A demonstrator for this circuit, the AHWR (Advanced Heavy Water Reactor), is being designed. The components of the AHWR (300 MWe, service life: 100 years, generation IV type safety) are being tested at several facilities. This reactor could be supplied with various uranium, plutonium and thorium-based fuels.

Finally, and over the longer term, India has projects for liquid metal-cooled high-temperature reactors or molten salt reactors, all supplied with ^{233}U. Moreover, the partitioning, followed by transmutation of minor actinides with FBRs or ADSs (Accelerator-Driven Systems) is being considered.

The implementation of a thorium circuit requires, at each of the three stages, that closed fuel cycles be associated with the reactors, at least for uranium and plutonium at stages 1 and 2 and for thorium and ^{233}U at stages 2 and 3. This implies the reprocessing of the irradiated or spent fuel assemblies from all reactors, whatever the type of fuel or its burn-up. It does not exceed 20 GWd/t for PHWR fuel. For the moment, high-level reprocessing waste management involves conventional vitrification of Purex process raffinates after partitioning of several fission products.

There are two major Indian nuclear energy research centres, IGCAR (Indira Gandhi Centre for Atomic Research) in Kalpakkam and BARC (Bhabha Atomic Research Centre) in Trombay. The Board has talked with the authorities and scientists from these centres about several points concerning FBR development and the management of spent fuel from current and future reactors, to ultimate waste disposal. These points reflect the assessments performed by the Board. Non-scientific aspects were not covered.

5.4.1 Fast-neutron reactors

For its studies, research and development, in support of its programme India possesses a fast-neutron reactor, the FBTR (Fast Breeder Test Reactor), supplied by uranium and plutonium carbide, a thermal neutron reactor, Kalimi (AHWR precursor) powered by metal alloy ^{233}U, reprocessing plants, hot cells for examining spent fuel and developing reprocessing procedures and a minor actinide partitioning pilot.

The key stage in the Indian nuclear programme is the implementation of the FBR. A 500 MWe prototype powered with uranium and plutonium MOx and sodium-cooled, the PFBR (Prototype Fast Breeder Reactor), should diverge in 2014 (Kalpakkam). It will be followed by two FBRs of same power and same design (2023) at the same site, then in 2030 by 1,000 MWe FBRs powered with metallic fuel (U, Pu, Zr). With such a fuel, the plutonium doubling rate is 4 times higher than with oxide fuel.[4] ^{233}U production will occur by thorium oxide irradiation in the blankets of these reactors. A reactor of this type is currently being studied. The target combustion rates for the FBRs are in excess of 150 GWd/t.

The irradiation tests for fuels containing uranium, plutonium and thorium (oxide, metal) have been under way for more than 20 years in the FBTR, up to combustion rates of 150 GWd/t.

The Coral facility, combined with the FBTR, allows the irradiated fuel to be examined and this reactor's fuel to be reprocessed. Currently, second generation uranium-plutonium oxide fuel is in the reactor.

5.4.2 Partitioning

The need to rapidly constitute a stock of plutonium to supply the FBRs has led India to rapidly reprocess the spent oxide fuel from PHWRs (Purex process) and it is preparing to do the same for spent FBR fuel. Thus, the FBTR's carbide fuel, burned at 150 GWd/t, is currently reprocessed two years after removal from the reactor in Coral (COmpact Reprocessing of Advanced fuel in Lead cells).

[4] "A conversion factor of 1.6, along with a cooling time of only 3 years are significantly better than the performance that can be achieved with an FNR-Na running on MOx fuel. Such performance could only be achieved in pyrochemical process metal fuel FNRs. Unfortunately, several technological obstacles must be dealt with simultaneously in the reactor and processing fields, not to mention the economic and safety demonstrations" in La lettre de l'Itésé, Issue 19 Summer 2013, page 22.

For the future, India is considering fuel processing one year after removal from the reactor. One aspect of the reprocessing is the extraction of some fission products, in particular Cs and Sr, for industrial applications, particularly irradiations. Currently, the high-level waste resulting from the reprocessing is vitrified in borosilicate glass by the conventional technique and the packages are placed in storage. A cold crucible is in demonstration at Tarapur and will be installed in-line.

A pilot, following on from Coral, is under construction to reprocess the PFBR fuel: DFRP (Demonstration Fast Reactor Processing). This latter provides a foretaste of a vast complex of plants (reprocessing, fuel manufacture, waste management, etc.) to close the cycle of power FBR reactors: the FRFCF (Fast Reactor Fuel Cycle Facility).

India has conducted numerous studies on the use of thorium, in oxide or metallic forms, as a nuclear fuel. Hundreds of oxide assemblies were irradiated in PHWR reactors, along with some in the FBTR blanket, then characterised and reprocessed by modifying the Purex process. The high-level waste is then vitrified. Similarly, the reprocessing procedure for the future AHWR fuel, aimed at retrieving pure ^{233}U, is currently being validated at the laboratory scale. An industrial reprocessing plant is planned (PRTRF – Power Reactor Thoria Reprocessing Facility).

Concerning the FBR cycle, several innovations are currently being studied: production of mixed oxide annular pellets by the conventional powder sintering process, sol-gel process for oxide fuel preparation and vibro-compaction of the resulting microspheres for needle preparation, separation processes for poorly cooled spent fuel, use of iron phosphate glass for improved incorporation of elements contained in FBR Purex raffinates, that differ significantly from those resulting from the reprocessing of PHWRs, or for caesium incorporation.

India is preparing to use metal fuel for its FBRs and to reprocess it by pyrometallurgy in an LiCl-KCl eutectic. A multi-kilogram pilot is in place at Kalpakkam. Waste packaging is under study.

5.4.3 Transmutation

Finally, India is considering transmutating minor actinides. For this purpose, the ASDF (Actinide Separation Demonstration FAcility), in line with the Tarapur reprocessing plant, has been in operation since November 2013. It has a capacity of 30 L/hour and has processed 6 m^3 of very high-level solutions. The process is broken down into three phases: residual uranium and plutonium extraction from Purex, actinide and lanthanide extraction (with ruthenium), followed by partitioning of the two groups. In the second stage, equivalent to the Diamex process, the extractant used is CMPO (first used in the Truex process in the US), then the extractants and chelating agents are the same as those used in France in Sanex. Yields are in excess of 99.5%. The aim is to prepare uranium-minor actinide mixed oxide needles for irradiation in the FBTR. The industrial partitioning of minor actinides is scheduled for 2025 and their transmutation in the FBR blanket for 2050.

S&R on an ADS, a 1 GeV-30 mA linear proton accelerator coupled with a 30 MWth lead-bismuth cooled reactor, are under way at Kolkata, at the VECC (Variable Energy Cyclotron Centre), where there is a 30 MeV variable energy cyclotron.

5.4.4 High-level waste management

India makes a distinction between alpha and non-alpha waste. Tarpur (SSSF – Solid Storage Surveillance Facility) and Kalpakkam (VWSF – Vitrified Waste Storage Facility) possess large storage capacities for vitrified very high-level alpha waste packages. These packages, along with those subsequently produced, are destined for geological disposal in granite, according to the conventional multi-barrier concept. Eventually, and assuming that the minor actinides are transmuted, India would only need to manage waste containing fission products and ^{233}U (and its daughter products), as thorium reactors are very efficient plutonium consumers.

India has prospected the geology of several regions. After having considered basalt, clay and granite, it would appear that the latter type is the only suitable for deep geological disposal, considering India's geological specificities. An operational repository will be required around 2075. Currently, no sites have been identified for in-depth exploration.

Whether for reactor fuel, nuclear materials circulating through the cycle, or high-level waste produced, there are currently no actual data, in public domain literature[5], concerning their characteristics or amounts involved.

5.4.5 Nuclear acceptance in India

The growth of the Indian economy should be very strong in the coming years, thus generating a significant increase in the demand for electricity; as India has no high-quality oil or coal reserves and as renewable energies have suffered from poor development, the nuclear choice was obvious for the authorities. It has been stated that the goal is to reach 9% of electricity production in the very short term and 50% in the long-term.[6] This goal may, however, raise the issue of the acceptability of this option by the population.

On this subject, the director of the Indira Gandhi Centre seemed very optimistic, considering that the population was only directly interested in the jobs created at the centres under construction. Conversely, at the BARC (Bhabha Atomic Research Centre), a more circumspect attitude was observed, along with interest in French experience. The topic of waste disposal reversibility was raised in the French presentation and this concept, along with its associated difficulties generated much interest. More importantly, the effective terms of interaction with the population raised questions: on this point it would appear that the authorities make a distinction between areas "controlled by the government" (sic), where the development of nuclear facilities is not a problem (such as, for example, the vast BARC domain), and regions where the populations could potentially oppose such developments: there are no formal consultative procedures. One specific concern was raised: that preliminary surveys could cause concern to the population, thus preventing project completion.

The Indian authorities are becoming increasingly aware of the need for public support in order to develop nuclear energy.

5.4.6 Conclusion

For the moment, nuclear electricity production in India remains modest. In fact, the use of low-power reactors is intended, in addition to electricity, to produce plutonium for an ambitious ramp-up in nuclear energy by the end of the century, based on an atypical programme aimed at the deployment of a Th-^{233}U circuit. India possesses expertise in moderate heavy water-cooled thermal neutron reactor technology, along with that of sodium-cooled fast-neutron reactors, with closed fuel cycles supplied with natural or slightly enriched uranium and ^{239}Pu-rich plutonium. It produces all the necessary components and fluids. This expertise, in particular the closing of the fuel cycle, opens the route to the reprocessing of spent thorium fuel and the partitioning-transmutation of minor actinides; in this field, it possesses an advance over other countries. Concerning the management of reprocessing waste, India has opted for high-level waste vitrification, a technique suited to the radiochemical nature of the solutions produced by the variants of the Purex process used, which are governed by the reprocessed fuel, the storage of vitrified waste packages and, eventually, their geological disposal. India is progressing slowly in this respect as the need for a repository is far off.

The greater increase in nuclear electricity power in India than allowed by the development of the Thorium programme, is and will be achieved over the coming decades using pressurised water power reactors purchased abroad (cf. Appendix VI, Indian Nuclear Organisation).

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[5] For example, in the proceedings of the latest international conferences: International Conference on Fast Reactors and Fuel Cycles, FR 13, March 4-7, 2013, Paris, France and International THorium Energy Conference, iThEC13, Geneva, Switzerland, October 27-31, 2013.

[6] In 2012, the total installed capacity in India was of 201 MWe, with an average annual growth of 6.9%. In 2012, the nuclear share in electricity production was of 3%.

APPENDIX I

COMPOSITION OF THE NATIONAL ASSESSMENT BOARD

JUNE 2014

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

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

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

Frank DECONINCK, Professor emeritus at Vrije Universiteit Brussel, Honorary Chairman of the Belgian Nuclear Research Centre, SCK•CEN.

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

Hubert DOUBRE*, Professor emeritus, University of Paris XI-Orsay.

Robert GUILLAUMONT – Member of the French Academy of Sciences (chemistry section), Member of the French Academy of Technologies (founding member).

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

Emmanuel LEDOUX, Vice-chairman of the National Assessment Board – Honorary project leader at the Paris school of mines.

Maurice LEROY, Vice-chairman of the National Assessment Board, Vice-chairman of the French federation for chemical sciences, Associate member of the French national academy of pharmacy , Professor emeritus– IPHC, University of Strasbourg.

Jacques PERCEBOIS, Professor, University of Montpellier I, Director of the CREDEN (Centre for economy and energy law research).

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

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

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

* Did not participate in drafting this report

APPENDIX II
GEOTHERMAL ENERGY

NOTE FROM THE BOARD ON THE GEOTHERMAL ENERGY RESOURCE IN THE BURE REGION

ANALYSIS OF THE CONCLUSIONS OF THE GEOWATT AG REPORT

The Board had expressed an opinion concerning the geothermal potential of the Trias in Appendix 3 of its report no. 4 dated June 2010. This opinion analysed Andra's reasoning point by point. Concerning the productivity measures, it noted: "a hole drilled according to good engineering practice... would doubtless enable greater performance levels to be achieved". It also noted that "the most permeable horizons were not necessarily tested". Finally, it observed that the transmissivity values "obtained in the transposition area are within the same range" [as those of the Dogger in the Paris region, where deep geothermal energy is exploited].

Finally, the Board's report noted that the extracted water contains salt, approximately five times more than sea water, thus requiring their re-injection, an operation whose feasibility remains to be demonstrated in a sandstone formation such as the Trias.

The Board concluded:

> *Like Andra, the Board accepts the conclusion that the Trias in the Bure region does not represent an attractive potential geothermal resource under the current technological and economic conditions. This consideration, however, is based more on the low temperatures involved and on the uncertainty concerning the possibility of reinjecting the water than on the productivity of the lower Trias aquifer, that has not as yet been demonstrated to be inferior to that observed at the existing Dogger geothermal facilities at the centre of the Paris Basin.*

The Board maintains this overall assessment, which is not very different from that made by the Geowatt AG agency.

The Geowatt AG study introduces several additional developments discussed below:

- The high salinity of the Triassic aquifer generates technical difficulties that can be overcome by current engineering means. The Board agrees only partially with this point of view. Consequently, the experience feedback from the Dogger geothermal facilities, whose salinity does not however exceed more than some thirty grams per litre, but also from the rock salt dissolution operations, where the brine is practically saturated with salt, clearly shows that salt water circuit corrosion problems can be overcome. The Board once more underlines, however, that there are a number of technical uncertainties concerning the ability to reinject the fluid after cooling in the Triassic sandstone. Tests were conducted in this formation during the early 1980s, in the Orléans region, leading to a rapid and irreversible plugging of the reinjection borehole. The mechanisms responsible for this phenomenon have not been fully elucidated. Studies and research would be required before these mechanisms could be controlled under industrial conditions. Furthermore, because of this difficulty, preference was given to the Dogger geothermal operation. It is less hot as it is less deep, but it presents no major difficulties during reinjection.
- The temperature range identified in the Bure region implies direct use of the hot fluid. The Board supports this remark. Indeed, the water produced is not in the form of steam and it is not economically feasible to convert the energy resource into electricity to enable its long-range transport. The use of water at a temperature of circa 70 °C (extrapolated value at

the base of the Trias) must therefore be considered, with distribution via a heating network with a scope of a few kilometres. This implies the presence of local users whose size is proportional to the extent of the resource. The reality of the geothermal resource, like all mining resources, results from the combination of favourable geological and economic conditions. It is for this reason that the use of deep geothermal energy in France is mainly concentrated in the Paris region, with its population densities allowing the resource to be used to heat large residential buildings. It would be useful to examine whether, within a time span for which a forecast would remain credible, there are, or could be users specifically interested in moving to the vicinity of Zira.

- The Geowatt report mentions the possible availability of geothermal resources outside of the Trias, at more or less superficial depths. The presence of a productive deep reservoir of hot water in the Permian, or in the bedrock under the Trias, can be excluded considering the very low permeability of the geological formations in the vicinity (clay rocks or crystalline and compact metamorphic rocks). The operation of a geothermal resource in this type of environment can be considered as "hot and dry rock" geothermal energy, a concept requiring rock fracturing, which was investigated in the 1980s with limited success. There remains the possibility of a very low temperature resource in the shallow aquifers of the upper Oxfordian or in the Barrois (Tithonian) limestone surface aquifers. This resource, whose use would by definition be highly localised, requiring the use of heat pumps, would not be impeded by the presence of the repository.
- The Geowatt report introduces the notion of underground use conflict by declaring that geological disposal prevents access to geothermal resources in a given region and generates economic losses. The Board's opinion is that this position must be qualified for two reasons.

Firstly, the presence of a repository does indeed prohibit, at least inside a protective perimeter that must be defined, the drilling of deep boreholes that could pass through the waste stock. This presence does not, however, impact the circulation of water in an underlying deep water reservoir such as the Trias. Experience has shown that the area covered by the fluid circulation of a geothermal facility with an economically viable power, is of a few km^2. This area is on the same scale as the Zira, meaning that a protective perimeter encompassing the Zira and including, for example, a one-kilometre strip beyond its limits, would not prevent the circulation of groundwater in this area and would therefore not significantly freeze the amount of energy stored in the Trias. Indeed it would be technically possible should the need arise, even though this solution would probably not be chosen for reasons of simplicity, to mobilise the hot water underneath the repository by means of pumping and reinjection facilities located on the periphery of the protected area. It will be up to Andra to define the scope of the protected area and to the project assessors to validate its relevance. In practice, it is reasonable to assume that virtually all the region would remain accessible for deep geothermal operation should the resource contained in the Trias become attractive.

Secondly, it should be noted that low-temperature hot water (below 150 °C) is a relatively trivial resource. As an example, nuclear power plants produce the majority of electricity consumed in France; however, they only use 40% of the energy contained in the hot water leaving the reactors in the form of steam. The excess heat, which is released to the atmosphere, rivers or sea, constitutes a potential non-negligible resource, with a low marginal cost, though practically unused due to the lack of local consumers. EDF has attempted to attract operators interested by the use of this hot water, but with little success. Hot water, even though it could be precious in the presence of local users specifically interested in this resource, thus possesses a limited value in use and does not represent a national-scale resource. Conflicts between the use of geothermal water with other underground uses must thus be assessed in this context.

In conclusion, the Board's opinion is that the Geowatt AG report does not affect Andra's interpretations and conclusions concerning the lack of an! exceptional geothermal resource in the investigated area. Should it be decided in the future, once any remaining technical problems had been solved, to make use of this source of energy, it could be achieved in accordance with the regulations governing the use of low-temperature geothermal energy[7] (below 150 °C), without the presence of a radioactive waste repository, as currently conceived by Andra, significantly hindering, at the departmental scale, the scope of the hot water resource.

[7] This type of facility is governed by the mining code, which distinguishes high-temperature geothermal energy (>150 °C) whose operation is subject to granting of a concession by the Council of State, as is the case for all mining resources of national interest, and low-temperature geothermal energy (<150 °C), whose use is subject to issuing of an operating permit by the prefect. The geothermal energy in the Meuse-Haute Marne Trias falls into this latter category.

APPENDIX III

ORGANISATIONS HEARD BY THE BOARD

20 November 2013:	Andra – Cigéo project flowchart.
21 November 2013:	CEA – Areva – EDF and Solvay – Cigéo project flowchart.
11 December 2013:	Andra – Scientific, technical and safety stakes of the Cigéo project lines of optimisation.
12 December 2013:	CEA – RNR/GAZ: Allegro – safety and technological obstacles – Overview of waste and inventories for FNR systems.
19 March 2014:	Andra – Operating safety – Evolution of the underground facility and package retrievability – Socioeconomic integration of Cigéo into the territory.
20 March 2014:	CEA – Scenarios – Astrid – Transmutation.
02 April 2014:	Andra – LLLLW Project & Cigéo optimisation: works progress.
03 April 2014:	CNRS & CEA – Upstream research and development.

RESTRICTED HEARINGS

22 January 2014:	Andra – Consequence of a public debate on the studies and research to be conducted in 2014, Cigéo project progress.
23 January 2014:	CEA – CEA's strategy and point of view.
03 April 2014:	Hearing of the High Commissioner for Atomic Energy.
10 April 2014:	Andra – Continuation of the public debate.

BOARD HEARINGS

03 December 2013:	Hearing of a Board delegation by Messrs. Bataille and Namy.
06 March 2014:	Hearing of the Board by the CLIS.
03 April 2014:	Hearing of the Board by the National Assembly Select Committee on the costs of the nuclear industry.

CNE2 VISITS

15 to 23 February 2014:	Study trip to India.
09 April 2014:	Visit to the EPR work site.

APPENDIX IV

LIST OF PERSONS HEARD BY THE BOARD

ANDRA

BUMBIELER Frédéric
BENARD Stéphanie
BOISSIER Fabrice
BOSGIRAUD Jean-Michel
BOURBON Xavier
BRULHET Jacques
BUTEZ Marc
CALSYN Laurent
DEWONCK Sarah
DUMONT Jean-Noël
DUPUIS Didier
DUPUIS Marie-Claude
FARIN Sébastien
GERARD Fanny
GIFFAUT Eric
GIGLEUX Sylvain
HARMAN Alain
HOORELBEKE Jean-Michel
HURET Emilia
KRIEGUER Jean-Marie
LABALETTE Thibaud
LAUMANN François
MARTIN Christelle
MUNIER Isabelle
PLAS Frédéric
RABARDY Myriam
ROBINET Jean-Charles
TALLEC Michèle
VOINIS Sylvie

AREVA

BARTAGNON Olivier
GAGNER Laurent
LEFEVRE Jean-Claude
MAURIN Matthieu
SIDANER Jean-François

CEA

ADVOCAT Thierry
BEHAR Christophe
BERTRAND Frédéric
BOULLIS Bernard
BEJAOUI Syriac
CARRERE Jean-Marie
CHABERT Christine
CHAFFRON Laurent
DELAHAYE Thierry
ESCHBACH Romain
GARNIER Jean-Claude
GAUCHE François
PEYCELON Hugues
POETTE Christian
POINSSOT Christophe
RIMPAULT Gérald
ROCHWERGER Daniel
ROUAULT Jacques

CNRS - IN2P3

BACRI Charles-Olivier
LELIEVRE Tony
MARTINO Jacques
NIKITENKO Sergeï
PELLET-ROSTAING Stéphane
ROUAULT Jacques
THIOLLIERE Nicolas

EDF

BEGUIN Stéphane
MONTCOMBLE Jean-Pierre
PONCET Bernard
SETTIMO David

HC

BRECHET Yves, High Commissioner for Atomic Energy

INERIS

TOULHOAT Pierre

PREFECTURE DE LA MEUSE

DILHAC Isabelle, *Prefect*

MANCHE SUB-PREFECTURE

NESTAR Florus, *Sub-Prefect*

SOLVAY

DELLOYE Thierry

APPENDIX V

LIST OF DOCUMENTS SUBMITTED TO THE BOARD IN 2013-2014

ANDRA

Proposal by Andra to implement the "Pre-Cigéo" expanded waste management programme – 24 October 2013.

Assessment of the influence of vitrified waste source term on radionuclide transfer in the Cavollo-Oxfordian: utilisation of the 2005 files safety calculation results – November 2013.

LLLLW Project – Soulaines community of municipalities – Exploration programme – 22 November 2013.

Radioactive waste: monitoring report – International monitoring of high-level and long-lived waste geological disposal projects, and of the management of radioactive waste – February 2014.

2013-2016 R&D programme – Executive Summary.

Reference document on the behaviour of radionuclides and toxic chemicals in the context of the Cigéo project.

Reference document on the behaviour of LLHLW – LLILW packages – Tome 1 – Spent fuel.

Reference document on the materials used for a long-lived high-level and intermediate-level waste repository – Tome 2: cementitious materials.

Reference document on the behaviour of LLHLW – LLILW packages – Tome 3 – LLILW.

Reference document on the behaviour of LLHLW – LLILW packages – Tome 2 – Vitrified waste.

Reference document on the THM behaviour of formations at the Meuse/Haute-Marne site – Meuse/Haute-Marne Centre.

Meuse/Haute-Marne site reference document – General Presentation.

Meuse/Haute-Marne site reference document – Tome 1 – The Meuse/Haute-Marne site: geological history and current state.

Meuse/Haute-Marne site reference document – Tome 2 – Natural evolution of the Meuse/Haute-Marne site.

Deliberation by the Board of Directors of the Agence Nationale pour la gestion des déchets radioactifs (National radioactive waste management agency) of 5 May 2014 concerning the follow-up to be given to the public debate on the Cigéo project – Text 8 of 118 of the Official Bulletin of 10 May 2014.

HC

Report: "Underground disposal of bituminous waste packages" – CAB/HC – January 2014.

APPENDIX VI

INDIAN NUCLEAR ORGANISATION

Due to its strategic nature, the Indian nuclear programme –both civilian and military– is placed under the Prime Minister's direct responsibility. This latter exercises his authority via the Department of Atomic Energy (DAE), equivalent to a Secretariat of State. The Atomic Energy Commission (AEC), consisting of 12 members, submits proposals for strategic orientations to the Prime Minister and plays an advisory role in nuclear issues. The DAE's secretariat holds the position, ex officio as the chairman of the AEC (currently Dr. R.K. Sinha). The figures given below were obtained from discussions between the Board and the Indian authorities during its study trip.

DEPARTMENT OF ATOMIC ENERGY

The DAE, created in 1954, is in charge of implementing the Indian nuclear programme, under the authority of the Prime Minister. It supervises:

- the major research centres:

- Bhabha Atomic Research Centre (BARC), in Mumbai. This centre is one of the country's leading research centres. It employs more than 15,000 individuals, including 4,200 scientists.
- Indhira Gandhi Centre for Atomic Research (IGCAR), in Kalpakkam, near Madras. This centre, that employs approximately 2,500 individuals (including 1,034 scientists), is specifically in charge of the fast-neutron reactor programme and associated cycle.
- Raja Ramanna Centre for Advanced Technology (RRCAT), in Indore. This centre employs some 560 scientists.
- Atomic Minerals Directorate for Exploration & Research (AMD), in Hyderabad. This centre employs approximately 2,400 individuals (including 1,035 scientists and technicians).
- Variable Energy Cyclotron Centre (VECC), near Calcutta. This centre, that employs approximately 190 scientists, conducts fundamental research in the fields of nuclear physics, particle physics, materials science, etc…

- public companies:

- Nuclear Power Corporation of India Ltd (NPCIL), in Mumbai, in charge of the construction and operation of nuclear electricity reactors other than the fast-neutron reactors.
- Bharatiya Nabhikiya Vidyut Nigam Ltd (BHAVINI), in Kalpakkam, in charge of the construction and future operation of the fast-neutron reactors.
- Uranium Corporation of India Ltd (UCIL), in Jaduguda (Jharkhand State), in charge of uranium mine operation.
- Indian Rare Earths Ltd (IREL), in Mumbai, specialises in the extraction, processing and marketing of heavy metals and rare earths, excluding uranium.
- Electronics Corporation of India Ltd (ECIL), in Hyderabad, possesses a broad range of activities in the instrumentation field, both nuclear and non-nuclear, including in particular reactor monitoring-control.

- Industrial complexes:

- Nuclear Fuel Complex (NFC), in Hyderabad, in charge of uranium conversion and nuclear fuel manufacturing, along with supplying fuel or core structural elements (sheaths, pressure tubes, etc.) made from zirconium allow or stainless steel, along with other special materials with a high degree of atomic purity.
- Heavy Water Board (HWB), whose head offices are in Mumbai, in charge of heavy water production.

- Board of Radiation & Isotopes Technology (BRIT), in Mumbai, whose activities cover, in particular, the production and marketing of radioisotopes, along with the supply of irradiation-related equipment and service.

- training centres:

- BARC Training School (BTS), in Mumbai, though with specialist branches in Indore (RRCAT), Hyderabad (NFC) and Kalpakkam (IGCAR), along with at the electricity production sites.
- Homi Bhabha National Institute, in Mumbai. Created in 2005, this institute possesses the status of "virtual" university and operates in network with the DAE's research centres, or those financially assisted by the DAE.
- National Institute of Science Education and Research (NISER), in Bhubaneshwar. Opened in September 2007, this institute focuses on training in the various technician and engineer trades in the basic disciplines: physics, mathematics, chemistry, mechanical engineering, civil engineering.
- Centre for Excellence in Basic Science (BSC), also in Mumbai. Opened in September 2007, in collaboration with the University of Mumbai, it focuses specifically on the training of future researchers.
- Board of Research in Nuclear Sciences (BRNS), in Mumbai. Also placed under the auspices of the DAE, the BRNS promotes and funds R&D programmes in the various field of interest for this latter, awards grants to researchers and promotes the emergence of excellence.

ATOMIC ENERGY REGULATORY BOARD – AERB (NUCLEAR SAFETY AUTHORITY)

Located in Mumbai, near the BARC, it employs approximately 270 individuals. The Chairman of the AERB reports on its activities to the Chairman of the AEC.

The AERB is financed directly by the Indian Government. Its annual budget is growing significantly. For its regulatory and control activities, the AERB makes free use of the BARC or IGCAR's expertise, along with that of external experts, frequently retired DAE or industrial employees. The Chairman of the AERB is the competent authority defined by legislation and regulations. The organisation regulates nuclear facilities governed by the DAE, but also medical diagnostics and therapy centres, industrial radiography facilities, food industry irradiation facilities, etc. (i.e. several tens of thousands of instruments and hundreds of facilities nationwide). Following the Fukushima accident, the national authorities decided to render the AERB more independent.

- The Safety Research Institute, created in 1999 as part of the AERB and located in Kalpakkam, is a small research structure that employs approximately twenty individuals (one half of whom are PhD students). Its work pertains to nuclear and radiological safety (reliability, probabilistic approach), reactor physics, fire and thermohydraulics issues, along with environmental protection. The purpose of this institute is to develop its expertise, to eventually become the AERB's technical support.

NUCLEAR ELECTRICITY FLEET

a) Fleet in operation

Twenty nuclear reactors are currently in operation, for an installed capacity of 4,780 MWe. The first two Tarapur units are built on American technology (General Electric). The first two Rawatbhata units (Rajasthan) along with the first two Kalpakkam units (Madras) are Canadian CANDU reactors by AECL (the first entirely and the others partially). All the other reactors are Indianised CANDU reactors (so-called "INDU" reactors).

b) Fleet in construction

Six reactors are under construction, for a total installed capacity of 3,400 MWe, including the two sections of the Kudankulam nuclear power plant, based on Russian technology (2 x 1,000 MWe).

To these commercial reactors, we should add the construction of the prototype fast breeder reactor (PFBR, 500 MWe) in Kalpakkam, under the responsibility of the public company BHAVINI.

c) Projects

In addition to the existing sites, the Indian government has selected six new nuclear sites with a total capacity of 32,100 MWe: Jaitapur (6 EPR), Mithi Virdi (6 Westinghouse reactors), Kovvala (6 General Electric reactors), Haripur (6 VVER), Bargi (2 PHWR) and Kumharia (4 PHWR). Foreign technology reactors shall be built at coastal sites (one site per reactor technology).

In the context of the 12th plan, the construction of 14 reactors has been approved in principle, for a total installed capacity of up to 13,900 MWe.

Reactor / Site	Type	Power (MWe)
KKPS 3 / Kudankulam **KKPS 4 / Kudankulam**	VVER	2 x 1000
JAPS 1 / Jaitapur **JAPS 2 / Jaitapur**	EPR	2 x 1650
Mithi Virdi (Gujarat)	AP 1000	2 x 1 000
Kovvala (Andhra Pradesh)	ABWR or ESBWR	2 x 1 400
Bargi (Madhya Pradesh)	PHWR	2 X 700
Kumharia (Haryana)	PHWR	2 X 700
Kalpakkam (Tamil Nadu)	FBR	2 x 500

The Kundankulam sites should house a total of six Russian VVERs, the Jaitapur site will initially house two EPR reactors, followed by four others. The sites intended to receive American reactors (General Electric/Hitachi and Westinghouse/Toshiba) are located in Andhra Pradesh and in Gujarat; they should also each house six reactors. The same applies to Haripur (West Bengal), allocated to Russian reactors, even though in August 2011, the federal authorities announced their decision to cancel this project following the Fukushima accident and the threat posed by such a project on local jobs (agriculture, fishing).

The Indians demand that all reactor construction contracts include the provision of fuel throughout the reactor service life. The Indians own the spent fuel.

THE FUEL CYCLE

The Nuclear Fuel Complex, located in Hyderabad, is in charge of all uranium fuel conversion, manufacturing and assembly operations required by the Indian nuclear programme. It also produces the fuel structural elements, along with certain stainless steel core internal structures for the FBTR and PFBR reactors.

MOx fuel for the PFBR reactor (under construction) is produced at Tarapur. The carbide assembly manufacturing line for the test reactor (FBTR) is located at the BARC.

Reprocessing Site / name	Capacity (tonnes/ year)	Type of fuel processed	Commissioned
Trombay (BARC) / Plutonium Plant	60	research reactors	1964
Tarapur / Prefre 1	50	PHWR	1975
Tarapur / Prefre 1 (extension)	50	PHWR	1990
Tarapur / RoP (extension)	nd	PHWR	
Tarapur	100	PHWR	2010
Kalpakkam Prefre 2	100	PHWR	1997
Kalpakkam Preffre 3A	nd	PHWR	
Kalpakkam / PPF - Coral	nd	FBTR	2003

Waste is managed locally, at each of the operational reactor sites, along with at the BARC and IGCAR research centres.

Gaseous effluent is filtered and released to the atmosphere. Low and intermediate-level liquid waste (short-lived) is chemically processed; the precipitates are packaged in cement into containers, then stored in semi-surface repositories. The same applies for solid waste fitting into this category.

Concerning high-level or long-lived waste, three vitrification facilities are in operation, associated with the Mumbai (BARC), Kalpakkam and Tarapur reprocessing facilities. The Waste Immobilization Plant (WIP), at BARC, started in 2002. An Advanced Vitrification System (AVS) was commissioned at Tarapur in 2007. At the Tarapur site, there is also a centralised storage facility for vitrified waste containers (Solid Storage and Surveillance Facility – SSSF), with a storage capacity of 6,000 containers, i.e. the equivalent of approximately 6,000 tonnes of reprocessed uranium. A similar facility is under construction at Kalpakkam. To date, no site has been pre-selected for the burial of vitrified waste.

APPENDIX VII

INDUSTRIAL SCENARIO

INTRODUCTION

For several years, CEA, EDF and Areva have been studying the possibilities of deploying 4th generation FNR reactors that could, in fine, constitute a fleet of FNRs using fuel requiring only small amounts of uranium. They are also analysing the possibility of combining the deployment of these FNRs with the transmutation (after partitioning, ST strategy) of minor actinides (MAs) of Am alone, in homogeneous or heterogeneous mode. Thus, several scenarios taking into account the theoretical possibility of possessing Pu, along with a few predictable industrial constraints, have been examined in order to guide the progressive implementation of FNR reactors in parallel to the 2nd and 3rd generation PWRs (EPRs). The facilities required to implement the ST strategy are also taken into consideration. Finally, the studies and simulations focused on the possible impacts of ST on waste disposal.

These studies started in 2007. In 2010, CEA submitted to the Board, in accordance with the 2006 act, a progress report on ST feasibility, followed in October 2012 by a comprehensive report in which CEA provided an overview of ST research in relation to FNR deployment limits.

The Board analysed these documents and issued its opinion in its reports of June 2010 and November 2011, 2012 and 2013, along with in its report to the minister of March 2013 (MEDDE). In its ruling of 04 July 2013, the ASN pointed out the lack of benefit of ST relative to geological disposal and its influence on the choice of 4th generation FNR technology. It based this conclusion on the CEA progress report of October 2010.

Since the start of 2013, CEA, EDF and Areva have been continuing their studies to provide more substance to the initial scenarios, to provide certain details and to modify or revise them. These scenarios now take better account of the industrial realities and means likely to be deployed following on from the existing facilities. A steering committee has been set up to coordinate three workgroups, one of which is assigned to examine industrial feasibility. The main objective of the scenarios being studied, however, is the production of electrical energy by optimising Pu and U recycling. The role of ST is not specified and there are not, for the moment, any supplemental ST-related scenario studies, considering that it may only be involved at an advanced stage of FNR deployment and that priority is given to energy production. The study summary report is planned for mid-2015.

The scenarios project energy production very far into the future, significantly beyond once century and, in fact the projection end date remains arbitrary. The exercise takes into account the very long time spans required to make changes in the nuclear industry. Whatever the decisions to bring these scenarios to fruition, they will commit society to nuclear energy for a very long period of time. These scenarios distinguish the successive existence of several fleets corresponding to the search for defined goals. Rather than characterising these states by milestones corresponding to a state of equilibrium as done by CEA, the Board prefers to refer to fleet configurations as it may be possible to switch from one configuration to the next without having reached a milestone.

The simplifying assumptions are as follows: FNRs are FNR-Na reactors of at least 1 GWe that, in the context of generation IV, will be the first to reach industrial maturity. At the start of FNR introduction, these will be Pu iso-generator reactors, then breeder reactors. The PWRs used to replace the current fleet will be generation III facilities, as the EPRs can be MOxed up to 100%. All reactors (PWRs and FNRs) will have a service life of 60 years. The coexistence of FNRs and MOxed PWRs is necessary to ensure the continuity of electricity production at competitive prices. Some quality constraints, in addition to the amount of Pu, must be taken into consideration. Indeed, FNR MOx may be prepared with an isotopic Pu composition containing less ^{239}Pu than PWR MOx. FNR Pu multi-recycling, serving to improve Pu quality, must be implemented. The time between two spent fuel recycling operations is of 5 years.

Four configurations are described, but the switch from one configuration to the next is not defined over time:

- Configuration A: PWR fleet;
- Configuration B: PWR fleet and a few FNRs used to stabilise the stock of spent PWR MOx fuel;
- Configuration C: PWR-FNR fleet used to stabilise the stock of Pu circulating through the cycle;
- Configuration D: FNR or PWR-PWR fleet providing complete independence from natural uranium.

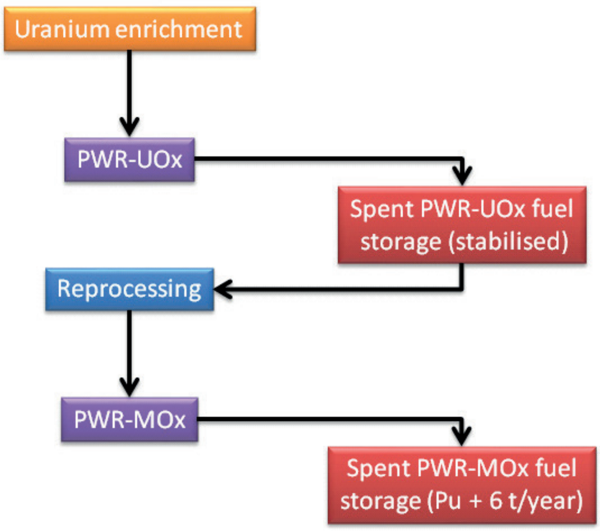
Each configuration is associated with nuclear fuel cycle facilities.

Any decision to move towards commercial iso-generator FNR reactors will first be governed by the success of the Astrid programme as a 4th generation FNR demonstrator. Astrid mobilised numerous industrial partners, in particular concerning the reactor's innovative design. The fuel production workshop, with a modest capacity of 10 tonnes MOx/year, shall be a replica of the Cadarache ATPu, which shall make use of REX from Melox. It will be started up 3 years before reactor commissioning. Its location remains to be determined.

CONFIGURATION A

Currently, the UOx SF from PWRs (Gen. 2) is processed to recycle 10.5 t of Pu in 22 PWRs (Gen. 2) and 600 t RepU in 4 PWRs (Gen. 2) (in the form of 75 tonnes of ERepU) setting aside 120 t of MOx SF (i.e. 6 t of second generation Pu) and 450 t of RepU. For this, 7,600 t of NatU is consumed (along with energy to enrich it).

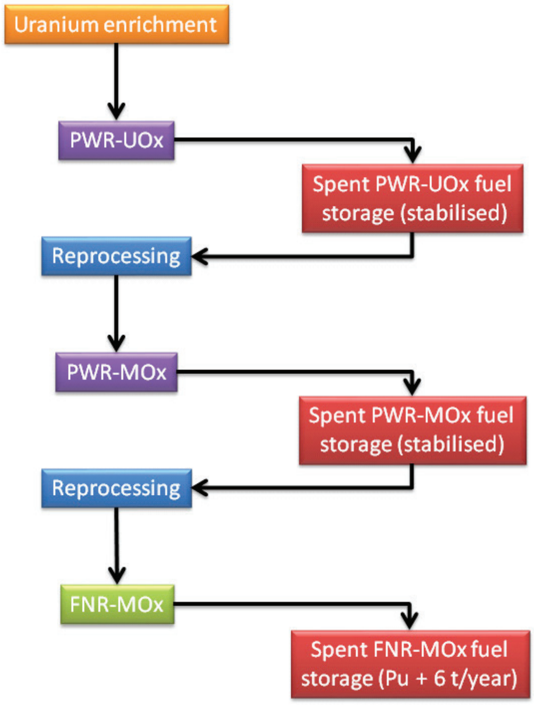
This situation may continue if the UOx SF from the PWRs (Gen. 2) is reprocessed until the closure of the reactors and UOx SF reserves are depleted and if these PWRs are replaced with EPRs that, in fine, will all be MOxed. The SF assemblies from the MOx PWRs (and ERepU PWRs), the only ones remaining, will be stored as the second generation Pu that they contain cannot be used. At this stage, configuration A would consist of 63% UOx EPRs, 29% of 30% MOxed EPRs and 8% of ERepU EPRs.



CONFIGURATION B

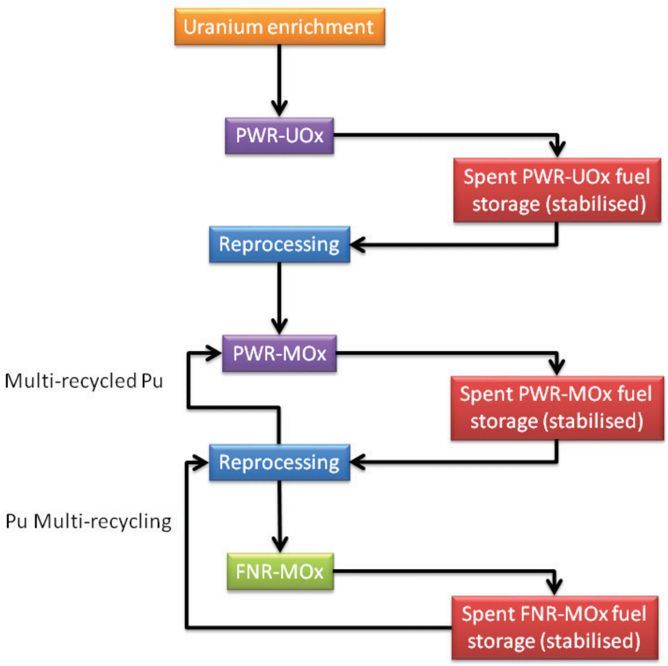
The fleet would consist of 58% of UOx EPRs, 25% of 30% MOxed EPRs, 8% of ERepU PWRs and 8% FNRs.

In this configuration, the spent UOx fuel and MOx in reserve will be reprocessed to obtain first and second generation Pu, this latter used to supply the FNRs. The FNR spent MOx fuel is sent to storage. If the Astrid program leads to commissioning of the reactor in 2025, the first iso-generator FNR could be commissioned around 2050 as approximately 10 years of Astrid operating experience feedback is required to launch the production of industrial FNRs. The time slot for deciding to launch the industrial FNRs will thus be between 2035 and 2040. This will be the first critical decision to be made if we wish to achieve independence relative to natural uranium (Configuration D). The first industrial FNRs would replace the last of the generation II reactors.



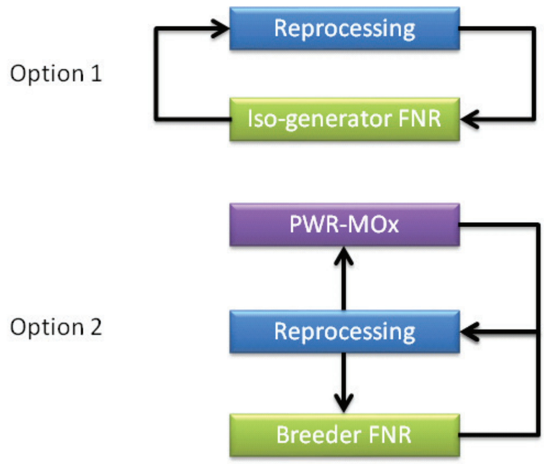
CONFIGURATION C

The third configuration (C), enabling the stabilisation of the Pu inventory, would consist of 5% of UOx EPRs, 49% of 30% MOxed EPRs and 46% of iso-generator FNRs. In addition of the UOx and MOx SF from the EPRs, the FNR MOx SF would need to be reprocessed, then recycled in FNR both to supply the FNRs and to improve the Pu isotopy to supply the EPRs. This isotopy improvement would be accelerated by using breeder FNRs. In this case, recycling will involve third, fourth, etc. generation Pu. This configuration leads to a stabilisation of Pu quantities, whereas the previous configurations lead to a 6 t/yr increase in Pu. This configuration can only be considered once the EPRs built to replace the current fleet require renewing (as of 2065-2085).



CONFIGURATION D

To reach configuration D, corresponding to reactors that no longer require natural uranium and lead to stabilised Pu levels of approximately 1,100 t, configuration C must have been operational for several decades. Such a fleet at equilibrium will only be possible around the middle of the 22nd century. Option 1 assumes a homogeneous fleet of iso-generator FNRs, option 2 allows the simultaneous use of breeder FNRs and PWRs.



CYCLE-RELATED CONSTRAINTS

Beyond the Astrid programme, even when reduced simply to the dimension of nuclear electricity FNR prototype, the industrial configurations are dependent upon PWR and FNR MOx SF reprocessing capacities. In this regard, Areva is studying the implementation, at the head of the current UP2 plant, of a dissolution workshop for assemblies other than UOx, with a capacity of 10 to 30 t MOx/year; this is the only point that needs to be addressed as the UP2 Purex process, modified to conform to criticality rules (Pu/U < 2.45%), is able to process PWR MOx (Pu/u = 5%) as has been widely demonstrated by Areva. These facilities could be used until 2040, or even ten years more. It is only when switching to configuration C that a new plant – UP4 – would be required, moreover integrating processing and production of UOx/MOx fuel, with a capacity of circa 1,000 tonnes/year. A plot is available at La Hague for this plant. None of these data expose a situation that a mature nuclear industry would be unable to control.

No long-term decisions will be made until we have addressed the question of how to burn the Pu should it be necessary to stop nuclear energy production at a given point in time, or at the end of service life of the last stage D reactors. In this respect, CEA is studying the possibility of transforming an innovative 4th generation FNR core into a Capra design core to obtain a modicum of feedback. This requires a research programme lasting approximately thirty years, making use of the Astrid reactor, as a very large number of modifications must be made, both to the reactor, to the fuel assemblies and to the fuel itself (MOx with 30-45% Pu) to ensure safety. Assuming that the FNRs are converted to Pu burners, it would take more than a century to consume the Pu (approximately 1,100 t) with several reactor passes, thus implying the reprocessing of very high Pu content MOx.

The studies conducted by CEA, EDF and Areva, have also looked as the economic from both a theoretical and comparative standpoint. In a situation of reactor industrial productivity, i.e. excluding any leader effects, an FNR would cost approximately 30% more than an EPR.

PARTITIONING-TRANSMUTATION RELATED CONSTRAINTS

It is while configuration C is in place that the transmutation of MAs in general, and of Americium in particular, can be considered, as it will be possible to dedicate FNRs to MA recycling with no impact on energy production. We need to ask the question whether it is worth it, as the later it starts, the more vitrified waste packages there will be, logically destined for geological disposal, resulting from PWR MOx SF reprocessing. The advantage of ST would be all the greater as it would start earlier during configuration C and that the use of FNRs will last a long time.

CONCLUSIONS

Overall, the new studies of scenarios for switching the current fleet of nuclear reactors and associated facilities to a large fleet of FNRs tend to confirm the previous studies and provide additional details. This transition, at constant power and electrical energy produced, could only be achieved through successive changes in nuclear electricity fleet configuration. The operating periods of each configuration, along with the reactor construction rates, remain to be defined. The faultless completion of the Astrid programme constitutes the main limiting step in such a transition; the safety tests and industrial qualifications of this reactor as an iso-generator will last for at least ten years after its construction. Following this, Astrid's reliability as a minor actinide burner or transmuter will need to be demonstrated. The Board has already recommended that this part of the programme should not be overlooked.

Plutonium availability and quality are key elements in stabilising a nuclear electricity fleet comprised of EPRs and FNRs operating independently of natural uranium supply. The spent fuel processing and fuel production capacities must be adapted to cross the fleet modification steps.

APPENDIX VIII

FUEL FOR AMERICIUM TRANSMUTATION

Over the past years, the studies performed on minor actinide (MA) partitioning and transmutation, with a view to reducing the radiotoxicity inventory of nuclear glass packages produced by a future nuclear electricity fleet comprising FNRs, have converged towards americium (Am) transmutation in a fast neutron spectrum. The Astrid programme should be able to demonstrate the feasibility of this by first irradiating a few needles of mixed uranium and americium oxide ($UAmO_2$; 10% Am in depleted U), placed around the periphery of the reactor core, either in a capsule or in an isolated manner (heterogeneous mode transmutation). Under these conditions, the reactor can operate at nominal rate. The aim will then be to irradiate a $UAmO_2$ fuel assembly located on the core blanket. Astrid will then be operating outside nominal rate. This concept of transmutation in Americium-loaded blankets is called CCAm concept (Couvertures Chargées en Américium). It could be industrialised along with the commercial FNRs. For this, the reprocessing and multi-recycling of the $UAmO_2$ fuel would need to be qualified, requiring the experimental scale to be changed.

This Appendix provides an update on the state of S&R into americium transmutation conducted in the context of the Astrid programme. This state has changed relative to that described in the Board's report n°. 4 (June 2010), in particular the milestone dates have been moved.

CEA has developed the EXAm process for the exclusive separation of americium from Purex process raffinates and intends to be able, by 2016, to prepare $UAmO_2$ pellets, requiring the partitioning of approximately 7 grams of Am (^{241}Am 60% + ^{243}Am 40%) contained in 4.5 kg of spent fuel (3 kg UOx and 1.5 MOx, with high combustion rates), preparation of powdered oxide by co-conversion and pellet manufacturing by powder sintering. This goal requires the sequencing of a series of complex operations in Atalante, enabling the performance of a process that prefigures the CCAm fuel preparation process to be tested.

In parallel to obtaining americium, CEA continues to study (using ^{241}Am at the tenth of a gram scale) several methods for preparing UAmO2 ceramics by powder sintering. These may be powders comprised of UO_2 (actually UO_{2+x}) and AmO2 (actually AmO_{2-x}) that are caused to react by sintering, or powders of the mixed oxide itself, in which case conventional sintering is used. The mixed oxide is prepared by three methods: hot reaction between simple oxides, co-conversion of nitric solutions of U and Am via mixed oxalate, or from U and Am-loaded resins. It is always non-stoichiometric, its formula is $U_{1-x}Am_xO_{2\pm\delta}$ with x variable and δ indicating the excess or lack of O^{2-} ions in the fluorine type structure, that depend on the relative degrees of oxidation of U: +4 and +5 and of Am: +3 and +4. Depending on the methods used, the ceramics are always single-phase, though they have different micro-structures and densities, factors governing their alpha irradiation/self-irradiation resistance and whether helium is released or not. For $0.075 < x < 0.7$, they are stable in air (no self-irradiation effect). CEA is also studying the solid solution $U_{1-x}AmxO_{2\pm\delta}$ (structure, density, non-stoichiometry), along with the as yet unknown U/Am/O ternary phase diagram. The thermodynamic properties of Am, such as its volatility according to content and temperature, are studied at the ITU (Institut des transUraniens – TransUranics Institute).

All of these studies constitute the essential initial steps required to optimise the properties of the future fuel. Subsequent or concomitant research will focus on irradiations.

For the past several years, CEA has conducted, either alone or in collaboration, analytical irradiation experiments on $UAmO_2$ samples. The most recent of these is the Marios experiment: dense mini-discs of $U_{0,85}Am_{0,15}O_{2\pm\delta}$ (diameter 5 mm, thickness 1 mm, 92% of theoretical density), prepared by reactive sintering, formed into mini-needles and irradiated in 2011-2012 in the HFR (Nuclear Research Group – NRG – Petten). The Diamino experiment, dense mini-discs of mixed oxide containing 7,5 and 15% Am (97% of theoretical density), prepared by conventional sintering, formed into mini-needles to be irradiated in 2014 and 2015 in Osiris, is being prepared. The irradiated Marios mini-discs are currently undergoing non-destructive post-irradiation examinations in NRG hot cells. The initial results provide information concerning the release of helium and fission gasses according to temperature. The mini-needles shall be transferred to CEA for subsequent examinations and shall *in fine* be analysed by destruction in Atalante after 2015.

CEA is projecting semi-integral experiments to test oxide-can interactions. These are the Marine experiment in HFR, in collaboration with ITU and NRG (irradiation in 2014-2015) and the Moma experiment in the Idaho ATR, in collaboration with the DOE (irradiation in 2017-2019).

The $U_{0,85}Am_{0,15}O_{2\pm\delta}$ sample preparation, irradiation and examination experiments shall span an extensive period of time. They will require at least ten years and will be conducted in collaboration. Each experiment serves to explore the behaviour of several samples under multiple experimental conditions (neutron flow, temperature effects, etc.).

After 2016, the CEA R&D programme on Am partitioning shall continue in several directions: increased Am production in Atalante, large-scale adaptation of the EXAm process (pulsed columns, solvent resistance, industrial reagent synthesis), co-conversion process tests, powder metallurgy technological developments. This programme must be completed in order to prepare partitioning-transmutation industrialisation.

CEA has long studied, frequently in the context of collaborations, the behaviour of other uranium, americium and plutonium-based compounds and of compounds based on other inert elements (in terms of neutrons), candidates for homogeneous mode transmutation in FNR (Superfact experiment initiated before 2000, along with others), or heterogeneous mode transmutation in FNR (on inert matrix target such as MgO) or in ADS (on non-oxide compounds). These are analytical experiments initiated more than ten years previously, to explore a broad spectrum of MA transmutation possibilities, or more recent experiments undertaken in the USA or Japan, for which CEA will have access to the results. The examination of irradiated samples continues and is scheduled to last until 2020, if not later.

APPENDIX IX

UPSTREAM RESEARCH

The upstream research into the choice of structural materials for the future reactors and facilities for the associated cycles, nuclear fuel ceramics, chemical processes for new fuel production and spent fuel reprocessing, along with computation and simulation codes, is performed in France by CEA (for its own account or that of industrialists), CNRS (IN2P3 and INC) and Universities, most frequently in the context of collaborations. It opens the future for nuclear energy in all its dimensions. When combined with education, it serves to maintain skills in support fields for all nuclear disciplines, frequently niche subjects, such as radiochemistry or radiolysis.

Only CEA possesses, with Atalante, the necessary facilities to work on highly radioactive material and to conduct efficient physicochemical measurements on radioactive samples. There are also a number of European programmes providing researchers with access to international collaborations and to other Atalante-like facilities (though in limited numbers), or to large instruments fitted with cells dedicated to radioactive materials.

CNRS, besides its own research into ADSs and molten salt reactors for a thorium circuit, conducted at the IN2P3, has implemented the Interdisciplinary Needs programme (Nuclear, Energy, Environment, Waste and Society) to federate and structure research efforts into nuclear energy. Needs is a reorganisation of the research conducted up to 2012 in research units grouped within the last Pacen programme (CNRS/IN2P3), thus ensuring the continued participation of the academic research world. Needs is co-financed by the CNRS Interdisciplinarity mission, CEA, Andra, Areva, IRSN, EDF and BRGM. There are 7 topics covering all nuclear aspects. Besides nuclear systems and scenarios (topic 1) and materials for nuclear energy (topic 7), presented during the 2013-2014 hearings, Needs also focuses on 5 other topics ranging from uranium mines (resources, mines, processes and economy – topic 2), waste disposal (waste processing and packaging – topic 3) and the study of low-permeability media (disposal material behaviour at various scales – topic 4), but also including the impact of nuclear energy on the environment (topic 5) and the societal aspect of nuclear energy (nuclear, risk and society – topic 6), around which CNRS continues to experience difficulties mobilising the SHS community. All the topics make direct use of modelling and many involve experiments in the presence of ionising radiation, involving radiochemistry in the broad sense of the term (radioelement chemistry and chemistry under ionising radiation). Such a range of topics enables the entire French scientific community and sociologists to present projects and to come together in Workshops. Needs operates on a call for projects basis to ensure that each discipline positions itself relative to the knowledge to acquire or increase. Calls for proposals are well-documented. Needs genuinely started at the beginning of 2013. Approximately one hundred projects were selected and modestly supported over 2 to 3-year periods, as Needs defines itself more as a research catalyst, providing a structure for academic teams and inter-organisation collaborations, than as a project funding system. The Needs geoscience topics, though focused on nuclear applications, also present a certain interest for cover resistance, subsoil management in general, but also fossil energy sources and CO_2 storage.

This year, the Board was informed of research into separative chemistry, conducted in Marcoule, at ICSM and CEA and into actinide chemistry, conducted mainly in Atalante and involved in European Euratom programmes.

The partitioning of elements from spent fuel for various recycling purposes is the central purpose of fuel reprocessing, but also of ore processing and of the nuclear electricity cycle in general. The current French fuel cycle, along with that associated with the FNRs, require so-called "solvent-based" extraction partitioning involving aqueous and organic solid and liquid phases. Only an in-depth understanding of the mechanisms at play will allow process optimisation progress and innovations to be made.

The ICSM is a mixed unit (CNRS, CEA, UM2 and ENSCM) whose programme is the study of phenomena at element extraction system interfaces: solid- liquid (ore leaching, fuel dissolution) and liquid-liquid (U, Pu and MA extraction). These are particularly complex phenomena because, as the element and reagent concentrations increase, the chemical species involved range from molecules to self-assembling molecular systems (colloids, micelles). Research is based on nanometric and mesoscopic modelling by quantum mechanics and static physics, along with experimental measurements (diffusion of X-rays, neutrons and light, microscopy) to analyse interface modifications, the structure of species formed, along with the transfer kinetics of these species between phases. The desire to perform green chemistry, using sonochemistry for example, is constant. Sonochemistry generates high-pressure high-temperature chemistry reminiscent of chemistry under ionising radiation.

Most of the upstream research into liquid-liquid partitioning processes for the downstream of the cycle (Purex, Diamex/Sanex, EXAm, Ganex) are conducted in the Department of radiochemistry and processes (DRP) at CEA (Atalante). This research involves the design of organic molecules for selective actinide extraction (and the non-extraction of fission products) and the study of their suitability for use in highly radioactive environments and in contact with concentrated nitric acid. The aim is also to gain an understanding of the origin of their selectivity, thus naturally leading to the study of the nature of chemical bonds in extracted species or complexes in solution (molecular modelling, structural and spectroscopic measurements) and of the thermodynamics of chemical equilibria. But the aim is also to better understand the extraction mechanisms of the processes that have long been used in the spent fuel reprocessing industry, such as the Purex process. The department possesses "nuclearised" facilities and equipment for conducting this research and for pushing to the process level, thus involving technological research. Analytical chemistry/ radiochemistry possesses a very high potential.

Atalante is also central to fundamental research into actinides in France and Europe. These radioelements, in particular the transuranic elements, are at the core of nuclear energy. Research at Atalante goes well beyond separative chemistry, which is essential molecular or supra-molecular chemistry or solution physicochemistry. It concerns solids and actinide-based materials (co-conversion solids, ceramic production, nuclear glass, etc.), thus covering the entire fuel cycle. Atalante is open to ICSM activities and those of the academic community.

Since 2008, Atalante has been actively involved in the succession of European programmes relating to actinide chemistry, as CEA is the coordinator or a partner. These programmes pertain either to partitioning (Acsept 2009-2013 and now Sacsess), to reprocessing, to safety aspects, or to actinides (Actinet 2004-2012 and currently Talisman). Talisman is a pooling of European infrastructures (laboratories and large instruments) with a training aspect. This aspect supplements the Cinch programme for nuclear chemistry training.

Like CNRS, CEA, Andra and other organisations possess their own research programmes.

In its last report, the Board drew up an overview of research and collaborations on ADS and molten salt reactors, supported in France mainly by CNRS-IN2P3, as shown in the 2012 CEA report. This year, the Board was informed of a few ADS reactor research developments. These are mainly comparisons between FNR and ADS for burning Pu or transmuting MAs. At first glance, ADS reactors display better theoretical performance than FNRs, respectively estimated and 80 and 112 kg/TWhe for Pu and of 5 and 112 kg/TWhe for MAs, but at the cost of predictable major difficulties, both in terms of the components of an ADS (accelerator, spallation target, FNR type reactor with sub-critical core cooled by a molten lead alloy, lead-related corrosion) and of the production and recycling of fuel with a very high Pu content (45%) or MA content (20%) in MOx, CERCER or CERMET. High-power ADS reactors (400 MWth), introduced into a fleet of FNRs or EPRs, would present advantages, in particular by uncoupling energy production from transmutation and by helping absorb the fleet's end-of-life Pu and MAs. As far as can be foreseen, they could be ready by 2080.

APPENDIX X

VARIETIES OF LLLLW

There is a great variety of LLLLW: historical waste (CEA and EDF), along with process and operation waste (Areva). These generally exist in large amounts and their characteristics do not allow them to be accepted at the Soulaines CSA, nor at the Morvilliers CSTFA. At the least, they contain long-lived radionuclides, ^{226}Ra, ^{14}C, ^{36}Cl, which may pose long-term problems in geological disposal as they are difficult to contain. LLLLW is thus characterised by its ^{226}Ra, ^{14}C and ^{36}Cl content, expressed as specific or total activity, whose units are practical for comparisons and for safety analyses, and by their chemical composition, which is an important parameter for potential shallow geological disposal. As a long-term effect, even after disappearance of radiological risk, erosion could bring the waste back to the surface.

RADIFEROUS WASTE

This waste contains daughter radionuclides of ^{238}U, ^{235}U, ^{232}Th, but only ^{226}Ra can raise radioprotection problems.

CEA Itteville near Le Bouchet.

There are 12,000 t of U and Th ore processing residues, along with treatment-associated sedimentation sludge, mixed with earth and rubble, "stored" in pit (90 to 100,000 m^3), also containing VLL waste (28,000 t). These residues contain 4.5 t of U, 13.4 t of Th and 0.8 TBq of ^{226}Ra (58 Bq/g), but also toxic chemicals (tonnes of Pb, U, As and Cr). Measurements are in progress (logging and coring) to better characterise the contents of the pit and to estimate what will be declared as LLLLW (content greater than 10 Bq/g) or VLL waste. LLLLW will be packaged in 15 m^3 metal casks (current option, total volume estimated at 9,600 m^3). Pit recovery is dependent upon the existence of an operational SCR repository, unless the waste needs to be moved to another storage facility for societal reasons.

Areva, (Cezus subsidiary) Jarrie.

The Jarrie plant produces zirconium compounds and, at a first stage, $ZrCl_4$. Until 2013, $ZrCl_4$ was produced from the processing of zircons ($SiO_4Zr_{(1-x)}Hf_x$) obtained from sand imported from Australia. The process used was the plant's main source of residues to date. There are thus 2,730 t of these residues, in 0.2 m^3 drums (0.2 t), stored in a building commissioned in 2005. These residues contain powdered Th, U and Ra compounds (mainly chlorides and some oxides), mixed with sand. They contain varying amounts of heavy metals U (IV) and U(VI), Th and ^{226}Ra (2,000 t with 60 t of U, 9 t of Th and 0.24 TBq of ^{226}Ra at 120 Bq/g and 700 t, with 20 t of U, 1.2 t of Th and 0.02 TBq of ^{226}Ra at 30 Bq/g).

Since 2013, $ZrCl_4$ is prepared from zirconia (ZrO_2) leading to fewer residues: approximately 80 t/year instead of 140 t/year and of a different chemical nature.

The ZrO_2 processing residues should be processed in line from 2014 (announced date) in order to insolubilise the heavy elements by a conventional process leading to the formation of a precipitate of radiferous barium sulphate (SO_4Ba/Ra) and Th and U oxides/hydroxides; the currently stored zircon processing residues will be reprocessed at a rate of 150 t/year. Industrial tests on zircon processing residues, to be reprocessed, have shown that the precipitate, a radiferous barium sulphate (SO_4Ba/Ra), along with Th and U hydroxide, possesses substantially the same specific radium activity (30 to 90 Bq/g) as the residues before processing, but is very poorly leachable (K_d for Ra of circa 10_4 Bq/litre/kg). Once dried, it will constitute the Jarrie plant's future LLLLW. It will be bagged in 200-litre drums. The storage package has not yet been defined.

Areva is not conducting tests on ZrO_2 processing residues.

Solvay Cadarache and La Rochelle.

The La Rochelle plant has had various activities: processing of monazite (phosphate of several rare earths, Th and U) to extract the rare earths and thorium, along with the preparation of various compounds of this element. These processes have led to the generation of several residues.

There are 5,120 t of radiferous barium and Th and U hydroxide, packaged in 25,300 special drums (5,578 m^3) stored at Cadarache, resulting from the rare earths activity, along with 213 t (247 m^3) packaged in 1,000 drums stored at La Rochelle, resulting from the thorium activity. The Cadarache storage contains 1 t of Th, 4.3 t of U and 1 TBq de ^{226}Ra at 200 Bq/g, and that of La Rochelle contains 7.6 t of Th, 0.1 t of U and 0.005 TBq of ^{226}Ra at 23 Bq/g.

These packaged residues are referred to as RAR (radiferous residue) waste by Solvay. They are unambiguously declared as LLLLW. The current packages should be the disposal packages, unless by special request from Andra if all SCR disposal packages were to be standardised. In this case, the re-packaging operations would be performed at La Rochelle.

There are also residues of monazite etching by nitric acid: 8,400 t (7,326 m^3) stored in bulk at La Rochelle. The contain many lanthanide series (Ln) compounds, Na, Ca, Ba, Si, Th, etc., phosphates, sulphates, hydroxides, oxides, etc., approximately 1,000 t of Ln, 31 t of Th, 4 t of U and 0.025 TBq of ^{226}Ra at 3 Bq/g. These residues are referred to as SSR (standardised solid residue) waste by Solvay. It is their U and Th content that prevent them from being integrated into the CSA and CSTFA circuits. They contain less ^{226}Ra than the mining waste residues stored in surface facilities in France (30 Bq/g). Once dried, calcined and packed in drums, they could be sent to an SCR LLLLW repository. They could, however, also be recovered to extract their rare earths, or to be included in a Th recovery programme (Valor Thorium) for which processes have already been defined. The ultimate SSR recovery waste would not, however, be systematically acceptable by the CSTFA. The status of SSR has thus not yet been defined.

At the La Rochelle site, there are non-packaged "thoriferous materials", residues of thorium hydroxide processes, called raw hydroxides (RHTh). After processing to recover the thorium (Valor Thorium), they could give rise to 1,200 t of waste (1,200 m^3) at 130 Bq/g of ^{226}Ra and to 8,200 t of Ra-free hydroxide waste, containing 14 t of Th, packaged in 3 m^3 casks. But these could also be recovered in the Valor Thorium programme. Again, the status of thoriferous materials is thus as yet undefined.

It should be noted that Solvay possesses Th compounds (nitrates and RHTh) containing 6,200 t of Th, along with mixtures of rare earth compounds and Th (SS – suspended solids) containing 4,000 t of Th. These are set aside for recovery (Valor Thorium).

GRAPHITE WASTE

This waste contains, at the least ^{14}C and ^{36}Cl, beta emitters.

Areva, La Hague.

The waste is generated by the reprocessing of fuel from UNGG (and FNR) reactors. It is stored in bulk in silos at La Hague (silos 115 and 130 and decanning workshop settling tanks 1 and 2). It consists of 1,050 t of liners mixed with Mg cans (silos) and 50 t of graphite powder mixed with various mineral and organic components (settling tanks). Their physical recovery, sorting, characterisation and processing, followed by packaging into 10 m^3 packages in cement, is planned before 2030. Considering the radionuclide inventory, in particular Pu and Am (36 TBq for the silos and 600 TBq for the settling tanks), the packages can only be placed in an SCI repository or in Cigéo. Andra has not made any decision concerning package acceptance in Cigéo.

CEA, Marcoule.

The waste comes from the Marcoule UNGG reactors (G1, G2, G3 and EL2 EL3) and those of Chinon (A2, A3). It consists of 3,900 t of stacks still in place in the reactors (105 TBq of ^{14}C, 1.8 TBq of ^{36}Cl, estimated values) and 730 t of cans (5 TBq of ^{14}C, estimated value). More precise radionuclide inventories, in particular for ^{14}C and ^{36}Cl are currently being drawn up via the collection of core samples from the G1 stack channels (programme to be completed by end of 2015). The graphite elements shall be packed into 10 m^3 packages, if the package (common with EDF) is approved by Andra for SCR LLLLW disposal. These operations are scheduled to take place before 2035 for the cans and as soon as a repository is operational for the stacks, but reactor dismantling will take decades.

EDF, Chinon, Saint Laurent, Bugey.

The waste will come from the dismantling of EDF's 6 UNGG reactors, that were decommissioned in 1990, which will be added to the waste stored at Saint Laurent. It will consist of 15,000 t of stacks (0.3 TBq of ^{36}Cl and ^{14}C activity to be defined) and 100 t of ion exchange resins used to process the water from 4 of the 6 reactor vessels. Graphite removal from the reactors will only start in 2025 (Bugey 1) as long as there is an operational repository at this date. At Saint Laurent, there are 2,000 t of liners (5 TBq in ^{36}Cl) contaminated with fission products (4,400 TBq) or even with actinides. Only the stacks and a fraction of the resins that do not contain ^{36}Cl (cationic resins) could be sent to an SCR LLLLW repository; in their current condition, the liners could only be sent to Cigéo. All graphite elements will be locked in cement in 10 m^3 packages currently being jointly designed by Andra and CEA. The packaging of anionic resins is being studied, while the cationic resins should be accepted as CSA. The graphite fuel liners from the Bugey reactors have been disposed of at CSA.

CEA, EDF and other graphite waste producers are studying a graphite heat treatment that would eliminate and trap the volatile radionuclides before combustion generating ash. EDF will build a pilot to assess the benefits of processing the graphite. Such processing would give rise to ultimate LLLLW, whose volume would be compatible with Cigéo disposal. A progress report on this research is required in the context of the PNGMDR in 2015.

BITUMINOUS WASTE

CEA. The waste is generated by the processing of Marcoule effluent, itself arising from irradiated fuel reprocessing operations in UP1. It consists of co-precipitation sludge coated with bitumen and packed in 220-litre drums, whose alpha activity and dose rate preclude its storage at CSA. There are 32,000 drums (alpha activity: 100 TBq, apparent half-life of approximately 300 years). These drums are at Marcoule, stored in the IEP (multi-purpose interim storage) in 380 l overdrums, or as is in hot cells, where they are being recovered for re-packaging. Eventually (2030), they will all be stored in the IEP. They are to be sent to an SCR repository in concrete packages containing 4 overdrums. The total package volume is estimated at 39,000 m^3.

The radiological, radiochemical and chemical characteristics (elements, chelating anions) of each package are determined during the recovery operations, such that the modelling of their SCR disposal behaviour is based on actual data. The activities of the most difficult to contain radionuclides ^{14}C, ^{94}Nb, ^{36}Cl, ^{129}I are limited by maximum values of a few Bq/g, those of ^{99}Tc, ^{63}Ni and 151Sm are measured. These packages contain small quantities of toxic chemicals Pb, Ni, Hg and As, whose potential very long-term toxic impact must be assessed.

OTHER AREVA WASTE

Operating waste in the La Hague workshops has been identified as LLLLW that can be sent to an SCR repository. It represents some 1,500 cylindrical concrete-fibre packages of 1.2 m^3 in which the primary waste packages are cast in concrete-fibre.

The process waste stored at Malvesi is specific in several respects, the quantities are very large, their radiochemical and chemical nature is ill-defined and it shall be stored on-site.

At the Malvesi Comurhex plant, nuclear grade UF_4 is prepared from Yellow Cake (YC), the commercial uranium compound obtained from uranium ore processing. It contains between 30 and 40% miscellaneous impurities (but little radium). The plant stated operations in 1960 and its current capacity is of 14,000 t uranium per year.

The process comprises several steps and produces mainly nitrate-containing liquid effluent (the TC is first dissolved in HNO_3 for U purification by solvent extraction), approximately 4 to 5 m^3 per tonne of uranium, which, after quenching with lime, are "lagooned" in several basins covering an area of 30 ha. Insoluble materials (sludge) are deposited more or less rapidly in the basins, either by settling, or by evaporation. Some basins contain only solid (B1 and B2 for example), while other contain solutions and yet others hold mixtures. Basins B1 and B2 (INB ECRIN – Contained storage of conversion residues) hold 77,000 m^3 of sludge containing U, ^{230}Th and YC impurities (Si, Fe, Na, Ca, V, Mo, etc.), along with artificial radionuclides (^{99}Tc, $^{238/241}$Pu, etc.) generated by UF_4 fabrication from reprocessing uranium for some twenty years after 1960, along with 162,000 m^3 of a mixture of this sludge and earth, covered by 43,000 m^3 of cover material (in total 280,000 m^3, 90 TBq of which 50% due to ^{230}Th and 1% to artificial radionuclides). The specific activity of the sludge is of 490 Bq/g, of which 380 Bq/g is due to alpha emitters. Basins B1 and B2 are no longer used. Basin B3 covers 23,000 m^3 of miscellaneous waste covered with earth (U, Th, ^{226}Ra, 0.075 TBq). Basins B3, B5 and B6 are settling/storage basins and hold 43,000 m^3 of settled sludge containing only natural radioelements (^{234} to ^{238}U, ^{230}Th, ^{226}Ra, 9 TBq, 230 Bq/g of which 160 Bq/g due to alpha emitters). Basins B3 to B6 are ICPE. Basins B1 to B6 are on wasters and sulphur extraction mining residues, of which 300,000 m^3 (out of 1,300,000 m^3) are contaminated by radioactive infiltrations of basins B1 and B2. Basins B7 to B12, also ICPE, are nitrate solution evaporation basins (approximately 320,000 m^3 and 1 TBq, presence of ^{99}Tc) and there is one regulating basin (0.5 TBq) with 80,000 m^3 of settled sludge loaded with toxic chemicals (tonnes of Cd, Cu, Hg and Se).

The current Malvesi waste is diverse, both from a radiological and from a physicochemical standpoint. The specific activity of the sludge is variable (from 500 Bq/g to less than 10 Bq/g) and relatively poorly known. Faced with the enormous quantity of waste, an on-site repository is being considered and it for this reason that the waste is not included in the LLLLW inventory for the SCR repository. An international group of experts examined the possibility of on-site disposal and made its recommendations for research aimed at determining whether it would be feasible. Several repository projects are thus being studied, either on the surface or at shallow depths, of SCR type.

In the context of the PNGMDR, Comurhex must provide studies aimed at providing better waste characterisation, along with their management in the short-term (B1 and B2 under bitumen cover and water treatment plant) and in the long-term (on-site disposal).

Comurhex II will generate slightly different waste to that produced by the current plant, as several process steps have changed. The unavoidable process sludge will be dewatered and placed in covered cells at the locations of basins B3, B5 and B6, subject to a safety analysis. Andra expects 200,000 to 300,000 m^3 of this type of waste by 2050, between 250 and 500 Bq/g and approximately 110,000 m^3 from the future processing of basins B7 to B12, with a specific activity of a few Bq/g.

By 2050, approximately 1 million m^3 of miscellaneous "Malvesi" waste will need to be managed.

ANDRA WASTE

This consists of between a few hundred and a few thousand packages of sealed sources and 17,000 m^3 of Augmented Natural Radioactivity.

APPENDIX XI

RETRIEVABILITY EXAMPLES

During the 1970s, radioactive waste was disposed of in a salt mine in Asse, Germany. This repository did not provide for retrievability. Following the unexpected ingress of brine into the mine, the issue of waste package recovery was raised. The drilling of holes providing access to the abandoned disposal chambers to analyse the atmosphere was very difficult, due in particular to the deformations of the rock massif. Public opinion was divided concerning the solutions to adopt: complete removal, package transfer, reinforcement and containment work. The cost of these solutions is high and their implementation remains to be established. This experience can be interpreted in term of reversibility as we can observe that, as package retrievability had not been prepared, it made situation management, along with the possibility of reversion of the decision problematic.

Germany also has salt mine chemical waste repositories that take packages from throughout Europe. Amongst this waste, is that referred to as C0 in French nomenclature, the most hazardous. These repositories do not include any reversibility measures. A similar repository, called Stocamine, was authorised in France in 1998. It provided for reversibility over a thirty-year period. In 2002, a fire following the deliberate introduction of non-compliant packages, led part of the public to demand that all waste be removed. It rapidly became obvious that this would be difficult as maintaining the conditions that would have allowed this removal had rapidly taken a back seat in the operator's concerns. Following several years of expert assessments and debates, the partial removal of the most hazardous waste was initiated a few months ago.

It should however be noted that removals were effectively performed: at Stocamine in 2001, before the fire, to recover packages containing PCBs, that failed to conform to the authorisation; in a German chemical waste disposal mine (Herfa Neurode), to recover copper; or in the American defence waste repository at the Waste Isolation Pilot Plant, New Mexico, to remove a non-compliant package.

APPENDIX XII

RETRIEVABILITY AND RECOVERY

The notions of reversibility and retrievability of nuclear waste stored in deep geological sites are frequently associated with the recovery of certain elements contained in this waste. Amongst the most frequently cited elements, we can obviously mention those of the so-called strategic metals and, in particular, the rare earths (or lanthanides) and platinoids.

The quantities available for recycling of these elements are assessed for the processing of approximately 1,000 tonnes of spent UOx fuel after being allowed to cool for approximately 10 years.

RARE EARTHS:

There are approximately 16.5 tonnes of rare earths, which, with the exception of terbium, represents less than 1% of national demand. CEA perfectly master the partitioning of rare earths contained in spent fuel; there remains however, that all elements possess radioactive isotopes, giving significant specific activities. Rare earth ores are relatively well-distributed over the planet and their pseudo-shortage results more from the lack of production units than from their actual scarcity. There are thus very few benefits to retrieving them from vitrified packages.

PLATINOIDS:

Palladium, ruthenium and rhodium are present in significant amounts as they respectively represent 25, 45 and 75% of French annual demand. Palladium must be set aside as it contains an isotope, ^{107}Pd, representing 15% of total palladium, and with a half-life of $6x10^6$ years, for an activity of 10^7 Bq/g. Ruthenium, with a production of 3.7 t/year, would be of potential interest after a 20-year cooling period. The same applies to rhodium, representing approximately 750 kg/year, i.e. 3% of worldwide production.

Ruthenium and rhodium, however, are contained in difficult to dissolve metallic precipitates and their chemistry, in particular that of ruthenium, is particularly complex. To date, there are no nitric ruthenium partitioning processes.

Even with advanced partitioning, these elements will contain very low quantities of radioactive isotopes and, to allow their use, they will need to be downgraded, which is not possible according to current French legislation.

In conclusion, retrievability is a technical operation that does not seem to need to be associated with the notion of recovery.

APPENDIX XIII

ORGANISATION OF MANAGEMENT, FUNDING AND PLANNED COST FOR A GEOLOGICAL REPOSITORY IN FRANCE

ORGANISATION IN CHARGE OF RADIOACTIVE WASTE MANAGEMENT

The act of 30 December 1991, updated by the act of 28 June 2006, established and defined the duties of the National radioactive waste management agency (Agence Nationale pour la gestion des Déchets Radioactifs – Andra), a 100% public organisation. Its current duties are:

- to draw up the inventory of radioactive materials and waste in France,
- to collect radioactive objects from individuals and local authorities,
- to manage the radioactive waste produced by the nuclear electricity industry, hospitals, laboratories and universities,
- to look for disposal solutions for all ultimate radioactive waste,
- to operate and monitor disposal centres in a safe manner for mankind and the environment,
- to secure and rehabilitate sites polluted by radioactivity,
- to inform the public concerning its duties and issues and to disseminate scientific culture,
- to disseminate its know-how internationally.

Andra is under the joint supervision of the ministries in charge of energy, research and the environment. The main supervisory duties (as of 30 March 2014) reside with the Ministry of ecology, energy and sustainable development, that defines and implements the orientations in terms of radioactive waste management, in line with the Government's energy policy. The Ministry of national education, higher education and research, via the Research Monitoring Committee on the Back-End of the Nuclear Fuel Cycle (Cosrac) defines and coordinates research into the management of radioactive waste, conducted by the various stakeholders (CEA, Andra, CNRS, Cogema, EDF, Areva and the concerned ministries).

Andra's activities are controlled by the French nuclear safety authority (Autorité de Sûreté Nucléaire – ASN). ASN uses the analyses and advice of the French Institute for Radioprotection and Nuclear Safety (Institut de Radioprotection et de Sûreté Nucléaire – IRSN), that conducts control measurements, amongst others, at nuclear and research sites, along with radioprotection work and training.

Each year, the National Assessment Board (Commission Nationale d'Evaluation – CNE) assesses the progress of research and studies pertaining to the management of radioactive materials and waste. It submits an annual report to the Government and to Parliament, which in turn submits to the French parliamentary office for the evaluation of scientific and technological options (Office parlementaire d'évaluation des choix scientifiques et technologiques – OPECST). The report is then made public.

The environment code gives the following definitions for radioactive waste and disposal:

- radioactive waste is, amongst the radioactive substances, that for which no subsequent use is planned or considered;
- ultimate radioactive waste is radioactive waste than can no longer be processed under the technical and economic conditions of the time, in particular by extraction of their recoverable fraction or by reduction of their pollutant or hazardous nature;
- radioactive waste disposal is an operation that consists in placing these substances in a purpose-built facility to store them potentially definitively;
- radioactive waste disposal in deep geological formation is the disposal of these substance in a purpose-built undergoing facility, in accordance with the principle of reversibility.

FINANCING AND ESTIMATION OF THE COST OF GEOLOGICAL DISPOSAL

The studies pertaining to the Cigéo project are funded by a "research" tax (tax on basic nuclear facilities). During the 2010-2012 period, this tax was of 118 million Euros per year, collected from the three main waste producers: EDF, CEA and Areva.

The construction and operation of Cigéo will be financed by the waste producers via agreements between Andra and the producers. The currently adopted allocation base is as follows: 78% for EDF, 17% for CEA and 5% for Areva.

By law, the producers must set aside the necessary provisions and secure these provisions through State-controlled investments. The producers are responsible for setting the discount rate. The French Court of Auditors cites a rate of approximately 5%, including inflation.

In 2005, Andra estimated the cost of disposal at between 13.5 and 16.5 billion Euros $_{2010}$, spread over more than 100 years, including 40% investments, 40% operation and 20% taxes and other expenses. Before 2015, the Minister in charge of energy will fix the estimated Cigéo cost based on various estimations, opinions and recommendations, including those of an ad hoc workgroup under the supervision of the Directorate General for Energy and Climate (Direction générale de l'énergie et du climat – DGEC).

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