FRENCH NUCLEAR FUEL CYCLE

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1. BACKGROUND

As part of its efforts to help resolve the major climate and energy issues facing future generations over the next decades, France is committed to a global energy transition materialised through the Act of 17 August 2015 on the energy transition for green growth (LTECV). This act defines the main objectives for the medium and long term. Among these objectives, it is worth highlighting:

— Reduction in greenhouse gas emissions by 40% between 1990 and 2030, and a 4-fold reduction in greenhouse gas emissions between 1990 and 2050;
— Development of renewable energy sources to reach 23% of the gross final energy consumption in 2020 and then 32% in 2030;
— Reduction in nuclear energy's contribution to electricity generation to reach 50% by around 2035.

To achieve these objectives, the LTECV Act specifies the definition of a French national strategy to lower carbon emissions (SNBC) and a multi-year energy programme (PPE). The first version of this programme covers the periods 2016 to 2018 and 2018 to 2023. It must be reviewed every 5 years over a 10-year period. The main orientations of this PPE programme for the 2019-2028 period were published by the French government within the scope of a project announced in January 2019; they will be open to public consultation before their adoption scheduled for the end of summer.

1.1. Limiting the fraction of nuclear energy to 50% of the electricity generation.

In an effort to diversify the French energy mix to include a higher fraction of renewable energy sources and staggered investments to renew the fleet (80% of the 63 GWe were built in about ten years), the French government has set the objective of reducing nuclear energy to 50% of the electricity generation by 2035.

For this reason, the French government has planned to shut down 14 reactors by 2035, including the two units at Fessenheim. These shutdowns will be programmed for their 5th ten-yearly inspection outage at their latest, i.e. shutdowns between 2029 and 2035. To balance out these shutdowns over time, two reactors will be shut down pending their 5th ten-yearly inspection outage.

Faced with uncertainty about the choice of technologies making it possible to renew the nuclear fleet beyond 2035 (availability, competitiveness, environmental footprint, social acceptance, etc.), we need to maintain our skills for building new nuclear reactors based on French technology and its industrial capacity.

The French government will continue its preparation with respect to all related financial, organisational, regulatory and legal aspects before deciding whether to launch a programme to build new reactors. The conclusions of this work are expected to be ready around 2021. This programme will also focus on the management of radioactive waste produced by a new fleet of nuclear reactors.

1.2. Maintaining the reprocessing-recycling strategy for spent fuel

The strategy currently deployed in France is based on once-through recycling with the future objective of being able to completely close the fuel cycle by implementing the multiple recycling of spent fuel in sodium-cooled fast reactors (SFR) in the long term. France is currently one of the only countries worldwide that has mastered all of the technologies required for the treatment and recycling of spent fuel thanks to La Hague plants in La Manche department and the Melox facility in the Gard department. These plants currently employ about 10,000 staff.

Once-through recycling leads to 20 to 25% savings in natural uranium (MOx and ERU) thanks to the recycling of reusable radioactive materials (uranium and plutonium), not to mention a 4-fold reduction in the quantity of spent fuel to be stored, and a 3-fold reduction in the total volume of HLLL waste. It also leads to an improved containment of final waste. It therefore offers a number of advantages for the overall energy system and also represents an economic and industrial sector in which France boasts specific skills. For these reasons, it is important to maintain the policy of treating and recycling spent fuel in France.

2. IMPROVING THE SUSTAINABILITY OF FUEL CYCLE MANAGEMENT IN FRANCE: EMPLOYING MOX IN THE 1300 MWE REACTOR SERIES.

The PPE programme confirms that the strategy implemented in France will be pursued for the duration of the programme and up to 2040. For this reason and to compensate for the closure of the 900 MWe reactors fuelled with MOX, **a sufficient number of 1300 MWe reactors could be fuelled with MOX to ensure the sustainability of nuclear fuel cycle management in France. This is a short-term objective (deployment is programmed to start in the late 2020s).**

Beyond this period, the French government together with the nuclear industry will have to review its strategic orientations with respect to the fuel cycle policy and the technical options to be studied in the field of fuel cycle closure based on R&D efforts that will be continued under the PPE programme. France must continue to study all technical options that will allow it to ensure the full closure of the fuel cycle in the long term.

3. CONTINUING R&D ON FUEL CYCLE CLOSURE AND GENERATION-IV REACTORS

Up until now, research has focused on deploying the fourth generation of sodium-cooled fast reactors (SFR). Within the framework of the 2006 Act on radioactive waste management, the conceptual design of an SFR demonstrator - called ASTRID - was launched in 2010. A detailed design phase then followed between 2016 and 2019. As natural uranium resources are currently abundant and available at a low price, at least for the second half of the 21st century, it was decided that a demonstrator and the deployment of SFRs was not necessarily useful at this stage.

The SFR programme is now being reviewed and will aim at resolving the scientific and technical issues identified during the ASTRID programme studies by exploiting the knowledge and skills developed over this period. The project to build a demonstrator has thus been shelved for a later date in preparation for the commercial-scale version of these reactors expected to be built in the second half of this century. This new programme will be focusing on developing numerical simulation capabilities and on implementing a targeted experimental plan.

This new orientation in R&D sets out to consolidate and maintain our skills and knowledge in SFR physics and the related fuel cycle processes. This is a long-term objective.

The level of R&D activities on the SFR fuel cycle is still high, with the development of fuel manufacturing processes using powder metallurgy by relying on past experience and by making any necessary improvements.

This research is equally important to ensure the development of a new head-end industrial pilot at La Hague to treat specific fuels such as those used in experimental reactors or those with high plutonium contents (typically but not limited to, spent fuel from fast reactors and unirradiated manufacturing scrap). This project is currently in its consolidation phase with the basic design phase expected to be launched sometime soon.

A significant part of R&D - deliberately focusing on breakthrough technologies and innovation - also aims at developing advanced processes to prepare for the construction of future fuel treatment and recycling plants for

a nuclear fleet comprising a large proportion of SFRs. These processes will have to be more compact, simple, flexible, reliable and of course safer, while reducing their environmental footprint.

4. INVESTIGATING THE INDUSTRIAL FEASIBILITY OF MULTIPLE RECYCLING IN PWRS

On a shorter time-scale, multiple recycling in pressurised water reactors (PWR) could be used to stabilise our inventory of plutonium in the fleet and spent fuel, which is not the case with once-through recycling currently in place. The feasibility of this type of solution should therefore be investigated.

The question of multiple recycling in PWRs is not a new one as studies were first launched in the late 90s. Irradiated MOX fuel cannot be recycled twice with current MOX fuel technologies due to the isotopic degradation of plutonium; this calls for compensating the drop in reactivity by increasing the plutonium content in new fuel assemblies, but this requires exceeding the current authorised threshold in place for reactor safety reasons. To remedy this problem, it is possible to incorporate the additional fissile material as enriched uranium in the MOX fuel assemblies in which the plutonium content has been kept below the safety threshold.

Studies jointly carried out by the CEA, Orano, Framatome and EDF in 2017 and 2018 show that it is possible to stabilise the energy level of plutonium from a physics viewpoint, thereby authorising multiple recycling and making it possible to achieve the balance needed to stabilise the stockpiles of plutonium and spent fuels (enriched natural uranium, enriched reprocessed uranium, MOX and MOX2) using technologies that currently appear feasible. The validation of the option for a potential industrial deployment, however, necessitate the implementation of major studies and technical assessments to examine the consequences of such a solution from a technico-economic and safety perspective. **Multiple recycling in PWRs is a medium-term objective with industrial commissioning deemed feasible by around 2040**.

The multiple recycling of plutonium in PWRs will require the development of new fuel technologies (MIX and CORAIL). The feasibility of implementing the fuel into reactor requires an in-depth R&D programme and engineering studies. It should also be pointed out that these options generate more minor actinides and burn more plutonium which may, under certain circumstances, contribute to limit the rapid deployment of a fourth generation of nuclear reactors. Additionally, a multiple recycling strategy in PWRs will require the adaptation of fuel cycle infrastructures (adaptation of La Hague and Melox facilities or new specific workshops). From a fuel cycle perspective, some treatment and recycling operations related to these options also represent a number of scientific and technical issues that the SFR fuel cycle is also facing, fostering technological bridges between current and future fuel cycle.

A fully-costed roadmap of the project on multiple recycling, integrating both reactors and related fuel cycle aspects, is currently being drafted. It starts from R&D needs and goes up to potential industrial deployment, by going through industrial qualification steps of fuel behaviour in reactor and fuel cycle technologies. A dedicated R&D programme will make it possible to study and confirm the relevance of the various solutions for reactor safety and performances, potentially different operating conditions, factory manufacturing, transport logistics, irradiated fuel treatment. It will also include an experimental programme in reactor with the irradiation of an experimental fuel assembly sometime between 2025-2028 in view of its potential industrial deployment around 2040.