ANNEX VII.

EVALUATION OF NATIONAL NUCLEAR ENERGY SYSTEMS BASED ON PLUTONIUM CYCLE WITH THE INTRODUCTION OF A NUMBER OF FAST REACTORS

VII-1. INTRODUCTION

This annex compiles the results of relevant French and Russian scenarios for closing the Plutonium cycle with the introduction of a number of fast reactors [VII-1, VII-2].

The studies presented in this annex fall into SYNERGIES Task 1 on Evaluation of synergistic collaborative scenarios of fuel cycle infrastructure development (see Section 2 of the report).

VII-2. OBJECTIVE AND PROBLEM FORMULATION

The objectives of the studies compiled in this annex are to address the problem of SNF accumulation from LWRs and to decrease natural uranium consumption based on possible closed fuel cycle scenarios involving the introduction of a number of fast reactors under development in France and Russia [VII-1, VII-2].

The French EDF study [VII-1] explored different ways of utilizing recovered plutonium in thermal and fast reactors. The current nuclear energy system (NES) in France is based on thermal reactors with uranium fuel and partial-loading of MOX fuel with a single recycling of plutonium. In future cycles, plutonium can come from different sources, but the content of plutonium in fresh light water reactor mixed oxide (LWR-MOX) fuel must remain under 12 % for safety reasons. MOX for sodium cooled fast reactors (SFRs) can be produced from plutonium recycling from its own fuel or from LWR spent fuel. The most effective scenarios are based on deployment of large-scale fast reactors (FRs) utilizing their own plutonium with start up on Plutonium recovered from thermal reactor spent fuel. However, such a scenario relies on a very large deployment of FRs, which may not be possible in the short and medium terms. The EDF study [VII-1] showed that plutonium multirecycling is possible with a symbiotic fleet composed of LWR uranium oxide (LWR-UOX), LWR-MOX and SFRs optimized to reach equilibrium between plutonium consumption and production [VII-5]. This scenario minimized the number of SFRs while maximizing the energy produced with LWRs-MOX using plutonium resources as fuel and are already widely used in the current French fleet. The plutonium produced in UOX-LWRs is used to feed LWR-MOX as in France, and SFRs are used to recycle plutonium from spent LWR-MOX fuel to improve its quality so it can finally be used together with spent UOX fuel to produce fresh LWR-MOX fuel (Fig. VII-1).

In the Russian case study [VII-2] the authors suggested an option for resolving the problem of SNF based on the use of technologies that rely on the BN type reactors and MOX fuel, as already demonstrated in Russia. To a certain extent, the variant proposed is similar to that of France. However, unlike the French variant, Russian one includes the first phase of solving the problem of VVER spent nuclear fuel (SNF) up to 2035, as shown in Fig. VII-2. The infrastructure for the option proposed includes an industrial plant for the acqueous reprocessing of UOX SNF unloaded from VVER and a facility for fabrication of MOX fuel for BN from Pu separated from SNF VVER. At this phase, it is suggested to fabricate MOX

fuel not for recycling in existing VVER, but for a single-run use of plutonium from VVER in the small number of BNs which serve for the utilization of plutonium from SNF of VVER (Fig. VII-2) and could be termed at this phase as “BN-utilizer”.

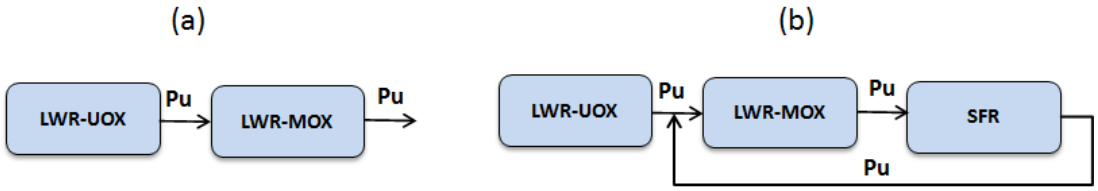

FIG. VII-1 French scenario: (a) First step of transition to sustainable NES based on closed NFC, (b) Second step of transition to sustainable NES based on closed NFC.

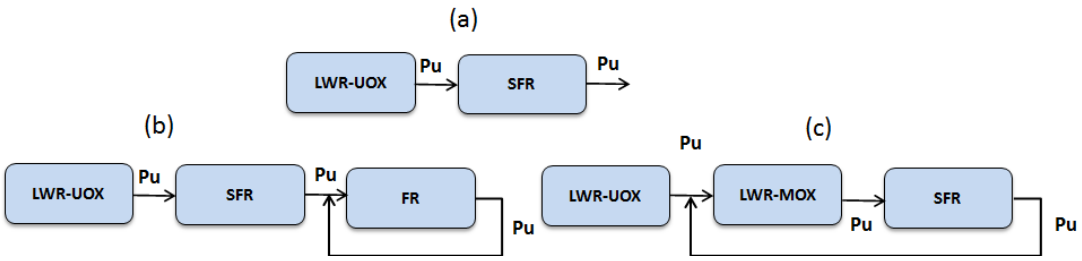

FIG. VII-2 Russian scenario: (a) First step of transition to sustainable NES based on closed NFC , (b) Second step of transition to sustainable NES based on closed NFC in case of high nuclear energy demand , (c) Second step of transition to sustainable NES based on closed NFC in case of nuclear energy demand stabilization.

VII-3. ASSUMPTIONS, METHODS, CODES AND INPUT DATA USED

Three scenarios were explored and compared in the EDF study [VII-1], these being:

— Scenario based on SFRs for replacing ageing LWRs, so that the French fleet is entirely composed of SFRs at the end of the century (scenario S_1);
— Partial SFRs deployment, the French fleet is thus composed of LWRs, loaded either with UOX or MOX fuels, and SFRs (scenario S_2);
— SFR deployment being delayed; advanced LWRs with a high conversion ratio (HCLWRs) allowing to multi-recycle plutonium are deployed as from mid of the century (scenario S_3).

The most relevant scenario is the second, with a limited share of SFR deployment beginning in the medium term with a French fleet composed of LWRs loaded either with UOX or MOX fuels, and SFRs. Scenarios have been computed with the EDF R&D fuel cycle simulation code TIRELIRE- STRATEGIE [VII-6] and optimized to meet constraints imposed on the NES, such as a reprocessing facility that temporarily stores masses of separated plutonium and MA under imposed limits and recycles older assemblies first. Details of reactor characteristics are provided the EDF study [VII-1]. For safety reasons, the Pu content must be kept under 12% in order to keep negative void coefficient. So the quality of the plutonium in LWR-MOX is not enough to be used again in LWR-MOX. No limitation has been considered on the fraction of LWRs fed with MOX fuel. The SFR CFV (non-positive sodium void reactivity effect) core concept used for the study has been developed by the CEA [VII-7]. It uses internal axial breeder zone, upper sodium plenum, upper absorbing zone, small core

height and different heights depending on the radius. This design has been modified to create a 3600 MWth core with a breeding ratio of nearly 1.18.

The Russian case study [VII-2, VII-3, VII-4] assumes a possibility to select, after 2035, one scenario for implementation from three scenarios which depends on macroeconomic situation in the country.

The optimistic scenario supposes an optimistic market forecast for the construction of new NPPs after 2030. The innovative technologies developed in the framework of Federal Target Program "Nuclear Power Technologies of the New Generation for the years 2010-2015 and for the perspective till 2020" (NPTNG) are assumed to be successfully demonstrated by 2035. The MOX SNF from BN (in this case they are not utilizers) reactors will be reprocessed using the closed NFC infrastructure that will be developed for large-scale nuclear power development based on advanced technologies. Plutonium separated from the SNF of the MOX fuel of BN reactors will be used for the fabrication of start-up loadings of the innovative FRs operating within a fully-closed nuclear fuel cycle.

The second scenario also assumes an rather optimistic market forecast for NPP construction after 2035, but takes into consideration that the industrial demonstration of innovative FRs and closed NFC technologies is delayed until the middle of the century. In this case, SNF accumulated from the BNreactors could be reprocessed and the plutonium separated can be used for the fabrication of start-up loadings of the new BN-1200 operating in a fully-closed fuel cycle.

The third pessimistic scenario assumes that there will be no increasing demand in nuclear energy after 2035. In this case, solutions to the problems related to SNF will have to be developed in the framework of the system presented in Fig. VII-1, e.g., via reprocessing of MOX SNF generated by BN-utilizers and organization of multiple recycling of plutonium in the form of MOX fuel, both in BN and in VVER reactors.

VII-4. SUMMARY PRESENTATION AND ANALYSIS OF THE RESULTS

Partial SFR deployment for the EDF scenario resulted in equilibrium with 29.5 GW(e) of LWR-UOX, 14.5 GW(e) of LWR-MOX and 16 GW(e) of SFR.

Annual uranium consumption would be 210 tons/year/GW(e). This indicator shows that scenario S_2 could make better use of its advanced reactors.

The plutonium inventory at equilibrium in S_1 is high – over 1100 tons, which is the plutonium inventory for S_BAU in 2130. Scenarios S_2 and S_3 have also high plutonium inventories of the same magnitude (compared to current inventory) but S_2 has better cycle performance in term of uranium consumption.

Spent fuel reprocessing capacity is driven by the need for plutonium to fuel reactors. At equilibrium, the reprocessing capacity needed by scenarios S_2 and S_3 is roughly the same and is nearly the capacity in mass of the current plant of AREVA NC La Hague. For scenario S_1, the reprocessing capacity needed is half in mass but the plutonium content of spent fuel at equilibrium is 2.5 higher than for other scenarios of plutonium multi-recycling, which will be a challenge for the reprocessing plant.

Current fuel cycles cannot use the plutonium from spent MOX fuel. Therefore, the sub-assemblies of LWR-MOX stay in cooling pools in S_BAU, which increases the capacity needed. All scenarios used plutonium multi-recycling permits to keep spent fuel storage under 19,000 tons, which is consistent with the current French capacity for spent fuel. At equilibrium, the storage needed is low compared to the current state: around 5000 tons for S_2 and S_3 and 2700 tons for S_1. Nevertheless, scenarios S_1 and S_2 have to use sodium cooling pools before spent fuel washing, which is technologically more advanced than current water pools.

As all scenarios assume the same production of electricity, the only difference in the mass of fission products melted in glass canisters is the net yield of the reactors. As the net yield is higher in SFR than in light water reactors (40.3 % versus ~34. %), scenario S_1 produces less fission products than S_2, which produces less fission products than S_3 and S_BAU. The number of glass canisters is roughly proportional to the fission products sent to waste. In 2150, a total of 8150 tons of fission products has been sent to waste through the reprocessing unit for S_1, 8450 tons for S_2 and 8740 for S_3.

Minor actinides (MA) are considered in the scenarios as final waste. At equilibrium, the mass of MA in cycle for scenarios S_1, S_2 and S_3 are low, respectively 14 tons, 22 tons and 27 tons. In 2150, scenario S_3 has a total inventory of MA of 570 tons which is more than a half more than scenario S_1 (370 tons in 2150). Scenarios S_2 and S_BAU produce the same amount of MA (500 tons in 2150). The reason is that the quality of plutonium in fresh LWR fuel is lower than the one of plutonium from LWR-UOX spent fuel and the quality of plutonium in SFR fresh fuel is also decreased by the irradiation in LWR-MOX.

The Russian case study emphasises the need in transition period from NES based on VVER reactors which generates increasing amounts of SNF to the plutonium balanced NES based on VVER/BN reactors. As it was mentioned above, at the very first phase of the transition, BN reactors works as pure utilizers. The number of BN-utilizers is determined from the annual balance of plutonium quantities accumulated in the VVER and the plutonium consumed for the fabrication of MOX fuel for the makeup of BN–utilizer. For example, if we accept the level of Pu accumulation in VVER of about 200 kg Pu/GW(e), and annual consumption of Pu for the manufacturing of MOX fuel for BN-1200 about 1200 kg Pu/GW(e), - this means that for the utilization of Pu received from six VVER, it will be necessary to commission one fast reactor of the same unit power level. Taking into account the additional demand of Pu for the initial loading of BN reactor, the resultant relationship in this NP system in terms of power between the VVER reactors and BN-utilizers may be defined in the range from 7 to 9. That is, if we have in the NP system about 10 per cent of power on the BN-utilizers, a complete utilization of plutonium from the SNF originating from VVER will become possible.

For this first phase comissioning of BN to NES aimed at solving the problem of accumulated SNF fuel it will be not necessary to construct the elements of infrastructure associated with reprocessing of SNF from BN reactors. The NES at this phase could include:

- a plant for the aqueous technology of reprocessing the SNF from VVER, with capacity depending on total power of the VVER fleet;
- a production line for the fabrication of MOX fuel for BN reactors from plutonium separated from VVERs; and,
- 4-6 units of BN-1200-utilizers to consume all plutonium from the VVER fleet by 2035.

The share of fast reactors after 2035 when the problem of the VVER SNF is mainly solved depends on specific situation on nuclear energy demand. For the case of nuclear energy demand stabilization, when plutonium production and consumption is balanced, the share of VVER UOX is 37%, the share of VVER-MOX with 43% of MOX fuel is 27%, the share of BN reactors is 36%. It is different, but not drastically, from the French case (49%/24%/27%).

VII-5. CONCLUSIONS

The EDF scenarios have considered different ways of plutonium utilization from spent MOX fuel, which is not possible in the current fuel cycle. They help to decrease natural consumption. Scenario S_1 is the most efficient but relies on a large scale deployment of SFR, which may not be realistic before 2100. Scenario S_2 permits the optimization of the fleet with less advanced reactors and only one fourth comprised of SFRs. This scenario can reduce natural uranium requirements by half. Scenario S_3 demonstrates how HCLWR can be considered in a closed NFC. This solution might be a more economical way to close the fuel cycle, but the performance of the cycle is low compared to Scenarios S_1 and S_2; the reduction of uranium consumption is limited, the plutonium inventory in the cycle is still high, the high level waste production is higher, and the capacity of the reprocessing plant would have to be very high.

The Russian study explored the idea of using the demonstrated technologies associated with BN type reactors and MOX fuel to resolve the pressing problems related to the accumulation of SNF from VVER. The authors of the study emphasise the need in transition phase approximately to 2035 to privide construction of small series of fast reactors and to start radical solving of SNF accumulation problem. It is proposed to build at this phase the facilities for reprocessing of SNF from VVER and for fabrication of MOX fuel, as well as several power units of BN-1200 up to 10% of overall nuclear power capacity. This option would allow to create preconditions for further recycling of MOX fuel for complete and efficient resolution of the problems of SNF from VVER, with decreasing storage capacity and minimization accumulation of radiotoxic Am-241 during VVER SNF storage. Moreover, in contrast with existing options (SNF disposal or MOX recycling in LWR), the proposed option would preserve all plutonium accumulated in VVERs in a consolidated form (SNF MOX BN) as a startup resource for potential large-scale deployment of advanced or innovative FR and CNFC technologies currently under development or large-scale deployment based on BN technologies in case of high nuclear energy demand. In case of stabilization of nuclear energy demand , plutonium from SNF MOX BN could be recycled as MOX fuel (30-40% of core) in current advanced VVER reactors followed by multirecycling in existing BN reactors.

REFERENCES TO ANNEX VII

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