Remix NFC: options, timeframe, technical and economic assessment of efficiency

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Abstract. REMIX conception is one of the advance option of NFC for LWR SNF management for U&Pu multyreycling in existing NPP fleet, which suppose more efficient usage of natural resource and energetic potential in SNF, provide non-accumulation SNF. Three experimental REMIX fuel assemblies, (FA) containing 18 REMIX-fuel elements have been manufactured. Since 2016, they are being irradiated at Balakovo NPP. In parallel, ampules for FA irradiation in MIR research reactor and post-irradiation investigations were manufactured – some of them have already been removed and are being investigated. The next stage is to have references in the full-scale FAs fabrication and irradiation. In 2018 there was the start of the safety case development program for REMIX fuel use in WWER-1000. The program includes the development and validation of computer codes for nuclear and radiation safety demonstration. There are plans for the industrial facility for REMIX-fuel fabrication construction. In 2018 the development of investment justification such facility was initiated.

1. Introduction
Despite that the nuclear power industry has more than 60-year history, the efficient mode of SNF handling has not been implemented yet.

Now, it is accumulated more than 360 th. t. of the SNF in the world and about 10.5 thous.t. of the SNF is produced annually. About 22.5 th. t. of the SNF is accumulated in Russia and 600-700 t. of the SNF is unloaded from reactors every year.

There are three main approaches to the SNF handling:
- open fuel cycle;
- closed fuel cycle;
- delay decision.

Each this approach has its own pro- and contra.

2. Differences of fuel cycle
The Russian Federation declares adherence to the closed nuclear fuel cycle (CNFC) providing reuse of regenerated fissile materials and environmentally safe handling of produced radioactive wastes.

At that, there are different methods of the NFC closing:
- closing within the two-component system which includes thermal and fast neutron reactors;
- closing in the power system consisting of only fast reactors;
- closing in the power system consisting of thermal neutron reactors using the mixed uranium and plutonium fuel (REMX fuel).

Fuel cycle comparison is given in table 1.
Table 1. Comparison of open and closed fuel cycles.

| Open NFC                                                                 | Closed NFC                                                                 |
|------------------------------------------------------------------------|---------------------------------------------------------------------------|
| Requires to arrange the SFA geological repository. The container with SNF is much greater than the volume of the SNF itself | The container with HLW for deep disposal is much smaller (by 5 times) than at SFA disposal. HLW fractionation provides further optimization of RW waste volume for deep disposal. |
| It is difficult to justify safety of the SNF storage during hundred thousands years (complex and expensive conservation solutions should be provided) | HLW radiotoxicity is much more lower: the activity decreases 30 times faster down to level of $U_{nat}$ |
| The power potential of NFM left in the SNF is not used (31.5 GW*h in one SFA) | The fissile (U, Pu) materials contained in the SNF are returned to the fuel cycle (effective use of natural resources, economy of $U_{nat}$) |
| Al fission products are “packed” compactly in the SNF | Different RW are produced at SNF reprocessing which require additional measures for their conditioning |
| It is not necessary to perform difficult radio chemical reprocessing of SNF | Radio chemical reprocessing of SNF is difficult, science-based and potentially dangerous process |
| For SNF, it is necessary to ensure compliance with safeguard the requirements for a long period ( for a million years ) | Susceptibility to the issue of NFM non-proliferation |

Considering the current structure of the reactor park in Russia and in the world and the rate of the fast power industry development, it is a fair assumption to say that:

- the light water thermal neutron reactors will be operated until 2100 at least;
- till 2050, the fast reactors will not have significant influence on the NFC on national basis due to their small number.

Hence, the repeated recycling of REMIX fuel in the thermal reactors will be the most promising problem solution in Russia regarding the accumulated and produced SNF handling within the time span till 2050. Besides, there is no operational fast power reactors abroad today, and the majority of countries are not going to build them. This makes REMIX a rather promising variant of the NFC for foreign markets.

3. REMIX fuel and REMIX NFC
REMIX fuel is a mixture of regenerated uranium and plutonium oxides. REMIX fuel includes all U and Pu, extracted from the SNF and involves partial enrichment of regenerated U and/or addition of enriched natural U. NFC diagram when REMIX is used, is shown in figure 1.
4. Advantages and difficulties of NFC with REMIX fuel implementation

NFC with REMIX fuel has both advantages and difficulties of implementation. The advantages of the NFC with REMIX fuel are the following:

- ensures utilization of regenerated material (U and Pu) power potential in the thermal reactors;
- Helps to safe natural uranium and ERR (~ 25%);
- ensures at least five-time recycling of NM from the SNF, i.e. the reactor can work using the same fuel (with make up by enriched uranium) during the 60-year reactor life time;
- enables complete loading of the WWER reactor core by REMIX fuel;
- will not require great capital expenditures for equipment modernization from energy companies;
- ensures compliance with the requirements of NM non-proliferation – pure plutonium is not extracted.

Difficulties of NFC with REMIX fuel implementation:

- REMIX fuel is more difficult to produce than uranium one (technologically and with regard to radiological safety ensuring);
- it is necessary to implement another procedure of “fresh” fuel handling at the NPP and during transportation.

There are different types of REMIX fuel differing in content of fissile components and makeup composition. The general types (groups) of REMIX fuel are given in table 2.

| Type      | Fuel Composition | Need of reclaimed product enrichment | Makeup composition | Number of recycles | SNF volumetric ratio |
|-----------|------------------|--------------------------------------|--------------------|--------------------|----------------------|
| REMIX A   | 0.5% 239Pu + 3.8% 235U | No                                   | 19.5% 235U         | >5                 | 1.20                 |
| REMIX B   | 3.0% 239Pu + 2.8% 235U | Yes                                  | -                  | 1-2                | 0.20                 |
| REMIX C   | 0.6% 239Pu + 3.4% 235U | Yes                                  | 3.5% 235U          | >5                 | 1.00                 |
| (“mixed”) |                  |                                      |                    |                    |                      |
Technical and economic assessment of REMIX fuel use performed by “Atomproject” JSC [1] and “ITCP Proryv” PE [2] gave the similar results and confirmed availability of economic effect. Key performance indicators of REMIX-NFC are given on figure 2.

![Figure 2. Key performance indicators of REMIX-NFC [1,2].](image)

**5. Progress of works on REMIX-NFC at the present time**

At present time, the State Atomic Energy Corporation “Rosatom” implements the program “Reviewing of REMIX-fuel for arrangement of its promotion to the foreign markets”. The program consists of three projects.

The first project is “Estimated and experimental confirmation of REMIX fuel” including:
- manufacture of experimental fuel elements and mixed experimental fuel assemblies containing REMIX fuel;
- reactor testings of experimental fuel elements in MIR reactor;
- reactor testings of MEFA at the Balakovskaya NPP;
- post-irradiation examinations of experimental fuel elements and MEFA.

Since September of 2016, the reactor testings are performed on the experimental fuel elements in MIR reactor and on the MEFA at the Balakovskaya NPP. The reactors testings will be finished in 2020. The postirradiation examinations will provide the data about condition of the fuel elements with REMIX-fuel at the burn-up range of up to 50 MW hour/kg.

The second project is “Safety justification for pilot operation of the RF core of WWER-1000 type with TVS-2M with REMIX fuel”. The following activity is performed under this project:
- verification of KATRIN-2.5, KASKAD software packages for REMIX,
- calculations for operational safety justification for WWER-1000 core with REMIX

The performed activity will result in the experimental data required for verification of software used for justification of FA working efficiency and safety when using REMIX fuel, in the essential calculations for safety justification, in certification and assurance of six experimental REMIX-FA operation in the operating reactor core of WWER-1000 type.

The third project is “Technology development and justification of REMIX fuel pilot production” including:
- development of technology and REMIX-FA pilot production;
- production of pilot batch consisting of six REMIX-FA for their following irradiation in WWER-1000 reactor;
- maintenance of availability to REMIX-FA industrial production for one WWER-1000 reactor.

Now, the key objective is to gain the benchmark experience of REMIX-FA production and operation resulting in specification of the REMIX-NFC technical and economic features and execution of the founded commercial proposal for the Russian and foreign customers.
The implementation stages of the program “REMIX fuel reviewing” are shown in figure 3.

![Figure 3](image)

**Figure 3.** The implementation stages of the program “REMIX fuel reviewing”.

Among the potential customers of REMIX-NFC, there are all operators of light water NPPs (reactors of WWER, PWR, BWR, APR, EPR types, etc.). About 10 reactors may become the first customers of REMIX-fuel by 2030.

The estimated income from REMIX-NFC supply to one unit with the capacity of ~1000 MW is ~$50 mln. per year.

6. **Conclusion**

The problem of SNF accumulation produced by light-water reactors may be solved by implementation of REMIX-NFC.

REMIX-NFC being the product is the complex service involving SNF reprocessing, uranium and plutonium fuel production out of regenerated materials for utilization in thermal neutron reactors and also minimization of RW volume.

Thus, REMIX-NFC is the unique product which allows the customer to eliminate SNF accumulation.

**References**

[1] 2014 *Feasibility studies “Efficiency of REMIX technologies in the nuclear power system with the closed NFC”* (Atomproject JSC)

[2] 2016 *Report about R&D “System research of the technical and economic parameters of the NFC with REMIX fuel”*. (ITCP Proryv PE)