**TECHNOLOGICAL SUPPORT**

**OF THE NON-PROLIFERATION**

**FOR SVBR-100 FUEL CYCLES**

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**Abstract**

One of the conditions for the large-scale development of nuclear power (NP) in the world energy mix is the solution of the problem of non-proliferation of nuclear fissile materials.

To solve this problem, both institutional measures (e.g. the country's membership in the IAEA, joining to the Treaty on the Non-Proliferation of Nuclear Weapons, IAEA inspection activities) and technological support measures (e.g. restrictions on the use of highly enriched uranium for the production of fresh fuel, lack of partial refueling, etc.) are used.

In the nearest future, unless economically competitive closed nuclear fuel cycle (CNFC) services will be commercially available, nuclear power plants (NPPs) with the SVBR-100 reactor are planned to operate in an open nuclear fuel cycle (ONFC) based on spent fuel made of uranium dioxide.

In the longer term, NPPs with the SVBR reactor can operate in various uranium-plutonium closed nuclear fuel cycles: on mixed uranium-plutonium oxide, nitride or carbide fuel; with a start on enriched uranium and a start on mixed uranium-plutonium fuels as a fresh fuels; in the mode of feeding its own spent nuclear fuel (SNF) and SNF of thermal reactors; in the mode of burning out minor actinides.

However, reactors implementing the described fuel cycles, in order to ensure IAEA safeguards, require significant control during their deployment in non-nuclear countries due to the presence of significant quantities of plutonium, americium and neptunium in the fuel of such reactors.

To increase the technological support for non-proliferation of nuclear materials, various ONFCs and CNFCs for SVBR-100 are considered. These fuel cycles deal with nuclear fuel with significant values of heat generation in plutonium and americium as well as nuclear fuel without significant quantities of neptunium in SNF.

## INTRODUCTION

The impact of current industrial human activities on the environment, as a result of which, according to experts, an increase in the share of greenhouse gases in the Earth's atmosphere (mainly CO2), can lead to global negative consequences for life on the planet (an increase in the average temperature of the Earth's surface, an increase in the level of ocean, etc.) [1] and does not correspond to the goals of sustainable development. Many countries are considering the use of energy sources without CO2 emissions - mainly renewable energy sources (RES) based on the use of solar and wind energy - as a socially acceptable means of reducing such negative impact of human industrial activities on the environment, and are also developing plans to significantly reduce CO2 emissions by significantly increasing the share of renewable energy sources for electricity production (the EU, for example, plans to achieve the share of renewable energy sources at the level of 32% by 2030 [2].

Nuclear power plants do not emit CO2 in power generation and therefore could be a way to reduce such emissions on an industrial scale. However, the climate summit in Paris does not consider nuclear energy as an option in solving global problems of reducing the harmful effects of human industrial activity on the environment (nuclear energy currently and in the forecasts of leading experts occupies a modest place in the world energy mix ~ 10% in 2018 and 3-5 % by 2050 [3]). The reasons for this are associated with the limitations and peculiarities of the existing NP, which do not allow the world community to fully consider it as a large-scale energy source of the future. The main limitations of the existing NP are:

* an extensive method of ensuring safety requirements that increase with the development of nuclear power (an increase in the number of safety systems with toughening of safety requirements after each of the severe accidents at nuclear power plants - Three Mile Island, Chernobyl, Fukushima);
* the associated increase in capital expenditures for the construction of nuclear power plants and the subsequent decrease in competitiveness, especially noticeable against the background of traditional thermal power plants using coal and natural gas;
* the unsolved problem of long-term handling of irradiated nuclear fuel and the associated low efficiency of using the energy potential of natural uranium (several percent of uranium nuclei are used in the ONFC);
* the need to ensure the regime of non-proliferation of nuclear materials (NM).

Overcoming the first three of these limitations of nuclear power is possible on the way of developing and introducing next generation reactor technologies that will ensure high safety, economic competitiveness, and a solution to the problem of spent nuclear fuel management and limited uranium reserves [4]. The SVBR-100 technology can be considered as one of the reactor technologies capable of realizing the advantages of next-generation technologies [5].

However, reactors that can be located in non-nuclear states require significant control in order to ensure IAEA safeguards due to the presence of significant amounts of plutonium, americium and neptunium in the fuel of such reactors (for ONFC, such amounts may also be contained in SNF). Taking into account the fact that a complete solution to the problem of ensuring the nuclear non-proliferation regime based only on technological solutions for the reactor is apparently difficult to implement, it is necessary to use both institutional measures (the country's membership in the IAEA, joining to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), comprehensive agreement on safeguards and subsequent IAEA inspection activities to monitor NPT implementation) and technological support measures (for example, restrictions on the use of highly enriched uranium for the production of fresh fuel, the absence of partial refuelling, etc.).

Possible measures of technological support for the nuclear material non-proliferation are determined by the peculiarity of a specific reactor technology and the fuel cycle adopted for it. In the short term, before the creation of a commercially available and economically competitive closed nuclear fuel cycle, NPPs with the SVBR-100 reactor are planned to operate in ONFC with uranium dioxide fuel. For such an SVBR-100 fuel cycle, technological support measures for the non-proliferation regime are [5]:

* the use of uranium with an enrichment of less than 20% for the fresh fuel production;
* a relatively long core lifetime (about 6-7 years) without partial refuelling;
* dense layout of the core and lack of space for unauthorized irradiation of nuclear materials;
* 30 days cooling time to hold spent nuclear fuel in the reactor before refuelling, as well as necessity to remove the massive reactor lid and use specialized equipment for refuelling.

In the longer term, it is possible to use various uranium-plutonium closed nuclear fuel cycle: on mixed uranium-plutonium oxide, nitride or carbide fuel; with a start on enriched uranium and a start on mixed uranium-plutonium fuel; in the mode of feeding its own SNF and SNF of thermal reactors; CNFC with burning out minor actinides. For such fuel cycles, the use of additional opportunities that appear in the presence of SNF reprocessing and the ability to control the initial nuclide composition of the fuel makes it possible to strengthen the measures of technological support for the NM non-proliferation. To enhance the technological support of the NM non-proliferation, the ONFC and CNFC with significant values of energy release in plutonium and americium and elimination of significant quantities of neptunium in spent nuclear fuel can be considered [6].

SVBR-100 core has a capability of working with various fuel compositions and in various fuel cycles (see, for example, [7]). That makes it possible to implement mentioned above approaches to increasing technological support of the NM non-proliferation.

## TECHNOLOGICAL SUPPORT OF THE NON-PROLIFERATION

According to the approaches outlined in [6], in order to increase the fuel cycle protection against the proliferation of nuclear materials, it is necessary to make the military use of plutonium and americium contained in nuclear fuel as difficult as possible (it is preferable to ensure the impossibility of such use), as well as to exclude the formation of significant amounts of neptunium in spent nuclear fuel. The following threshold values ​​of energy release in plutonium and americium (see Table 1) are proposed as criteria for assessing the complexity of using these nuclear materials, the excess of which does not allow technically to manufacture hypothetical nuclear explosive devices (HNED) on their basis.

TABLE 1. THRESHOLD VALUES OF ENERGY RELEASE (KW) IN PLUTONIUM AND AMERICIUM [6]

|  |  |  |  |
| --- | --- | --- | --- |
| Chemical element;  (weight, kg) | The level of technology for the production of HNED | | |
| Low (ELA-ELH) | Medium (EMA-EMH) | High (EHA-EHH) |
| Pu; (9,2) | 0,12-0,46[[1]](#footnote-1) | 0,24-0,46 | 0,37-0,96 |
| Am; (32) | - | - | 2,4-2,4 |

### 2.1. Open nuclear fuel cycle

At the current stage of nuclear power development, up to the appearance of commercially available services for reprocessing spent nuclear fuel and fabricating fresh nuclear fuel with recycling of uranium, plutonium and minor actinides, NPPs with SVBR-100 are planned to operate in an open nuclear fuel cycle. At the same time, the 235U available in the fuel (about 1,5 t for a fresh core) in the form of oxide fuel with an enrichment of less than 20% (classified by the IAEA as a material for indirect use with a significant amount of 235U equal to 75 kg, [8]) and plutonium in spent nuclear fuel (classified The IAEA, as a material of direct use with a significant amount of Pu equal to 8 kg, [8]) requires the implementation of the above-mentioned institutional control measures as well as technological support for compliance with the NM non-proliferation regime.

In addition to the mentioned above measures to support the NM non-proliferation regime, the energy release in plutonium and americium, which can be extracted from SNF of the SVBR-100 reactor in several types of ONFC (the characteristics of the ONFC are given in Table 2), was assessed (see Figure 1). The calculations were carried out based on the model described in [9].

TABLE 2. CHARACTERISTICS OF ONFC SVBR-100

|  |  |  |  |
| --- | --- | --- | --- |
| Fuel Cycle Parameters | Nuclear Fuel Cycle | | |
| ONFC-UO2 | ONFC -RUOX1 | ONFC -RUOX2 |
| Fuel type |  |  |  |
| Uranium content | Uranium with an average enrichment of 235U ~ 16.7% | Uranium with an average enrichment of 235U ~ 17,6% | Uranium with an average enrichment of 235U ~ 16.7% |
| Core Lifetime, full power hours | 50000 | 50000 | 50000 |
| - | 1,089 – 1,026 | 1,123 – 1,026 | 1,10 – 1,026 |
| - | 1,19 – 1,26 | 1,22 – 1,22 | 1,22 – 1,25 |
| Fresh nuclear fuel production | Enrichment of natural uranium | Uranium re-enrichment from VVER SNF[[2]](#footnote-2), the ratio of enrichment increments of 235U and 236U is assumed to be 4/3 [6] | Uranium re-enrichment from SVBR-100 SNF (ONFC-UO2), the ratio of enrichment increments of 235U and 236U is assumed to be 4/3 [6] |



FIG. 1 Energy release in plutonium and americium separated from SNF of the SVBR-100 reactor at the ONFC in relation to the threshold values of energy release (see Table 1)

Neptunium accumulated in spent nuclear fuel and having a critical mass of about 45 kg [6] also requires technological support for the non-proliferation regime. At the same time, there is practically no energy release in neptunium accumulated in spent nuclear fuel, which does not allow using energy release as a measure of technological support for the non-proliferation regime. Table 3 shows the total amounts of neptunium accumulated in the SNF of SVBR-100 operating in the ONFC.

TABLE 3. TOTAL QUANTITIES OF NEPTUNIUM (KG) ACCUMULATED IN SNF SVBR-100 OF ONE LOAD IN THE ONFC

|  |  |  |
| --- | --- | --- |
| Fuel Cycle (see table 2) | | |
| ONFC-UO2 | ONFC-RUOX1 | ONFC-RUOX2 |
| 7,6 | 76,3 | 37,1 |

The results obtained show that the energy release of americium in SNF SVBR-100 in the considered ONFC does not allow using it for the production of nuclear weapons even with a high level of development of technologies for their production (the energy release significantly exceeds the threshold value of EHH Am, see Table 1). The production of neptunium does not allow it to be used to produce nuclear weapons in the ONFC-UO2 and the ONFC-RUOX2 (the mass of the produced neptunium is less than 45 kg). As for the plutonium accumulated in the SNF of the considered ONFC, the use of oxide fuel based on re-enriched uranium from SNF VVER or SVBR-100 makes it possible to achieve only the initial level of technological support for the non-proliferation regime (at the level of threshold values ​​of the Pu ELA energy release, see Table 1).

### 2.2. Closed nuclear fuel cycle

Due to the used neutron spectrum (typical for fast neutron reactors), the SVBR-100 reactor plant can operate in various fuel cycles and with various types of fuels with recycling of uranium, plutonium and minor actinides [7]. To analyse the level of technological support for the non-proliferation regime during the operation of SVBR-100 in a closed nuclear fuel cycle, the characteristics of several types of closed nuclear fuel cycle were considered (see Table 4). The calculation results are presented in Figure 2 and Table 5.

The results obtained show that the energy release of americium in SNF SVBR-100 in the considered closed nuclear fuel cycles does not allow using it to produce HNEDs even with a high level of development of technologies for their production (the energy release exceeds the threshold value of EHH Am or is at the level of EHH Am, the EHH values ​​are given in table 1). The production of neptunium in the spent nuclear fuel of one core does not allow its use to produce HNEDs (the mass of the produced neptunium is less than 45 kg, see Table 5). As for the plutonium accumulated in the SNF of the considered closed nuclear fuel cycle, for all the considered closed nuclear fuel cycle options, the energy release from a significant amount of plutonium exceeds the threshold energy release level ELA Pu and is at the EMA Pu level (see Table 1), which will probably require special cooling with liquid nitrogen or helium for the production of HNEDs, even in the presence of an medium level of development of technologies for their production.

TABLE 4. CHARACTERISTICS OF CNFC SVBR-100

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Designation | Characteristics | | | | | |
| Fuel Type | Fuel content | Core Lifetime, full power hours | ,% |  | Fresh nuclear fuel production |
| MOX1 | MOX | Equilibrium composition[[3]](#footnote-3) | 50000 | 1 | 1,243 | Pu recycle from SNF SVBR-100 of the previous loading, feed of 238U with natural uranium |
| MOX2 | MOX | Equilibrium composition | 50000 | 1 | 1,238 | Recycle of Pu from SNF SVBR-100 of the previous load, feeding of SNF VVER (in SNF VVER the separation of heavy nuclei and fission products is not performed, removal of volatile and gaseous fission products) |
| MOX3 | MOX | Equilibrium composition | 50000 | 1 | 1,239 | Fuel cycle start-up on re-enriched uranium from SNF SVBR-100 (like the ONFC-RUOX2, see Table 2). Recycle of Pu and U from SNF SVBR-100 of the previous loading, feed of 238U with natural uranium |
| MOX4 | MOX | Equilibrium composition | 50000 | 1 | 1,240 | Fuel cycle start-up on MOX+MA (Pu and U from ONFC-UO2, see Table 2; Am – 4% from SNF VVER). U and Pu recycle from SNF SVBR-100 of the previous loading, feed of 238U with natural uranium |
| dMOX1 | MOX | Equilibrium composition | 50000 | 1 | 1,237 | Fuel cycle start-up on MOX+MA. Pu from SNF VVER, UO2 ONFC (Burnup 50 GWd/t, cooling time - 10 years); depleted U; Am – 4% from SNF VVER, UO2 ONFC). U and Pu recycle from SNF SVBR-100 of the previous loading, feed with depleted uranium (0,2% 235U). |
| dMOX2 | MOX | Equilibrium composition | 50000 | 1 | 1,237 | Fuel cycle start-up on MOX+MA. Pu from SNF PWR, MOX (Burnup 50 GWd/t, cooling time - 10 years); depleted U; Am – 4% from SNF VVER, UO2 ONFC). U and Pu recycle from SNF SVBR-100 of the previous loading, feed with depleted uranium (0,2% 235U). |
| dMOX3 | MOX | Equilibrium composition | 50000 | 1 | 1,240 | Fuel cycle start-up on MOX+MA. Pu from ONFC-UO2 (see Table 2); depleted U; Am – 4% from SNF VVER (UO2 ONFC). U and Pu recycle from SNF SVBR-100 of the previous loading, feed with depleted uranium (0,2% 235U). |

TABLE 5. TOTAL QUANTITIES OF NEPTUNIUM (KG) ACCUMULATED IN SNF SVBR-100 OF ONE LOAD IN THE CNFC

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Fuel Cycle (see table 4) | | | | | | |
| MOX1 | MOX2 | MOX3 | MOX4 | dMOX1 | dMOX2 | dMOX3 |
| 27,7 | 24,1 | 34,0 | 26,1 | 11,4 | 11,8 | 10,7 |



FIG. 2 Energy release in plutonium and americium extracted from SNF of the SVBR-100 reactor at the CNFC in relation to the threshold values of energy release (see Table 1)

The energy release in plutonium obtained in the considered closed nuclear fuel cycle corresponds to the equilibrium composition of the fuel during the recycle of uranium and plutonium from its own SNF. It is known that in fast reactors the proportion of 238Pu in plutonium decreases with increasing fuel burnup (due to the higher ratio of the rates of fission reactions to neutron capture). Therefore, to maintain a high proportion of 238Pu in fresh MOX fuel [6], it is possible to use plutonium from SNF of LWR with a 238Pu fraction of about 7-10% for the MOX fuel production. However, in this case, it is necessary to periodically restore the required proportion of 238Pu to achieve the necessary degree of technological support for the regime of non-proliferation of nuclear materials.

The principal possibility of maintaining a high proportion of 238Pu is confirmed by the results of calculations (see Fig. 3) of getting the stationary mode of closed nuclear fuel cycle using plutonium from SNF LWR operating on MOX fuel (dMOX2 option, see Table 4).



FIG. 3 The energy release in plutonium and americium, as well as the 238Pu fraction in plutonium extracted from SNF of the SVBR-100 reactor at the closed nuclear fuel cycle dMOX2 (see Table 4, threshold values of the energy releases ELA, EMH and EHH - see table 1) as a function of the number of completed core lifetime

In accordance with the results obtained, the use of plutonium from SNF LWR (operating on MOX fuel) to form the initial loading of the core every 5-6 core reloading leads to energy releases in plutonium above or on the order of the threshold value EMA Pu (see Table 1). It means that HNEDs production requires special cooling with liquid nitrogen or helium, even if there is a medium level of development of technologies for their production. At the same time, the energy release in americium remains at a rather high level (slightly less than the threshold value of EHH Am), which also requires special cooling with liquid nitrogen or helium for HNEDs production, even in the presence of an average level of development of technologies for their production.

## CONCLUSION

The characteristics of various fuel cycles of the SVBR-100 reactor plant are considered from the point of view of the degree of technological support for ensuring the regime of non-proliferation of nuclear materials.

For the open nuclear fuel cycle, in addition to the previously mentioned measures of technological support for non-proliferation of nuclear materials (use of uranium with an enrichment of less than 20%, a long campaign of the core without refueling, lack of space in the core for unauthorized irradiation of nuclear materials, the need for cooling spent nuclear fuel in the reactor for 30 days before refueling and the use of specialized refueling equipment), the energy release in plutonium, americium, as well as the amount of neptunium produced in SVBR-100 SNF were estimated:

* the energy release of a significant amount of americium does not allow it to be used for the HNEDs production, even if there is a high level of development of technologies for their production;
* there are variants of fuel cycles in which the mass of the accumulated neptunium also does not allow it to be used for the HNEDs production;
* there are fuel cycle options that make it impossible to use plutonium from SVBR-100 spent nuclear fuel for the HNEDs production in countries with a low level of technology development.

For the closed nuclear fuel cycles, it is also possible to provide a fairly high level of technological support for the nonproliferation regime:

* the energy release of a significant amount of americium in SVBR-100 SNF does not allow it to be used for the HNEDs production, even if there is a high level of development of technologies for their production;
* the production of neptunium in the spent nuclear fuel of one core does not allow it to be used for the HNEDs production;
* the energy release of a significant amount of plutonium from SNF SVBR-100 requires special cooling with liquid nitrogen or helium for the HNEDs production, even if there is an average level of development of technologies for its production.

In general, due to the flexibility of the possible fuel cycles of the SVBR-100 reactor, the technological support of the non-proliferation regime allows us to consider the NPP with the SVBR-100 reactor as a possible energy option for the countries that have joined to the NPT and have comprehensive safeguards agreements.

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1. Here and below in the table: the first figure is the threshold power release for natural air cooling condition (hereinafter ELA); the second number is the threshold energy release for cooling with liquid helium (hereinafter ELH). Threshold values EMA, EMH, EHA and EHH are defined similarly. The accepted definition of different levels of technology (Low, Medium and High ones) is placed in [6]. [↑](#footnote-ref-1)
2. Burnup 50 GWd/t, cooling time - 10 years [↑](#footnote-ref-2)
3. Hereinafter, the steady-state refueling is considered to be a state in which the change in reactivity per core lifetime in two successive reloading is ~ 1% rel. [↑](#footnote-ref-3)