Next generation control rods for fast neutron nuclear reactors

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Abstract. Boron carbide with different boron-10 isotope content is used in the control rods of liquid sodium-cooled fast neutron nuclear reactors as absorbing material. “Trap” type control rods with heterogeneous placement of absorbing (B₄C or Eu₂O₃) and moderating (ZrH₂) materials were developed. These products did not become widely used due to the high activity of europium radioisotopes and the high damageability of boron carbide. This article examines the design of next-generation control rods with boron carbide in the form of large diameter rings, hafnium hydride (HfHₓ, where x = 1.0-1.5) and made from a mixture of europium oxide and cobalt (Eu₂O₃ + Co) for fast neutron reactors. The use of a closed cycle using boron-10 isotopes, as well as spent absorbing kernels from Eu₂O₃+Co as gamma-ray sources is examined. It also deals with the prospects for the use of control rods with dysprosium hafnate (nDy₂O₃+mH₂O₂) for lead-cooled fast reactors type BREST-OD-300.

1. Introduction
So far, both in our country and abroad, sodium-cooled fast neutron reactors (FN-reactors) have been built and continue to be operated in Russia, India, China and Japan. The approaches to the use of absorbing materials of control and safety rods (hereinafter referred to as control rods) in these reactors were similar and based on the peculiarities of the reactor core. [1-3]. To ensure a large reactivity margin with a relatively small number of seats (cells) for the control rods, absorbing materials with high neutron absorption cross-sections in the fast neutron energy spectrum are required. Boron-10 isotopes have the highest absorption efficiency of fast neutrons, together with boron carbide (B₄C, where x = 4-10) with boron enrichment up to 97% by boron-10 isotope when speaking about boron-based materials. Boron carbide may be considered as a homogeneous absorbing material (boron-10 isotopes) and moderating material (carbon atoms and B-11 isotopes). Carbon atoms and boron-11 isotope in the fast neutron spectrum have the role of a moderator and reduce the neutron energy resulting in an increase in the neutron capture rate by boron-10 isotopes. Despite the high radiation damageability of boron carbide, rather low compatibility with structural materials, the high cost of boron with a high content of boron-10 isotopes, all existing sodium-cooled fast neutron reactors use boron carbide of various enrichment by boron-10 isotope (19.8% to 97%) in the control rods [1, 4]. At the same time, Russia has no facilities for boron enrichment with boron-10 isotopes, which makes the operation of BN-800, BN-600 and BOR-60 reactors dependent on foreign supplies.

Europium oxide (Eu₂O₃) and metal matrix europium oxide (Eu₂O₃ + Mo) were also used in the control rods of fast neutron nuclear reactors. [5, 6]. Various matrices, including copper, niobium, nickel, cobalt and others, have been studied and tested. The control rods based on those materials were used in the BOR-60 and BN-600 fast neutron reactors, but due to the high activity of the Eu-152, 154, 155 radionuclides with a long half-life (up to 13 years) accumulating in them, they were replaced with boron carbide.
“Trap” type control rods with heterogeneous placement of absorbing (B₄C or Eu₂O₃) and moderating (ZrH₂) materials were developed. These products did not become widely used due to the high activity of europium radioisotopes and the high damageability of boron carbide.

This article examines the design of next-generation control rods with boron carbide in the form of large diameter rings, hafnium hydride (HfHₓ, where x = 1.0-1.5) and made from a mixture of europium oxide and cobalt (Eu₂O₃ + Co) for FN-reactors. The use of a closed cycle using boron-10 isotopes, as well as spent absorbing kernels from Eu₂O₃ + Co as gamma-ray sources is examined. It also deals with the prospects for the use of control rods with dysprosium hafnate (nDy₂O₃mHfO₂) for lead-cooled fast reactors type BREST-OD-300.

2. Physical efficiency of absorbing materials in the fast neutron spectrum

One of the main requirements for absorbing materials of control rods is their high physical efficiency of neutron absorption and its preservation during the entire life-cycle. Table 1 gives the experimental and calculated results of studies into the physical efficiency of a number of materials at a neutron energy of 0.5 MeV [1].

Table 1. Physical efficiency of absorbing materials in the fast neutron spectrum with an average energy of 0.5 MeV.

| Absorbing material | Physical efficiency, relative units |
|--------------------|-----------------------------------|
| B₄C with natural content of B-10 and B-11 isotopes (19.8% and 80.2%, respectively) | 1.000 |
| B₄C (40% B-10) | 3.093 |
| B₄C (60% B-10) | 4.588 |
| B₄C (80% B-10) | 5.345 |
| B₄C (85% B-10) | 6.747 |
| Eu₂O₃ | 1.459 |
| Eu₂O₃+Co | 1.300 |
| Ta | 0.970 |
| HfHₓ | 5.0 |
| Hf | 0.364 |
| Dy | 0.315 |
| nDy₂O₃mHfO₂ | 0.372 |

* calculated values

Boron-10 isotopes have the highest rate of neutron absorption. With an increase in the nuclear density of boron-10 isotopes (boron enrichment with boron-10 isotope), the physical efficiency of the material increases in almost linear fashion. So, if boron carbide (B₄C) with natural content of boron-10 and boron-11 (19.8% and 80.2%, respectively) is taken as a reference, then boron carbide with boron-10 isotopes enrichment of 95% has its physical efficiency increased by more than 7 times. According to nuclear-physical characteristics, to ensure physical efficiency, along with materials based on boron-10 isotopes, europium and tantalum may also be used in control rods of FN-reactors. Tantalum has comparable efficiency with boron carbide with natural content of boron-10 and boron-11 isotopes, while europium oxide has the efficiency almost one and a half times higher than the reference values. When hydrogen is introduced into hafnium to obtain a homogeneous absorbing and moderating material - hafnium hydride, the physical efficiency of such kernel increases by more than 15 times and becomes comparable to boron carbide with 80% enrichment with boron-10 isotopes.

In other types of fast neutron nuclear reactors, for example, lead-cooled BREST-OD-300, the reactivity margin may not be so large. They may use absorbing materials with relatively low neutron absorption cross-sections as absorbing materials of control rods. According to nuclear-physical
characteristics, it is boron in the form of boron carbide with natural content of boron-10 and boron-11 isotopes, dysprosium (Dy), hafnium (Hf) and even tungsten (W).

3. Control rods with boron carbide
The main characteristics of control rods of fast neutron nuclear reactors are outlined in [1-4, 7-9]. All basic designs of control rods for domestic fast neutron nuclear power reactors (BN-600, BN-800) were initially tested in the experimental reactor BOR-60. Eight design modifications were studied. Sealed absorber elements filled with air and helium were originally used. Depending on the purpose, four or seven absorber elements were used. To reduce the irradiation temperature and prolong the life of the products, later they switched to non-sealed design of absorber elements filled with sodium. When switching to a design with one absorber element with boron carbide pellets of 33 mm in diameter, it was possible to significantly, by more than 20%, increase the physical efficiency of the control rods while maintaining their life. The gap between the pellets and the shell was also filled with sodium and had a permeability assembly to release the accumulating helium and tritium gases from the shell. Europium oxide design, which consisted of seven sealed absorber elements or one sealed annular absorber element of europium oxide with the moderator element of zirconium hydride (ZrH2) in its centerline, worked well as automatic control rods (ACR) and shim rods (SR). The use of “trap rods” allowed for a 15% increase in physical efficiency compared with the design of seven absorber elements with europium oxide.

The existing BN-800 and BN-600 reactors also use designs consisting of seven permeable absorber elements located inside the cover and connected to the head and the bottom fitting (figure 1).

![Figure 1. Design of control rod of BN-600 reactor: 1-head; 2-cover; 3-bottom fitting; 4-absorber elements.](image)

The diameter of the boron carbide pellets is about 20 mm. At the same time, only in the shutdown rods (SDR) of the BN-600 reactor, boron carbide with 80% boron-10 isotopes enrichment is used, other products use boron carbide pellets with natural content of boron-10 and boron-11 isotopes. In the
BN-800 reactor, all rods already contain boron carbide of various enrichment with boron-10 isotopes up to 92%. A single load of boron-10 isotopes in the rods of the BN-800 reactor has been increased many times.

The design of control rods with seven absorber elements has reached its limit in ensuring the main requirement - high physical efficiency. The closeness of boron carbide pellets in them is raised to the limit values and is more than 98% of the theoretical one. But meeting of this requirement resulted in a decrease in the radiation resistance of the absorbing kernel due to the high neutron capture density with nuclear reactions on boron-10 isotopes with the formation of lithium and helium and the release of large amounts of energy (2.78 MeV).

To further enhance the physical efficiency and radiation resistance of the control rods with boron carbide, designs with an absorbing kernel in the form of large diameter rings were proposed and tested in the BOR-60 reactor. Figure 2 shows various cross-sections of similar control rods of the SVBR-100 reactor being currently designed.

![Figure 2](image)

**Figure 2.** Cross-sections of control rods of SVBR-10 reactor (from left to right: design with seven absorber elements, annular design with preservation of B$_4$C load, annular design with increased B$_4$C load).

Physical efficiency of the control rods as a function of thickness of the rings (weight of boron carbide) is given in table 2.

| Parameter                        | Options |
|----------------------------------|---------|
| Number of absorber elements      | a 7  b 1  c 1 |
| Weight of boron carbide, relative units | 1 1 1.35 |
| Physical efficiency, relative units | 1.00 1.05 1.21 |

While maintaining the weight of boron carbide, the physical efficiency of the control rod with rings is 5% higher than that of a design with seven absorber elements. At the same time there is a possibility of increasing the thickness of the rings and the weight of boron carbide at least by 35%, which leads to an increase in physical efficiency by 21%. There are opportunities to reduce the weight of boron carbide, to reduce their closeness and increase their radiation resistance. Both boron carbide rings and its segments may be used. To further improve the reliability of operation of such items, another shell of metal mesh is placed between the outer surface of the rings and the shell. Introduction of an additional element makes it possible to reduce the corrosion of the shell and retain the shape of the absorbing kernel during operation, when it cracks and is fragmented into small pieces. Similar designs with a single absorbing kernel consisting of boron carbide ring of various boron-10 isotopes enrichment with larger diameters are recommended for all control rods for fast neutron nuclear reactors where maximum physical efficiency is required, especially for shutdown rods.
4. Closed cycle in the use of materials with boron-10 isotopes

The shutdown rods (SDR) of FN-reactors use boron carbide with the highest physical efficiency which is achieved by the design of products, a large load of boron carbide with its maximum physical density and maximum nuclear density of boron-10 isotopes. During operation of the reactor shutdown rods are raised above the reactor core. Their life cycle is determined by the radiation resistance of structural materials. The shutdown rods are unloaded from the reactor, when the average burn-up of boron-10 isotopes in boron carbide does not exceed 1-2%.

As a rule, even when 20% of boron-10 isotopes are burned up, the shutdown rods have sufficient physical efficiency and can perform their functions to shut down the reactor. Therefore, the purpose was to develop a technology for refabricating irradiated boron carbide and reusing it in control rods. It was necessary to solve the following problems: to eliminate the dependence on foreign supplies of boron-10 isotopes, to use them more economically, to remove radioactive waste in the form of spent control rods from the NPP spent fuel storage pools.

The Research Institute of Atomic Reactors (Dimitrovgrad) in cooperation with Beloyarsk NPP (Zarechny), Afrikanov Experimental Design Bureau for Mechanical Engineering (N.Novgorod), the Institute of Physics and Energy (Obninsk), TVEL JSC (Moscow), IZOSTER LLC (Yekaterinburg) have successfully achieved these tasks. Figure 3 shows the closed-cycle diagram implemented in the BN-600 and BOR-60 reactors in the use of boron-based materials with a high content of boron-10 isotopes.

In total, the Research Institute of Atomic Reactors manufactured over 20 experimental and operational (with the letter О1) control rods in 2000-2007. The life cycle of the BN-600 reactor rods was increased from 330-420 effective days for regular products manufactured by the Moscow Polymetallic Plant up to 745 effective days [9]. The appearance of the control rod with refabricated boron carbide of the BN-600 reactor is shown in figure 4.
For the first time, a design with one absorbing component instead of two was developed for the BN-600 reactor, which made it possible to increase their physical efficiency by 8% by increasing the weight of boron carbide loading [4]. Today the task is to master the industrial processing of irradiated boron carbide, which will make it possible to dispose of all the control rods of fast neutron reactors that have already been spent or just planned for use.

5. Control rods with hafnium hydride

The use of a homogeneous kernel made from a mixture of absorbing and moderating materials in control rods of fast neutron nuclear reactors was first proposed in the late 1980s, when “trap” type designs with heterogeneous absorbing and moderating elements were developed. High-tech Research Institute of Inorganic Materials (Moscow) manufactured hafnium hydride (HfH₁,₆₅) pellets, which were irradiated in the BOR-60 reactor. The material demonstrated high radiation resistance and the results of research were included in the monograph “Hafnium in Atomic Engineering” [10], which in 1993 was published in Russian, and in 2001 in English in the USA [11]. Later in Japan, computational and experimental studies were carried out under the direction of Professor Kanashi, and it was shown that hafnium hydride already containing 50% of the maximum amount of hydrogen (HHH) in hafnium hydride has a physical efficiency of high-energy neutron absorption equal to boron carbide with 80% enrichment with boron-10 isotopes (figure 5). Moreover, if boron carbide has boron-10 isotopes that burn out and physical efficiency decreases, then for hafnium hydride over 10 years of operation in a JSFR type fast nuclear reactor (Japan), physical efficiency decreases by less than 10%. This is explained by the slowing down of fast neutrons, the presence of resonance absorption region in the intermediate energy range in hafnium, the presence of a chain of daughter isotopes with fairly high neutron absorption cross-sections. In 2009-2012, the BOR-60 reactor was used to test coated hafnium hydride samples with various stoichiometry and compositions. Irradiation was carried out at various temperatures, including those that exceeded operational parameters. The main operational characteristics were studied: dimensional and structural stability, hydrogen yield, hydrogen permeability through the shell, compatibility, and others. Samples made in Japan and in the Research Institute of Atomic Reactors were studied. Studies have supported the promising use of hafnium hydride in the control rods of fast neutron nuclear reactors. It is planned to continue the initiated research with the development of an experimental batch of control rods and to test them in the experimental nuclear reactor BOR-60. The use of control rods with hafnium hydride is most appropriate in automatic control rods (ACR) and rods for compensation of power and temperature effects (shim rods) directly in reactor cores where there are high damaging doses and high radiation damages of boron carbide.

Figure 4. Appearance of a control rod with refabricated boron carbide of the BN-600 reactor.
Figure 5. Variations in the physical efficiency of boron carbide (B\(_4\)C) of various enrichment with boron-10 isotopes and hafnium hydride (HfH) as a function of the operation time in the designed JSFR fast neutron reactor (Japan).

6. Dual-use control rods with Eu\(_2\)O\(_3\)+Co

Europium oxide and europium oxide in a metal matrix, for example, made of cobalt, have very high radiation resistance. They do not accumulate gaseous products of nuclear reactions, as in boron carbide, there is no risk to reduce performance, as in control rods with hafnium hydride, in case of possible emergency situations associated with overheating of products up to 1100 °C [8,9].

Russia has accumulated a unique long-term experience of using europium-based absorbing materials in the control rods of nuclear reactors of various types. In 1975-2000, shutdown rods with europium were operated in the BOR-60 reactor, and in 1980-2000 shim rods with europium were used in the BN-600 reactor. Each shim rod contained 8 kg of europium oxide. After operation for 330-420 effective days, the total activity of europium radioisotopes in one rod reached 400 kCi. At the end of the last century, due to the problems encountered in handling spent products, their transportation, and the need for long-term storage in storage pools, rods with europium were replaced with control rods with boron carbide.

The disadvantages of high specific activity and a large half-life of europium radionuclides when they accumulate in the control rods, may be an advantage when using spent products in next-generation gamma-ray sources. Table 3 shows basic consumer properties of the europium-154 radioisotope compared with the currently used Co-60 and cesium-137 (Cs-137) radioisotopes in gamma-ray sources for various purposes.

Table 3. Basic consumer properties of radioisotopes in gamma-ray sources.

| Properties                              | Co-60   | Cs-137 | Eu-154  |
|-----------------------------------------|---------|--------|---------|
| Shape of the active part                | Coated metal | Salt CsCl | Oxide Eu\(_2\)O\(_3\) |
| Energy, MeV                             | 1.17 and 1.33 | 0.66 (average) | 0.8 (average) |
| Half-life, years                        | 5.3     | 30.0   | 13.5    |
| Specific activity, Ci/g                 | 50-110  | 20-25  | 50-70   |
| Thermal neutron absorption cross-section, barn | 36 (Co-59) | -     | 4500 (Eu-153) |
| Time to obtain 50 Ci/g, days            | 300-600 | -      | 40-60   |
In addition to Eu-154 radioisotopes, when using europium with natural content of radioisotopes (48% Eu-151 and 52% Eu-153), other long-lived and highly active radioisotopes Eu-152 and Eu-155 are also accumulated in it.

It can be seen that europium radioisotopes are inferior to cesium-137 in terms of half-life period, and are slightly inferior to Co-60 in terms of specific activity and energy of gamma quanta. Table 3 shows the average energy of gamma quanta of cesium-137 and europium-154. It is important that the maximum energy of gamma quanta is higher than that of Co-60 and is 1.8 MeV. Therefore, in terms of efficiency, for example, of material decontamination and treatment, the use of europium isotopes is more preferable.

The shortage of Co-60 in the world market is increasing and it is necessary to find new effective solutions for its elimination. Cesium-137 is extracted from spent nuclear fuel in the form of a chemically reactive salt CsCl. It has only one advantage over Co-60 - a higher half-life (30 years compared with 5.3 years). But high chemical reactivity of the cesium salt creates big problems for the safe operation of sources. There were incidents of leakage of even double shells of sources with severe environmental pollution. Therefore, one should not expect its wider use in gamma-ray units.

The solution to the shortage of Co-60 when loading existing and projected gamma-ray units may be next-generation gamma sources based on europium radioisotopes and europium radioisotopes with cobalt-60. They should have the same shapes and sizes as gamma sources with Co-60, in particular, a diameter of about 7 mm and a height of up to 100 mm. This requirement is easily satisfied for control rods in which the absorbing kernel may have a similar diameter. At the end of the control rod life, an absorbing kernel is removed from it, which becomes, after being placed in a sealed shell, a gamma source.

7. Control rods with dysprosium hafnate
Very few materials and structures are known that have unlimited radiation resistance [12, 13]. They are characterized, first of all, by the preservation of the shape, size and structure at high damaging doses. These include fluorite structures of a number of oxygen-complex lanthanide compounds with a large number of non-stoichiometric oxygen vacancies. Of the materials that are classified as absorbers, it is, first of all, dysprosium hafnate (mDy2O3·nHfO2) with 13 neutron absorbing isotopes. Its properties are well studied and presented in [12]. Dysprosium hafnate pellets retain their shape, size and structure after prolonged reactor irradiation (figure 6).

![Dysprosium hafnate](image)

**Figure 6.** Cross section (left) and structure (right) of dysprosium hafnate after irradiation in a BOR-60 reactor with a neutron fluence of 10^{22} cm^{-2} (E> 0.1 MeV).

Dysprosium hafnate was developed at the Research Institute of Atomic Reactors [12]. Well-studied gadolinium zirconate (Gd2O3ZrO2) having a similar crystal structure and dysprosium titanate (Dy2O3TiO2) used in the control rods of the VVER-1000 and RBMK-1000 reactors were taken as prototypes. But dysprosium titanate is characterized by a very narrow region of presence of fluorite structure with four polymorphic transformations. Replacing titanium atoms with hafnium atoms allowed evolutionally obtaining a unique absorbing material with a large area of homogeneity of the
solid solution and high physical efficiency due to the presence of 13 isotopes of dysprosium and hafnium with large neutron absorption cross-sections in the energy range of 50-100 eV [1].

Since for the isotopes of dysprosium and hafnium the absorption cross-sections of neutrons of different energies do not coincide, the change in the Dy/Hf ratio in the composition of the material makes it possible to adjust its physical absorption efficiency over large range while preserving the structure of the fluorite solid solution. To extend the range of adjustment of the initial physical efficiency, dysprosium and hafnium oxides in the initial mixture may be partially replaced with chemically related oxides. Dysprosium oxide may, for example, be partially substituted by oxides of other rare-earth elements (for example, gadolinium, erbium, yttrium). Hafnium oxide may be substituted by zirconium oxide. Due to the high chemical affinity of the substituted components, this does not lead to a change in the structure of the synthesized material and its high radiation resistance is preserved. In these terms, dysprosium hafnate is a versatile absorbing material with “adjustable” physical absorption efficiency.

The main advantages of hafnate dysprosium (mDy2O3·nHfO2):

- unlimited radiation resistance;
- two absorbing components, Dy and Hf, provide high physical efficiency in the thermal and intermediate neutron spectra;
- high melting point (2600–2800°C);
- ability to change the ratio of Dy and Hf with the preservation of operational properties;
- high manufacturability of dysprosium hafnate synthesis and the manufacture of high-density pellets (7.7–8.2 g/cm³);
- high compatibility with construction materials;
- relatively cheap raw materials.

In its operational characteristics, dysprosium hafnate has no world analogues. It is recommended for use not only in thermal neutron control rods, but also in products used in fast neutron nuclear reactors which do not require the highest possible physical efficiency.

In 2014 FSUE “SSC RF RIAR” developed and delivered to the Customer (NIKIET) “Basic design of absorber element RO AR RU BREST-OD-300” (3Б2956.000.00ТП) based on Dy2O3·HfO2. In support of the performance of dysprosium hafnate in the developed absorber elements, prototypes with pellets made of this material manufactured at RIAR were tested in the BOR-60 reactor. The maximum neutron fluence was 7x10²³cm⁻², the irradiation temperature of the shell was (450–470)°C. The test results fully confirmed the high radiation resistance of dysprosium hafnate and the efficiency of absorber elements design based on it. The original fluorite crystal structure of the material and its crystalline parameters have been preserved. The diameter of the pellets has not changed.

8. Conclusion

Boron carbide with different boron-10 isotope content is used in the control rods of liquid sodium-cooled fast neutron nuclear reactors as absorbing material. The use of next-generation rods with annular samples of boron carbide improves physical efficiency and radiation resistance, reduces boron enrichment with boron-10 isotopes to 60% and reduces their cost. A closed cycle in the use of materials based on boron-10 isotopes has been developed, which is proposed for industrial use.

The use of more radiation-resistant and cost-effective absorbing materials based on europium and hafnium hydride is recommended in the control rods permanently located in the core of FN reactors. This makes it possible to reduce and, when using a closed cycle, eliminate dependence on foreign supplies of boron-10 isotopes, increase the life characteristics of products and reduce their cost.

Designs of “trap” type control rods have been proposed, where radioisotopes may be accumulated, for example, Co-60. Instead of moderating elements of zirconium hydride (ZrH₂), it is proposed to use a homogeneous kernel made of absorbing and moderating materials in the form of hafnium hydride (HfHₓ).

For control rods with lead coolant of BREST-OD-300 type, it is proposed to use dysprosium hafnate (mDy₂O₃·nHfO₂) as the absorbing material, which has 13 absorbing dysprosium and hafnium
isotopes with resonant absorption of epithermal neutrons (50-100 eV) and unlimited radiation resistance.

9. References

[1] Risovany V D, Zakharov A V, Klochkov E P, Ponomarenko V B and Muraleva E M 2013 Absorbing materials of control rods of nuclear reactors (Ulyanovsk: UlGU)
[2] Risovany V D, Zakharov A V, Klochkov E P 2012 Absorbing materials and control elements of nuclear reactors: manual for graduate students (Moscow: Publishing House MEI)
[3] Dunner Ph, Heuvel H-J, Horle M 1984 Absorber materials for control rod systems of fast breeder reactors J. of Nucl. Mater. V 124 pp 185-194
[4] Risovany V D, Zakharov A V, Klochkov E P, Guseva T M 2003 Boron in nuclear engineering (Dimitrovgrad: RIAR)
[5] Risovany V D, Klochkov E P, Ponomarenko V B, Zakharov A V 1998 Europium in nuclear engineering (Dimitrovgrad: RIAR)
[6] Risovany V D, Klochkov E P, Ponomarenko V B, Zakharov A V 2004 Europium in nuclear engineering 2nd edition, revised and added (Dimitrovgrad: FSUE “SSC RF RIAR”)
[7] Risovany V D, Zakharov A V, Klochkov E P 2011 Operating history of absorbing materials with europium in the BN-600 reactor and the prospects for their further use in innovative nuclear reactors News of Higher Educational Institutions Nuclear power engineering 1 pp 110-114
[8] Rysovany V D, Zakharov A V, Guseva T M et al. 1996 Operating experience and materials research of the control rods spent in the BOR-60 reactor from 1969 to 1994 Collection of reports of the 4th interdisciplinary conference on reactor material science (Dimitrovgrad: SSC RF RIAR) vol 4 pp 92-106
[9] Risovany V D et al. 2011 Development of shutdown rods of the BN-600 reactor on the basis of refabricated boron carbide with a life of 745 effective days// News of Higher Educational Institutions Nuclear power engineering 1 pp 249-259
[10] Risovany V D, Klochkov E P, Ponomarenko V B 1993 Hafnium in nuclear engineering (Dimitrovgrad: RIAR)
[11] Risovany V D, Klochkov E P, Ponomarenko V B 2002 Hafnium in nuclear engineering (American Nuclear Society)
[12] Risovany V D, Zakharov A V, Ponomarenko V B, Klochkov E P, Muraleva E M 2010 Dysprosium in nuclear engineering (Dimitrovgrad)
[13] Koshkin V M, Dmitriev Yu N, Zabrodsky Yu R, Tarnopolskaya R L, Ulmanis U A 1984 Abnormal radiation resistance of loose crystalline structures Physics and technology of semiconductors 18(8) pp 1373-1378
[14] Koshkin V M, Zabrodsky Yu R, Podorzhanskaya N M 1979 Instability areas of interacting point defects in periodic structures Problems of Atomic Science and Technology Series Physics of radiation damage and radiation material science 3(11) pp 21-25