THE MAIN PRINCIPLES OF IRRADIATED DISPERSION TYPE FUEL FOR FLOATING POWER UNIT BEHAVIOR

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ABSTRACT

Floating Power Unit (FPU) is an autonomous power facility, which is end-manufactured at the shipbuilding yard as a non-self-propelled vessel transported on sea or river to the operation site. It is prospective project for installations in remote regions which are difficult of access. SC VNIINM has developed a novel fuel element for FPU on the base of “UO_2 + aluminium alloy”. In-pile tests have been performed in the loops of the MIR reactor (RIAR, Dimitrovgrad). The post-irradiation examinations of fuel elements (with burn up to 150 MW d/kg U) were carried out in RIAR and showed promise of their application in low power reactors. In order to demonstrate this technology in practice, a pilot FPU “Academician Lomonosov” is currently being constructed to supply heat and electricity to Peveck.

1. Introduction

Development of Low Power Reactors which can be applied for Floating Power Unit (FPU) is prospective project for installations in remote regions which are difficult of access in Russia (North regions, Siberia, Far East) as well in other parts of the world which are difficult to reach. FPU is an autonomous power facility, which is end-manufactured at the shipbuilding yard as a non-self-propelled vessel transported on sea or river to the operation site. The requirements on FPU core reliability and safety under normal and abnormal conditions compared to WWER are enhanced. These requirements can be proved and verified by long term operation of such kind of nuclear reactors in icebreakers. In order to demonstrate this technology in practice, a pilot FPU “Academician Lomonosov” with KLT-40S reactor plant (the prototype of which is the reactor plant installed in operating ice-breakers) has been constructed to supply heat and electricity to Peveck. The development of fuel elements for the FPU is through the modernization of the fuel rods of nuclear icebreakers, based on proven designs and technologies.

High-Technology Research Institute of Inorganic Materials (SC VNIINM) has developed novel dispersion rod element on the base of “UO_2 + aluminium alloy” fuel [1-5]. The pilot reactor for FPU has 2.1 TW·h power resource and it has been designed with cylindrical fuel rods the cladding of which are made from zirconium alloy E110. Fabrication technology of fuel elements was developed by SC VNIINM and successfully applied at Elemash-STP (Electrostal City).

2. Out-of-pile investigations

The out-of-pile tests and examinations were carried out. They included:

- long-term thermal tests of fuel elements at the temperatures of 500 and 550 º C;
- thermal tests of fuel rods by heating to 800 º C.
- thermal cycling of the fuel elements;

The thermal cycling of fuel elements within 20-350 ºC at the quantity of the cycles up to 200 does not affect the fuel elements structure. A good metallurgical bonding between fuel and cladding is remained. No cracks in fuel meat and splitting of fuel from cladding were observed. Fuel element microstructures (before and after thermal cycling tests) are shown in Fig 1.

Studies of compatibility of UO_2 particles with an aluminum matrix alloy at 550 °C and holding time up to 1000 h have shown that granules did not essentially interact with the matrix. Fuel element microstructures after long-term thermal tests are shown in Fig 2.

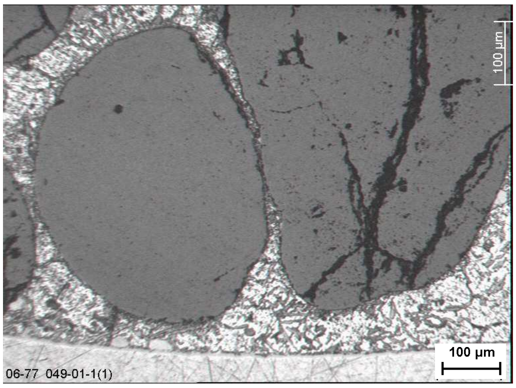


Fig 1. Microstructure of fuel after 200 thermal cycles

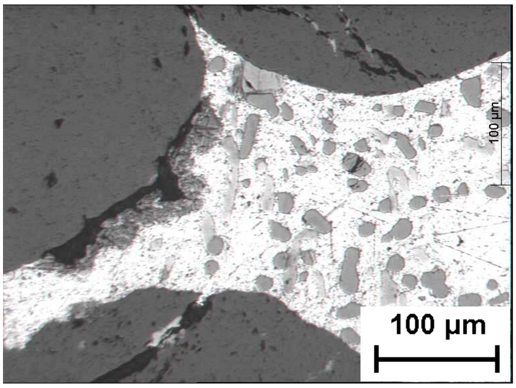


Fig 2. Microstructure of fuel after long-term thermal investigation (550 °C, 1000 h)

The simulation of an off-design accident has shown that between UO_2 particles and the matrix of aluminium alloy no diffusion interaction takes place up to 750 °C during 10 minutes. At 800 °C and the same hold-up time an intermetallic interaction layer around UO_2 particles has arisen. The interaction layer on the cladding increases from 5 to 160 µm.
Out-of-pile investigations have shown the possibility of designed fuel rods irradiation.

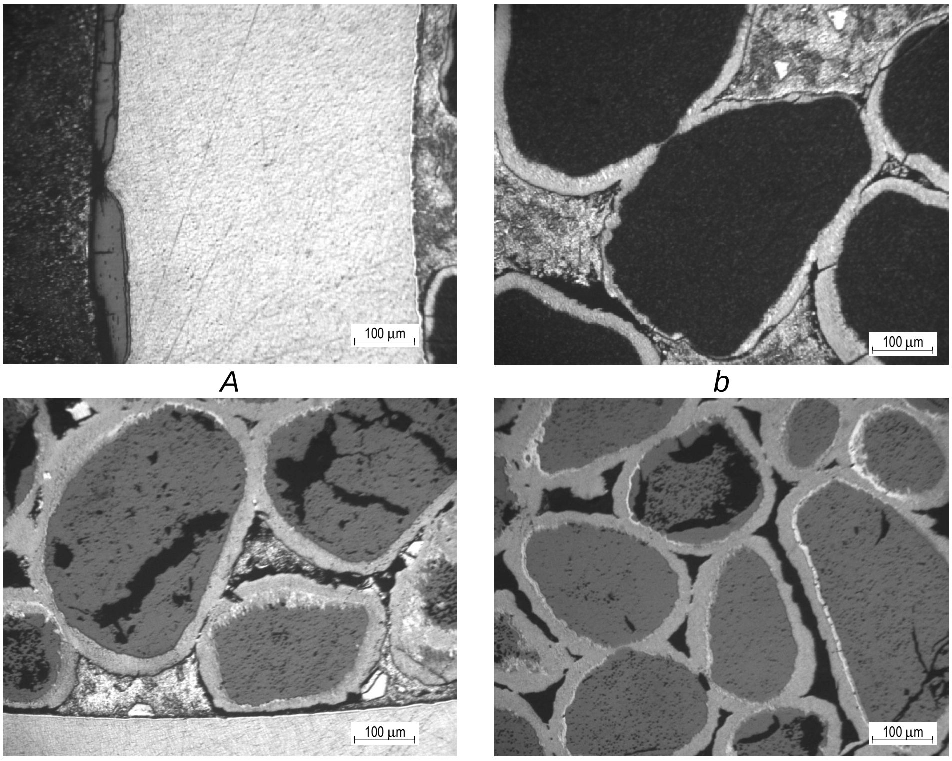
3. In-pile tests and post-irradiation investigations

In-pile tests of fuel elements have been performed in the loops of the MIR reactor (RIAR, Dimitrovgrad). In-pile tests of eight irradiation devices with shortened fuel elements and a full-scale fuel assembly have been finished, the test of some irradiation devices are in progress. Post-irradiation examinations of fuel elements that reached the burnup of up to about 130-150 MW·d/kg U were carried out in RIAR; they attested their reliability and serviceability under conditions of their operation in FPU core.

The irradiation conditions varied significantly; in particular, the maximum heat flux changed from 180 to 300 W/cm. In all tested conditions, the fuel composition "uranium dioxide + aluminum alloy" is completely operable. However, the radiation resistance of this fuel composition is sensitive to the thermal conditions of irradiation.

3.1. Interaction of uranium dioxide with an aluminium matrix

Interaction occurs under irradiation of uranium dioxide with an aluminium matrix, which is observed in the form of light bands around the fuel particles and results in the UAl_x type uranium intermetallics formation; the degree of the interaction increases with the burnup, heat flux and the uranium content of the fuel composition (Fig 3).
As time goes by, the formation, growth and coalescence of interaction layers go on. Aluminium matrix disappears in the central region of the core and doesn't disappear only near the core-cladding boundary. A good metallurgical bond retained between the cladding and the fuel composition, diffusion layer between them doesn't change (Fig 3a, 3c).



A *b*

C *d*

Fig 3. The microstructure of the cross-sections of irradiated fuel element:
Burnup, MW·d/kg U: a, b – 150; c, d – 100;
Average linear heat flux, W/cm: a, b – 200; c, d – 300;
Cross-section: a, c – cladding / fuel boundary; b, d – the center of the core

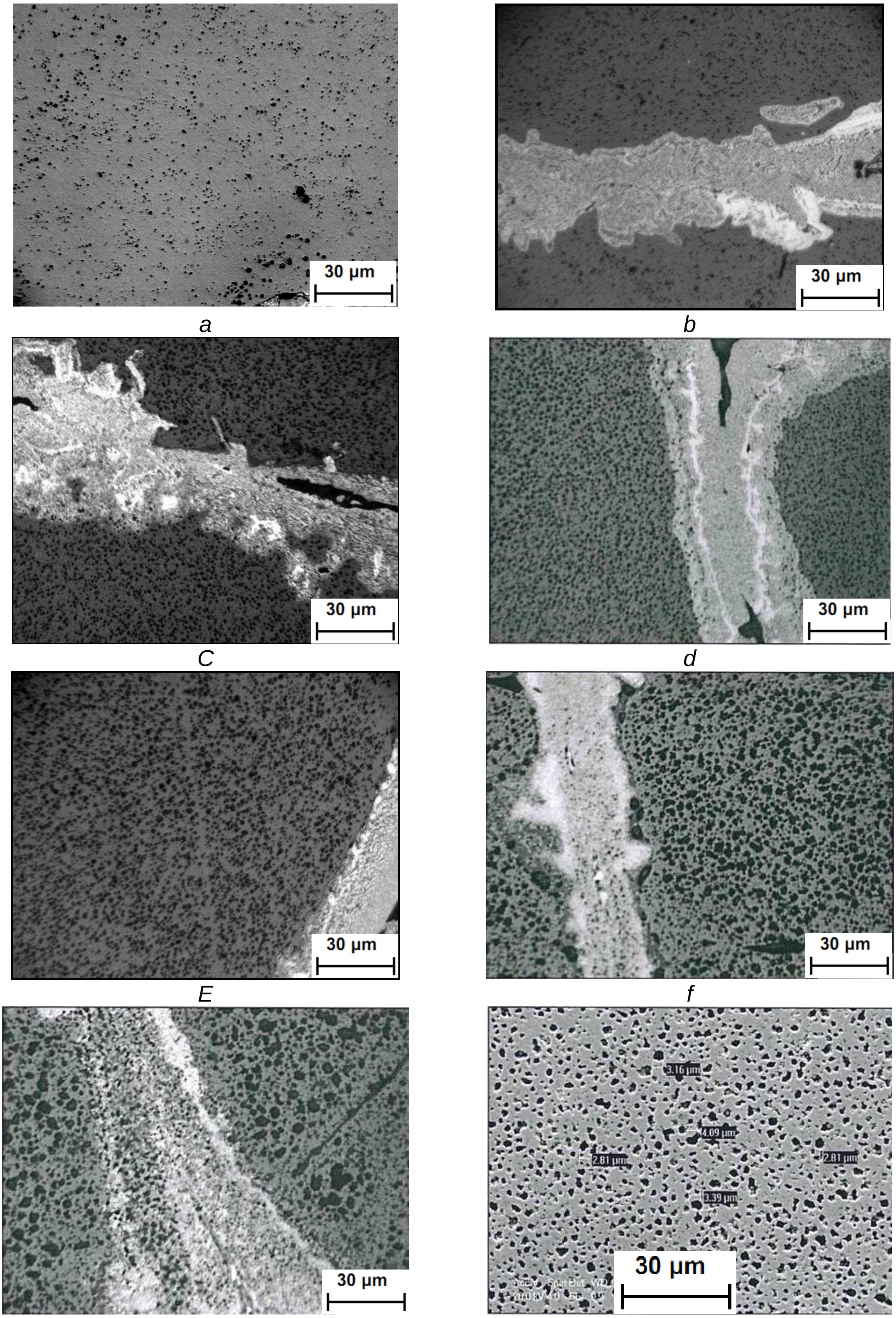
When linear power up to 200 W/cm degree and layer thickness of interaction between the particles of uranium dioxide and aluminium matrix are small (Fig 3a, 3b). A significant amount of the aluminium matrix doesn’t disappear up to 150 MW·d/kg U. However, you can see the beginning of the formation of porosity in the centre associated with the influence of the contact layers of interaction.

With linear power near 300 W/cm degree of interaction between the particles of uranium dioxide and aluminium matrix significantly increases, porosity between the grains begins to develop (Fig 3c, 3d).

This process, if all other things being equal (the density of the uranium in the core, temperature, burnup) is controlled mainly by the value of the linear power of the fuel element. This process is irreversible and accelerated with the burnup (average burnup over the cross-section) increasing due to restructuring of the meat and reducing of the thermal conductivity.

3.2. Porosity

Porosity is generated in the fuel particles at the stage of manufacturing. It is formed due to the shrinkage of the material during sintering of the fuel particles and is irregularly arranged pores and cracks (Fig 4a). In the irradiated fuel that porosity partially "healed" in the process of radiation sintering fuel particles, however, an additional porosity as a result of irradiation appears. Distribution of porosity in the irradiated fuel particles is relatively regular; the pores are close to spherical shape (Fig 4b-4h). With the burnup increasing size of these pores increases, some of the pores are united. Dimensions of the largest pores are 3-4 µm (Fig 4h).



a b C d E f G H

Fig. 4 The porosity in the fuel particles: a - unirradiated fuel; b-e - irradiated fuel; burnup, MW·d/kg U: b - 80; c - 90; d - 100; e - 110; f - 150; g - 153; h - 153

3.3. Scanning electron microscopy

To obtain data on the structure and composition of the fuel studies with using scanning electron microscopy (SEM) and electron probe microanalysis (EPMA) were conducted. Studies were conducted on a scanning electron microscope Philips XL 30 ESEM-TMP, with a system of EPMA. The system consists of EPMA microprobe energy X-80 and Mach wave microanalyzer INCA Wave 700. Secondary electron images of the microstructure of the fuel in the core were obtained during the registration mode signal in a secondary electron at an accelerating voltage of 20 kV. EPMA results were obtained using an accelerating voltage of 20 kV and 30 kV.

Fig 5 shows the microstructure of the interaction layer. Note that the clear outer boundaries of the fuel particles are retained; there is no vagueness inherent in diffusion processes. Electron microscopic and element analysis of irradiated fuel showed that uranium atoms migrate in the matrix, as well as, matrix elements migrate in fuel particle. Matrix elements (especially aluminium) form compound phases with the fuel elements (and, possibly with elements, fission products), the uranium and oxygen out of the fuel particles in the interaction layers.

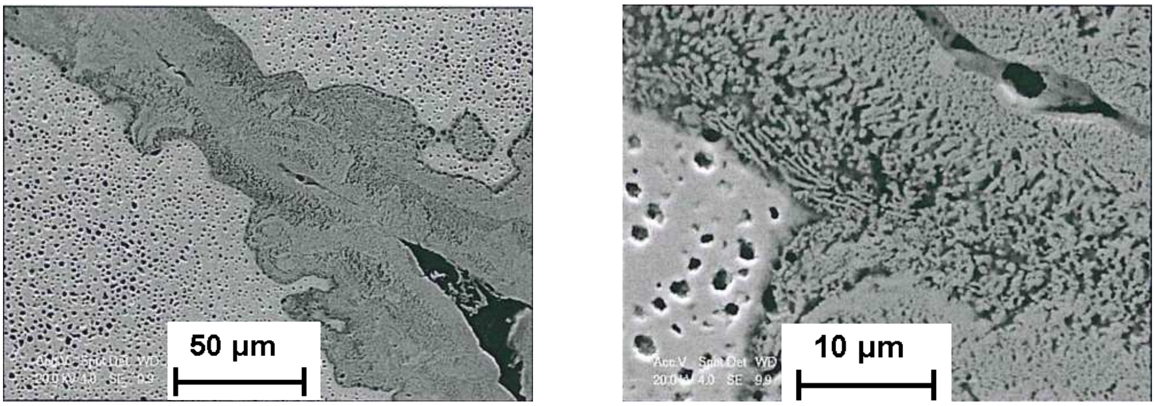


Fig 5. Structure of the interaction layer (burnup ~ 150 MW·d/kg U)

Interaction layers have a heterogeneous structure consisting of at least two phases: light and dark. The higher is the atomic number of the element in the phase, the lighter (brighter) this phase is, and, accordingly, it is mainly determined by backscattered electrons. To determine the composition of the phases of data electron probe microanalysis was used. Scanning was conducted by the electron probe between adjacent fuel particles through interaction layers with the construction of the distribution curves of aluminium, uranium, xenon, caesium, zirconium, and oxygen. Analysis of the results shows that the dark phase is composed of aluminium and oxygen. The basis of the light phase is aluminium and uranium. Accurate assessment of the composition of the phases detected by EPMA in these conditions is not possible due to the presence of high background X-ray emission from the test sample and the small size of the phases.

3.4. Swelling

As a result of analysis of the post irradiation investigations data (measurement of cross-sections of irradiated fuel elements) it was found that the swelling data for the dispersion fuel compositions may be closely fitted with the equation

$$\frac{\Delta V}{V_0} \approx \frac{\Delta S}{S_0} = \begin{cases} 0 & B \leq B_0 \\ A\left(B - B_0\right) & B > B_0 \end{cases}, \tag{1}$$

$\frac{\Delta V}{V_0}, \frac{\Delta S}{S_0}$ - relative changes of volume and area (of cross-section) of fuel meat under irradiation,%;

B - burnup, MW·d/kg U;

A - swelling rate, %· kg U/MW/d;

B_0 – incubation period for burnup; value from which statistically significant dimensional change in fuel composition begins, MW·d/kg U.

Using the Eq. (1) it is allowed to fit closely the swelling data for fuel composition "UO_2 + aluminium alloy". We processed experimental data which were obtained from the post-irradiation examination of fuel elements with such fuel composition irradiated in the reactor MIR. The results are presented at Fig 5. Evidently, increasing of the linear power resulted in a significant increase of the rate of swelling

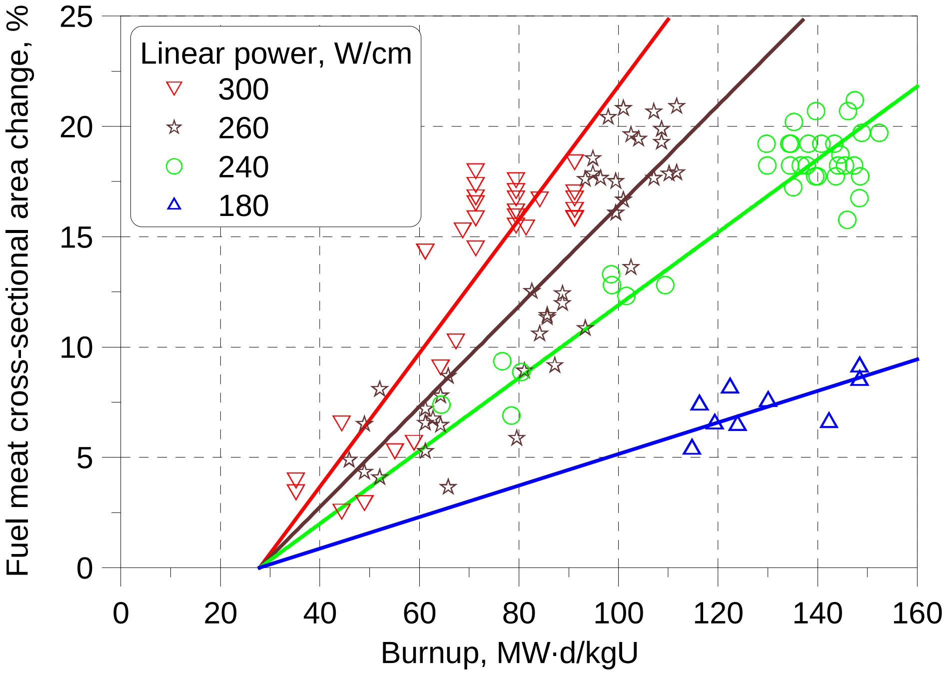


Fig 5. Fuel meat cross-sectional area change for fuel composition "UO_2 + aluminum alloy" under irradiation vs. burnup

Swelling speed determined by the rates of several parallel ongoing processes:

- fission product accumulation in the core (mainly in the fuel particles and the interaction layers);
- formation of porosity (between the fuel particles and in fuel particles themselves);
- structural changes in fuel composition (primarily associated with interaction);
- "healing" of defects due to the radiation creep of the fuel composition.

By increasing the linear power the last three of these processes are intensified.

3.5 Thermal conductivity of fuel

In addition to the standard tests of fuel elements some special investigation of irradiated fuel elements were carried out including the measurement of the thermal conductivity of the irradiated fuel composition.

Structural changes occurring in the fuel element cores reduce the thermal conductivity of the fuel composition. Fig 6 shows the results of measuring the thermal conductivity of the fuel composition of irradiated fuel elements at 350 ℃. It can be seen that the thermal conductivity of fuel elements is decreased constantly with increasing accumulation of fission products and can be fitted as a single curve. This is due to the gradual disappearance of the aluminium matrix in these fuel elements with burnup increasing until complete replacement to the intermetallic matrix.

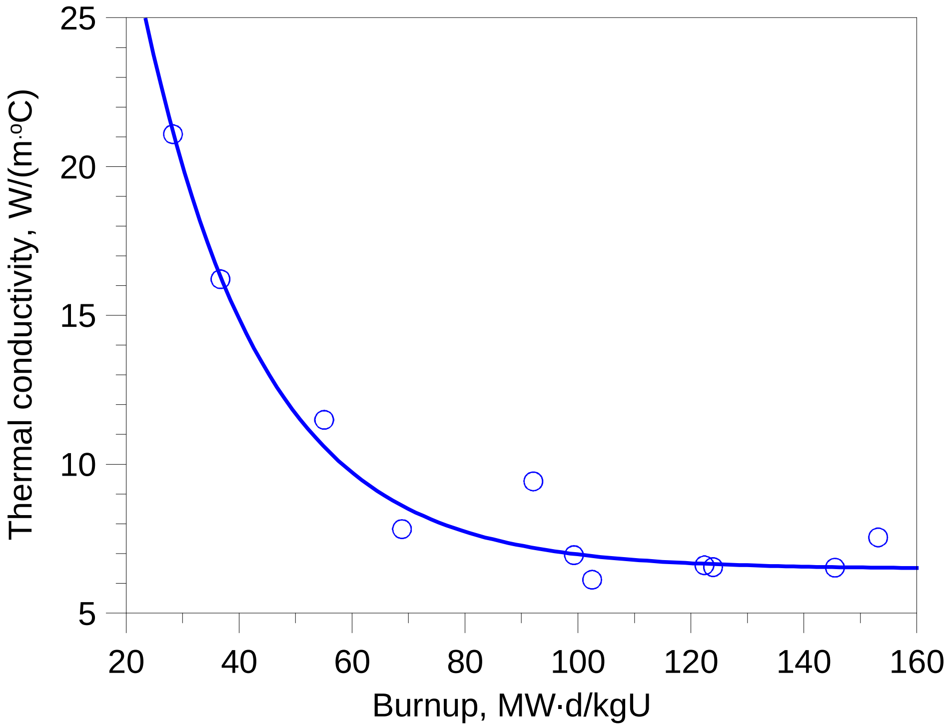


Fig 6. The thermal conductivity of the irradiated fuel at 350 ℃ vs. burnup

4. Floating power unit " Academician Lomonosov"

At present, the floating plant " Academician Lomonosov" for the world's first floating nuclear power plant in Chukotka has been completed at the SC “Baltic Shipyard”.

The floating power unit was transported to Murmansk in May 2018. Loading of nuclear fuel is planned for the third quarter, physical launch - at the beginning of the fourth quarter of 2018. In August 2019, the FPU will be delivered to Pevek.

The floating nuclear power plant will replace the Bilibino nuclear power plant and Chaunskaya thermal power plant, which are technologically obsolete. It is planned that a floating FPU with a capacity of 70 MW will be put into operation in 2019.

5. Conclusion

1 SC VNIINM has developed fuel rods with a matrix of aluminum alloys and claddings of zirconium alloys for the core of the floating power unit (FPU).

2 Out-of-pile and in-pile investigations have been carried out, the results of which have shown the prospects of using these fuel rods in the core of FPU.

3 Specific features of the behavior under the irradiation of dispersion fuel rods with the fuel composition "uranium dioxide + aluminum alloy" have been identified.

4 The core of the pilot FPU "Academician Lomonosov" has been manufactured. The world's first floating nuclear power plant with a capacity of 70 MW will be put into operation in Pevek in 2019.

5. References

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