CALCULATED INVESTIGATION OF ACTINIDE TRANSMUTATION IN THE BOR-60 REACTOR

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ABSTRACT

In the course of reactor operation the formation of fission products and accumulation of minor-actinides and plutonium take place in the nuclear fuel. These materials define the radiation hazard to a great extent. Of one possible ways lowering the activity of irradiated nuclear fuel is transmutation of long-lived radioactive isotopes in the stable or short-lived ones, that allows to facilitate the problem of the high-level waste and to improve the efficiency of nuclear fuel use at the expense of its recycling and burnup increasing.

INTRODUCTION

With the development of nuclear energy the available power resources have been greatly extended at the expense of uranium, but with provision of the possibility of nuclear fuel breeding in fast reactors they have become practically unlimited. But, nuclear energy has set up new problems, in particular radioactive waste.

At present the problem of nuclear waste is one of the most acute in nuclear power engineering, which attracted increased attention both on the part of specialists and public. Their most concern is “long-lived” radioactive waste, that will determine radiation danger on length of millenniums. But in the nuclear engineering realisation of the principle of radiation balance is possible – how mach natural radioactive materials is extracted from the land of so much should be brought back.

TRANSMUTATION

In the course of reactor operation the formation of fission products and accumulation of minor-actinides and plutonium take place in nuclear fuel. Spent fuel consists of 94,5% from uranium, 4,4% fission products, 1,1% plutonium and 0,08% minor-actinides. Besides, significant resources of power- and weapon-grade plutonium are accumulated world-wide, that to a considerable extent defines nuclear and radiation danger. Long-term storage of plutonium is problematic and requires greater economic expenses. So, in the first place, it is necessary to burn plutonium, however, in this case accumulation of minor actinides should be limited.

Among possible ways of reducing the activity of spent fuel and reducing the plutonium resources, burning out of plutonium and transmutation of the most dangerous radioactive long-lived isotopes in to stable or short-lived by irradiating them in reactors is considered, what is suitable for disposal or long-term storage. This is only one of the possible directions of reducing the general activity (in particular, its long-lived component), that allows to facilitate the problem of the high-level waste in nuclear engineering and to improve the efficiency of nuclear fuel usage at the expense of its recycling and utilisation of plutonium recourses.

However transmutation of plutonium and minor-actinides must not be considered in isolation from the process of conversion and decontamination of nuclear wastes, as well as possible incineration of the most dangerous fission products, since at a specific stage they will determine the activity of wastes. It is necessary to note that burning out plutonium and transmutation of minor-actinides can bring energy advantage.

Therefore the main purposes of transmutation are the reduction of high-level waste volume and, in the first place, reduction of the long-lived component, increase of efficiency of nuclear fuel usage, utilisation of weapon-grade plutonium. Besides, possible production and separation of useful radioactive isotopes.

ACTINIDES-BURNER REACTORS

The studies carried out in different countries validated the possibility of transmutation to be performed in power reactors. However, these reactors have neutron spectra which are not sufficiently hard for nuclear fission of minor actinides. Therefore, special Actinides-Burner Reactors (ABR) are more preferable because they will provide the optimum transmutation conditions.

These reactors provide a purposeful implementation of optimum characteristics for actinide transmutation, which are “hard” spectrum and high density of neutron flux, small factor of nuclear fuel breeding as well as stable neutron-physical features, that allow a considerable amount of actinides be loaded into the core without a significant influence on the reactor (in the first place, on its safety). One of the most suitable ABR is the fast breeder reactor. The rate of actinide fission in the burner-reactor core should exceed the rate of accumulation that can be realised if the breeding ratio is much less than 1. Therefore, more emphasis is put on the FBR-type reactors of low power because they have a low breeding ratio and hard spectrum at high density of neutron flux. In loading minor actinides into large power reactors the problem appears related to decreasing of sodium void reactivity effect.

Specifically should be noted that efficient transmutation can not be isolated from the closed fuel cycle. In the closed system, consisting of different types of reactors, the necessary number of ABR is defined so that annual destruction of minor actinides (MA) in the ABR is equal to their annual generation in other types of reactors (one ABR for 5-7 power reactors).

REACTOR BOR-60

One of the possible types of ABR is an experimental fast reactor – BOR-60. The availability of the reactor BOR-60 in SSC RIAR and its powerful experimental base allow different calculation-experimental studies to be conducted, including improvement of the closed fuel cycle, burning out of plutonium and MA transmutations.

In the reactor BOR-60 the core assemblies, radial blanket and control rods are located in a hexagonal lattice. On the whole there are 265 cells (Fig. 1) in the lattice with a pitch is equal to 0,045 m. The fuel core occupies 114 cells (6 rows), control rods – 7 cells and the remaining cells are loaded with blanket assembles. Besides, practically in any cell (except those for control rods) can incorporate experimental fuel and fuelless packages.

All assemblies have similar hexagonal wrapper tubes of which the across-flats-dimension equals 0,044 m. Besides standard 37-pin fuel assemblies and 7-pin uranium assemblies of radial blanket experimental 19-pin fuel assemblies (Fig. 2) are used as well.

The reactor BOR-60 can be considered as optimum for demonstration of the burnup efficiency of MA and plutonium, because the fraction of neutron flux density with an energy above 0,1 MeV makes-up 73÷86 %, neutron flux density – up to $3{,}55 \cdot 10^{15}$ $cm^{-2*}s^{-1}$, mean neutron energy in the core – 200÷390 keV, negative effect of the sodium void reactivity (– 0,052÷0,068 Δk), small breeding factor (<0,28), wide experimental opportunities of the reactor facility.

The main features of BOR-60 are presented in the Table.

During 30 years of the BOR-60 reactor operation significant calculation and experimental experience has been gained. The reactor provides the investigation and evaluation of the possibility and efficiency of minor-actinide and plutonium transmutation:

– calculation investigations of critical mass, neutron-physical characteristics of the reactor fuel with various minor-actinide compositions, their quantitative and qualitative behaviour in time;

– carrying out experiments on the definition of the main neutron-physical characteristics (flux density, neutron spectrum, reaction rate and so on), change of nuclear fuel composition (burn-up, isotopic kinetics and

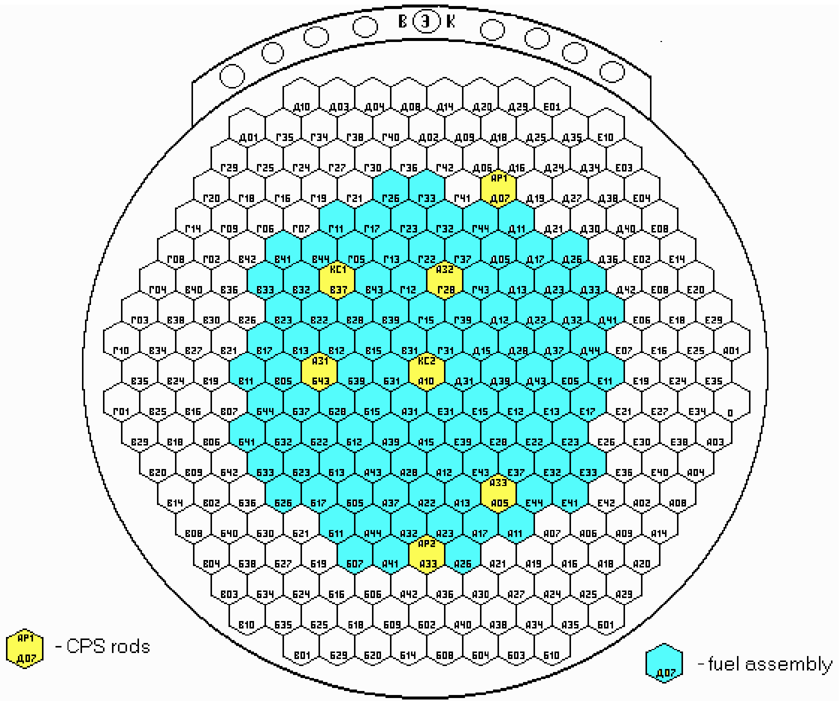


FIGURE 1. Loading cartogram of the reactor BOR-60

so on) of separate fuel assemblies, fuel elements, capsules and reactor as a whole, comparison of experimental and calculated investigation results;

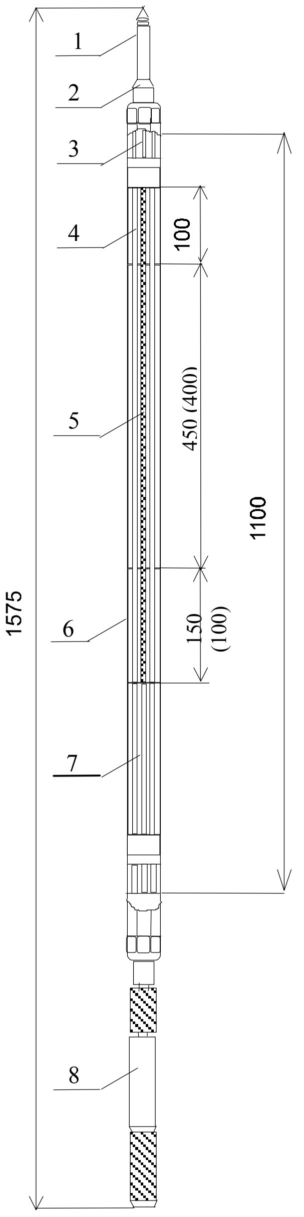
– testing and adaptation of program and constant support of the BOR-60in order to improve the calculation accuracy of neutron-physical characteristics.

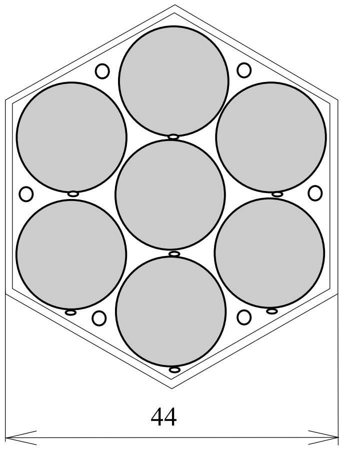
Long-term experience of the reactor BOR-60 operation in the mixed uranium-plutonium fuel, multiple calculated and experimental studies on the plutonium and MA burning out have shown great prospects of the given direction. In the reactor hundreds of assemblies were irradiated and explored with the power-grade plutonium (record values of burnup equal 30-35 %), some tens of assemblies with weapon-grade plutonium, separate assemblies, pins and capsules with spent fuel from other reactors, with neptunium, americium and other MA were prepared and irradiated. The reactor continues to fulfil main purposes (experimental research, production of energy and heat, production of radioactive sources) with the observance of all safety requirements.

A regularly performed comparison between calculated and experimental data concerning the nuclear fuel burnup in the fuel assemblies and minor-actinides in the capsules demonstrated a well agreement in the results. The numerous calculated investigations defining the possibility and efficiency of the BOR-60 operation as a minor-actinide burner were carried out. Various configurations of the BOR-60 core were considered with power- and weapon-grade plutonium, neptunium and minor-actinides in the core, as well as in separate assemblies. The calculations have shown the reactor BOR-60 loading with up to 40% of MA does not bring about essential changing in its features and safety factors.

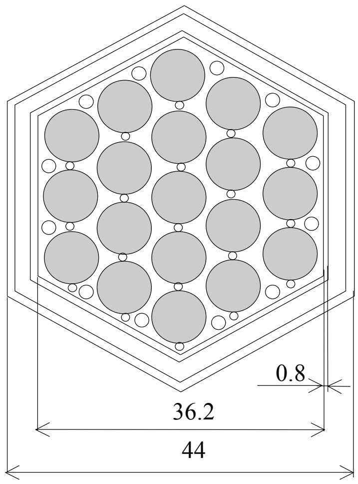
CONCLUSION

The conducted researches have shown that the reactor BOR-60 is an optimum one for demonstration of plutonium and minor-actinide burning efficiency, which are comparable with efficiency factors of the designed ABR. In the reactor both homogeneous (addition of MA in the core fuel), and heterogeneous (separate assemble-targets with high fraction of MA and the most dangerous fission products are in the blanket) loading of MA that will allow the optimum use of the reactor and its features. The influence of MA on the main neutron-physical features and safety of the reactor BOR-60 was evaluated. The studies have shown that introduction of plutonium and MA in to fuel does not bring about observable increase in activity of the irradiated assemblies that it is important from the standpoint of their transportation and conversion, since at the end of irradiation the activity is determined by fission products.

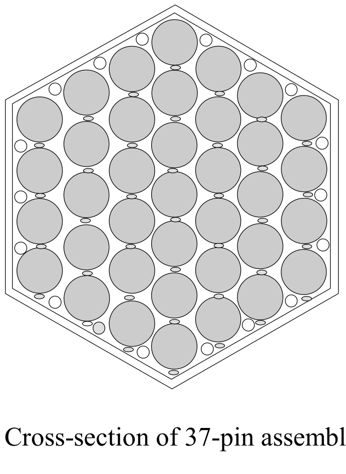




Cross-section of 7-pin assembly



Cross-section of 19-pin assembly



Cross-section of 37-pin assembly

FIGURE 2. Fuel assemblies of the core and blanket
1 – Head, 2 – place of marking, 3 – plug of fuel pin, 4 and 6 – top and bottom axial breeding zones,
5 – fissile part of assembly, 7 – fission gas plenum, 8 – tail

TABLE. Basic performances of the reactor BOR-60

Characteristic	Dimension	Value
Maximum thermal output of the reactor	Mw	up 60
Coolant		Sodium
Number of control rods: scram/control/automatic control	p.c.	3 / 2 / 2
Number of assemblies: core / radial blanket	p.c.	85÷114 / <170
Across flats dimension of assembly	m	0,044
Lattice pitch	m	0,045
Size of pin (diameter * thickness of a clad): core / radial blanket	10^{-3} m	6,0*0,3 / 14,5*0,4
Number of pins in standard assembly: core / radial blanket	p.c.	37 / 7
Standard fuel of the core:		PuO_2-UO_2, UO_2
Fraction of PuO_2 in fuel mix	%	20÷28
Fraction of ^{239}Pu in plutonium	%	63÷95
Enrichment of uranium in ^{235}U	%	45÷90
Material of axial breeding blanket		UO_2
Fuel core height	m	0,40 , 0,45
Thickness of axial breeding blanket: lower / upper	m	0,10; 0,15 / 0,10
Material of the radial breeding blanket		UO_2(depleted), steel
High of fertile material	M	0,90
Maximum value:		
Power of assembly	kW	750
Density of heat flow – volumetric / linear	$(Mw/m^3)/(kW/m)$	1200 / 55
Neutron flux density – core / radial blanket	10^{19} $m^{-2*}s^{-1}$	3,08÷3,55/1,60÷1,75
Fraction of neutrons with E> 0.1 MeV: core / radial blanket	r.u.	0,73÷0,86 / 0,41÷0,75
Mean energy of neutrons: core / radial blanket	keV	200÷390 / 90÷30
Breeding ratio: core / reactor	r.u.	0,03÷0,04 /<0,28
Loading of equivalent mass of ^{239}Pu in the reactor	kg	90-125
Effective fraction of delayed neutrons	r.u.	0,0046÷0,0070
Sodium void effect of reactivity	□k	-(0,052÷0,068)