Title of the Paper: Improving inherent safety BN-800 by the use of fuel assembly with (U, Pu)C microfuel.

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Abstract. The task undertaken in the report is to increase inherent safety of the fast reactor with a sodium coolant of type BN-800 due to considering the possibility of using an innovation fuel assemblies with mixed uranium-plutonium carbide fuel in form of coated particles. Fuel assemblies with pellet MOX fuel and fuel rods are directly replaced by microspherical mixed (U,Pu)C-fuel. Calculation evaluations of characteristics of fuel assemblies with microspherical fuel are realized. A calculation comparison of neutron physics and thermal hydraulics characteristics of the innovation fuel assemblies with microspherical mixed (U,Pu)C-fuel and the traditional fuel assemblies with pellet MOX fuel and fuel rods was conducted. The chosen calculation model was BN-800 reactor core with MOX fuel, where a three-zone radial power density field flattening due to plutonium content change in fuel was used. Thanks to microspherical carbide fuel, inherent safety of the reactor increases in accidents with loss of coolant flow and introduction of positive reactivity because the coated particles have developed heat-exchange surface and their coats are able to keep fission products at higher temperatures than the steel cladding of traditional fuel rods.

1. Introduction

The present conceptual paper studies the possibility of using fuel assemblies (FA) with coated particles in the core of a reactor type BN-800 [1] in order to increase inherent safety. The microfuel were developed for high-temperature gas-cooled reactors (HTGR). It is due to microfuel design that HTGR characteristics were validated: helium coolant temperature above 750°C, supercritical parameters of steam, coefficient of efficiency above 45% for the steam turbine and about 50% for the gas turbine, confinement of fission products up to temperature (1600-1800)°C in a coolant loss accident.

Unfortunately, the advantages of using microspherical fuel for inherent safety increase have not been studied sufficiently in the atomic sector. There are grounds for considering that microfuel can be used in reactors of different types with extra technical and economic effect in addition to safety enhancement. The unique features of microspherical fuel give us a reason to consider it a new elemental basis of nuclear power engineering.

If FAs with microfuel with (U, Pu)C-fuel are applied in the reactor of type BN-800, (U,Pu)C fuel temperature is not expected to rise above 750°C at maintaining sodium average mixed temperature 550°C at the core outlet.

The reasons for using FAs with microfuel in the reactor core of type BN-800 are:

- increase of inherent safety in emergency states;

- no limitations of steam parameters and future possibility of reaching a high coefficient of efficiency at increase of sodium average mixed outlet temperature and using high parameters of steam in prospect up to (37 MPa, 700°C) [2];

- low fuel temperature makes it possible to expect average burnup 10% of heavy atoms (h.a.) at relatively small thickness of microfuel outer coat;

- decrease of steel quantity in the core and use of mixed uranium-plutonium carbide fuel ensure improved characteristics of fuel breeding.

The main factor limiting increase of energy conversion efficiency for modern liquid metal coolant (sodium or lead) reactors is the necessity of using steel claddings of fuel elements. Their permissible temperature does not exceed (700-710)°C even in nominal conditions of operation. So steam temperature is only 480-500°C and coefficient of efficiency about ~ 42%. At that, temperature increase margin is small for steel claddings in emergencies. It is already at temperature ~ 900°C that steel claddings are no more hermetic and gaseous fission products get to the primary circuit coolant. If we use microspherical fuel that has a large cladding temperature margin, it becomes possible to prevent much activity from getting to the coolant even in case of sodium boiling.

2. Reactor BN-800 Microspherical Fuel Core Arrangement

It was decided at the present stage of work to take the same core cartogram as in the standard BN-800 core with full MOX fuel charge [3]. A three-zone arrangement with different plutonium content in fuel was also accepted in order to flatten radial power density. Calculated validation of plutonium content in the core was performed with program JARFR [4].

The purpose of variant design studies was to ensure required design values for the following neutronics characteristics: power peaking factor, reactor breeding ratio, core breeding ratio, sodium void effect, contribution of each subzone to the breeding ratio, reactivity balance.

It was decided to use microfuel with the coolant feed from the centre to organize coated particles cooling. This type of FA is suitable because such FA can be used well in the standard BN-800 core without changing the reactor design and sodium flow rate profiling method. Fig. 1 shows microfuel FA schematic diagram.

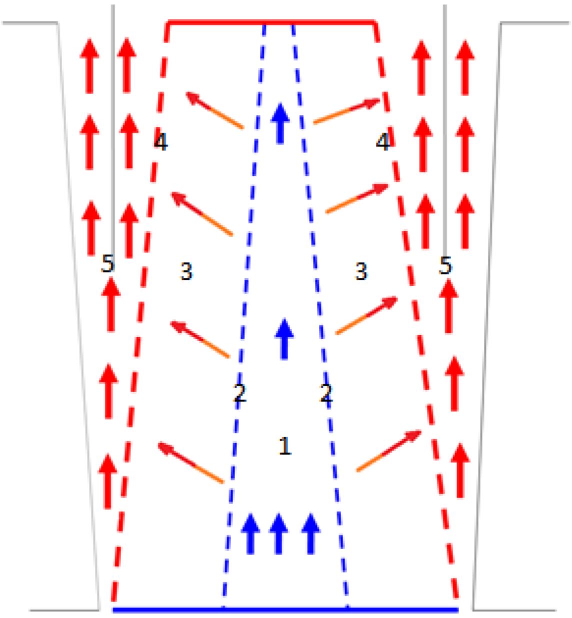


FIG.1. FA Schematic diagram with coolant feed from the centre. 1- distributing header. 2-perforated wall. 3-microspherical fuel charge. 4-perforated outer wall. 5-inter-FA space.

Fuel assembly with microfuel bottom nozzle is accepted the same as in BN-800. Coolant is supplied through the bottom nozzle to the perforated distributing header dispensing coolant to FA coated particles fuel charge. Then coolant passes perforation holes in the outer FA clad and is collected in the inter-FA space. All sodium of the core takes part in heat exchange in such type of FA.

Fig. 2 shows the construction diagram for used in calculation microspherical fuel; the construction diagram is analogous to developed one at NRC “KI” for FGR [5] and table 1 presents material composition of the layers. Such construction diagram of coated particles was chosen as an example and demonstration of the possibility of using fuel of such type in the fast sodium reactor.

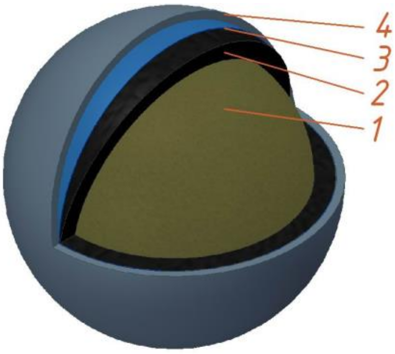


FIG.2. Microspherical particle.

Table 1. Coated Particle Composition

#	Layer Material	Diameter/Thickness, mm	Density, g/cm^3
1	fuel kernel UC+PuC;	1.64 /-	12.0
2	porous PyC;	- / 0.125	0.8
3	dense PyC;	- / 0.005	1.8
4	SiC.	- / 0.05	3.2

Table 2 presents comparison of microspherical fuel FAs and BN-800 FAs.

Table 2. Comparison of microfuel FA and BN-800 FA.

Parameter	microfuel FA	BN-800 FA
Na maximal temperature at outlet, ºC	604.5	605
Na average temperature at outlet, ºC	555	547
Maximal temperature of fuel elements coatings, ºC	700	700
Maximal permissible temperature of fuel elements coatings, ºC	1600	900
Width across fields, mm	96	96
Flow rate through 1 FA, kg/s	13,7	13.7
Maximal sodium heating, ºC	250.2	248.6
Pressure differential, bar	1.5	7
Maximal fuel temperature in the operating mode ºC	740	2100
Maximal permissible fuel temperature, ºC	1596.8	2696.8

3. Thermal Hydraulics Calculation Procedure

NRC “KI”, All-Russian Research and Design Institute for Atomic Power Engineering (VNIIAM), Joint-Stock Company "I.I. Polzunov Scientific and Development Association on Research and Design of Power Equipment" (NPO CKTI) in Russia developed the microfuel coolant cross flow FA calculation procedure. These works were a basis for a mathematical model and two-dimensional program RCOL for FA thermal hydraulics calculation with coolant cross flow in microfuel charge. The full description of the mathematical model used in the program RCOL is presented in paper [6].

As it had been shown, microfuel FA was the design with coolant feed from the centre to the inter-FA space. The headers’ porosity was chosen on the basis of factors of coolant rate consistency in the inlet header and coolant temperature in the outlet header.

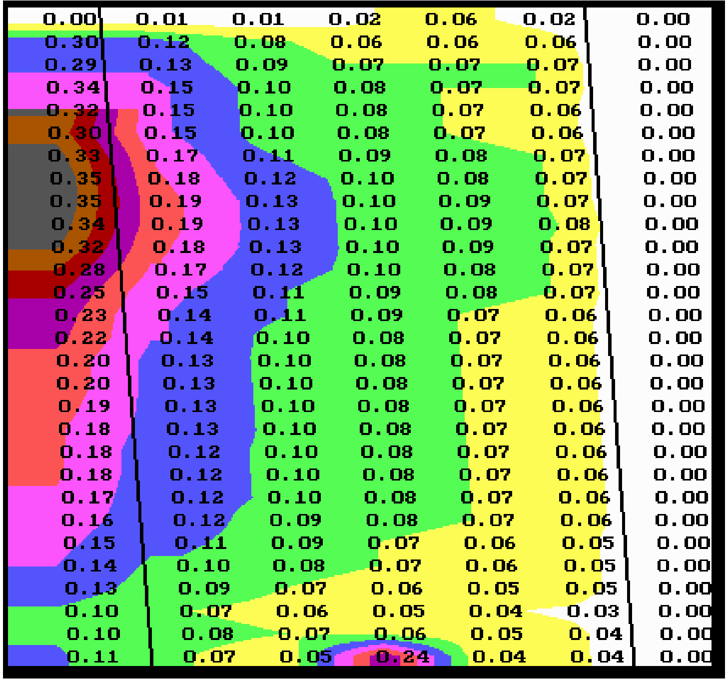
The task of FA thermal hydraulics calculation with cross flow of coolant is to ensure necessary coolant flow rate distribution according to power distribution along the core height as well as ensure acceptable pressure difference and maximal fraction of volume occupied by microfuel charge. Flow nonuniformity along height is conditioned by a so called header effect for FA of such type.

Choice of flow areas of inlet and outlet headers, it means choice of diameters of the inlet header truncated cone and maximal and minimal clearances between FA enable acceptable pressure differential. The same parameters influence to the greatest extent nonuniformity of flow rate distribution along FA height. The maximal rate of sodium was accepted as a limiting parameter with regard to clads erosion.

The engineering one-dimensional procedure based on flow equation was used to describe the coolant flow in the headers.

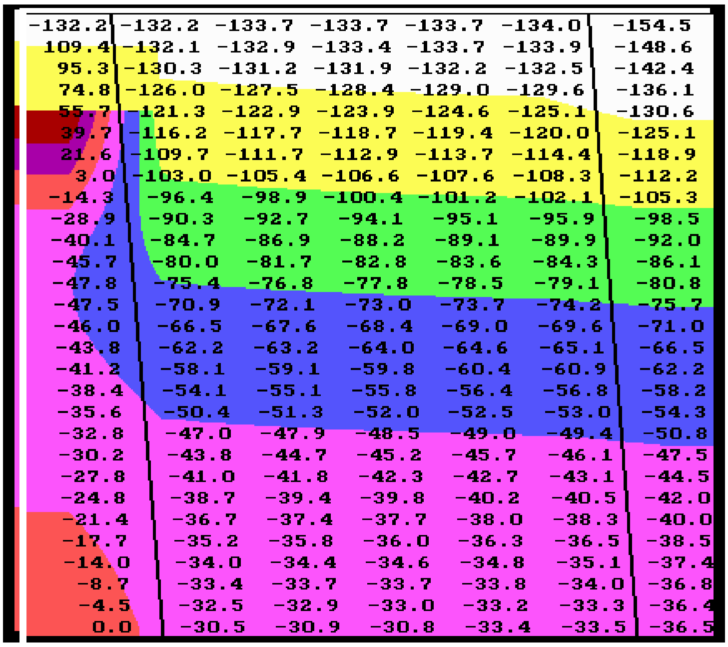
4. Results of Thermal Hydraulics Calculation

Below there are some results of FA thermal hydraulics calculation.



0.00	0.01	0.01	0.02	0.06	0.02	0.00
0.30	0.12	0.08	0.06	0.06	0.06	0.00
0.29	0.13	0.09	0.07	0.07	0.07	0.00
0.34	0.15	0.10	0.08	0.07	0.07	0.00
0.32	0.15	0.10	0.08	0.07	0.06	0.00
0.30	0.15	0.10	0.08	0.07	0.06	0.00
0.33	0.17	0.11	0.09	0.08	0.07	0.00
0.35	0.18	0.12	0.10	0.08	0.07	0.00
0.35	0.19	0.13	0.10	0.09	0.07	0.00
0.34	0.19	0.13	0.10	0.09	0.08	0.00
0.32	0.18	0.13	0.10	0.09	0.07	0.00
0.28	0.17	0.12	0.10	0.08	0.07	0.00
0.25	0.15	0.11	0.09	0.08	0.07	0.00
0.23	0.14	0.11	0.09	0.07	0.06	0.00
0.22	0.14	0.10	0.08	0.07	0.06	0.00
0.20	0.13	0.10	0.08	0.07	0.06	0.00
0.20	0.13	0.10	0.08	0.07	0.06	0.00
0.19	0.13	0.10	0.08	0.07	0.06	0.00
0.18	0.13	0.10	0.08	0.07	0.06	0.00
0.18	0.12	0.10	0.08	0.07	0.06	0.00
0.18	0.12	0.10	0.08	0.07	0.06	0.00
0.17	0.12	0.10	0.08	0.07	0.06	0.00
0.16	0.12	0.09	0.08	0.07	0.06	0.00
0.15	0.11	0.09	0.07	0.06	0.05	0.00
0.14	0.10	0.08	0.07	0.06	0.05	0.00
0.13	0.09	0.07	0.06	0.05	0.05	0.00
0.10	0.07	0.06	0.05	0.04	0.03	0.00
0.10	0.08	0.07	0.06	0.05	0.04	0.00
0.11	0.07	0.05	0.24	0.04	0.04	0.00

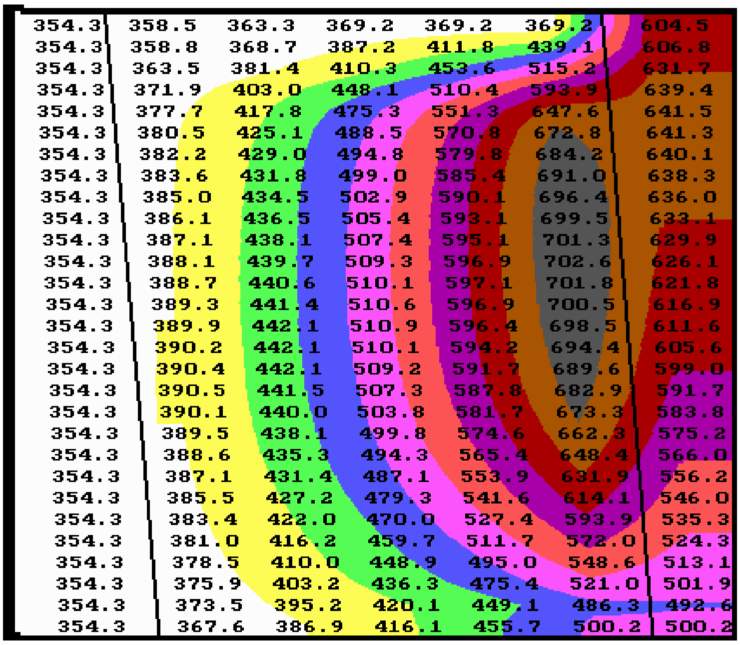
FIG.3. Radial velocity of sodium by height (m/s).



-132.2	-132.2	-133.7	-133.7	-133.7	-134.0	-154.5
109.4	-132.1	-132.9	-133.4	-133.7	-133.9	-148.6
95.3	-130.3	-131.2	-131.9	-132.2	-132.5	-142.4
74.8	-126.0	-127.5	-128.4	-129.0	-129.6	-136.1
55.7	-121.3	-122.9	-123.9	-124.6	-125.1	-130.6
39.7	-116.2	-117.7	-118.7	-119.4	-120.0	-125.1
21.6	-109.7	-111.7	-112.9	-113.7	-114.4	-118.9
3.0	-103.0	-105.4	-106.6	-107.6	-108.3	-112.2
-14.3	-96.4	-98.9	-100.4	-101.2	-102.1	-105.3
-28.9	-90.3	-92.7	-94.1	-95.1	-95.9	-98.5
-40.1	-84.7	-86.9	-88.2	-89.1	-89.9	-92.0
-45.7	-80.0	-81.7	-82.8	-83.6	-84.3	-86.1
-47.8	-75.4	-76.8	-77.8	-78.5	-79.1	-80.8
-47.5	-70.9	-72.1	-73.0	-73.7	-74.2	-75.7
-46.0	-66.5	-67.6	-68.4	-69.0	-69.6	-71.0
-43.8	-62.2	-63.2	-64.0	-64.6	-65.1	-66.5
-41.2	-58.1	-59.1	-59.8	-60.4	-60.9	-62.2
-38.4	-54.1	-55.1	-55.8	-56.4	-56.8	-58.2
-35.6	-50.4	-51.3	-52.0	-52.5	-53.0	-54.3
-32.8	-47.0	-47.9	-48.5	-49.0	-49.4	-50.8
-30.2	-43.8	-44.7	-45.2	-45.7	-46.1	-47.5
-27.8	-41.0	-41.8	-42.3	-42.7	-43.1	-44.5
-24.8	-38.7	-39.4	-39.8	-40.2	-40.5	-42.0
-21.4	-36.7	-37.4	-37.7	-38.0	-38.3	-40.0
-17.7	-35.2	-35.8	-36.0	-36.3	-36.5	-38.5
-14.0	-34.0	-34.4	-34.6	-34.8	-35.1	-37.4
-8.7	-33.4	-33.7	-33.7	-33.8	-34.0	-36.8
-4.5	-32.5	-32.9	-33.0	-33.2	-33.3	-36.4
0.0	-30.5	-30.9	-30.8	-33.4	-33.5	-36.5

FIG.4. Pressure of sodium by height, (kPa)

Pressure loss in microfuel FA makes 154 kPa, this is 5 times less than pressure loss in the standard FA of BN-800. This is conditioned by the efficient use of FA volume space as well as accepted limit of the maximal sodium speed in the headers as well as acceptable nonuniformity of the coolant temperature.



354.3	358.5	363.3	369.2	369.2	369.2	604.5
354.3	358.8	368.7	387.2	411.8	439.1	606.8
354.3	363.5	381.4	410.3	453.6	515.2	631.7
354.3	371.9	403.0	448.1	510.4	593.9	639.4
354.3	377.7	417.8	475.3	551.3	647.6	641.5
354.3	380.5	425.1	488.5	570.8	672.8	641.3
354.3	382.2	429.0	494.8	579.8	684.2	640.1
354.3	383.6	431.8	499.0	585.4	691.0	638.3
354.3	385.0	434.5	502.9	590.1	696.4	636.0
354.3	386.1	436.5	505.4	593.1	699.5	633.1
354.3	387.1	438.1	507.4	595.1	701.3	629.9
354.3	388.1	439.7	509.3	596.9	702.6	626.1
354.3	388.7	440.6	510.1	597.1	701.8	621.8
354.3	389.3	441.4	510.6	596.9	700.5	616.9
354.3	389.9	442.1	510.9	596.4	698.5	611.6
354.3	390.2	442.1	510.1	594.2	694.4	605.6
354.3	390.4	442.1	509.2	591.7	689.6	599.0
354.3	390.5	441.5	507.3	587.8	682.9	591.7
354.3	390.1	440.0	503.8	581.7	673.3	583.8
354.3	389.5	438.1	499.8	574.6	662.3	575.2
354.3	388.6	435.3	494.3	565.4	648.4	566.0
354.3	387.1	431.4	487.1	553.9	631.9	556.2
354.3	385.5	427.2	479.3	541.6	614.1	546.0
354.3	383.4	422.0	470.0	527.4	593.9	535.3
354.3	381.0	416.2	459.7	511.7	572.0	524.3
354.3	378.5	410.0	448.9	495.0	548.6	513.1
354.3	375.9	403.2	436.3	475.4	521.0	501.9
354.3	373.5	395.2	420.1	449.1	486.3	492.6
354.3	367.6	386.9	416.1	455.7	500.2	500.2

FIG.5. Sodium temperature distribution by height in the central FA, (^oC).

5. Neutronics Calculation Procedure

The calculation was conducted in the program system JARFR [4]. The program system JARFR is intended to calculate neutronics characteristics of the fast neutron reactors in multigroup diffusion approximation for two-dimensional and three-dimensional computational models at different angles of symmetry and geometries of the calculation cell in plan. Increase of energy at neutron dissipation is not considered.

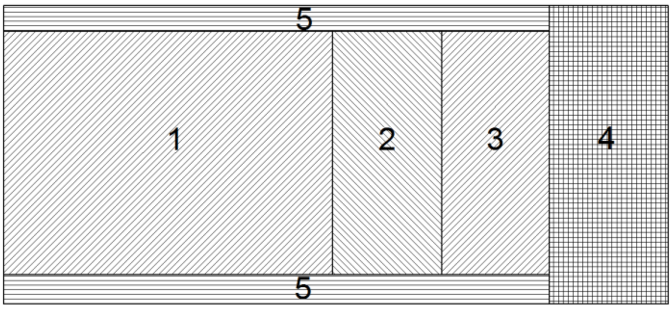


FIG.6. Diagram of data assignment by radius and height. 1st, 2nd and 3rd zones of various content of plutonium. 4-side breeding zone 5 – end breeding zones.

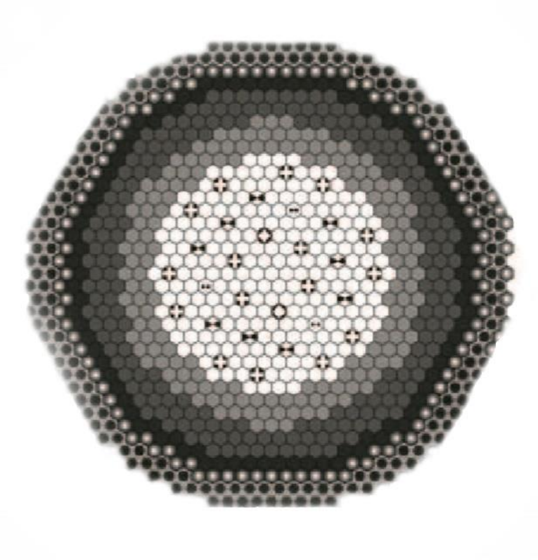


FIG.7. Computational model of microfuel BN emergency protection (EP) (it was accepted analogous to BN-800 with full MOX-fuel charge).

⬡	low enrichment area FA	211
⬡	middle enrichment zone FA	156
⬢	high enrichment zone FA	198
⬢	side breeding zone FA	90
⬡	steel protective shield assembly	155
✚	shim rods	16
⧓	scram rods	9
⋈	passive safety rods	3

6. Obtained Results

The core height and plutonium content varied to determine the most suitable variant of the core with microfuel FA, characteristics of which comply with design values of the standard core of BN-800 with mixed dioxide fuel.

It is possible to draw a conclusion based on analysis of considered variants of the cores with microfuel that close to design characteristics are for the core variant with plutonium content in zones 1, 2, 3 13.5%, 15.5% and 18.5% respectively and core height 90 cm. Table 3 presents isotope composition of used plutonium.

Table 3. Isotope composition of used plutonium

Isotope	Pu-239	Pu-240	Pu-241	Pu-242
Content, %	56	30	13	1

The present paper estimates full sodium void reactivity effect for the whole core, which turned out to be negative. The variant with emptying the central part of FA by height from the 1st to the 11th FA row having positive sodium void reactivity effect was calculated to determine the most possible reactivity jump due to void (density) effect realization.

It is possible that in the first place sodium cooling microspherical fuel charge can boil in emergency due to FA design peculiarity. Sodium temperature in the inlet header is lower than the boiling temperature. Conducted calculation resulted in estimation of the maximal positive void reactivity effect ~2.6 β.

The Doppler (fuel temperature) coefficient was also determined:

$$\alpha_{\mathrm{T}doppler} = -1.09 \cdot 10^{-5}\ 1/{}^{o}\mathrm{C}$$

The negative Doppler effect of reactivity can compensate ~ 2.7β in case of emergency temperature jump up to 1600 °C (maximal operating temperature for the microspherical fuel coating) and sodium boiling.

7. Microfuel thermomechanic Calculation Procedure

Code GOLT [7] developed by A.A. Bochvar All-Russian Scientific Research Institute for Inorganic Materials for thermomechanical calculation of coated particles for HTGR reactors was used at the initial stage of work to determine operability of the proposed design of the coated particle.

Code GOLT calculation resulted in building a relation of microfuel coating (SiC layer) destruction probability and burnup shown in Fig. 8. It is obvious from the figure that, if burnup is 10%, SiC layer destruction probability is 0.001%.

The integral flux (fluence) of fast neutrons $3 * 10^{23}$n/cm^2 for fuel campaign ~1.5 years is typical for fast neutron reactors. It takes about 6 years to reach such a fluence in HTGR reactors.

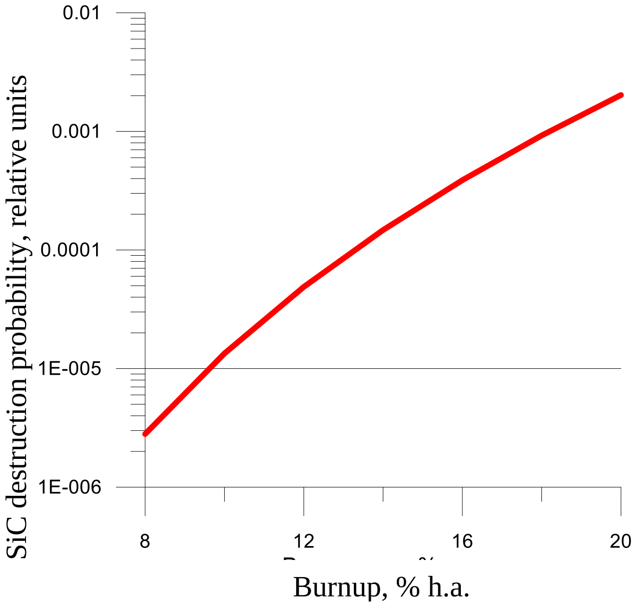
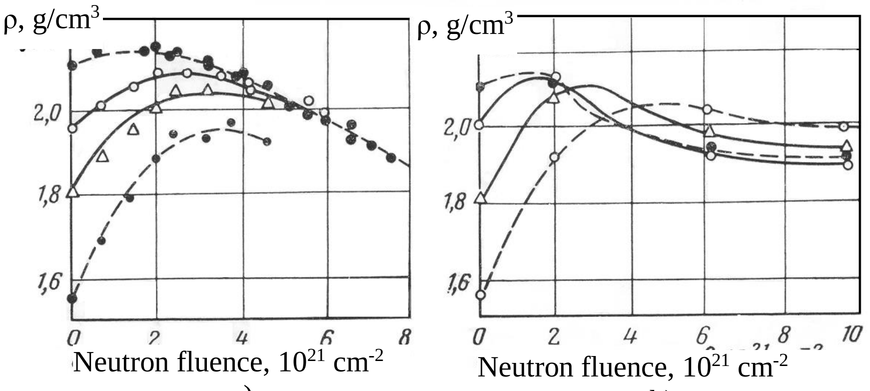


FIG. 8. Relation of microfuel coating (SiC layer) destruction probability and burnup according to code GOLT.

Shrinkage and swelling of the buffer layer of porous pyrolitic graphite (PyC) in coated particles of high-temperature reactors (HTGR) determine microfuel operability to a great extent. The porous pyrolitic graphite (PyC) layer contains gaseous fission products (GFP). It means that it "transmits" GFP pressure to the following (hermetic) microfuel layers. At the initial moment of microfuel operation there is a gaseous clearance between the kernel and porous PyC layer about 12 µm. The swelling kernel and swelling porous PyC layer fill this clearance. At that the swelling PyC layer and gaseous fission products exert increasing pressure on the following hermetic microfuel layers.

Paper [8] provides experimental data of PyC behavior depending on irradiation temperature. These data provided in Fig. 9 were used in design of all HTGR.



a)

b)

FIG. 9. Relation of density of pyrocarbons (ρ) with turbostratic structure ($3.0<L_c<200Å$) and neutron fluence with $E>0.18$ MeV irradiated at temperature 900 (a) and 1250°C (b). The curves have various initial graphite density.

A peculiarity of the curves in Fig. 9 is obvious shrinkage of PyC and then its swelling.

Further on the coated particle operability will be estimated supposing that the following two independent processes take place during irradiation of porous PyC:

- -PyC shrinkage due to rather high temperature 900-1250°C for a long period;
- -simultaneous swelling due to fast neutron flux.

Long shrinkage is "distorted" by the swelling process under effect of fast neutron flux. It is evident from some curves in figure 9 that shrinkage and swelling processes can compensate each other completely and PyC density almost will not change. These processes are not studied separately.

So it is expedient to study shrinkage due only to temperature and consequently separate shrinkage and swelling processes. This separation is not very urgent for HTGR because the above data was obtained for conditions typical for HTGR.

If we use coated particles for reactors of other types for example WWER or BN, such separation is quite urgent because BN-800 core coated particle temperature is 700°C (550°C less) and WWER core is only 300°C. Direct use of data provided in Fig 9 to calculate microfuel operability in WWER and BN will possibly give results of great uncertainty.

Further Table 4 contains the main parameters of BN-800 with coated particles charge.

Table 4. Main parameters of BN-800 with microfuel

Parameter	BN-800 microfuel
Emergency protection (EP) height, mm	900
EP diameter, m	2.56
Coated particle fuel charge, t	16
Width across fields, mm	Top 96/ Bottom 88.5
Content by plutonium in 3 subzones, %	13.5/15.5/18.5
FA clad material	EP-450
Specific charge by 239+241 plutonium per GW, kg	2183
Specific excess production of fuel per GW*year, kg	190
Reactor campaign, eff. days	155
Fuel campaign, eff. days	465
EP breeding ratio	0.97
Reactor breeding ratio	1.24
Radial power peaking factor	1.17
Average burnup, %	6.4
Maximal burnup, %	9.8

8. Conclusion

The present paper demonstrates calculation substantiation of possibility of using FA with microspherical (U, Pu)C-fuel in the fast sodium reactor core using BN-800 reactor as an example. Use of such type of fuel with developed heat removal surface and design solution on microspherical fuel charge cooling in FA gives additional possibilities of inherent safety increase and competitiveness enhancement of reactors of such type.

The main positive moments of conversion to FA with microspherical fuel are:

- increase of inherent safety in emergencies due to developed surface of heat removal, low part of stored heat and microfuel high temperature resistance.

- improvement of neutronics characteristics due to low fuel temperature, decrease of steel quantity in FA and use of highly heat conducting dense mixed carbide fuel in the closed fuel cycle.

- increase of fuel breeding ratio and decrease of reactivity margin; it is possible to optimize and improve these parameters further taking into consideration that study was conducted within the framework of BN-800 reactor core.

There are reasons for believing that thanks to such tolerant fuel, it is less probable that fission products get to the primary circuit in emergencies with coolant loss and positive reactivity introduction because the coating of coated particles can withstand higher temperatures than a steel coating of traditional fuel elements (rods).

At the moment it is necessary to solve a number of following problems for experimental substantiation of such fuel use in fast sodium reactors in practice:

- Study of microfuel corrosion in sodium,
- Microfuel test in a research fast reactor at fluence 10^{23} n/cm^2,
- Study of the header effect at the large-scale FA models,
- Study of mechanical interaction of microfuel charge and clads during thermal oscillations in the temperature range 20-600^{o}C.
- Study of thermomechanical model of microfuel behavior in BN core.

If the proposed above experimental substantiations give positive results, it will be possible to achieve considerable effects in the future using coated particles at development of a new fast sodium reactor design or for inherent safety increase of already existing reactors.

References

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