Analysis of the Characteristics of the Fast Breeder Reactor with Metallic Fuel

I.I. Drobyshev[1], E.F. Seleznev[2]

[1]All-Russian Research Institute for Nuclear Power Plants Operation», JSC ("VNIIAES JSC"),
25, Ferganskaja st., Moscow, 109507, Russia

[2]Nuclear Safety Institute of the Russian Academy of Sciences, 52, B.Tulskaya st.,
Moscow 115191, Russia

*E-mail contact of main author:*dr.yuri92@yandex.ru

Abstract

A lot of approaches are considered to increase a marketability of fast breeder reactors producing two products – electricity and exceeding nuclear fuel. To increase a production of exceeding nuclear fuel it is proposed to switch from widely used oxide fuel to carbide, nitride and the densest metallic uranium fuel. In a fabrication chain of the exceeding nuclear fuel a cost of spent nuclear fuel refabrication is also important. From all kinds of nuclear fuel, considered worldwide at the fast breeder reactors' area, the metallic fuel provide the highest values of the exceeding nuclear fuel production i.e. the highest value of the breeding rate (BR) and the lowest refabrication cost for spent nuclear fuel due to melting technology.

But the reactors with metallic fuel have issues which lead to the absence of completed projects and their realizations. The main problem of the safety assurance of such reactors is related to a weak reactivity feedback by fuel temperature. To solve this problem an approach with heterogeneous placement of the fuel at the axial direction is suggested. Layout of the depleted metallic fuel is proposed at the bottom blanket region and at the top blanket region above the sodium cavity to receive high breeding rate. In addition, placement of the oxide fuel with central thin layer made of metallic fuel in the core is proposed to provide sufficient level of temperature feedback. An improvement of this approach with replacement of the oxide fuel from the bottom part of the core by a metallic plutonium fuel is considered at the paper.

It is shown by calculations that the suggested approach together with the replacement of the oxide fuel by the metallic depleted uranium fuel at the assemblies of a radial blanket region ensures the high reactor BR with sufficient level of the temperature feedback. The high BR value is provided by using of the metallic fuel in the majority of reactor's volume. Substantial feedbacks are provided by the utilizing of the oxide fuel at the area of high coolant, fuel and cladding temperatures. At the same time the metallic plutonium fuel is placed at the area of high power density and low temperature of the core components.

Key words: Fast breeder reactor, metallic fuel, core performance parameters.

1. Introduction

The main advantages of the fast reactor core with a metallic fuel:

- high value of the breeding rate of a core(BRc) ;
- low burnup reactivity loss at the reactor's operation campaign;
- high thermal conductivity, providing low fuel temperature;
- smaller core components size to provide the same neutron characteristics it with other fuel types.

In addition metallic fuel has many advantages with using it in a closed fuel cycle. Manufacturing process produce a lower waste, largely meets environmental requirements, the production takes a small area and provides high performance [1]. Pyrochemically recycling of spent U-Pu-Zr Fuel requires 5 times less expensive than dioxide, allows to recover of isotopes U and Pu separetly and the fission products is consist around 1% wt [2].

Disadvantages of the metallic fuel is related with the properties given advantage to it:

- high thermal conductivity results to small temperature differences at fuel element radius, that leads to a significant reduction in compartment with oxide fuel a value of the fuel temperature reactivity feedback;
- a hardness of the core neutron spectrum leads to an increase in the value of the sodium void reactivity effect.

To find a decision of a problem of providing significant reactivity feedback in the fast breeder reactor (FBR) with metallic fuel let us consider option of the heterogeneous (hybrid) layout core, consisting of a metal fuel in its lower part, i.e. at low temperature area separating by a sink layer of metallic depleted uranium with oxide fuel in the upper part of the core where there are high fuel and coolant temperatures, providing sufficient temperature reactivity feedback.

2. Input data and model description

Based on the 1980s development, where it was shown that in the core size meter long optimum reproducing metallic layer size is about 10 cm without expansion of the core compared with the original homogeneous core [3]. The reproducing layer improves the axial heat production alignment that compensates for a relatively small energy production in it. The main advantage of this type of heterogeneity is hybrid area having been installed instead of homogenous without any design change of the reactor and discharge collector.

The influence of the sink layer on the breeding is to move of the breeding process from the core to the axial blanket region (BR). Initial height of the core is set to (80 cm) and the thicknesses of the upper and lower BR to 35 cm with reducing the thickness of boric upper shield up to 10 cm. The radial structure of a reactor core, including fuel assembly design is identical to the original (homogeneous) core with radial blanket. The differences are only in the axial structure. Axial structures of the heterogeneous (or hybrid) core are included layers with different types of utilized uranium. There are two part of the core with both enrichment uranium oxide at the top and metallic fuel at the bottom separated by central sink layer of metallic alloy with depleted uranium. Another difference in axial reactor structure is a presence of top blanket region of metallic alloy with depleted uranium in heterogeneous case instead of sodium void at homogeneous. Illustration of the axial structure of the core in homogeneous and heterogeneous layout cases is shown in Fig. 1.

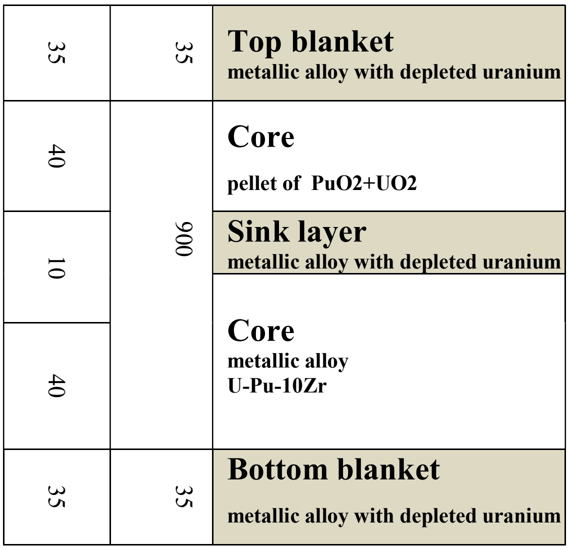

Fig. 1. - Axial structure of heterogeneous core, layer size in cm.

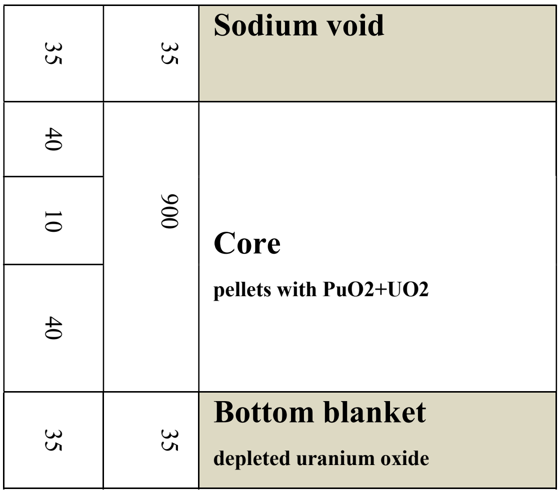

Fig. 2. - Axial structure of homogenious core, layer size in cm.

The main input data are common to both options considered cors are presented in Table 1.

The reactor was considered in a closed fuel cycle. The isotopic composition of fuel are calculated on the assumption that:

- blanket are processed together with the core, all the plutonium is mixed, excess plutonium removed;
- spent nuclear fuel delay in the external cycle of 3 years: 2 years in the internal reactor fuel storage and 1 year for the processing, manufacturing and transport [4].

In order to align the axial field energy production in the axial direction by setting enriched in a ratio of 1 / 1.38, equal placement of fissile nuclides in the upper and lower parts of the core are got, so that the growth of linear heat are related with the utilize of sink layer.

TABLE I: INPUT DATA FOR FBR WITH THE HETEROGENIOUS CORE [5].

Power, heat/electric., MWt	2800 / 1200
Core fuel load	U-13.3Pu-18.5Zr/(Pu-U)O_2
Density of the fuel [2], g/cm^3	14.1/9.0
Estimated thermal conductivity of the fuel[2,6] , w/(m K)	16.0/2.3
Campaign lasting, effective days	330
Breeding region material	depleted metallic uranium
Smear density of the metallic fuel, g/cm^3	10.6
Depleted uranium fraction U-235, %	0.2
Blanket region height, cm	2*35
Number of control rods	27
Fuel assembly pitch, mm	185
Fuel element diametr×thickness of cladding, mm	9.3×0.6
Number of fuel element in the assembly	271
Fuel volume fraction in the assembly	0.498
Coolant volume fraction in the assembly	0.298

To take into account all the factors affecting the performance of the fuel supplied from the processing of a closed fuel cycle manufacture is currently impossible, then to calculate the characteristics of the reactor has been conditionally accepted the composition of plutonium, corresponding to a closed fuel cycle of fast neutron reactors [5]. For the calculations the following option of placement fuel assemblies in the core model (Fig. 2). The core consists of a 3 fuel assemblies types that are differ in a fuel composition. To the reactivity control in the model placing 27 control rods, divided according to their functions into three groups: AR - automatic control, KS – to compensate the reactivity loss, AZ - emergency protection. The core is surrounded by two rings of blanket assemblies and also radial steel shield.

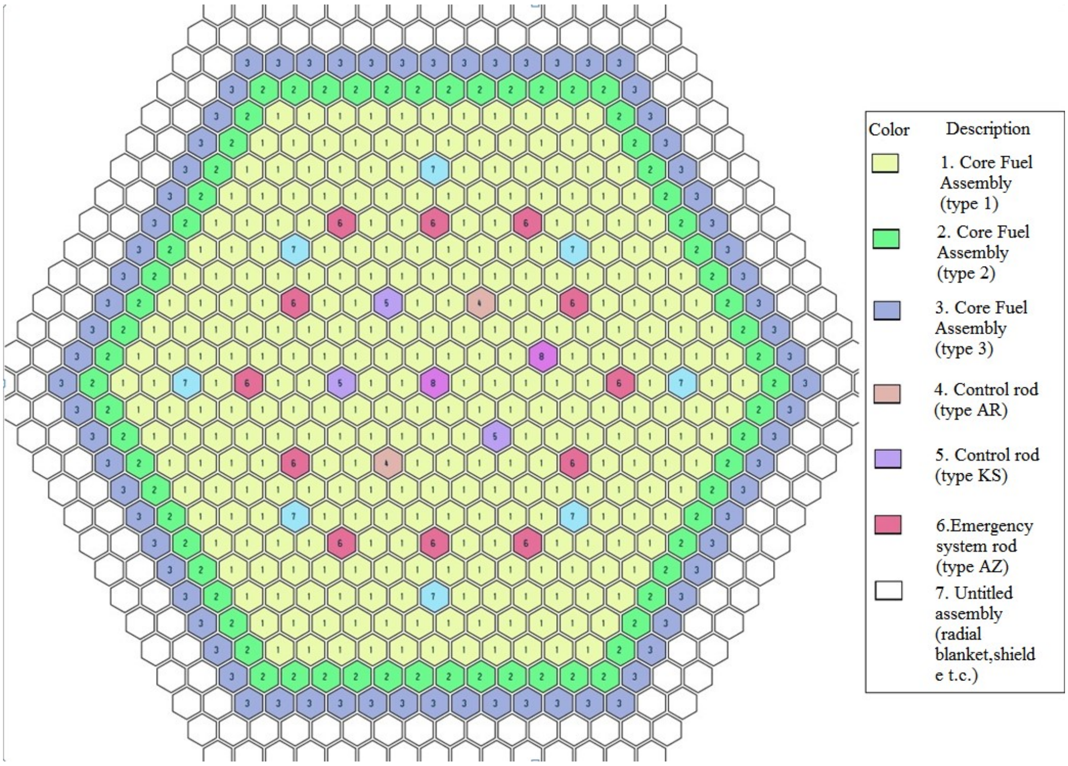

Fig. 3. Radial core layout of the model

3. Core calculation results with homogeneous and heterogeneous fuel layout

Modules of the software package «GEFEST» are used as calculation software which are utilized for support of the commercial fast reactor operation [6]. As the results of calculation neutron flux, energy production, the temperature of the core components and key nuclides burnup fields and characteristics of the effects of reactivity, delayed neutrons and reproduction were obtained. To burnup reactivity loss assessment burnup calculation on 330 effective days or one calendar year was performed.

On Fig. 4 are shown the distribution of energy production along the central row in homogeneous and heterogeneous layout from the center to the edge of the core, normalized to the maximum value of the homogeneous option. Near-zero point values correspond to cells with partially inserted control rods. To align radial field of heat production in the heterogeneous option is proposed a not using the sink layer of depleted uranium at fuel assembly in the two outer rows, that should been affected on plutonium accumulation in the radial blanket region. In addition the accumulations of plutonium in the axial sink layer at the two fuel assemblies on edge of the core significantly lower.

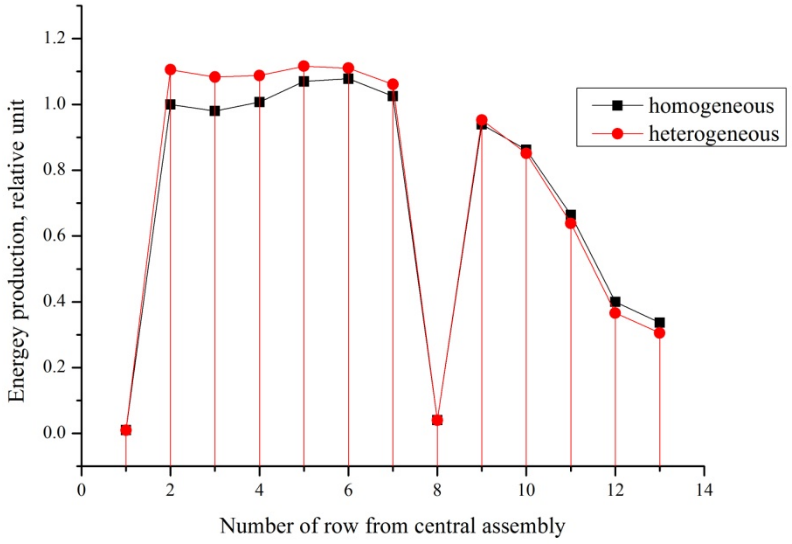

Fig. 4. The distribution of energy production along the central row in homogeneous and heterogeneous option.

Thus is proposed to modelling edge rows of assemblies without axial sink layer. Such a method is considered by both Russian and Japanese experts [3, 7]. It allows:

- to increase the power of edge fuel assembly on ~ 20%;
- align the accumulation of plutonium in the sink layer.

Estimation of the breeding ration (BR) in the whole reactor and its components for core areas: the radial blanket (RB), top (TBR) and bottom (BBR) blanket regions for the two options is shown in Table 2. The data indicate a significant advantage heterogeneous layout in terms of fuel reproduction.

TABLE 2: COMPAREMENT THE BREEDING RATIO AND COMPONENT.

Model type	Heterogenious	Homogenious
BR lower core part	0.52	-
BR upper core part	0.362	-
BR core	0.88	0.98
BR RB	0.16	0.12
BR TBR	0.20	-
BR BBR	0.18	0.12
BR sink layer	0.21	-
tot. BR	1.50	1.20

The distribution of the coolant temperature, fuel cladding and fuel into the channel from fuel assembly with peak value of the power are shown on Fig.5, calculated under the condition of heating the coolant in the core at 150 ° C.

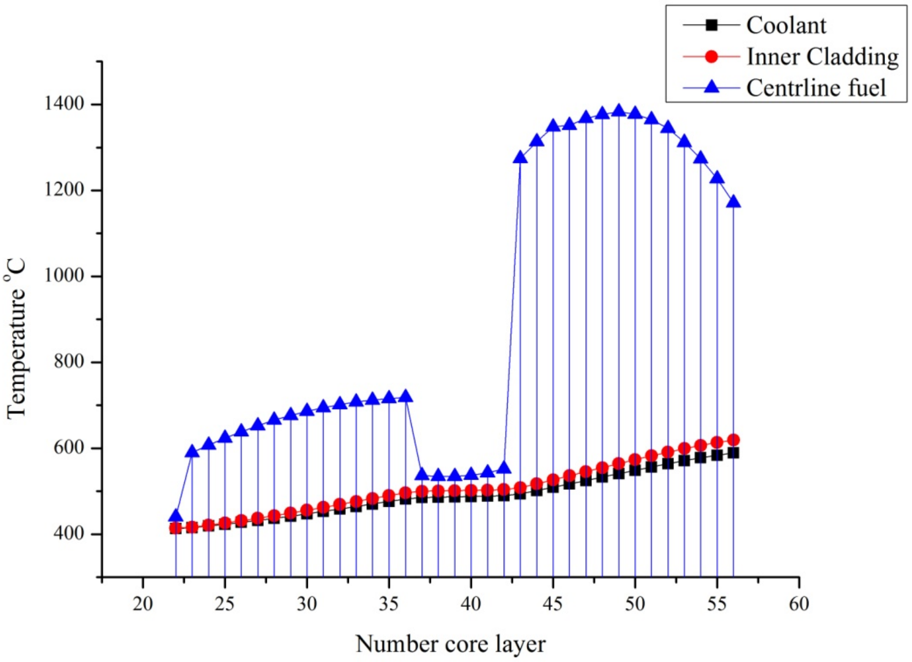

Fig. 6 Distribution of the coolant, fuel and inner cladding temperature in the channel with the peak power.

It follows from the Fig. 6 that the temperature of the fuel rod cladding does not exceed 650 ° C, e.g. is away from the critical limits. Metallic fuel temperature does not exceed 750 ° C, while in [2] shows that when using a doped zirconium metallic fuel and austenitic steels as a cladding with burnup slows the migration of actinides and lanthanides in the cladding to the austenitic steel, iron and nickel - to fuel. These protective functions metallic alloy with zirconium stored at temperatures up to 780 °C, which exceeds the maximum operating temperature of the fuel element.

The results of the core characteristic calculation for both layout options including the feedback and burnup values are presented in a table 3.

TABLE 3: CHARACTERISTICS OF THE CORE.

Characteristic description	Unit	Heterogeneous model	Homogeneous model
Effective delayed neutron fraction	10^{-3}	4.16	4.06
Peak linear power density	kWt/m	39.2	43.5
Peak inner temperature cladding in lower part	°C	535	-
Peak inner temperature cladding in upper part	°C	639	642
Breeding ratio		1.5	1.25
Breeding ratio of the core		0.88	0.96
Unevenness of axial linear power		1.12	1.2

Coolant inlet temperature reactivity coefficient	pcm/°C	-0.54	-0.85
Power reactivity coefficient	pcm/% power	-1.32	-2.91
Sodium void worth	% ΔK/K	2	1.6
Burnup reactivity loss	% ΔK/K	0.33	1.3

The obtained results demonstrate the advantages of a heterogeneous layout option compared to homogeneous in terms of energy production field alignment and a less value of burnup reactivity loss. It should be noted that the use of the oxide fuel is possible to achieve acceptable values of the power and inlet temperature reactivity coefficient having the same sign and order with homogeneous layout option. It is possible because of higher value of radial temperature gradient at oxide fuel pellet due to lower value of the thermal conductivity for oxide fuel (see Table 1) and placing it in a «hot» part of assembly. From the presented data is followed in the heterogeneous option achieving a significant value of the sodium void reactivity effect that could be reduced by creation a sodium void up from the core upper part [4]. In addition during the analysis of contribution components in the value of sodium void effect was found increasing the difference in enrichment between the core axial parts reduces the value of sodium void effect. Calculation results of the hybrid core with the sodium void and with a ratio of enrichments U-12.5Pu-18.8Zr / (Pu-U) O_2 between parts are given in Table 4.

The obtained results demonstrated that an insertion of sodium void it can be reduced the value of sodium void effect below of delayed neutron fraction, but it grows considerably reactivity margin for the campaign, and increases the axial energy production unevenness. However, it should be noted that the basic parameters of such layout option is preferred than homogeneous layout.

TABLE 4: CHARACTERISTICS OF THE HYBRID CORE WITH THE SODIUM VOID.

Characteristic description	Unit	Heterogeneous model
Effective delayed neutron fraction	10^{-3}	4.12
Peak linear power density	kWt/m	43.2
Peak inner temperature cladding in lower part	°C	552
Peak inner temperature cladding in upper part	°C	670
Breeding ratio		1.3
Breeding ratio of the core		0.85

Unevenness of axial linear power		1.18
Inlet temperature reactivity coefficient	pcm/°C	-0.6
Power reactivity coefficient	pcm/% power	-1.48
Sodium void worth	% ΔK/K	0,34
Burnup reactivity loss	% ΔK/K	0.90

4. Conclusion

The report is presented a description of the initial studies of the of the fast breeder core with U-NPu-10Zr metal alloy fuel, where N - variable. The results of the calculations demonstrates that the heterogeneous layout option of the core by using a metallic fuel at the bottom at the cold part of core, and an oxide fuel in the upper hot parts of it, with a sink layer of metallic depleted uranium between has significant advantages in terms of fuel breeding which is the main purpose of fast neutron reactors. In the future is planned to continue research to find the most satisfied layout heterogeneous core assemblies in terms of safety and breeding and receive the characteristics of such assemblies in a closed fuel cycle.

References

1. Yu.M. Golovchenko Some results of Developments and Investigations of Fuel Pins with Metal Fuel for Heterogeneous Core of Fast Reactors of the BN-type, Energy Procedia 7 (2011), pp. 205–212
2. W.J. Carmack ,D.L. Porter, Y.I. Chang, S.L. Hayes, M.K. Meyer, D.E. Burkes,C.B. Lee,T. Mizuno,F. Delage,J. Somers, Metallic fuels for advanced reactors, Journal of Nuclear Materials,Volume 392, Issue 2, 15 July 2009, pp. 139–150
3. V.A. Eliseev, V.I. Matveev Report on the Soviet-Japanese Seminar "Optimization of heterogeneous core with axial layer" IPPE, Obninsk, 16/06/87
4. B.A. Vasiliev, V.A. Vasyaev, D.L. Zverev, S.F. Shepelev et al. BN-1200 project as the basis for the transition to a two component nuclear power energy. Plenary presentation on MNTK-2016 "Security Efficiency and Economics of Nuclear Power", Tenth International Scientific Conference MNTK 2016 JSC "Concern Rosenergoatom" 25-26.05.2016.
5. V.M. Poplavskii, A.M. Tsibulya et al. The core and fuel cycle for future fast neutron reactors, Atomic energy, t. 108, issue 4, pp. 206-212.
6. E.F. Seleznev, A.A. Belov, Calculation support operation of BN-600. Atomic Energy, 2010, t.108, issue 4, pp. 256-259.
7. Kamei T., Jamaoka M., Moriki Y. et al. An Axially and Radially Two-zoned Large LMFBR Core Concept. Nucl. Technology, v. 71, No 3, p. 548, Dec. 1985