Experience And Applicability Of High Dense Metal Uranium In Advanced BN-reactors

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Abstract: JSC «SSC RIAR» has large experience of manufacturing the fertile columns of various types from the metal uranium, the experience of manufacturing and irradiation in fast reactors BOR-60 and BN-350 of full-size elements (FE) and fuel assemblies (FA) that have such columns (more 4000 elements in part of 108 fuel assemblies).

Besides the obtaining of the inherent safety in advanced BN-reactors with the heterogeneous oxide-metal cores of various types (by FA-heterogenization of the core, IFAH – by intra FA-heterogenization, IFEH – by intra fuel elements heterogenization) we could achieve considerable additional economic and ecological preferences. Among them there are the increase of the admissible average burnup of MOX-fuel by ≈20%, the decrease of the mass of manufactured and consumable Pu-containing MOX-fuel by ≈30%, the decrease of consumable Pu-containing FA by ≈30% and other effects.

Key Words: Fast reactors, breeding ratio of active core, metal uranium, irradiation in fast reactors BOR-60 and BN-350.

1. Introduction

At present various scenaria of development and long-term safe operation of a large-scale nuclear power engineering have been under consideration both in our country and abroad. A conclusion that it is necessary to use fast neutron reactors and closed nuclear fuel cycle (CNFC) for commercial purpose is common for these scenaria.

Problems of choosing a type of commercial fast reactor, a fuel type for this reactor, CNFC type have remained debatable.
Backgrounds, content and causes of discussions are apparently in variety and significant differences of problems and tasks (scientific, technical, economical, ecological etc) which can be solved in the course of mass (commercial) application of fast reactors and CNFC.

Nowadays reactors of the BN-type and oxide fuel are the most commercial ones. Aqueous reprocessing of spent fuel (of PUREX type) is the most suitable for application in CNFC. That is why, now and in the nearest future it is urgent to solve the problems and settle the matters relating to construction and application of advanced (commercial) BN-reactors.

2. Requirements for advanced BN -reactors.

Among the requirements set for commercial reactors (BN – C), the most important one is to provide inherent safety of the reactor. This requirement is met at a value of the inner (in the core) breeding ratio at least 1,0. BRC like these can be achieved in BN-C when applying fuel elements with denser fuel than commonly used oxide fuel.

Dense fuels are carbide, nitride and metal ones.

TABLE I: PRESENTS THE MOST IMPORTANT CHARACERISTICS OF OXIDE FUEL AND DENSE FUELS FOR PRACTICAL PURPOSES.

TABLE 1. CHARACTERISTICS OF FUELS [1]

Fuel **Characeristics**	**Oxide** $U_{0,8}Pu_{0,2}O_2$	**Nitride** $U_{0,8}Pu_{0,2}N$	**Metal alloying** **U-19Pu-10Zr**	**Metal alloy-free U**
Density, g/cm^3	11,q4	14,32	15,73	19,06
Density in h.a., g h.a./cm^3	9,74	13,51	14,16	19,06
Smear density in fuel element cladding, g h.a./cm^3	***8***	***≤11***	***≤11***	***≥13***
Melting temperature, ˚C	2750	2797	1128	1132
Thermal conductivity at 1000K, W/m·degree C	2,6	15,8	25	42

The Table ***also shows*** reached or planned values of the smear density in heavy atoms (U, Pu) in the fuel elements of the following reactors:

-operating BN-600 and BN-800 reactors with $UPuO_2$ fuel,

-previously operated reactors (EBR-II, FFTF) with UPuZr fuel,

-advanced reactors (BN-800, BN-1200) with UPuN fuel and

-in U-containing fuel elements of BN-800 and BN-1200 type reactors with heterogeneous oxide-metal cores of various types.

From the above table it is obvious that metal alloy-free uranium posseses significant advantages in such parameters as density and thermal conductivity. Combination of sufficiently high thermal conductivity with quite low melting temperature of metal fuel provides possibility of metal fuel element operation under thermal loadings no less than they are ($q_l^{max} \leq 50 \ \frac{kW}{m}$) for oxide fuel elements.

High smear density in heavy atoms for alloy-free metal uranium fuel elements ($\gamma_{sm.dens.} \geq 13$ g h.a./cm^3) makes it possible to achieve BRC≥ 1,0 in oxide-metal heterogeneous core (OMHC).

In nuclear-physical characteristics heterogeneous oxide-metal cores of various types (fig.1) with a ratio of “oxide ($UPuO_2$) fuel component” to “metal breeding component (U)” (oxide-to-metal ratio) equal to 2:1 are similar to homogeneous cores with such dense fuels as nitride one (UPuN) or alloyed metal fuel (UPu+10Zr).

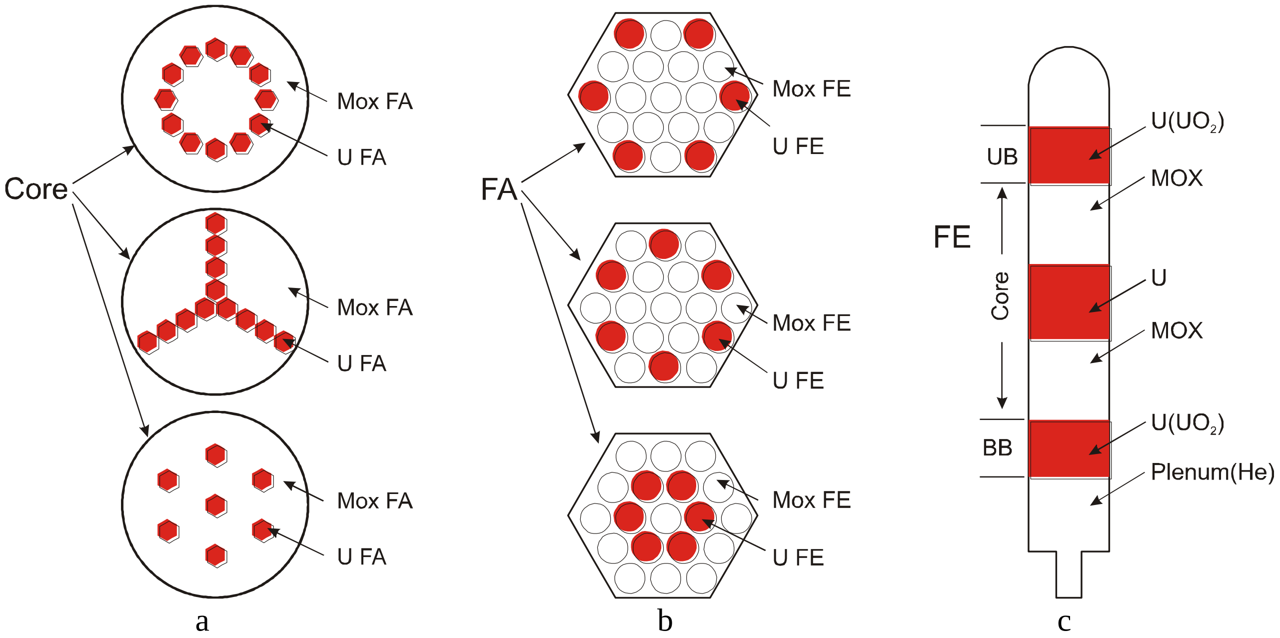

Fig. 1. Versions of oxide-metal heterogenous cores with U:MOX ratio ~30%.

Among other important requirements for advanced BN-reactors the requirement of the maximum possible depth of fuel burnup should be noted. At present fuel burnup depth in the BN-reactors is limited by admissible damage doses of claddings (dpa) made of commercialized stainless steels. This is a reason for limitation of admissible average burnup for fuel elements being developed for the BN-800 reactor with homogeneous core (MOX-fuel in the cladding made of ChS-68 cold-worked steel) by 66MWday/kg. Operating period of the rector at a nominal power between reloading is 140 days (equivalent full power days) [2].

Nuclear-physical peculiarities of the BN-800 heterogeneous core determine possibility of MOX-fuel burnup increase by ≈ 20% without increasing the addmissible damage dose for claddings.

Application of fertile high-dense metal fuel elements in OMHC with BRC≥1,0 makes it possible to meet the requirement of increase in refuelling period up to about a year. Ecological burden caused by production of plutonium-bearing components can also be reduced, because in all versions of the heterogeneous core a volume (mass) of produced and consumed MOX-fuel falls by 30%. Besides, the number of manufactured and consumed MOX fuel assemblies falls by 30% under BFAH (by FA heterogenization of the core) (fig.1a), the number of manufactured and consumed MOX fuel elements falls by 30% under IFAH (by intra FA heterogenization of the core) (fig.1b) [3].

The most important economical requirement is technological effectiveness of fuel production. Metal uranium should be referred to the metals having high technological effectiveness, as it possess high ductility and rather low strength, in particular, at increased temperatures.

3. Experience in development and investigations of metal uranium and uranium-based alloys

Throughout many years beginning from mid 60s JSC «SSC RIAR» has been carrying out research and developments aimed at studying metal fuel applicability in BN-reactors[4]. Metal fuels of various types have been under study: low-, middle- and high-alloy fuels, fuels obtained by moulding and powder metallurgy techniques and after thermal treatment of various kinds. Radiation resistance (radiation growth, swelling, etc) of more than 200 fuel types have been investigated under conditions typical of the BN-reactors.

The most promising fuels were used as fuel columns in the fuel elements irradiated in the SM-2 and MIR reactors. Radiation resistance (integrity and deformation of cladding, fuel column deformation, corrosion damage of the cladding, etc) has been under study in more than 20 dimension types of fuel elements with metal fuel columns of various types (fig.2).

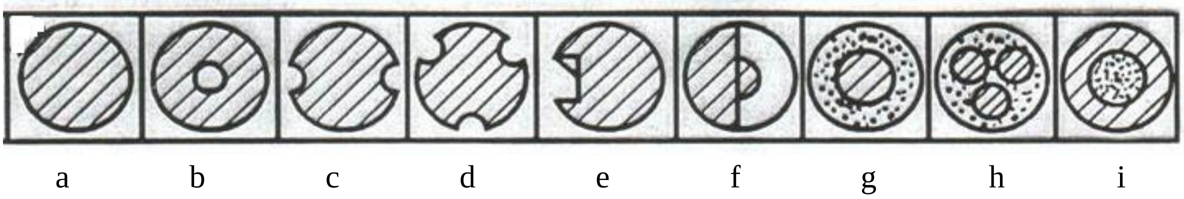

Fig.2. Shape of metal fuel columns in the studied elements.

Various shapes of the metal fuel columns are attributable to the use of various competing production methods and facilities. For example, fuel columns of a traditional simple cylindrical shape (Fig. 2a) were produced using the gravity casting technique. These fuel columns were used in the elements with sodium filled in to the “fuel column-cladding” gap.

All other shapes of the fuel columns were intended to be used in the elements filled with helium instead of sodium. These fuel columns were fabricated using hot or cold mechanical treatment of the blanks:

- Hot pressing of tubular (Fig. 2b) or contoured (Fig. 2c, d) rods;
- Cutting spiral or transverse notches on the lateral face of the rod using a lathe (Fig. 2 e, f);
- Filling uranium granulate in to the cladding in which cylindrical or tubular rods are located (Fig. 2 g,h,i).

Smear density of heavy atoms in the elements was not lower than 13 g/cm^3 at any shape of the fuel columns.

The most promising versions of fuel elements and fertile elements were subjected to comparative, forced and life-time tests in reactors MIR, BOR-60 and BN-350.

These are elements filled with helium with contoured fuel columns (Fig.2c) made of alloy-free metal fuel (U, UPu); the elements were manufactured by hot pressing of cast blanks through a contoured matrix.

The elements with such fuel columns have the following advantageous features:

- easy to fill them with helium;
- easy to press them through a contoured matrix since the blanks material has low strength and high plasticity under rather low temperatures (≤800 °C);
- mechanical and thermal contact between the fuel column and core at the beginning of irradiation caused by an increasing volume and outer dimensions of the fuel column because of phase transformation α –β, β-γ and increased radiation swelling rates of alloy-free metal fuel;
- low risk of an axial mass transfer under linear power loads that may cause melting of the fuel column center.

These are elements subjected to the life-time tests in rectors BOR-60 and BN-350.

The elements with "combined" fuel columns (Fig.2 g, h, i) underwent comparative tests. These elements have peculiar properties that could be used for promising BN-type reactors. Among these peculiar properties are:

- less strict requirement to the geometry of void-free components of the fuel columns (Fig.2 g, h) that simplifies their manufacture;
- granulated uranium prevents from a direct contact with the cladding of more corrosive (U-Pu) void-free component of the fuel column that diminish the risk of FCCI;
- increased Pu concentration in the void-free component of the fuel column (Fig.2 g, h) allows a reduction in mass of radiation-hazardous Pu-containing blanks and items;
- presence of uranium in the combined fuel column (Fig. 2 g, h, i) allows adding granules of other materials to reach different aims.

The total quantity of irradiated full-size elements of various types and purposes containing metal uranium/or uranium alloy fuel columns were the following:

- in BOR-60 - 2188 elements (incorporated in 88 FAs);
- in BN-350 - 1882 elements (incorporated in 20 FAs).

Obtained experience in developments and research comprises:

- a set of observations of metal fuel radiation features (radiation growth, swelling, fuel-cladding interaction, etc);
- "design" principles and methods (that were not caused by fuel alloying) of struggle against uranium radiation growth and swelling, improvement of fuel-cladding compatibility (mechanical restraints of growth and swelling, application of protective coatings of fuel columns and claddings) developed on the basis of observations of metal fuel radiation features.

4. Experience in applicability of the obtained results.

The results of comparative and forced tests were applied for designing and realization of a number of lifetime tests of full-size elements incorporated in full-size FAs in the BOR-60 reactor (Table 2).

TABLE 2. MAIN PARAMETERS OF THE FUEL ELEMENTS TESTED UNDER STANDARD CONDITIONS IN THE BOR-60 REACTOR

Purpose of elements, quantity of elements/FA, pcs.	**Cladding dimensions d×δ, mm**	**Fuel**	**Protective coating**	**Smear density $\gamma_{eff.}$, g/cm^3**	**Designed burnup B^{max}, % h.a.**	**Actual burnup B^{max}, % h.a.**
Fuel elements, 74/2	6 x 0,3	U-15Pu	W, Cr	13	5,8	6,2 … 6,8
Fuel elements 37/1	6 x 0,3	U	UO_2	13	5,8	7,3
Blankets in UO_2 fuel elements, 592/16	6 x 0,3	$U_{lower\ blanket}$ $U_{upper\ blanket}$ $(UPu)O_2$	UO_2 UO_2 -	14,7 ... 17,5 14,7 8,6 … 9	0,8 0,8 10	0,8 … 1,0 0,8 … 1,0 10 … 14
Radial blanket, 161/23	14,5 x 0,4	U	UO_2	14,3	1,6	1,6 … 1,9

Metal layers (W, Cr) used in these elements were covered on inner surfaces of steel claddings by either thermo-chemical or thermal decomposition of metal-containing gases passing through the cladding. The oxide protective layer (UO_2) was coated on the outer surfaces of the metal uranium fuel columns by their heating in air.

Standard tests of the elements described in table 2 (in total 864 fuel elements incorporated in 42 FAs) were carried out by direct replacement of the standard FAs of the appropriate purpose without putting additional restrictions on the operating conditions of the reactor. As a result of the tests neither failures nor loss of integrity of fuel elements were found.

During the tests, the following maximal values were achieved that were close to the design operational conditions of elements with oxide fuel:

- for fuel elements with U and (U-15Pu) fuel columns: linear power - 475W/cm, cladding temperature - 650°C;

- for blankets in $UPuO_2$ fuel elements with U blankets: liner power - ≤ 70 $^{W}/_{cm}$, lower/upper cladding temperature - 350/650°C;
- for radial blankets: linear power - 350 $^{W}/_{cm}$, cladding temperature - 540 °C.

Besides, the life time tests (under standard mode) in the BN-350 reactor and postirradiation examinations were successfully accomplished for the following elements:

- absorbing elements incorporated in fuel-absorber assemblies (95 elements in each of 6 assemblies);
- fuel elements containing oxide fuel in active parts and uranium fuel columns in lower blankets (127 fuel elements in each of 6 FAs);
- fertile elements of radial blankets (37 fuel elements in each of 6 FAs);
- elements of the inner breeding zone (127 fuel elements in each of 2 FAs);
- elements of upper axial blanket (37 fuel elements in each of the same 2 FAs).

5. Applicability of experience.

Applicability of a gained experience in advanced BN-reactors is connected with purposes of construction of these reactors.
However, by the moment these purposes are disputable and even can be contradictory (for example, to burn out accumulated excess weapon grade plutonium at BR ≈ 1,0 or to achieve breeding at BR >>1,0, etc.).

It should be noted that every BN-reactor under design or under building is unique, their number is insignificant, the rate of commissioning is low (1 generating unit – BN- 600 over the past 30 years), types and parameters of advanced (being designed) fast reactors are mutually dependent on types and parameters of their fuel cycles.

In the BN-800 reactor application of fertile elements containing metal uranium (either in the core or in axial and radial blankets) is technically feasible and experimentally validated. However, such an improvement of the design will result in delaying of the reactor startup and increasing breeding ratio.

Fast reactors of the BN-1200 type that are under development in Russia are considered commercial ones. These reactors are to be constituent of closed fuel cycle.

Among various versions a modification of BN-1200 with OMHC providing achievement of BR≥ 1,0 should be considered

Appropriate favourable effects will be similar to those mentioned above for the BN-800 with OMHC.

At present India declares long-term programs of development, construction and application of serial commercial BN-reactors with oxide metal fuel in large-scale power engineering. At the same time applicability of JSC «SSC RIAR»’s experience in the field of alloy-free metal fuel elements (CFBR-500,1000) with high fuel breeding (BRC≈1,0, BR >>1,0) and closed fuel cycle is also under consideration by Indian specialists [5,6].

Alloy-free metal uranium can be also used as a fuel component (enriched uranium) and fertile component (non-enriched uranium) in heterogeneous metal-metal core of the BN –reactors of TWR type (Travelling Wave Reactor) or TR-1 type (TerraPower-1) [7,8] .

Construction and operation of the reactors like these having BRC≈ BR ≈ 1,0 can delay for a long time both necessity of construction and operation of closed fuel cycle enterprises and necessity of production of source plutonium-containing fuel and fabrication of Pu-containing fuel elements and FAs.

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