RBEC LEAD-BISMUTH COOLED FAST REACTOR: REVIEW OF CONCEPTUAL DECISIONS

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Abstract

A concept of the RBEC lead-bismuth fast reactor-breeder is a synthesis, on one hand, of more than 40-year experience in development and operation of fast sodium power reactors and reactors with Pb-Bi coolant for nuclear submarines, and, on the other hand, of large R&D activities on development of the core concept for modified fast sodium reactor. The report briefly presents main parameters of the RBEC reactor, as a candidate for commercial exploitation in structure of the future nuclear power.

Introduction

Development of RBEC reactor became a logical continuation of a Russian conceptual R&D direction related to advanced fast reactors based, first of all, on experience gained in operation of fast sodium reactors existent in Russia: BOR-60, BR-10, BN-350 and BN-600.

In the late 70s – early 80s at *a first stage* of this direction a concept was developed for the core of a fast sodium-cooled reactor with extended nuclear fuel breeding and a number of innovations [1], including wide fuel rod lattice, fuel assemblies (FAs) without shrouds; low core hydraulic resistance; low coolant heating-up; heterogeneous U-Pu core composition with core breeding ratio (CBR) close to 1, etc. As a result of the first stage:

- proposals were formulated by Kurchatov Institute on sodium-cooled reactor BN-500EC with coolant natural circulation, FAs without shrouds and wide fuel rod lattice;
- a technical project was prepared for an advanced BN-1600M sodium-cooled fast reactor;
- proposals were formulated for modification of the BN-800 core.

In the mid-80s at *a second stage* of the fast reactor R&D direction a conceptual project was developed for lead-bismuth fast breeder reactor RBEC, reviewed in details in this report. Scientific leader at the first and second stages was Kurchatov Institute.

Currently, there are several directions for conceptual development of advanced LBFBRs in Russia:

1. concepts oriented at the use in the nearest future and based, as much as possible, on traditional decisions and technologies, for example, on the use of lead-bismuth coolant experienced in nuclear submarines; integral layout of primary circuit; hexagonal fuel assemblies; mixed uranium-plutonium oxide fuel; intermediate circuit; steam parameters close to those used in existing reactors, etc.;
2. advanced concepts requiring additional studies and based on an number of innovations, for example, on the use of pure lead coolant; square fuel assemblies; high-density mixed nitride fuel; two-circuit scheme with elimination of intermediate circuit; supercritical steam parameters, etc.

The RBEC [2-4] and SVBR [5] reactor projects can be assigned to the first direction, while BREST-type reactor projects [6] to the second direction.

Reactor general parameters

The aim of the RBEC project [2-4] was creation of a nuclear steam-generating power plant on the basis of Russian experience in design and operation of fast reactors and liquid-metal technology. High self-protection level should be provided by inherent core safety properties, thermal-physical properties of lead-bismuth coolant, use of natural circulation for emergency core cooling, application of passive safety systems along with traditional active ones, qualitative factory fabrication of the equipment.

Three-circuit scheme was implemented in the reactor design of 900 MWt and 340 MWe power unit by OKB Gidropress, Kurchatov Institute, and IPPE. The design and thermal-hydraulic parameters of RBEC are based, as much as possible, on technical decisions proved in BN-type reactors cooled by sodium, and they correspond to existing experience on fuel, structural materials, and technology of liquid-metal coolant. Major technological processes of the NPP equipment fabrication were chosen to be mainly based on the previously developed nuclear power technologies.

The RBEC reactor facility contains the following main systems (Fig. 1):

- primary system structurally made as a monoblock unit;
- intermediate (secondary) system;
- turbine system;
- air emergency core cooling system;
- refueling system;
- system for gas heating or emergency cooling of monoblock vessel;
- system for electric heating of secondary circuit;
- system for filling and drainage of primary and secondary coolant;
- clad failure detection system;
- system of the primary and secondary coolant technology;
- control and protection system, automatic control, etc.

The design of main equipment was developed using the following basic principles:

- dimensions of basic equipment (in particular, vessel and other components of the monoblock) are restricted by limits allowing for factory fabrication and transportation of equipment or components to the site by railway, water or auto transport;
- thermal-hydraulic parameters of the unit were chosen to solve the problems of coolant technology and corrosion resistance of structural materials using heavy-metal coolant experience;
- seismic resistance of the facility is provided up to earthquakes of magnitude 8 on MSK-64 scale.

The plant is placed in the hermetic reinforced concrete containment which may be partly or fully installed underground in order to increase the equipment seismic stability and to create the best conditions for localization and elimination of hypothetical accident consequences. On the basis of an estimation of the seismic stability of the monoblock vessel, the depth of the containment location, corresponding to the zero level of the monoblock support structures, was accepted in the given project. The RBEC major characteristics are given in Table 1.

Table 1. RBEC reactor major characteristics

Primary circuit	
Coolant	Pb-Bi
Thermal power, MW	900
Electric power, MW	340
Number of loops	6
Number of reactor pumps	12
Total reactor flowrate, t/h	220,000
Core inlet/outlet coolant temperature, °C	400/500
Primary coolant pressure in the core, MPa	2
Helium pressure above free level of primary and intermediate coolant, MPa	0.09
Power removed by natural circulation with rated heating-up, % of rated power	11
Total power of air cooling heat exchangers, % of rated power	3
Total mass of Pb-Bi, t	~6500
Metal consumption, t	3500
Seismic resistance (MSK-64)	8
Fuel cycle duration, year	4
Time interval between refuelings, year	1
Annual excess fuel production (292 eff.days), kg	~160
Design lifetime of main equipment, year	40
Intermediate circuit	
Coolant	Pb-Bi
Number of intermediate heat exchangers (IHX)	12
Intermediate temperature at steam generator inlet/outlet, °C	480/380
Turbine circuit	
Coolant	water
Feedwater temperature, °C	260
Generated steam pressure, MPa	15
Generated steam temperature, °C	460
Steam production, t/h	1580

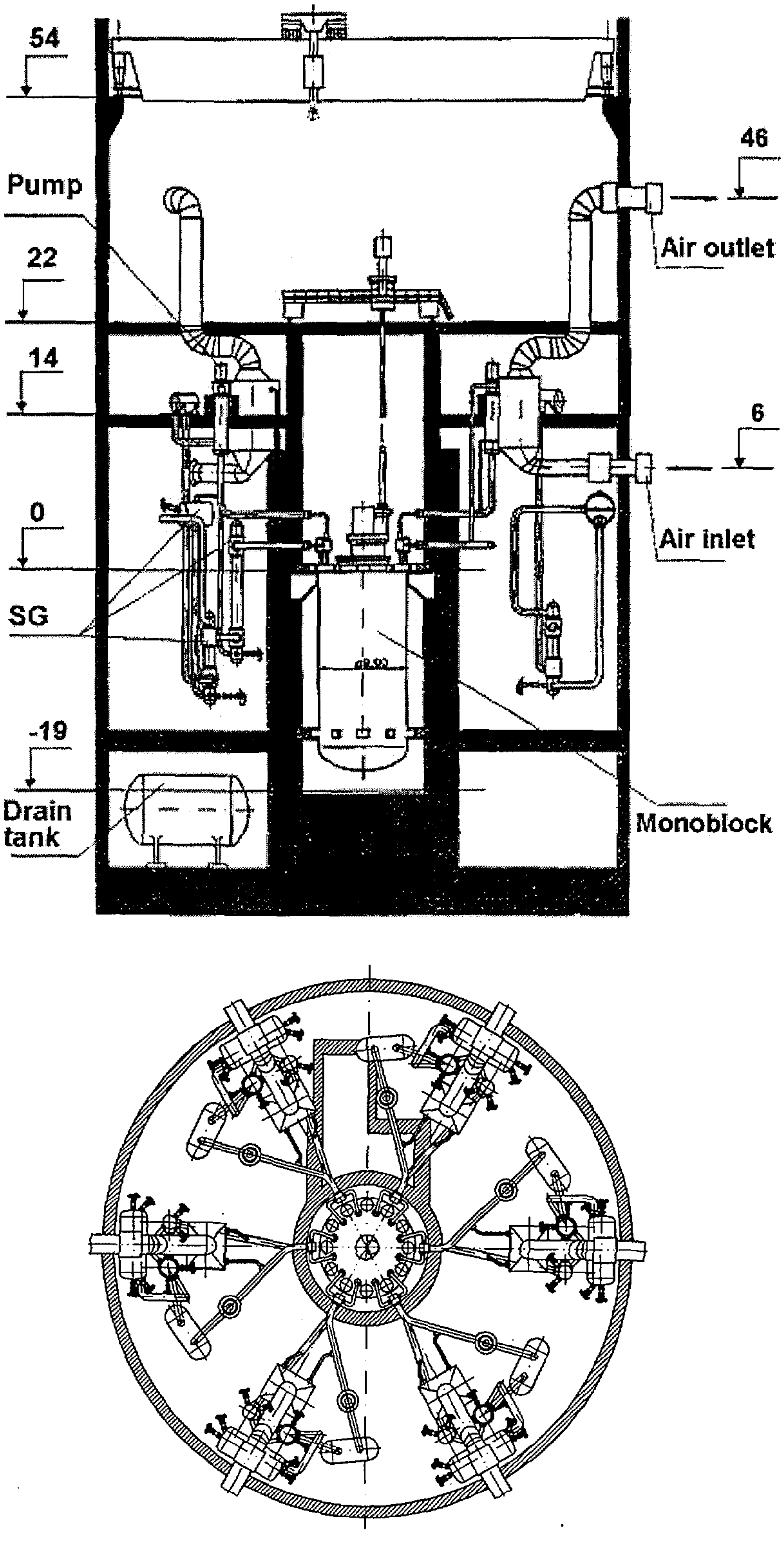

Fig. 1. General view of RBEC reactor

Core parameters

In-assembly heterogeneity is used in the RBEC core: 78 fuel rods with mixed uranium-plutonium oxide fuel and 42 fertile rods with depleted uranium carbide are installed in hexagonal fuel assembly without shroud with pitch of 15.3 mm (Fig. 2b). FA pitch in the cold conditions is 176 mm.

The RBEC reactor core (Fig. 2a) consists of 253 hexagonal fuel assemblies (FA). Two types of MOX fuel with different Pu content are used in fuel rods to flatten the power density radial distribution. The central low-content zone (LCZ) consists of 121 fuel assemblies with 27.5% Pu content in fuel rods. The high-content zone (HCZ) includes 132 FA with 37.1% Pu content in fuel rods. The core is surrounded by 126 assemblies of radial blanket with fertile rods of depleted uranium carbide. 192 assemblies of neutron reflector are installed around the core.

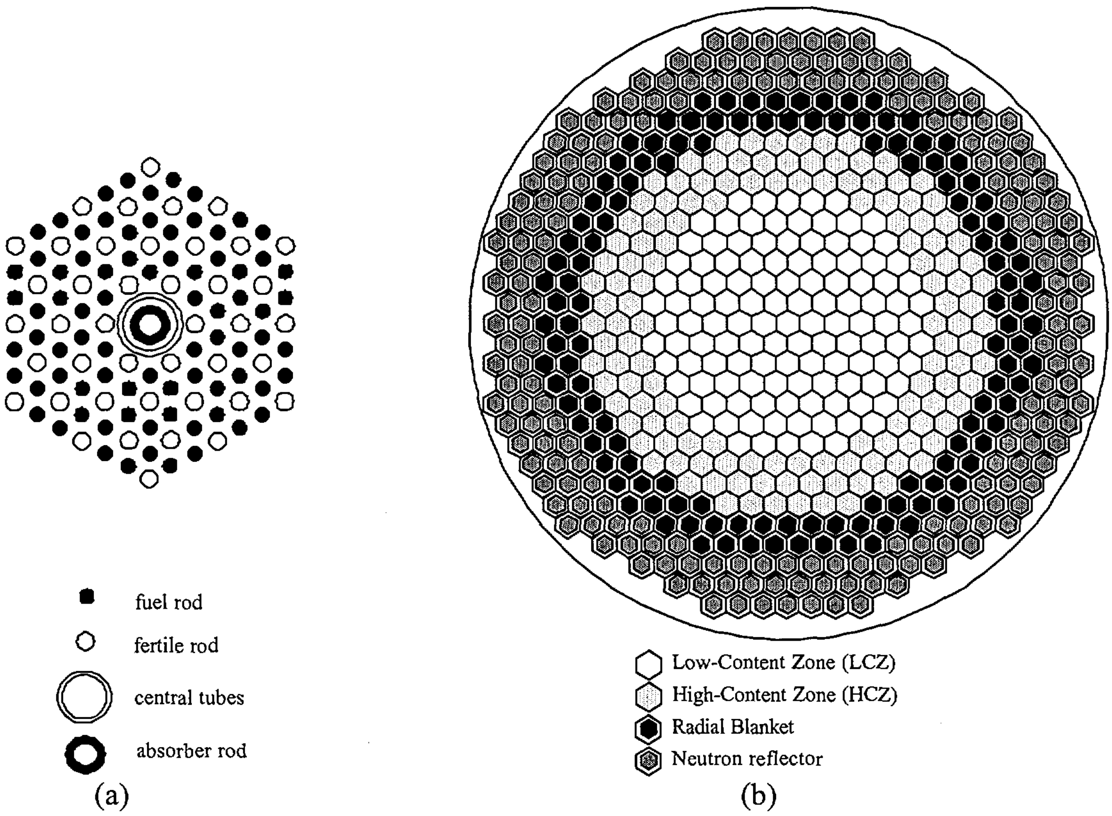

Fig. 2. RBEC core (a) and fuel assembly (b)

The hollow pellet of mixed uranium-plutonium oxide fuel with density of 9.03 g/cm^3 has outer diameter of 7.9 mm and inner diameter of 1.2 mm. Fuel cladding of 12%Cr-Si steel (EP-823 in Russian classification) has outer diameter of 9.0 mm and thickness of 0.45 mm. The active part of fuel rod was determined in order to reach the CBR value close to 1 and equals 1500 mm. The top and bottom axial blankets of 350 mm each contains the pellets of low enriched UO_2 with density of 9.5 g/cm^3. Thus, column of fuel rod pellets include 350 mm of bottom blanket, 1500 mm of MOX fuel and 350 mm of top blanket. The pellet of low-enriched uranium carbide with density of 12.4 g/cm^3 has outer diameter of 10.7 mm and no inner hole. Cladding of the same steel as for fuel rod has outer diameter of 11.0 mm and thickness of 0.45 mm. The column of fertile pellets has height of 2200 mm.

The fuel and fertile rods are initially filled with helium at pressure of 1 MPa. Gas plenum of 800-mm height is designed in the bottom of fuel and fertile rods. Initial gas pressure and height of the gas plenum were chosen to have gas pressure inside fuel rod below coolant pressure by the end of fuel life. Two coaxial steel tubes with diameters of 39 and 33 mm, correspondingly, are installed in the center of each FA. The outer tube is used as a support structure for 10 spacer grids installed with axial step of 312 mm. The inner tube is secured by the bayonet grips in the supporting plate and prevents the floating up of FA. In 144 central FAs the inner tube is also used as a guide tube for absorber rod of active or passive type. The hollow pellet of B_4C with density of 2.1 g/cm^3 and 80%-enrichment by ^{10}B has outer diameter of 20 mm and inner diameter of 14 mm. Cladding of the same steel as for fuel rod has outer diameter of 23 mm and thickness of 0.5 mm. The column of absorber pellets has height of 1500 mm.

Main data on the RBEC core design characteristics are summarized in Table 2. Geometrical data correspond to the cold (T=20°C) conditions.

Table 2. RBEC reactor core design parameters.

Parameter	**Value**
Number of FAs in the core, including low-content zone (LCZ) high-content zone (HCZ)	253 121 132
Number of FAs in radial blanket	126
Number of fuel rods in FA Number of fertile rods in FA	78 42
Number of absorber rods in the core	144
Outer/inner fuel pellet diameter, mm Outer/inner fertile pellet diameter, mm	7.9/1.2 9.8/0.0
Fuel rod outer diameter, mm Fertile rod outer diameter, mm	9.0 11.0
Clad thickness, mm	0.45
Thickness of absorber rod clad, mm	0.5
Outer diameter of absorber rod, mm Inner diameter of absorber rod, mm	23.0 14.0
FA pitch, mm Fuel rod pitch in FA, mm	176 15.3
Height of the core, mm Height of the top axial blanket, mm Height of the bottom axial blanket, mm Height of the gas plenum, mm	1500 350 350 800

Operational parameters

A partial fuel cycle in RBEC reactor is 292 effective days long. Pu content in fresh fuel, which satisfies the demands of reactor criticality for this period is presented in Table 3. Replacement of 63 or 64 FAs in the core and 15 or 16 in the radial blanket is supposed in one reloading. Thus, fuel life for the radial blanket is twice as much as fuel life for the core.

Table 3. Pu content in the fresh fuel rods and FA in equilibrium fuel cycle of the RBEC core, % h.a.

Parameter	LCZ		HCZ	
	FA	MOX fuel rod	FA	MOX fuel rod
$^{(239+241)}$Pu/(U+Pu)	8.7	19.5	11.8	26.3
Pu/(U+Pu)	12.3	27.5	16.6	37.1

Fuel mass for different burnup stages is presented in Table 4. About 160 kg of major fissile Pu isotopes is produced in a partial fuel cycle of 292 effective days.

Table 4. Fuel mass for different burnup stages, t.

Region	**Fuel mass**	**First cycle**	**Equilibrium fuel cycle**	
		BOC	**BOC**	**EOC**
Core	$^{(239+241)}$Pu	2.86	2.85	2.86
	h.a.	27.64	26.98	26.74
Radial blanket	$^{(239+241)}$Pu	-	0.96	1.05
	h.a.	33.70	33.57	33.55
Axial blanket	$^{(239+241)}$Pu	-	0.21	0.27
	h.a.	13.15	13.13	13.12
Total for reactor	$^{(239+241)}$Pu	2.86	4.02	4.18
	h.a.	74.49	73.68	73.41

Power output of each reactor region is mainly determined by the fission of heavy nuclei ^{235}U, ^{238}U and ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu and by radiative capture. Maximal fuel rod linear power rating and fuel burnup in RBEC reactor are given in Table 5. Power peaking factors in the core and the power fraction for the separate reactor regions averaged over the whole fuel cycle are given in Table 6. The values of the breeding ratio and its components at the different burnup stages are given in Table 7.

Table 5. Peak fuel rod linear power rating and fuel burnup in RBEC reactor

	Peak fuel rod linear power, W/cm		Peak fuel burnup, % h.a.
	BOL	EOL	
Fuel rod	450	345	11.6
Fertile rod	70	274	3.4

Table 6. Power distribution in RBEC reactor

Axial power peaking factor in the core		1.29
Radial power peaking factor in the core		1.20
Power fraction generated in region , %	LCZ	47.4
	HCZ	42.9
	Total in core	90.3
	Axial blanket	2.9
	Radial blanket	6.8
	Total in blankets	9.7

Table 7. Breeding parameters in RBEC reactor

Breeding ratio component	**Fresh fuel**	**Equilibrium cycle**
LCZ	0.66	0.59
HCZ	0.46	0.42
Total in core	1.12	1.01
Radial blanket	0.26	0.26
Axial blanket	0.18	0.17
Total in blankets	0.44	0.43
Reactor	**1.56**	**1.44**

Safety parameters

Effective delayed neutron fraction for RBEC reactor is 0.38 %. Prompt neutron lifetime is $5.1 \cdot 10^{-7}$ s. Components of temperature and power reactivity effects are presented in Table 8.

Table 8. Components of temperature and power reactivity effects

Components	Temperature reactivity coefficient, $\delta(1/k_{ef})/°C$, 10^{-5}	Power reactivity coefficient, δ δ $\delta(1/k_{ef})/MW$, 10^{-5}
Doppler	-1.657	-0.724
Coolant expansion	0.152	0.042
Radial reactor expansion	-0.650	-0.086
Axial reactor expansion	-0.164	-0.132
Total	-2.319	-0.900

The value of full void reactivity effect is equal to 1.15 % $\delta(1/k_{ef})$. Reactivity change during the partial fuel cycle with account for neptunium and americium effects is equal to 0.21 % $\delta(1/k_{ef})$.

Two independent control and protection systems (CPS) – active and passive - are used in the RBEC reactor to meet the Russian regulatory guides requirements. Each of these systems can shutdown reactor and keeps it in a subcritical state from all possible nominal and accident conditions under assumption about a single failure of the most effective cluster. As it was mentioned above, absorber rods of both active and passive CPS systems are installed in the 144 central channels of FAs of RBEC reactor.

Active CPS consists of 72 absorber rods located in the central tubes of 72 FAs of LCZ zone. The absorber rods of the active CPS are moved by the driving rods controlled with the use of electric motors. The driving rods of the active CPS are combined in 24 clusters each of which controls three absorber rods. Each three-rod cluster is coupled with and controlled by one shaft. The driving rods of CPS are not coupled with the active absorber rods. In normal operation the 48 active absorber rods follow the driving rods moved by operator and the 24 active scram rods are kept below the bottom axial blanket by the driving rods.

Under emergency conditions, all driving rods are set free and flowing up with all active rods which enter the core. This design of the CPS was chosen due to features of heavy coolant application and provides:

- exclusion of coupling of driving rods with absorber rods and, therefore, increase of structural reliability;
- insertion of the absorber rods into the core during refueling, when the driving rods should be raised above the fuel assemblies;
- insertion of the absorber rods into the core during hypothetical severe accidents accompanied by a damage of the vessel components, for example, in failure of the rotating plug fasteners and flowing up of the rotating plug with shafts and driving rods.

Passive CPS consists of 72 absorber rods located in the central tubes of 49 FAs of LCZ and 23 FAs of HCZ. The passive absorber rods are kept in the same position below the core as the active absorber rods with the use of special triggers which are bimetal plates made of steels of ferrite-martensitic and austenitic grades with different thermal expansion coefficients. The trigger is installed in the FA central tube and via the shaft prevents flowing up of a passive absorber rod. When coolant temperature at the FA outlet exceeds 580°C thermal deformation of the trigger reaches the critical value and leads to release of the shaft and flowing up of the passive absorber rod.

Primary circuit

An integral layout of the primary circuit is used in the RBEC reactor. The monoblock containing primary circuit is a vessel with double walls to prevent a loss-of-coolant accident. The gas gap between external and internal walls (70 mm) is under control and used for gas heating of the monoblock before reactor is filled with coolant or for emergency cooling of the vessel. The monoblock unit of 9000-mm diameter contains the core with axial and radial blankets, 12 (two for each loop) intermediate heat exchangers, 12 (two for each loop) circulation axial pumps with electric drives, thermal and neutron vessel shield. The design value of reactor vessel thickness ranges from 90 to 120 mm for different structural parts. Reactor pump has nominal rotation speed of 985 r.p.m., drive power of 200 kW and head of 2.75 m. The check valves are installed at the pump outlets to prevent an inverse flow of primary coolant through the intermediate heat exchangers after trips of several pumps. After trip of all pumps (under natural circulation conditions) the check valves are kept open.

Intermediate and turbine circuits

The secondary (intermediate) circuit is formed by six circulation loops, each of them is connected with two intermediate heat exchangers. The secondary loop contains the pump, buffer tank, steam generator with multiple natural circulation and steam superheating (see Fig. 3). Secondary intermediate heat exchanger inlet and outlet are connected to air-cooled heat exchangers of emergency cooling system. The whole facility is located in the hermetic reinforced concrete containment.

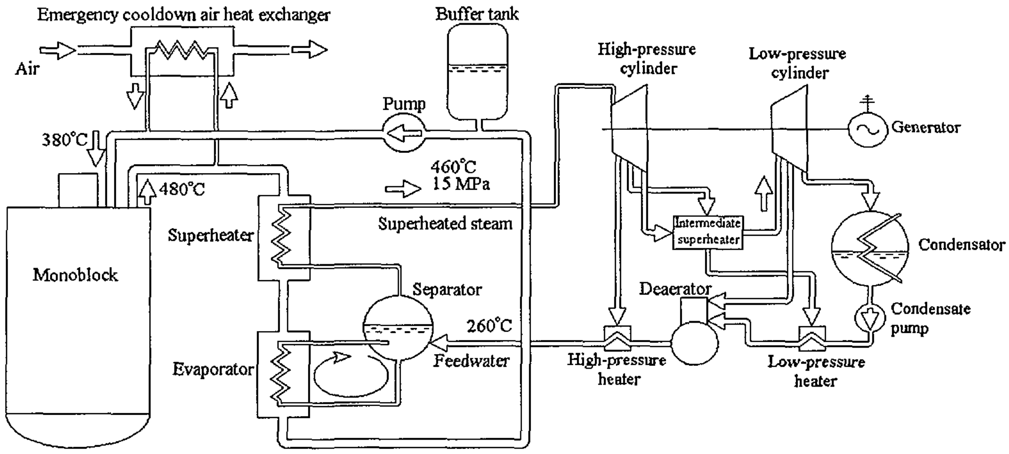

Fig. 3. Diagram of the RBEC intermediate and turbine circuits

The intermediate circuit of the RBEC facility allows to exclude the following potential dangers:

1) possibility of steam or water entrainment in the core during an emergency intercircuit leak in steam generator that can cause inadmissible changes in reactivity, power density, and heat transfer in the core;
2) possibility of primary circuit overpressurization during an emergency intercircuit leak in steam generator, as well as damage, in this case, of reactor in-vessel devices as a result of hydraulic impacts, which can accompany fast evaporation of water in liquid-metal coolant;
3) possibility of primary coolant freezing in steam generators, for example, because of steam header break and intensification of heat transfer from primary to turbine circuit; such scenario with coolant freezing is possible in RBEC reactor only in secondary steam generators; thus, the primary coolant circulation is preserved and decay heat removal from the primary circuit can be organized through channels of emergency cooldown; in particular, in RBEC reactor heat removal from the primary circuit with freezing steam generators will be organized through the intermediate heat exchangers to coolant in non-freezing, adjacent to the intermediate heat exchanger, sites of secondary pipelines and then through emergency air cooling heat exchangers to atmospheric air;

The intermediate heat exchanger is a shell-and-tube once-through counter-flow heat exchanger with thermal power of 75 MW. Primary coolant velocity is 0.7 m/s, secondary coolant velocity is 1.2 m/s. The intermediate coolant temperatures at monoblock inlet and outlet are 380 and 480°C. Coolant flowrate through one intermediate heat exchanger is the same as in the primary circuit, 5092 kg/s. Pressure drop is 0.3 MPa. The pump of the secondary circuit is a centrifugal one similar to accepted in sodium-cooled facilities. The pump drive power is 2.4 MW. The head is 16.7 m.

The design of RBEC steam generator is similar to design of steam generator used in the BN-600 reactor. The steam generator consists of the evaporator, separator, and superheater. The evaporator is a counterflow heat exchanger with multiple natural circulation and superheater is a once-through counterflow heat exchanger. The RBEC scheme uses feedwater heating in a large-volume separator at pressure of 15 MPa and water saturation temperature of 613 K, significantly exceeding lead-bismuth freezing point. The use of such a steam generator scheme in the RBEC reactor allows to significantly decrease the probability of intermediate coolant freezing in steam generator at accidental drop of feedwater temperature. Thermal-hydraulic parameters of the steam generator are given in Table 10.

Table 10. Thermal-hydraulic parameters of RBEC steam generator

Intermediate circuit	
Thermal power, MW	150
Secondary Pb-Bi coolant inlet temperature, °C	480
Secondary Pb-Bi coolant outlet temperature, °C	380
Coolant flowrate, kg/s	10180
Coolant velocity between evaporator tubes, m/s	1.3
Coolant velocity between superheater tubes, m/s	1.7
Total coolant pressure drop , MPa	1.1
Turbine circuit	
Feedwater injection rate, kg/s	73.1
Feedwater temperature, °C	260
Superheated steam pressure, MPa	15
Superheated steam temperature, °C	460

The air cooling heat exchanger is connected to the hot and cold legs of each secondary loop. Under the plant normal operating conditions, the heat exchangers are isolated from air by means of the cut-off valves. The coolant flow rate through them is kept at the minimal level to prevent the heat exchangers from freezing. Under the emergency conditions with plant black out, the electric magnets, keeping the cut-off valves closed, are de-energized. The cut-off valves are opened and natural circulation of air and coolant establishes through the heat exchangers. The use of the air cooling heat exchangers, according to the completely passive scheme, is possible too. In this case, they must be continuously in operation that leads to the external losses of about 3 % of the plant thermal power.

Conclusions

The main aim of the RBEC development was to demonstrate the possibility to combine existent advantages of each reactor technologies in one nuclear power facility to improve economic and breeding parameters compared to reactors of BN-type with simultaneous safety enhancement and environmental acceptance due to application of heavy-metal coolant.

Design and technological decisions experienced in practice and checked experimentally became the basis of the RBEC design:

- *wide fuel rod lattice*, allowing to reduce hydraulic resistance in fuel assemblies; to increase the coolant natural circulation level; to use fuel assemblies without shrouds; to decrease fraction of steel in the core and, thus, not only to improve core breeding ratio (CBR), but also to create conditions for reducing the void reactivity effect;

- *in-assembly heterogeneity*, allowing to increase effective fuel density in the core without development of new types of mixed fuel; to obtain CBR above 1; to increase fuel burnup without increase of neutron fluence;
- *high-density carbide fuel* in fertile rods with low linear rating power and burnup, not requiring filling of fuel-clad gap with liquid metal;
- *parameters of turbine circuit experienced in the nuclear power*, allowing to use design decisions for steam generator and turbines checked in practice.

The use of lead-bismuth coolant at low heating-up in the core and outlet temperature allows to use 12%Cr ferrite-martensite steels resistant against radiative swelling and radiative creep. Corrosion resistance of this fuel clad material was checked in practice for these temperatures with the use of special technological processes of oxygen concentration maintenance in the coolant.

On our opinion, if during the nearest years creation of fast reactor with heavy-metal coolant is required to demonstrate advantages of such reactors in economics, breeding properties and inherent safety, then one of the best projects from viewpoint of feasibility and provision of mathematical modeling for normal and accident conditions will be a reactor of RBEC type.

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