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SAFETY PARAMETERS OF ADVANCED RBEC-M LEAD-BISMUTH COOLED FAST REACTOR

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ABSTRACT

The main objective of developing the RBEC-M lead-bismuth fast reactor project was to demonstrate the possibility to combine advantages of existent reactor technologies in one nuclear power facility to improve economic and breeding parameters in comparison with BN-type reactors and, simultaneously, to enhance safety parameters. Main RBEC-M reactor parameters, especially related to reactor safety, are considered in the paper.

1. INTRODUCTION

The RBEC-M lead-bismuth fast reactor project[1] was developed on the basis of the RBEC project[2] designed by OKB Gidropress, RRC KI and IPPE, with participation of Bochvar Institute and RIAR.

The following design and technological decisions, proved in practice and experimentally verified, formed the RBEC-M concept basis:

1) The core outlet temperature allows to use 12%Cr-Si ferritic-martensitic steel as a core and steam generator (SG) structural material. This steel was checked in practice as resistant against radiative swelling and radiative creep [3]. Corrosion resistance of this steel is provided by the use of proper technological processes for maintenance of oxygen concentration in the coolant [4].
2) Wide fuel rod lattice allows to reduce hydraulic resistance in fuel assemblies (FAs) and to increase the coolant natural circulation level.
3) Hexagonal FAs without shrouds allow to decrease fraction of structural materials in the core and, thus, to improve neutron balance, core breeding ratio (CBR), decrease void reactivity effect and mass transfer of structural materials.
4) High-density mixed (U-Pu)N fuel based on ^{15}N and depleted UN as fertile material of blankets provide the necessary breeding parameters and optimization of reactivity effects.
5) Fuel rod reliability is ensured by elimination of pellet-clad mechanical interaction during the whole fuel cycle, as well as by compatibility of fuel and clad materials. Filling of fuel rod free volume with helium has an impact on the choice of fuel rod diameter to ensure acceptable fuel temperatures.
6) Application of the gas lift with argon supply under the core allows for improvement of neutronics, safety and economical parameters. The gas lift system provides decrease of reactor power at spatially uniform changes (both reduction and increase) of gas void in the core. Refusal from main circulation pumps and use of the gas lift system to ensure the primary coolant circulation improves economics and reliability of the reactor system, increase natural circulation level in the primary circuit. Besides, the gas lift system can be used as a part of the coolant technology system

for transporting and introducing necessary gas components (oxygen, hydrogen, etc.) into the coolant directly under the core

7) Two-circuit nuclear steam-supply system (NSSS) scheme with integral layout of primary equipment and minimization of coolant volume in the reactor module allows for improvement of economic indices, in particular, due to refusal from intermediate circuit and reduction of the reactor module height compared to the three-circuit NSSS scheme of basic RBEC project.

High level of reactor self-protection is based on thermal-physical properties of the lead-bismuth coolant, low reactivity change with burnup (provided by proper choice of isotopic composition of the loaded fuel), negative fuel temperature and coolant effective density feedbacks, high heat capacity of the reactor module, use of built-in passive reactor auxiliary cooling system (PRACS) and passive systems for reactor shutdown, high level of coolant natural circulation, etc. Height of the reactor module is chosen, among others, from the viewpoint of necessity to ensure acceptable level of temperatures of structures and removal of core decay heat power by built-in PRACS in the NPP blackout accident.

2. MAIN PARAMETERS OF RBEC-M REACTOR MODULE

The RBEC-M reactor module (Figure 1) has an integral layout and includes core with axial and radial blankets, 12 once-through SGs of tube-and-shell type, 12 PRACS, gas lift system, control and protection system (CPS), emergency depressurization system in case of SG failure, etc. All primary systems are located in a double-wall cylindrical vessel. Dimensions of main and guard vessels are ∅8400×80 mm and ∅8000×80 mm, respectively. The vessel height is about 10 m. The gap between the main and guard vessels is filled with gas and under control. This gap is used for heating the reactor module before start of operation by forced convection of hot gas. Besides, the guard vessel serves for localization of radioactive coolant in case of the main vessel failure. Main parameters of RBEC-M reactor are given in Table I.

The Pb-Bi coolant circulates according to the following scheme. The cold coolant from downcomer and lower plenum enters the gas lift system. The coolant in the gas lift system is mixed with argon and directed into assemblies of the core and lateral blanket at 650 K. After passing the core, the heated two-phase mixture of liquid metal and argon at 792 K elevates in the channels formed by displacers and shrouds of CPS drives, and reaches free coolant level where gas is separated from lead-bismuth. A dominant fraction of gas bubbles is assumed separated on the coolant mirror in the cover gas volume, because vertical component of velocity of coolant flowing down in SGs and PRACS is not high (about 0.5 m/s). Reverse flow is established in the core radial reflector because gas in the gas lift system is not bubbled under radial reflector. Hot coolant flows down in the core lateral reflector and specially designed tubes in the gas lift system, and mixes with cold coolant in the reactor lower plenum. Reverse flow through the core radial reflector flattens radial temperature fields of coolant and structures in the chimney above the core. After gas is separated on the coolant mirror, the coolant through perforation in the CPS column shroud and in the core barrel enters the chamber at the SG and PRACS inlet. The coolant flow is separated here. About 85% of flow enters SGs and goes downward in the space between tubes, transferring heat to the secondary steam-water mixture. About 15% of flow through the spilling windows enters 12 PRACS, where also goes downward, transferring heat to the environmental air. In this regime about 1.4 % of generated power is lost in 12 PRACS. Optimization of location of the spilling windows with respect to coolant free level can reduce the power losses under nominal conditions. After passing SG, cold coolant at 620 K enters the chamber which is common for all 12 SG, and through lower windows of PRACS goes into the PRACS plenum to mix with hotter coolant at 767 K, which passed the PRACS.

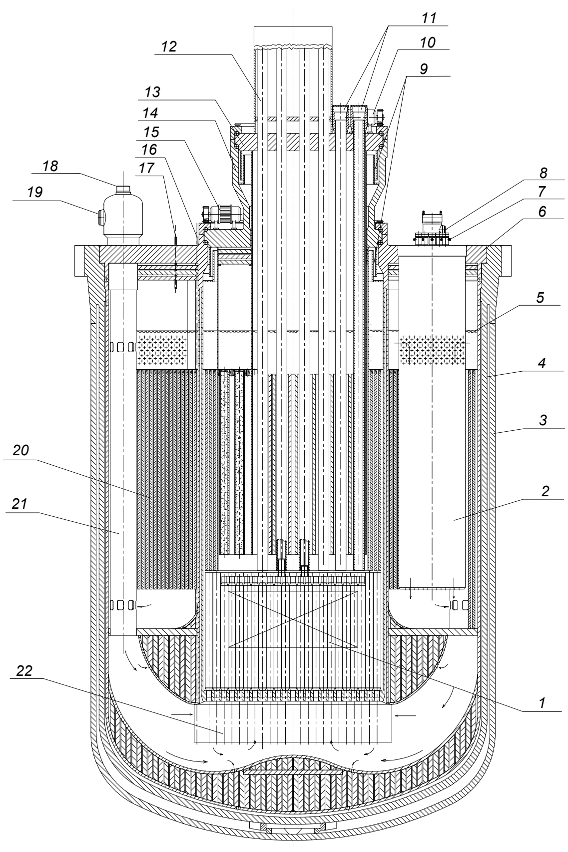


Figure 1. General view of RBEC-M reactor module

Table I. Main operational parameters of RBEC-M reactor

Primary circuit	
Coolant	Pb-Bi
Thermal/electric power, MW	900/340
Coolant flow organization	Gas lift
Coolant flowrate in the core, kg/s	44527
Argon flowrate in the core, kg/s	2.3
Average gas void in the core, %	31
Inlet/outlet coolant temperature, K	650/792
Coolant pressure at FA inlet, MPa	0.7
Coolant velocity in the core, m/s	1.2-1.6
Primary coolant inventory, t	900
Primary hydraulic resistance, MPa	0.2
Fuel cycle duration, EFPD	1800
Interval between refuelings, EFPD	300
Number of refuelings per fuel cycle	6
Secondary circuit	
Working fluid	Water
Number of steam generators	12
Feedwater temperature, K	561
Feedwater flowrate per SG, kg/s	450
Generated steam pressure, MPa	15
Generated steam temperature, K	762

1 – core
2 – SG
3 – reactor guard vessel
4 – reactor main vessel
5 – coolant free level
6 – reactor cover
7 – steam outlet from SG
8 – feedwater inlet in SG
9 – seals
10, 15 – electric drives
11 – refueling channels
12 – CPS drives, 24 pcs.
13,14–large and small rotation plugs
16, 17 – gas lift system inlet/outlet
18, 19 – PRACS inlet and outlet
20 – displacers
21 – PRACS
22 – gas lift system

3. MAIN PARAMETERS OF RBEC-M CORE

Three zones with different fuel rod diameters are used in the RBEC-M core to flatten fields of power, coolant temperature and velocity in the core. The fourth type of pin is used, as a fertile rod, in the lateral blanket. RBEC-M core layout is shown on Figure 2. Main parameters of RBEC-M core are given in Table II. Mixed uranium-plutonium nitride fuel with density of 13.3 g/cm^3 and plutonium content of 13.7 % is used in all core zones. Axial and lateral blankets of 100 mm height each contain pellets of depleted uranium nitride with density of 13.3 g/cm^3. Nitride fuel is assumed manufactured by technology, which provides the level of admixtures of oxygen and carbon in fuel below 0.1 mass % each. Nitrogen is used with enrichment of 99.9% by ^{15}N, providing both good neutron-physical parameters and acceptable amount of ^{14}C, generated in reactor for fuel irradiation period. Fuel and fertile rods have claddings of ferritic-martensitic stainless steel EP-823 (12%Cr-Si). Pin free volume is filled with helium at pressure of 1 MPa. A gas plenum of 500 mm height is designed in the lower part of fuel and fertile rods to mitigate effect of fission gas release. Because of high pin pitch-to-diameter ratio in the RBEC-M core, fuel and fertile rods are fixed with spacer grids. Fuel assemblies of all three core zones have no shrouds. Assembly of the lateral blanket has a shroud. Peak fuel and cladding temperatures in axial section with peak power for the first core zone in nominal conditions are equal to 1375K and 881K, correspondingly.

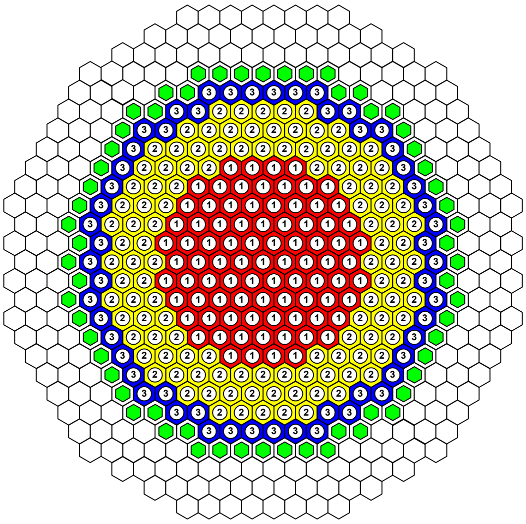


Figure 2. Neutronics core design

Table II. Some parameters of RBEC-M as-fabricated core

Zone	1	2	3	LB
Symbol on Figure 2	①	②	③	🟩
Number of FA	85	114	54	60
FA pitch size*, mm	178			
Number of pins in FA	252			120
Fuel rod pitch in FA*, mm	10.8			15.3
Pin pitch-to-diameter	1.54	1.44	1.26	1.39
Pellet outer diameter*,	5.7	6.2	7.2	9.7
Radial fuel-clad gap*, mm	0.15			0.10
Cladding thickness*, mm	0.5			
Outer clad diameter*, mm	7.0	7.5	8.6	11.0
Core height*, mm	1000			

* at 293 K

Two coaxial steel tubes are installed in the center of each FA. The outer tube is used as a support structure for 10 spacer grids installed with uniform axial step. The inner tube is secured by the bayonet grip in the supporting plate and prevents the floating up of FA. In 120 central FAs the inner tube is also used as a guide tube for an absorber rod of active or passive types. The hollow pellet of B_4C with 80%-enrichment by ^{10}B has the ring form to reduce a self-shielding effect.

The driving rods are not coupled with the active absorber rods. In normal operation active absorbers either follow the driving rods moved by operator or kept below the lower axial blanket. Under emergency conditions, the operator sends the signal to free all driving rods and they flow up with all active absorbers, which enter the core. Such 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 FAs, and during NPP blackout, when CPS drives are de-energized;
- 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.

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 ferritic-martensitic and austenitic grades with different thermal expansion coefficients. The trigger is installed on the top of FA central tube and the shaft prevents the flow up of a passive absorber rod. When coolant temperature at the FA outlet exceeds 900 K thermal deformation of the trigger reaches the critical value and leads to release of the shaft and flow up of the passive absorber rod.

4. RBEC-M CORE NEUTRONICS

Fuel cycle length for RBEC-M reactor was chosen, first of all, on the basis of analysis of fuel rod behavior under base irradiation. A criterion of fuel rod cladding integrity was chosen to be absence of pellet-clad mechanical interaction during all fuel operation. Other factor, which imposes limits on fuel cycle length for reasons of safety assurance, can be corrosion and erosion of structural materials in Pb-Bi coolant. However, limited amount of test data does not currently allow for development of corresponding criterion. It is supposed in the current study that the use of technologies, based on available experience in heavy-metal coolant application, provides reliable operation of reactor structures during the reactor lifetime.

A six-batch fuel cycle is accepted in RBEC-M reactor with 300 EFPDs of operation between refuelings. Reactor is shut down for refueling for 60 days. FAs are not reshuffled for all fuel cycle. Time history of RBEC-M core reactivity during the equilibrium fuel cycle is shown on Figure 3. Radial and axial power peaking factors were estimated 1.25 and 1.19, respectively. Fuel breeding ratio is 1.3. Effective fraction of delayed neutrons and lifetime of prompt neutrons were estimated as $3.7\cdot10^{-3}$ and $4.5\cdot10^{-7}$ s, respectively.

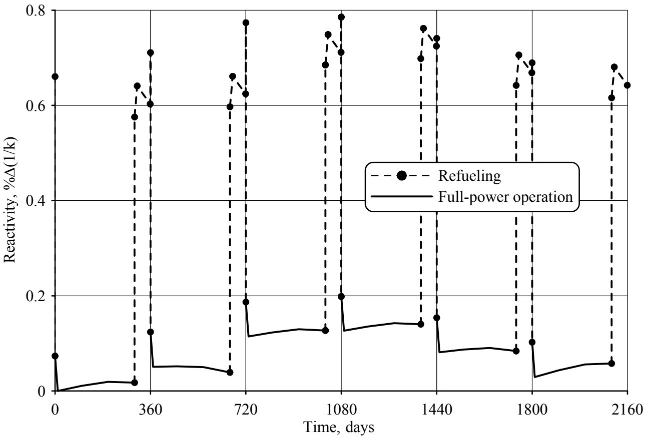


Figure 3. Reactivity in RBEC-M fuel cycle

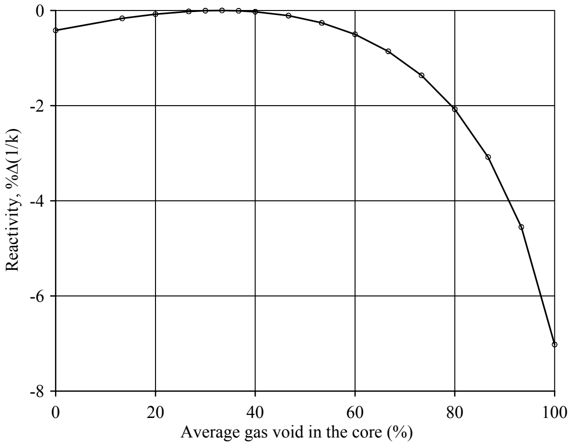


Figure 4. RBEC-M reactivity vs core gas void

Reactivity is shown on Figure 4 as a function of average gas void in the core. Non-perturbed state corresponds to reactor full-power operation with established non-isothermal profile of gas void at the nominal parameters of the gas lift system. As seen, any uniform variation of gas void in the core causes insertion of negative reactivity, thus, providing reactor safety in a number of accident scenarios. 100% gas void corresponds to the void reactivity effect value, which is negative and by absolute value equals 7%Δ(1/k). Calculated values of RBEC-M core reactivity coefficients are given in Table III. State of the reactor, for which reactivity coefficients were determined, was assumed reactor full-power operation with nominal parameters of gas lift, coolant temperature and flowrate at core inlet.

Table III. Temperature reactivity coefficients, Δ(1/k)/K

Parameters	After refueling	Before refueling
Doppler coefficient	$-3.38\cdot10^{-6}$	$-3.20\cdot10^{-6}$
Core axial expansion	$-1.63\cdot10^{-6}$	$-1.70\cdot10^{-6}$
Core radial expansion	$-9.12\cdot10^{-6}$	$-8.91\cdot10^{-6}$

5. ANALYSIS OF ACCIDENTS

The following accidents without scram were considered by comprehensive transient model [5] with account for thermal mechanics of fuel rods and thermal hydraulics in the core and primary circuit:

1) insertion of positive reactivity 1 $ for a second;
2) trip of gas supply to the gas lift system;
3) two-fold increase in the rate of gas supply to the gas lift system;
4) drop of feedwater temperature at steam generator inlet to 300 K;
5) total NPP blackout (trip of gas supply to the gas lift system and feedwater supply to steam generator).

The following effects, impacting reactivity, were simulated:

1) Doppler effect under assumption about logarithmic dependence of reactivity on fuel temperature;
2) change in core effective height due to thermal expansion of fuel column under assumption about absence of pellet-clad mechanical interaction;
3) change in core effective radius due to thermal expansion of core support plate and FA top spacer grid structures;
4) change in spatial distribution of effective coolant density in the core, blankets, at core inlet and in chimney with account for coolant thermal expansion and variation of gas void in the coolant.

5.1 TRANSIENT OVERPOWER ACCIDENT

Design features of RBEC-M reactor module allow to reduce probability and mitigate consequences of accident with insertion of positive reactivity, in particular, to provide:

- low value of reactivity which can be inserted in full-power operation because of erroneous ejection of control rods due to small value of reactivity change with burnup;
- elimination of fast ejection of control rods from the core due to CPS design;
- passive actuation of passive absorber rods at significant temperature rise at core outlet;
- decrease of reactor power, when gas void in the core is uniformly changed (both increased and decreased).

A hypothetical accident without scram initiated by insertion of positive reactivity of 1$ for 1 second was considered in the given study. Calculational results are shown on Figure 5. Doppler effect and fuel column axial expansion decreases the rate of positive reactivity insertion at the initial stage of the process. After coolant temperature at core outlet exceeds a set value for actuation of passive protection system, power drops to decay heat level. Variations of gas void and coolant density in the core are insignificant. Peak fuel and cladding temperatures reach 2382K and 1303K, respectively. Reactor power at the pulse peak is 8 times as high as the nominal value. Melting temperature of mixed nitride fuel is 3050K, however, there are experimental evidences that ultimate allowable temperature for mixed nitride is about 2000 K. Above this point production of metal phase and evaporation of Pu become possible. These processes can cause sudden change in fuel structural state. In the considered accident peak fuel temperature exceeds 2000 K for about 2 seconds, growing up to almost 2400 K. Thus, analyzed scenario can be considered as close to ultimate for RBEC-M reactor from viewpoint of fuel integrity.

5.2 UNPROTECTED ACCIDENT WITH CHANGE OF GAS FLOWRATE IN GAS LIFT SYSTEM

High level of coolant natural circulation and negative coolant effective density reactivity feedback allow to mitigate consequences of accident with change of gas flowrate in gas lift system. The accident with trip of gas supply (Figure 6) is accompanied by fast decrease of coolant flowrate to natural circulation level of about 18% of nominal reactor flowrate. Negative core gas void reactivity feedback causes drop of reactor power to decay heat level. Short-term clad temperature growth (up to 1010 K) is caused by faster decrease of flowrate compared to power at the initial stage of the process.

The accident with increase in gas supply rate to the gas lift system can be initiated, for instance, by gas pressure and flowrate growth in the gas lift system caused by steam generator leakage in the primary circuit and steam entrainment in the cover gas volume above the free coolant level. Hypothetical two-fold increase in gas flowrate causes gas void increase in the core and chimney. As a result, coolant flowrate grows by 10% and reactor power drops by 15% that causes some decrease in fuel and cladding temperatures.

The obtained dependence of reactor power on gas flowrate into the gas lift system testifies that the gas lift system can be used not only for prompt reactor shutdown, but also for reactor transition to partial power level, i.e. can supplement and probably replace control and protection system in accidents and load-follow regimes. Thus, a possibility can be considered to classify regime with variations in rates of gas supply to the gas lift system not as accident, but as design operational regime.

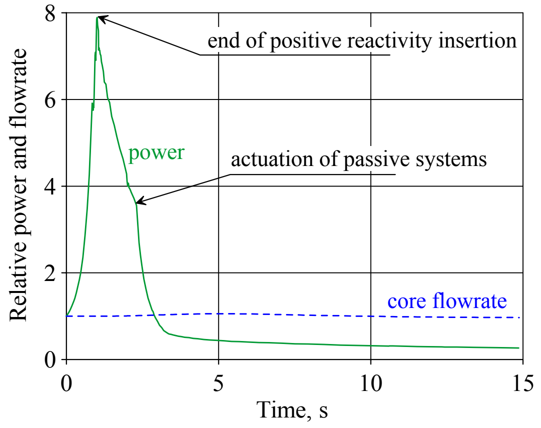
5.3 UNPROTECTED OVERCOOLING ACCIDENT

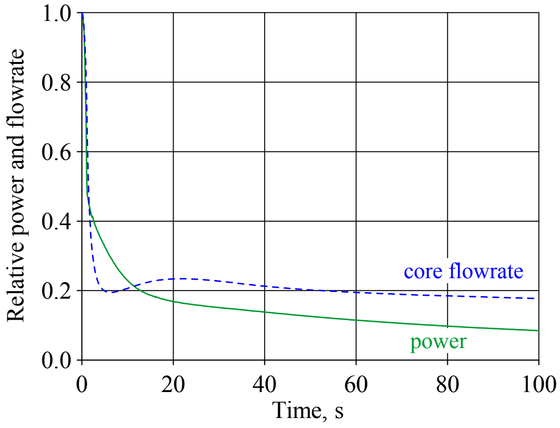
Accident with growth in heat transfer to the secondary circuit was simulated by hypothetical decrease of feedwater temperature at SG inlet from 561 K to 300 K for 1 second (Figure 7). Coolant temperature at the core inlet drops, causing decrease in the core effective radius and insertion of positive reactivity. Reactor power increases by 40 %, peak fuel temperature grows by up to 1536 K. Although, according to the accident conditions, feedwater temperature drops by 261 K, growth of reactor power causes additional heating-up of primary coolant and, as a consequence, coolant temperature at the core inlet decreases by only 73 K, remaining considerably higher than lead-bismuth freezing point. Doppler effect and fuel axial expansion compensate the insertion of positive reactivity.

5.4 UNPROTECTED BLACKOUT ACCIDENT

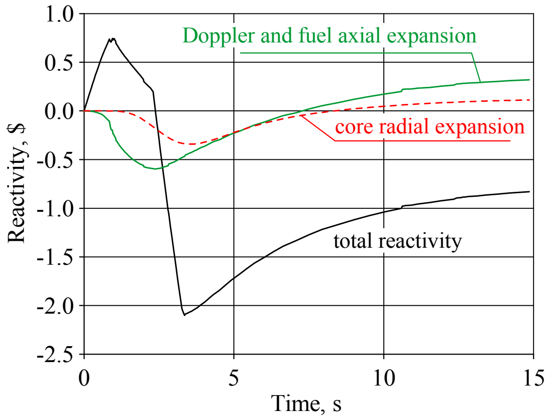
NPP blackout accident was simulated by trip of gas supply to the gas lift system and feedwater supply to the steam generators (Figure 8). Neither active nor passive absorber rods were conservatively assumed to enter the core in the accident. Insertion of negative reactivity and drop of reactor power to decay heat level are provided, mainly, by trip of gas supply to the gas lift system and corresponding increase of the core effective coolant density. Approximately in 20 s after initiation of the accident steam generators are totally dried out. In about 2 days and 10 hours after initiation of the accident the PRACS power reaches core decay heat power. Up to this moment the temperature growth was limited by heat capacity of coolant and structures of reactor module. Peak temperature of reactor structures in the accident does not exceed 1000 K.

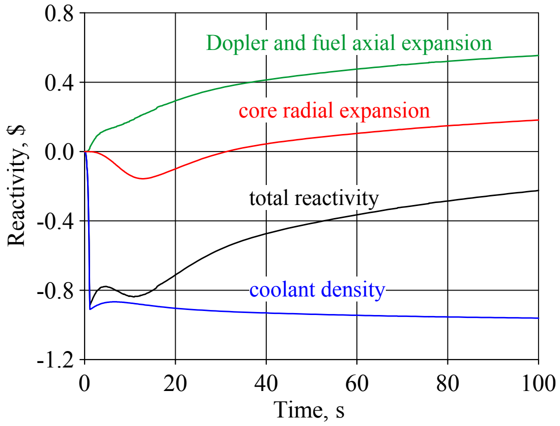
NPP blackout accident is seemed the most dangerous event for cladding integrity, because cladding in this accident remains at temperature of above 900 K for a long time. Lack of available test data on strength and corrosion properties of EP-823 steel at high temperatures does not currently allow to make a final conclusion about fuel rod failure probability in this accident.



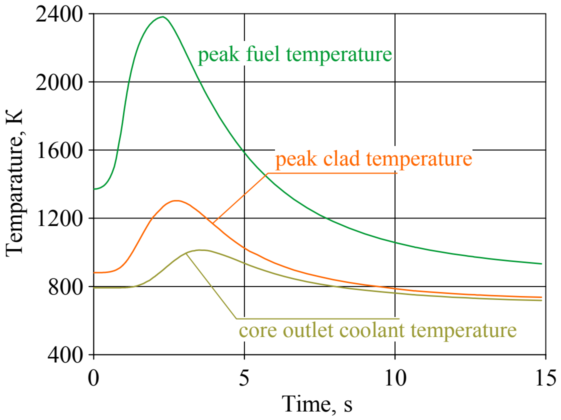


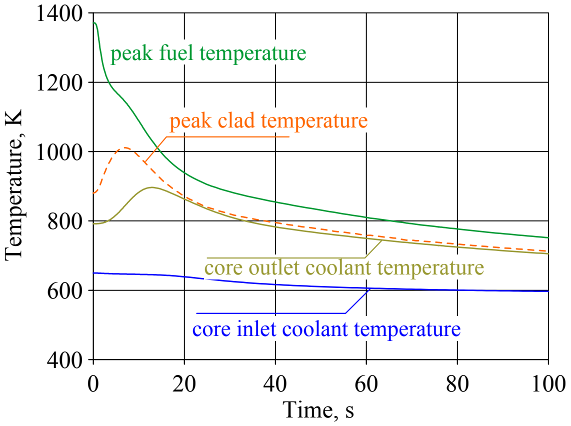
a) relative power and reactor coolant flowrate





b) reactivity components

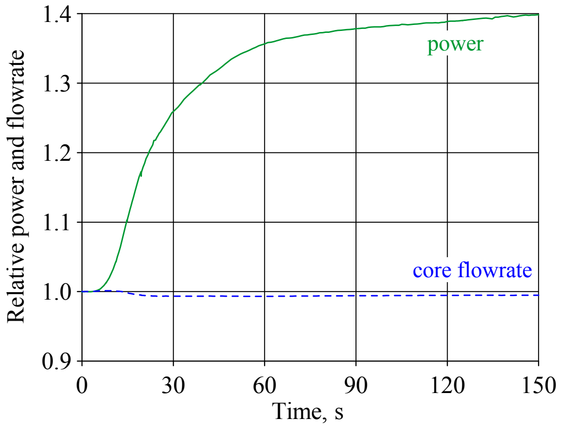


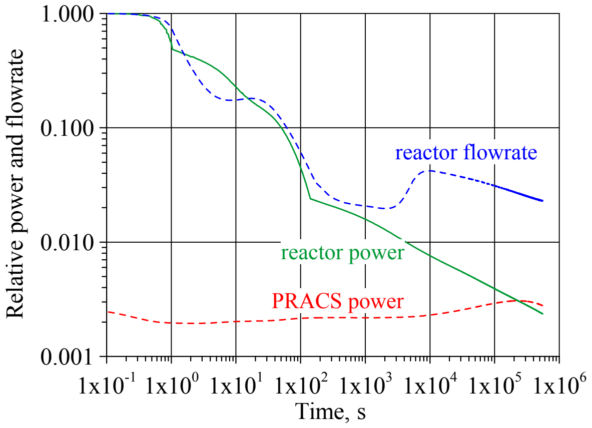


c) fuel, cladding and coolant temperatures

Figure 5. Calculational results for transient overpower accident in RBEC-M reactor

Figure 6. Calculational results of loss-of-gas-flow accident in RBEC-M reactor





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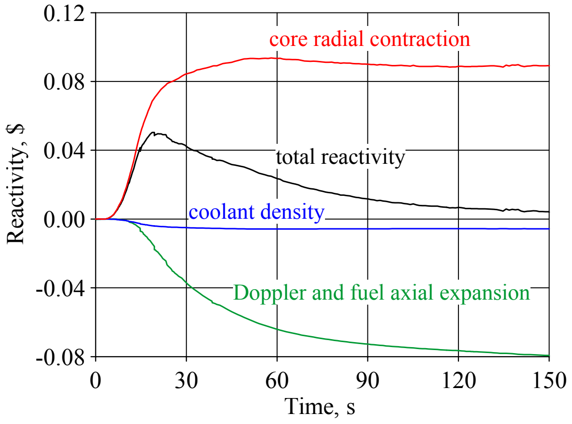
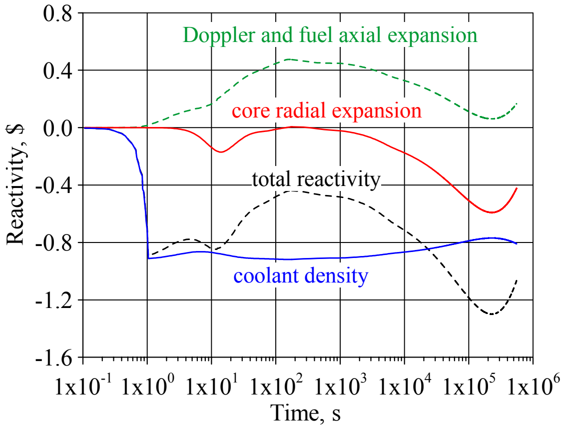
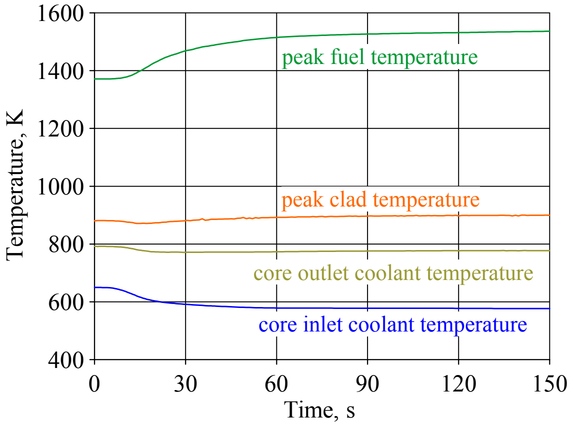
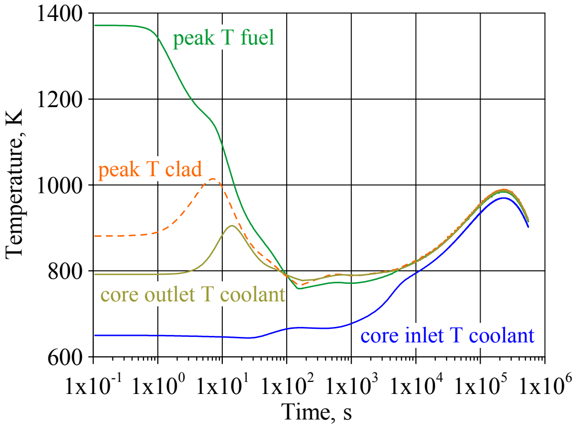




b) reactivity components





c) fuel, cladding and coolant temperatures

Figure 7. Calculational results of accident with increase of heat transfer to secondary circuit in RBEC-M reactor

Figure 8. Calculational results of NPP blackout accident in RBEC-M reactor

CONCLUSIONS

The main objective of developing the RBEC-M lead-bismuth fast reactor project was to demonstrate the possibility to combine advantages of existent reactor technologies in one nuclear power facility to improve economic and breeding parameters in comparison with BN-type reactors and, simultaneously, to enhance safety parameters. Main RBEC-M reactor parameters, especially related to reactor safety, were considered in the paper.

High level of RBEC-M reactor self-protection is based on thermal-physical properties of lead-bismuth coolant, low reactivity change with burnup, negative fuel temperature and coolant effective density reactivity feedbacks, high heat capacity of the reactor module, use of built-in passive reactor auxiliary cooling system and passive systems for reactor shutdown, high level of coolant natural circulation, etc. The gas lift system with argon supply under the core provides decrease of reactor power at spatially uniform changes (both reduction and increase) of gas void in the core.

The calculational analysis of RBEC-M reactor behavior in the accidents, including transient overpower (TOP), change of gas flowrate in the gas lift system, core overcooling, and NPP blackout proves the high level of reactor self-protection.

The considered TOP accident with insertion of positive reactivity of 1$ for 1 second was found close to ultimate for RBEC-M reactor from viewpoint of fuel integrity, because peak fuel temperature in this accident exceeds 2000 K (ultimate for mixed nitride) for about 2 s. The TOP accident scenarios require further detailed consideration with application of spatial neutron kinetics model.

NPP blackout accident is seemed the most dangerous event for cladding integrity, because cladding in this accident remains at temperature of above 900 K for a long time. However, lack of available test data on strength and corrosion properties of EP-823 ferritic-martensitic steel at high temperatures does not currently allow to make a final conclusion about fuel rod failure probability in this accident.

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