Minimization of reactivity margin in equilibrium cores of liquid metal cooled fast reactors

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Abstract. In the framework of "Proryv" project, not only the problem of minimization of potential nuclear accident consequences was set up, but also that of minimization of its initial cause, i.e. core reactivity margin. Minimization of the core reactivity margin is possible within the framework of so called concept of "equilibrium reactor core" (reduction of reactivity margin provided for the fuel burn-up), and also with the use of liquid metal bond high conductivity fuel elements (temperature-power effect). In the paper, "equilibrium reactor core" concept is specified and possibilities of its implementation are analyzed.

Studies were made on dependence of scenarios, key design characteristics and accident consequences on the added total reactivity margin value. Advantages of low reactivity margin of about 1–2 β_{eff} are quantitatively demonstrated from the standpoint of nuclear safety assurance and decrease of accident consequences down to the level excluding public local evacuation and resettlement.

Key words: safety, burn-up, reactor unit, reactivity, equilibrium reactor core, nuclear accident

1 Introduction

The possibility of reactor operation without any noticeable reactivity change is, along with the fuel breeding, an unquestionable advantage and particular feature of related to fast reactor neutronics. The absence of strong absorbents and "iodine well" type effects are favorable for safety assurance during reactor operation in transient modes. The concept of equilibrium reactor core using high density fuel with $BR_c \sim 1$ allows minimization of reactivity changes during the fuel burn-up. Actually, it gives another application of fundamental physical property of fast reactors (fuel breeding), which allows to compensate for the effect of fuel burn-up. Using fuel with high thermal conductivity and providing good thermal contact between fuel and cladding by filling fuel-cladding gap with liquid metal make it possible to minimize, as well, temperature-power reactivity effect.

Taking into account all of this, it can be stated that reactivity margin required for compensation of these effects in fast reactor could be significantly lower than that in the other types of reactor units (RU). Potentially, it can be reduced down to the level below β_{eff} excluding in principle a possibility of uncontrolled prompt neutron excursion of the reactor. Is it possible to achieve significant safety advantages using this feature? What is the value of maximum reactivity margin (RM) excluding severe accidents with disastrous radiation consequences? These are the key questions for forming up a safety concept within the framework of philosophy based not on the safety systems buildup, but on maximal reduction of potential nuclear danger due to the use of RU "natural safety" features.

2 Equilibrium reactor core and equilibrium fuel concepts

The need to reduce maximum reactivity margin and rule out accidents leading to potential need of population evacuation and resettlement is taken in the "Proryv" project as one of basic principles of "inherent safety" [1,2] for practical development and implementation at design level.

A possibility of creating equilibrium reactor core with breeding ratio (BR_c)~ 1 and low reactivity margin, as it was shown in BREST design in 1990-ies and confirmed by further studies (for instance, see [3]), requires the use of high density nitride fuel and low power density in 9–10 mm diameter fuel elements. These possibilities were fulfilled within the framework of "Proryv" project in lead cooled BREST-OD-300 [4] and sodium cooled BN-1200 [5] reactor designs. In equilibrium mode with repeatedly recycled fuel in reactor operating at rated power maximum reactivity margins for BREST-OD-300 and BN-1200 are, respectively, equal to ~0.23%Δk/k and ~0.5%Δk/k.

High BR_c stabilizes not only reactivity, but also power density in the fuel subassemblies (SA) in the process of fuel burn-up, thus giving one more advantage to such core design from technical and economical standpoints. It allows elimination of need to profile power density by fuel enrichment. In the BN-1200 design, there is a possibility to use single enrichment core with unified fuel element and SA designs. In BREST-OD-300 reactor, SA power profiling is achieved by choosing fuel element diameter (see Fig. 1).

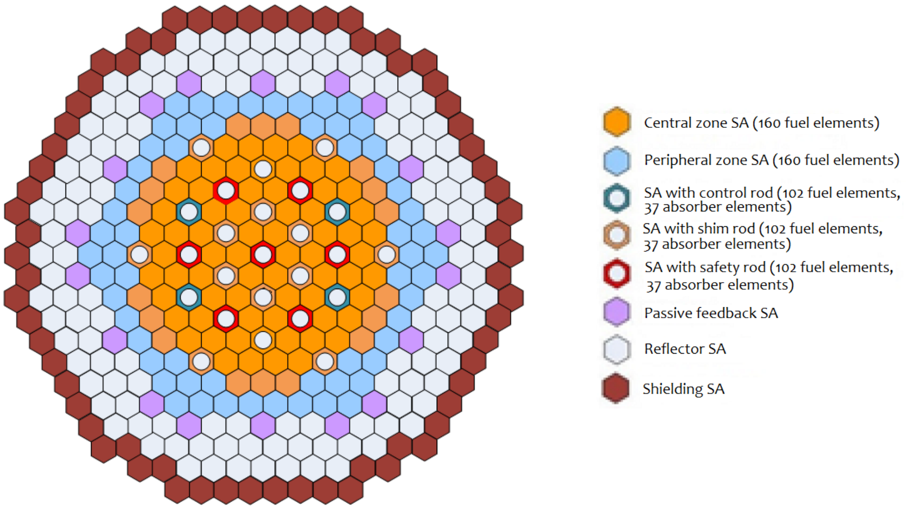


Fig.1. BREST-OD-300 reactor core map.

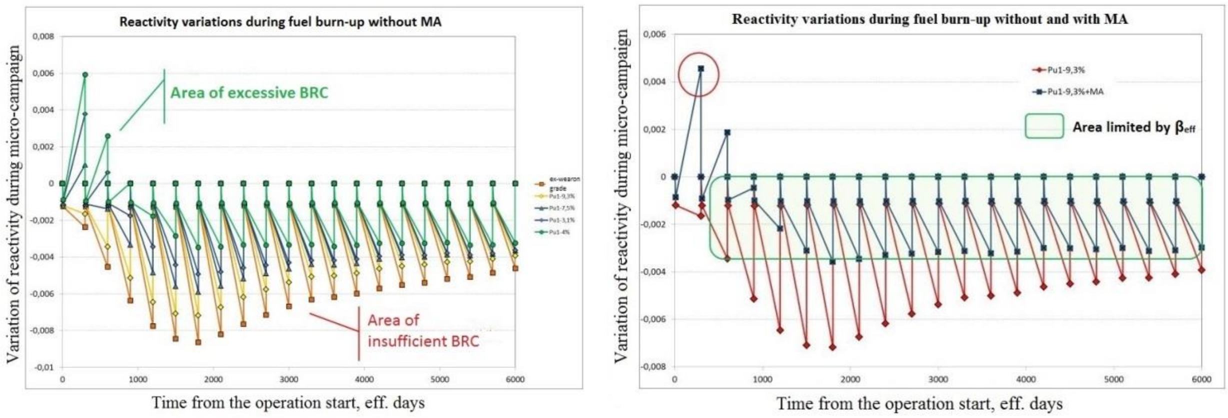
The results of study confirm the possibility of development of equilibrium reactor core with low reactivity margin. The goal set by the authors of this paper (and that set by "Proryv" project) is to assure high safety level during this transition period of equilibrium fuel formation, as well. It is suggested to extend "equilibrium core" and "equilibrium fuel" concepts, respectively, to the core with low (although variable) reactivity margin and to the fuel with virtually constant Pu isotopic composition after repeated recycling.

For definiteness, reactor core with "equilibrium fuel" can be called "asymptotically equilibrium core". Within this meaning "equilibrium reactor core" having practical importance from safety standpoint operates directly from the date of reactor start-up during its lifetime.

In the period of transition to equilibrium fuel reactivity change potentially increases depending on the initial Pu composition (see Fig. 2a). Use of MA (see Fig. 2b) reduces reactivity margin and potentially (after practical assimilation of fuel with MA additives) gives a solution to this problem.

It should be also noted that reactivity margin required to compensate for the fuel burn-up increases with burn-up (see Fig. 3) due to negative influence of fission products accumulation. We consider the increase of average burn-up level over 12% as an additional problem for reactivity minimization.

Taking into account the above statements, the problem of joint optimization of fast reactor technical and economic characteristics and parameters determining their safety looks highly relevant. It is important to make quantitative estimates of how strong is dependence of accident scenarios and their consequences on reactivity margin. Herewith the requirement of exclusion of population evacuation is of top priority, and reactivity margin in the reactor on power is an optimized parameter, which value should not exceed significantly β_{eff}.



a) Without MA b) With MA

Fig. 2. Reactivity variation with different Pu and MA compositions.

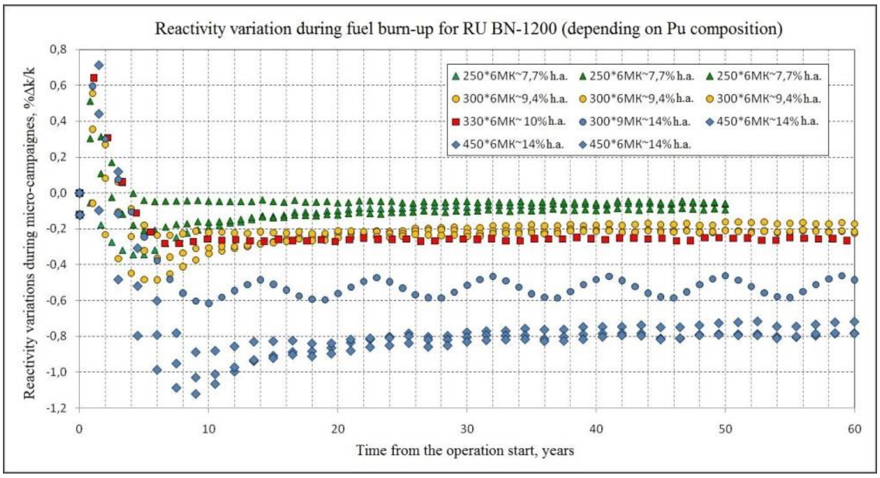


Fig. 3. Variation of reactivity vs. fuel burn-up.

3 Analysis of transients and accidents in equilibrium core of BREST-OD-300 reactor with different levels of maximum reactivity margin

3.1 Initial events, scenarios, and computation codes

Withdrawal of control rods from the core with addition of total reactivity margin in the reactor operating at nominal power was considered as the initial event (IE). Calculations made for ductless core with RM variation by changing fuel enrichment (Pu mass fraction) and critical position of control rods, included:

– estimates made for reactivity variation within the range of (0.2–2.0 β_{eff});

– detailed calculations for RM equal to 0.43 β_{eff}, 0.65 β_{eff}, 1.0 β_{eff}, and 1.2 β_{eff}.

The speed of control rods withdrawal varied from maximum value assuring practically instantaneous rods withdrawal to technically feasible value for withdrawal period of 30 s. Multiple safety systems failures including safety rods failure were superimposed onto IE. The scenario of failure of coolant flow rate passive feedback system in case of the primary pump shutdown caused by coolant temperature increase at the steam generator outlet over preset value of 520°C was considered.

There were two different models used for simulating the processes, namely: simplified model with concentrated parameters (point kinetics) and 3D model of neutronics and thermohydraulics of the reactor core using DINAR code.

3.2 Results of computational modeling

According to the results of simplified calculations by point kinetics model, short power "pulse" strongly depends on added reactivity within the range of 0.4 to 2 β_{eff}, its value changing by several orders of magnitude (see Fig. 4).

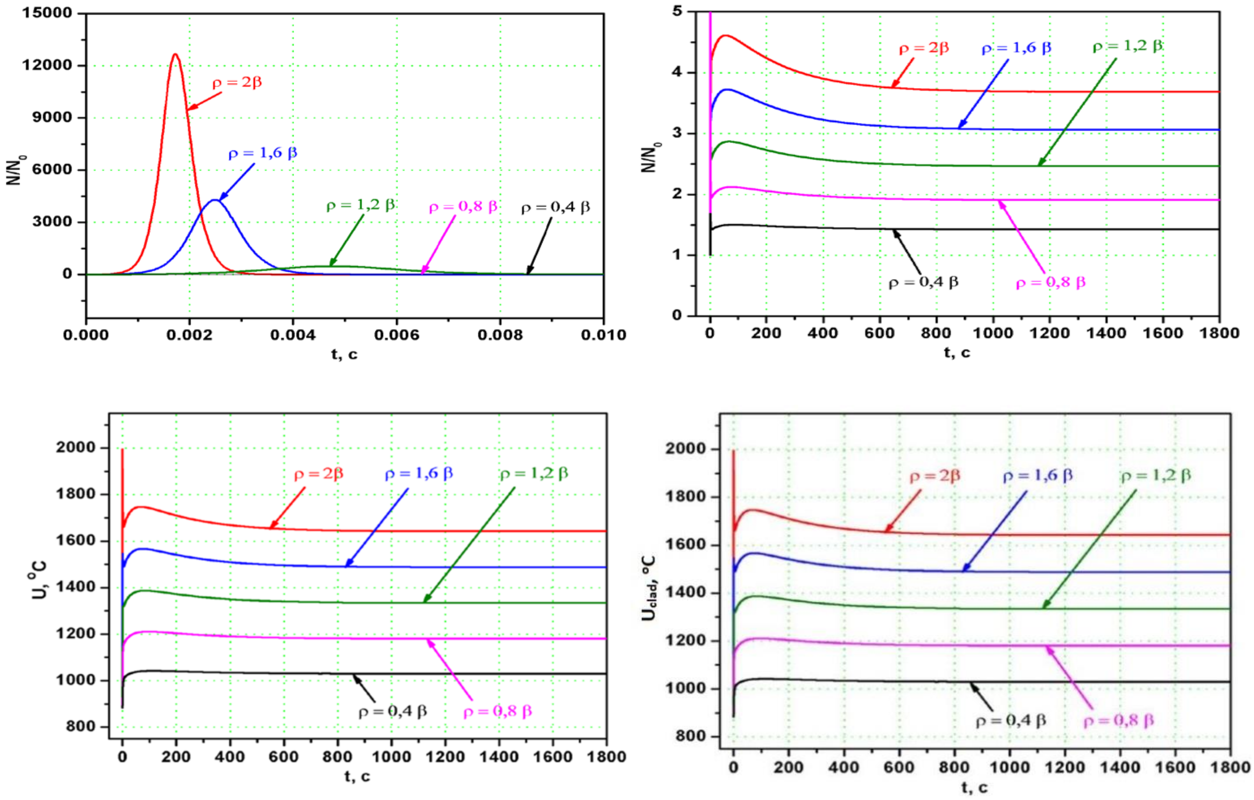
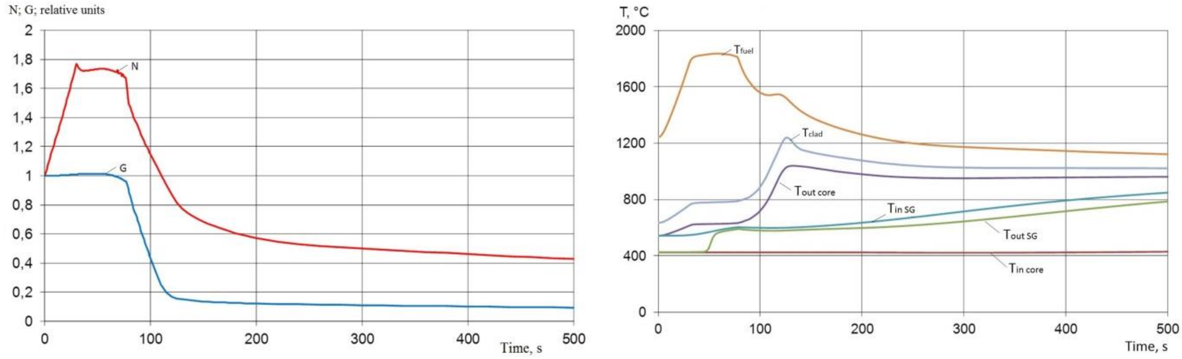


Fig. 4. Behavior of relative reactor power (N/N_0, where N_0 – rated power), fuel temperature (U), and fuel element cladding temperature (U_{clad}) vs. reactivity margin.

Due to feedback (mainly Doppler effect) the parameters are stabilized at the level significantly depending on reactivity margin:

- from ~1.5 N_0, ~1020°C and ~670°C – with 0.4 β_{eff} reactivity;
- to ~3.5 N_0, ~1650°C and ~1070°C – with 2 β_{eff} reactivity.

Results of 3D modelling of reactivity insertion at the realistic velocity are presented in Fig. 5. Uncontrolled power increase is blocked at the level of ~1.8 N_0, and then power decreases down to minimum values allowing decay heat removal by natural coolant flow, temperature feedbacks and negative reactivity inserted by passive feedback system upon accidental pump shutdown. Fuel/cladding peak temperatures do not exceed ~1850/1200°C values, thus excluding materials melting. The probability of such scenario is ~$3 \cdot 10^{-9}$ year^{-1}. Taking into account that relatively small number of fuel elements will be overheated (see Fig. 6) the level of their damage is estimated at ~7%, the release of radioactivity by Kr and Xe (total) – at $6.1 \cdot 10^{10}$, ^{137}Cs – at $3.6 \cdot 10^{6}$, and ^{131}I – at $5.2 \cdot 10^{6}$ Bq/day, thus not exceeding reference level at normal operation.



N – reactor power, G – coolant flow rate, T_{clad} – max fuel element cladding temperature, $T_{out\ core}$ – core outlet coolant temperature, $T_{in\ SG}$ – SG inlet coolant temperature, $T_{out\ SG}$ – SG outlet coolant temperature, $T_{in\ core}$ – core inlet coolant temperature, T_{fuel} – max fuel temperature

Fig. 5. Variation of BREST-OD-300 reactor main parameters in UTOP accident.

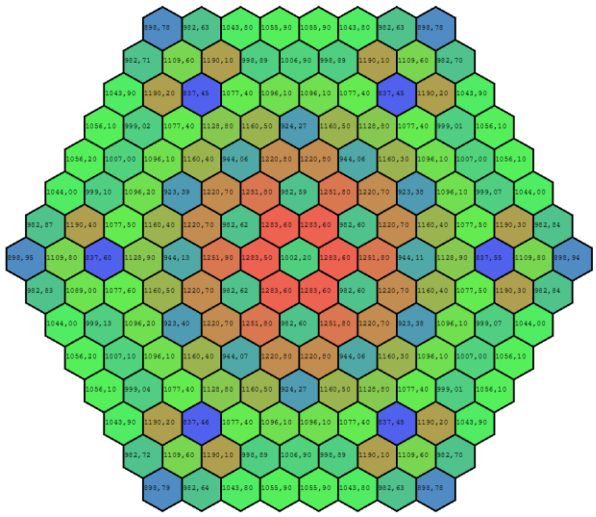


Fig. 6. Distribution of maximum cladding temperatures.

In case of passive feedback system failure with constant coolant flow rate (interconnected parameters), the reactor power does not decrease lower than ~1.4 N_0, however maximum fuel temperature is kept almost constant and does not exceed 1850°C, while cladding temperature reaches ~815°C value (see Fig. 7).

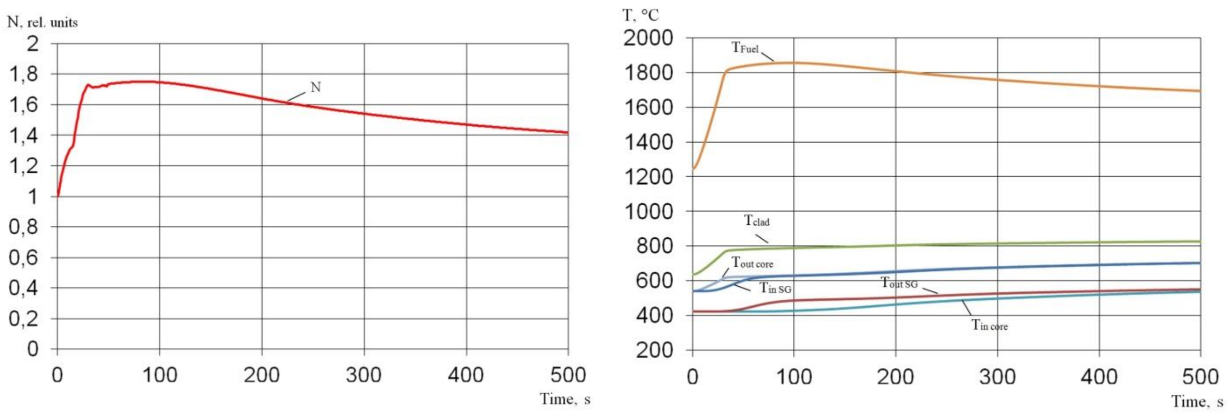


Fig. 7. Behavior of BREST-OD-300 main parameters in scenario with failure of coolant flow rate passive feedback system.

4 Analysis of consequences of accidents with positive reactivity insertion in the BN-1200 reactor nitride core

4.1 Core characteristics and initial event

The reactor core consists of 432 single enrichment SAs spaced in triangular grid with 185 mm pitch and 31 control rods. The core is surrounded by 2 rows of steel shielding subassemblies, 2 rows of in-core storage (ICS) B_4C shielding subassemblies, and 3 rows of in-vessel components radial shielding subassemblies. Fuel subassemblies contain fuel element bundles (either 271 fuel elements of 9.3×0.5 mm diameter, or 217 fuel elements of 10.5×0.5 mm diameter), sodium plenum of the fuel elements and absorber elements (AE) zone above (Fig. 8)

Complete withdrawal of control rods during 14 s in the reactor operating at nominal power level with failure of all safety rods was considered as IE.

4.2 Computational models and codes

Analytical studies on IE consequences were made in two stages. In the first stage engineering code SOKRAT-BN based on one-dimensional thermohydraulic models of reactor elements [7] was used for the analysis of accident consequences for various inserted reactivity values within the range of (0.6–1.6 β).

Further detailed calculations of accident caused by the unauthorized control rods withdrawal were made by COREMELT code designed for improved estimate of severe accidents [8]. The code includes 3D neutronics module RADAR-3D and 2D thermohydraulic module COREMELT-2D allowing simulation of sodium boiling and reactor core elements melting processes.

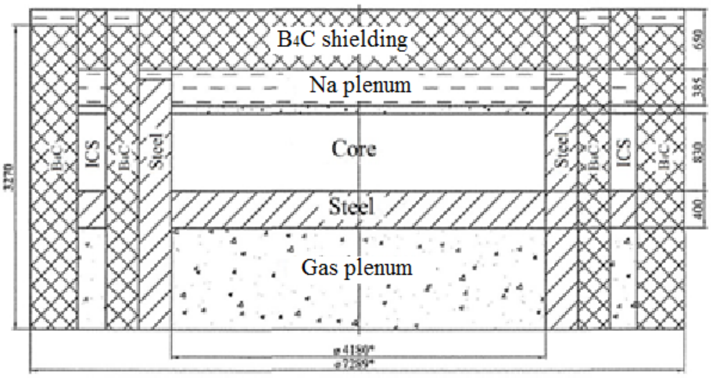


Fig. 8. BN-1200 reactor core arrangement.

4.3 Results of analytical studies

The general picture of BN-1200 reactor parameters dynamics before the beginning of possible phase transitions stage is, in principle, similar to that obtained for BREST-OD-300 reactor. Upon the end of the short transient, temperatures no more increasing are stabilized (see Fig. 9) at the level strongly dependent on the inserted reactivity. If the inserted reactivity $\rho > \beta_{eff}$, then cladding temperature gradually exceeds maximum permissible value (900°C) specified in the Russian regulatory documents as fuel element safe operation limit (max design limit).

Detailed studies on reactivity accident consequences in the BN-1200 reactor were carried out for two levels of reactivity margin, namely: 0.5%Δk/k and 0.75%Δk/k.

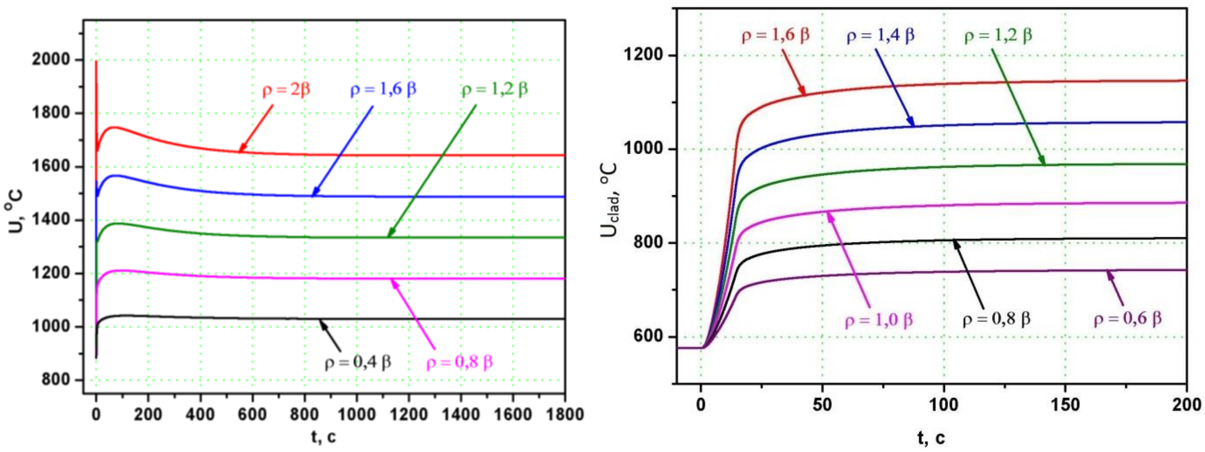


Fig. 9. Temperatures of fuel (U) and cladding (U_{clad}) vs. inserted positive reactivity.

According to calculations made by COREMELT code, power increase leads to sodium boiling in 27 s after initial failure, and 3 s later onset of departure from nucleate boiling takes place in the hottest subassembly resulting in the fuel elements melting (see Figs. 10 and 11). The subsequent power decrease causes slowing down of reactor core destruction process to the following degree: fractions of fuel subassemblies that have lost their integrity are 73% and 81% and fractions of molten fuel elements in the core are 20% and 25%, respectively, for 0.5%Δk/k and 0.75%Δk/k reactivity margin values. However, even in this case, public radiation dose (see Table I) is much lower than that requiring resettlement ($D_{eff} \geq 50$ MSv).

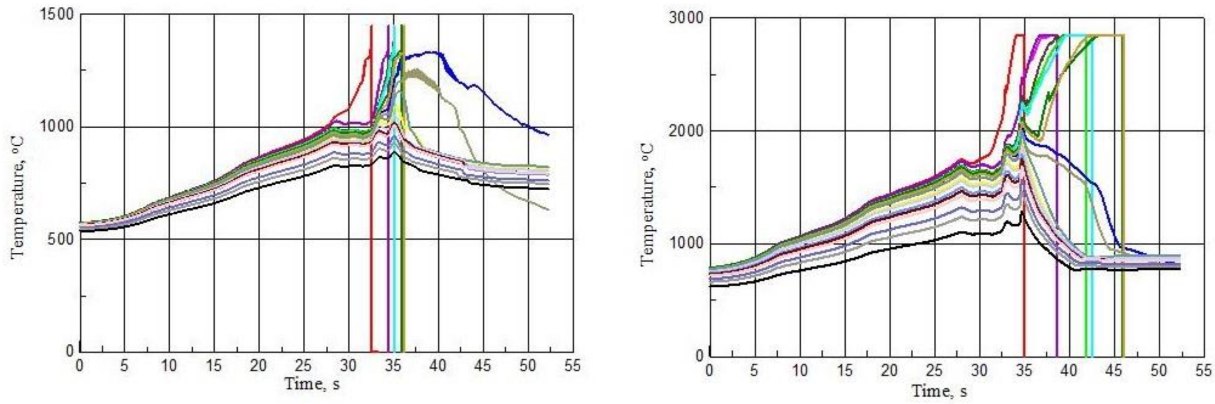
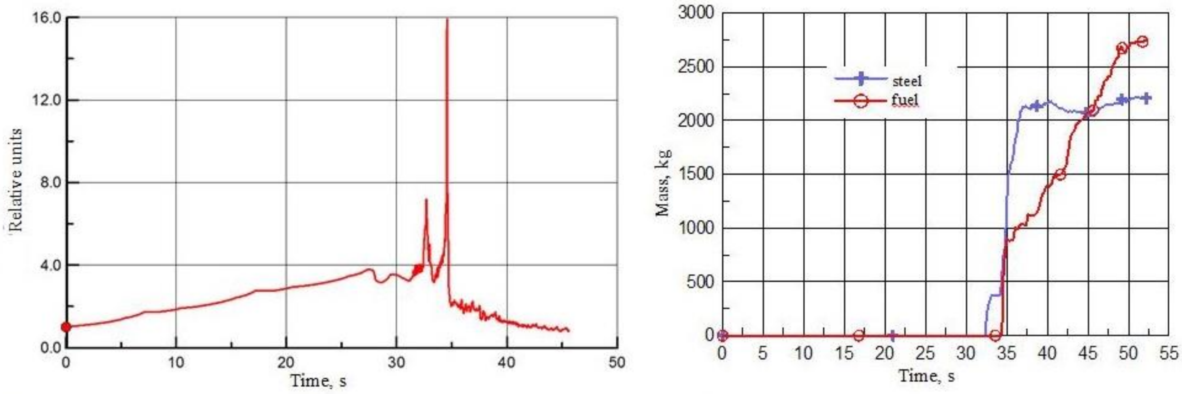


Fig. 10. Maximum temperatures of fuel element cladding (on the left) and fuel (on the right) in the different fuel subassemblies.



a) Reactor power b) Mass of molten materials

Fig. 11. Reactor power and mass of molten materials during accident.

TABLE I: RESULTS OF CALCULATION OF EFFECTIVE RADIATION DOSE OF RESIDENTS BEYOND THE NPP SITE BORDERS VS. INSERTED REACTIVITY FOR BN-1200 REACTOR.

Inserted reactivity, %Δk/k	Number of fuel SAs with gas leakage, pc./%	Number of fuel SAs with molten fuel, pc./%	Effective radiation dose D_{eff}, mSv
0.5	314 / 73%	88 / 20%	7
0.75	349 / 81%	110 / 25%	9

According to calculation data, release of radionuclides into the environment determined by the fission gas and Cs could be as high as $2.65 \cdot 10^{17}$ Bq, and $1.05 \cdot 10^{12}$ Bq, respectively.

It is also important that the accident does not lead to so called "energetic" scenario with possible explosion type thermal and mechanical energy release that may occur in case of release of large amount of dispersed molten fuel into the upper reactor plenum and its intensive thermal interaction with sodium, thus causing pressure increase and possible loss of integrity of the primary circuit. It should be also noted that if molten fuel volume becomes sufficiently large, then prompt neutron recriticality due to sloshing cannot be ruled out. Low reactivity margin in the BN-1200 reactor prevents such unfavorable accident process.

5 CONCLUSIONS

Conceptual idea of reactors with BR_c~1 and low reactivity margin (1–2 β_{eff}) is confirmed by the experience gained in developing designs of BREST-OD-300 and BN-1200 reactors with nitride fuel within the framework of "Proryv" project. Low level of reactivity margin significantly reduces requirements to control rods worth and provides compliance with nuclear safety rules taking into account requirements of at least one year reactor run (micro-campaign) and 0.9 load factor.

Increased reactivity change with fuel burn-up in the early stage of transit to equilibrium composition fuel requires detailed optimization of reactivity margin and reactor technical and economical parameters (fuel burn-up, potential limitations and increased requirements to fuel, and control rods worth). Parametric studies of influence of reactivity margin value on safety in case of complete withdrawal of control rods and insertion of total reactivity margin gave the following results:

- assurance of reactivity margin within β_{eff} value makes it possible to avoid not only reactivity accidents caused by prompt neutrons, but also fuel and fuel element cladding steel melting in both Pb and Na cooled reactors;
- increasing reactivity margin up to the range of (1–2 β_{eff}) in sodium cooled reactor does not lead to prompt neutron reactor excursion. However, fuel melting probability still exists, but on condition of keeping design integrity of the primary circuit (reactor vessel), it does not lead to radiation consequences that would require resettlement of population outside the boundaries of controlled access area;
- further increase of reactivity margin is undesirable from the standpoint of scenarios under study.

6 LIST OF REFERENCES

[1] E.O. Adamov, A.V. Lopatkin, V.A. Pershukov, V.I. Rachkov, and V.M. Troyanov, Strategy of the large scale development of nuclear power in the Russian Federation based on fast reactors and CNFC technologies // In proc.: International Conference on Fast Reactors and Related Fuel Cycles: Safe Technologies and Sustainable Scenarios (FR13), Paris, France, 4–7 March 2013, Vol.1, p. 175-192.

[2] E.O. Adamov, Project "Proryv" – technological foundation for large-scale nuclear power / E.O. Adamov, R.M. Akeksakhin, L.A. Bolshov et al. // Academy of Sciences Proceedings. Energetics. – 2015. – No 1. p. 5-12.

[3] E.O. Adamov, L.M. Zabudko, V.I. Matveev, V.I. Rachkov, V.M. Troyanov, Yu.S. Khomyakov, and V.N. Leonov, Comparative analysis of advantages and disadvantages of using metal and nitride mixed uranium-plutonium fuel in fast reactors. Academy of Sciences Proceedings. Energetics. – 2015. – No 2. p. 3-15.

[4] Yu.G. Dragunov, V.V. Lemekhov, V.S. Smirnov, and N.G. Chernetsov, Technical solutions and development stages of reactor unit BREST-OD-300 // Nuclear energy, v.108, issue 4, 2012, p. 58-64.

[5] V.I. Rachkov, V.M. Poplavsky, A.M. Tsibulya et al. Concept of advanced power unit with fast sodium reactor BN-1200 // Nuclear energy, v.108, issue 4, 2010, p.201-205.

[6] V.M. Poplavsky, A.M. Tsibulya, Yu.S. Khomyakov et al. Reactor core and fuel cycle for advanced fast sodium reactor // Nuclear energy, v.108, issue 4, 2010, p. 206-211.

[7] N.A. Rtishchev et al., "FIRST VERSION OF SOCRAT-BN", in Third International Scientific and Technical Conference “Innovative Designs and Technologies of Nuclear Power” (ISTC NIKIET-2014). Moscow, October 7-10, 2014.

[8] Iu.M. Ashurko, A.V. Volkov, and K.F. Raskach, Coremelt-2D code for analysis of severe accidents in a sodium fast reactor. In: Intern. Conf. on Fast Reactor and Related Fuel Cycle: Safe Technologies and Sustainable Scenarios (FR13), Paris, France, 2013. — IAEA, 2013, T1-CN-199/453, track 03.