Prospects for the development of the concept of a safe nuclear reactor BREST of maximum limiting power for nuclear energetics of the middle of the XXI century

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Abstract. In Russia (JSC NIKIET) a project of a fast reactor BREST-1200 is being developed. The article analyzes the safety of the BREST reactor with maximum limiting power (BREST-2000, -2400). In BREST reactors with an electric power of 1200 MW and more, the void reactivity effect can be positive. The most dangerous scenario is associated with the entrainment of bubbles into the central part of the core (with a volume fraction of bubbles of 50 ... 60%). In this case, the magnitude of the void reactivity effect is several times higher than the effective fraction of delayed neutrons $\beta$. For the BREST-2400 reactor, the maximum void reactivity effect is about $7\beta$ (for BREST-2000, about $6\beta$). When other ATWS are implemented against the background of erosion and corrosion of structural steel, the total introduced reactivity can also exceed $\beta$, which will lead to an accident. To ensure safety, it is necessary to adjust the design solutions. When used as a coolant, lead extracted from thorium ores (with a concentration of $^{208}$Pb isotope from 75 to 98%) and tungsten coatings of fuel claddings, the void reactivity effect is negative even in the BREST-2400 reactor, and when switching to a new cermet fuel (0.8 MN - 0.2 U) it is easy to ensure the safety of the reactor.

1. Introduction

Promising energy sources capable of meeting the needs of mankind for the long term are based on the transmutation of atomic nuclei. Fusion of light nuclei is energetically beneficial. The principle of operation of fusion reactors is based on this. The decay of heavy atomic nuclei into lighter ones is also energetically beneficial. The principle of operation of fission reactors and radionuclide sources is based on this. Among the power plants based on nuclear transmutation, the most developed and industrialized are fission reactors. In addition to large-scale energy production, additional requirements are imposed on new generation energy sources. They are well known. These are economic efficiency (in the absence of competitors, this requirement can be formulated as the production of useful energy, that is, the production of energy must exceed the energy consumption of the installation), safety, and fuel availability for the long term. For sources based on the transmutation of atomic nuclei, the safety requirement includes nuclear and radiation safety (exclusion of unacceptable emissions of radioactive substances outside the nuclear power plant), non-proliferation of technologies and materials that can be used in the production of weapons of mass destruction, transmutation of radioactive waste.

Nuclear energetics is one of the youngest and fastest growing industries in the world economy. The development of nuclear energetics is caused by the growing demand for energy of mankind with limited non-renewable resources, uneven distribution of organic (hydrocarbon) fuel in the earth’s crust.
Compared to other energy sources, nuclear fuel has a millions of times greater energy concentration. The prospects for the development of energetics in a number of countries around the world provide for the gradual involvement and increase in the share of nuclear power plants in electricity production. (Electricity is the most convenient form of energy for the consumer.) In the world, under the auspices of the IAEA, the concepts of fourth-generation nuclear reactors (“Generation IV” or “GIF”) are being developed that satisfy most of the listed requirements [1]. In 2006, Russia joined the Generation IV International Forum, whose members are developing several types of fourth-generation nuclear reactors. Among the concepts of fourth-generation reactors are fast reactors with sodium and heavy coolants (lead or eutectic lead-bismuth alloy). Fast reactors with sodium or lead coolant are considered as the main world concepts of liquid metal fast reactor [2-5].

For large-scale nuclear energetics, a lead coolant is more preferable due to the high cost of bismuth and the possibility of producing polonium-210 from bismuth-209. In Russia, the USA and France, the possibility of using an alloy of lead and bismuth as a coolant is being studied [6]. In total, there are 79 experimental installations for research of reactors with sodium coolant, 72 installations for research of reactors with lead coolant, and 14 installations for research of reactors with Pb-Bi coolant [6]. Belgium, the Czech Republic, the European Union as a whole, Italy, Spain and Sweden are showing interest in lead-cooled reactors. China, France, Germany, Japan, Republic of Korea, Latvia, Russia, and the USA are showing interest in both sodium and lead coolants [6].

2. Problem

Lead-cooled and mixed mononitride (MN) fueled fast reactors are attractive because they can meet all of the above requirements for the energy sources of the future. Projects of such reactors have been developed in Russia. This is a series of projects “BREST” (“fast reactor of natural safety”) [7]. The technical design of the BREST-OD-300 reactor [8], the conceptual designs of the 1200 [9], and the technical proposal for the BREST-2400 [10, 11] have been developed. However, the BREST concept does not address all security issues. With an increase in the reactor power from 600 MW (e) and higher, the void reactivity effect (VRE) is positive and exceeds the effective delayed neutron fraction (β). This can lead to accidents and is unacceptable for new generation fast reactors. The implementation of a positive VRE is possible when the central part of the core is drained, for example, when bubbles appear (when the fuel-element cladding is depressurized). The involvement of bubbles in the core during depressurization of the steam generator tubes is unlikely, but it is not excluded in reactors with a high proportion of natural circulation of the coolant (BREST-2400).

The electric power of 2,400 MW can be considered the maximum limiting power for a power unit with a nuclear reactor. By limiting power we mean the smallest power at which the reactor operates stably and without damage. In other words, this is the maximum long-term power of the reactor. (This definition is borrowed from theory of acoustics.) Loss of stability is possible for LMFR electrical power of about 2000 MW. This value is close to the power limit. Moreover, further power increases may not be economically viable. The cost of produced energy decreases with increasing reactor power only up to a certain limit. This limit is about 2000 ... 2400 MW (e). When shutting down a high-power reactor, difficulties arise for energy consumers associated with the need to replace this power.

The main problem of the research is to analyze the safety of the high-power BREST reactor (BREST-2000 and -2400) and adjust the design solutions based on such an analysis. The traditional (cylindrical) geometric shape of the core was considered. The core of BREST-1200, -2000, -2400 consists of three profiling zones. The fuel assemblies and fuel pins of the BREST-OD-300 reactor are used. The diameter of the fuel pellet in the zones is 7.9; 8.3 and 9.0 mm, respectively. The height of the fuel column is 0.95 m. At the first stage of the research, the possibility of improving the safety of the BREST-1200 reactor was analyzed using a new cermet fuel (with the addition of uranium nanopowder up to 40% by weight [12]), a coolant based on lead extracted from thorium ores, and tungsten coatings of the fuel element cladding. Optimization of the core characteristics makes it possible to obtain a negative VRE not only when draining the entire BREST-1200 reactor, but also when draining the central part of the core. However, the most dangerous scenario for the implementation of VRE is associated with the entrainment
of bubbles in the central part of the core (with a volume fraction of bubbles of 50 ... 60%). In this case, for BREST-1200 VRE is about 5 β. In what follows, we will consider such a scenario. The proposed innovations make it possible to ensure the internal safety of the BREST-1200 reactor. The reactor is ATWS resistant. VRE is negative (even in the most dangerous scenario of its implementation). The results of first stage have been published (see, for example, [12, 13] and other works of the author).

At the second stage, the possibility of achieving the internal safety of the BREST reactor of maximum power is analyzed. This article is devoted to this problem. Note that with a change in the lattice of fuel elements or fuel assemblies, the isotopic composition of the coolant, the use of uranium nanopowder additives to the fuel, the maximum dependence of the VRE on the fraction of bubbles in the central part of the core changes. For example, when using natural lead, the maximum corresponds to a 60% decrease in lead density. When using lead, thorium ores, the maximum is observed with a decrease in density by 20%.

3. Safety analysis: results and discussion

3.1. ATWS modes

Safety analysis involves the study of the behavior of the reactor in all emergency modes that are not deterministically excluded. First of all, emergency situations are considered, accompanied by a failure of emergency protection (anticipated transients without scram - ATWS modes). All ATWS modes can be combined into a small number of groups. The classification feature is a disturbance that initiates an emergency mode (change in flow rate, change in inlet coolant temperature, reactivity input, drainage of the core or its central part). There are only five groups of ATWS modes. Among them: LOF WS (loss of flow without scram), TOP WS (transient overpower without scram), LOHS WS (loss of heat sink without scram), OVC WS (overcooling accident without scram) and LOCA WS (loss of coolant accident without scram). This classification was first used by specialists from Idaho National Laboratory when analyzing ATWS for the EBR-II reactor (see, for example, [14] and other articles published in Nuclear Engineering and Design, 1987, no. 101).

The BREST-1200 reactor is considered as a basic option for the power industry of the future. Let's carry out a safety analysis for an abnormally high power reactor BREST-2400. The author uses the MCU code [15] and the many times modernized author’s codes Dragon-M and FRISS-2D [12].

3.2. ATWS analysis

The approximate mathematical model of ATWS analysis is based on the solution of three groups of equations: a system of equations of point neutron kinetics with a six-group description of delayed neutrons (for the relationship between power and reactivity); non-stationary heat equation and coolant energy equation (to determine the relationship between power and temperature changes); conditions for the balance of reactivity (for the connection of reactivity with temperature changes) [12].

When simulating the LOF WS, it was assumed that all main circulation pumps were de-energized simultaneously. The LOHS WS was triggered by a failure of the secondary pumps. For a conservative assessment of internal self-protection, it is assumed that a coolant heated to the outlet temperature is supplied to the entrance to the core. The TOP WS is initiated by introducing the maximum possible positive reactivity (about β) linearly with time. It was assumed that the OVC WS could be caused by an increase in flow rate or a decrease in the coolant temperature at the inlet to the core. Both of these events do not pose a serious hazard to the reactor in question. The decrease in the flow rate in the LOF WS mode is determined by the difference in the levels of the ascending and descending lead sections in the nominal operating mode of the BREST reactor. Suppose that when all the main circulation pumps are de-energized, the coolant flow rate decreases to the $G_{nc}$ level determined by natural circulation.

Figure 1 (a) shows the time dependence of the maximum fuel-element cladding temperature $T_c (t)$ in the LOF WS. After the lead transport time has elapsed along the primary loop, “hot” coolant will enter the core, which will lead to expansion of the base plate (collector) and, as a consequence, the introduction of negative reactivity, which in absolute value exceeds other components of the temperature
coefficient of reactivity. In this case, the temperatures increase slightly (local maximum); however, the effect of negative feedback on the lead temperature at the inlet to the core ultimately leads to a decrease in the maximum temperatures in the reactor. The maximum fuel temperature does not exceed the permissible values. At temperatures above 1800 ... 2000 K, a significant increase in gas evolution in MN-fuel and fuel decomposition are possible. However, such temperatures are practically not reached in emergency modes. Fuel cladding is a critical element from the point of view of the possibility of ensuring internal self-protection.

![Graphs showing temperature changes](image)

**Figure 1. ATWS analysis**

Studies of the dependence of the maximum temperatures on the time $t_G$ of the decrease in lead consumption show that with an increase in $t_G$ from 3 to 10 ... 15 s, the maximum temperatures decrease significantly, and the maximum shifts in time to the region of the steady state. A further increase in $t_G$ has practically no effect on the safety functional (maximal temperatures and power of core). It should be noted that the scenario for changing the maximum fuel temperature in LOF WS is different for different $G_{nc}$ values. (Depending on the $G_{nc}$, the role of the Doppler reactivity coefficient can be reversed.) In general, to reduce the fuel temperature in the transient mode at large $G_{nc}$ (in BREST-2400 $G_{nc} = 37\%$ of the nominal), it is necessary to increase the negative Doppler reactivity coefficient in absolute value, at small $G_{nc}$ (for example, in BREST-OD-300 $G_{nc} = 6\%$ of the nominal) it is necessary to reduce this coefficient in modulus. In the steady-state mode of natural circulation, the situation is the opposite: to reduce the temperature of the fuel at large $G_{nc}$, it is necessary to decrease the negative Doppler coefficient in absolute value; at small $G_{nc}$, it must be increased.

Elementary analysis shows that reactors of the BREST-1200 [12, 13], -2000 and -2400 types can achieve the properties of internal safety even in the absence of passive safety systems.

3.3. Analysis of the most dangerous combinations of emergency modes

Due to the mutual neutralization of disturbances that initiate emergency modes, the simultaneous superposition of the four modes LOF WS, LOHS WS, TOP WS and OVC WS is less dangerous than superposition any three of them. From the point of view of increasing the temperature of the fuel element cladding, the LOF WS mode is the most dangerous. The most dangerous combinations of emergency modes can be considered the superposition of three of the above, and one of them is LOF WS: (LOF + TOP + LOHS) WS or (LOF + TOP + OVC) WS. The uncertainty of the delay time of one or another process in the case of non-simultaneous superposition (LOF + TOP + LOHS) WS is illustrated in Figure 1 (b, c). Here $t_{TOP WS}$ and $t_{LOHS WS}$ are the latency times of the TOP WS and LOHS WS processes, respectively. When (LOF + TOP + LOHS) WS is applied, the sheath temperature is practically independent of the flow rate decrease time in the interval 2 ... 7 s. Similar results were obtained for any combination of LOF WS, TOP WS, LOHS WS, and OVC WS.

3.4. VRE analysis

It is known that VRE is characterized by strong spatial dependence. For this reason, with an increase in the reactor power (due to an increase in the size of the core), these reactivity effects increase. For this reason, the analysis of VRE requires special attention.
As a rule, by minimizing VRE in the problem of optimizing the core of the BREST-1200, -2000 and -2400 reactors, it is possible to obtain an arrangement of core for which the VRE is negative even in the most dangerous scenario of its implementation (drainage of the central part of the core). The most dangerous is the decrease in the density of the lead coolant in the central part of the core by 50 ... 60%. In a reactor of an infinitely large radius, VRE (the absence of neutron leakage through the side surface is postulated) reaches \(7\beta\) (\(\beta\) is the effective delayed neutron fraction). In this scenario, for a reactor of the type BREST-2400 VRE is more than 6 \(\beta\). In this case, the presence of bubbles (lead emulsion) in the core is postulated. If these bubbles contain hydrogen, then the VRE will be noticeably higher. (In cause of depressurization of the heat exchanger tubes in a two-circuit energy conversion scheme.) VRE becomes negative only when the density of the lead coolant decreases to 2 g/cm\(^3\) and below (including with complete drainage: in the presence of a large bubble in the center of the core).

The use of a coolant based on lead extracted from thorium ores with a concentration of \(^{208}\text{Pb}\) isotope allows one to reduce the VRE in a reactor of infinite radius to a value of about 1 \(\beta\). The use of tungsten coatings of the cladding of fuel elements allows one to minimize the VRE to zero and negative values (depending on the thickness of the tungsten coating). The maximum VRE corresponds to a decrease in lead density by 20 ... 30%.

Thus, to improve the safety of the high-power BREST reactor, it is necessary to switch from natural lead to lead extracted from thorium ores.

3.5. “Corrosive” absorber
Erosion and corrosion of structural steels in liquid lead is one of the major problems. If in BREST-OD-300 the removal of steel only from the core is 39 kg/year, then for BREST-1200, -2000 and -2400 this value will increase by 4, 6.7 and 8 times, respectively. In terms of reliability and economics, the need to minimize the rate of erosion and corrosion is obvious. From a safety point of view, these processes, accompanied by the removal of structural steel (a “parasitic” neutron absorber) from the core and the deposition of erosion and corrosion products outside the core (in cold sections of the duct or in filters), is the input of positive reactivity. This phenomenon must be taken into account in neutron balance and reactivity balance. In BREST reactors, erosion and corrosion of structural steels in the core helps to minimize the positive reactivity margin for fuel burnup and, from this point of view, plays a positive role. (A “corrosive” absorber is, to a certain extent, an analogue of burnable absorbers in thermal reactors.) The problem of minimizing the reactivity margin for fuel burnup can be solved due to natural processes of corrosion and erosion of structural steels and their gradual removal from the reactor core [13].

At the same time, when steel is removed from the core, positive reactivity is introduced. Thus, the destruction of even a small part of the fuel claddings as a result of superposition (LOF + LOHS + TOP) WS can lead to an injection of reactivity greater than 1 \(\beta\). (The density of steel is approximately 1.5 times less than that of lead; therefore, fragments of destroyed claddings will float even in the absence of natural circulation.) The introduction of reactivity greater than \(\beta\) can be excluded if the destruction of the cladding of the fuel elements is excluded, for example, when using tungsten coatings of the cladding and a denser and more heat-conducting fuel. For example, to reduce the maximum temperatures in ATWS, it is possible to propose the use of pellet fuel based on MN micro grains and uranium nanopowder (up to 20% by volume), filling the pores between micro grains [12].

4. Conclusion
For existing high-power BREST reactor designs, inherent safety is not fully ensured. This is due to the positive VRE, which is several times higher than the effective fraction of delayed neutrons (up to 7 \(\beta\)).

Erosion and corrosion of structural steel can lead to an additional reactivity input of more than 1 \(\beta\) and the maximum temperatures exceeding the permissible values in complex combinations of ATWS modes or even to a reactivity accident (“neutron burst”).

To ensure safety, it is necessary to adjust the design solutions for high-power BREST reactors. It is associated with the transition to a coolant based on lead extracted from thorium ores, with the transition
to fuel based on MN micro grains and uranium metal nanopowder placed between the grains, and with tungsten coatings of the fuel element cladding. Tungsten cladding of the fuel elements will make it possible to soften the requirements for the quality of the coolant. The use of lead with a high concentration of $^{208}\text{Pb}$ helps to reduce the risk of reactivity accidents due to a smaller neutron absorption cross section (the prompt neutron lifetime is maximum). With such a correction, the VRE is negative even for a reactor of infinite power (infinite radius of the core). The ATWS modes are terminated without failures even in the absence of passive safety systems for the BREST-2400 reactor.

With such an adjustment, reactors of the BREST-1200 [12], BREST-2000 and -2400 types can become the basis for safe large-scale nuclear power, capable of meeting humanity’s energy needs in the long term. Thus, in the case of adjusting the design solutions, safety will not be a factor limiting the maximum power for BREST reactors.

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