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ATWS Analysis for Innovative Lead-Cooled High-Power Fast Reactor with Accident Tolerant Materials of Core

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Abstract. The main purpose of the article is to substantiate the safety of a lead-cooled fast reactor of high power. Thermal power of the reactor is about 5600 MW, electric power is about 2400 MW. The design is similar to the BREST-OD-300 project developed at NIKIET JSC. The safety of a high-power reactor is ensured only with the use of innovative core materials (previously the author proposed to use fuel based on micrograins of UN-PuN mononitride and uranium metal nanopowder, a coolant based on lead of thorium ores, fuel element cladding based on EP823 steel with nanopowder of titanium oxide and yttrium, tungsten-coated cladding are used). Research methods are mathematical modeling of the reactor and reactor emergency modes. The most dangerous emergency modes (ATWS – anticipated transients without scram and their combinations, taking into account the non-simultaneous start) are considered. The studies used the codes developed by the author (Dragon-M, FRISS-2D) and the well-known code for precision neutron-physical calculations (MCU). A safe reactor corresponds to the fulfillment of restrictions for a number of functionals characterizing emergency modes. Studies have shown that when using innovative core materials, any combination of emergency modes does not lead to unacceptable releases of radioactive substances outside the Nuclear Power Plant. The results of the study show the possibility of developing reliable, safe, environmentally acceptable nuclear power based on reactors of this type.

1. Introduction

Energy sources based on the transmutation of atomic nuclei will make it possible to provide humanity with energy on the required scale for the long term. This is an urgent task of our time. Energy production facilities must meet the requirements of economic efficiency, safety, and fuel availability. The efficiency of new energy sources may be inferior to alternative sources in the absence of acceptable competitors. Safety has a major role to play. For nuclear power plants (NPP), consider the following factors:

- There is a potential possibility of eliminating accidents with unacceptable releases of radioactive substances outside the NPP and fuel cycle facilities (at all stages of the fuel cycle);
- There is a potential for the safe disposal (transmutation) of radioactive waste;
- There is a potential for the implementation of the weapons non-proliferation regime.

All these possibilities are achievable in practice in a high-power reactor. Without solving these problems, nuclear and thermonuclear energy are not viable.

Nuclear power sources use the least amount of fuel and generate the least amount of waste. This will minimize fuel production and transportation costs. Nuclear power sources allow operating in a self-sustained fuel mode. Nuclear power sources allow operating in a self-sustained fuel mode. In fast reactors, secondary fuel breeding is possible (transmutation of raw nuclides into fissile ones). Therefore, from thorium-232 it is possible to produce uranium-233, from uranium-238 - plutonium-239. In fusion reactors, tritium is producing by irradiating lithium-6 with neutrons generated in fusion reactions.

The ecological acceptability of new generation energy sources corresponds to the criterion adopted in Buddhism: "leave no trace" [1].

An equally important problem, automatically solved by the massive introduction of NPP into the world energy, is associated with the uneven distribution of hydrocarbon fuel in the earth's crust [2-3]. There are countries and regions of the world rich in hydrocarbon fuels, and there are countries where there are practically no reserves of hydrocarbon fuels, or their production is unprofitable (economically ineffective and / or associated with unacceptable environmental impact). In the recent past, the problems associated with the production of shale gas and oil in the United States was clearly demonstrated [4-6]. The “shale revolution” did not take place: the prices for such fuel are high, and the environmental impact is unacceptable. Relatively low prices for hydrocarbon fuels make the extraction of shale hydrocarbons unprofitable, and surges in energy prices introduce uncertainties in the development of "shale energy".

The focus on the use of hydrocarbon fuels leads to economic crises and military conflicts. Nuclear energy sources equalize the position of countries rich and poor in natural resources. The massive introduction of nuclear power plants into energy systems will make it possible to use hydrocarbons for non-energy purposes (for example, in the chemical industry). A well-known aphorism of D.I. Mendeleev: “Burning oil is the same as stoking the stove with banknotes” or “You can, after all, heat up with banknotes” [7].

In recent decades, there has been a tendency to transfer large-scale environmentally harmful industrial production to less developed countries [8] with a high population density, forgetting that we all live on the same planet. This requires special attention to safety and environmental friendliness of production.

Among the energy sources based on the transmutation of atomic nuclei, fission reactors of heavy atomic nuclei are ready for industrial implementation. Among the projects of new generation reactors, only the domestic development of a fast reactor with lead cooling and mononitride fuel (BREST-OD-300 [10]) meets the above requirements, including those related to safety. However, when the electric power of the reactor is increased to the industrial level (600, 1200 MW and more), it is not possible to exclude severe accidents.

2. Materials and methods

2.1. Innovations for the Safety of a High-Power Lead-Cooled Fast Reactor

BREST-OD-300 is a project of a pilot demonstration reactor [10]. Nuclear power will require much larger reactors. Increasing the power of the BREST-OD-300 type reactor does not allow excluding accidents with unacceptable releases of radioactive substances outside the NPP. To solve the problem, the author proposed the following innovations [11-12]:

- Use of lead extracted from thorium ores as a coolant. (Lead-208 is the product of the decay of thorium-232.) Analysis of thorium deposits shows that the content of the doubly magic isotope ^{208}Pb in lead of thorium ores averages 69 to 98% [11]. The cross sections for inelastic processes (the cross section for neutron absorption and the cross section for inelastic neutron scattering) are minimal for doubly magic nuclei. This helps to minimize the void effect of reactivity when draining the core;
- ● Use of pellet fuel based on UN-PuN micro grains and nanopowder (up to 39% by mass) of metallic uranium. (The fuel uses plutonium recovered from light-water reactors, purified from the ^{238}Pu isotope, and depleted uranium.) This significantly increases the average density and

thermal conductivity of the fuel. The maximum permissible temperature of such a fuel corresponds to mononitride (about 2000 K, which corresponds to the beginning of nitrogen evolution). As a result, the self-protection of the reactor from accidents increases. Uranium metal acts as a getter of free nitrogen released from the fuel, migrating to the cladding of the fuel element and increasing the corrosion rate of the inner surface of the cladding [12];

- ● It is proposed to use tungsten cladding of fuel elements [12]. This helps to reduce corrosion and erosion of structural steels in liquid lead. Tungsten absorbing neutrons helps to reduce the void effect of reactivity. The technology of low temperature plasma spraying of tungsten is well known [12-13];
- ● Use of structural steel (primarily for the manufacture of fuel element cladding) stabilized with yttrium and titanium nanooxide [9; 12; 14]. With an increase for oxides (0.4% by mass of Y_2O_3 with characteristic dimensions of 40 ... 100 nm; 0.06 ... 0.30% by volume of Y_2O_3-TiO_2 with characteristic dimensions 2.5 ... 3.3 nm), the strength characteristics noticeably improve steels [9; 14].

The BREST reactors are equipped with passive protection systems [10]. However, some of them may not work in an accident. They may not have the expected effect. For this reason, the author considers innovative materials for the core, which make it possible to exclude accidents with unacceptable releases of radioactive substances outside the nuclear power plant. When using the proposed innovations, you can abandon passive protection systems.

2.2. Investigated Emergency Modes
When designing new generation reactors, first, one should consider the most dangerous emergency modes accompanied by failure of emergency protection (ATWS - Anticipated Transients Without Scram). Moreover, the analysis of emergencies took into account the most dangerous events from among the ATWS, including their various combinations.

The safety analysis of the reactor required the study of the following groups of emergency modes [15]:

- LOF WS (Loss of Flow Without Scram). This emergency mode assumes the simultaneous failure of all main circulation pumps. After the pumps run out (determined by the coast-down time τ_p), the mode of natural circulation of the coolant through the core is set;
- LOHS WS (Loss of Heat Sink Without Scram). This emergency mode assumes the simultaneous failure of all circulation pumps of the secondary circuit. At the entrance to the core, the coolant temperature is equal to the outlet temperature (when the reactor is operating at rated power);
- TOP WS (Transient Overpower Without Scram). In new generation reactors, the operating reactivity margin does not exceed the effective fraction of delayed neutrons (β);
- OVC WS (Overcooling Accident Without Scram). The mode can be initiated either by transferring the main circulation pumps to a higher capacity, or by connecting a reserve "cold" loop, if it is provided for by the reactor design;
- LOCA WS (Loss of Coolant Without Scram). The mode initiated by the appearance of bubbles in the core and a decrease in the average density of the coolant. The most dangerous is the draining of the central part of the core. The mode characterized by a void reactivity effect.

We will assume that there are no passive safety systems.

2.3. Mathematical Model
The optimal layout of the reactor is the result of solving the problem of mathematical programming in a deterministic formulation and under conditions of uncertainty of scenarios for the development of emergencies. The calculation and optimization complex Dragon-M [11] is used. Safety in all of the

above emergency modes corresponds to the fulfillment of restrictions for the corresponding functionals of the task of optimizing the reactor core. The void effect of reactivity is an optimality criterion. The restrictions on functionals that characterize reliability, safety, fuel balance are taken into account. Among the constraints of the problem are constraints on functionals characterizing reliability, safety, fuel balance, etc. Among the control parameters were considered the parameters of the lattice of fuel elements, the composition of the fuel, the flow rate of the coolant, the volume fractions of the casings of the fuel assemblies, etc. The multigroup diffusion approximation (Dragon-M program [11]) is using for the neutron-physical calculation of the reactor. To simulate emergency modes, the approximation of point neutron kinetics is used (the FRISS-2D program [11]). To refine the effects and reactivity coefficients, the MCU program was used [16].

2.4. Initial Data

The initial layout (design) of the reactor is similar to the BREST-OD-300 [10], but with a significantly higher power. Thermal power is about 5600 MW, electric power is about 2400 MW. Three zones along the radius of the reactor contribute to the equalization of the energy release. In the profiling zones, coverless fuel assemblies of the BREST-OD-300 reactor design are used [10]. The assemblies have a square cross-section with fuel elements of different diameters in different zones [10]. In order to minimize the void effect of reactivity, the height of the core is reduced (compared to BREST-OD-300) to 0.95 m. The reflector is an assembly containing long-lived waste (for the purpose of transmutation): tubes (fuel rods) with technetium-99 (the first two rows of assemblies) and with a mixture of technetium-99 and carbon-14 powders.

3. Results

3.1. LOF WS and TOP WS Analysis

The most dangerous of the above modes is LOF WS. The rest of the modes (with real perturbations of reactivity, flow rate and coolant temperature at the inlet to the core, realizing these modes) do not pose a serious danger. In figure 1 shows the dependence of the maximum temperature T_{cl} of the cladding on time t in the LOF WS mode. The first maximum corresponds to the run-on time of the pumps (τ_p = 3 s), the second - to the arrival of "hot" lead at the entrance to the core. Figure 2 illustrates the influence of the uncertainty in the time τ of lead transport along the contour on both of these maxima. In the TOP WS mode (with a reactivity of 0.99 β in 10 s), the maximum fuel temperature T_f does not exceed 1543 K, and the maximum cladding temperature does not exceed 985 K.

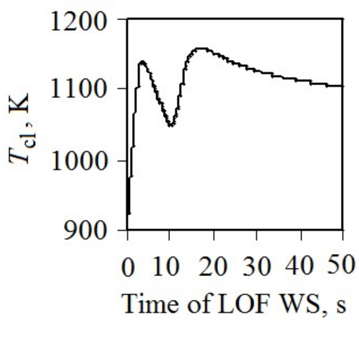

Figure 1. Dependency T_{cl} (t) [11].

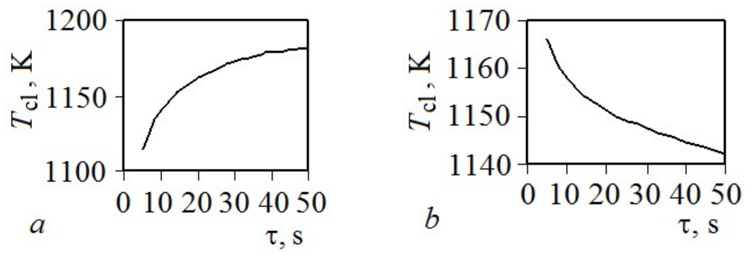

Figure 2. Influence of uncertainty in the time τ of lead transport along the contour on the first (*a*) and second (*b*) maxima of the T_{cl} (t) dependence (figure 1).

3.2. Analysis of the Void Reactivity Effect

One of the functionals characterizing the LOCA WS mode is the void reactivity effect. When using lead with a concentration of ^{208}Pb isotope more than 75% and tungsten coatings of fuel element cladding as a coolant, it is possible to provide a zero or negative value of the void effect under the most dangerous scenarios of its implementation.

3.3. The Most Dangerous Combinations of Emergency Modes Analysis

The delay in the start of the flow rate decrease in the LOF WS mode (by 20 s), envisaged in the BREST-OD-300 project [10], has a negative effect on the development of some combinations of emergency modes from among the ATWS. Thus, when (LOF + TOP + OVC) WS is applied, the maximum cladding temperature exceeds the maximum allowable one by 1.3 times, and the maximum fuel temperature exceeds the allowable one by 1.2 times (figure 3).

The (LOF + TOP + LOHS) WS mode is less dangerous. Delaying any of the processes (except LOF WS) has a beneficial effect on the safety of the reactor. For example, with a LOF WS delay of 6 s or more, the maximum fuel temperature decreases from 1467 K to 1404 K. However, a 5 s LOF WS delay leads to an increase in the maximum fuel-element cladding temperature to 1231 K. The minimum value of T_{cl} = 1212 K is achieved with a LOF WS delay for 27 seconds or more. The delay of the TOP WS and LOHS WS modes by several seconds (from three ... 7 s and more) has a beneficial effect on the development of an emergency.

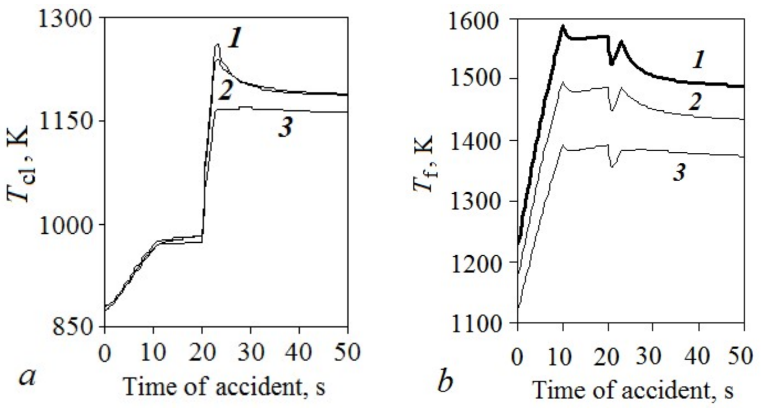

Figure 3. Dependence of the maximum temperature of the cladding of fuel elements (*a*) and fuel (*b*) on time with the superposition of the modes (LOF + TOP + OVC) WS. The numbers near the curves correspond to the grading zones.

The overlap of (LOF + TOP + OVC + LOHS) WS is even less dangerous due to the neutralization of the disturbances that initiate the OVC and LOHS, LOF and OVC modes.

When using innovative fuel with additives of uranium nanopowder (39% by weight) and structural materials based on EP823, steel [10] stabilized with yttrium and titanium nanooxide, any combination of emergency modes is not dangerous. The temperatures of the fuel, coolant and fuel element cladding do not exceed the maximum permissible temperatures. However, LOF WS lag should be avoided when overlapping (LOF + TOP + OVC) WS.

4. Discussion

Calculated studies show that when using the innovations proposed by the author earlier (see charter 2.1), in a high-power reactor with a lead coolant, severe accidents with unacceptable releases of radioactive substances outside the nuclear power plant are excluded. In the absence of innovations, an increase in the power of a BREST-type reactor can lead to the potential danger of severe accidents. These accidents are associated with the following factors:

- It is proposed to use natural lead with a relatively low concentration of the isotope ^{208}Pb (the void effect of reactivity exceeds 7 β).
- Availability of a twenty-second reserve before the flow rate decreases in LOF WS mode (with combinations of emergency modes).
- The density and thermal conductivity of the fuel for a safe exit from emergency modes of the ATWS type is not large enough.
- Corrosion of the inner surface of the fuel element cladding is high.

The innovations proposed by the author, related to the adjustment of the used core materials, exclude all these hazards. In particular, any combination of emergency modes from among the ATWS does not lead to an accident (formally, to violation of the restrictions for the corresponding functionals: maximum temperatures of core components, reactor power, pressure in the gas cavity of fuel elements).

5. Conclusion

Innovative lead-cooled fast reactors of high power, using materials resistant to accidents, can form the basis of the energy sector in countries developing such technologies. Research has shown the following:

- In such innovation reactors, accidents with unacceptable releases of radioactive substances outside the NPP are deterministically excluded;
- Such innovation fast reactor reactors operating in power mode (the main goal is power generation) are capable of simultaneously (without affecting power generation) transmutation of radioactive waste disposed directly in the fuel (minor actinides) or blanket (long-lived fission products and carbon-14);
- Non-proliferation of materials is achieved (by analogy with the BREST reactor [10]);
- The considered capacity (thermal - about 5600 MW, electric - about 2400 MW) is not limiting from the point of view of ensuring self-protection from accidents. The optimal electrical power of industrial nuclear power reactors in our country is equal to 1200 ... 1300 MW ("by default"). However, reactors with a high level of inherent safety can be oriented towards higher power.

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