

The concept of a fast reactor with liquid metal fuel in tungsten capsules

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Abstract. The concept of a dual-purpose high-power nuclear reactor is proposed. One of the goals is the production of electricity, the other is the production of high-potential thermal energy. It is proposed to use liquid fuel based on waste uranium and plutonium extracted from the spent fuel of VVER reactors (purified from the ^{238}Pu isotope). The fuel is in sealed tungsten capsules. Lead extracted from thorium ores is used to cool the reactor. The electrical power of the reactor is 3.3 GW. The layout of the reactor is identical to the BREST-OD-300 reactor under construction. The analysis of emergency modes from among ATWS (anticipated transients without scram) is carried out. The reactor is reliable and safe. The maximum temperature of a high-temperature reactor coolant is close to the boiling point of lead. By the nature of the change in the maximum temperatures of the core components, the reactor occupies an intermediate position between a reactor with solid metallic fuel and a reactor with cermet based on UN-PuN and metal uranium nanopowder.

1 Introduction

The melting of solid nuclear fuel during the operation of traditional reactors can lead to a severe accident. For this reason, the author initially tried to use liquid fuels. As a rule, all concepts of liquid fuel reactors (liquid-salt thermal reactors [1-2], liquid-fuel fast neutron reactors [3-4] assume fuel circulation through the core.

Liquid fuel reactors have a number of advantages. Among these advantages is the ability to organize a continuous replacement of fuel without shutting down the reactor. In thermal neutron reactors, it becomes possible to remove xenon to prevent poisoning of the reactor.

"Initially developed in the 1950s, molten salt reactors have benefits in higher efficiencies and lower waste generation [1]. Liquid salts are characterized by high corrosivity. Such reactors are characterized by higher dose loads during the repair of the primary circuit. Tritium is produced in liquid fuel. This means that tritium emissions are possible. Scientists from ORNL (USA) have achieved the greatest success in the development of molten-salt reactors. The first projects of molten salt reactors were implemented in the USA. These are Aircraft Reactor Experiment (1954) and Molten-Salt Reactor Experiment (1964). "The fluid fuel in these reactors, consisting of UF_4 and ThF_4

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dissolved in fluorides of beryllium and lithium, is circulated through a reactor core moderated by graphite. These reactors can be initially fueled with ^{233}U , ^{235}U , or Pu" [1].

2 Materials and methods

2.1 The concept of the core. materials

Previously, the author proposed the concept of the active zone of a fast reactor with an electric power of 2.4–2.9 GW [5]. A two-circuit power conversion scheme is used. It was proposed to use cermet fuel based on UN-PuN micro grains and uranium metal nanopowder. The average density of such fuel is 14.2 g/cm^3 (mononitride - about 13 g/cm^3 , metal - slightly higher than 19 g/cm^3). Lead extracted from thorium ores was used as a coolant. The concentration of the ^{208}Pb isotope is about 80%. Tungsten capsules were considered as fuel claddings. Water vapor is considered as the working fluid of the secondary circuit.

In the present studies, the cermet fuel was replaced by liquid metallic U-Pu. The fuel contains waste uranium (80% wt.) and plutonium extracted from spent fuel from VVER reactors (purified from the ^{238}Pu isotope). The electric power of the reactor reaches 3.3 GW.

The core design is similar to the BREST-OD-300 reactor [6]. The active zone consists of three profiling zones (along the radius). The zones differ in the diameter of the fuel rods used. In the original version, the diameter of the fuel column in the zones increases from the center to the periphery of the core and is equal to 7.9; 8.3 and 9.0 mm [2]. Fuel assemblies with perforated covers are used. The fuel rods are located in the nodes of a square lattice. The height of the active zone is 1.10 m. The outer radius of the zones is 2.23; 2.99 and 3.22 m [5].

In the manufacture of fuel rods, uranium and plutonium powder is poured into tungsten capsules. The capsules are sealed. Above the fuel there is a cavity for collecting gaseous fission products. It also serves as a compensation volume during the transition of fuel from a solid state to a liquid one (starting the reactor) and vice versa (shutdown of the reactor).

During reactor operation, natural (spontaneous) convection of liquid fuel is observed in the fuel rods. It is related to the fuel temperature difference on the fuel rod axis (fuel movement upward) and on the periphery near the cladding (fuel movement downward). These convection flows contribute to the transfer of light elements (products of nuclear reactions) to the top of the fuel element. Relatively light fission products will float and accumulate at the top of the fuel rod. This part can be placed above the active zone. Gaseous products of fission and other nuclear reactions will also accumulate in the cavity above the active zone above the fission products.

Relatively heavy isotopes of uranium, plutonium and trans-uranium elements will settle in the lower part of the fuel element. The circulation of liquid fuel in the fuel element promotes the mixing of these isotopes and their transmutation in the neutron field.

When the reactor is operating, the height of the fuel column (core) will decrease. This is due to a decrease in the concentration of uranium-238 in the core. There are two main channels for the loss of uranium-238. Some of the uranium-238 is fissioned, and some is converted into uranium-239 in the radiative capture reaction. Fission products float in liquid fuel. Uranium-239 decays to plutonium-239. At BRC (breeding ratio in the core) = 1, the amount of fissile material in the core remains practically unchanged during reactor operation.

Reducing the height of the core during operation of the reactor helps to reduce the void effect of reactivity. At the same time, the concentration of fissile materials in the core is

maintained. To ensure the critical state of the constantly flattening core, a BRC slightly exceeding 1 is provided. $BRC = 1.06$.

When creating a high-temperature reactor, options are considered with a decrease in the ratio of coolant volume to fuel volume. This is ensured by reducing the relative pitch of the fuel pin array.

2.2 Fuel operating temperature range

The melting point of uranium is 1405.45 K, the boiling point is 4404.2 K. The melting point of plutonium is 912.55 K, the boiling point is 3505.15 K. The melting point of uranium and plutonium is sensitive to the content of impurities [7–9]. The pressure in the burnt-out fuel element of a fast reactor is 20–30 atm. This lowers the boiling point of liquid nuclear fuel.

2.3 Thermo-physical properties of fuel

Under normal conditions, the density of uranium is 19.05 g/cm^3 , plutonium - 19.84 g/cm^3 . The density of nuclear fuel decreases with increasing temperature. Figure 1 shows the dependence of the density of solid and liquid uranium on temperature (according to [7, 8]). The density of uranium during the transition from solid to liquid state decreases abruptly. This transition occurs at a temperature of 1405.45 K. According to [8], at 1300 K uranium in the solid state has a density of 17.620 g/cm^3 , and at a temperature of 1410 K the density of liquid uranium is 16.630 g/cm^3 .

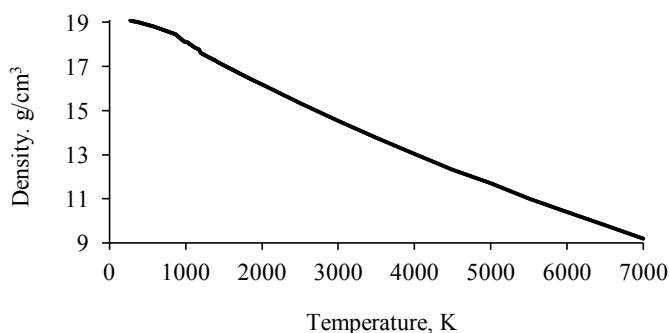


Fig. 1. Temperature dependence of uranium density.

Uranium, depending on temperature, has a different crystal structure: α -phase (up to 930 K); β -phase (from 930 to 1045 K); γ -phase (above 1045 K). The difference in the crystal structure affects the density of uranium. For example, at 935 K, the α -phase uranium has a higher density than the β -phase; with further heating to 1045 K, the density of the γ -phase uranium decreases.

Plutonium in the range from room temperature to the melting point (912.55) exists in six allotropic modifications [9]. Allotropic transformations are accompanied by abrupt changes in density: 19.816 (at a temperature of 298 K); 17.77 (423 K); 17.19 (483 K); 15.92 (593 K); 15.99 (738 K); 16.48 (773 K) g/cm^3 [9]. Unlike other metals, when heated from 310 to 480 °C, plutonium shrinks.

The density of plutonium in the liquid phase (from the melting point to the boiling point) is usually assumed to be 16.65 g/cm^3 [10].

Figure 2 shows the temperature dependence of the thermal conductivity λ of uranium (according to [7, 8]). Figure 3 shows the dependence of specific heat capacity c_p at constant pressure on temperature for uranium (according to [8]).

2.4 Tungsten

As is known, tungsten has high corrosion and erosion resistance. It is stable even in alkaline solutions and mineral acids. Tungsten practically does not interact with liquid lead and bismuth (up to 980 °C); nitrogen, uranium and plutonium. When interacting with steel, tungsten actively forms carbides, including refractory carbide W_2C , as well as intermetallic compounds Fe_3W_2 , Fe_3W , and others [11].

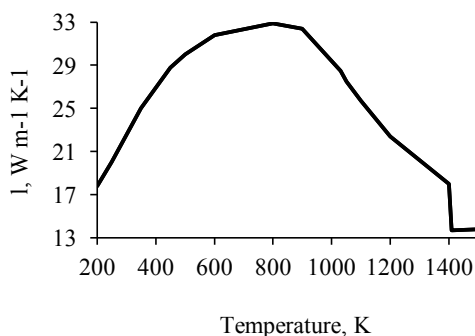


Fig. 2. Temperature dependence of the thermal conductivity (λ) of uranium.

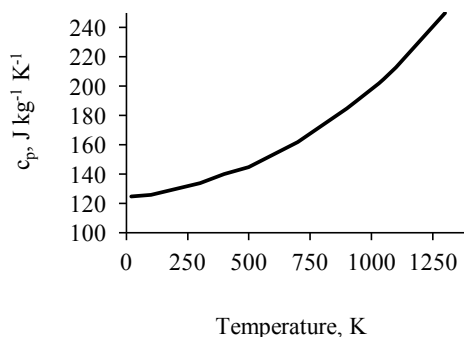


Fig. 3. Dependence of specific heat at constant pressure (c_p) on temperature.

2.5 Methods

In the research, the author used calculation methods and computer codes. Experimental studies have not been carried out.

The following computer codes developed by the author were used in the research:

- Calculation and optimization code Dragon-M [12].
- FRISS-2D code for simulation of emergency modes [12].

The following well-known computer codes were used in the research:

- MCU code for precision neutron-physical calculations [13].
- WIMS code for calculations of the rail grid of nuclear reactor fuel rods [14].

3 Results

3.1 Analysis of thermo-physical properties

An analysis of the thermo-physical properties made it possible to draw preliminary conclusions.

- An increase in the temperature of the liquid fuel leads to a decrease in the density of the fuel. This, in turn, leads to a decrease in the power of the reactor.
- In addition, when approaching the boiling point of the fuel, the density of the fuel is approximately equal to the density of the mononitride fuel. In this case, there is no need to switch to liquid metal fuel.
- Increasing the temperature to the boiling point leads to a decrease in thermal conductivity to the level of mononitride fuel. In this case, there is no need to switch to liquid metallic fuel.
- Increasing the specific heat capacity c_p will favorably affect the development of emergency modes.

An analysis of thermo-physical properties shows that liquid fuels have no clear advantages over mononitride solid fuels.

3.2 ATWS analysis

The fuel rod array of the BREST-OD-300 reactor was considered as the initial option. When using liquid U-Pu-fuel in a reactor with an electric power of 2.9 GW, the maximum temperature of the fuel when operating at rated power is 1158 K, the coolant is 937 K.

Under the void reactivity effect is understood the effect that is realized when the core or part of it is drained. In the considered version of the reactor, the most dangerous is the depressurization of the tubes of the lead-water vapor heat exchanger and the entrainment of bubbles in the central part of the core. The most dangerous decrease in coolant density by 30...50%.

When using lead extracted from thorium ores as a coolant and when using tungsten capsules, the void effect is negative. The void effect is negative even in the most dangerous scenario of its implementation.

In the emergency mode TOP WS (transient overpower without scram), initiated by the introduction of reactivity 1β (β is the effective fraction of delayed neutrons), according to a linear law, the maximum temperature of the fuel is reached at the asymptotics and is equal to 1565 K, the coolant is 1152 K. At the time 10 s after the beginning of TOP WS, the maximum temperature of the fuel is 1518 K, the coolant is 1110 K.

The nature of the dependence of the maximum temperature of the fuel, coolant, tungsten cladding of fuel elements and the reactor power in the TOP WS mode is identical to similar dependences in fast reactors of all types. Temperatures and power increase, reaching a maximum value at the time equal to the time of the positive reactivity input (first maximum). Then temperatures and power decrease, but soon increase again with time (second maximum). The maximum values of the maximum fuel temperature and reactor power are reached at the moment of time equal to the reactivity input time. The second maximum is local. For the maximum temperature of the coolant and fuel rod claddings, the first maximum is local. The temperatures of the coolant and fuel cladding are maximum on the asymptotics (in the steady quasi-stationary regime).

In the emergency mode LOF WS (loss of flow without scram), initiated by the simultaneous blackout of all main circulation pumps of the primary circuit, the maximum

coolant temperature reaches 1009 K, then decreases to 970 K (Figure 4). The maximum fuel temperature decreases in the transient mode (Figure 4).

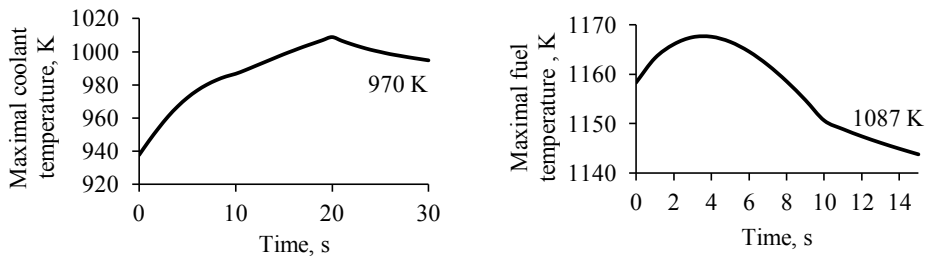


Fig. 4. Changing the maximum temperatures of coolants and fuels in the LOF WS mode.

In the emergency mode LOF WS, the character of the change in the maximum coolant temperature is intermediate between UN-PuN-U cermetes [5] and solid metallic fuel. The nature of the change in the maximum temperature of the fuel is closer to oxide fuel. A slight increase in the fuel temperature (by 10 K) in the first seconds of the emergency mode (0 ... 7 s) is explained by the "warming up" of the fuel rods. This is an unexpected result. From the point of view of an unacceptable increase in fuel temperature, the LOF WS mode is not dangerous. As a result, when the LOF WS and TOP WS processes are simultaneously superimposed, the situation (maximum temperatures) does not differ much from the TOP WS regime.

The emergency mode LOHS WS (loss of heat sink without scram), initiated by the termination of heat removal from the primary circuit to the second, does not pose a danger.

In the emergency mode OVC WS (overcooling accident without scram), initiated by an increase in coolant flow by 50% in 10 s, the maximum fuel temperature is reached at the asymptotics and is equal to 1190 K.

With the simultaneous imposition of emergency modes LOF WS and TOP WS, the maximum fuel temperature reaches 1458 K (10 s after the start of the emergency), the maximum coolant temperature reaches 1225 K (20 s after the start of the emergency). Figure 5 shows the values of the maximum liquid fuel temperatures in nominal and emergency modes (overlapping LOF WS and TOP WS) with a change in the diameter of the liquid fuel column in the fuel pins.

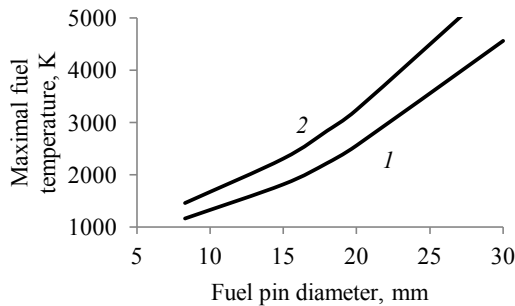


Fig. 5. Dependence of the maximum fuel temperatures in nominal (1) and emergency mode (2) with a change in the diameter of the fuel column.

In this case, the ratio of the volume of coolant to the volume of fuel in the core is preserved. As a result, the temperature of the fuel increases. The fuel boils when the reactor is operating at rated power with an increase in the diameter of the fuel column above 25

mm. For safe completion of emergency modes, the diameter of the fuel column should not exceed 20 mm.

When designing an very-high temperature liquid fuel reactor, it is important to reduce the ratio of coolant volume to fuel volume in the core. This is achieved by reducing the relative pitch h of the fuel rod array and increasing the diameter of the fuel rods. The maximum fuel temperatures in emergency modes LOF WS and when LOF WS and TOP WS are superimposed are practically indistinguishable (Figure 6). The difference between the maximum coolant temperatures in emergency modes LOF WS (the curve lies between 1 and 3 and is not marked in Figure 6) and when LOF WS and TOP WS are superimposed are noticeable (curve 3). With a small spacing of the fuel element lattice ($h = 1.1$), the fuel boils already in the nominal mode, which is unacceptable.

4 Discussion

4.1 Advantages of the liquid fuel concept in tungsten capsules

Fuel pins with liquid fuel are practically indistinguishable from fuel rods with solid fuel. The illusion of using conventional solid fuel is created. Natural (spontaneous) convection of liquid fuel will exist in the fuel rods. It is related to the fuel temperature difference on the fuel rod axis (fuel movement upward) and on the periphery near the cladding (fuel movement downward). These convection flows contribute to the transfer of light elements (products of nuclear reactions) to the top of the fuel element. This natural separation of relatively light nuclides will facilitate the processing of solidified fuel.

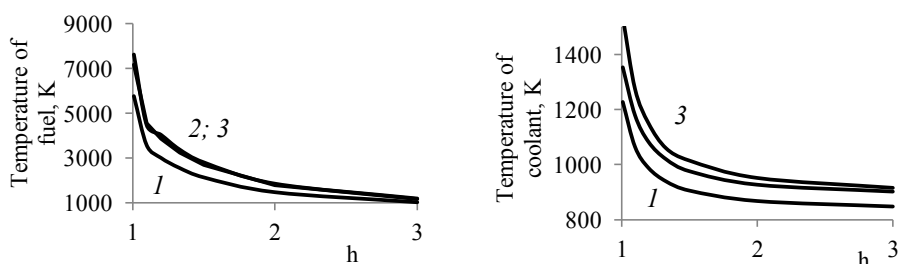


Fig. 6. Dependence of the maximum temperatures in nominal mode (1), in emergency modes LOF WS (2) and when LOF WS and TOP WS (3) are superimposed on the relative spacing of the fuel element array.

Relatively light fission products will float and accumulate at the top of the fuel rod. This part can be placed above the core. Gaseous products of fission and other nuclear reactions will also accumulate in the cavity above the core above the fission products.

Relatively heavy isotopes of uranium, plutonium and transuranium elements will settle in the lower part of the fuel element. The circulation of liquid fuel in the fuel element promotes mixing of these isotopes and transmutation in the neutron field.

4.2 On the way to a high-temperature reactor of anomalously high power

A decrease in the share of lead and an increase in the share of fuel leads to an increase in the core temperature to the values typical for fourth-generation ultrahigh-temperature nuclear reactors [15-16].

For the core of such a reactor, it is easy to ensure $BRC \geq 1$. An increase in the diameter of the fuel column leads to an increase in BRC. On the one hand, it is dangerous from the point of view of the development of TOP WS accidents. On the other hand, this makes it possible to reduce the amount of fissile material (including ^{239}Pu) in the core. This contributes to ensuring the non-proliferation regime. It also allows the core to be made flatter to further reduce the void reactivity effect. Fission products float up into the gas cavity (above the top edge of the core) without accumulating in the core. This virtually eliminates slagging and increases the campaign. Heavy actinides ($A > 239$) sink in the fuel and fission in the hard spectrum. Within the framework of the proposed concept of a nuclear reactor, it is possible to solve the problem of minimizing the loading of fissile material into the core and maximizing the utilization of waste uranium, i.e. $^{239}\text{Pu}/^{\text{waste}}\text{U} \rightarrow \text{min}$. Such a reactor is designed to simultaneously solve two problems: the production of electricity and high-potential heat.

5 Conclusion

When designing a power reactor of anomalously high power (electric power 3.3 GW), liquid fuel has no obvious advantages compared to UN-PuN-U cermets considered in [5]. Moreover, there is no need to use tungsten capsules for UN-PuN-U fuel. The necessary absorption of neutrons to reduce the void reactivity effect to negative values can be achieved by using absorbing elements (with boron carbide) as part of fuel assemblies.

Advantages are observed in the design of a dual-purpose power very-high-temperature reactor.

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