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ANALYSING THE SAFETY OF THE FLIGHT OPERATION OF A PROMISING NUCLEAR-POWERED AIRCRAFT

Summary. This article analyzes the safety of flight operations for a promising aircraft with a nuclear propulsion system. The initial experimental models of atomic-powered aircraft underwent operational testing during the first half of the twentieth century but were subsequently deemed unsuitable due to the heightened radiation and nuclear risks to humans and the environment. In light of the growing urgency surrounding the use of alternative fuels for engines, including those used in aircraft, it would be prudent to consider the resumption of the project to develop aircraft with a new-generation nuclear propulsion system utilizing low-enriched fuel. The results are characterized by the following features and distinctive features that allow the problem under study to be solved:

- The occurrence of the initiating factors of an accident at a 6 MW nuclear power reactor with low-enriched nuclear fuel will not entail an aviation accident or incident involving increased human exposure and environmental radiation contamination.
- An aviation accident accompanied by a nuclear and radiation accident with destruction of the reactor core is possible only if an aircraft crashes into a nuclear propulsion system, the probability of which does not exceed the risk of a similar event involving aircraft using conventional aviation fuel.

The results of nuclear propulsion system safety analyses would also be in demand in energy, research and development, and other areas where nuclear reactors are used.

1. INTRODUCTION

The results of this research can be used in civil aviation as arguments in favor of resuming the project of creating an aircraft with a nuclear propulsion system operating on low-enriched nuclear fuel and differing from the original prototypes by an increased level of nuclear and radiation safety for humans and the environment. The nuclear and radiation safety assessment of a reactor for a turbojet nuclear propulsion system may also find application in other areas of nuclear energy utilization. In addition, even low-enriched nuclear fuel with a ^{235}U concentration of less than 20% is 1000 times more energy-dense than Jet-A1 aviation fuel, making the project of nuclear-powered aircraft economically attractive.

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The possibility of using nuclear propulsion systems on long-range aircraft was first realized in the 1950s, ensuring flight continuity for several dozens of hours. The leading nuclear powers thoroughly studied the effects of ionizing radiation from an operating nuclear reactor on aircraft crews and their onboard radio-electronic equipment. Even though an 11-tonne lead shield was used to protect the cockpit to protect the crew from ionizing radiation generated by the nuclear propulsion system, the effective radiation dose to each of them was 50 millisieverts (mSv) for two days of flight, with a permissible limit of 20 mSv per year for personnel working with manufactured radioactive sources [1]. No malfunctions in the onboard radioelectronic equipment were detected during chronic exposure to reactor radiation. By now, reactors have evolved to the fourth generation and have become much safer, even when compared with serial models of the late 20th century [2]. The IV generation reactors have two major environmental advantages: the high waste activity is retained for hundreds, not thousands, of years, and they can be reused in the nuclear fuel cycle. At the same time, even low-enriched fuel obtained from reprocessed uranium retains a high energy release density and increases radiation safety. In view of the above, the use of promising nuclear-powered aircraft has undeniable advantages over traditional turbojet engines:

- They can perform non-stop long-haul flights due to the greater energy potential of nuclear fuel.
- Gaseous emissions of nuclear fission products due to short half-lives will not increase radioactive contamination of the environment, increase radiation load on humans, or contribute to the greenhouse effect.
- The high energy density of nuclear fuel in the order of 50 MW × h per 1 kg, coupled with lower consumption, will reduce the cost of aircraft flights.

The implementation of a project to create an aircraft with a nuclear propulsion system running on low-enriched nuclear fuel should begin with the solution of the problem of assessing the safety of its flight operation. The results of this assessment can be applied not only in civil aviation but also in a number of other industries and energy sectors, which is highly relevant. The well-known codes and software products PARET v7.2, MCU-BUR, and RASCAL 2.2 were used for the safety assessment of nuclear-powered aircraft in order to ensure the reproducibility of the results. A nuclear-powered aircraft safety assessment includes the computational prediction of spontaneous removal of the reactivity compensation (RC) working body (WB) with the simultaneous jamming of the emergency protection (EP) rods, the complete blocking of the gaps between fuel elements of the fuel assembly (FA), failure in the power supply system, the rupture of the reactor core cooling pipeline, as well as the quantitative assessment of the fall of an aircraft with a nuclear propulsion system.

Since the heavy lead shield of the cockpit makes up a significant proportion of the aircraft's takeoff weight, an unmanned nuclear-powered aerial vehicle would be more attractive due to a higher payload. However, despite the economic efficiency, the project of unmanned nuclear-powered aircraft is not being considered due to the lack of remote-control technologies for a nuclear reactor, especially at a distance of 1000 kilometers from the operator.

2. METHODS OF RESEARCH

The object of the study is the core of a 6 MW nuclear reactor with low-enriched fuel for the nuclear propulsion system of an advanced aircraft. In addition, the work aimed to estimate the crash probability of an aircraft with a nuclear propulsion system to predict the consequences of this aircraft accident, which may be the subject of a subsequent study.

The following assumptions and simplifications were adopted in the research process:

1) Intra-reactor processes that may lead to an accident of an aircraft nuclear propulsion system include:
    - the spontaneous removal of the WB of RC with simultaneous "jamming" of the EP WB
    - complete blocking of gaps between fuel elements of the FA
    - failure in the power supply system
    - rupture of the core cooling circuit pipeline

2) Known codes and software products PARET v7.2, MCU-BUR, and RASCAL 2.2 were used to calculate the operating parameters of the reactor core during the occurrence of accident-initiating factors.
3) The crash of a nuclear-powered airplane is accepted as a more dangerous event compared to the initiating factors of a reactor accident in its core.
4) The probability of crashing an airplane with a nuclear propulsion system was estimated using the results of statistical analysis of flight safety in the world regarding airport capacity using Almaty International Airport (UAAA) as an example.

The study was conducted using a theoretical model of a nuclear propulsion system with a 6 MW low-enriched fuel nuclear reactor for an advanced aircraft, as well as codes and software products PARET v7.2, MCU-BUR, and RASCAL 2.2.

The described experiments provide in vitro reproducibility and validation of the proposed solutions.

3. LITERATURE ANALYSIS AND PROBLEM STATEMENT

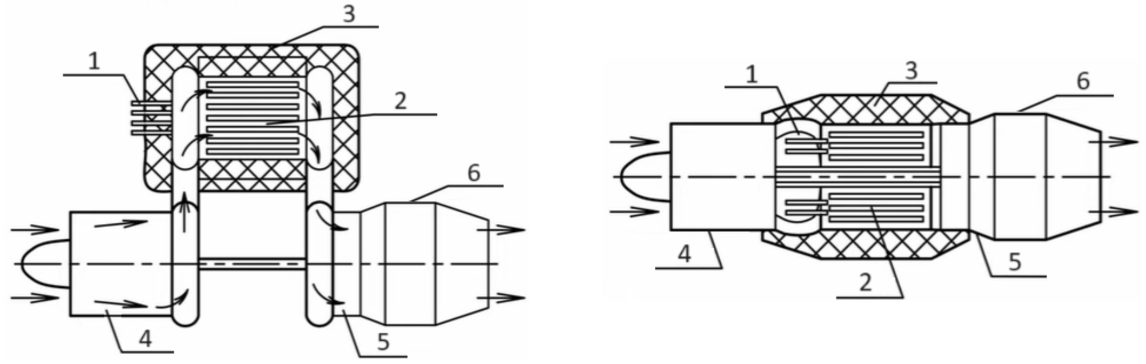
Even though works on the creation and improvement of nuclear aircraft were stopped in the 20th century, modern scientists and experts in the aviation and aerospace field offer innovative projects of equipping aircraft with atomic propulsion systems. For example, the paper [3] considers an electric scientific aircraft ("Titan") with a fusion reactor configured as a closed-cycle energy generator. The reactor is based on the Princeton Field-Reversed Configuration (PFRC) concept, which combines Field-Reversed Configuration FRC and a magnetic mirror. The Princeton Field-Reversed Configuration uses a novel radio-frequency plasma heating system and deuterium-helium-3 fuel. The lower temperature plasma flows around the closed-field Field-Reversed Configuration region, removing fusion products. However, the Titan nuclear-powered aircraft project proposed by the authors of [3] is a spin-off of the direct fusion drive (DFD) orbital transport vehicle. The DFD propulsion configuration would allow a large spacecraft to orbit Titan and then fly anywhere on the moon at subsonic speeds, changing the inclination of the orbital stage to cover different areas of the surface. This kind of technology is not required for civilian aviation's nuclear-powered aircraft. A nuclear propulsion system with a 6 MW nuclear reactor using low-enriched fuel is sufficient for non-stop long-haul flights at echelons not exceeding the tropopause.

This thermal power value was experimentally established in the mid-1960s before the closure of the state program to build nuclear-powered aircraft. This is mentioned in [4], which also describes the project of the Tu-95M bomber with a nuclear reactor and four turboprop engines, each with a capacity of 15,000 horsepower. If we take as a basis for this project and use the power scheme developed in the design bureau 'Tupolev' power scheme of four screw motors, working from a nuclear small-size electric generator, the thermal capacity of the latter should be at least 6 MW [4]. Undoubtedly, using a nuclear propulsion system instead of traditional petrol and paraffin aircraft engines requires the fuselage of a promising aircraft to be re-engineered, as stated in [5].

The technical and operational characteristics of a turbojet nuclear propulsion system for a supersonic nuclear aircraft are presented in [6]. However, given that the studies described in [4-6] were conducted about 60 years ago, it is necessary to calculate the radiation hazards and risks associated with the use of nuclear propulsion systems of modern Generation IV reactors using nuclear fuel with a low percentage of ^{235}U enrichment (up to 20%).

Two types of nuclear propulsion systems—open and closed—were proposed. The operating principles of both types of nuclear propulsion systems developed by the Pratt & Whitney design bureau are presented in [7]. The schematic diagram of an open-type nuclear propulsion system consisting of a nuclear reactor and a turbojet engine is shown in Fig. 1.

The principle of operation of such a nuclear propulsion system is that the air stream enters the vane compressor (4), where it is multistage compressed, then the compressed air enters the reactor core (2), protected by the containment (3), where it is heated to high temperatures. Then, the superheated air enters the turbine (5), connected by a shaft to the compressor (4), and rotates it, after which it is ejected through the nozzle (6), creating a jet thrust. The entry of compressed air into the reactor core for heating and subsequent ejection through the nozzle distinguishes the open scheme of the nuclear propulsion system from the closed one and causes its low weight and simplicity of construction; however, it releases radioactive pollution into the environment.



a **b**

Fig. 1. Schematic diagram of an open-type nuclear power plant (a) with the reactor outside the air path of the turbojet engine and (b) with the reactor built into the air path of the turbojet engine: 1 – control rods, 2 – reactor active zone outside the turbojet engine air path (a) or built into the turbojet engine air path (b), 3 – reactor biological protection, 4 – compressor, 5 – turbine, 6 – nozzle

The closed nuclear propulsion system is more environmentally friendly due to its double-circuit design. The schematic of this system is shown in Fig. 2.

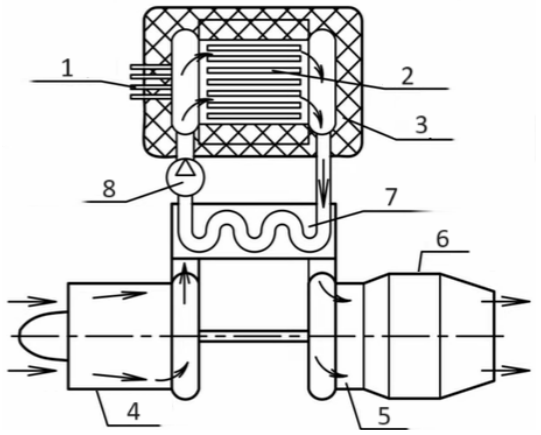


Fig. 2. Schematic diagram of a closed-type nuclear power plant: 1 – control rods, 2 – reactor active zone outside the turbojet engine air path, 3 – reactor biological protection, 4 – compressor, 5 – turbine, 6 – nozzle, 7 – heat exchanger, 8 – coolant pump

Just as in the open circuit, the airflow gets to the vane compressor (4), where it is multistage compressed, but instead of in the reactor core, its heating takes place in the heat exchanger (7), in which the heat transfer takes place from the closed hermetically sealed coolant circuit to the air circuit isolated from it. The coolant (water or metallic sodium), circulated by the pump (8), is supplied to the reactor core (2), heated therein by heat removal from fuel elements and assemblies. After that it enters the heat exchanger (7) to transfer heat to the air circuit, the air in which is not contaminated. The heated air, by analogy with the open scheme of the nuclear propulsion system, is fed to the turbine (5), connected by a shaft to the compressor (4), and rotates it, after which it is ejected through the nozzle device (6), creating a jet thrust without releasing radioactive pollution into the environment. The main disadvantage of the closed-circuit nuclear propulsion system is the higher mass and complex construction due to the use of two circuits.

Aircraft power units have not undergone any fundamental changes since the middle of the last century. The configuration of the nuclear propulsion system is also unsuitable for re-engineering, except that the model of a promising atom aircraft with a turbojet engine will integrate a nuclear reactor of the IV generation using nuclear fuel with a low percentage of enrichment in ^{235}U (up to 20%).

The authors of [8], continuing the research described in [5], proposed an aircraft layout considering the placement of the nuclear propulsion reactor on board. Since a ram air turbine (RAT) is required to cool the reactor and create jet thrust due to the air heated in the core, it is necessary to provide additional air intakes in the fuselage, as well as openings to discharge excess air. Blisters under the TV cameras allow visual inspections of the nuclear engine to be carried out during maintenance and (optionally) in flight.

A prototype of a modern reactor as part of a nuclear propulsion system for a promising aircraft was proposed in [9]. This reactor is schematically depicted in Fig. 3.

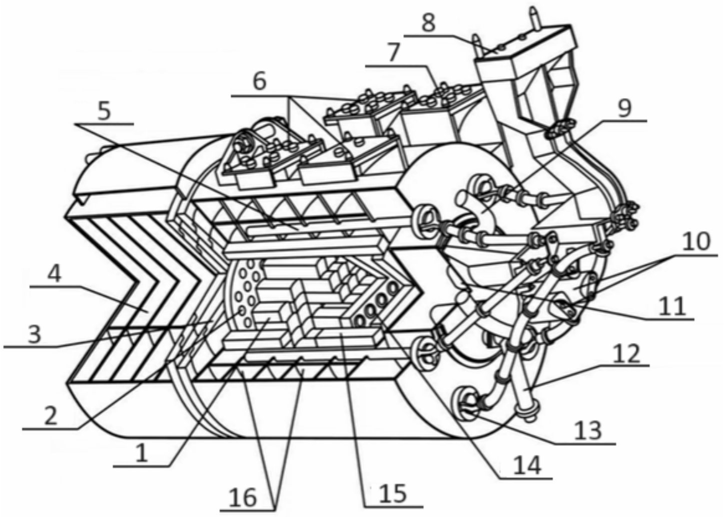


Fig. 3. Schematic diagram of nuclear reactor for nuclear propulsion system of a promising aircraft: 1 – fuel elements, 2 – frontal tube board, 3 – lead rings and discs, 4 – front water tanks, 5 – ionization chamber, 6 – water supply boards, 7 – water supply unit, 8 – cable supply unit, 9 – water supply, 10 – control units, 11 – temperature sensors, 12 – safety valve, 13 – ionization chamber, 14 – rear pipe board, 15 – leaded pressure pipe, 16 – main water tanks

A reactor accident occurs when the balance between reactor power and heat removal is seriously disturbed. Such an accident results in the overheating of the fuel and release of fission products, which, upon entering a living organism through the environment, cause its irradiation with high doses created by spectra of different isotopes depending on the nuclide composition of the core contents. The temperature increase in the core causes a sudden increase in gas pressure and depressurization of the reactor containment. A safety valve (12) is provided to release excessive gas pressure through pipelines (15), but this is accompanied by radioactive contamination of the environment, so it is necessary to monitor the temperature in the core by readings from sensors (11), and in case of exceeding its permissible value, to take measures to cool down the reactor up to emergency shutdown. The need for structural modifications to the core and containment of the reactor presented in [9] should be determined while considering the use of low-enriched nuclear fuel.

4. PURPOSE AND OBJECTIVES OF THE STUDY

The study analyzes the safety of flight operation of a promising aircraft with a nuclear propulsion system. This study will make it possible to assess the feasibility of developing the design of aircraft with a nuclear propulsion system consisting of a turbojet engine and a new-generation nuclear reactor that runs on low-enriched fuel.

Two tasks were set to achieve this aim: (1) to assess the possible consequences of the occurrence of the initiating factors of an accident in the core of a 6 MW low-enriched fuel nuclear reactor and (2) to estimate the probability of a crash of an aircraft with a nuclear propulsion system on the example of Almaty International Airport (UAAA).

5. RESULTS

5.1. Assessment of Possible Consequences of Accident Initiating Factors in the Core of a 6 MW Low-Enriched Fuel Nuclear Reactor

The RC WB can be spontaneously removed by a malfunction in the control circuits of its drive. In the configuration of a 6 MW water-cooled reactor with a thermal power of 6 MW, the energy stress of the RC WB averages 2.11% Δk/k, and that of the EP WB averages 1.10% Δk/k. The results obtained using the PARET code show that when the power exceeds 20%, the EP WB is automatically reset in 0.9 second with the introduction of a negative reactance of -1.96%. At the same time, the EP WB with an energy intensity of 1.10% Δk/k will continue to move at a speed of 4 mm/s, introducing a positive reactance. The named velocity is considered the spontaneous extraction velocity of the RC WB. Thus, the extraction of the RC WB immersed 400 mm into the core will occur in 100 s. The efficiency of the remaining RC WB immersed in the core to the same depth will be 2.19% Δk/k. Figs. 4 and 5 show plots of the change in reactor power and core reactivity over 100 s when the reactor is operating at 6 MW.

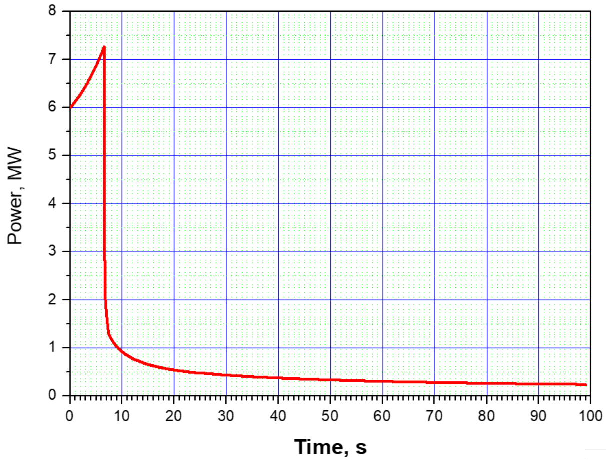


Fig. 4. Change in reactor power over 100 second

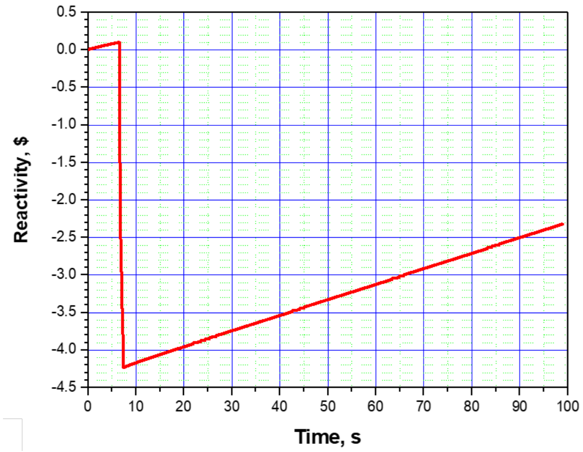


Fig. 5. Change in core reactivity over 100 second

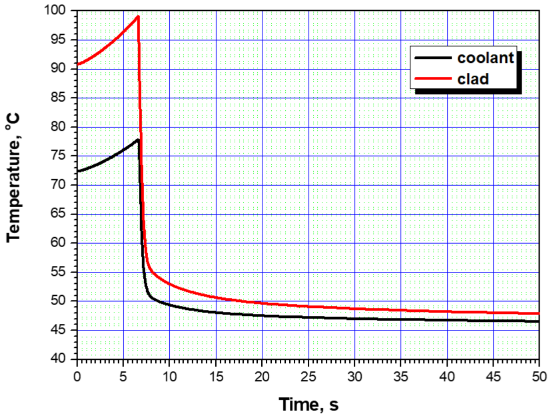


Fig. 6. Variation of the wall temperature of the most energy-stressed fuel element and the temperature of the coolant in the gap between fuel elements for 100 second

Fig. 4 shows that the reactor power first increases, reaching a peak value of 7.28 MW after 6.6 s, and then drops rapidly. After 9.2 s, it decreases to 1 MW; after 22.7 s, it drops to 0.5 MW; and after 100 s, it drops to 0.25 MW. As can be seen in Fig. 6, the maximum temperature and maximum power are reached after 6.6 s, when the reactor power increases to 7.28 MW. When the coolant temperature at the core inlet is 45°C, the fuel element cladding temperature in its "hot" section reaches 99.1°C, which will not have destructive effects on the fuel element cladding material. Even the maximum coolant temperature of 77.9°C will not lead to surface boiling.

In addition to the spontaneous removal of the RC WB, the EP WB can become jammed. Then, 0.4 s later, an alarm signal will be generated to reduce the coolant flow rate by 20%, and the reactor will be shut down by the emergency protection system in 1 s, as shown in Fig. 7. Fig. 8 illustrates the dynamics of the hot fuel element section temperature and coolant temperature in the gap between fuel elements, which remain at safe levels even at maximum values.

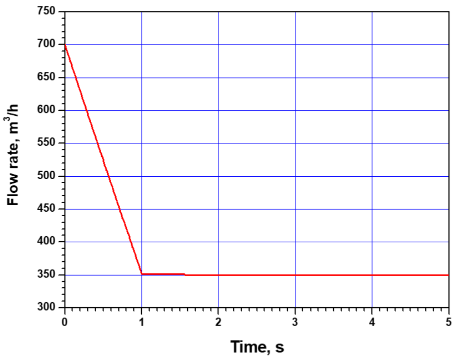


Fig. 7. Change of the coolant flow rate for five second after EP WB jamming

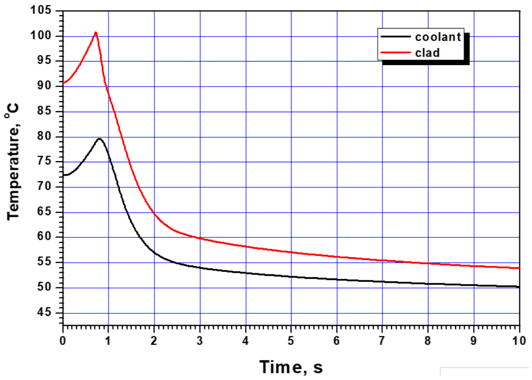


Fig. 8. Variation of shell and water temperatures for 10 second after EP WB jamming

Thus, the spontaneous removal of the RC WB with a simultaneous jamming of the EP WB will not result in a nuclear accident on the nuclear propulsion system of the aircraft. If the coolant passage between fuel elements in the core becomes blocked, the fuel assembly will be partially melted and gaseous fission products (GFPs) will be released into the environment. If a foreign object blocks the upper cross-section of the fuel assembly in the inter-tube gaps, coolant circulation will cease, the coolant will turn into a vapor, and the specific heat conductivity coefficient will sharply decrease, resulting in an unacceptable increase in the temperature of the fuel element walls.

The melting of the fuel cladding and fuel core material will cause fission products to escape outside the cladding, which will increase the activity of the coolant, the air under the reactor lid, and the gas emissions to the environment. MCU-BUR calculations have shown that the fission product (FP) activity values in the fuel assembly of a 6 MW reactor core range from 6.2×10^{16} to 6.5×10^{16} Bq.

The gaseous FP released from the melted fuel elements will first enter the coolant and then the air space under the reactor lid, after which they will end up in the atmosphere. Any warning signals of increasing activity in the coolant of the suction pipe or gas under the reactor lid must be silenced by resetting the EP WB.

The elemental spectrum of the release from the fuel assembly and the specific activities of the radionuclides it contains were obtained using the ICU-BUR code. Experimental estimates of the partial relative yields of radionuclides from the aluminum matrix to the coolant, according to available literature data [10, 11], are presented in Table 1.

The value of the total accumulated activity of GFP emitted into the environment for time t is calculated by the following formula [12]:

$$\boldsymbol{A} = \sum_i \boldsymbol{A}_i^W \times \boldsymbol{c}_i^W \times \frac{1-e^{(\lambda_i + c_i^W + c_i^p)\times t}}{\lambda_i + c_i^W + c_i^p}, \tag{1}$$

where:

A – the total activity entering the pipe during time t

A_i^W[6] – activity of the i-th radionuclide transferred from the fuel to the coolant

c_i^W – the yield constant of the i-th radionuclide from the reactor tank

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[6] In A_i^w from formula (1) the data of Table 1 are already taken into account, i.e., it is the activity of the i-th radionuclide that got into the coolant.

λ_i – decay constant of the i-th radionuclide
c_i^p – purification factor due to ion exchange resins for i-th radionuclide
t – time elapsed from the moment of activity release from the fuel

The activity calculation by Formula (1) for time intervals from 0–1 hour with data from Table 1 shows that 12 PBq will enter the coolant immediately. However, no more than 2.64×10^{11} Bq will enter the environment in the first minute due to the delayed residence time in the coolant. The integral release to the atmosphere in one hour would be about 7 TBq.

Table 1

Fractions of radionuclide release from aluminum matrix into coolant

Xe, Kr	I, Br	Cs, Rb	Te, Se, Sb, As	Sr, Ba	Ru, Rh, Pd, Mo, Tc	La, Nd, Eu, Y, Ce, Pr, Pm, Sm, Np, Pu, Zr, Nb, Ge, Ag, Cd, In, Sn
1	0.5	0.1	0.15	0.1	0.03	0.03

Estimates of integral environmental emission activity and 1-hour average emission rate are presented in Tab. 2.

Table 2

Integral activity and time-averaged emission rates

Time	A, Bq	$(\Delta A/\Delta t)_{ave}$, Bq/min
1 min	2.64E+11	2.64E+11
5 min	1.02E+12	2.03E+11
10 min	1.77E+12	1.77E+11
1 hour	6.99E+12	1.17E+11

The escape of GFP into the cockpit is prevented by the creation of air rarefaction under the reactor lid. The consequences of a potential accident are considered only for the environment. The consequences of the accident are assessed using the RASCAL 2.2 computer code, which is used to obtain calculated values of doses and dose effects on human health. Table 3 presents the estimated partial contributions of radionuclides to the total activity released to the environment in the first minute. The calculations show that the rate of activity release is maximum in the first minute. It decreases rapidly (by a factor of ~5 by the end of the first day, by a factor of ~15 in 15 days, and by a factor of ~50 in a month) due to radioactive decay and scattering in the atmosphere.

During normal reactor operation, the emergency core cooling system pumps, capable of providing a water coolant flow rate of up to 90 m^3/h, are in standby mode. In the event of loss of external power supply, a voltage relay is activated, closing the contacts and connecting the core coolant pumps to the auxiliary power plant and the surge generator. The protection control system (PCS), also connected to the auxiliary power unit (APU) and the surge generator, is not de-energized and causes a reactor shutdown when the coolant flow rate is reduced by 20%, when all the PCS WB are immersed in the core for one second. The emergency coolant pumps are immediately shut down with a run-out time of about 45 second. The experimentally measured run-out curve of both emergency core cooling pumps is shown in Fig. 9.

Immediately after the APU is switched on or the RAT is operated, the emergency pumps are switched on automatically, providing the active zone with additional coolant flow (the capacity of one pump is about 45 m^3/h). Thermal-hydraulic calculations performed with the PARET code, taking into account the run-out of the emergency pumps and the jamming of the EP WB, show that a 20% reduction in coolant flow rate will occur after 6.4 s (Fig. 10). The change in reactor power over 50 s is shown in Fig. 11. The changes in the cladding temperature of the most energy-stressed section of the hottest fuel element and the coolant temperature in the gap between fuel elements opposite the hot section are shown in Fig. 12. The estimated maximum temperature of the "hot" section of the most energetically stressed fuel element is far from the melting point of RAS.

Table 3

Contributions of radionuclides to the total activity released to the environment in the first minute

Nuclide	A, %	A, Bq
Kr, Xe	99.9689	2.63E+11
Ru, Mo	0.0005	1.29E+06
Te, Sb	0.0035	9.17E+06
I, Br	0.0157	4.13E+07
Cs, Rb	0.0027	7.23E+06
Ba, Sr	0.0042	1.11E+07
La, Y, Te, Ce, Nd, Pm, Rh, Np, Pr	0.0035	9.25E+06
Ge, As, Se, Zr, Nb, Ag, Cd, In, Sn, Sm	0.0010	2.67E+06
TOTAL:	100.000	2.64E+11

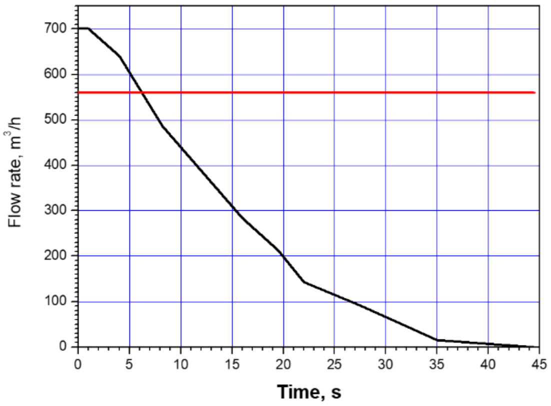

Fig. 9. Experimentally measured run-out flow rate of two emergency core coolant pumps

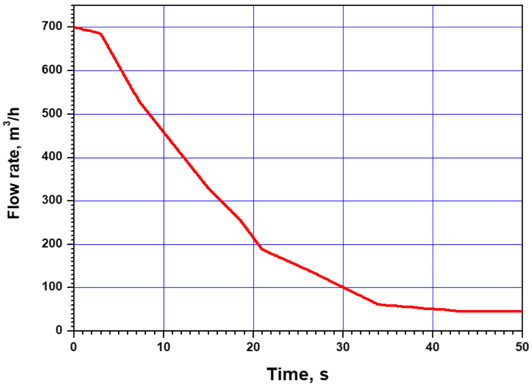

Fig. 10. Variation of water flow rate in the core

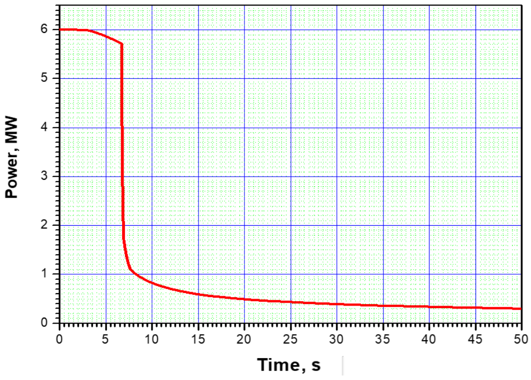

Fig. 11. Change in energy release core

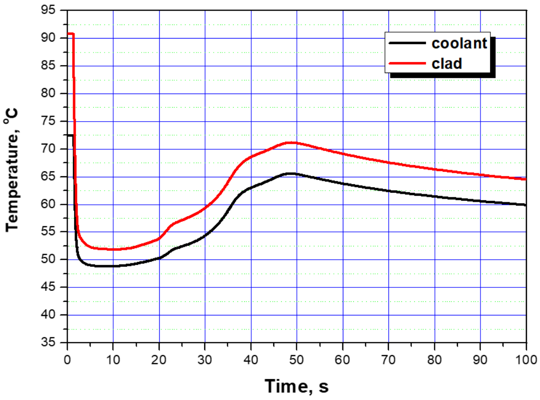

Fig. 12. Temperature change of coolant and fuel element cladding for 100 s

With one emergency pump operating at a flow rate of 45 m^3/h, the baseline event under consideration will not result in an accident. A core cooling circuit piping rupture may occur if a foreign object collides with the nuclear power plant. In the event of a complete instantaneous rupture of the core cooling circuit piping, the coolant flows out rapidly. As a result, the coolant flow rate in the core drops sharply, and the reactor is automatically shut down by the protection control system based on an emergency signal of a 20% decrease in coolant flow rate. The PARET v7.2 code was used to determine the maximum core cladding temperature before the onset of core denudation during the first 9.5 s, considering the reduction in coolant flow rate. Even though the coolant pressure in the core will decrease from 1.79 MPa to 1 MPa and the pressure drop across the core from 800 Pa to 500 Pa in 9.5 second, the PARET calculations for these two core inlet pressures show very similar results. The calculation takes into account a coolant flow rate of 20 m^3/h. The results of calculations for the "hot" channel are shown in Fig. 13, which shows that the maximum temperature of the fuel element cladding material is many times lower than the melting point of RAS (620°C).

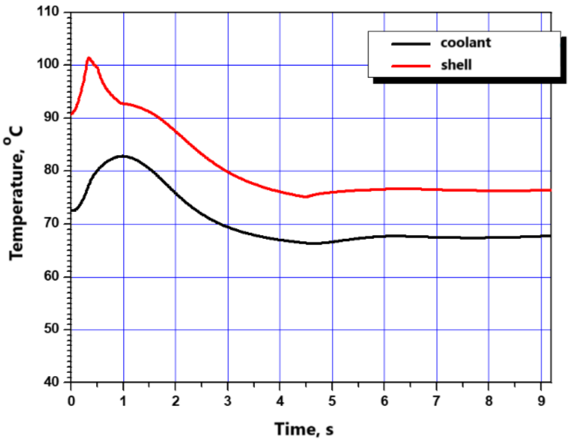

Fig. 13. Variation of maximum values of temperatures of fuel element cladding and coolant for 9 s

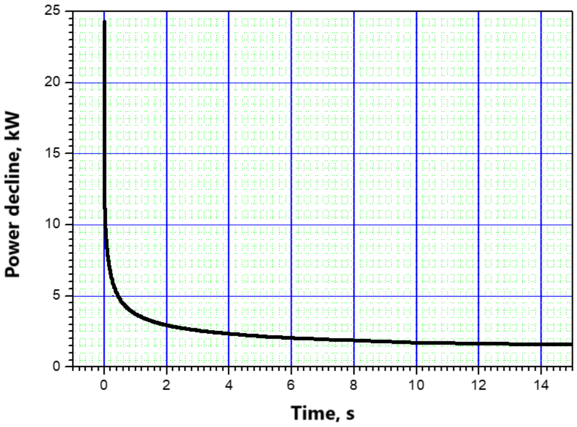

Fig. 14. Graph of the change in fuel assembly power after reactor shutdown

The residual core energy release (Q_0 = 6 MW) in the most energized fuel assembly (Q_0 = 409 kW) for one hour was calculated using the Wigner-Way formula [12]:

$$\boldsymbol{P(t) = P_0 \times 0.00648 \times \left[t^{-0.2} - (t + T_0)^{-0.2}\right]}, \qquad (2)$$

where:

P_0 – the power of the core/fuel assembly before reactor shutdown (6 MW/409 kW)
P(t) – power of the core/fuel assembly by the moment of time t
T_0 – duration of the campaign, h
t – time elapsed after reactor shutdown, h.

The calculation results are summarized in Tab. 4 and Fig. 14.

Table 4

Residual energy release in the active zone and the "hot" fuel assembly for one hour

Elapsed time, s	P_i/P_0	Core	"hot" fuel assembly		
		кВт	kW	kW/m^2	W/cm^2
0.0	100%	6000	409	303	30.3
1.0	5.94%	356	24.28	17.99	1.80
9.5	3.66%	219	14.95	11.11	1.11
20.0	3.10%	186	12.68	9.40	0.94
3600.0	0.87%	52	3.55	2.63	0.26

5.2. Assessment of the probability of a crash of an aircraft with a nuclear propulsion system on the example of the Almaty International Airport (UAAA)

The crash of an aircraft with a nuclear propulsion system is a more dangerous event than the initiating factors of an accident at a reactor in its core. Therefore, the statistical probability of a crash of an aircraft with a nuclear propulsion system should be assessed.

In civil aviation, there are about 200 air incidents per year. The distribution of such incidents by year for the 100-year period from 1918-2018 is shown in Fig. 15 [13]. Published statistical analyses of air safety show that, on average, there are 0.032 air incidents per 1 million flights per year worldwide [13-14]. The average annual statistical estimate of the probability of air incidents (AAs) in the Almaty International Airport (UAAA), which handles about 300 flights per day, or about 110,000 flights per year, is 0.35%:

$$\boldsymbol{P_A = 110,000 \times 0.032 \times 10^{-6} = 0.00352} \qquad (3)$$

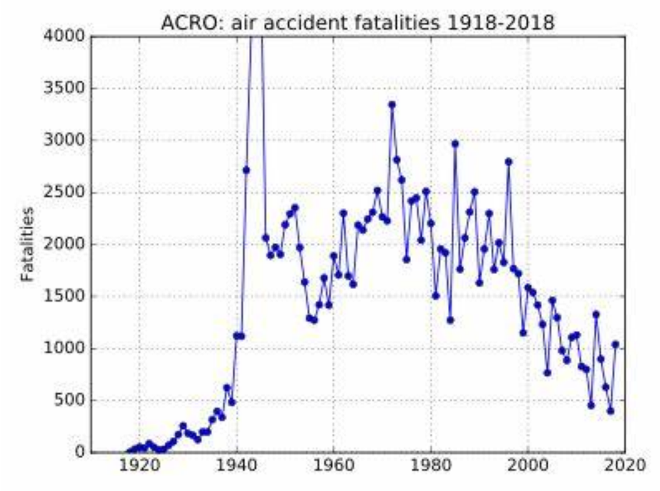

Fig. 15. Number of air accidents in the world from 1918-2018

Fig. 16 shows the results of statistical analysis of aviation accidents involving civil aviation aircraft from 2004-2023 [13-14]. As the statistical analysis in Fig. 16 shows, more than half of all accidents involving civil aviation aircraft occur during descent, initial approach, final approach, and landing. The probability of an accident during takeoff and initial climb is relatively low, but the aircraft is as close to the ground as during approach and landing and is in a more vulnerable state compared to other phases of flight due to increased functional and psycho-emotional stress on the flight crew and limited opportunities for maneuvers.

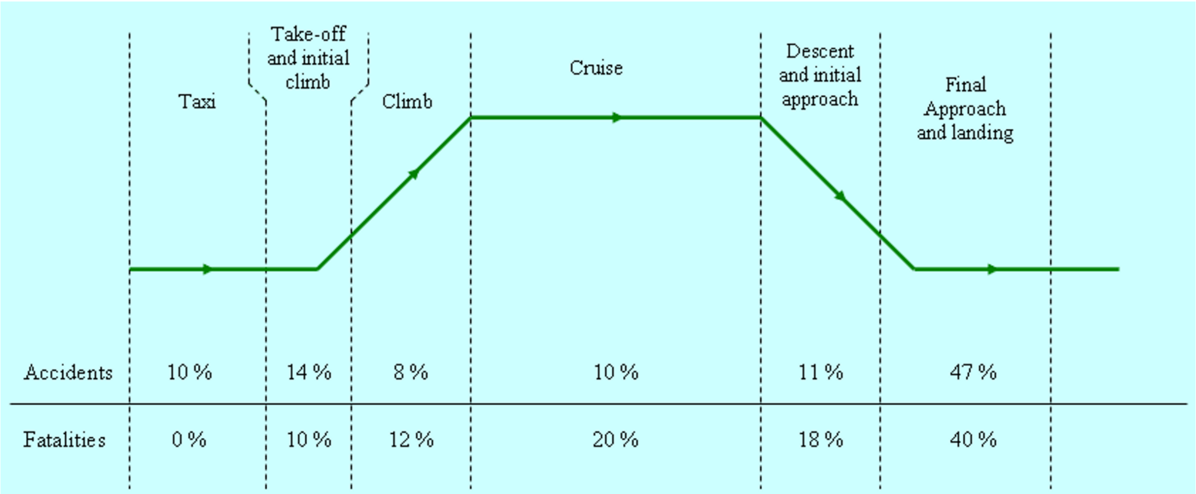

Fig. 16. Probabilistic analysis of aviation accidents from 2004-2023

Given the average annual statistical probability of air incidents at Almaty International Airport (UAAA), calculated by Formula (3), it is possible to calculate the probability of a nuclear-powered airplane crash (P_S) during takeoff, initial climb, descent, initial approach to the destination, final approach, and landing [14]. Since the total probability of an airplane crash at the stages of takeoff, initial climb, descent, initial approach to the destination, final approach, and landing is 72%, the exact value of P_S at Almaty International Airport (UAAA) is 0.25%:

$$\boldsymbol{P_S = 0.00352 \times 0.72 = 0.00253} \tag{4}$$

6. DISCUSSION

The jamming of the EP WB, which can occur along with its spontaneous retrieval, can also introduce positive reactivity. A calculation using the PARET code shows that with an introduced reactivity of 1.9% (=$2,500), the reactor will shut down after 0.43 s due to excessive boiling. Several initial insertion reactance values from 1.5-1.9% were analyzed to determine the maximum allowable insertion reactance, as shown in Fig. 17.

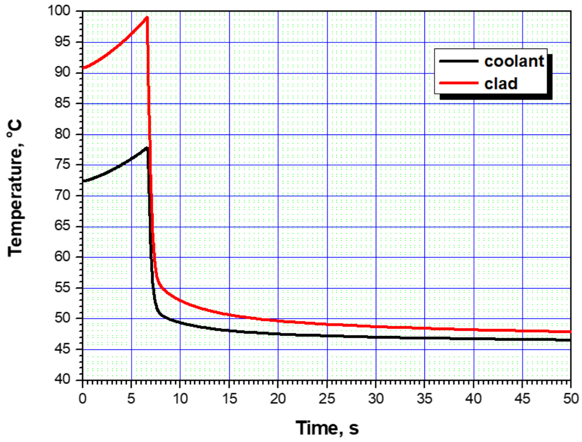

Fig. 17. Variation of coolant and shell temperatures under positive reactivity introduced by jamming the EP WB

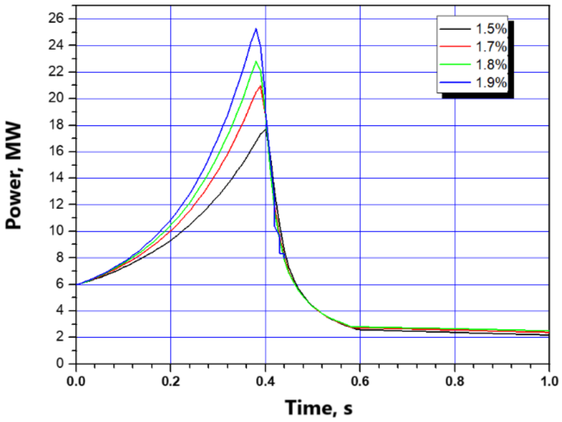

Fig. 18. Change of energy release in the core for 1 s

The variation of the power output over the entire range of the considered insertion reactivities is shown in Fig. 18. In about 0.4 s, the reactor power increases dramatically, reaching 16 MW for a reactivity of 1.5% and 25 MW for a reactivity of 1.9%.

Based on the results presented in Fig. 17, and following a conservative approach, 1.5% should be taken as the maximum reactivity value above which an automatic reactor shutdown should occur.

The integral activity of fission product fragment emissions into the environment due to blocking the coolant passage between fuel elements is calculated and estimated considering several assumptions. These assumptions are based on experimental data, which consider the delay of GFP in the coolant and their release into the atmosphere:

- by being in the coolant:
  - the constant of the GFP release from the coolant is 10^{-6} s^{-1}
  - the yield constant of iodine and non-gaseous FP from the coolant is 3×10^{-10} s^{-1};
- on filter efficiency:
  - the filtration coefficient for non-gaseous FP is 10^{-5} s^{-1};
  - the efficiency of iodine and particle filters is 90%.

These assumptions are conservative because the values of fission product yield constants correspond to the water coolant and chain reaction moderator, and the values of filtration coefficients correspond to ion exchange resins. Other possible materials used in the reactor core of a nuclear propulsion reactor of a prospective aircraft will be characterized by lower fission product yields and higher filtration coefficients.

The minimum number of pumps of the emergency core cooling system is two, one of which should act as a backup. Calculations have shown that in case of failure of one of the two pumps, the flow rate of the water coolant will be halved, but this will not lead to an accident. The supply of water coolant at an intensity of 45 m^3/h will be sufficient to maintain the thermal balance between reactor power and heat removal in the reactor core. However, if both fail, this balance will be disturbed, leading to fuel overheating and emergency release of fission products into the environment. The emergency core cooling pumps should be connected in parallel with each other to the APU and to the RAT in order to increase their reliability.

Depressurization of the core cooling pipeline will not lead to an instantaneous increase in criticality, and the temperature increase will not cause the fuel element materials to melt, but in the first hour after its emergency shutdown, the thermal power of the reactor would decrease perceptibly. This creates the need to further determine the run-out time of the nuclear propulsion turbine by the moment of inertia and its rotation speed after reactor shutdown to calculate the remaining flight time of a prospective aircraft in case of failure of both engines. In addition to the mechanical rotational inertia dissipated in friction, the turbine runaway is affected by thermal inertia, which is not limited by the heat capacity of the structure. Thus, the residual flight time of the advanced aircraft at engine failure should be determined experimentally.

The calculation of the probability of a nuclear-powered aircraft crash is based on statistical data on the flight load of a particular airport. Although the statistical probability of the most dangerous aircraft accident was less than 1%, it may be higher at another airport. In addition, further development should include a technical solution to separate the nuclear propulsion system from the fuselage in the event of an imminent crash and land it safely on a parachute system to avoid radioactive contamination of the environment in the area of a drop from the height of the aircraft's imminent stall.

7. CONCLUSIONS

The spontaneous ejection of the RC WB with the simultaneous jamming of the EP WB would not lead to a nuclear accident in the nuclear propulsion system of a prospective aircraft. At a spontaneous extraction rate of RC WB of 4 mm/s, the insertion positive reactivity of 1.5% or more should indicate an emergency shutdown of the reactor of a nuclear propulsion system. However, the increase in temperature and gas pressure in the reactor would not lead to its destruction even if reactivity above 2% is introduced.

As a result of blocking the coolant passage between fuel elements, more than 30 gaseous fission products may be released into the atmosphere, but the largest partial contribution (99.97%, or 263 GBq) to the total release activity (264 GBq) will be made by the noble gas isotopes xenon and krypton with half-lives ranging from three minutes (^{89}Kr) to 9.2 hours (^{135}Xe), which would not lead to significant and long-term environmental contamination.

If a power outage that could cause a failure of the emergency core cooling system occurs, it would not cause a nuclear accident at the reactor of a nuclear power plant, and the operating condition of even one pump would provide the minimum required coolant circulation intensity. In order to eliminate the risk of complete failure of the emergency core cooling system, it is necessary to resort to loaded redundancy of its pumps connected to the APU and/or to the RAT.

If the cooling circuit pipeline is ruptured, this will cause an automatic shutdown of the reactor based on an emergency signal to reduce the coolant flow rate by 20%. This prevents the core temperature from reaching the melting point of the fuel element cladding material and eliminates the interaction between the fuel and the coolant. However, a more-than-100-fold reduction in reactor power within one hour of an emergency shutdown requires the nuclear power plant to be started and operated from a backup source for an experimentally determined turbine run-out time.

Since disturbances of internal processes in the reactor core do not lead to turbojet engine failure, it is acceptable to determine the probability of a crash of an advanced aircraft with a nuclear propulsion system by running a statistical analysis of previous aviation accidents. The quantitative values of the risks of crashing a prospective aircraft with a nuclear propulsion system will depend on a variety of airworthiness indicators that will exceed 0 in all cases. When implementing a nuclear-powered aircraft project, this will require special design solutions to prevent radioactive contamination of the environment even in the case of an unlikely crash of a prospective aircraft with a nuclear propulsion system.

The present results show that nuclear-powered aircraft flight operation has a fairly high level of safety. However, the low probability of an accident due to disruptions in the operation of the nuclear propulsion system does not detract from the consequences of the crash of the nuclear aircraft for the environment. As part of further research in aircraft flight operations, we plan to forecast and assess the environmental consequences of possible accidents involving nuclear-powered aircraft.

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