ACCUMULATION OF XENON AFTER REACTOR SHUTDOWN

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Accumulation of xenon after reactor shutdown. In the process of fission of uranium nuclei, during the operation of a nuclear reactor, among otherfission products, a radioactive isotope of iodine 135I is formed. As a result of β-decay with a half- life of 6.57 hours, it turns into an isotope of xenon 135Xe.This isotope is also radioactive, but its half—life is longer - 9.14 hours. 135Xe absorbs neutrons very well. The neutrons absorbed by it obviously cannot participate in the chain reaction of uranium fission, so the presence of 135Xe reduces the reactivity reserve of the reactor. In a reactor operating at high power, the loss of 135Xe is determined by its radioactive decay and "burnout" as a result of neutron capture.

Xenon poisoning of the reactor is associated with a temporary decrease in the reactivity reserve due to the accumulation of xenon nuclei after the reactor shutdown. The iodine pit (Figure 1) is the process of a temporary decrease in the reactivity reserve after the shutdown (power reduction) ofthe reactor, which occurs due to a violation of the balance between the rates of loss and the formation of He135.

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In order to exclude the formation of harmful and dangerous impurities in the reactor plant and to avoid deposits on the surface of fuel rods, the coolant must have thermal and radiation resistance. To ensure safe operation conditions, it must have low chemical activity in the absence of toxicity and induced radioactivity. To ensure acceptable technical and economic indicators of the reactor installation, the coolant must have a low cost.

Analysis of the properties of various heat carriers (Table.1) shows that there is no ideal coolant that equally satisfies all the requirements imposed on it. Each of them has advantages and disadvantages that determine the area of its most effective application. Therefore, the choice of a coolant requires a comprehensive consideration of all factors related to its use:

Table-1 - Comparative characteristics of the main heat carriers [1]

Property	Liquid coolant (water)	Liquid metal coolant (sodium)	Gas coolant	
			Carbon Dioxide	Helium
Melting point, °C	0	98	-	-
Boiling point (at 0.1 MPa), °C	100	883	-	-
Neutron capture cross section, Barn	0,6	0,5	0,003	0,001
Thermal conductivity, W/(m • K)	0,55	70	0,04	0,4
Kinematic viscosity, m/s	1	$3,2*10^{-5}$	$8*10^{-3}$ (at 0,1 MPa)	$8*10{-3}$ (at 0,1 MPa)
Specific heat capacity, J/(kg * K)	5,8	1,27	1,066	5,2
Relative power spent on Pumping	1	1,05	3-4	3-4
Scope of application (reactor type)	Hot neutrons	Rapid neutrons	Heat neutrons	Heat or rapid neutrons
Pressure, Mpa	Up 20	~1	2-3	5-10
Maximum temperature, °C	330	600	500	1000

Let's consider the individual characteristics of heat carriers used in nuclear power. Currently, ordinary water has become the most widespread as a coolant in shipboard nuclear power plants. This is one of the most studied heat carriers available. Water has a high heat capacity and heat transfer coefficient, which leads to relatively low power costs for pumping it. The disadvantages of water as a heat carrier are its activation as a result of neutron irradiation and decomposition under the influence of radiation.

Significant disadvantages of water are low boiling point and high vapor pressure. Parameters of the critical state of water: pressure - 22.6 MPa, temperature - 374 °C. To prevent the coolant from boiling, it is necessary to maintain high pressure in the reactor. This leads to an increase in the thickness of the reactor vessel, pipelines, volume compensators and complicates the sealing system. Heavy water as a coolant in ship installations is not used because of its high cost and the inability to replenish reserves in ship conditions. The maximum heating temperature of gases in the reactor is mainly limited by the properties of nuclear fuel and structural materials. A significant disadvantageof gas heat carriers is their low density, and therefore low heat capacity. In this regard, it isnecessary to pump a large amount of gases through the reactor to remove a given amount of heat,which increases the power spent on pumping the coolant.

Gases have a low heat transfer coefficient even at high speeds, which requires an increase in heat exchange surfaces and entails an increase in the overall dimensions of the core. From gas heat carriers can be used: helium, nitrogen, carbon dioxide, air. Helium is one of the best gas heat carriers

due to its inertia and high heat capacity. In the presence of a helium coolant, a single-circuitgas turbine installation can be used. The disadvantages of helium are a significant cost, very high fluidity and the inability to replenish in ship conditions. The use of nitrogen as a primary heat carrier is associated with the consumption of a large amount of energy for pumping it due to its low heat capacity. In addition, nitrogen has a relatively large neutron absorption cross-section.

Carbon dioxide is cheap, affordable, has a small neutron absorption cross-section, and is stable.In terms of nuclear-physical properties, it even surpasses helium. The disadvantage of carbon dioxide, like all other gas coolants, is that thermal neutron reactors, where carbon dioxide is used, have large overall dimensions. The air is characterized by low thermophysical parameters and is not used in powerful power plants. The main advantages of liquid metal heat carriers are their high heat transfer properties and the possibility of heating to high temperatures at low pressure in the reactor. Liquid metal heat carriers are radiation resistant due to the simple structure of the molecules. Their disadvantages include the need for additional devices to maintain the coolant in a liquid state when the reactor is idle. The following liquid metal heat carriers can be used in nuclear reactors: sodium, potassium, mercury, sodium-potassium and lead-bismuth alloys, lithium.

Sodium has a fairly high melting point. Alloys of sodium with potassium have a lower melting point, for example, an alloy of 56% Na and 44% K [2]. It has a melting point of 19 °C, as well as good heat transfer properties, is resistant to radiation, is lighter than water, a small amount of energy is spent on pumping it. The disadvantages of this alloy are high activity with respect to oxygen in the air and low heat capacity. The latter forces a large temperature drop to be created in the reactor system, which leads to significant thermal stresses in the structures. When contaminated with oxygen, sodium oxide is formed in the alloy, which causes intercrystalline destruction of the coolant circuit in a hot medium.

Lead-bismuth alloy is a heavy alloy, its density is 10,000 kt/mj. It weakly interacts with water, itscorrosive effect on structural materials is small. At a temperature of 300-450 °C, stainless austenitic steels of the 1X18N9T grade do not react with it. At 500-600 ° C, this steel corrodes, nickel is washed out of it. As a result, elongation and tensile strength are reduced. Additives to nickel, barium, and calcium alloys reduce the leaching of nickel from steel. Up to a temperature of 550 ° C in the lead-bismuth alloy, structural elements based on nickel alloys are sufficiently stable.

Lithium's chemical properties are very close to sodium and potassium. Solid lithium interacts with water, but this reaction does not occur as violently as between sodium and water. Molten lithium interacts more vigorously with water. When heated, lithium can ignite in air. This complicates the handling of it during operation (when snoring, filling and draining the circuit, etc.). The main advantages of lithium compared to other liquid metal heat carriers are low density and high heat capacity, approximately equal to the heat capacity of water. The disadvantages of lithium are a high melting point and higher corrosion aggressiveness to structural materials than other liquidmetal heat carriers. [3]

Lithium naturally occurs as a mixture of two isotopes: U7, of which 92.5% is contained in natural lithium, and U6 (7.5%). The isotope U6 has a large neutron absorption cross-section. Currently, the costs of separating the isotopes of U6 and U7 are high. Therefore, U7, used for thermal neutron nuclear reactors, is expensive. Lithium purified from the isotope U6 is 40 times more expensive than sodium at the same volume.

From organic heat carriers in nuclear reactors, diphenyl, diphenyl ether, naphthalene, dauterm, etc. can be used. Compared to water, they have the following advantages:
– high boiling point and low vapor pressure at operating temperatures;
– comparatively small thermal neutron absorption cross-section;
– weak corrosion effect on structural materials and weak interaction with water;
– slight activation of the coolant during circulation through the core.
– decomposition under the action of radiation (radiolysis) and high temperature (pyrolysis);

   – lower heat transfer coefficient compared to water, which requires an increase in the heat exchange surface in the reactor and an increase in the flow rate of the coolant;

   – relatively high melting point and cost;

   – the inability to replenish stocks in ship conditions.

The maximum permissible temperature of organic heat carriers at the reactor outlet is determined by the so-called transition temperature, at which the pyrolysis rate increases sharply. The transition temperatures for different organic heat carriers are different: for example, for diphenyl it is 435 ° C, for tri-phenyl - 425 °C.

CHANGES IN THE ISOTOPIC COMPOSITION OF THE CORE DURING THE OPERATION OF THE REACTOR

Poisoning of the reactor with xenon after starting, stopping, or when its power changes is shifted in time, i.e. it is non-stationary. To consider the processes of non-stationary poisoning, it is necessary to have a solution of the system of differential equations. We will solve this system under the following assumptions:

   – the reactor worked with this power for several days, the concentrations of iodine and xenon reached stationary values;

   – the density of the neutron flux and the concentration of nuclei and (that is Σ_a^5)they do not depend on time;

   – when switching from one power to another, stopping or starting, the power changes abruptly.

Under these assumptions, the solution of the system of next equations [4]:

$$N_I(t) = N_I^{\text{ст}} + (N_I - N_I^{\text{ст}})e^{-\lambda_I t}; \qquad (1)$$

$$N_{Xe}(t) = N_I^{\text{ст}} + \frac{\lambda_I}{\lambda_{Xe}^* - \lambda_I}(N_I - N_I^{\text{ст}})\left(e^{-\lambda_I t} - e^{-\lambda_{Xe}^* t}\right) + (N_{Xe} - N_{Xe}^{\text{ст}})e^{-\lambda_{Xe}^* t},$$

Where He are the stationary concentrations of iodine and xenon in the newly established reactor operation mode; and mHe are the concentrations of iodine and xenon before the power change begins; Xe is the effective decay constant Xe in the operating reactor, which determines the resulting rate of xenon loss due to both radioactive decay and its burnout: $\lambda_{Xe}^* = \lambda_{Xe} + \sigma_a^{Xe}\Phi$

Dependence of the multiplication coefficient on the isotopic composition of nuclear fuel

The composition of nuclear fuel both during the operation of the reactor and after its shutdown is continuously changing. The greatest changes occur, of course, during the operation of the reactor, when the density of the neutron flux is high, which causes a high intensity of neutron reactions. A significant contribution in this case belongs to the nuclear transformations of radioactive fission products. After the reactor shutdown, the fuel composition changes mainly due to the ongoing radioactive decay of accumulated fission products.

Changes in the composition of nuclear fuel are mainly reduced to the processes of burnout, reproduction, poisoning and slagging. Burnout is the process of reducing the concentration of nuclei of a fissile substance initially loaded into the core. As a result of burnout, the total reactivity margin decreases. Reproduction is the process of formation of new fissile materials. Fissionable isotopes of Ri and Ri41 are formed in water-water reactors on enriched and due to neutron capture by nuclei. Reproduction leads to an increase in the total reactivity reserve.

Fission products arise and accumulate in the nuclear fuel of a working reactor. All fission products (about 140 nuclides) can be divided into four groups:

   – radioactive short-lived products - He, Kg, He, Ce141, RG44, having large thermal neutron absorption cross sections;

$$\sigma_a^i \gg \sigma_a^5$$

   – stable strongly absorbing products are fission products for which the absorption cross-section is commensurate with the absorption cross-section and other products with weak absorption.

Poisoning is the process of accumulation in the fuel of radioactive short-lived nuclides (of the first group) involved in unproductive neutron capture.

Slagging is the process of accumulation of stable and long-lived nuclides in fuel, also involved in unproductive neutron capture. By definition, burnout, poisoning and slagging lead to a gradual decrease. Therefore, if the initial loading of the reactor exactly corresponded to the critical one, its use for energy production would be impossible. In this regard, the fuel load must exceed the critical mass, and this excess ultimately determines the duration of operation of the reactor.

The reactor criticality condition, as shown above, is expressed in the form of equality

$$K_{\text{эф}} = \frac{K_{\infty} e^{-B^2 \tau}}{1 + L^2 B^2} = 1 \qquad (2)$$

Since the geometric parameter B~ remains constant during reactor operation, a change in the fuel composition can affect AGef only through K = cebf, age t and duration of neutron diffusion. Of the listed indicators, the coefficients and f in water-water reactors operating in a constant temperature regime practically do not change, since the concentration also decreases slightly during the campaign in such reactors.

Age of neutrons depends on the scattering properties of the medium. The change in the isotopic composition of the fuel has little effect on the values? The age of thermal neutrons also practically doesnot change during the campaign.

$$\tau = \frac{1}{3 \Sigma_{\text{тр}} \xi \Sigma_s} \ln \frac{E_f}{E_c} \qquad (3)$$

The multiplication factor is most strongly affected by the change in the thermal neutron utilization factor 0, which can be conventionally represented as

$$\frac{1}{\Theta(t)} = 1 + \sum_i q_i + q(t) \qquad (4)$$

Where $\sum_i q_i$ is the total relative absorption of thermal neutrons in all materials of the core, except and and fission products;

Conclusion. When designing the reactor, the effect of the iodine pit is taken into account. High specific power values require an additional increase in the loading of nuclear fuel to compensate for the iodine pit. Otherwise, it will be impossible to bring the shut-down reactor to power (especially at the end of the campaign) for several tens of hours until the almost complete decay of 135Xe in the core occurs.

References

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