TOMSK POLYTECHNIC UNIVERSITY

EQUIPMENT OF THREE-CIRCUIT NPP

MAIN FEATURES

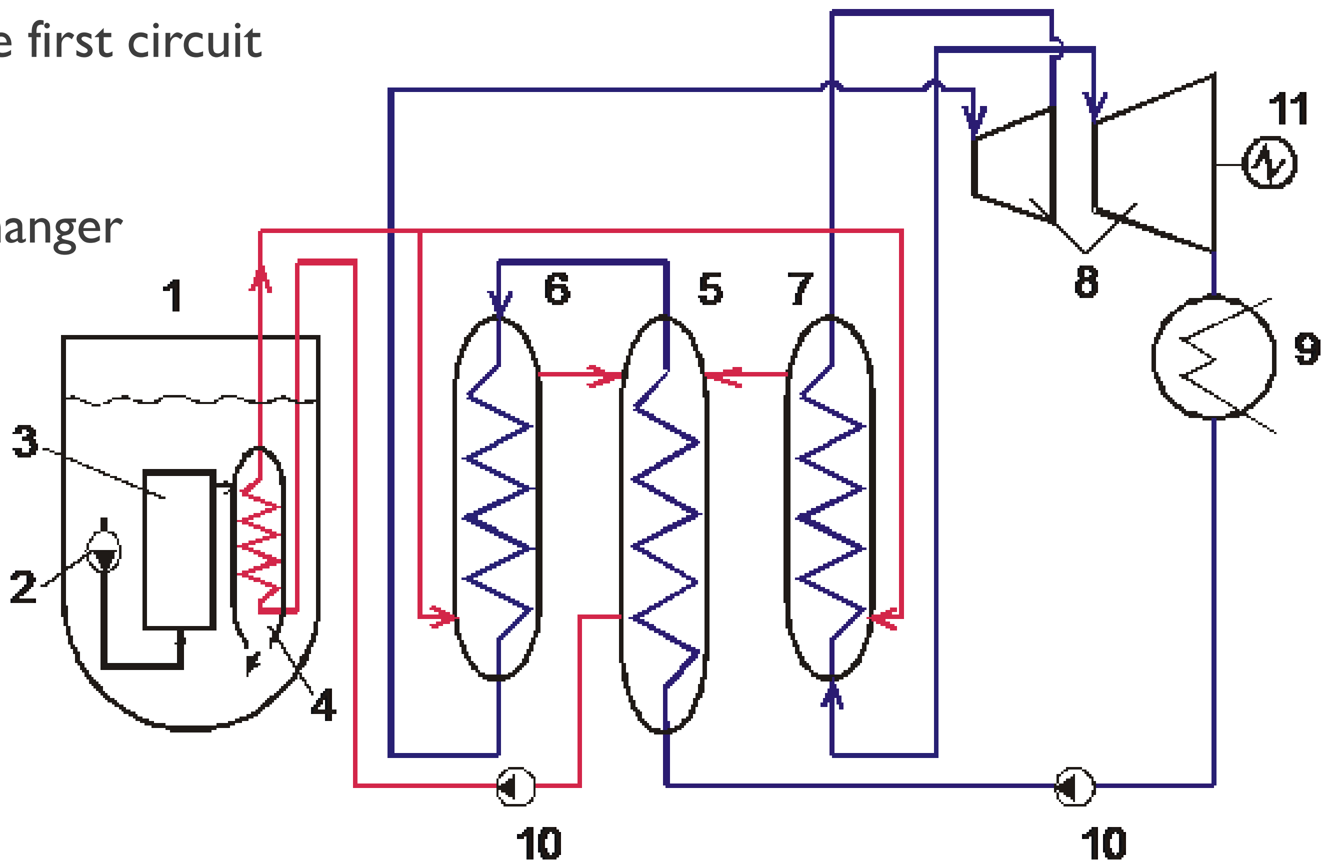
- Definition and main properties of reactor
- Main schemes and equipment
- Construction of reactor part
- Subsystems of 3-circuit NPP

CONSTRUCTIONAL FEATURES OF 3-CIRCUIT NPP

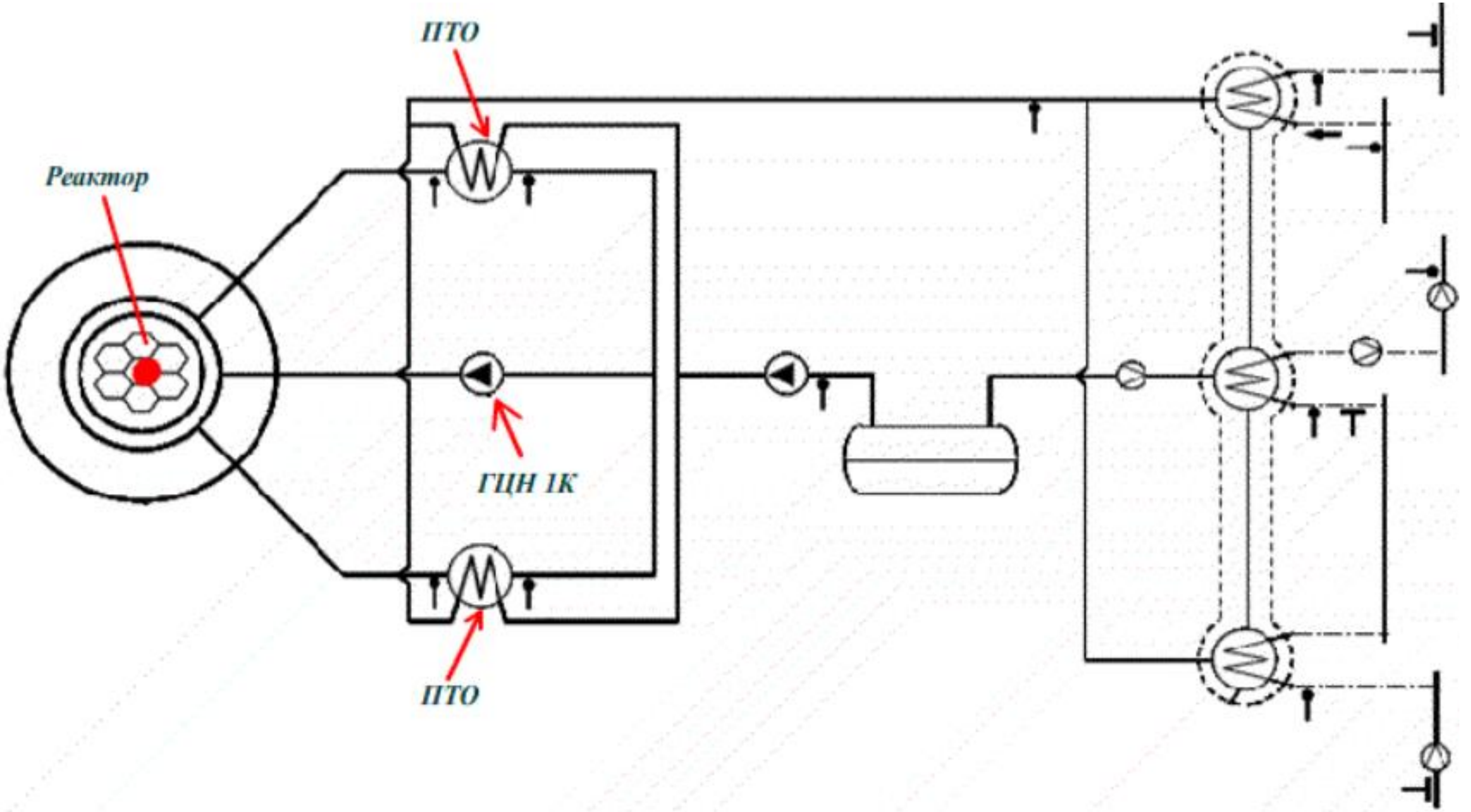
- Main features of 3-circuit NPP are connected to its characteristic features like high thermal loads and low distances between heat releasing compounds. Considering high irregularity of heat generation in active zone (common maximal to minimal heat flux ratio is 1,5-2) the following features of 3-circuit reactors could be distinguished:
  1. Need for significant power of heat removal results into large velocities of circulating sodium, hydraulic resistance, head of circulation pump;
  2. Tendency to increase volumetric share of fuel causes high temperature differences of coolant into active zone;
  3. Irregularity of heat releasing results into effective profiling of coolant flow into active zone.
- Combining those features results into active zone in form of cylinder with diameter to height ration close to 3. Thermodynamic calculation of optimal heating of coolant requires active zone height of 1m while diameter is usually defined by its overall thermal power. Excess pressure of sodium is rather small: with active zone diameter 2,5-3,0 m the thickness of walls will be 30-50 mm. The need for third circuit is defined by tendency to prevent possible contact of radioactive sodium with water due to formation of isotope ^{24}Na with 15 h half-life and active interaction with water with formation of hydrogen.

THERMAL SCHEME OF 3-CIRCUIT NPP

1. Reactor
2. Circulating pump of the first circuit
3. Active zone
4. Intermediate heat exchanger
5. Steam generator
6. Steam superheater
7. Intermediate heater
8. Turbine
9. Condenser
10. Feed water pump
11. Generator



CIRCULATION SCHEME OF 3-CIRCUIT NPP

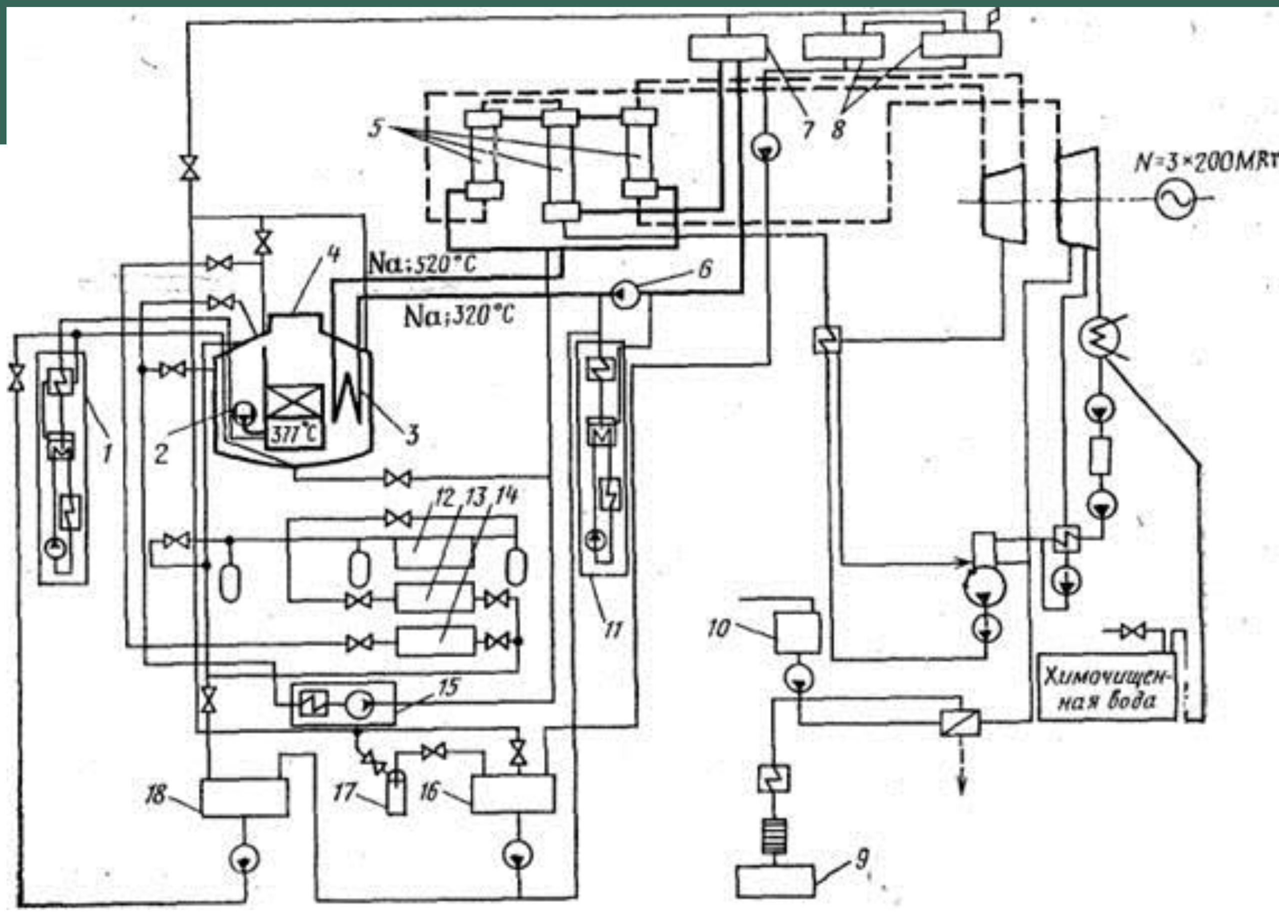


CHARACTERISTICS OF 3-CIRCUIT NPP

- The first circuit pressure is defined by pressure of gas (argon). Maximal pressure is defined by pressure losses and close to 1 Mpa. To prevent assess of radioactive sodium into the second circuit its pressure is higher. Some other characteristics are given below.

Characteristic	BN-350	BN-600	BN-800
Electrical power, MW	350	600	800
Material of fuel element	Stainless austentic steel		
Linear heat flux density in active zone, kW/m: • maximal • mean	 44 21	 47 32	 48 -
Coolant inlet/outlet temperature, °C	270/450	377/550	354/547
Inlet/outlet temperature into intermediate circuit ,°C	270/450	328/518	309/505
Steam pressure/temperature after superheater, MPa/°C • Main • Intermediate	 4,9/435 -	 13,7/507 2,9/500	 13,7/490 -/470
Steam capacity, kg/s	83	551	736

CHARACTERISTICS OF 3-CIRCUIT NPP



1. Sodium cleasing
2. First circuit MCP
3. Intermediate heat exchanger
4. Reactor
5. Steam generator
6. Second circuit MCP
7. Intermediate tank
8. Emergency tanks
9. Pure condensate tanks
10. Tanks of contaminated water
11. Second circuit sodium cleansing
12. Argon cleansing
13. Active argon storage
14. Active argon cleansing
15. Gas accumulating tanks

CHARACTERISTICS OF 3-CIRCUIT NPP

- The three turbine units and three corresponding loops were applied. This number is defined by maximal power of thermal equipment but complex calculations (taking into account efficiency, reliability etc.) reveal that optimal number of circuits is 3-4 as well.
- Each loop has its own pump and two intermediate heat exchangers (due to high value of heat exchange surface area per loop). The section construction of steam generators was used with 24 sections (8 per each loop). Large number of sections makes thermal scheme more reliable but more complicated and metal consuming at the same time.
- Intermediate tank acts as the volume compensator, the special reservoirs are used for utilization of products of reaction between water and sodium in circuit pipeline or steam generator.

CHARACTERISTICS OF REACTOR PART OF THE 3-CIRCUIT NPP

- Reactor BN-600 is realized with integrated compounding: active zone and equipment of the first circuit is situated inside reactor casing.
- The reactor vessel is a cylindrical tank with an elliptical bottom and a conical upper lid which is made with eleven necks - for a rotary valve, pumps, intermediate heat exchangers, elevators of the fuel load system. The cylindrical part of the body is connected to the bottom by welding through a transitional support ring where the bearing belt is installed. It is the basis of the supporting structure inside the reactor vessel: it forms a system of radial ribs with three drain chambers for sodium after heat exchangers.
- All equipment is mounted on the support belt: pressure chamber with fuel assemblies of the active zone, reproduction zone and internal storage of fuel assemblies, primary radiation protection, intermediate heat exchangers, main circulation pumps of the primary circuit. The load from the mass of the reactor through the support ring is transmitted to the roller bearings, which are situated on the base plate.
- The reactor is placed in a concrete shaft with a diameter of 15 m. The material of the reactor is X18H9 grade stainless steel. In the center of the upper part of the reactor a rotary device is mounted, consisting of large and small rotary plugs, eccentric relative to each other; on a small rotary plug an emergency cooling column is mounted, carrying the actuators of the main systems: control and protection, fuel assembly load, core monitoring.
- To compensate the temperature lengthening of the primary circuit pumps and intermediate heat exchangers relative to the reactor vessel, the compensators are welded to the inlet of the reactor vessel. The reactor vessel is enclosed in a safety casing, which excludes the possibility of sodium leakage from the reactor, even when its shell ruptures.

CHARACTERISTICS OF REACTOR PART OF THE 3-CIRCUIT NPP

- The core and the breeding zone are assembled from cassette-type hexagonal fuel assemblies with a 96 mm size. A fuel assembly consists of fuel rods, casing, a head for capturing fuel assemblies during overloads, and a shank which is used to install an assembly in socket and is supported vertically. Throttle devices are made in the fuel assembly shank and in the pressure collector to ensure the required distribution of coolant flow through the fuel assembly. The fuel rods are interconnected by fasteners and fenced by case.

- The fuel rods are filled along the length of the core with bushings of enriched uranium oxide (or a mixture of uranium oxide) and plutonium oxide, while end and bottom screens made of the "dump" uranium oxide and located above and below the core. The fuel rods of the breeding zone are filled with briquettes of waste uranium. The gas cavities above the sodium level in the reactor are filled with argon.

- Partitioned steam generators (SG) are used, which consist of a large number of steam generating units of relatively low power. Thus, at BN-600, eight steam generating sections were installed in each loop (four for each turbine unit), each includes three distinguished functional modules: evaporator, main and intermediate superheaters.

- The possibility of independent shutdown of any section of the steam generator when a leakage is detected in a separate module allows to keep the corresponding loop in operation, and replace defective modules on a running unit with virtually no decrease in its power. However, with a large number of SG sections operating in parallel, the thermal scheme of the block is significantly complicated, the intensity of the metal and the cost of SGs, and the volume of the corresponding station premises increase. The need for a large amount of gas and sodium valves reduces the overall reliability of the unit. It is difficult to automate and control the power unit during operation due to the need for automatic control of the uniform distribution of water and sodium flows between sections.

CHARACTERISTICS OF REACTOR PART OF THE 3-CIRCUIT NPP

- For large power units with BN reactors, the application of large unit-capacity SGs is promising based on:

- one SG per loop or

- one SG for turbine.

- Such a solution ensures the maximum simplicity of the thermal circuit of the unit, a minimum of communications, valves and control devices, with a reduction in the capital cost of the unit building.
- Various solutions of intermediate superheating organization are also possible.
- So, on the unit with the BN-600 reactor, sodium reheat was applied in a separate PG module connected in parallel with the main superheater. In the "Superfenix" plant, reheating is carried out by steam from turbine selections. In the latter case, an industrial steam reheater (SR) is introduced into the circuit. Steam reheating with hot sodium is more thermally efficient and makes it possible to reduce the surface of the industrial superheater. However, the block diagram is obtained in this case more complicated because of the need to exclude thermal shocks in the superheater at the launch of the block; requires the introduction of steam pipes of large diameter and length. The heat exchanger steam - steam is more reliable than sodium, and due to the possibility of its location in the immediate vicinity of the turbine (in the engine room), the length and intensity of the steam lines are reduced. The decisive advantage of the steam-superheated circuit is the simplified control of the installation in the block start and stop modes. Therefore, this scheme is considered currently preferred.

CIRCULATION OF SODIUM IN THE FIRST CIRCUIT OF THE 3-CIRCUIT NPP

- The generally accepted solutions include, in particular, a scheme with an upward movement of the coolant in the active zone and lowering in the second. For BN, unlike other types of reactors, this issue is very closely related to the design of the reactor and other components of the installation. One of the features of the hydraulic circuit of the primary circuit of the BN is the high hydraulic resistance of the core. It constitutes the main part (85–90%) of the total hydraulic resistance is of the primary circuit. Therefore, the direction of movement of sodium through the core largely determines the excess pressure in the gas cavity of the reactor, under which the reactor vessel operates. Due to the upward movement of the coolant, this pressure is usually 0,05–0,09 MPa, so that the load on the body of the RBN is determined mainly by the mass of the coolant and the upper protection of the reactor with the mechanisms.

- The upward movement of the coolant in the BN and the associated distribution of static pressure across the height of the core require special measures to prevent the fuel assembly from floating up under the action of hydraulic forces, the results of which acts on the fuel assembly in the upward direction. In modern BN the task of fixing fuel assemblies is solved, as a rule, by the method of hydraulic unloading by organizing a low-pressure cavity under a pressure manifold. The differential pressure on the lower sealing of the shank acts downwards and, together with the weight of the assembly, compensates for the hydraulic ejection force acting on the upper sealing of the fuel assembly and on the end parts of the fuel rods. There are projects of the BN (“Enrico Fermi”, “Clinch River”), in which the assemblies are held by a special plate or a lower camera, the pressure head of the fuel assembly above. In this case, the design should provide for the possibility of expanding the fuel assembly during heating, as well as the means to control the separation of the plate from the fuel assembly heads before starting reloading operations.

CIRCULATION OF SODIUM IN THE FIRST CIRCUIT OF THE 3-CIRCUIT NPP

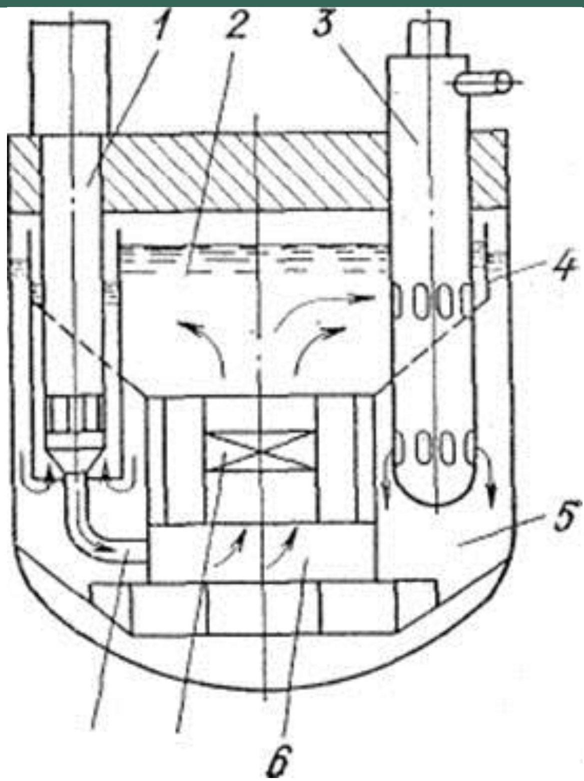


Fig. 3. Hydraulic diagram of an integral type reactor: 1 - primary circuit MCP; 2 - hot sodium; 3 - PTO; 4 - partition between hot and "cold" sodium "; 5 - "cold" sodium (intermediate collector); 6 - pressure manifold; 7 - active area; 8 - pressure pipe.

The advantages of the scheme with MCP on the "cold" contour branch are as follows:

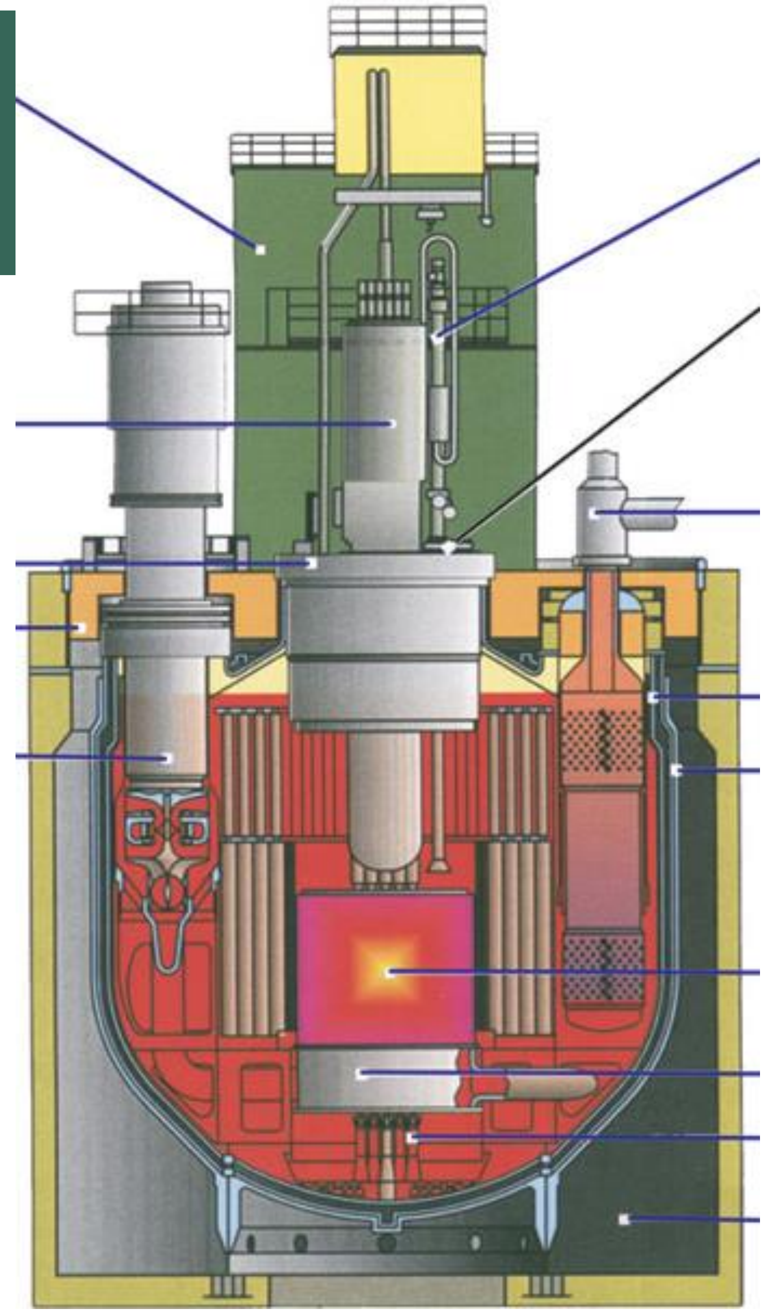
The lighter thermomechanical conditions of operation of the main units of the MCP, since the heat fluxes along the shaft and the temperature levels in the design are relatively small. Non-stationary thermal stresses at the MCP nodes associated with transient operating conditions are practically excluded, since the turbine is an effective temperature damper between the reactor and the MCP.

Lower pressure in the turbine unit (by the amount of pressure of the MCP), which makes it possible to reduce the thickness of its tube plates and the level of thermal stresses. It allows to have a minimum pressure in the second circuit, the value of which is chosen from the condition of preventing the spread of radioactivity.

Areas of pipelines that have both high temperature and the highest pressure are eliminated; more simple is the connection of the MCP with pipelines for self-compensation of thermal expansions (fewer are the number of pipe bends).

POWER UNIT WITH REACTOR BN-800

- The 800 MW power unit currently under construction with a fast neutron reactor is a modified and improved version of the BN-600 reactor. During the development of the BN-800 reactor, the project introduced technical solutions to bring it to a level that meets the safety requirements for a new generation of reactors: passive means of influencing reactivity, emergency cooling systems through heat exchangers, a pan to collect molten fuel. The probability of an accident with the melting of the reactor core BN-800 is an order of magnitude lower than in light-water reactors. The increase in capacity of the unit from 600 to 800 MW was achieved within the limits of the BN-600 dimensions. The volume of active zone and the number of fuel assemblies are increased.
- The traditional homogeneous zone with a mixed oxide uranium-plutonium fuel was adopted as the basis.



SODIUM CLEANSING SYSTEMS

- The selection of the composition of the cleansing system and its performance is determined primarily by the total amount of impurities that must be removed from the coolant over the service life of the installation. In addition, the time requirements for cleansing the circuit should be taken into account in the event of possible accidental contamination (in the second circuit - if the contact products of sodium with water enter), as well as considerations of ease of operation. The time for sodium purification in case of accidental contamination with its impurities should not be excessively long, in any case, not more than 2 ... 3 days.

- The total amount of impurities introduced into the circuit is given by the following sources:

1) the initial contamination, which is approximately directly proportional to the contour surface. For the calculation of the first contour, the specific pollution value (in terms of oxygen) of 3.4 g O_2/m^2 is recommended, for the second contour 2.2 g O_2/m^2. The higher value for the primary circuit is associated with the longer installation and adjustment work inside the reactor;

2) impurities that are systematically introduced when loading fresh fuel assemblies. According to the BN-350 experience, the specific contamination of the surface of the assemblies is approximately 2 g/m^2;

3) the introduction of corrosion products of structural materials. The intensity of this source of impurities is mainly determined by the oxygen concentration in the coolant and the operating temperature.

- When a reactor is operated with unsealed fuel rods, fission products also enter the circuit: ^{137}Cs, ^{134}Cs, ^{131}I, ^{132}Te and some others, and in case of severe damage to fuel rods (fuel contact with sodium): ^{140}Va — ^{140}La, ^{95}Zg - ^{95}Nb, as well as Pu and Am .

- Gaseous fission products — the Xe and Kr nuclides do not dissolve in sodium and exit into the gas cavities of the reactor. For the second circuit, additional sources of impurities should be taken into account, such as the ingress of water into sodium during SG flows (in emergency conditions it can reach tens of kilograms, however such situations are rare) and the diffusion of corrosive hydrogen from the third circuit. Given the intensity of all active sources, they determine the total amount of pollution introduced into the circuit over the service life of the unit (20 ... 30 years).

SODIUM CLEANSING SYSTEMS

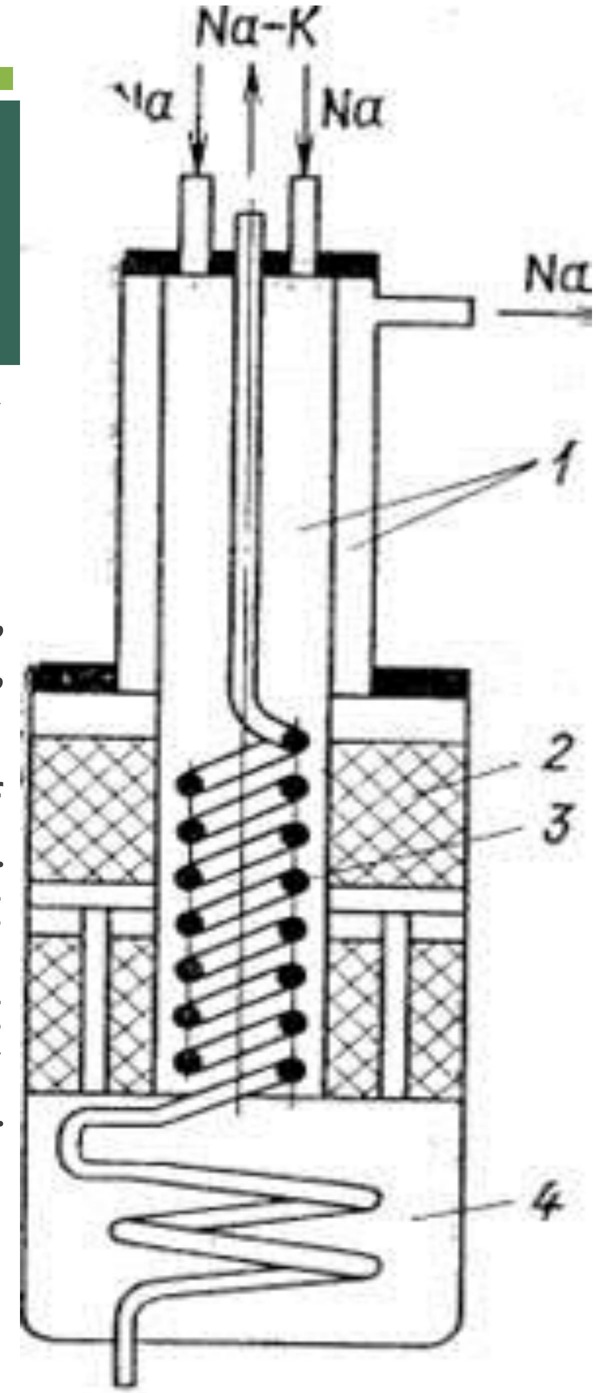
- Introduction of corrosion products into coolant

O_2 concentration, %	Intensity of introduction, g/(m in year)			Concentration, kg/year	
	300 °C	500 °C	700 °C	1st circuit	2nd circuit
• 5	0,15	6	57	18	3,5
• 10	0,5	20	182	60	11,5
• 25	1,7	65	603	194	37
• 45	9,2	108	4100	221	29,7

- A significant decrease in the solubility of the main impurities with a decrease in the temperature of sodium, as well as its good thermal performance, contributed to the fact that the “cold capture” method was most common in the BN. Filtration devices based on this method, the so-called “cold filter traps” (CFT), are the main and in most cases the only means of cleaning the coolant in the BN.

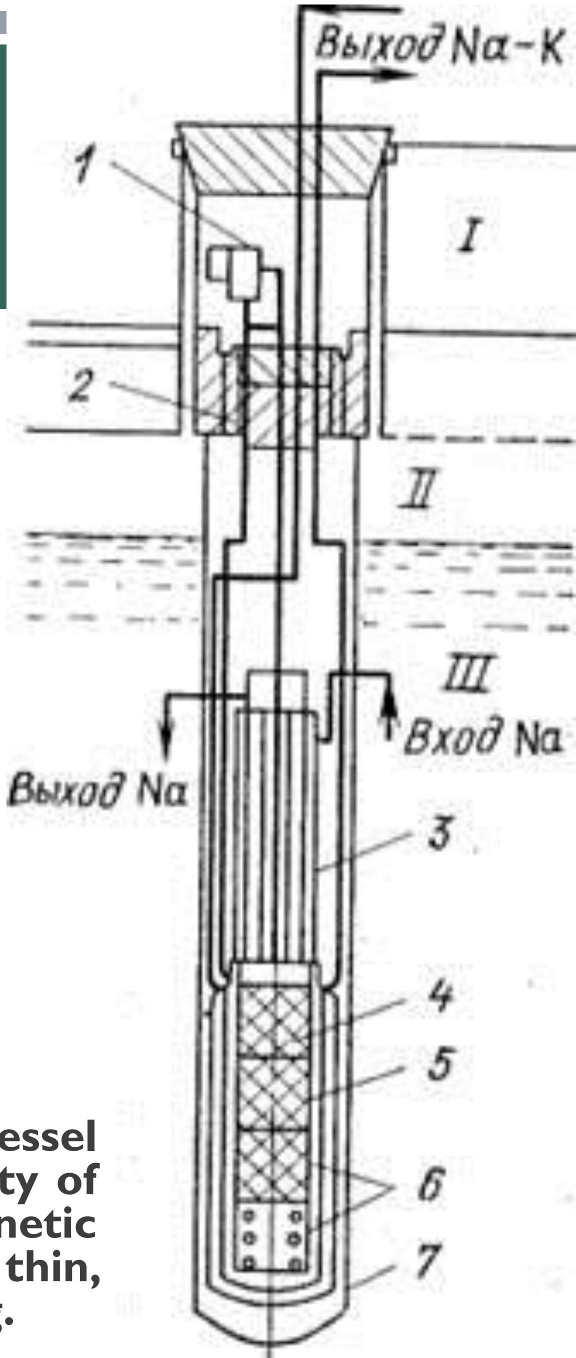
COLD FILTER TRAP OF BN REACTOR

- Sodium oxide is the main form of impurities captured by CFT. The capacity for oxides of one standard trap of the BN-350 reactor is about 1200 kg (310 kg of oxygen). In addition to oxides, CFT partially removes radionuclides from sodium (tritium, iodine, tellurium, antimony), reduces activity in the contour of cesium by 20 ... 50%, captures undissolved corrosion products, fuel particles.
- Knowing the capacity of CFT, determine the number of traps that must be installed in the circuit cleaning system. When calculating the number of traps in the cleaning system of the second circuit, it should also be taken into account that a significant part of the impurities entering the second circuit are hydrogen compounds, the capacity of which for CFT is 1.5 times lower than for oxides. Corrosive hydrogen that diffuses through the walls of SG pipes can dramatically accelerate the exhaustion of the trap capacity as a result of clogging with hydrides.



COLD FILTER TRAP OF SUPERPHOENIX

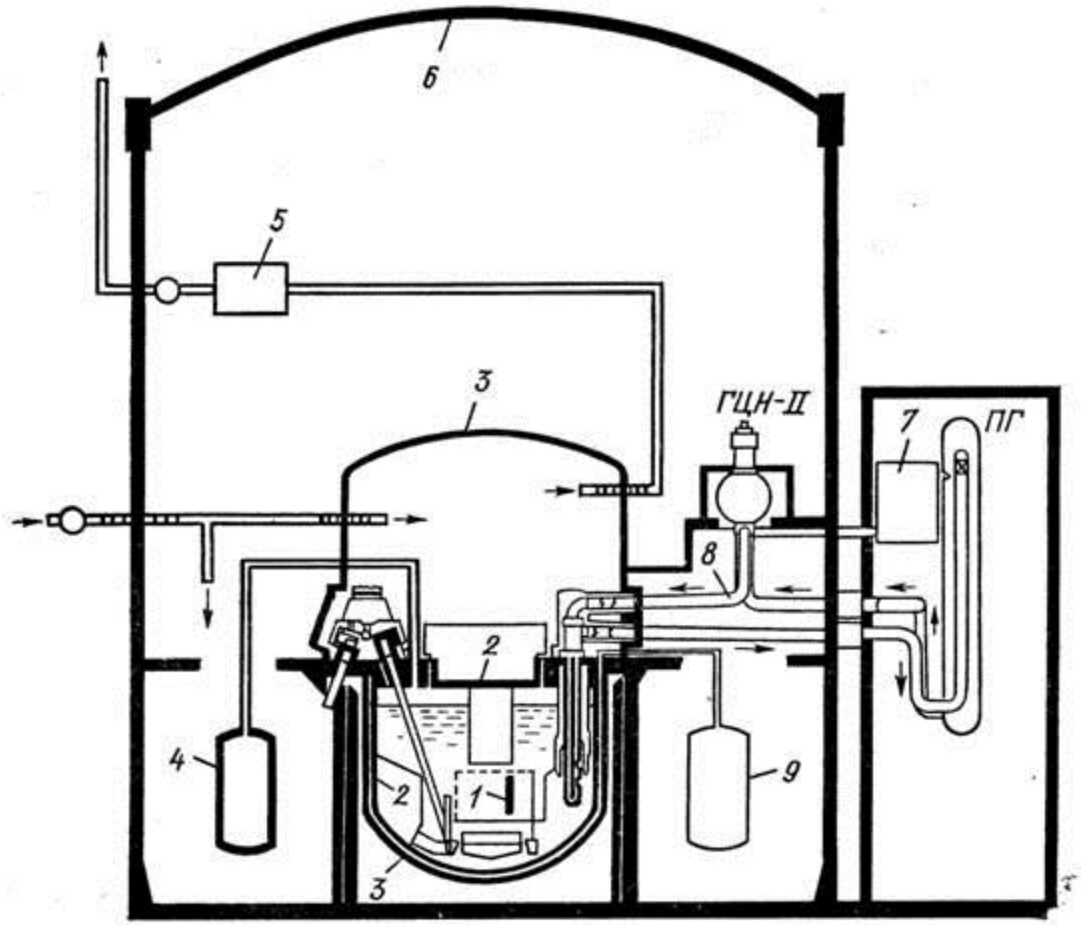
The replacement and regeneration of the primary loop traps are technologically complex operations due to the high levels of radioactivity and the large physical volume of the existing HFL (on the BN-600, the volume of one trap is 6.5 m^3). The experience of conducting such operations is virtually absent. The simplest solution in this case is to reserve CFT without replacement during the entire lifetime of the reactor. This solution involves additional material costs. The solution that allows the remote replacement of CFT has been developed for the Superphenix reactor. This CFT is made in the form of a single unit, in the case of which there are cooling system pipelines (Na-K), recuperator, partitioned wire filter, radiation protection



- **Image of a cold filter trap operating in the reactor vessel "Superphoenix": I - upper protective cap; II - the gas cavity of the reactor; III - “hot” volume of sodium; 1 - electromagnetic pump; 2 - biological protection: 3 - recuperator; 4, 5, 6 - thin, medium and coarse wire filters, respectively; 7 - trap casing.**

SAFETY SYSTEMS

- 1 - active zone;
- 2 - the boundary of the primary circuit;
- 3 - main containment;
- 4 - argon system;
- 5 - ventilation system with filtration of radioactive aerosols and gas emissions;
- 6 — secondary containment (containment);
- 7 - air heat exchanger of the emergency cooling system;
- 8 - sodium pipelines of the second circuit;
- 9 - nitrogen system



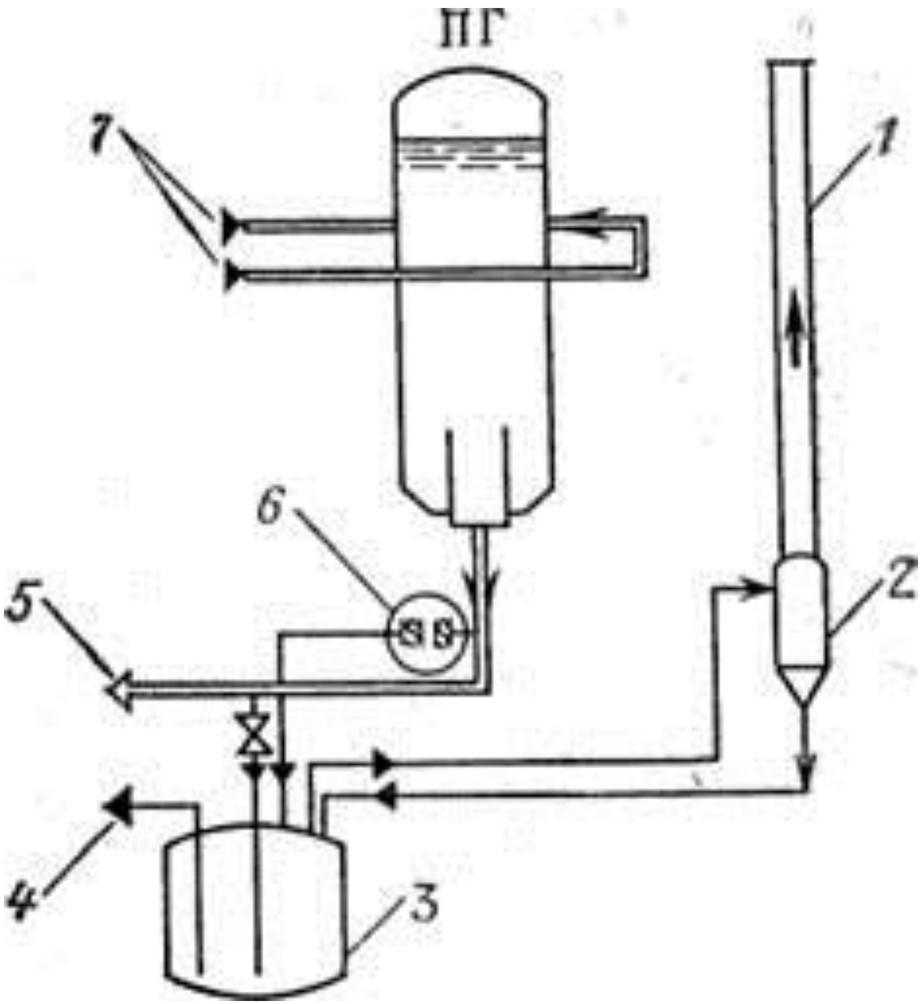
EMERGENCY PROTECTION OF STEAM GENERATOR

- In accordance with the accepted classification, the following types of water leaks to sodium are possible in steam generators of the BN:

1) small leaks - leaks up to 0.1 mg/s; accompanied by a rather slow erosion-corrosive damage to the tubes surrounding the defective one;
2) medium leaks - leaks from 0.1 g/s to 1 kg/s; accompanied by the formation in the reaction zone of the torch interaction products with a very high temperature, the rapid destruction of adjacent tubes as a result of the dissolution of the metal, contamination of sodium of the second circuit;
3) large leaks - leaks of more than 1 kg/s (correspond to the complete rupture of one tube); accompanied by strong hydrodynamic effects that create significant loads on the structures of the second circuit, namely, pressure waves in the SG itself and the corresponding loop, variations in sodium levels in the gas cavities of the loop; In addition, there is a strong contamination of sodium and all secondary circuit equipment with corrosive products of interaction.

The compensation of these leakages is realized using system of emergency protection.

EMERGENCY PROTECTION OF SG



- Scheme of the SG emergency protection of the Superphenix reactor: 1 - hydrogen yield; 2 - cyclone separator; 3 - waste tank; 4 - on the sodium purification system; 5 - sodium output from PG; 6 - rupture membranes; 7 - sodium intake in PG

THANK YOU FOR YOUR ATTENTION