Development experience for experimental reactor facility cooled with evaporating liquid metals

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Abstract. SC RF-IPPE developed a technical project of the experimental reactor facility cooled with evaporating liquid metals in 1988-97. Evaporating sodium is used as a coolant of the facility core. Evaporating sodium-potassium eutectic alloy is used as a coolant for the second loop. The third loop is fulfilled with gas – working fluid of Sterling or Bryton cycle. Nuclear and thermo-hydraulic calculations are performed for a 1.2 MWt nuclear facility. Many thermo-hydraulic experiments with single-element, three-element and seven-element electrical imitators of fuel roads are performed. So, calculated parameters of the core elements are validated. Two fuel rods cooled with evaporating sodium are tested in the nuclear fast reactor. Three-loops sector mock up including 72 imitators of fuel rods is created and tested as well. It corresponds to 1/6 part of the core. Beside it, the mock up includes imitators of a neutron reflector, shield and natural size dome. Outside the dome interlope heat exchanger and the third lope of the facility are placed. Many thermo-hydraulic experiments are performed but not finished, unfortunately.

Key Words: Reactor facility, evaporated liquid metal.

1. Introduction

Nuclear fast reactors cooled with liquid metals are well known. The BN-600 reactor cooled with sodium successfully operates for over 30 years. The BN-800 reactor unit has been commissioned recently. But they are rather expensive and cannot compete with water-cooled reactors. In particular, this is due to a large volume of sodium used as the coolant in the first and second loops.

One of the possible ways to improve this type of reactor is their evaporative cooling in nominal and emergency modes. During evaporative cooling, heat removes not due to the heat capacity of the coolant, but due to its evaporation heat. This requires a much smaller flow rate of coolant (for one or two orders of magnitude) and a very small difference in temperature between the heater and the cooler. Circulation of the coolant occurs naturally without circulating pumps. So, there is a possibility to reduce consumption of materials, dimensions and cost significantly. There are other advantages, such as a possibility of a completely passive system of emergency cooling and residual heat removal.

A method of evaporative cooling and technical devices for its implementation – heat pipes, thermosyphons, vapor chamber, etc. are widely used in non-nuclear energy (see for example

[1-5]). There are some publications on using of heat pipes in nuclear power engineering as well [6, 7, 8, 9].

Development experience of an experimental reactor plant cooled with evaporating alkali metals is considered in this paper, in order to demonstrate feasibility of such plants. The work was carried out in IPPE in 1988-1997. At that time, such facilities or their projects were unknown in the world. A basis for this work was almost twenty years' experience in the development of liquid metal heat pipes, their production and research in IPPE.

2. Basic parameters of the facility

The project of a 1.2 MW heat capacity experimental reactor plant was developed. The main design parameters of the core are as follows. The fuel residence time proposed 25000 effective hours. Uranium nitride and highly enriched U-235 are proposed as fuel, with the load of U-235 being approximately 100 kg.

The core equivalent diameter is 350 mm, its height is 300 mm and it is surrounded by neutron reflector. The end reflectors are made of steel rods, which are 13 mm in diameter and 50 mm in height, included in the fuel rod structure at the top and bottom. The lateral reflector is configured as a block of beryllium or beryllium oxide, its thickness being 150 mm including steel coating. Nuclear safety is provided by 22 control rods, 12 of which are located in the reflector and used during normal operation. The remaining 10 rods are located in the core to compensate excess reactivity in case of hypothetical water flooding of the reactor plant.

Structurally, the reactor system designed as a monoblock is shown schematically in Figure 1. It has a double body. The internal hot body (1) of the reactor is a cylindrical vessel which is 3800 mm in height and 960 mm in diameter. During normal operation, the temperature of the hot body is not more than 720^{o} C. The external durable body (2) 20 mm thick is separated from the hot body by thermal insulating annular gap (3) and its temperature is not more than 260 °C.

Heat removal from the core (4) is provided by evaporation of sodium from the capillary-porous structure (CPS) placed on fuel rods and on other elements of the core. Sodium vapor (6) exits the core through its end surfaces and radially through spaces between the fuel rods. Next, the vapor flows to the top of the monoblock through annular slits between the reflector block (7), radiation sheet (8) and internal body to the interloop heat exchanger – condenser-evaporator (9). There sodium vapor condenses and flows under gravity into capillary plenums (10) located above and below the core. Liquid sodium is distributed by means of CPS for all fuel rods and other things, in particular the control rod claddings (14). The condenser-evaporator has capillary-porous structure, both on sides of the first and the second loops. The second loop CPS is filled with eutectic sodium-potassium alloy (11) which evaporates under condensation heat of primary loop sodium, and the vapor (12) transfers heat to gaseous coolant (13) of the third loop.

Parameters of the fuel rod: outer diameter is 14 mm, steel cladding thickness is 0.4mm, maximum heat flux from the surface is 0.4 MW/m^2, maximum temperature of the surface is 700 °C, temperature at the center of fuel region is 960^{o} C. The total number of fuel rods in the core is 360. The fuel rods are arranged in a triangular lattice with relative increments of 1.15.

Capillary-porous structure of the rods is made of two layers of wire grid whose overall thickness is 0.6 mm. The inner layer of the grid is corrugated, therefore, a longitudinal artery for sodium flow is formed. The sodium supply of fuel rod is provided by CPS through capillary inset into upper and lower ends of the fuel rods, immersed in upper and lower capillary plenums (10).

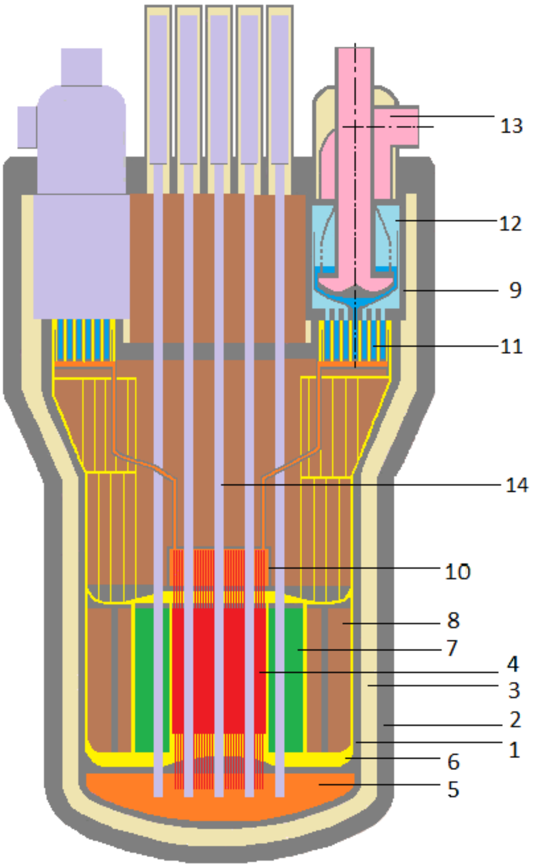

FIG. 1. General view of the reactor facility

Gaseous coolant of the third loop is a working fluid of Stirling or Brayton cycle.

3. Safety of the facility

The developed reactor facility safety is generally defined by a complex of physical and technical characteristics. The isothermal first loop has no thermal stresses in the core elements. The reactor plant contains a small amount of coolant both in the first and the second loops; their pressure is low in the whole operating temperature range. Therefore, accumulated chemical and potential energy is low, so hypothetical damage process will be relatively calm. The sufficiently large heat capacity of the monoblock contributes to safety as well. The reactor has a negative void reactivity effect in the whole temperature range so little overall reactivity is required for the above-mentioned campaign. The dual reactor vessel, three-loop system removing heat from the core to environment, low second coolant radioactivity and passive residual heat removal system are additional properties which improve safety of the reactor facility. There are six safety barriers for radioactive fission products: fuel matrix, fuel cladding, hot body, durable body, a concrete box and a building. The above-mentioned physical properties and engineering characteristics provide a high self-protection degree of the reactor during its startup, steady state and transient operating modes.

4. Experimental studies and tests

Theoretical and experimental researches and tests of mockups of all core components were carried out before and during the project development. Geometric dimensions of the core and the fuel rods were defined by neutron-physics calculations. Thermo-hydraulic calculations to determine thermal power, which is limited by sound speed in the vapor (sound limit), by hydraulic resistance of the wick (capillary limit) and others, were performed. It turned out that the area of the core upper end and its lateral surface is not sufficient for the heat removal by means of sodium vapor. Therefore, additional vapour output was organized through the core lower end. To overcome capillary limitation, composite wick was developed. It included an artery for liquid sodium flow and a finely porous mesh screen, to provide the needed capillary pressure. The total thickness of the wick was 0.6 mm. The effective pore radius of the screen grid was 17-20 micrometers.

Several variants of arteries and wick were considered and experimentally tested, such as an annular gap, longitudinal grooves on relatively thick cladding and a corrugated grid. The best results were obtained with grooves wick. The fuel rod imitator with this wick was consistently operated at 5 kW while the design power was 3.5 kW. The arterial structure with the corrugated grid ensures removal of 4 kW and this CPS was adopted for all the core elements. Supplying the wick of the fuel rod with liquid sodium was realized through both upper and bottom ends. The ends of the fuel rods 8 mm in diameter were supplied with wicks immersed partially into capillary plenums of liquid sodium arranged above the core and under it. All parts of the CPS and their variants were tested experimentally in multiple electrically heated mockups and models. Fuel rod imitators were tested at sodium supply through either upper or lower end or both and the maximum power was determined for every case.

A large number of tests using single rod imitators, three-rod and seven-rod assemblies were carried out. Temperatures of the cladding, liquid and vapor in the start-up and steady state conditions were measured. The measurements were carried out for different power values, up to the wick drying and failure of the electric heaters. The three-rod and seven-rod assemblies and single fuel rod imitators have three loops and interlope heat exchanger sodium – sodium-potassium, and a water cooler, discharging the heat from the second loop. The capillary structure chosen for the reactor core was used in these assemblies. Hydraulic parameters of the vapor flow were simulated as well. The temperature distribution in the first and the second loops was registered, the temperature difference between the loops was measured and transferred heat power was determined. In the three-rod assembly, when the thermal power was 3 kW per imitator, the temperature drop in the interlope heat exchanger, i.e. between the sodium temperature and sodium-potassium one, was only 7 degrees. In the seven-rod assembly, when the power was 3.5 kW per imitator, the temperature drop was 10-15 degrees.

To test the basic design solutions for the reactor facility, a thermo-hydraulic sector mock-up simulating the 1/6 part of the reactor was created. It was also used to study heat and mass transfer process in the first and the second loops and to check calculated thermo-hydraulic parameters as well. It was supposed to elaborate technique and technology of filling complicated heat pipes with liquid metal coolants, such as the sector mock-up loops. It was also necessary to elaborate the technique of a startup from cold state to steady state and shut down of future reactor facility. It was supposed as well to research heat transfer and temperature distribution in the first and the second loops in the operation temperature range of 550-700^{o} C. It was important to explore transient modes and to determine allowable rate of power change. Determining the quality of liquid metal coolants, the content of non-condensable gases and elaborating the technique for their removal are important tasks as well.

The sector mock-up consists of 72 fuel rod imitators, imitators of emergency protection rods, a neutron reflector, and a radiation shield and an interlope heat exchanger. This equipment is placed in the real dimension body of the reactor. The interlope heat exchanger is located outside the body to transfer heat to the third loop. The sector mock-up is equipped with a large number of thermocouples placed under wick of each fuel rod imitator, in capillary plenum of liquid sodium, in vapor space, in interlope heat exchangers. In general, the mock-up adequately represented all constructive peculiarities of the future reactor facility. Figures 2 and 3 show a photograph of the first loop of sector mock-up under assembling and its schematic view respectively.

Figure 2 presents a bundle of the fuel rod imitators (1), thermocouples (2), shot pipes (3), reflector imitator (4) and shield imitator (5). The thermocouples (2) are installed under wick, two units per every rod imitator (1). The pipes (3) are destined for the sodium vapor flow. Positions (4) and (5) indicate the stainless steel blocks. They have no CPS as they are not heated. The capillary plenums will be placed on both the upper and lower sector-shape flanges, so the ends of the fuel rod imitators will be immersed into the liquid sodium. Slots between the bundle of fuel rod imitators, the reflector, and the shield are used as an additional way for sodium vapor flow. The main way for the vapor is the space between the upper and lower ends of the fuel rod imitators.

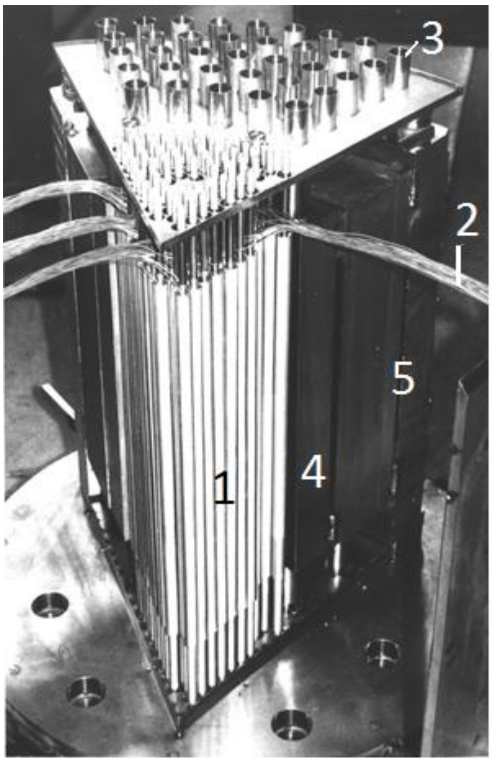

FIG. 2. Building of sector mock-up

Figure 3 presents schematically the entire sector mock-up. There are the above-mentioned fuel rod imitators (1), the emergency protection rod (2), the reflector (3), the radiation shield (4), the upper and lower capillary plenums of liquid sodium (5) and (6) the upper radiation shield (7), the interlope heat exchanger (8), the vapor flow pipe (9), the liquid sodium-potassium pipe (10), the heat exchanger of the second and the third loops (11). The (12) and (13) are sealing thermocouple outputs, (14) and (15) are liquid sodium-potassium plenums, (16) and (17), are sodium vapor and liquid sodium respectively. The (18) is vapor of sodium-potassium, (19) is liquid sodium-potassium alloy and (20) is gas coolant of the third loop. The unmarked pipes are designed for evacuation of the mock-up and for filling with coolants and drainage.

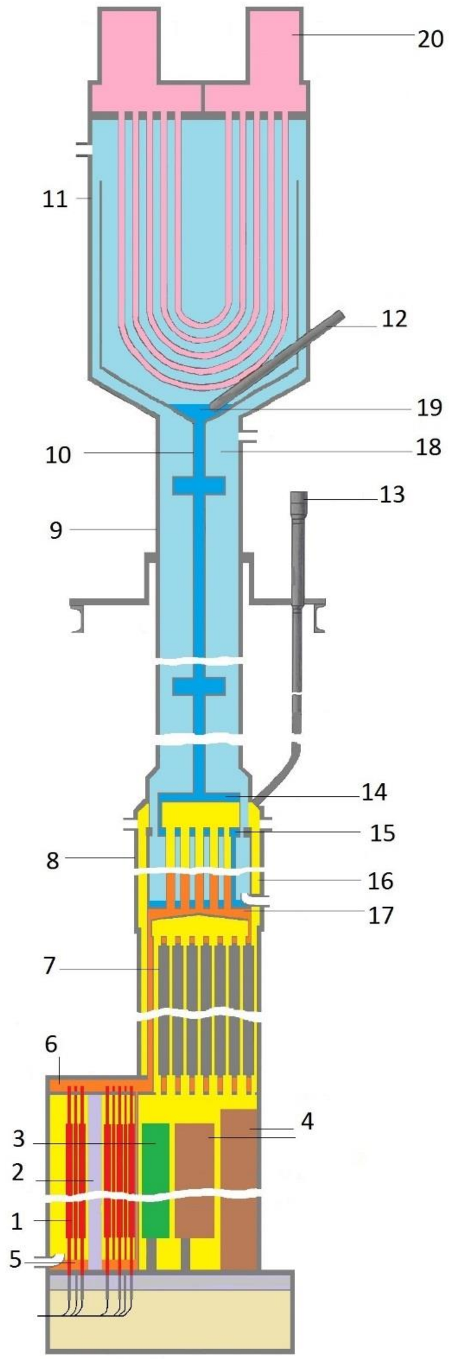

FIG 3. Thermo-hydraulic sector mock-up

The heat exchanger (8) of the first and the second loops consists of a tube bundle and a cylindrical body. Sodium vapor flows inside the tubes and condenses on the walls coated with wick. Liquid sodium flows down to the capillary plenum. The outer surface of the heat exchanger tubes is also coated with wick. The sodium-potassium alloy contained in the wick is vaporized by the condensation heat of the sodium and moves upward along the pipe (9) to the heat exchanger of the second - third loops. It condenses there on the U-shaped tubes and transfers its condensation heat to the gaseous coolant of the third loop. The reactor facility project assumed thermal energy conversion by means of Brayton or Stirling cycle. It was not supposed to simulate energy converter, therefore, compressed air is used in the third loop.

Technology of the sector mock-up filling with sodium and sodium-potassium alloy is based on the standard heat pipe technology but it is more complicated. The technology of filling heat pipes and other heat transfer equipment with liquid metal coolants is developed and patented [10].

One of the first points of this technology is thermo-vacuum degassing of the equipment when the temperature is slightly higher than the working one. For this purpose, the sector mock-up is supplied additionally with external heaters. Degassing of the second loop was performed relatively quickly, but degassing of the primary loop took two months because of massive blocks of stainless steel, simulating reflector and shield. Only after that, the mock-up was filled with distilled sodium and sodium-potassium.

Filling was performed in several steps including intermediate washing of the loops with sodium (ore sodium-potassium alloy) and re-distillation of the coolants. In the process of filling the content of oxygen in sodium and in sodium-potassium was determined repeatedly, by means of sampler-distiller. 14 analyses of sodium were performed. After the first washing, the oxygen content in sodium was 58 ppm. The next samples contained 5.6 ppm of oxygen on the average, whereas the final ones contained 1.6 - 1.0 ppm. After the first washing, the sodium-potassium alloy contained 6.8 ppm averaged over 11 samples, with 1.7 - 0.9 ppm contained after the final washing. At that time, a new method of titration of samples was tested, namely a dilution method. As a result, existence of complex chemical compounds such as $NaCrO_2$ was confirmed. These compounds exist as a dispersed phase with a particle size of about one nanometer. It was found that these compounds decrease the surface tension of sodium approximately by 20% [11].

Tests of the sector mock-up were performed at the power of fuel rod imitators less than the designed one, but the operating temperature was kept at 680-700^{o} C in the first loop according to the design. Temperature in the second loop was approximately 50^{o} C less than in the primary loop. Measuring vapor temperature at different points of the first loop showed its good isothermity, i.e. vapor temperature in the condenser-evaporator is only15 degrees less than the temperature at the outlet of fuel road imitators. It agrees with the results of thermal-hydraulic calculations of the mock-up, confirming the adequacy of the calculation method and a possibility to use it for the real reactor facility. The mock-up second loop was isothermal too, with approximately the same temperature difference as in the first loop.

In addition to the work mentioned above, two fragments of the fuel rod with the same wick as in the sector mock-up were tested in the BR-10 reactor. Each fragment of the fuel rod 150 mm long was placed in a hermetic capsule. The inner surface of the capsule had capillary structure the same as in the condenser-evaporator of the sector mock-up. The capsule with CPS was filled with sodium. The fragments of the fuel rod contained tablets of uranium nitride the same as those supposed to be used in the developed reactor facility. The ampoule was cooled partially, above the fuel rod segment by sodium of the reactor first loop. When operating, the reactor fuel rod fragment heated, vaporized sodium passed into the upper part of the capsule, condensed there and returned to the capillary structure of the fuel rod fragment. The ampoule was equipped with 12 thermocouples for measuring the temperature of the fuel element cladding at four positions. Thermocouples, which were 0.5 mm in diameter, were used. Two of them were used in the emergency protection at excess temperatures. Other thermocouples were used to measure the temperature in evaporation and condensation zones of the capsule and the temperature of sodium in the reactor first loop at the top and bottom ends of the capsule, to determine evacuated power.

The estimated power of the fuel rod fragment is 1.9 kW, which corresponds to 3 MW power of the BR-10. The reactor capacity at the start was 1.15 MW, which corresponds to 0.72 kW of fuel rod fragment power. At that time, there was a large difference in temperature (250°C) between the evaporation and condensation zones of the capsule. With power increasing up to 0.82 kW, the temperature difference began to decrease, but at a power of 1.32 kW the cladding temperature reached 740^{o}C and the emergency protection system shut down the reactor. When the reactor was restarted, the test continued for 4 hours, the power of the tested fuel rod fragment reaching 1.58 kW (83% of nominal). The temperature proved close to the calculated one: the cladding temperature was 680^{o}C, the temperature in the evaporation zone was 650°C, the temperature in the condensation zone was 630^{o}C. However, three thermocouples mounted on the fuel rod cladding, including the one used for emergency protection, got damaged and further tests had to be stopped according to safety requirements. As a result of the performed tests, a good correlation between calculated and observed results was found for nuclear heating, as well as for electric heating.

5. Conclusion

The results of the work performed are as follows:

1. Technological and thermo physical researches confirm feasibility and serviceability of the main elements of the reactor core – fuel rods, which are provided with capillary-porous structure at the following project parameters:
Sodium and sodium-potassium are working fluids;
Power of a fuel rod is 3.5-4.0 kW;
Surface specific heat flux is 25-30 W/cm^2;
Working temperature is 650-750^{o}C.

2. The reactor test of 1/2 nuclear fuel rod fragment having capillary-porous structure confirms its serviceability at the predictable parameters.

3. The technology of filling the complicated heat pipe system allows getting high purity of liquid metal coolants (1-2 ppm of oxygen) needed for successful operation.

4. Everything said above allows developing the low power experimental nuclear reactor cooled with evaporating liquid metals.

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