Atomic Energy, Vol. 116, No. 4, August, 2014 (Russian Original Vol. 116, No. 4, April, 2014)

COMPUTATIONAL AND EXPERIMENTAL VALIDATION OF THE PLANNED EMERGENCY HEAT-REMOVAL SYSTEM FOR BN-1200

D. G. Zaryugin,[1] V. M. Poplavskii,[1]
V. I. Rachkov,[1] A. P. Sorokin,[1]
Yu. E. Shvetsov,[1] S. A. Rogozhkin,[2]
and S. F. Shepelev[2]

UDC 621.039.516.25:621.039.526

The results of computational and experimental validation of the design of the emergency heat-removal system for BN-1200 are presented. The results of experimental studies performed on a water model of the V-200 integrated stand are presented, and the planning of experiments on the TISEI stand for validation of the efficiency and operating regimes using the BURNA, GRIF, and Flow Vision computational design codes is discussed.

The removal of the residual heat released in the core remains a pressing problem, increasing as reactor power increases. In accordance with current trends, the problem here is to meet during emergency cool-down safety requirements that are more stringent than those determined in OPB 88/97, viz., for advanced designs the probability of serious damage to the reactor core must not exceed 10^{-6} per reactor per year.

At the same time, the current trends in nuclear power are toward validated reduction of safety costs with a positive economic outcome. For the sodium-cooled fast reactor BN-1200, the technical task is to lower the cost of a power-generating unit to the cost of VVER at the same power. The cost reduction of the emergency heat-removal system can make an appreciable contribution to the reduction of the cost of a power-generating unit.

The heat-removal system based on heat-exchangers immersed in the coolant in the first loop and final heat removal accomplished through an intermediate loop into the environment was chosen at the design variant for BN-1200.

Accurate modeling of heat and mass transfer on small-scale models with a natural coolant is impossible because the similarity criteria are not satisfied: Peclet number ($\mathrm{Pe} = wl/a$), Reynolds number ($\mathrm{Re} = w/\nu$), and Froude number ($\mathrm{Fr} = w^2/g\beta\Delta Tl$) [1]. The experimental facilities and research are expensive because large-scale models with natural coolant are used. The main objective of the computational and experimental validation is to confirm the serviceability of the system passively removing the residual heat release. For routine functioning, it must keep core operation within safe operating limits according to the maximum admissible temperature of the fuel-element cladding and the reactor vessel, which are set during the validation of the corresponding materials in the design [2].

Two stands were developed to study the thermohydraulic processes in the new-generation emergency heat-removal system: V-200 and TISEI. The integrated V-200 stand takes account of the characteristics of the in-take arrangement of BN-1200 as a whole on a 1:10 scale [3]. The TISEI stand with a 1:5 scale ensures more accurate geometric similarity of the

---

[1] State Science Center of the Russian Federation – Leipunskii Institute for Physics and Power Engineering (GNTs RF – FEI), Obninsk, Russia.
[2] Afrikantov Experimental Design Bureau of Mechanical Engineering (OKBM Afrikantov), Nizhnii Novgorod, Russia.

Translated from Atomnaya Énergiya, Vol. 116, No. 4, pp. 222–228, April, 2014.

Fig. 1. Overall view of the V-200 stand.

processes being studied within one sector of BN-1200. In addition, experiments to validate the sector model are conducted on a coarser integrated model of the V-200 stand and the initial data for planning experiments on a more accurate model of the TISEI stand are determined. The final conclusion as to the serviceability of the emergency heat removal system will be obtained by performing experiments on the TISEI stand.

The experimental data make it possible to verify the computational codes for conditions that are as close as possible to BN-1200 and, in combination with previous verification performed on reactors and stands with sodium, to validate decisions adopted during the development of the emergency heat-removal system [4–6].

Regular Design of the Emergency Heat-Removal System. The passive emergency heat-removal system in BN-1200 is intended to remove the residual heat release from the reactor to the final absorber – atmospheric air. It consists of four independent circuits, each of which includes three heat-transmitting loops: a loop in the reactor tank and intermediate and air loops. The total capacity of the system in the cool-down regime is 80 MW, which is approximately 2.9% of the nominal thermal power of the reactor. The first-loop sodium, circulating through the fuel assemblies and autonomous sodium–sodium heat exchangers located in the reactor tank, removes heat from the core. The sodium in the intermediate loop circulates through the heat-exchangers, expansion tank and two sodium–air heat-exchangers and it transfers the heat from the first-loop sodium to the atmospheric air. In the air loop, the air passes through air ducts, sodium–air heat-exchangers (with gates) and an exhaust pipe and is discharged into the atmosphere. In all loops of the emergency heat-removal system, natural circulation of the coolant is realized in all operating regimes of the system.

The concept of direct heat removal due to sodium being fed into the fuel assemblies is implemented in the emergency heat-removal system in BN-1200. Structurally, this is secured by introducing a pipe connecting an autonomous heat exchanger and a pressure chamber of the reactor with a check valve installed on it.

Experimental Validation of the Design of the Emergency Heat-Removal System. Analysis of emergency cool-down with the assistance of autonomous heat-exchangers shows that the approximate modeling on water-cooled models makes it possible to reveal the particulars of thermohydraulic processes in nonisothermal flows [7].

The modeling of natural circulation regimes on the TISEI and V-200 stands is made possible by the following:

1) geometric similarity of the model and the BN-1200 reactor (TISEI 1:5, V-200 1:10);

2) equality of the determining similarity criteria: Richardson (Froude) and Euler numbers, heat balance, the determining ratio of the energy release to heat removal, homochronicity;

3) identity of the coolant circulation channel in the first loop in the nominal operating regime and during emergency cool-down;

4) simulation in the emergency cool-down regime of the change in the power of the simulators of the assemblies, temperature, water flow rate in the second loop, run-out of the main circulation pumps of the first and second loops of an actual facility;

5) simulation of the transverse profile of the energy release;

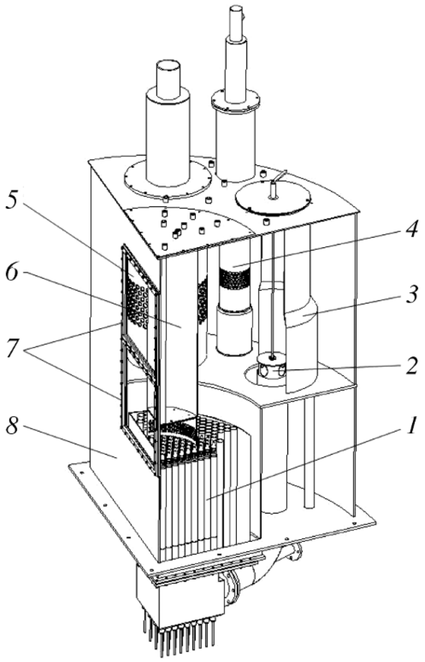

Fig. 2. TISEI stand (model of a sector of BN-1200): *1*) core; *2*) manual valve; *3*) GTSN-1 displacer (part of the displacer is shown); *4*, *5*) autonomous and intermediate heat-exchangers, respectively; *6*) displacer of the central rotary column; *7*) transparent windows; *8*) body.

6) similarity of the hydraulic characteristics in the simulators of the fuel assemblies in the core and lateral protection;

7) requisite throttling of the flow in the assembly simulators in accordance with the change in the radial heat release in the core; and

8) conditions of hydraulics and temperature conditions in the intermediate and autonomous heat-exchangers on the first-loop side close to the natural conditions.

The V-200 integrated stand comprises a complete integrated model of BN-1200 in a 1:10 scale (Fig. 1). The first loop of the reactor model consists of two parallel circuits, each of which contains two model intermediate heat-exchangers and one model of GTsN-1 [Main Circulation Pump]. The integrated model contains all the main elements of the first loop: the reactor vessel, core, intermediate and autonomous heat-exchangers, central rotary columns, supporting hoop, thermal screens, reflector, pressure chamber with simulators of the core assemblies, simulators of GTsN-1. In addition, the following are installed in the top vessel of the model: simulators of filter-traps, ionization chambers for monitoring the energy level and subcritical state, setup for covering (opening, closing) the openings in the reflector above the top plate of the pressure chamber.

The intermediate and autonomous heat-exchangers have similar designs. Emergency cool-down of BN-1200 can be simulated on the stand by means of four intermediate heat-exchangers with coolant fed into the pressure chamber. The results of the measurements will be conservative compared with the actual setup. In BN-1200, four autonomous heat exchangers are provided for emergency cool-down.

The second loop also comprises a closed circulation system with a pump, filled with a distillate and intended for removing heat from model intermediate and autonomous heat exchangers.

The TISEI stand developed at OKBM Afrikantov is intended for investigating thermohydraulic processes in the reactor tank and the circuit of the emergency heat-removal system. There are plans to use the emergency heat-removal system to simulate on this stand the normal operating regime of the reactor and stationary and nonstationary cool-down regimes. The external loops and the height markers of the equipment in the stand and the reactor are geometrically similar, the modeling scale being 1:5. The capacity of the model of the reactor core is no more than 350 kW in the nominal regime and no more than 70 kW in the cool-down regime. The total height of the stand is 21 m.

Similarly to the regular design, the stand includes a loop in the sector model of the reactor tank with aperture angle 80°, an intermediate loop and a loop for cooling the models of the intermediate and air heat-exchangers (Fig. 2). Distilled water is used in these loops as the coolant. The air heat exchanger is cooled by pumping distilled water instead of air, which is used in the regular heat-removal system. The final heat absorber on the stand is the air circulating through the cold setup.

Sixty-three electrically heated (separated into three groups of electric heating) and sixty-seven unheated channels, simulating hydraulic resistance and heating in the regular fuel assemblies, are used in the model of the core. The channel contains seven cartridge-type tubular electric heaters with a 400 mm long active part. The maximum channel power is 8.5 kW.

Similarly to the regular design, in the TISEI stand a check valve is installed at the exit from the autonomous heat-exchanger. After the shell is dismantled at the exit from the model of the autonomous heat-exchanger and forced closure of the check valve there is a possibility of studying cool-down when coolant is fed into the space between the fuel assemblies. These additional studies will make it possible to compare two concepts for removing heat in one stand under identical conditions.

The TISEI stand is equipped with a large number of means for performing measurements and checking the thermohydraulic and electrophysical parameters.

The velocity in the top part of the mixing chamber of the reactor model is to be monitored with the aid of a system based on digital tracer visualization.

To validate the serviceability and functioning of the emergency heat-removal system of BN-1200 and to obtain data for verifying the computational codes on the V-200 stand, experimental studies were performed of the stratification processes in the coolant in the top vessel of BN-1200 in the forced circulation regime of the coolant and emergency cool-down in the regime of steady natural circulation during regular functioning of the emergency heat-removal system. The steady forced circulation regime models on the V-200 stand the natural distribution of the temperature in the tank of the setup prior to the transition into the emergency cool-down regime. The non-isothermal regime 6.6PTs100 of forced circulation was established in the following sequence. First, the total water flow rate 6.6 m^3/h was created in the first loop, which by means of throttling the tracks was distributed as follows (in m^3/h): 5.8 on two simulators of GTsN-1; 0.5 in the simulator of the vessel cooling track; 0.2 in the cooling track of the GTsN-1 supports; 0.1 in the simulators of the cool-down of the ionization chambers. Next, water flow rate 4.7 m^3/h was organized in the second loop of the intermediate heat-exchanger with temperature 10–15°C at the entrance or the minimum possible value, the electric heating system was switched on (kW): ~70 on the central heaters of the core, ~30 on the exterior heaters, 0.87 on the fuel-assembly simulators of the internal storage area for spent assemblies.

Analysis of the experiments showed that a stable zone of cold coolant formed on the periphery of the bottom region of the top vessel. Significant temperature gradients and pulsations were recorded at the interfaces of the cold and hot regions. The temperature distribution indicates stratification of the coolant. Along the height of the elevator between the cold vortex at the bottom and the hot vortex at the top the temperature differential in a narrow high-gradient separation layer equals the heating of the coolant in the core simulator.

The temperature with regular functioning of the emergency heat-removal system in the natural circulation regime in the experimental model stabilized in approximately 24 h after emergency cool-down started at power 8.7 kW (4 kW on the interior and exterior heaters). The temperature and motion of the coolant with natural circulation stopped in the V-200 model were studied for different variants of emergency cool-down:

4ETs8VN regime – four intermediate heat-exchangers with open GTsN-1 valves instead of four autonomous BN-1200 with recalculation of the flow rate of the intermediate loop, which can be regarded as a conservative variant;

2ETs8VN regime – partial shutdown of the equipment in the emergency heat-removal system – use of two of four intermediate heat-exchangers;

4ETs8VN regime (valves do not open) – cool-down with closed check valves of the emergency heat-removal system (cool-down by natural circulation through the entry windows of the intermediate heat-exchanger, its outer surface, surface of the vessel with closed valves of the simulators of GTsN-1).

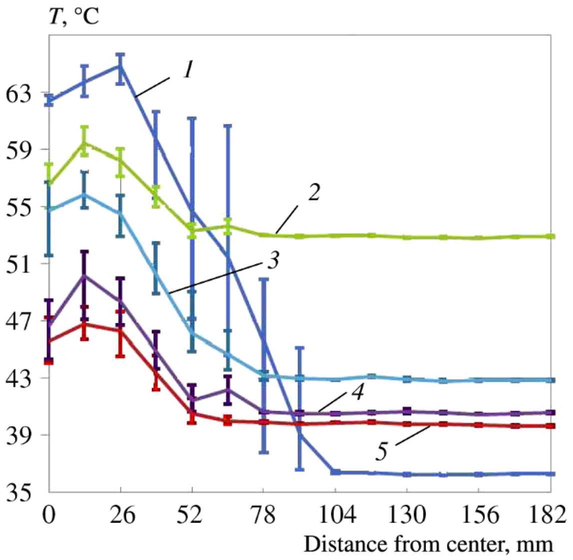

Fig. 3. Distribution of the average temperature and pulsations along the radius of the core at height 20 mm from the fuel assembly heads for the regimed 6.6PTs100 (*1*), 2ETs8VN – two intermediate (*2*), two autonomous heat exchangers (*3*), and 4ETs8VN – valves do not open (*4*) and are open (*5*).

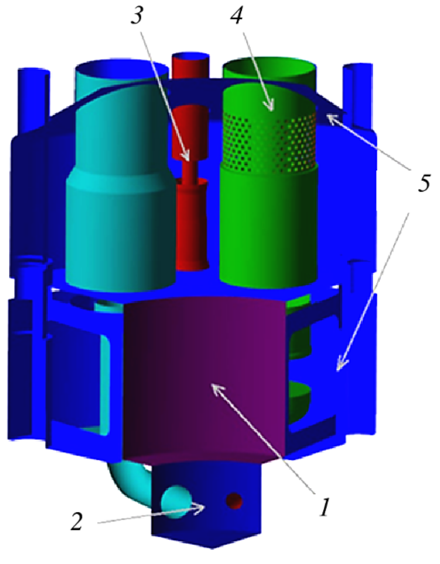

Fig. 5. Computational model of the BN-1200 reactor setup in the design code FlowVision: *1*) core; *2*) pressure chamber; *3*, *4*) autonomous and intermediate heat-exchanger, respectively; *5*) reactor vessel.

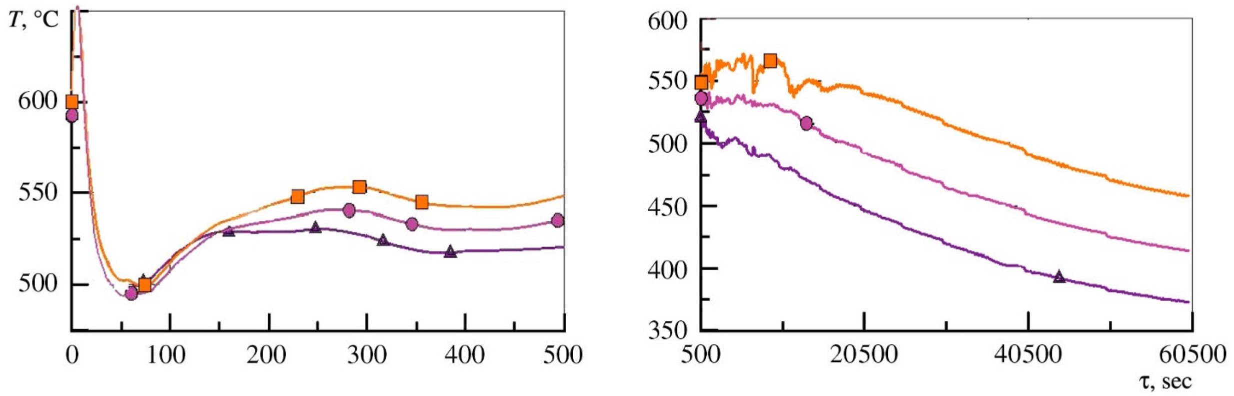

Fig. 4. Temperature of the fuel-element cladding at the exit from the core for different variants of cool-down: ▲, ●, ■) number of autonomous fuel assemblies equal to four, two and one, respectively.

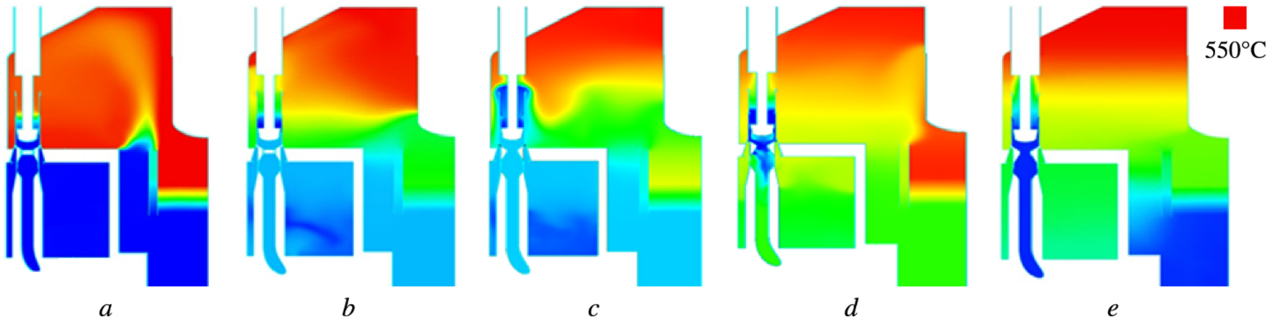

Fig. 6. Numerical modeling for the cool-down regime using the emergency heat-removal system in a plane intersecting an autonomous heat-exchanger (temperature field): *a*) initial state – nominal regime; *b*, *c*, *d*) the times 47, 68, and 148 sec, respectively; *e*) 2980 sec – steady flow regime.

The distribution of the average temperature and pulsation characteristics over the radius of the core at height 20 mm from the fuel-assembly heads for different variants of the forced circulation regime is shown in Fig. 3. In all cool-down variants studied, the coolant temperature at the exit from the fuel-assembly heads of the core decreases while in the peripheral zone of the top vessel it increases compared with the forced circulation regime.

The temperature distribution at the exit from the simulators of the core assemblies, along the radius and the height of the mobile thermal probes 1-PZ and 2-PZ, in the thermoprobe unit shows that in the regime of natural circulation of the coolant the hot coolant rises along the central rotary column to the separation surface of the coolant in the placement tank. A wide hot zone from which the coolant flows into the entry to the intermediate (autonomous) heat-exchanger forms in the top region of the mixing chamber.

Computational Validation of the Design of the Emergency Heat-Removal System. A computational analysis was performed for the regular construction with cool-down through the submersion-type emergency heat-exchangers in the first loop of the reactor and intermediate loop of the emergency heat-removal system, the exit of the emergency heat-exchangers is directed by means of a special pipeline onto the pressure chamber of the reactor. A computational analysis of the validation of the effectiveness of the emergency heat-removal system at a transition from the nominal into the cool-down regime was performed with the aid of three codes: the certified code BURAN and the verified codes GRIF and FlowVision. A characteristic of the GRIF code is the possibility of modeling the thermohydraulic processes not only in the main duct of the reactor but also in the interpacket space of the core, which is important for analyzing the emergency cool-down regimes. The GRIF code was verified on a large amount of experimental data, including reactor experiments on the transition into the cool-down regime in the Japanese NPP Monju and the French reactor Phenix.

The BURAN and GRIF codes were used to analyze the effectiveness of the system with loss of part of the circuits. The dynamics of the maximum temperature of the fuel-element cladding with a different number circuits connected is shown in Fig. 4. The maximum temperature of the fuel-element cladding in the core 650°C is reached briefly several seconds after the initial failure, which is lower than the limit for safe operation for fuel-element cladding and is essentially independent of the number circuits connected. The maximum temperature at the next, longer stage of cool-dawn increases with decreasing number of connected circuits, but in all cases it does not exceed the limit of safe operation of the reactor vessel.

In addition, calculations were performed with the CFD-code FlowVision to determine the temperature in the reactor tank. The use of this code is justified by the LMS model implemented in it to take account of the specifics of turbulent heat transfer of the sodium coolant. The LMS model in FlowVision was verified by modeling the mixing of sodium coolant flows with different temperatures, studied experimentally on the TEFLU stand and in the top vessel of BN-600 [8]. The modeling was done for one sector of the reactor (Fig. 5).

The reactor equipment (intermediate heat-exchanger, MCP, pressure chamber, core) was modeled using methods that make it possible to avoid direct modeling of the equipment. In this connection, the heat-exchangers and pumps were modeled by replacing them with a continuous porous medium with an equivalent hydraulic resistance. A negative source of power was used to model heat removal (Fig. 6).

The first-loop sodium temperature at the entry into the intermediate and autonomous heat-exchangers starts to decrease 20–30 sec after cool-down starts owing to heat-removal into the second loop with the pumps running out. By the time the valve opens (49th sec), the temperature at the entry into the autonomous heat-exchanger reaches 490°C. The temperature in the delivery pipeline from the autonomous heat-exchanger to the pressure chamber with the check valve closed is constant and equals 410°C. By the 47th sec of the cool-down regime, the character of the coolant flow in the top chamber of the reactor changes. The upward motion of the sodium after leaving the core is observed only near the bottom of the central rotary column. Next, the direction of the flow changes to horizontal and a vortex is formed. Coolant motion in the delivery pipeline from the pressure chamber upward to the autonomous heat-exchanger starts to form 68 sec after the start of the cool-down regime under the excess pressure after the check valve is opened. Some cooled sodium flows from the autonomous heat-exchanger into the top mixing chamber of the reactor. By the 148th sec after GTsN-1 stops, the coolant moves from the autonomous heat-exchanger downward to the pressure chamber, and the cooled sodium starts to flow into the delivery pipeline and by the 200th sec it reaches the core. The steady state of the cooldown in the reactor is observed after 1000th sec.

Conclusion. Preliminary computational and experimental studies attest that the emergency heat-removal system of BN-1200 has a high efficiency. Thus, in the standard regime heat due to the residual energy release from the reactor is removed within safe operating limits, and there are significant reserves of self-protection with respect to additional failures. Even if the three autonomous heat exchangers fail, the temperature of the equipment inside the reactor remains within admissible limits.

Subsequent experimental studies of the processes in BN-1200 in the emergency cool-down regime performed in the V-200 stand will make it possible to identify the key factors that must be taken into account when performing experiments on the TISEI stand. The final conclusion about the effectiveness of the emergency heat-removal system in BN-1200 can be drawn after a series of validating experiments is conducted on the TISEI stand.

REFERENCES

1. *Specialists Meeting of IAEA of Evaluation of Decay Heat Removal by Natural Convection*, Japan, Feb. 22–23, 1993.
2. I. A. Kuznetsov and V. M. Poplavskii, *Safety of NPP with Fast Reactors*, V. I. Rachkov (ed.), IzdatAt, Moscow (2012).
3. D. G. Zaryugin, S. G. Kalyakin, A. N. Opanasenko, et al., “Investigation of the stratification of the coolant and pulsations in nuclear power reactors,” *Teploenergetika*, No. 3, 12–21 (2013).
4. S. A. Rogozhkin, S. L. Osipov, V. A. Sobolev, et al., “Computational and experimental investigations for validating setups for localizing melted fuel of a fast reactor,” *At. Énerg.*, **115**, No. 6, 341–344 (2013).
5. Yu. E. Shvetsov, “Verification of single-phase thermohydraulic codes GRIF and HYDRON,” in: *Computational Codes for Fast Reactors: Tasks and Problems of Verification*, Obninsk (2013).
6. S. A. Rogozhkin, S. L. Osipov, I. D. Fadeev, et al., “Numerical modeling of thermohydraulic processes in the top vessel of a fast reactor,” *At. Énerg.*, **15**, No. 5, 295–298 (2013).
7. D. G. Zaryugin, S. G. Kalyakin, S. T. Leskin, et al., “Computational and experimental investigations of the thermohydraulic characteristics in the fast-reactor tank in the SARKH integrated model in different operating regimes of the setup,” *Izv. Vyssh. Uchebn. Zaved. Yad. Energet.*, No. 2, 96–104 (2013).
8. Yu. Shvetsov and A. Volkov, “GRIF and HYDRON – 3D codes for analysis of thermal and hydraulics parameters of reactors with 1-phase coolant,” in: *Proc. 10th Int. Meeting of IAHR Group on Advanced Nuclear Reactors Thermal Hydraulics on Thermal Hydraulics for Fast Reactors with Different Coolants*, Obninsk (2001), pp. 119–137.