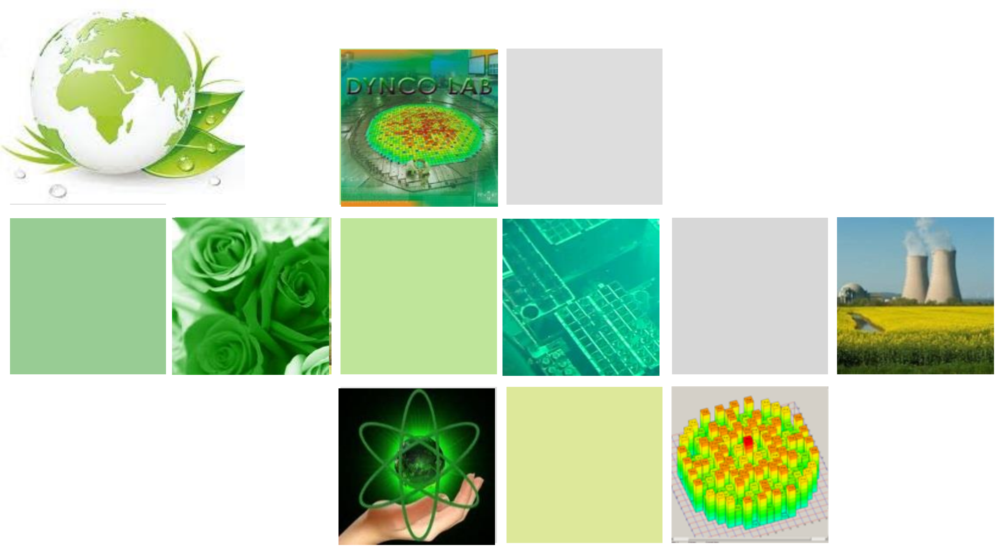
Experimental Scientific-Research and Methodology Center

“Simulation Systems”

Small-sized Nuclear Power Plant of Ultra-small Power for the Far North Conditions



N.V. Ivanov, A.V. Levtchenko, G.I.Toshinsky

Basic requirements for the ultra-small NPP concept in the Far North conditions

Basic requirements:

- low ambient temperature (~60 °C);
- lack of water for equipment cooling;
- simplicity of the layout and equipment design;
- long-term fuel campaign (20 years);
- possibility of transportation of equipment by railway and road transport;
- providing fast installation of the plant.

Possible Solutions

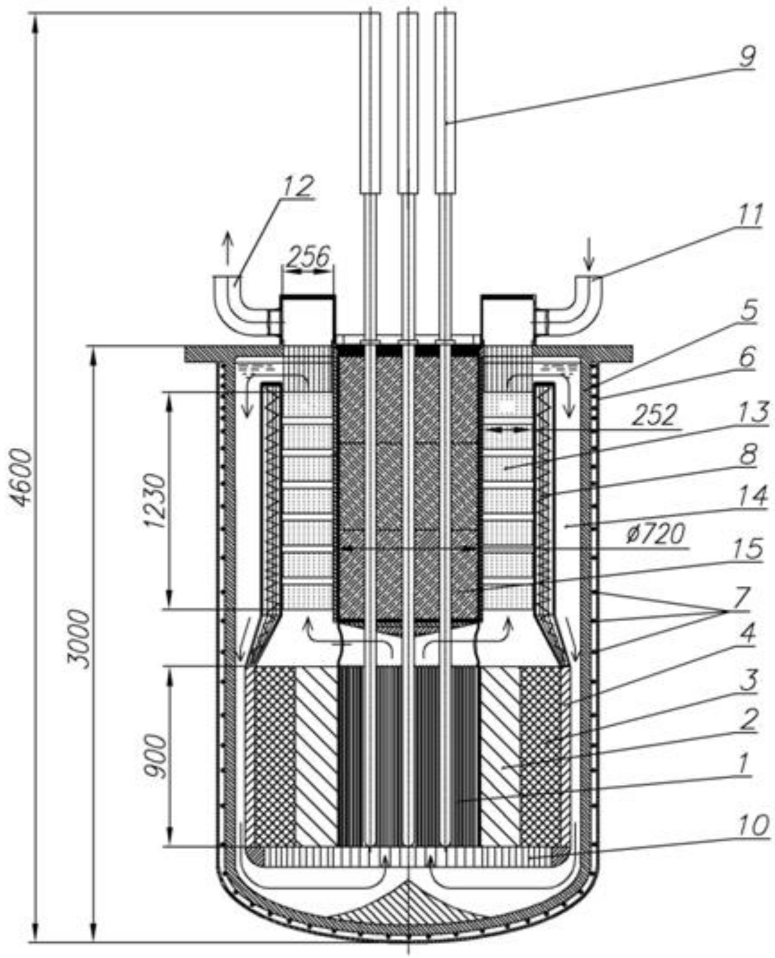
To the full extent these requirements can be satisfy by a technology based on the use of lead-bismuth coolant reactors.

Advantages of coolant:

- High boiling temperature (~1670 ^{o}C);
- The possibility of obtaining superheated steam of higher parameters;
- Chemical inertness of coolant;
- low coefficient of volume expansion;
- low melting point (~123,5 ^{o}C);
- zero variation in the volume of lead-bismuth coolant during melting/solidification;
- transportation of the core at the "frozen" in the primary circuit of the lead-bismuth coolant.

Termolan coolant was considered as the working fluid of the second circuit. Termolan – eutectic composition of two organic compounds: biphenyl and diphenyl oxide (boiling temperature – 181°C, freezing temperature – (-80)°C).

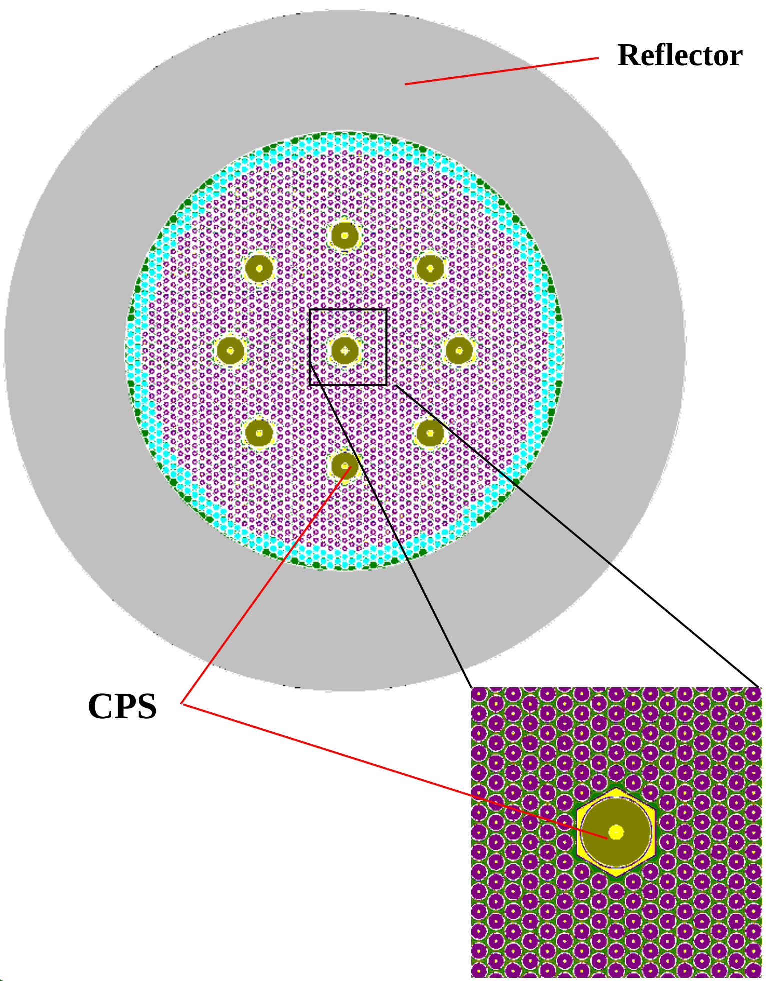
Reactor monoblock



1 – Reactor core
2 – Reflector core (steel)
3 – Boron carbide
4 – Shield (steel)
5 – Main vessel
6 – Protection shroud
7 – Heater
8 – Dividing wall
9 – CPS drives
10 – Input grid
11 – Feeder II c – 2 units
12 – Coolant outlet II c – 2 units
13 – Steam generator
14 – Primary circuit
15 – Shielding plug

Basic parameters of the core

Radial section



Parameter	Value
Reactor core	
Thermal power, MW	8
Electric power, MW	1,5
Power plant efficiency, %	18,75
Core height, mm	500
Diameter (unreflected), mm	725
Number of fuel rods, units	1966
Number of channel CPS, units	9
Fuel material/enrichment, %	UO_2 /35
Channel CPS	
Flat-to-flat dimension, mm	55
Outer diameter of rod, mm	50
Temperature of operation	
Core outlet temperature, ° C	450
Core inlet temperature, ° C	250
Average fuel temperature, ° C	588

Reactor neutronics

Reactivity margin in various reactor states

Reactor state	Reactivity margin, %Δk/k
Cold zero power. Fresh fuel	**10,49**
Hot zero power. Fresh fuel (250°C)	**10,14**
Hot full power . Fresh fuel	**10,03**
Hot full power (20 years).	**0,99**

Reactor neutronics
(cont.)

Efficiency CPS

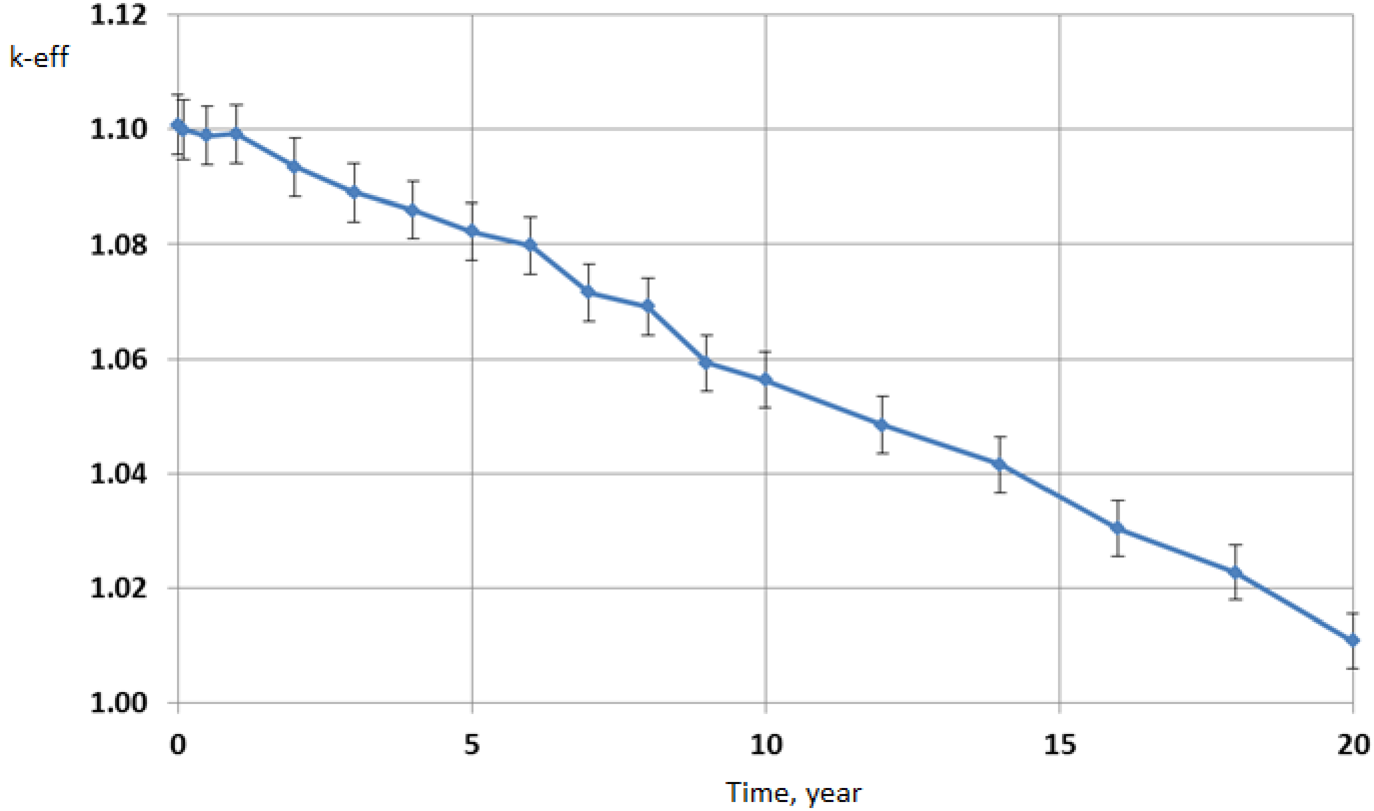
Control rods	Reactor state		
	CZP	HZP	HFP
Emergency protection rods	3,48	3,36	3,31
Regulating Rod	0,99	0,93	0,87
Compensating rods	9,71	9,44	9,41

Reactor neutronics
(cont.)

Reactivity coefficient

Reactivity coefficient	Value, 10^{-6}
Fuel temperature, Δk/k/C	**-1,59**
Coolant temperature, Δk/k/C	**-4,83**
Power, Δk/k/MW	**-6,39**

Reactor neutronics
(cont.)



The dependence of the values of k-eff on the operating time of the reactor at full power

Conclusion

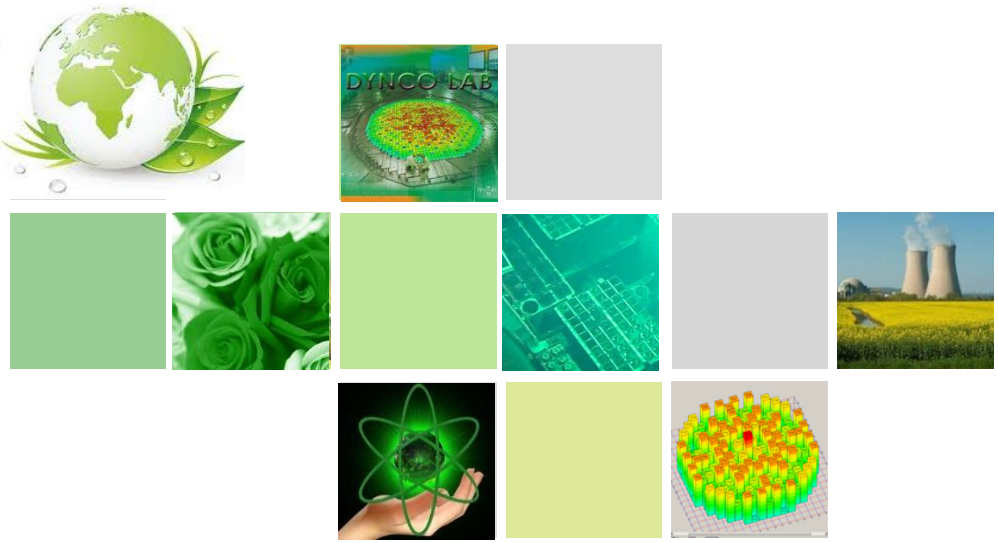
• In the primary circuit a lead-bismuth coolant is used. It use has been worked out over many years of operation of the above-ground prototype of transport facility and the nuclear submarine reactors;

• A feature of the proposed facility compared with earlier developed is the use as a working fluid of the second circuit of an organic liquid with a low freezing point;

•The resulting reactivity coefficients are negative, which is important for reactor safety;

• The initial reactivity margin of the reactor is sufficient for the required fuel campaign.

Thank you



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ROSATOM

ГОСУДАРСТВЕННАЯ КОРПОРАЦИЯ ПО АТОМНОЙ ЭНЕРГИИ «РОСАТОМ»

The Fifth International Conference «Heavy Liquid-Metal Coolants in Nuclear Technology (HLMC-2018)» (Obninsk, SSC RF-IPPE, October 09-11, 2018)

Experimental modeling of hydrodynamics and heat exchanger in reactors with heavy liquid metal coolants

A.P. Sorokin, Ju.A. Kuzina, A.I. Orlov

The main directions of hydrodynamics and heat exchange studies in fast reactors with liquid metal coolants

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One of the most important problems of the creation and development of new types of reactors always has been the issues of thermophysics - the choice and mastery of coolants, the study of heat exchange and hydrodynamics

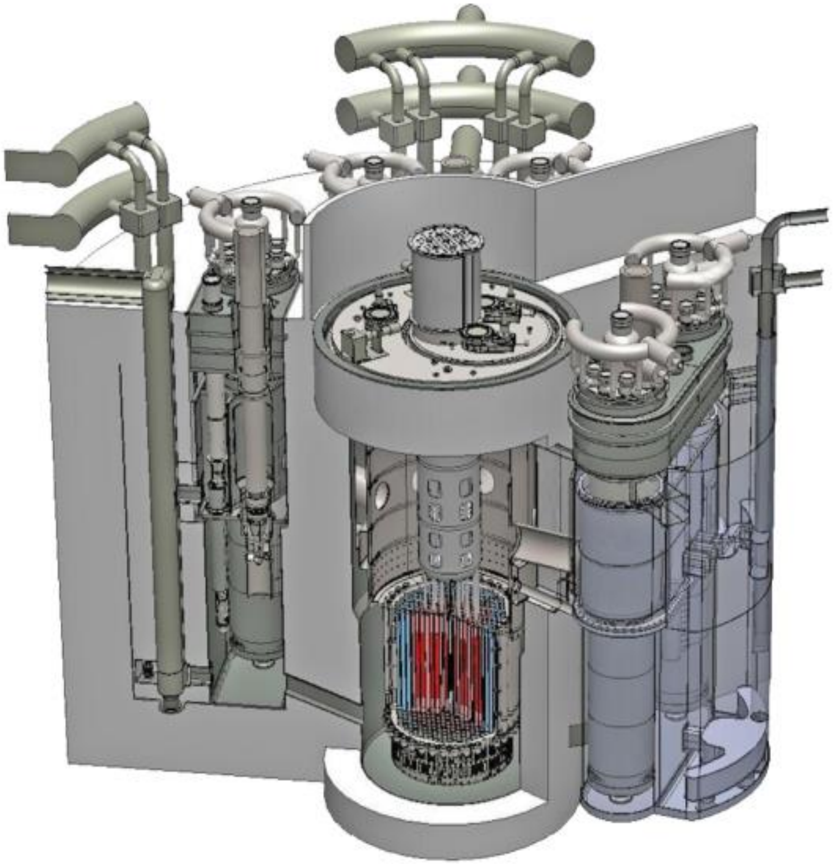
This is best understood by I.V. Kurchatov, D.I. Blokhintsev and A.I. Leipunsky, on which initiative to solve these problems in a month after the launch of the first nuclear power plant in July 1954 in Laboratory «B» (hereinafter - the State Scientific Center of the Russian Federation - Institute of Physics and Power Engineering named after A.I. Leipunsky (SSC RF - IPPE)), it was created by the Thermophysical Department under the leadership of V.I. Subbotin

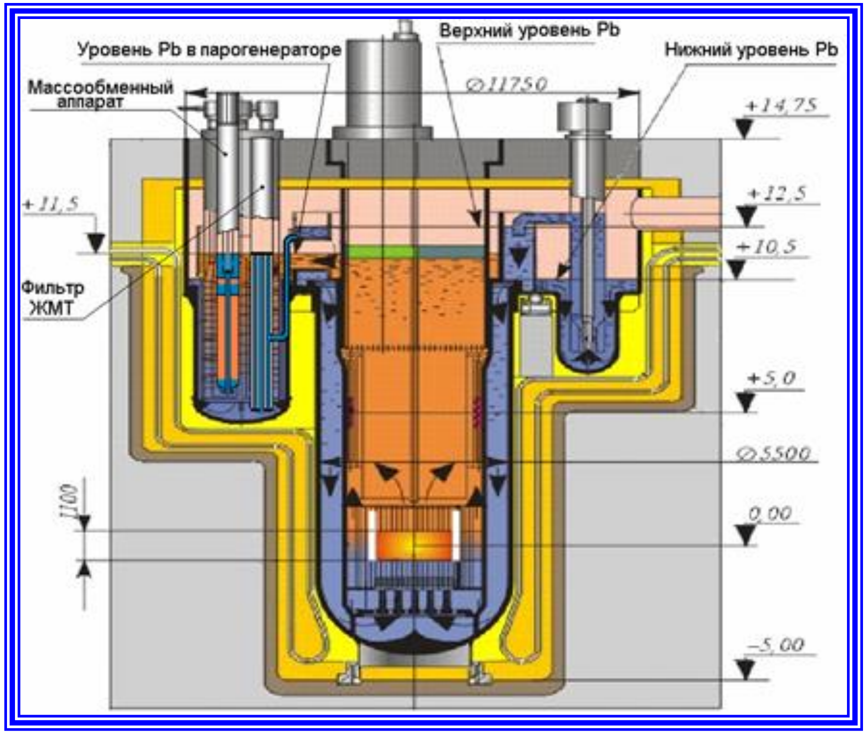
Its creation marked the beginning of the formation of the scientific school of the SSC RF - IPPE «Heat and mass transfer, physical chemistry and heat carrier technology in power systems», which has more than 60 years for development

The main directions of hydrodynamics and heat exchange studies

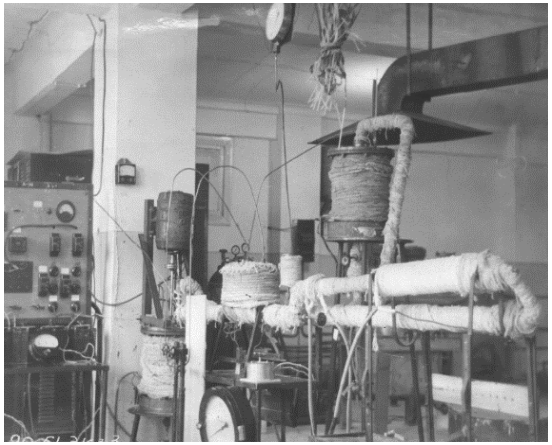
- ✓ substantiation of operating regimes of operating and projected reactor facilities
- ✓ substantiation of innovative technical solutions of the core and equipments for the reactors of new generation
- ✓ optimization of the design for reactor facilities
- ✓ increase of security, improvement of economic characteristics, achievement of resource ~ 50-60 years

Reactor facility BREST-OD-300



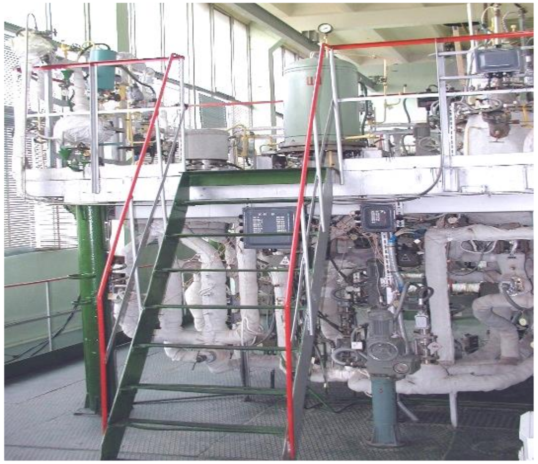


Experimental base of the SSC RF - IPPE for studies of thermophysical Problems of HLMC



The first Pb-Bi stand (1951)

Aerodynamic stand «SGDI»



Stand "TT-1M" with Pb and Pb-Bi for technological research

Stand "6B" for thermohydraulic research

Needs for the development of methods for numerical simulation of hydrodynamics and heat exchanger require experimental studies

- ✓to obtain data on physical laws and, characteristics of hydrodynamics and heat transfer in reactor facilities,
- ✓relations for closing the equations of numerical models.
- ✓verification of computer codes.

To solve these problems, a complex of experimental liquid metal stands has been created, equipment, modeling methods, experimental techniques and measurement techniques have been developed, sensors, automation tools for extracting and processing experimental information have been created.

The problems of the theory of modeling of thermophysical processes

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✓When preparing and conducting thermophysical experiments, one of the most important questions is the fulfillment of the conditions for mechanical, thermal and thermodynamic similarity that establishes the dependence of the physical properties of the moving heat-conducting medium on the state parameters and the most general dependencies for the description of heat exchanger in various liquids under the most diverse conditions of hydrodynamics and heat exchanger in the investigated objects.

✓The similarity analysis and the following criteria and asymptotic solutions should be applied in full. In the event that a sufficiently complete analytical solution or numerical study of a mathematical model is possible, the purpose of the experiments is to test its basic premises, and also to refine the calculated coefficients.

✓In recent decades, many monographs and textbooks on this subject have been written. But, as S.S. Kutateladze, «the external simplicity of the foundations of this analysis and the ever-increasing multiparametric nature of problems in physical and mathematical modeling lead to many misunderstandings and direct mistakes».

The purpose of this report is to analyze the application of the principles of modeling the processes of hydrodynamics and heat transfer in heavy liquid-metal coolants and the theory of the similarity of thermophysical processes in carrying out experimental studies on models using other media to substantiate hydrodynamics and heat exchanger in reactors with heavy liquid metal coolants and transfer data to reactor conditions.

Main characteristics and features of liquid metals (1)

Liquid (molten) metals from the point of view of heat excnge form a special class of coolants, characterized by considerable volumetric heat capacity and high thermal conductivity. The kinematic viscosity coefficient is much less than the thermal diffusivity, or, what is the same, the Prandtl number is much less than one (Pr << 1).

Thermophysical properties of liquid metals at a temperature of 500 ° C

Melt	T_{melt}, °C	T_{boil}, °C	R_{melt}, kJ/kg	R_{boil}, kJ/kg	ρ, kg/m^3	*Cp*, J/(kg K)	λ, W/(m K)	ν 10^{-8}, m^2/s	*a* 10^{-6}, m^2/s	Pr 10^{-3}
Lithium (Li)	180.5	1347	663	19400	486	4178	49.98	59.2	25.6	2.3
Sodium (Na)	97.8	883	113	3870	883	1262	66.34	25.9	62.86	4.624
Potassium (K)	63.6	774	61.4	1983	739	763	41.9	24	–	3.2
Na-K (22%Na +78%K)	-12.5	784	96	2540 ha	751.9	871.9	26.2	23.4	40.1	5.86
Na-KCs	-78	–	–	–	1235	384	13.7	15.4	–	5.3
Cesium (Cs)	28.5	678	15.73	495.9	1597	220	18.5	12.8	–	2.1
Lead (Pb)	327.4	1745	25	860	10470	147.3	15.45	17.62	9.82	17.8
Bismuth (Bi)	271.4	1533	50.15	857	9854	150	14.2	13	–	13.5
Pb-Bi (44,5% Pb+ +55,5% Bi)	125.0	1638	39	860	10050	145	14.2	13.6	9.7	14.7
Pb-Li (99,32% Pb+ +0,68% Li)	235.0	–	29.6	–	9326	175	51	13		27
Mercury (Hg)	-38.9	356.7	1.62	289	12370	139	13.36	6.48	7.78	8.3
Gallium (Ga)	29.8	2403	80.2	3673	5822	380	50.9	15.9	–	6.9
Indium (In)	156.2	2080	28.47	1972	7010	252	48	–	–	

Main characteristics and features of liquid metals(2)

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Thermal perturbations associated with molecular thermal conductivity propagate into the depth of the flow for much longer distances than the perturbations of the velocity field due to the action of molecular friction. In liquid metals the dynamic boundary layer "drowns" in the thermal boundary layer, and the notion of a thermal boundary layer that extends to the center of the channel loses its meaning.

Due to the good thermal conductivity because electronic conductivity, liquid metals are characterized by high heat transfer coefficients, which ensures acceptable temperature conditions of the heat exchange surfaces at sufficiently high heat flux densities. .

Liquid metals have high boiling points and do not require high pressures to prevent their boiling.

A disadvantage for most liquid metals is the large chemical activity when interacting with air oxygen, water and structural materials. Under certain conditions, this leads to a deterioration in heat exchager.

A feature that should be taken into account when studying heat transfer to liquid metals in the region of the heat-transfer surface is the behavior of the impurity composition of the liquid-metal coolant when the liquid metal circulates near the heat exchange surface under nominal conditions and deviations from the normal operation regimes, and the need to monitor their state.

Principles and conditions for physical simulation of the processes of hydrodynamics and heat exchanger (1)

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Direct physical modeling consists in reproducing a process of the same physical nature as in the actual sample, but the same characteristics of the process are changed (reduced or increased) by some constant factors. In other words, any two physically similar phenomena can form a pair: the actual sample is a model.

Hence follows the fundamental rule of modeling, formulated by M.V. Kirpichev and A.A. Guchman: similar to systems of one physical nature, the conditions of single-valuedness of which are similar, and the criteria of the same name, made up of single-valued conditions, are numerically identical.

To fully simulate the model of the full-scale sample, the following conditions must be fulfilled:

a) the process reproduced in the model refers to the same class of physical phenomena as the process in the actual sample, both processes obey the same equations and are characterized by the same physical quantities;

b) the model is geometrically similar to the actual sample;

c) dimensionless boundary conditions in the actual sample and the model are the same qualitatively and numerically;

d) dimensionless independent variables (defining criteria), the variables in the actual sample and the model have the same numerical value in pairs.

When these conditions are met, the simulation is straightforward and complete.

Principles and conditions for physical simulation of the processes of hydrodynamics and heat exchanger(2)

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Physical modeling with sufficiently clearly delineated boundaries of the reliability of the results obtained with its help is possible only on the basis of some pre-selected mathematical model.

Practically direct modeling can be applied indefinitely only for processes, the determined similarity numbers of which are functions of only geometric simplices of the system and one defining criterion. The presence of two defining criteria, such as, for example, the numbers *Re* and *Pr* during heat exchange, significantly complicates the simulation. With three defining criteria, direct modeling is usually not feasible. In such cases, it is necessary to establish systematic multivariate experiments.

The purpose of such modeling experiments is the real identification of effects that are solved by a very general mathematical model, but not reproducible at the modern level of mathematical technologies, either analytically or in numerical studies. For example, the elucidation of complex vortex structures in viscous fluid flows, the correlation functions of specific turbulent flows, etc.

In this paper, we present the results of an analysis of the features of the application of the similarity theory of thermophysical processes to modeling;:

– hydrodynamics and heat exchanger in liquid metals in channels of complex shape;

– thermal hydraulics in rod systems with liquid-metal coolants (core, heat exchangers);

– Fields of temperature and velocity in the hot chamber of the reactor in various operating regimes.

Basic definitions in the region of modeling of thermophysical processes

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The motion of a viscous and heat-conducting liquid is described by the Navier-Stokes equations, continuity, heat transfer, and thermodynamic equations (equations of state and expressions for the specific enthalpy *i* or entropy *s* through the thermodynamic parameters *p, T*). In most cases, the traffic parameters (velocity *w*, pressure *p*, density ρ, liquid temperature *T*) change continuously over time τ.

The equations of motion and heat transfer for a viscous and heat-conducting liquid are reduced to a dimensionless form with the introduction of dimensionless variables determined by the following conditions: $x^* = x/l,\ z^* = z/l,\ \tau^* = \tau w_0/l,\ w_x^* = w_x/w_0,$

where *l* is characteristic size, m; w_0 is characteristic velocity, m/s; $T_{ст} - T_0$ is characteristic temperature difference,°C; p_0 is characteristic pressure, Pa. For non-stationary processes, the number of dimensionless parameters is included $Fo = at_0/l^2$ – Fourier number.

The values *l*, w_0, $T_{ст} - T_0$, ν, *a* are called characteristic, since they determine the conditions under which the fluid moves, while *l*, w_0, $T_{ст} - T_0$ – are set arbitrarily, *ν*, *a* – are characterize the properties of the liquid.

The coefficient of thermal diffusivity characterizes the ability of the medium to react with a change in temperature to the passage of the heat flux. The kinematic viscosity coefficient characterizes the ability to react by changing the velocity to the flow of the flow of momentum.

The parameter complexes in the equations are dimensionless and are called similarity criteria:

$Re = w_0 l/\nu$ – Reynolds number, $Pe = w_0 l/a$ – Peclet number, $Ma = w_0/c$ – Mach number,

$\mathrm{Eu} = \frac{p_0}{\rho w_0^2}$ – Euler's number , $Pr = Pe/Re = \nu/a$ – Prandtl number, $Nu = \alpha l/\lambda$ – Nusselt number,

$Ar = \frac{gl^3}{\nu^2}\frac{\Delta\delta}{\rho}$ – Archimedes number, $Ga = \frac{gl^3}{\nu^2}$ – is Galileo number, $Fr = \frac{w_0^2}{gl}$ – is Froude number.

Similarity criteria establish a dynamic or kinematic similarity, the essence of which is that for the same value of the components of the criteria the ratio of two physical (for example, forces) with the same flow geometry have the same value. The similarity criteria determine the relative influence of both the forces acting in the flow and the transfer processes occurring in the flow (momentum transfer due to viscosity and heat transfer by means of thermal conductivity).

Modeling of hydrodynamics of liquid metals in channels (1)

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It should be noted that in the 1930s the first works were carried out showing the belonging of molten metals to Newtonian liquids. The defining criterion for modeling hydrodynamic processes in channels of complex shape is the Reynolds criterion. In the 1940s, the identity of the velocity profiles was shown for flow in mercury pipes and ordinary liquids. Later it was confirmed by studies V.M. Borishansky and CC. Kutateladze.

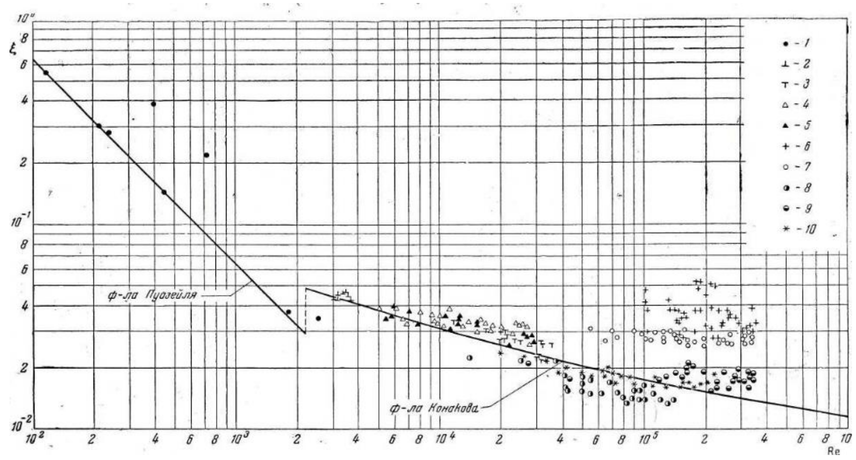
In the CKTI, data were obtained on the flow of mercury in glass pipes. Deviations from the Blasius formula were not noted.

In the 1950s, similar results were obtained for mercury and tin flowing in smooth steel pipes. Similar experiments were performed with molten iron and cast iron in ceramic pipes. Tolstoy D.M. theoretically and experimentally established that slipping during the movement of mercury takes place, but it affects only when moving in pipes of very small diameter. Thus, for a pipe with a diameter *d* = 7 microns, the volume slip effect is about 28% and for *d* = 26.6 microns about 6%.

The experiments showed that the order of the numerical values of the friction coefficients for mercury and mercury-magnesium amalgam in the pipes is the same as for the motion of ordinary liquids.

The high thermal conductivity and the weak dependence of the thermophysical characteristics of liquid metals on temperature lead to a weak dependence of the temperature profile in the liquid flow on the amount of the heat flux. As a result, the heat flux has little effect on the hydraulic resistance in the flow of liquid metals. Data for rough pipes M.A. Stirikovich et al also did not have any features of the flow of liquid metals.

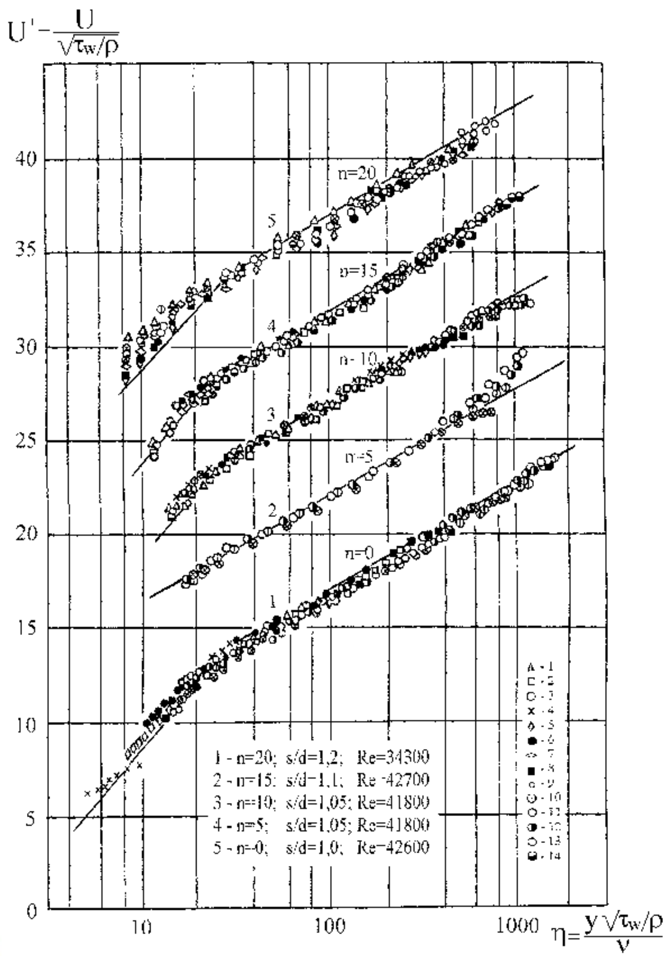
This makes it possible to simulate the hydrodynamics of liquid metals on water and gases.

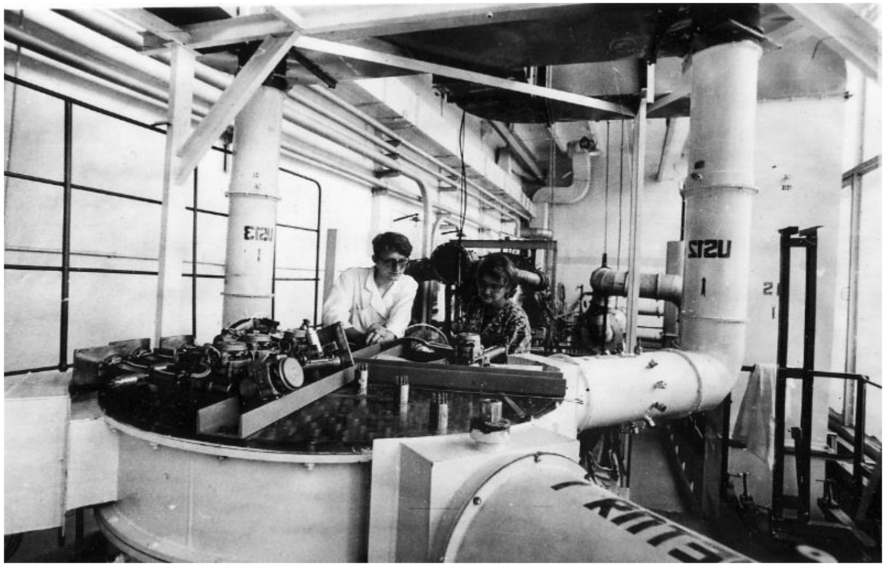


Comparison of the dependences for the coefficients of the hydraulic frictional resistance ξ on the motion regime for water, mercury and mercury-magnesium amalgam in the pipes

Modeling of hydrodynamics of liquid metals in channels (2)

The velocity profiles on the normals to the walls of complex channels during the flow of liquid metals are described by the universal Prandtl-Karman law





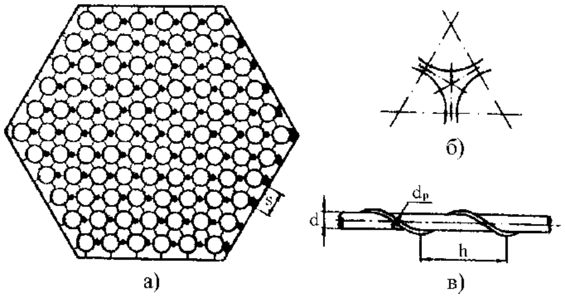
Measurement technique - hydrodynamic probes, thermo-anemometers, laser doppler-speedometer, electromagnetic flowmeters

$$U^{+} = \begin{cases} \eta & \text{при} \quad \eta < 5 \\ 5\ln\eta - 3{,}05 & \text{при} \quad 5 \le \eta \le 30 \\ 2{,}5\ln\eta + 5{,}5 & \text{при} \quad \eta \ge 30 \end{cases}$$

Hydraulic resistance of channels

$$\frac{1}{\xi} = \frac{1}{8}\,\mathrm{Re}\int_0^1 \left(\frac{R\,dR}{1 + \frac{\varepsilon\,\sigma}{\nu}} \right) R\,dR$$

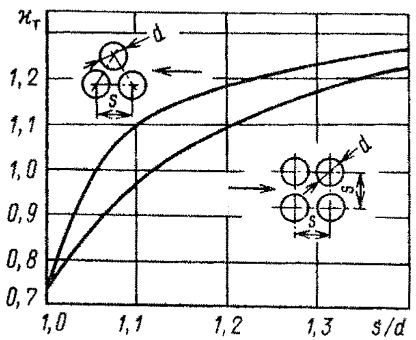
Hydraulic resistance of rod bundles

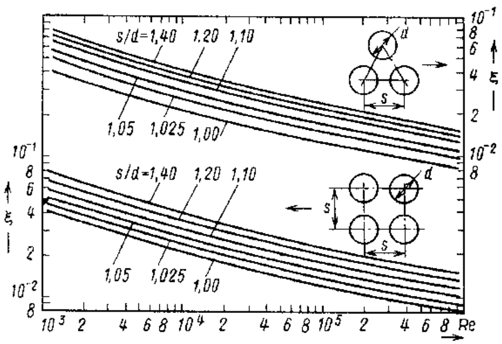


Triangular grid of smooth fuel elements

$$\xi = \frac{0{,}210}{\mathrm{Re}^{0{,}25}}\left[1+\left(s/d-1\right)^{0{,}32}\right]$$

$$1 \le s/d \le 1{,}5 \qquad 6\cdot 10^{3} \le \mathrm{Re} \le 2\cdot 10^{5}$$





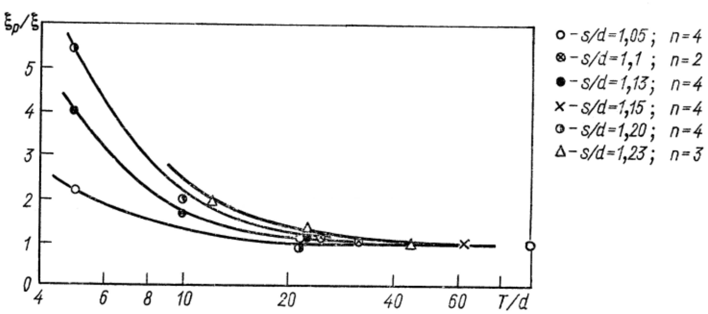
Square grid of smooth fuel elements

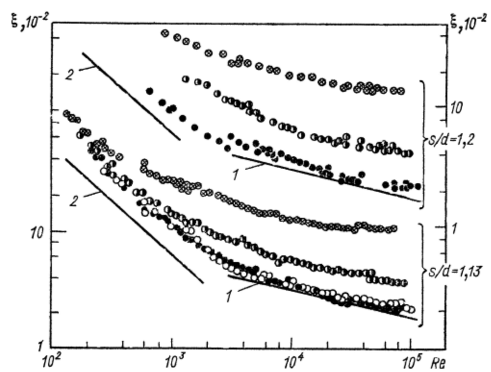
$$\xi/\xi_{\text{Тр}} = 0{,}59 + 0{,}19\left(s/d-1\right) + 0{,}52\left[1-\exp\left(-b\right)\right]$$

$$b = 10\left(s/d-1\right)$$

$$1 \le s/d \le 2 \qquad 10^{4} \le \mathrm{Re} \le 2\cdot 10^{5}$$

Triangular grid with fins on rods of type «fin to fin»





$$\xi_P = \frac{0{,}210}{\mathrm{Re}^{0{,}25}}\left\{1+\frac{600}{\left(h/d\right)^{2}}\left(s/d-1\right)\right\}$$

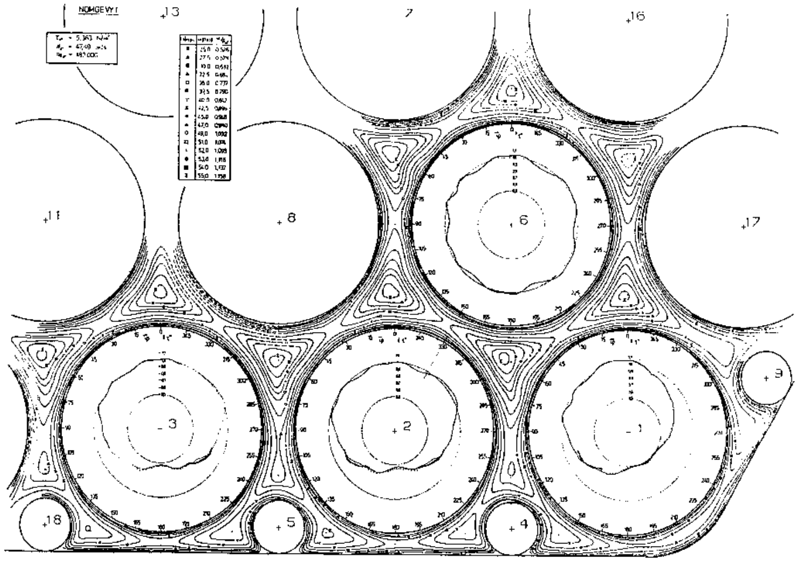
$$1{,}05 \le s/d \le 1{,}25 \qquad 5 \le h/d$$

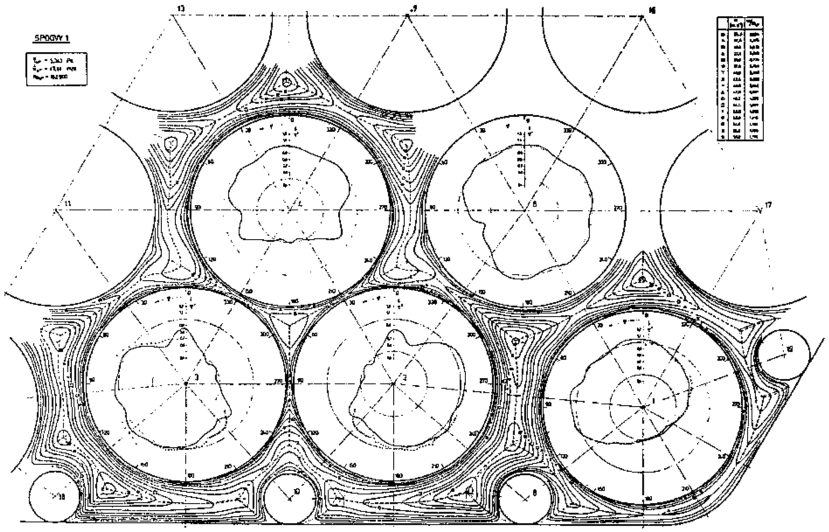
$$10^{4} \le \mathrm{Re} \le 2\cdot 10^{5} \qquad 2 \le n \le 4$$

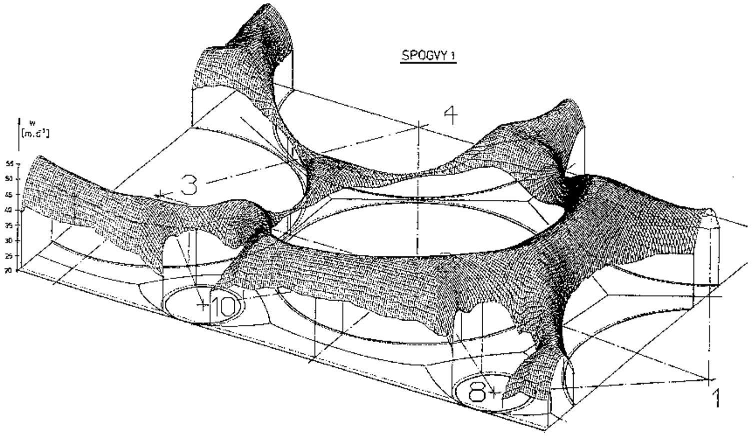
The distribution of velocity and tangential stresses in the cross section of the rod bundles

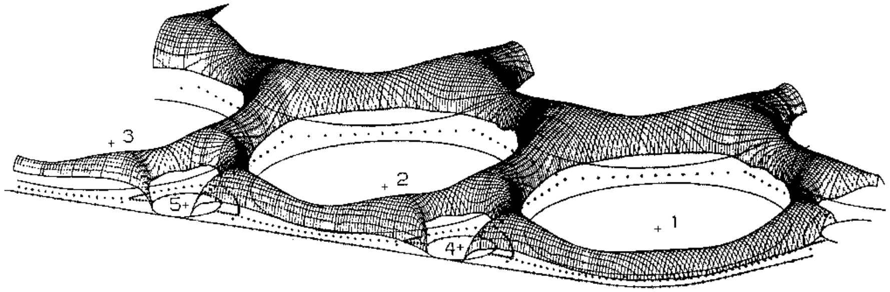
Nominal geometry

Deformed geometry

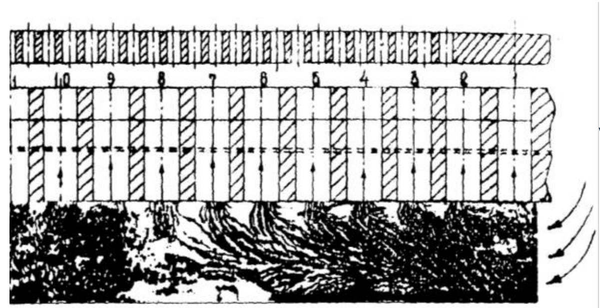




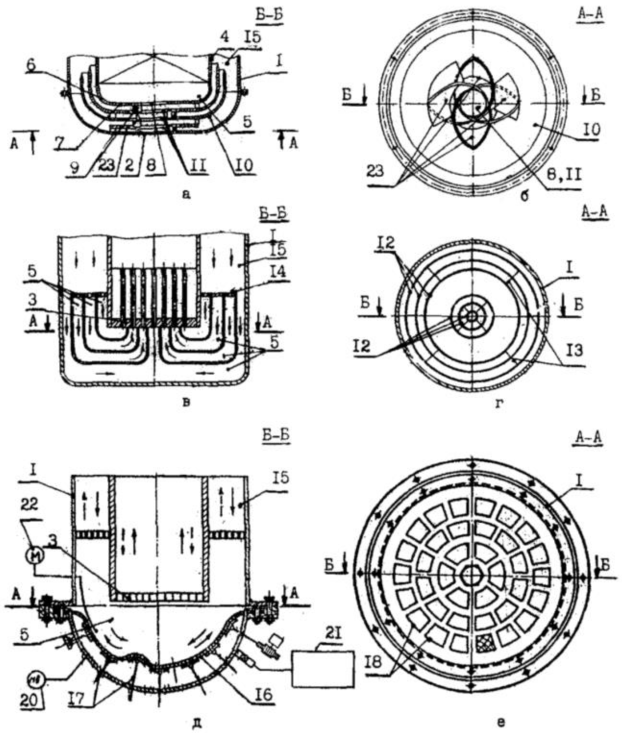




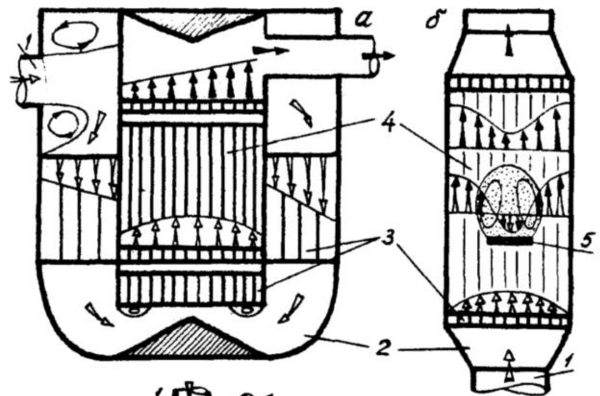
Hydrodynamics of the inlet manifolds and the flowing part of the reactor facilities

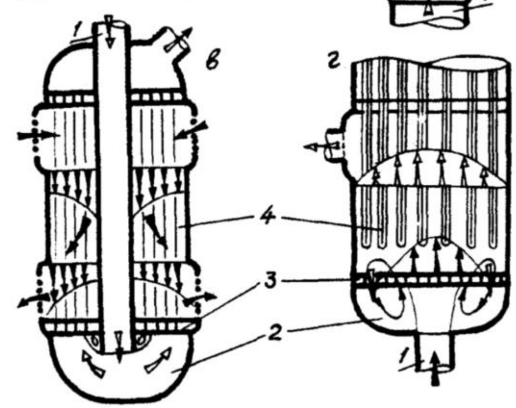


The effect of a horizontal flat vortex on the distribution of the coolant flow in the pressure chamber of the reactor



Distributing collector systems with lateral approach and central outlet of coolant

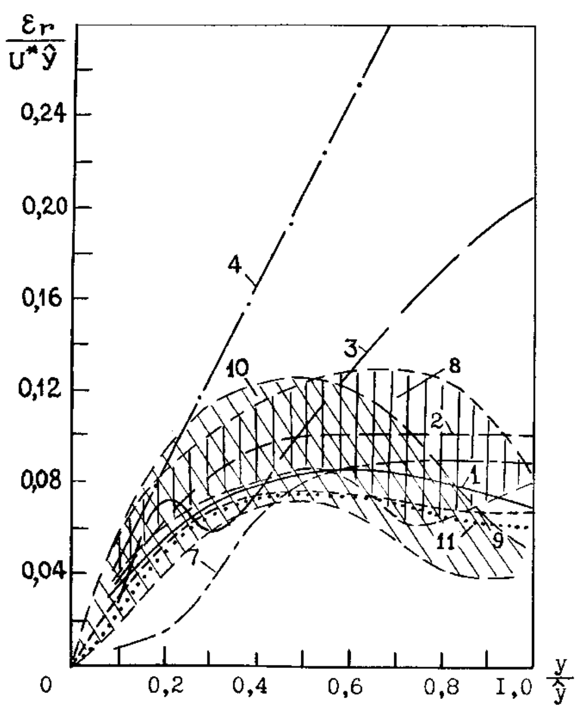




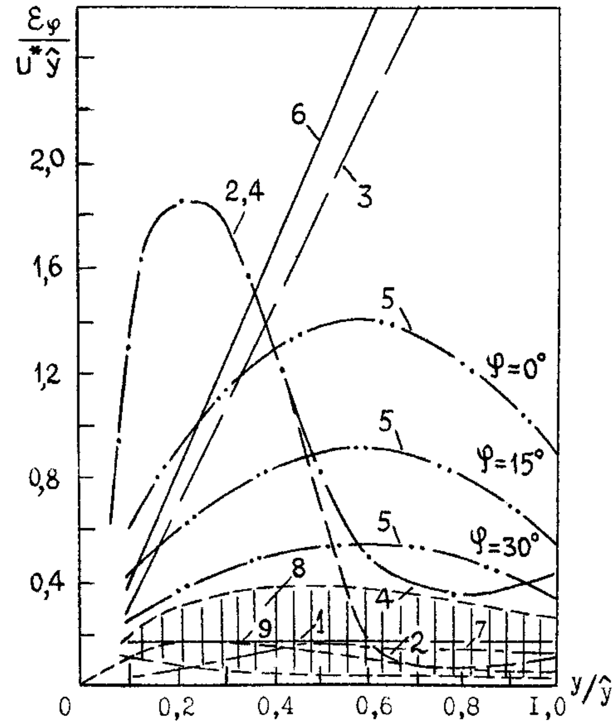
Characteristic complex flows in the reactor vessel and in fuel fuel subassemblies

Turbulent transport in bundles with smooth rods

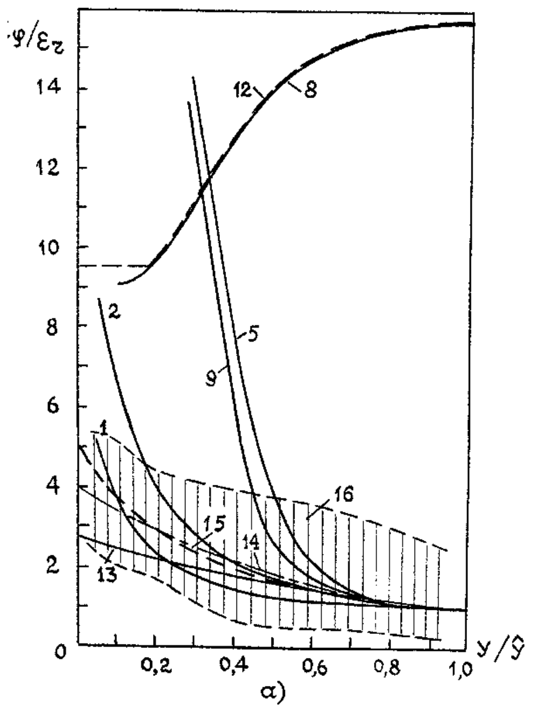
The distribution of the coefficient of radial turbulent diffusion along the normal to the wall according to the data of various authors



The distribution of the azimuthal turbulent diffusion coefficient along the normal to the wall according to the data of various author



Comparison of the dependences for the anisotropy coefficient of turbulent momentum transfer in triangular lattice rods



$$U^* = \sqrt{\tau_W / \rho}$$

1 - Nyasing; 2 - Mantlek; 3 - Milbauer; 4 - Yang and Jiang; 5 - Nelenium; 6 - Shimizu; 7 - Ibragimov; 8 - experiment; 9 - Reichard pipe; 10 - the experiment of Kjöletrem; 11 - Remus

Dependencies of turbulent transport in bundles with smooth rods

ROSATOM

- ✓ **Intensification of turbulent momentum transfer in all channels in comparison with a circular tube, not always the monotonic nature of the change in the intensity of turbulent pulsations is observed**
- ✓ **The distribution of the radial tangential stresses in the fuel rod assembly differs from the linear distribution law in the pipe**
- ✓ **The obtained relations for the coefficients of turbulent momentum transfer in fuel element lattices are significantly different. Calculation techniques assume the independence of small-scale turbulent diffusion and large-scale turbulent transport**
- ✓ **The turbulent momentum transfer anisotropy coefficient varies up to 50 times**
- ✓ **Analysis shows that a significant intensification of turbulent momentum transfer in the peripheral region of fuel assemblies and in deformed fuel rod lattices is due to the onset of intense large-scale momentum transfer (secondary currents)**

Modeling of heat exchange of liquid metals in pipes (1)

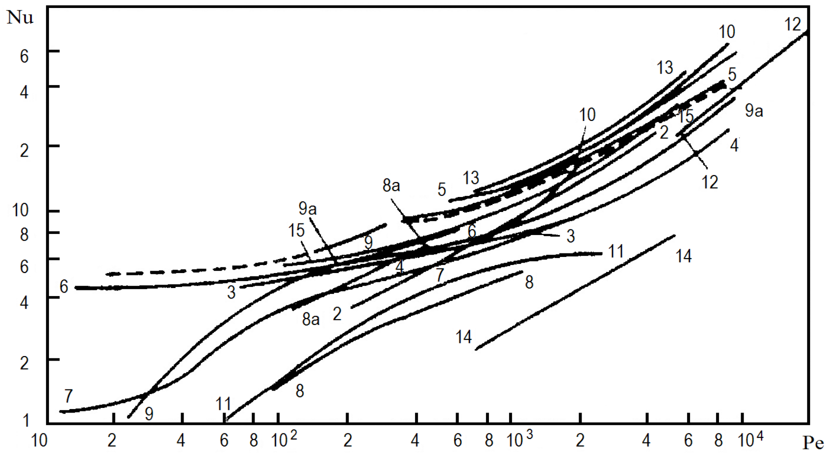
In the study of heat transfer in liquid metals for a steady flow, the hypothesis is used that in the criterion equation *Nu = f (Re, Fe)*, the Reynolds number can be approximately eliminated. Work indicating additional errors in its use is unknown .

Lyon (1951), using the integral method of calculation and the condition of equality to the unit of the turbulent Prandtl number, obtained a theoretical relationship for heat exchange in pipes

$$Nu = 7 + 0{,}025 \cdot Pe^{0,8}$$

Intensive studies of heat transfer in liquid metals began in the 1950s in connection with the development of nuclear power and the development of reactors on the *Pb-Bi* alloy for submarines. Systematic studies have been carried out since 1953 under the scientific guidance of V.I. Subbotin.

In 1956-1959 in the IPPE large experimental stands were created, on which a large amount of data on heat exchange in *Hg, Pb-Bi, Na, Na-K, Li, Cs* and other coolants was obtained. Studies continued for the following period up to the present time



Heat exchange of mercury in round tubes (l / d> 30). The state of research before 1965: 1 – Stary-kovich; 2, 3 - Korneev; 4 - Mikheev; 5 - Kirillov; 6 - Petukhov; 7 - Deriugin; 8, 8a - Dudy, Jünger; 9, 9a - Johnson; 10 - Isakov; 11 - Bailey; 12 - Brown; 13 - Borishansky; 14 - Elser; 15 - Ushakov

Formal accumulation of experimental data produced little - on the charts appeared "clouds" of points.
After rejecting unreliable and erroneous data, it is clear that the experimental data on the heat transfer of liquid metals in the pipes are grouped between two predictable dependences.

For the purified from impurities LM

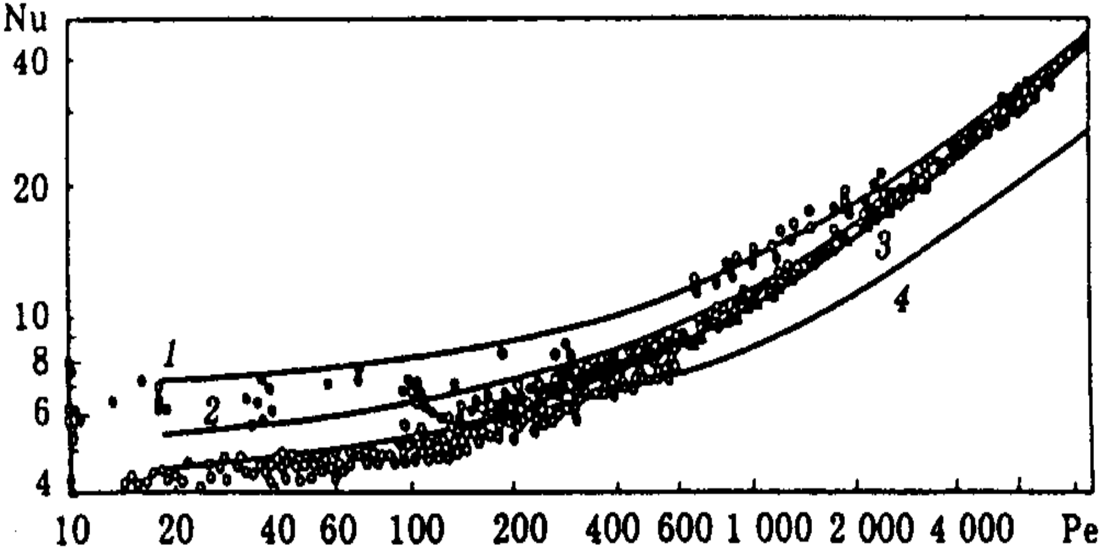
$$Nu = 5 + 0{,}025 Pe^{0,8}$$

Deteriorated heat transfer by impurities in LM

$$Nu = 3 + 0{,}014 Pe^{0,8}$$

Modeling of heat exchange of liquid metals in pipes (2)

The difference between the theoretical formula of Lyon and other formulas is explained by the difference in the boundary conditions on the heat transfer surface (condition d) of complete similarity in Section 1). At the boundary of the heat-transfer surface with liquid metals, a thermal contact resistance is observed. His origins remained unclear for a long time, and the results of the measurements were contradictory.



Data of control measurements of heat exchange in mercury and Na-K alloy in round tubes: calculation by the formula: 1 – $Nu = 7 + 0{,}025Pe^{0{,}8}$; 2 – $Nu = 5{,}2 + 0{,}025Pe^{0{,}8}$; 3 – $Nu = 4{,}3 + 0{,}025Pe^{0{,}8}$; 4 – $Nu = 5 + 0{,}014Pe$; △ – mercury-nickel; ▲ - mercury-stainless steel; ● - sodium potassium-copper; ◌ - mercury

Special experiments on heat transfer with mercury in pipes made of nickel and sodium-potassium alloy in pipes made of copper and stainless steel, made by two independent groups of IPPE employees in 1962-1965 (VD Talanov, IP Sviridenko) under the direction of P .A. Ushakov, with a more thorough purification of liquid metals, gave the same results, close to the calculations for the formula for purified media.

The results of the works of P.L. Kirillov et al and M.Kh. Ibrahimov et al in which the temperature distribution in the *Na*-K and *Pb-Bi* flows was measured are close to calculations using the Lyon formula.

Modeling of heat exchange of liquid metals in pipes (3)

ROSATOM

✓It was shown that when the concentration of impurities in the coolant does not exceed their solubility at the temperature of the circulating liquid metal, then the contact thermal resistance at the interface between the coolant and the heat exchange surface is absent.

✓As a result of systematic studies carried out in the IPPE Yu.I. Orlov, M.N. Ivanovsky, P.L. Kirillov, it was shown that the main cause of the contact thermal resistance is the precipitation of solid particles suspended in the flow of liquid metals on the heat exchange surfaces.

✓Near the wall in the region of the laminar sublayer, the impurities accumulate in a layer adhered to the wall and representing an almost dense packing of the impurity crystals, and in the transition region into a layer with variable concentration. In a turbulent flow, the concentration of suspended impurities is thousands of times smaller than that of the wall, and is close to the saturation concentration.

P.L. Kirillov proposed an approximate model that reflects the effect of contact thermal resistance on heat transfer.

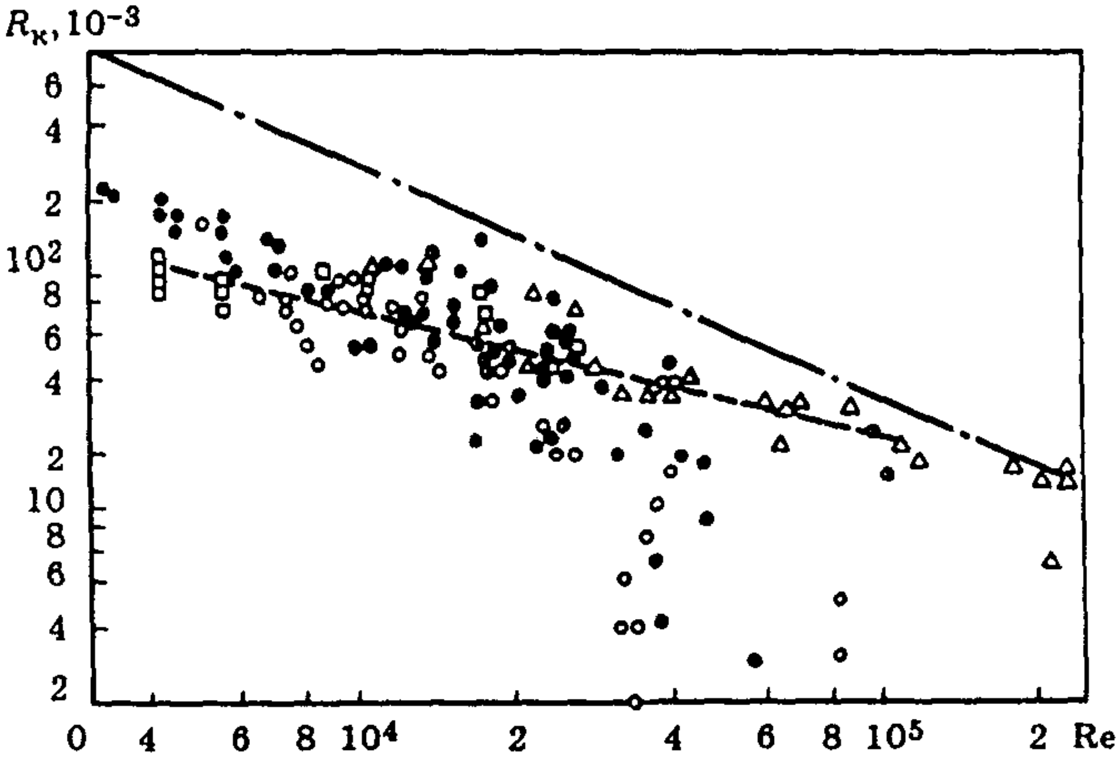
We propose the formula (4)

$$\mathrm{Nu} = \frac{\mathrm{Nu}_0}{1 + \varphi \cdot \mathrm{Nu}_0}$$

where $\varphi \cong \left[1600 C_{\mathrm{O}_2} - 5000 C_{O_2}^2 - 30\right] \mathrm{Re}^{-0,7}$ – correction for contact resistance, depending on the mass concentration of oxygen in sodium and the number Re. The formula is of a rather particular character, since it refers to the case of heating a liquid metal in a stainless steel pipe, provided there is a formed impurity layer near the wall.

Effect of contact thermal resistance on heat transfer in pipes

ROSATOM



The maximum possible contact resistance can be estimated on the basis of the PL formula. Kirillov's (5)

$$R_k \approx 200 \frac{\lambda_f}{d\ \mathrm{Re}^{0{,}75}}$$

Dependence of the contact thermal resistance in the pipes on the Reynolds number: calculation by formulas (4) - - - - and (5) – – - - – ; ◑ - sodium-potassium alloy in a copper pipe; ◌, ● - sodium-potassium alloy in molybdenum pipe; ⊗ - lithium in molybdenum pipe; □ - from measurements of lithium temperature in the wall layer near the steel pipe; △ - lead-bismuth alloy in a steel pipe

Modeling of thermal hydraulics in fuel subassemblies of fast reactors

ROSATOM

Since heat transfer in fuel subassemblies is carried out by convective heat transfer, high thermal conductivity does not guarantee the absence of large temperature irregularities in structures cooled by liquid metals. The low Prandtl number inherent in liquid metals does not give any advantage in reducing the temperature non-uniformities of structures in comparison with water. The temperature fields are determined by the degree of the coolant jets heating and not by heat transfer coefficients, which significantly increases the requirements for the organization of hydrodynamics of the reactors.

When stating the problems of convective heat transfer V.I. Subbotin and his co-workers focused on the development of the theory of approximate thermal modeling in the active zones of reactors – the modeling of fuel rods by multilayer or single-layer tubes with electrical heating from the inside.

P.A. Ushakov has shown that convective exchange in complex channels should be considered in conjunction with heat transfer by thermal conductivity in the walls, that is, in fuel elements in assemblies of reactors the "conjugate problem" of heat transfer from fuel elements is solved

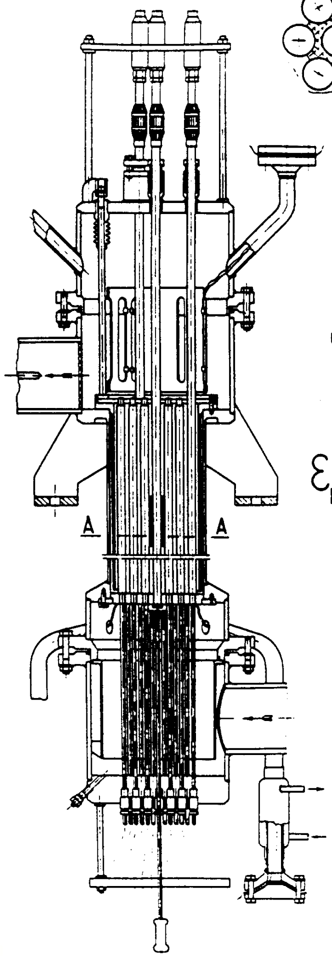
The distribution of the temperature of the fuel elements in the beam depends not only on the classical similarity criteria, but also on the design and thermophysical characteristics of the fuel element elements and the fuel assembly.

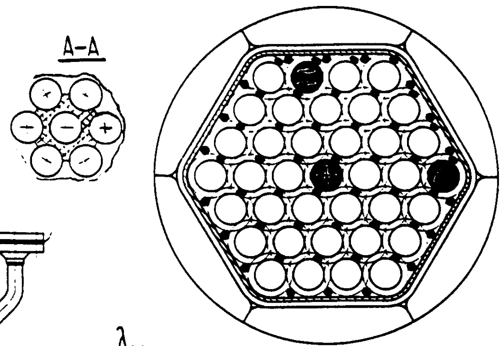
The formula for the coolant temperature takes the form:

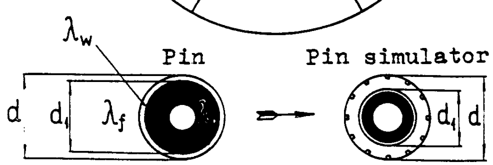
$$T_f = f_2\left(\xi, z, \varphi, \mathrm{Re}, \mathrm{Pe}, \varepsilon_{\mathrm{k}_0}\right)$$

The essence of the approximate thermal similarity consists in taking into account only the fundamental harmonic in the Fourier series. The value is called the criterion of approximate thermal similarity of fuel elements. The main harmonics are : k_0 = 6 for triangular and k_0 = 4 for square grating, k_0 = 1 for eccentric annular channels and fuel elements for a flat wall.

Technique of the experiment on heat transfer in assemblies of fuel elements of fast reactors

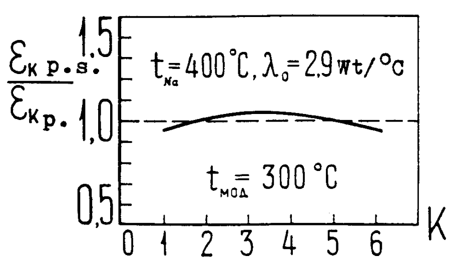


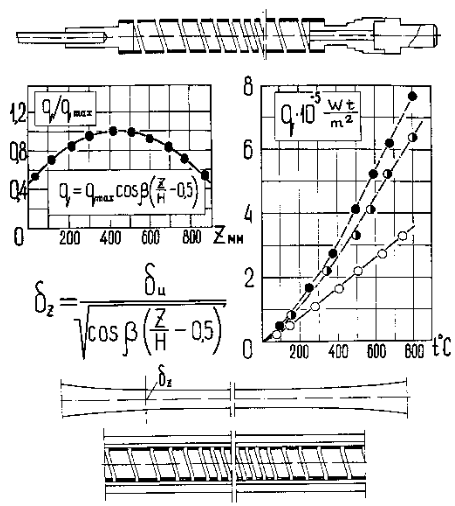


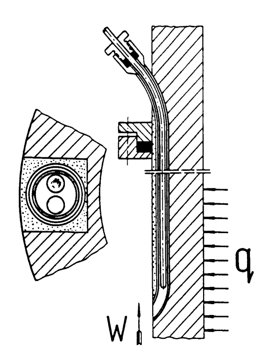


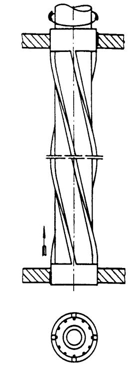
$$\varepsilon_K=\left\{\frac{\lambda_w}{\lambda_f}\cdot\frac{1-m\left(\frac{d_1}{d}\right)^{2K}}{1+m\left(\frac{d_1}{d}\right)^{2K}}\right\}_T=\left\{\frac{\lambda_w}{\lambda_f}\cdot\frac{1\mp\left(\frac{d_1}{d}\right)^{2K}}{1\pm\left(\frac{d_1}{d}\right)^{2K}}\right\}_M$$

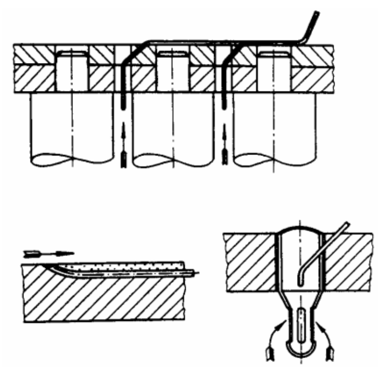
$$m=\frac{\lambda_w-\lambda_0}{\lambda_w+\lambda_0};\ \begin{cases}\lambda_0\ll\lambda_w,\ m=+1\\ \lambda_0\gg\lambda_w,\ m=-1\end{cases}$$



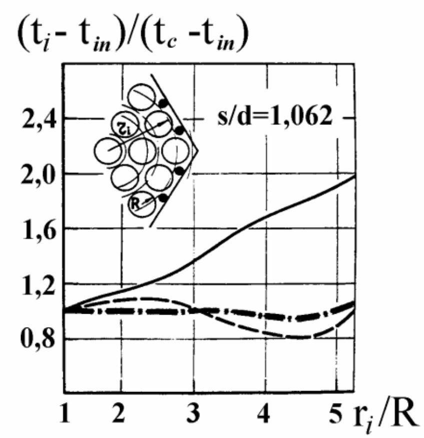




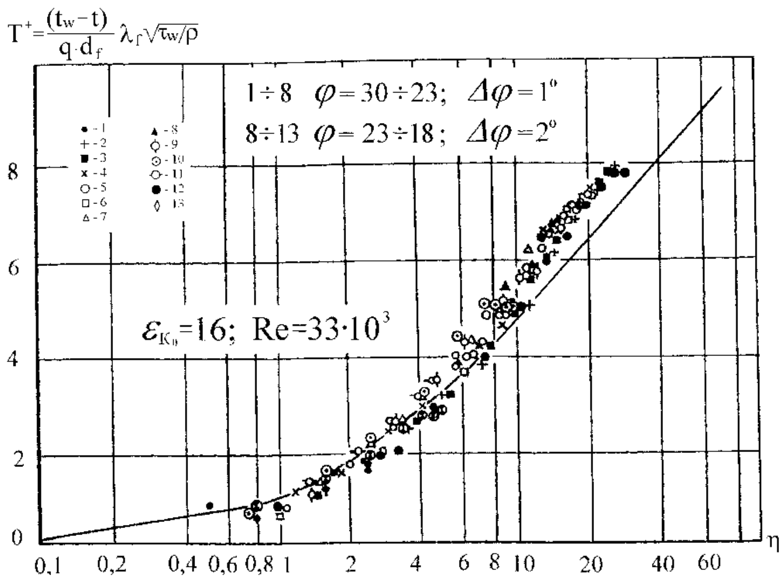




Thermo electrode diameter,mm	0,05	0,10	0,15	0,20
Depth of groove,mm	0,06	0,12	0,18	0,25
Width of groove,mm	0,12	0,25	0,35	0,55



Heat transfer of fuel rods in fuel subassemblies



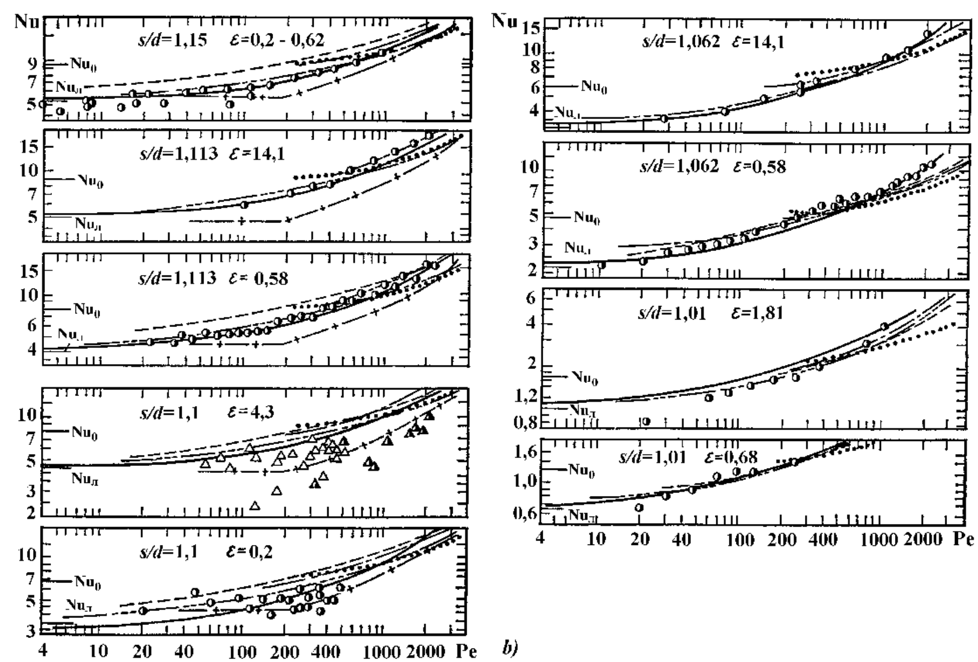
$$T^{+} = 4{,}75 \ln \eta - 7{,}5$$

The quasi-universality of the dimensionless temperature profile on the normals to the channel walls is confirmed In the case of heat transfer by liquid metals.

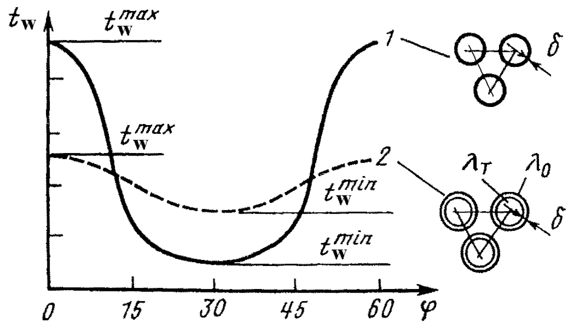
A.V. Zhukov et al recommended generalized dependencies for the calculation of heat transfer and temperature fields in channels of complex shapes, taking into account the influence of the geometry and materials of the fuel elements

$$\mathrm{Nu} = \mathrm{Nu}_{\text{лам}} + \frac{0{,}041}{x^{2}}\left[1 - \frac{1}{\dfrac{x^{30}-1}{6} + \left(1{,}15 + 1{,}24\varepsilon_{6}\right)^{1/2}}\right]\mathrm{Pe}^{a}$$

$1 < x = s/d < 2$; $1 < Pe < 4000$; $0{,}01 < \varepsilon^{6} < \infty$



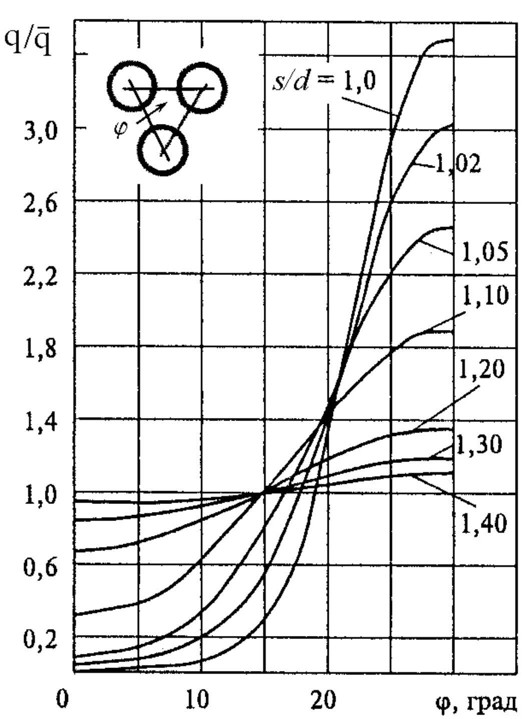
Azimuthal temperature unevenness of fuel rods in fuel subassemblies

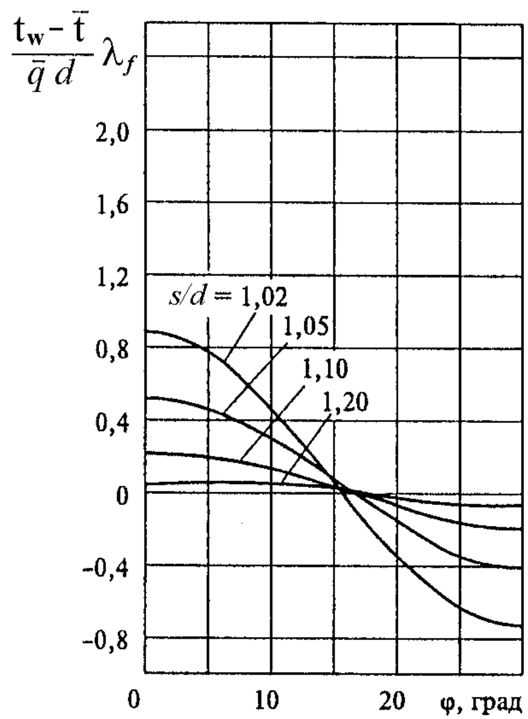


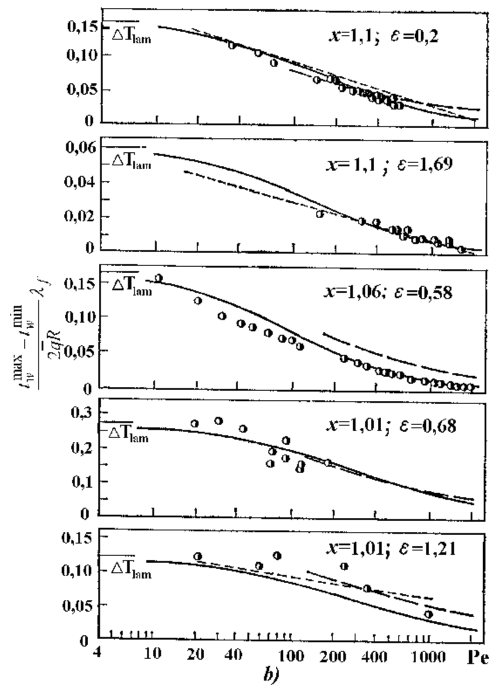
$$\Delta T_w^{\max} = \frac{t_w^{\max} - t_w^{\min}}{\bar{q}R}\lambda_f = \frac{\left(\Delta T_w^{\max}\right)_{лам}}{1 + \gamma\left(\varepsilon_6\right)\mathrm{Pe}^{\beta(x)}}$$

γ(ε $\gamma(\varepsilon^6) = 0{,}008(1 + 0{,}03\varepsilon^6)$; $\beta(x) = 0{,}65 - 51\,(\lg x)/x^{20}$

$\varepsilon^6 > 0{,}2$; $1 < x < 1{,}15$; $1 < Pe < 2\,000$







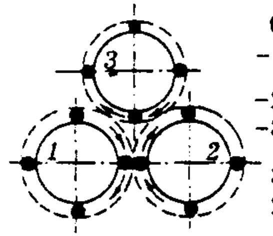
Interchannel exchange in fuel rod assemblies (1)

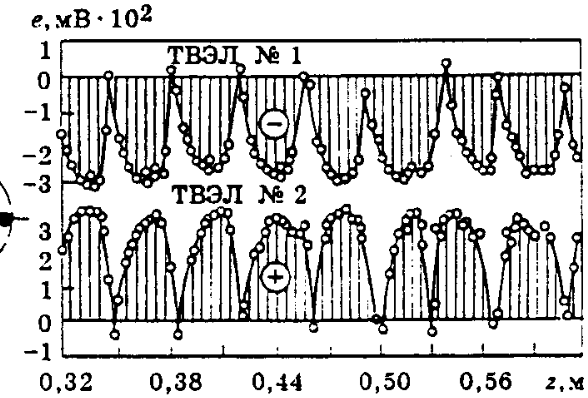
An important feature of thermal hydraulics of fuel assemblies is the influence on the distribution of parameters of inter-channel mass and heat transfer.

Investigations of inter-channel exchange were initiated by Academician A.I. Leipunsky. Inter-channel exchange refers to the phenomenon of the transfer of a substance between two neighboring media streams in channels (cells).

To measure the coefficients of inter channel interaction, thermal and electromagnetic methods, the Freon tracer method, as well as sensors for measuring the temperature and flow rate of the coolant along the assembly height have been developed.

Convective interchannel transfer in assemblies of fuel rods of reactors with heavy LMT is provided by spacing gratings or spacing ribs with a "rib-on-edge"





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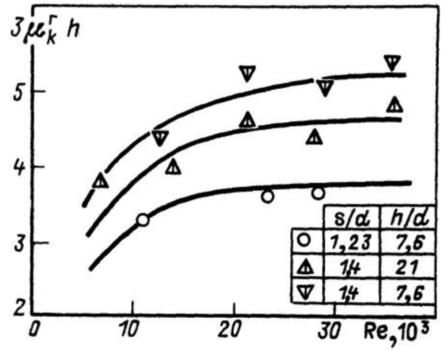
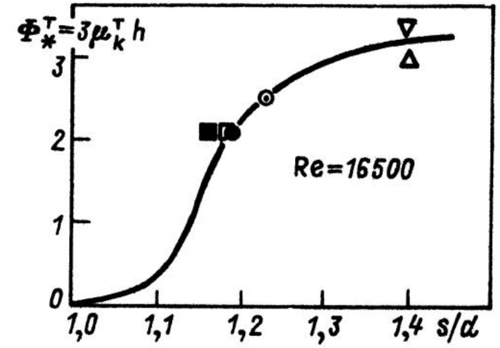




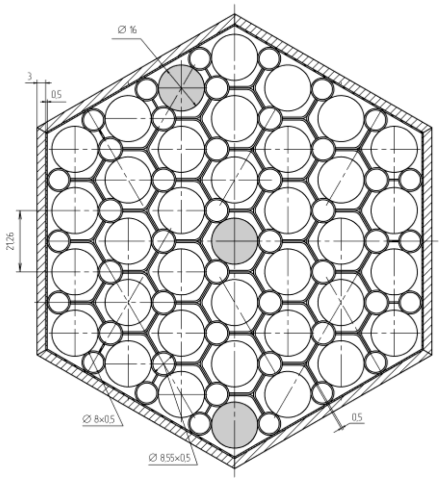
$$\mu_{\text{к}}^{\text{м}} = \frac{1}{3h}\Phi_*(x)\Psi(\text{Re})\ \text{и}\ \Phi_*(x) = A(x) + B - C\exp(-D)$$

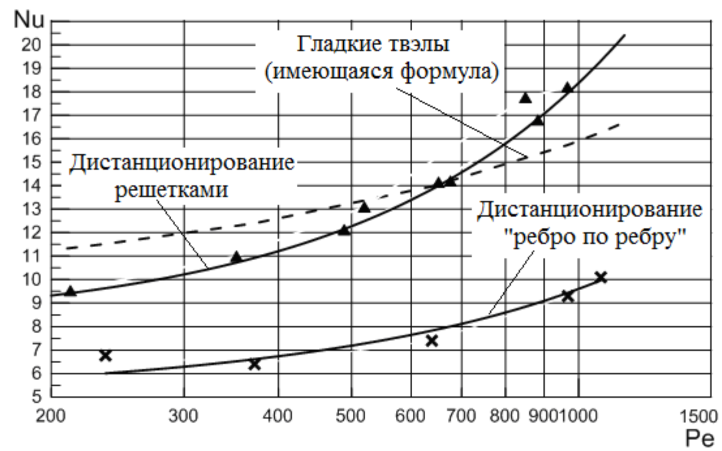
1,01 < x < 1,5; 5·103 < Re < 105; 5 < h/d < 65

Experimental researches of thermal hydraulics of fuel assemblies of the reactor core of BREST at the stand «6B» (1)

ROSATOM

Using the proprietary methodology of the SSC RF-IPPE, data on heat transfer and temperature fields were obtained on a 37-element model fuel assembly in steps of 1.33 with smooth fuel rods, with wire spacing and four spacer gratings (modeling coolant Na-K)



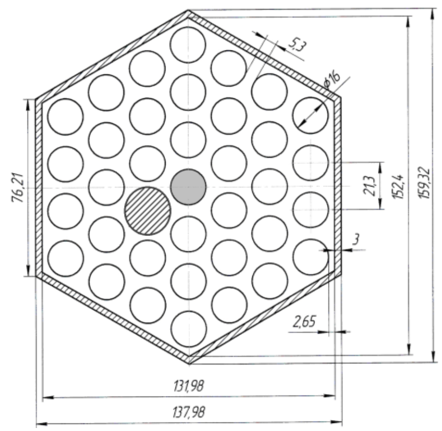


- ✓ The heat transfer coefficients for the "smooth" fuel element region are close to those previously recommended for smooth fuel rods of LM reactors and are much higher than for the previously investigated edge-to-edge spacing
- ✓ Low temperature unevenness around the perimetre of fuel rods
- ✓ In the area of the spacing lattices, a local increase in heat transfer (up to 50%) is observed in comparison with smooth areas

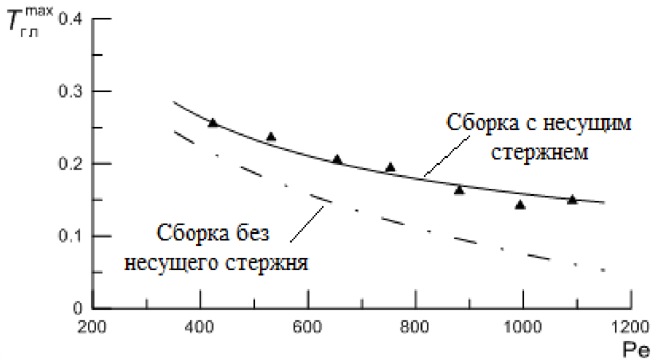
Experimental researches of thermal hydraulics of fuel assemblies of the reactor core of BREST at the stand «6B»(2)

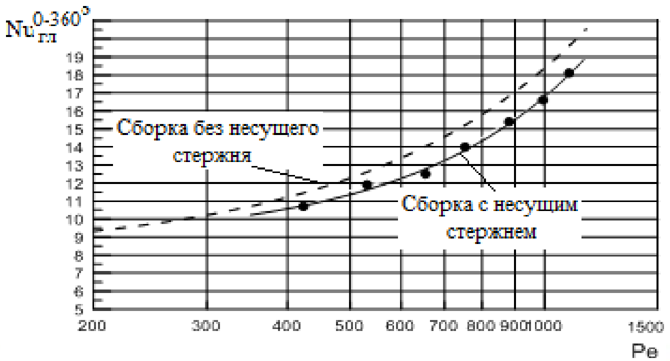
ROSATOM

The data on heat transfer and temperature fields in 37-rod model fuel assemblies with non-standard geometry (the zone of an unheated carrier rod with spacing by gratings)



- ✓ There is a drop in the temperature of the surface of the measuring simulator and the temperature of the coolant in the cells from the side of the support rod. This causes an increase in the maximum temperature unevenness along the perimeter of the simulator in comparison with the assembly without a supporting structure, almost 3 times
- ✓ A certain decrease in the heat transfer of the simulator near the supporting rod (about 10%) is revealed in comparison with the model assembly without the supporting structure
- ✓ The formulas for all the investigated values used for the thermohydraulic justification of the BREST reactor core and code verification received





Modeling of thermohydraulic processes in a vessel of fast reactors

ROSATOM

The primary coolant circulation loop (vessel structure) of a fast reactor is a complex combination of successively and in parallel connected elements with different orientations in the gravity field, the geometric characteristics of the cross sections of which change sharply in the course of travel

Errors in the modeling of thermal hydraulics on fragmentary sectoral models with isothermal flow are largely due to the lack of spatial 3-dimensional effects and the temperature non-uniformity of the flow.

The coolant is always non-isothermal due to uneven energy release, temperature difference between the units of the circulation loop, features of heat removal in transient and accident operation regimes.

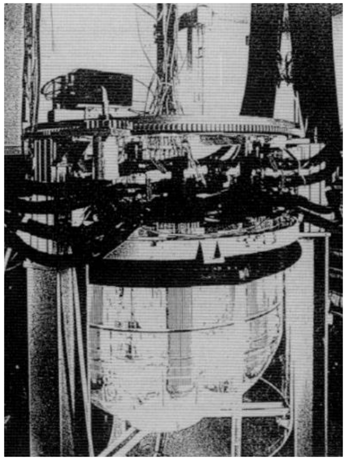
Large-scale stands for simulating of thermal hydraulics in the reactor vessels and DHRS of fast reactors

ROSATOM

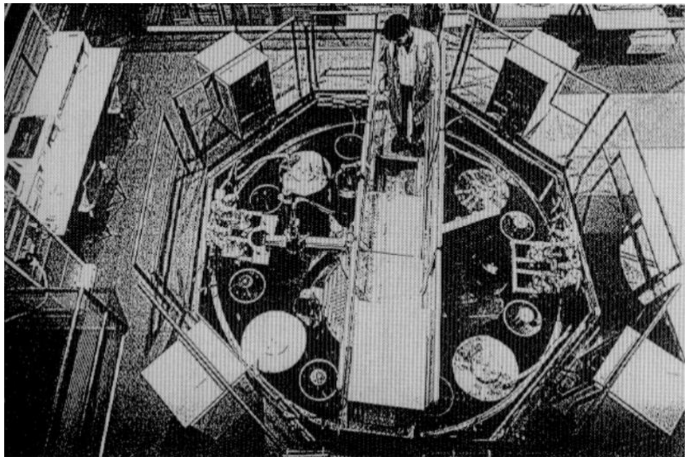
To study the thermohydraulic processes in the reactors tanks and elements of DHRS in Germany, the European Rapid Reactor (EFR) project created complex water stands

- ✓RAMONA (M: 1:20), NEPTUN (1:5), water-air stand KIVA (M: 1:10),
- ✓sodium-air stand ILONA (1:3),
- ✓to justify the DHRS of the Japanese demonstration reactor water stands (M: 1:20, 1:6, 1:8),

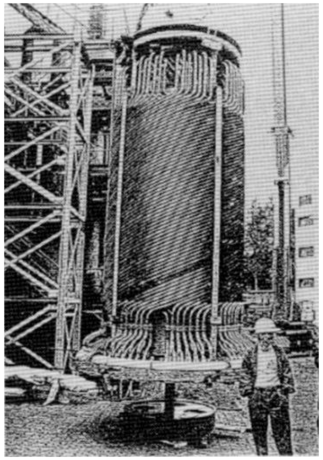
on which wide data were obtained for the verification of settlement codes.



RAMONA



NEPTUN



ILONA

The use of large-scale models with full-scale coolant leads to the high cost of experimental facilities and the performance of research

Modeling of thermohydraulic processes in a vessel of fast reactors

ROSATOM

On fine-scale models with full-scale coolant (liquid metal), accurate simulation of hydrodynamics and heat transfer in the reactor vessel is impossible due to the impossibility of simultaneously meeting the most important similarity criteria – Reynolds numbers ($Re = w\ell/\nu$), Peclet ($Pe = w\ell/a$), Froud ($Fr = w^2/g\beta\Delta T\ell$).

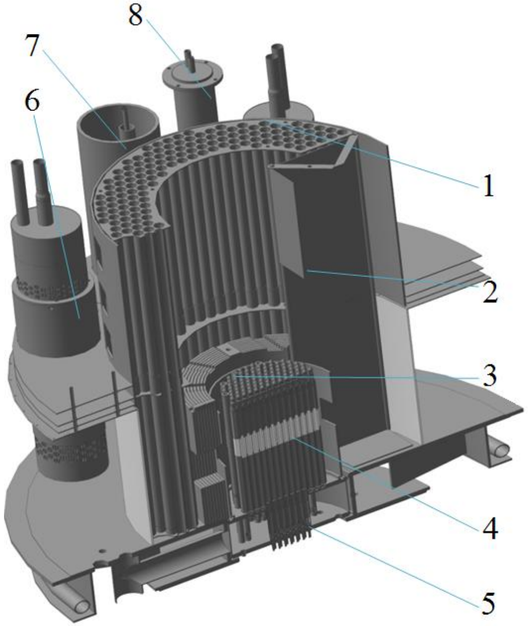
The carried out studies showed that with the number Re > 104 the dimensions of stagnant and recirculation formations with equal Froude numbers for the model and reactor ($F_{гм} = F_{гр}$) do not change. Thus Reynolds number simulation is not required.

In a viscous fluid it is possible to model by Froude and Richardson numbers without saving the Reynolds number in this case.

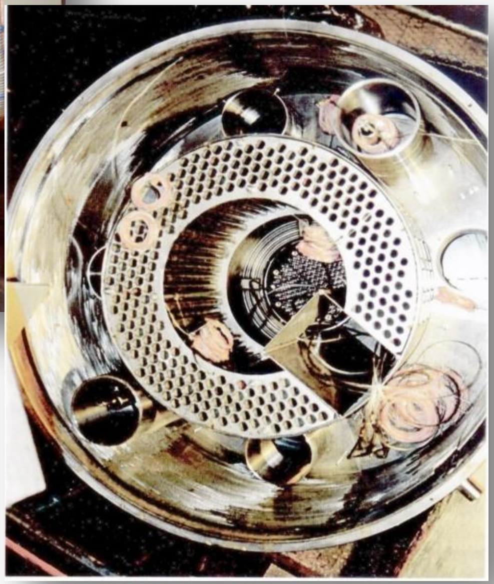
Approximate modeling of natural circulation regimes is provided by conservative Eulerian $Eu = \Delta P/\rho W^2$.

Model of a fast reactor with integral arrangement on the water stand «V-200»

In the SSC RF – IPPE together the Thermophysics Department of NRU «MPEI» and the JIHT RAS the thermal hydraulics research on the water model of the primary circuit of a fast reactor with a liquid metal coolant and integrated arrangement of equipment in the scale ~ 1:10 were carried out.



General view of the experimental model



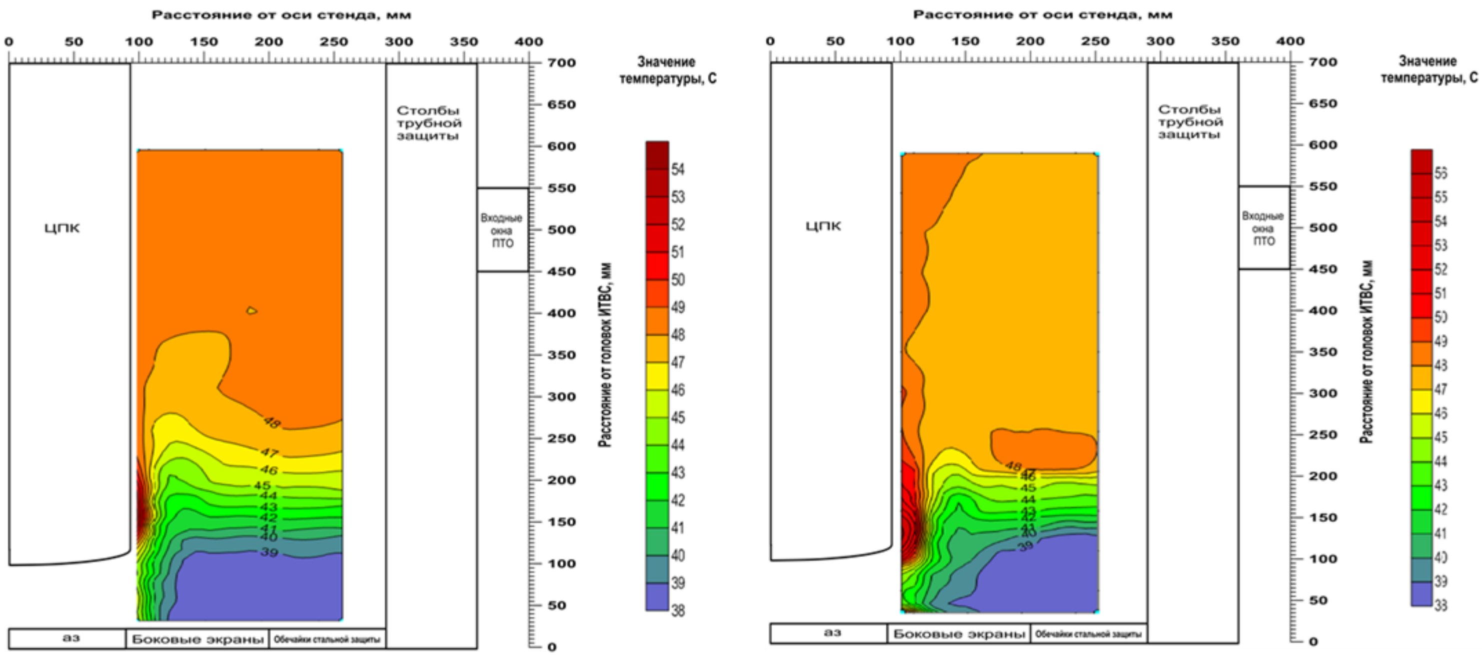
Experimental water model of the primary circuit of the reactor with integrated equipment layout: 1, 6 - intermediate heat exchanger; 2 - elevator recess; 3 - elements of in-vessel protection; 4 - core (fuel elements simulators); 5 - pressure chamber; 7 - simulator MCP-1; 8 - autonomous heat exchanger

In-vessel equipment of the experimental model

Modeling of thermohydraulic processes in the fast reactor vessel (1)

ROSATOM

The averaged fields of the coolant temperature above the side screens in the moving planes along the height of the mobile thermosondes PZ-2 and PZ-3



The distributions of the temperature and velocity fields of the coolant along the height of the upper chamber are not isotropic in the azimuthal direction.

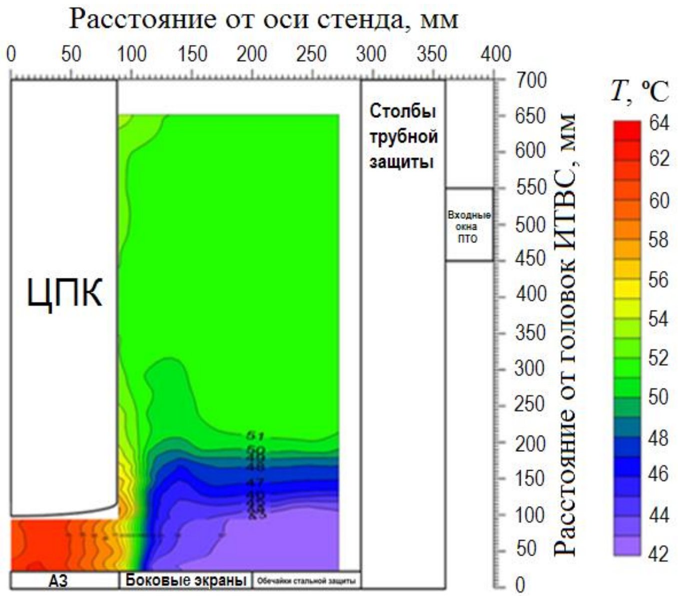
The secondary layered flows in these zones are associated with a radial temperature gradient caused by the hot flow along the central rotary column and the relatively cold surface of the intermediate heat exchangers

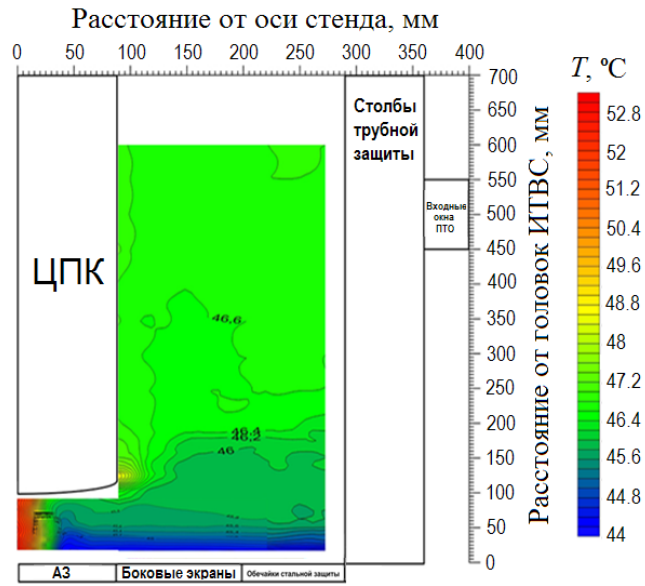
Modeling of thermohydraulic processes in the fast reactor vessel (2)

The results of the experimental studies carried out on the model have shown that the effect of thermogravitational forces leads to a temperature stratification with the appearance of stagnant and recirculation formations, the reconstruction of the nature of the flow and the temperature regime.

Intrinsic waves appear on the stratified interfaces, which cause temperature pulsations on the walls of the reactor equipment. This leads to thermal fatigue of the construction materials and a reduction in the lifetime of the reactor equipment.

The steady regime of natural circulation is characterized by considerably smaller temperature gradients in the vertical direction above the side shields.



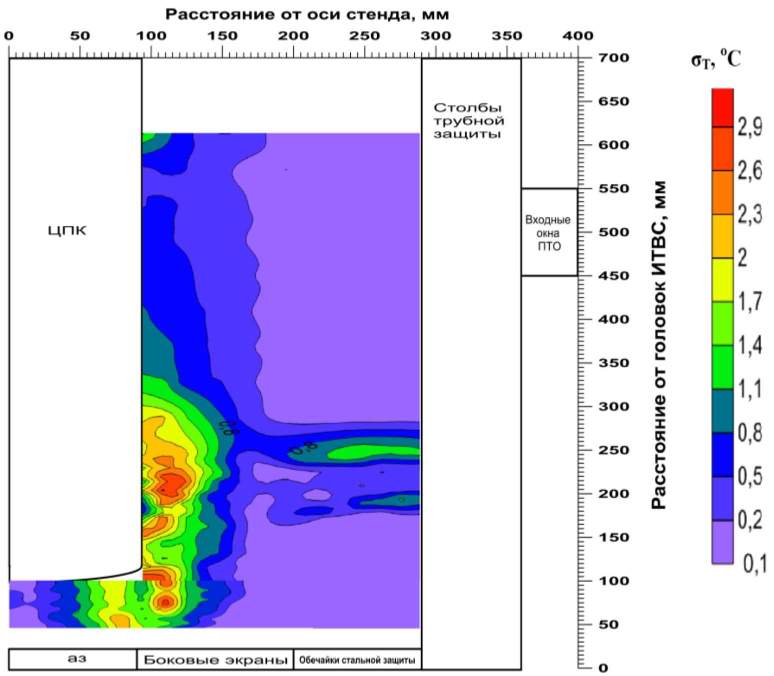


The average temperature of the coolant in the upper chamber when moving mobile thermosondes in height in the nominal and steady-state cooldown regime by natural convection.

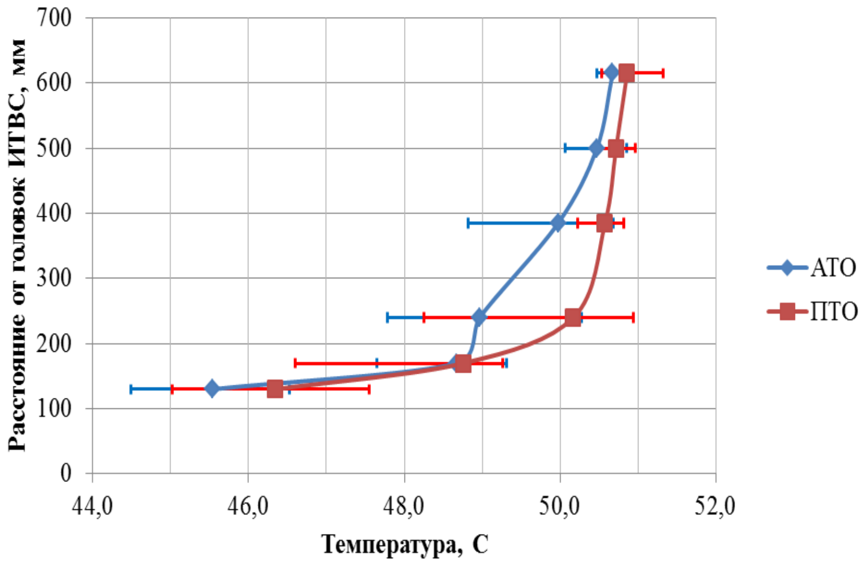
Modeling of thermohydraulic processes in the fast reactor vessel (3)

ROSATOM

The intensity of pulsations of the coolant temperature in the upper chamber of the reactor



The distribution of the pulsation temperature along the height of the upper chamber



The distribution of the averaged and pulsating temperature along the height of the upper chamber at a distance of 125 mm from the core axis

Turbulent vortices from the upper hot and lower cold zones with scales $l > \ell_n$ are suppressed in the separating layer and create internal waves that cause temperature pulsations in the material of the equipment walls

Criteria for the similarity of flows in stably stratified coolant zones

ROSATOM

Criteria determining the similarity of the complex structure of the motion of a non-isothermal coolant in the stratified zones of the coolant in the upper chamber of a fast reactor under forced circulation are the Froude numbers (*Fr*), Peclet (*Pe*) and the local gradient Richardson number (*Ri*), under the condition of self-similarity in numbe *Re*

$$Fr = \frac{W^2}{g\beta \Delta t L}; \quad Pe = \frac{W \cdot L}{a}; \quad R_i = \frac{g\beta(\partial t / \partial z)}{(\partial W / \partial z)^2}; \quad \mathrm{Re} = \frac{W \cdot L}{\nu};$$

The most common characteristic stratified flow are Vaisal-Brent frequency and buoyancy scale

$$N^2 = -\frac{g}{\rho}\left(\frac{\partial \rho}{\partial z}\right)^{-1}; \quad l_{пл} = \rho\left(\frac{\partial \rho}{\partial z}\right)^{-1}$$

In a stably stratified turbulent flow the maximum size of the vortices can not exceed the buoyancy scale. Therefore large-scale vortices larger than the buoyancy scale are suppressed and spread along the stratified region of separation in the form of internal waves. Internal waves create temperature pulsations in the material of the equipment walls with frequency $f \leq N$.

In the extreme case for example when a rapid emergency protection is triggered, when $l_п < l_К$, convective transfer through the interface between the cold and hot regions of the flow is completely suppressed. Here $l_К = (\upsilon^3/\varepsilon)^{0,25}$ – scale of Kolmogorov, ε – the rate of dissipation of the kinetic energy of turbulence.

Заключение (1)

When planning an experimental study, generalizing its results, the similarity analysis and the following criteria and asymptotic solutions should be applied in full.

The results of the study show:

✓<u>Fluid Dynamics in Channels</u>:

The defining criterion for modeling hydrodynamic processes in channels is the criterion *Re*. The high thermal conductivity and the weak dependence of the thermophysical characteristics of the liquid crystal on temperature lead to a weak dependence of the temperature profile on the magnitude of the heat flux. This makes it possible to model hydrodynamics of liquid metals on water and gases.

✓<u>Heat transfer in liquid metal for steady flow in channels</u>:

As a result of the completed complex of theoretical calculations and generalization of the experimental material, including the distribution of temperature in the liquid metal flow, it is shown that the thermal (contact) resistance is absent at the interface between the coolant and the heat exchange surface when the impurity concentration in the coolant does not exceed their solubility at the temperature of the circulating liquid metal. Under these conditions, heat transfer to liquid metals *Pb, Pb-Bi, Hg, Na, Na-K, Li et al* is described by a single criterial dependence on the number *Pe*.

As a result of systematic experimental studies it was shown that the main cause of the contact thermal resistance is the deposition of suspended solids suspended in the flow of liquid particles on the heat exchange surface. The dependence of the contact thermal resistance on the *Re* number and the oxygen content was established.

Заключение (2)

✓**Hydrodynamics and heat exchange in the liquid metal in the fuel assemblies of the reactor core** :

Heat exchange infuel assemblies is carried out mainly by convective heat transfer, the temperature field is largely determined by the heating of the liquid metal. The temperature distribution depends both on the classical similarity criteria *Re, Pe (Pr), Gr,* and the design and thermophysical characteristics of fuel elements and fuel assemblies – a criterion for the approximate similarity of fuel elements.

✓**Hydrodynamics and heat transfer in the liquid metal in the reactor vessal:**

In forced circulation regime, modeling on small-scale models is performed by the number of *Fr* и *P*e when water is used as a modeling fluid.

Approximate modeling of the natural circulation mode is provided by Eulerian $Eu = \Delta P/\rho W2$.

The similarity of flows in the stably stratified zones of the coolant is determined by the numbers *Fr, Pe* and the locally gradient Richardson number $Ri = g\beta(\partial t/\partial z)/(\partial w/\partial z)2$.

The characteristics of a stably stratified flow of the coolant are the Vaisala-Brent frequency $N2 = (g/\rho)(\partial\rho/\partial z)$ and buoyancy scale $l\pi = \rho(\partial\rho/\partial z)\text{-}1$.

The studies using the theory of physical modeling of hydrodynamics and heat transfer in liquid metals were made it possible to obtain data on the physics and characteristics of processes in liquid metal-cooled reactors. These data are the basis for the development of methods of thermal hydraulic calculation and three-dimensional thermal hydraulic codes.

Thank you for your attention!

ИАТЭ НИЯУ МИФИ

MULTI-PURPOSE NUCLEAR POWER UNIT WITH ELECTRIC CAPACITY OF 75 MW

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Preface

ИАТЭ НИЯУ МИФИ

- **The presentation is devoted not so much to a power unit, as to a special reactor that burns minor actinides (MA) with a hard neutron spectrum (average neutron energy (En average = 0.87 MeV) and a high proportion (35%) of hard neutrons (En> 0.8 MeV) .**
- **This is due to the fact that the reactor-burner is supplied with innovative fuel with enrichment exceeding the enrichment allowed for the power units (19.75%).**
- **The presentation considers only the concept of a reactor with a thermal power of 25 MW.**

Contents

The need for reactors with a hard neutron spectrum

ИАТЭ НИЯУ МИФИ

- **As is known, a number of practical nuclear reactions such as (n, f), (n, p), (n, a) for some chemical elements are effective only in hard neutron spectra, at neutron energies above 0.8 MeV.**
- **Examples include the fission reactions (n, f) for burning the actinides Am-241, Pu-240, Pu-242, the reaction (n, p) to obtain the P-32 radioisotope on the S-32 target, the (n, a) to obtain a radioisotope P-33 on a target from Cl-36.**

The need for reactors with a hard neutron spectrum

ИАТЭ НИЯУ МИФИ

- **As a rule, high neutron flux density, more than 3·E+15 1/cm2·s, is required to effectively carry out these reactions in the reactor core.**
- **Such high-flux reactors are fast sodium reactors - BN-600, BN-800 and in the future - BN-1200M, BREST OD 300, BR-1200.**
- **However, using the example of the known neutron spectra of the BN-600 reactor, it will be shown that the average neutron energy in the core of fast sodium reactors does not exceed 0.5 MeV.**

The need for reactors with a hard neutron spectrum

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Sub core of the BN-600	Average neutron energy in the subcore, MeV	Share of hard neutrons in the spectrum , %	Am-241 one-group fission cross section, barn	Am-241 one-group capture cross section, barn	Am-241 probability of fission, $P = \sigma_{fis} / (\sigma_{fis} + \sigma_{cap})$, %
LEC	0.425	13.20	0.271	1.751	13.40
MEC	0.462	14.68	0.291	1.630	15.40
MOX	0.495	15.86	0.318	1.594	16.63
GEC	0.482	14.91	0.317	1.790	14.91

The need for reactors with a hard neutron spectrum

- **It follows from the Table that in the core of the BN-600 reactor the mean neutron energy does not exceed 0.5 MeV, and the fraction of hard neutrons (E_n > 0.8 MeV) in the spectrum is not more than 16%.**
- **At the same time, the maximum average (one-group) fission cross section of Am-241 is 0.3 barn, which at a large neutron capture cross section (1.7 barn) leads to a probability of fission of not more than 17%.**
- **The goal is to get the average neutron energy in the core of the reactor above 0.5 MeV, and the fraction of hard neutrons in the spectrum to be much more than 16%.**

Selection of core dimensions

- **The first necessary condition for the creation of such a reactor is the choice of dimensions of the core, in which there is no moderating neutrons during the their transport through the core.**
- **We believe that the maximum height and equivalent diameter of the core should not exceed 0.8 meters. With such dimensions of the core, the thermal capacity of the reactor will not exceed 200 MW.**
- **The report examines the design of a reactor with a thermal capacity of 25 MW.**
- **<u>The possibility of increasing the reactor capacity to 200 MW is currently being investigated</u>.**

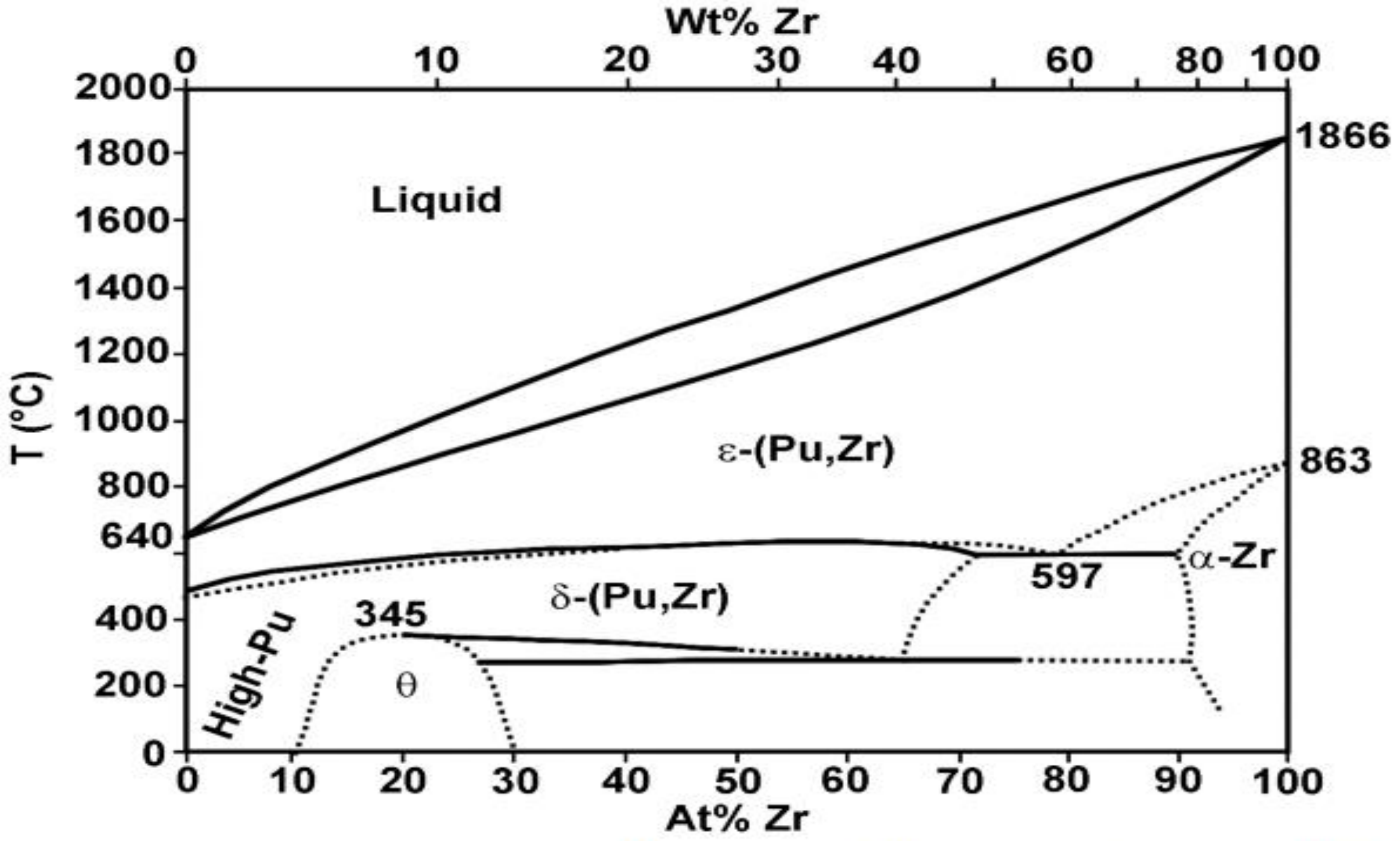
Choice of fuel

ИАТЭ НИЯУ МИФИ

- **The next condition for obtaining a hard spectrum is the choice of fuel. It should be only a metal fuel, without light chemical elements O, N, C.**
- **An example of such fuel is U-Pu-10Zr fuel, developed to a high level of technological readiness, TRL = 10, and now recommended in a fast sodium reactor ABR.**
- **In the report, in order to achieve an increased average neutron energy, Pu-42Zr plutonium fuel was considered, the level of technological readiness of which is currently not high, TRL = 5.**
- **From the Diagram of the state of the Pu-Zr alloy it follows that at a temperature of 1400 °C the Pu alloy with 42% of zirconium remains in the solid state.**

Choice of fuel

Background: Pu-Zr alloys



H. Okamoto, J. Phase Equilibria, 16 (1995) 287-288

Choice of fuel

Table of inelastic neutron scattering cross sections

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g ABBN	Low value MeV	High value MeV	Inelastic scattering of neutrons cross section, barn						
			Zr-nat	Pb-nat	U-235	U-238	Pu-238	Pu-239	U-233
1	6.500	**10.5**	1,55724	2,38149	1,01154	1,01826	0,71642	0,83171	0,61819
2	4.000	6.500	1,65030	1,38157	2,22165	2,66934	1,40124	1,67949	1,43121
3	2.500	4.000	1,56016	0,62579	2,40206	3,09087	1,59455	1,82475	1,54045
4	1.400	2.500	0,72001	0,24467	2,31038	3,16768	1,53693	1,82806	1,42405
5	**0.8**	1.400	0,20541	0,02520	1,93283	2,52269	1,13524	1,55875	1,07374
Average value:			**1.13862**	**0.93174**	**1.97569**	**2.49377**	**1.27688**	**1.54455**	**1.21753**

Choice of fuel

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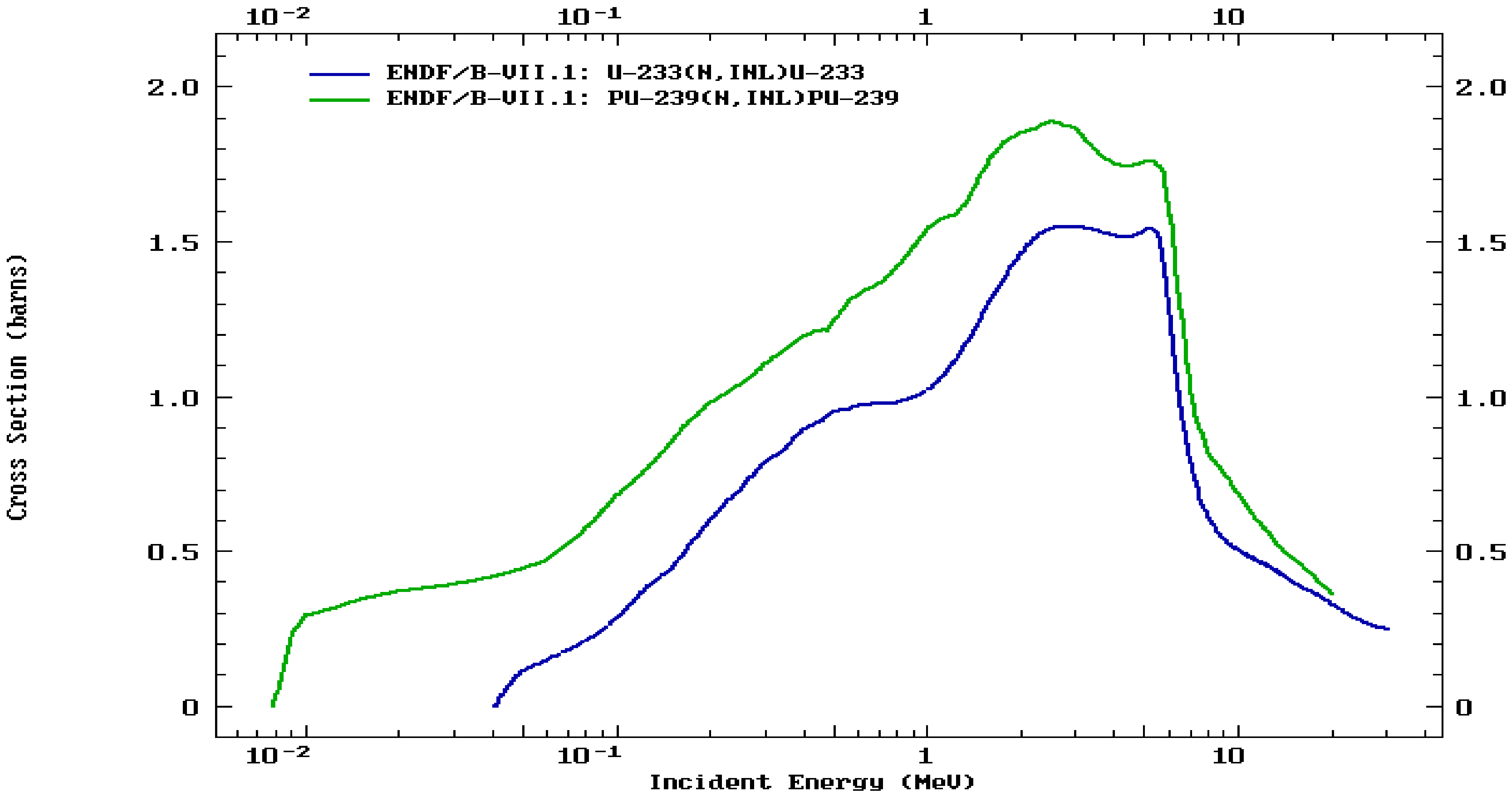
Cross sections of inelastic scattering of neutrons by U-233 and Pu-239 nuclei



Choice of coolant

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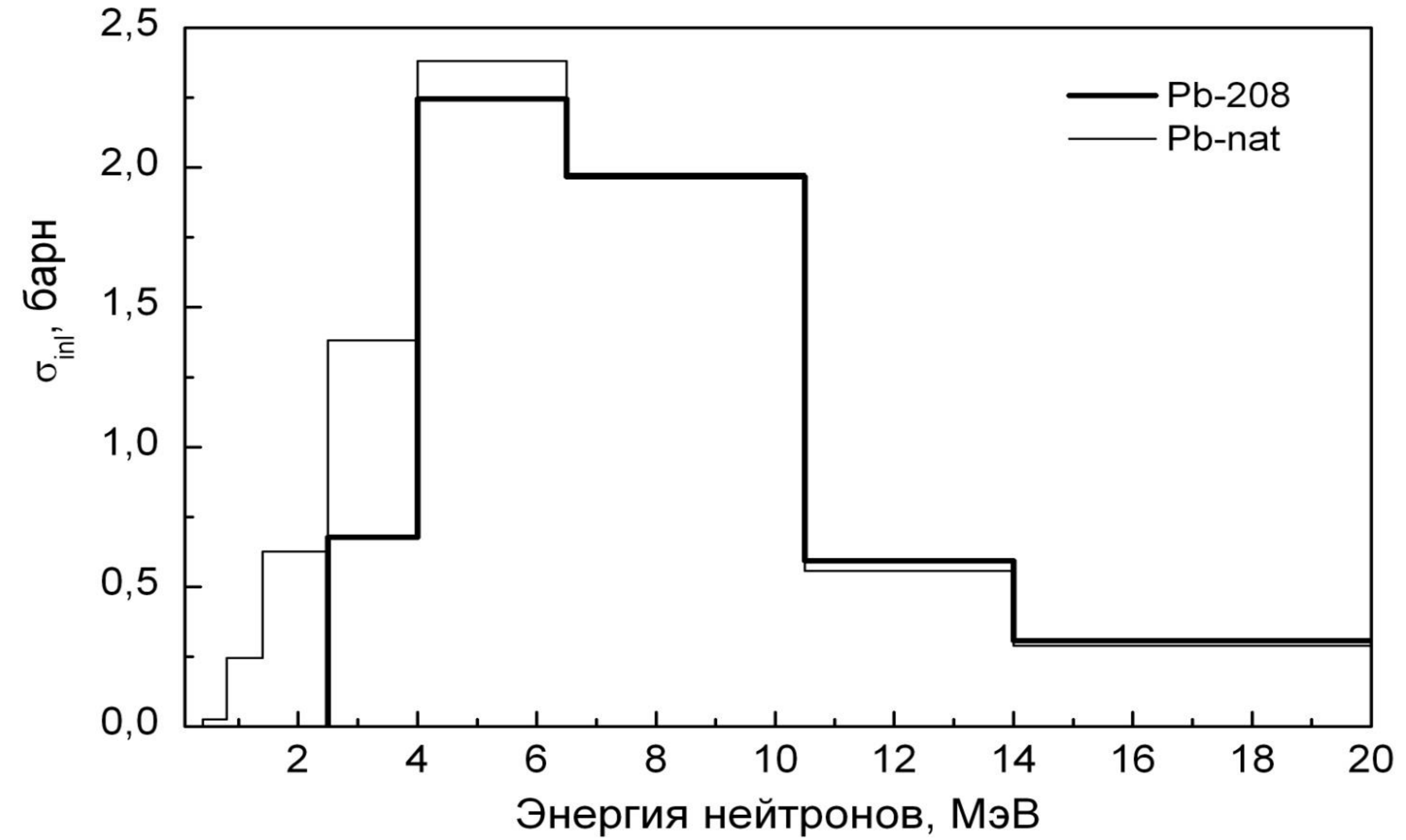

Design parameters of the BRUTS-25 reactor

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PARAMETER	VALUE
Thermal capacity, MW	25
Diameter and height of the core, m x m	0.4 x 0.42
Fuel	58Pu-42Zr
Mass of Pu power-grade in the core, kg	53
Coolant	Pb-nat
Coolant temperature at the core inlet/outlet, °C	450 / 530
Heat strength in the core, kW/l	396.7
Linear heat rates, kW/m	67.8
Cladding temperature, °C	610

Neutron characteristics of the core of the BRUTS-25 reactor

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PARAMETER	VALUE
Density of neutron flux in the core center, $1/cm^2 \cdot s$	$3.4 \cdot 10^{15}$
Average neutron energy in the core center, MeV	0.869
Share of hard neutrons, E_n>0,8 MeV, in spectra, %	34.61
^{240}Pu one-group fission cross section, barn	0.759
^{242}Pu one-group fission cross section, barn	0.599
^{241}Am one-group fission cross section, barn	0.640
^{241}Am one-group capture cross section, barn	0.784
^{241}Am fission probability, %	44.92

BRUTS-25 as a possible transmutator of minor actinides

ИАТЭ НИЯУ МИФИ

- **In fast reactors fueled by MOX fuel, the isotope Am-241 inevitably appears. Its source is Pu-241, whose share in the isotope power-grade plutonium vector is 2-3%. Pu-241 is beta-active with a half-life of 14 years and its decay product is Am-241, with a half-life of 432 years.**
- **Storage of Am-241 is inadvisable due to its high heat generation, 100 kW / ton, high alpha toxicity and volatility at high temperatures.**
- **At present, Am-241 together with other MA and FP are separated from SNF, vitrified and buried.**

BRUTS-25 as a possible transmutator of minor actinides

ИАТЭ НИЯУ МИФИ

- **In fuel BN-1200 after the first fuel campaign (5 years) contains up to 25-40 kg MA. (Data of OKBM and “Proryv"). At the end of the reactor (60 years), the amount of MA unloaded for 60 years will be 2.5 tons. If the fuel is recycled together with MA, then after 60 years the equilibrium content of MA will be 300-500 kg. But at the same time, Cm-245 (T=8500 y) is accumulated and the radiation properties of the fuel and the radiation situation on the fabrication factory are deteriorating:**

  - potential Am "volatility" when sintering mixed fuel pellets;

  - the increase in the radiation dose rate from recombined fuel, fuel elements and fuel assemblies ≈10 times (with the recurrence of the role of the Am-242m and Am-243 isotopes as recycled; (T_{Am242m} = 140 years, T_{Am243} = 7340 years);

  - the increase of neutron radiation by 2 orders of magnitude.

- **In the BN spectrum, Am-241 is divided with a low probability, not more than 17%, but mainly transmutes into Am-242 with beta decay into Cm-242 and Pu-242 (17%) and then to Cm-245.**

- **Using the example of a small lead reactor BRUTS-25, the path to burning Am-241 is indicated with a probability of fission by 3 times greater than in BNs and with Am-241 fission cross section by 2-2.5 times greater than in BNs.**

Conclusions

- **The increased average energy of neutrons in the core, and, most importantly, a high fraction, of 35%, of the hard neutrons is provided due to the following three factors:**
- **- the dimensions of the core are less than 0.8 x 0.8 meters,**
- **-an uranium free plutonium fuel, with a cross section for inelastic neutron scattering on fuel nuclei not more than 2 barns, using of U-233 can be considered .**
- **-heavy lead coolant with inelastic neutron scattering cross section on the coolant nuclei not more than 2 barns.**
- **In the case of lead with high content of Pb-208 isotope (up to 100%) in the BRUTS-25 reactor, the share of hard neutrons increases to 40-45%.**
- **Estimates show that for one fuel cycle of the BRUTS-25 (2 y) reactor it is possible to burn up to 15% of Am-241, which is put into the core. To burn large quantities of MA will require a line of several, up to 7-8, reactors of the BRUTS.**
- **In addition to burning actinides, such reactors may be in demand for obtaining radioisotopes and studies of the durability of nuclear materials in hard neutron spectra.**

Thank you for your attention!