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STUDIES OF LIQUID METAL BOILING IN FUEL ASSEMBLIES OF FAST REACTORS IN ACCIDENT CONDITIONS

The IAEA Technical Meeting on State-of-the-art Thermal Hydraulics of Fast Reactors / September 26-30, 2022, in ENEA Brasimone Research Centre, Camugnano, Italy

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Problematic issues of heat transfer studies during sodium boiling in fuel assemblies of a fast reactor in accident regimes

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- ✓ **Studies of the development of the boiling region, physics of the boiling process, regimes of a two-phase flow of sodium in the fuel assemblies of the core, their characteristics**
- ✓ **Studies of inter-channel instability of the circulation of a two-phase flow of a liquid metal coolant in a parallel fuel assembly system**
- ✓ **Validation of thermohydraulic calculation methods and verification of thermohydraulic codes to analyze the development of the boiling process in an individual fuel assembly and in a system of parallel fuel assemblies in the core in the circulation loop**
- ✓ **Experimental and computational studies of accident regimes (ULOF, UTOP) with sodium boiling in the fuel assemblies of the fast reactor core**
- ✓ **Approbation of a new technical solution (sodium cavity between the reactor core and the upper end shield)**

Features of the liquid metal boiling process

An important feature of fast reactors that affects heat transfer conditions is the low pressure in the coolant and the large difference in the density of the vapor and liquid phases, which is about three orders of magnitude

Compared to boiling water, the process of boiling liquid metals has significant features:

- ✓ **the interaction of individual factors is so complex that the initial overheating for boiling liquid metals is difficult to predict**
- ✓ **alkali metals form bubbles of a sufficiently large size on a limited number of centers of vaporization, the main part of the bubble formation cycle time falls on the waiting period**
- ✓ **alkali metal vapor bubble growth is explosive; growth velocities ~ 10 m/s**
- ✓ **the main flow regimes of two-phase flows of alkali metals are the same as that of conventional coolants: at a pressure close to atmospheric, the annular-dispersed flow regime prevails**
- ✓ **friction resistance in two-phase flows with heat input is lower than in adiabatic flows, which is associated with the displacing effect of the flow**
- ✓ **the phase transition during the annular-dispersed flow of alkali metals in the channels, as a rule, is carried out by evaporation from the surface of the wall film of liquid metal without the formation of bubbles (boiling) on the wall, while the effective heat transfer coefficient reaches hundreds of kW/m^2**

High temperature liquid metal facility «AR-1»

The three-circuit liquid metal facility "AR-1" (accidental regimes) is purposed for research of experimental modeling of the thermohydraulic processes in the equipments of a nuclear power plant at starting, transitive and accidental regimes, including the heat transfer process and the stability of circulation during boiling of a liquid metal coolant in a fuel assembly

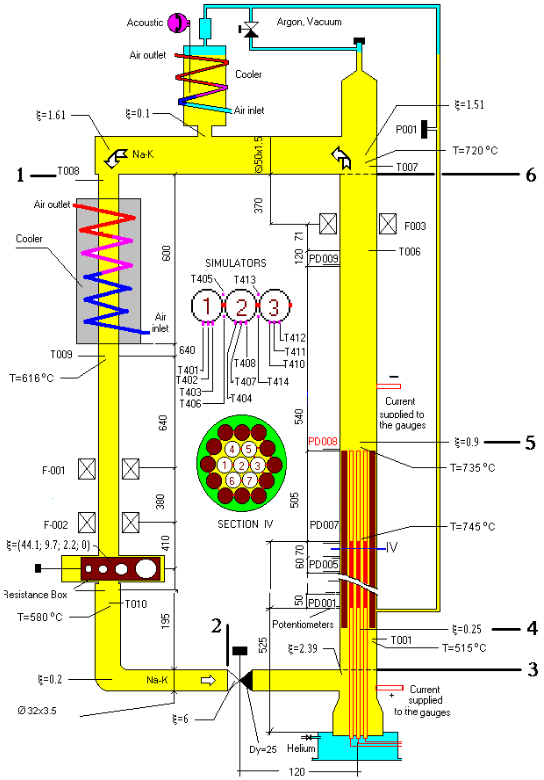
Measured parameters: power, flow rate, temperature, velocity, pressure of the coolant, pressure in the gas circuit, indication of boiling modes (acoustic sensors, potentiometry)

Experimental research

- ✓ study of hydrodynamics and heat transfer processes in the equipment of fast reactors with sodium coolant
- ✓ studies of the characteristics of the decay heat removal system of a fast reactor with heat exchangers integrated in the reactor vessel
- ✓ study of the process of boiling of liquid metals in fuel assemblies of the core of fast reactors in accidental regimes

Coolant	Na	Na-K
Flow rate, m^3/h	50	5
Pressure, MPa	1	0.6
Maximum temperature, °C	up 1100	up 700
Power, kW	750	750

An experimental installation for studying heat transfer during boiling of a sodium-potassium alloy in a fuel assembly in a circuit with natural coolant circulation



The installation for studying the boiling of a sodium-potassium alloy (22% Na + 78% K) in a fuel assembly contains two vertical channels 3 m high, connected at the top and bottom and forming the lowering and lifting branches of the circulation circuit of coolant.

In the lower part of the lifting channel there is a working section containing an assembly of 7 fuel element simulators and 12 displacer rods in a triangular lattice with a step of 1.185, enclosed in a stainless steel pipe measuring 50×1.5 mm and 3 m long.

The fuel rod simulators are calibrated stainless steel tubes of the grade X18H10 with a diameter of 8 mm and a thickness of 1 mm, inside of which spiral molybdenum wire heaters with a diameter of 1 m are installed. The diameter of the spirals is 4 mm, the length is 420 mm. The space between the spiral and the shell is filled with high-temperature electrical insulating backfill and helium.

The installation is equipped with a significant number of measuring channels containing various sensors.

Methodology and measurement system for studies of boiling up and boiling development of sodium-potassium alloy in a model fuel assembly in a circuit with natural coolant circulation

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- ✓ The experiments were performed with a stepwise increase in the power of energy release in the range from 100 to 270 kW/m^2 at reduced pressure: the pressure in the respiratory containers was about 0.6 bar, which corresponded to the pressure in the upper energy release region in the FA models in the range of 0.59–0.62 bar
- ✓ The measurement system during the experiments controlled the following parameters:
  - electric power supplied to the fuel elements and electric heaters of the installation
  - coolant flow rate at the entrance to the working section
  - static pressure and pressure pulsations in the boiling zone
  - pressure drop in fuel assembly models in the areas of heat generation
  - surface temperature of fuel elements in 3 sections along the height of the energy release section
  - coolant temperature along the height of the energy release section and at a number of points in the circulation circuit
  - readings of potentiometric sensors
  - cooling water consumption
- ✓ To measure the flow at the entrance to the energy release zone, a magnetic flow meter is installed
- ✓ The static pressure in the boiling zone was monitored using an exemplary pressure gauge. The pressure drop across the working areas was measured by Sapphire-22DD transducers. Measurement of pulsations of the coolant pressure in the boiling zone was carried out by the PULS sensor
- ✓ The temperature of the outer surface of the simulators and coolant was measured by chromel-alumel thermocouples in stainless steel cases with a diameter of 0.5–0.8 mm
- ✓ The collection and registration of experimental data was carried out in a digitalized form by an automated research management system

Boiling heat transfer of a sodium-potassium alloy in a model fuel assembly with fuel element simulators with low surface roughness

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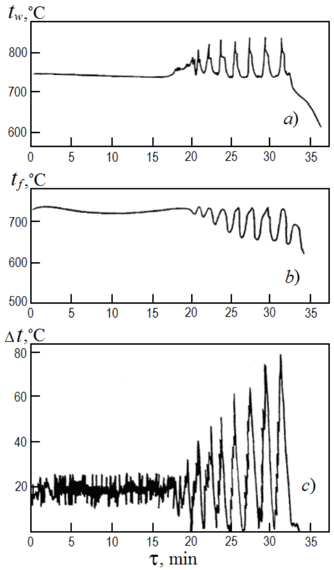
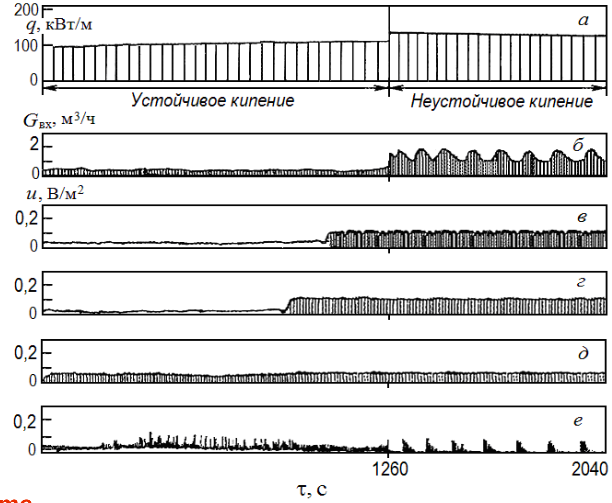
The experiments were carried out on smooth, specially cold-rolled tubes



Temperature characteristics reflecting the dynamics of the thermal regime of the fluidized assembly: temperature change of the wall of fuel rod simulators (a), coolant at the exit from the energy release zone (section IV) (b) and temperature difference between wall and liquid in section III (c)

Steady Boiling Regime

Boiling begins at the very end of the energy release section (sensor No. 3) at a heat flux density of 117 kW/m^2 and, as the input power increases, it spreads to the entire energy release zone (sensors No. 2 and No. 1) at a constant coolant flow



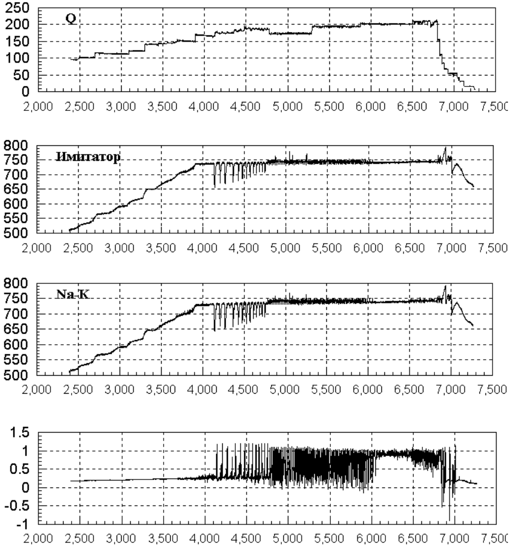
Unstable pulsating boiling regime

At a heat flux density of 133 kW/m2, there was a transition to a pulsating regime. At the beginning of the cycle, the energy release zone was steamed, then the resulting plug surfaced, and the vacated zone was filled with a “cold” coolant that entered the working section inlet. The change in the signal of the potentiometric sensor (sensor No. 4) acquired a character similar to the change in flow. There were sharp bursts of temperature on the wall of the simulators with an amplitude of up to 90°C

With an increase in the heat flux density up to 150 kW/m2, the coolant flow rate decreased almost to zero, and then sharply increased

Boiling heat transfer of a sodium-potassium alloy in a model fuel assembly with fuel element simulators with industrial surface roughness

The experiments were carried out on rough prefabricated tubes



The heat flux density, the temperature of the simulator and the coolant at the outlet of the energy release zone, and the volumetric flow rate of the coolant in the experiment with the throttle

Bubble regime

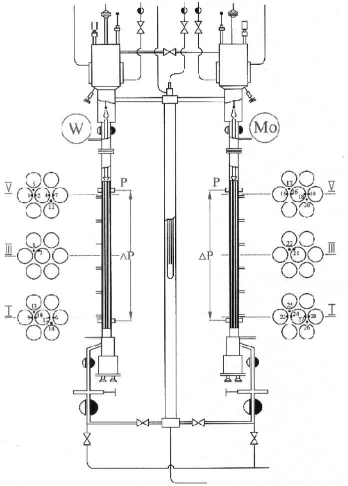
Feature – stable temperature values of the coolant and simulators, differential pressure on the assembly, coolant flow

Slug regime (heat flux density from 125 to 170 kW/m²). The pulsation nature, the formation of large steam bubbles (shells) with an interval of 40 s or more, which at the time of ascent cause a sharp increase in the flow of coolant at the inlet and significant fluctuations in the measured parameters. The shell temperature of the simulators does not exceed the saturation temperature, which indicates a liquid film on the surface of the simulators. An increase in assembly power leads to an increase in the frequency of formation of shells and a decrease in the amplitude of temperature pulsations

Annular-dispersed regime

Stable behavior of the measured parameters. Evaporation of liquid and entrainment of droplets from the surface of the simulators leads to drainage of the surface – a heat exchange crisis, melting of the shell of the simulators and a transition to a severe accident. Therefore, the *annular-dispersed* is the limiting boiling mode that provides cooling of the fuel assemblies

Studies of inter-channel instability of circulation during boiling of a sodium-potassium alloy in a system of two parallel fuel assemblies (1)



Experimental model for research of boiling in a system of parallel fuel assemblies

The measurement system and experimental procedure for the experimental version for a parallel fuel assembly system are similar for the experimental version for a single fuel assembly

- The test section consists of two natural circulation contours, in each of which model assemblies with 7 simulators are installed, with a common lowering section of the circuit in which the refrigerator is located. Capacities above assemblies are also connected
- Each of the assemblies can operate autonomously in its circulation contour
- The diameter of the simulators is 8 mm, the relative step of the grating is 1.19, and the length of energy release is 830 mm
- In front of the energy release zone, a hydrodynamic stabilization section 130 mm long. Above the energy release zone, an unheated section of the traction arm 800 mm high
- The pressure is changed by pumping argon from the gas cavities of the tanks located above the fuel assemblies
- In front of the fuel assemblies, throttle devices with washers of 12 mm, 16 mm and 20 mm are installed in the right and left contours
- Heat removal from the contours is carried out by Field Tube type refrigerators on the lowering lines of the contours, and by shirts on the tanks in the upper part of the circulation contour

Studies of inter-channel instability of circulation during boiling of a sodium-potassium alloy in a system of two parallel fuel assemblies (2)

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During experiment the coolant temperature has attained of saturation temperature more quickly in left fuel assembly than n the right

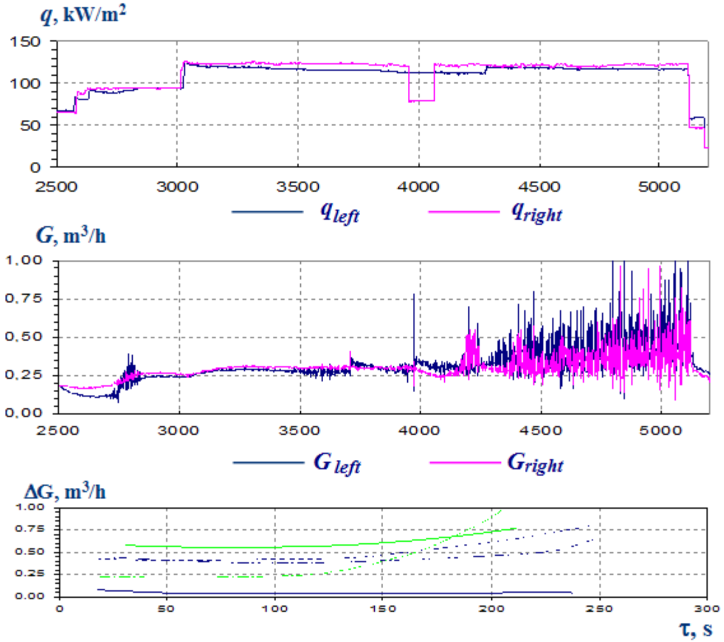
At a heat flow from simulators ~95 kW/m² the boiling up of coolant has **begun in left fuel assembly, the coolant flow rate in the left contour has sharply decreased. The jump of the coolant flow rate in both contours up to ~0.45 m³/h was occur through ~30 s**

At increase in a heat flow up to 130 kW/m² the change of parametres values occurred synchronously in the left and right contours

The parametres oscillations with small amplitude and period ~3 s (self-oscillations) were observed in interval from 3500 to 4200 s

Then an out-of-phase regime of oscillations with big amplitude and period 20–35 s occur with superposition of self-oscillations regime

The amplitude of coolant flow rate oscillations has increased up to ~ 0.50 m³/h in comparison with a contour of single fuel assembly ~ 0.05 m³/h, it is indicate on effect of a intensification of pulsations owing to hydraulic interacting of parallel channels – effect of inter-channel instability. Thus the falling of coolant flow rates in left and in right contours up to 3–5 times is observed

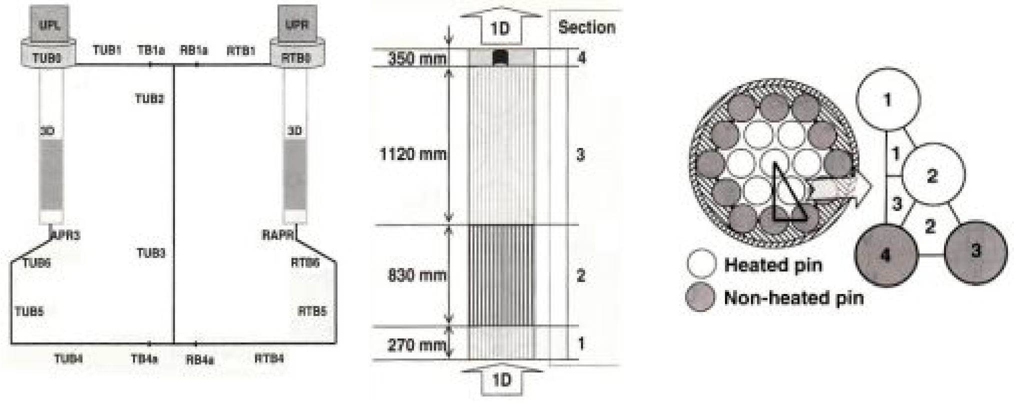


Change over time of a heat flow density and a coolant flow rate on an input in left and right fuel assembly

Методика численного моделирования кипения жидкого металла в системе параллельных ТВС

Для численного моделирования гидродинамики и теплообмена при кипении жидкого металла в системе параллельных ТВС развита новая версия кода SABENA-3D, разработанного ранее для теплогидравлического анализа кипения натрия в ТВС быстрых реакторов, реализующая двухжидкостную модель двухфазного потока жидкого металла в приближении равных давлений в паровой и жидкой фазах.

- ✓ Сборка тепловыделяющих элементов моделируется в многомерном поканальном приближении, остальная часть контура циркуляции в одномерном приближении.
- ✓ Реализованная в коде численная процедура решения системы уравнений сохранения массы, импульса и энергии двухфазного потока по методу конечных разностей позволила выполнить численное моделирование теплогидравлики в циркуляционном контуре как для случая одиночной ТВС, так и системы параллельных ТВС.
- ✓ Замыкающие соотношения и теплофизические свойства эвтектического натрий-калиевого сплава уточнены путем проведения анализа.



Схематическое изображение контура циркуляции, продольного и поперечного сечений ТВС

The results of numerical simulation of boiling liquid metal in a parallel fuel assembly system

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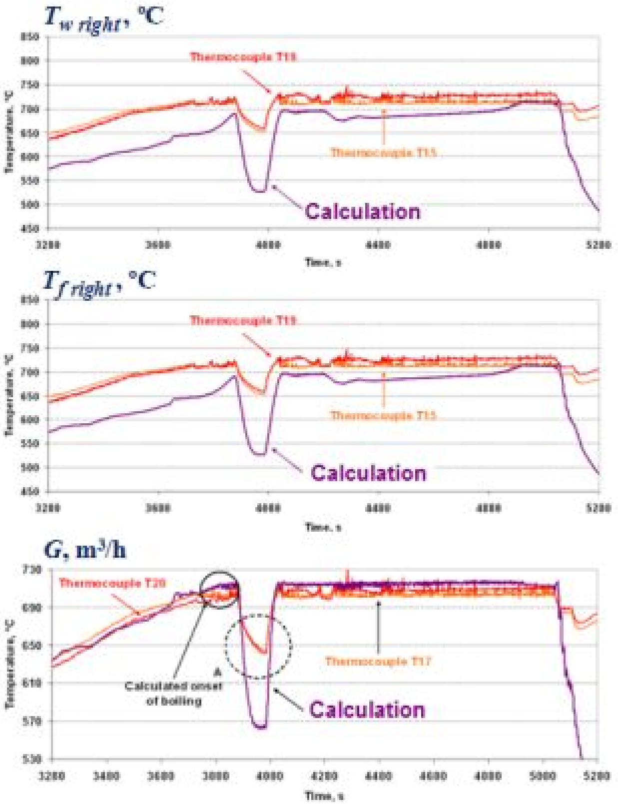
The modified SABENA-3D calculation code made it possible to carry out numerical modeling of heat transfer processes and stability of the coolant circulation during boiling of liquid metal both in single fuel assemblies and in a parallel fuel assembly system in a circuit with natural convection

Comparison of calculated and experimental distributions in time of the surface temperature of the fuel elements (a), the temperature of the coolant (b), the flow rate of the coolant (c) in the right fuel assembly during parallel operation of the fuel assembly with the same energy release



a)

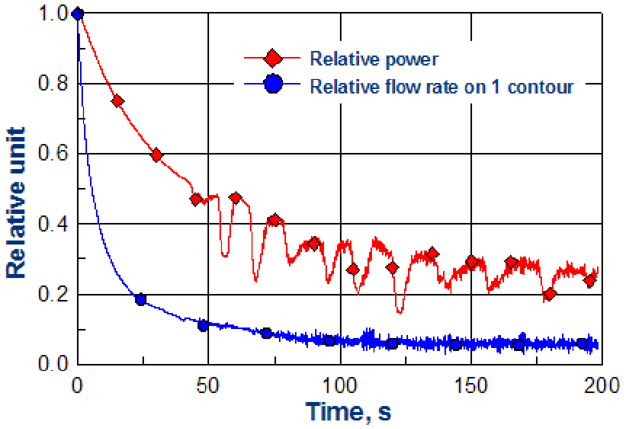
b)

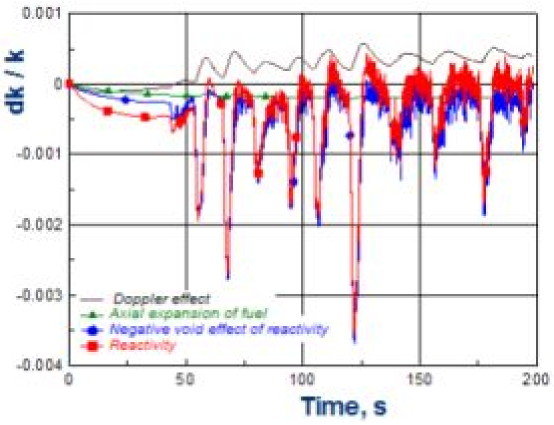
c)

Investigations of the cooling of fuel assemblies of a core with a sodium cavity in an ULOF accident with sodium boiling

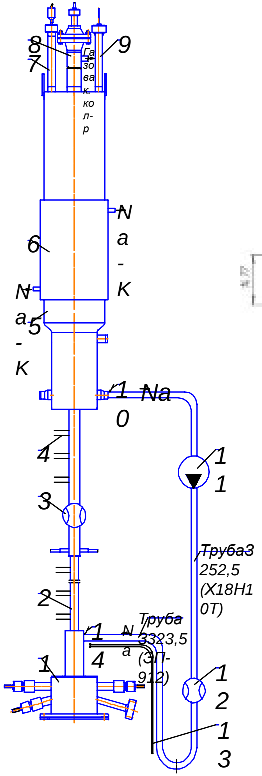
The task – the technical solutions adopted should exclude the development of emergency situations leading to a heat transfer crisis and the destruction of core elements

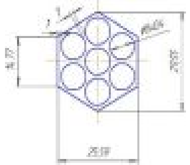
- ✓ **The computational studies using the COREMELT code in the SSC RF – IPPE of the self-protection of a fast neutron reactor with respect to the ULOF accident showed the possibility of cooling fuel assemblies with a sodium cavity above the core in the event of sodium boiling**
- ✓ **After sodium boiling, it is partially removed from the upper region of the fuel bundle. The negative sodium void effect of reactivity in this area leads to a decrease in reactor power and a decrease in the rate of boiling of the coolant**
- ✓ **As a result, against the background of a general decrease in power, a regime of periodic boiling of sodium is realized with a decreasing amplitude of fluctuations in power, flow rate and reactivity**





An experimental facility for the study of sodium boiling in a seven element fuel assembly in emergency conditions

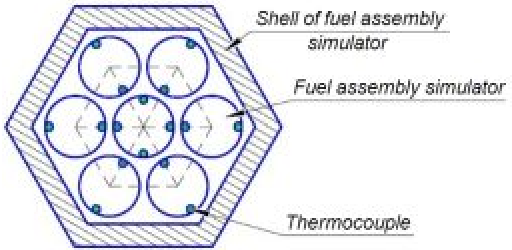




The experimental setup consists of two circulating contours: the main contour with sodium coolant and the auxiliary contour with an air heat exchanger (cooler jacket mounted on the outer surface of the expansion tank)

1 – *Node for locating current leads and thermocouples*
2 – *Bundle of fuel pin simulators*
3 – *Flow meter*
4 – *Potentiometric sensors of vapor generation*
5 – *Sodium vessel*
6 – *Cooler jacket*
7 – *Acoustic sensors of boiling*
8 – *Thermocouples lead*
9 – *Level gauge*
10 – *Thermocouple (on outlet vessel)*
11 – *Electromagnetic pump*
12 – *Magnetic Flow meter*
13 – *Heater*
14 – *Thermocouple (fuel bundle inlet)*

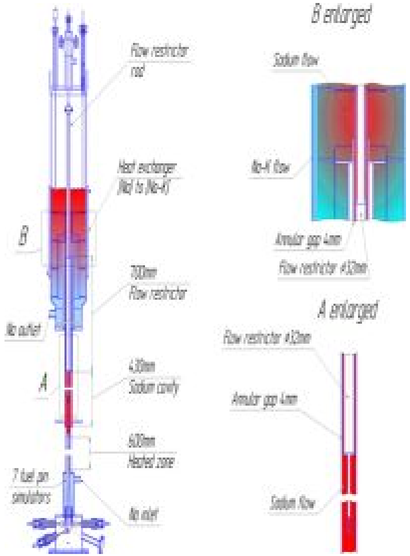
Experimental model with seven elements for research of sodium boiling in fuel subassembly with sodium cavity



The assembly of fuel simulators consists of 7 elements with a diameter of about 9 mm and a length of 1200 mm with electric heating, packaged in a triangular grid with a relative pitch of 1.11 and spacing with wire winding with a pitch of 180 mm

The assembly is placed in a hexagonal case made of heat-resistant steel, which serves as a housing

Its outer surface is equipped with potentiometric sensors, thermocouples, a security heater and is enclosed in a layer of thermal insulation



After pre-heating in the loop direct-heating heater, sodium first enters the inlet chamber of the experimental section, then into the region of the core model, where it is heated by fuel element simulators

A 430 mm long sodium cavity is located above the core model. Further, sodium passes through an area obscured by a simulator of the upper end shield, which, together with the model body, forms a narrow annular gap

Methods and results of the heat transfer study during sodium boiling in a model of fuel assemblies with a sodium cavity in natural convection regimes

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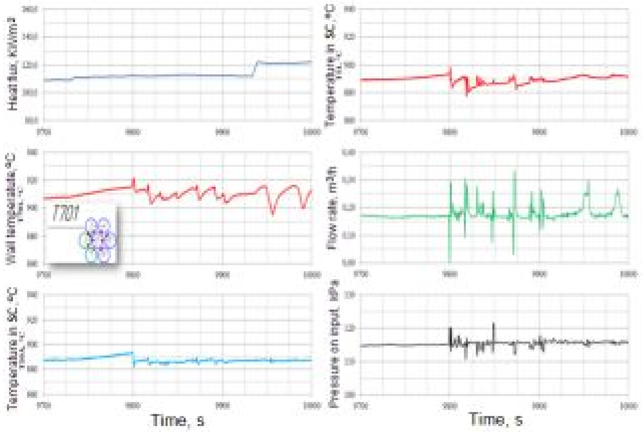

Change in the wall temperature of the central simulator (T701), the temperature of the coolant in the sodium cavity and the flow rate during boiling of sodium in the heat flux range from 115 to 120 kW/m²

- ✓ The sodium boiling regime is reached in a fuel assembly model with a "sodium cavity" and an installed model of the upper end screen, and without an end screen, by increasing the power of energy release of fuel element simulators
- ✓ The heat flux values in the experiment ranged from 110 kW/m² to 140 kW/m², the heating medium was 260−265°C, the inlet temperature was 636°C, and the saturation temperature at the outlet of the heating zone was 890−900°C
- ✓ The boiling of the coolant was recorded at a time of 9799 seconds according to the readings of the flow meter of the boiling indicator, the flow meter in the single-phase region, the signals of the acoustic and pressure pulsations

At this point, the flow rate drops to zero. After 0.5 s, a short-term jump in the wall temperature of the central simulator was recorded, which is associated with a stop of the coolant flow, the temperature of the liquid in the initial region of the “sodium cavity” increases by 6°C, then the flow increases to 0.3 m³/h and the temperature of the simulator wall decreases to 911 C for 3 s. This process is repeated several times and represents an intense boiling and attenuation of sodium boiling due to increased consumption

In the rest of the time, the bubble regime with variable intensity prevails, now completely damping then significantly intensifying and accompanied by an increase in flow for a period of up to 10 s

Cartogram of a two-phase flow during boiling of alkali liquid metals in fuel assemblies fast reactors

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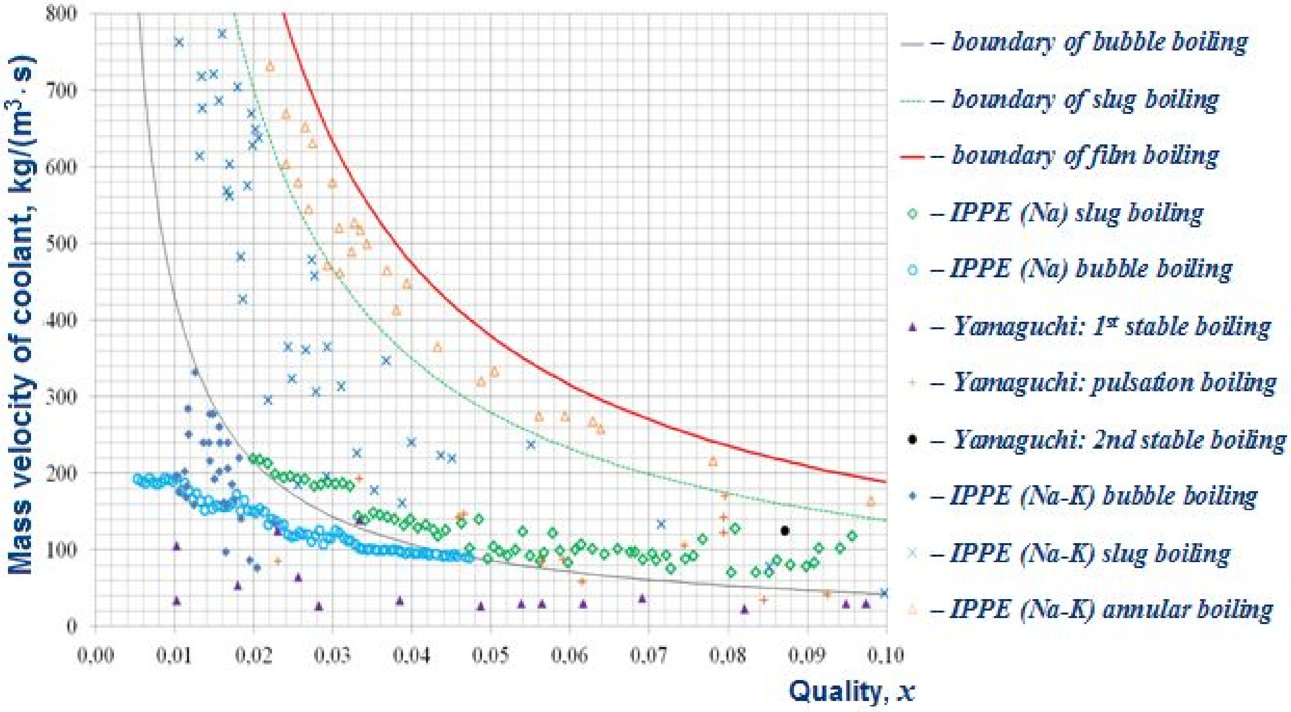
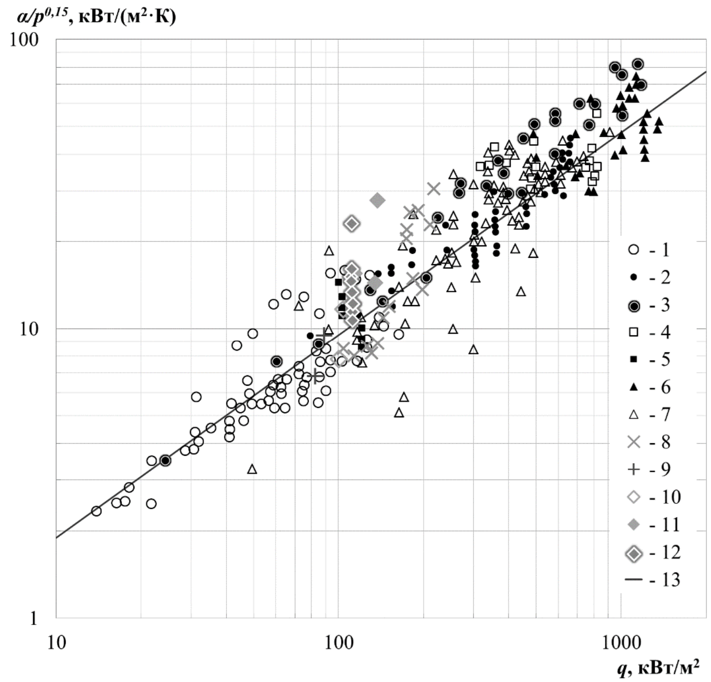


The experimental data for the FAs model with a sodium cavity are coralated with data from a series of experiments on FAs models without a sodium cavity in contours with natural circulation by liquid metal coolants

Heat transfer during boiling of alkaline liquid metal coolants in pipes and fuel assemblies



Comparison of the experimental data of different authors on the heat transfer during liquid metals boiling in pipes with the data of IPPE JSC for fuel rod bundles

At heat flux density above 100 kW/m^2 the heat transfer during liquid alkaline metals boiling in fuel assemblies and pipes is higher than at pure boiling in 1.5 times

Since, according to the idea of the thermodynamic similarity of alkaline metals, the thermophysical properties (λ, r, σ, ρ, T_S) can be discrabed in terms of p/p_{cr}, the formula for heat transfer during boiling of liquid metals has the form:

$$\alpha = Aq^{2/3}\left(p/p_{cr}\right)^n$$

where q is is the heat flux density, W/m^2;
p is the pressure, MPa

The presented formula is coralated with the formulas for the bubble boiling of water and other liquids at p = 0.1 MPa

The reason for the similarity is the close value of the evaporation rate ($w_{ev} = q/(r \cdot p'')$), since the heat of evaporation per unit volume of different liquids is approximately the same

Conclusion

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The results of experimental studies of the boiling of liquid metals in model fuel assemblies in natural convection mode show:

- ✓ steady bubble boiling in model fuel assemblies is observed only in a limited region of heat fluxes; its transition to an unstable pulsed plug boiling regime is determined by various factors
- ✓ in an assembly with a low surface roughness of the fuel element simulators, the development of an unstable regime with sharp fluctuations in the coolant flow rate and overheating of the wall of the simulators can lead to a heat exchange crisis, there is essentially no reserve before the crisis
- ✓ for simulators with industrial surface roughness due to the appearance of liquid on the surface of the film, there is a transition from an unstable plug to a stable annular-dispersed regime
- ✓ the occurrence of an oscillatory process during boiling of the coolant in one of the parallel fuel assemblies leads to an out-of-phase oscillatory process in the other fuel assemblies; subsequently, oscillations in various circuits are of an out-of-phase nature
- ✓ the hydrodynamic interaction of the circuits over time leads to a significant increase in the amplitude of fluctuations in the flow rate of the coolant in them (“resonance” of flow rate pulsations) and the possible “blocking” or inversion of flow rate of the coolant in the circuits, an increase in the temperature of the coolant and the shell of the fuel elements (inter-channel instability effect) and, in ultimately, the occurrence of a heat transfer crisis
- ✓ the cartogram of the flow regimes of a two-phase liquid metal flow differs significantly from the cartogram for water
- ✓ heat transfer coefficients of fuel element simulators during boiling of liquid metal in fuel assemblies in single circuits and during their parallel operation are agree with each other and are in the same range as the data in heat transfer during boiling of liquid metals in pipes and in large volumes
- ✓ experimental studies of heat transfer during sodium boiling in fuel assemblies with a "sodium cavity" between the core and the upper end shield showed the possibility of cooling fuel assemblies in emergency modes (ULOF, UTOP)

The modified SABENA-3D calculation code can simulate the processes of heat transfer and hydrodynamic stability of the coolant circulation during boiling of liquid metal both in single fuel assemblies and in a parallel fuel assembly system in circuits with natural convection

Thank you
for your attention

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