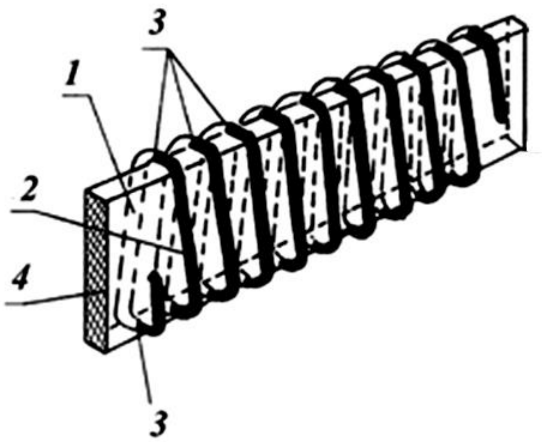
SECTION 3. DEVICES

DOI: 10.46299/ISG.2024.MONO.TECH.1.3.1

3.1 Heat flux sensors for harsh operating conditions

Thermopile heat flux sensors (HFSs), which are made on the basis of a wire spiral made of thermoelectrode material, are widely used throughout the world. Separate sections of coupled thermoelectrode material are galvanically applied to the spiral [212-214]. Such sensors have become widely used to solve the problems of diagnostics and monitoring of various objects in energy, construction and aerospace engineering, as well as the construction of various measuring devices, including calorimetric ones. [214-219]. The basis of such a battery of thermoelements is a flat spiral, which is wound onto a tape frame made of electrical insulating film (Fig. 1). The spiral is made of wire of the main thermoelectrode material with a periodically applied coating of paired thermoelectrode metal. At the same time, the boundaries of the transition from the main (carrying) thermoelectrode 1 to the bimetallic 2 are "joints" 3, which are located along both edges of the frame tape.



1 – main thermoelectrode; 2 – bimetallic thermoelectrode; 3 – thermocouple junctions; 4 – strip frame made of electrical insulating film.

Figure 1. A thermopile of thermoelements with electroplated application of thermoelectric material

In the manufacture of traditional flat HFS, a spiral of thermoelements is placed in a special matrix and filled with an electrically insulating epoxy compound with a thermally conductive filler to give it the shape of a monolithic plate. Such sensor is a so-called "additional wall", on opposite sides of which the junctions of thermoelements are located. In the presence of a heat flux passing through an additional wall, i.e. sensor plate, and accordingly, in parallel through all elements of the thermopile, a temperature difference occurs between the junctions, as a result of which an electrical signal is generated in each of the thermoelements connected in series. The total output signal of the sensor is proportional to the value of the heat flux [212-214].

The most common are sensors made of constantan-copper and nichrome-nickel thermoelectric pairs. Methods of calculation and construction of galvanic HFS have been developed, as well as technology and mechanized equipment for the manufacture of a spiral with galvanic coating [212, 214]. Such sensors have high sensitivity, since their manufacturing technology allows placing up to several hundred thermoelements per square centimeter of the sensor surface.

The practice of long-term operation of thermoelectric bimetallic multi-element HFSs has revealed their shortcomings, the main of which are a limited operating temperature range, the dependence of the conversion function on temperature, the instability of characteristics during long-term operation and under the influence of ionizing radiation and high temperature. The stability over time of the characteristics of sensors, in particular metrological ones, depends on many factors, some of them are similar to those that affect thermoelectric temperature sensors (thermocouples), but there are also a number of factors specific to HFS. During operation, HFS are subject to physical aging, as a result of which the properties of thermoelements change. The main reasons for these changes are oxidation and diffusion of thermoelectrode metals, changes in the structure of metals and the filling compound, diffusion of impurities and contamination of metals. Particularly difficult, but at the same time urgent, is ensuring the stability of the characteristics of sensors in-reactor calorimeters operating under harsh operating conditions, namely at elevated temperatures and under conditions of nuclear radiation [220-222]. Most materials that are used for the manufacture of thermopile HFSs with electroplated application of thermoelectrode material change their characteristics under the influence of ionizing radiation and are even destroyed.

This applies to copper and its alloys and epoxy resins, and the polyimide film is somewhat more stable compared to other polymers [221], but also cannot provide sufficiently long operation in the core of a nuclear reactor. Significantly more resistant metals are aluminum, nickel, chromel-alumel thermoelectrode pair; electrical insulators are mica, fiberglass; fine filler made of corundum (aluminum oxide Al_2O_3) and magnesium oxide (MgO) [222].

The problem associated with the temporal stability of HFS metrological characteristics has been resolved by moving from the widely used copper and precious metal platings to nickel platings. Due to the high corrosion resistance of nickel and its higher resistivity, copel-nickel and constantan-nickel pairs have been obtained, which are highly stable over time even under HFS operating conditions at temperatures up to 500 K. Moreover, in the temperature range from 300 K to 500 K, the change in the conversion function of such HFS does not exceed 3%. A further increase in temperature leads to a significant change in the HFS conversion function and the appearance of peaks at the Curie point temperature for nickel. This drawback was eliminated by the creation of bispiral HFSs, that have two thermopiles in their structure. Moreover, both thermopiles are made with a nickel coating, and the basis of the additional thermopile is a paired thermoelectrode [215, 223].

For calorimetric means operated in nuclear reactor conditions, it is proposed to use bispiral sensors using two series-connected spirals, the base wire of one of which is alumel, and the other is copel. Nickel is applied to both spirals of thermoelements using galvanic deposition as a paired thermoelectrode material.

When designing an HFS, the most important characteristic is its sensitivity and temperature dependence over the operating temperature range. Temperature dependences for thermoelements, which were made of alumel and chromel coated with nickel, were obtained experimentally in the temperature range up to 1070 K. Temperature dependences for thermoelements made of alumel and chromel coated with nickel were obtained experimentally in the temperature range up to 1070 K. In this case, each galvanic pair was simulated by pairs of wires twisted together from the main and paired thermoelectrode materials: chromel and alumel with nickel. The different ratio of the number of wires in each galvanic pair corresponded to the different thickness of the coating of the pair thermoelectrode. The working junction of galvanic pairs was placed in a cylinder made of stainless steel and filled with sand, which ensured a uniform temperature field and excluded electrical contact of the junction with the body of the metal cylinder. The measurements were carried out using a multi-channel computerized complex, from which the measurement information was transmitted to a personal computer via a USB interface. The measurement results are systematized in Fig. 2, where, f_3/f_1, f_3/f_2 is the ratio of the cross-sectional areas of nickel to the cross-section of chromel and the cross-section of nickel to the cross-section of alumel.

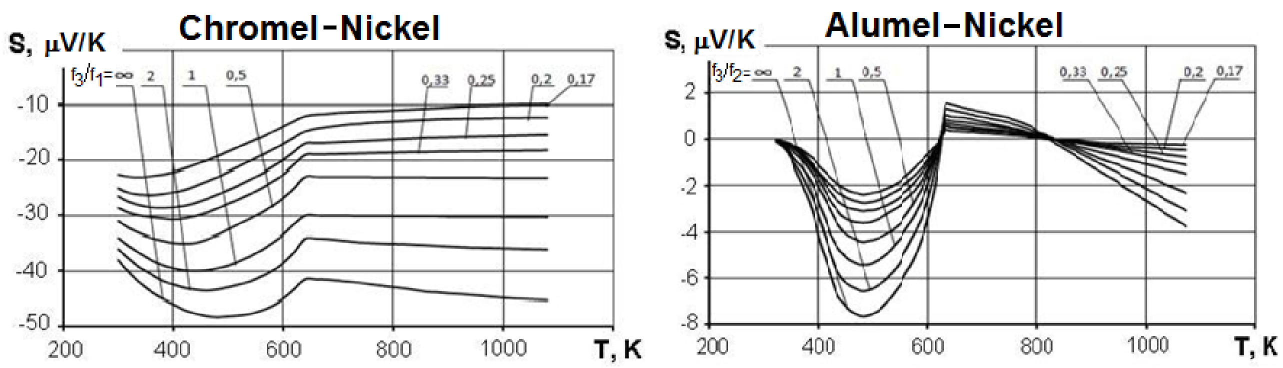


Figure 2. Temperature dependences of the sensitivity of single thermoelements made of alumel and chromel with a nickel coating.

Alumel contains about 95% nickel [224], therefore the absolute value of the thermo-emf of the alumel – nickel couple is relatively small and even changes sign in the zone near the Curie point temperature for nickel 631 K. The absolute value of the thermo-emf of the chromel – nickel couple is much greater, but has a significantly nonlinear dependence on temperature in the range from room temperature to the Curie point.

Figure 3 shows an equivalent electrical circuit of a bi-spiral sensor, which shows only two turns of each of the spirals, and point A is the connection of the two spirals.

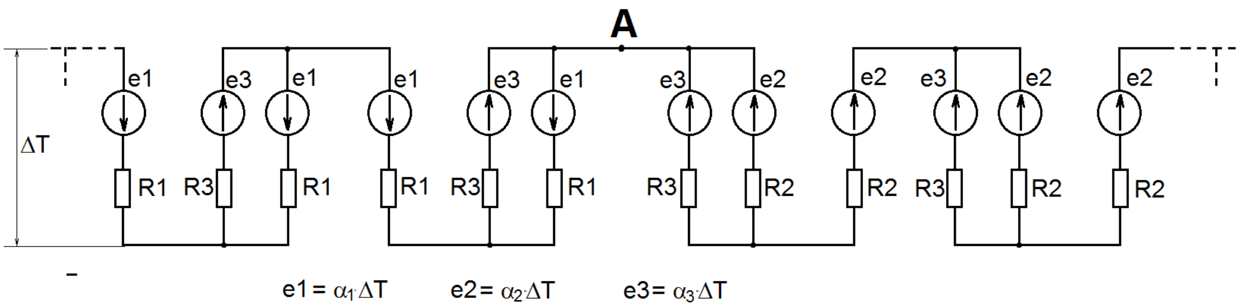


Figure 3. Equivalent electrical circuit of a bispiral sensor: R1, R2, R3 – electrical resistances of half-turns of the spiral (branches of thermoelements) made of chromel, alumel and nickel coating; e1, e2, e3 – thermo-emf, which is formed in the corresponding branch of the thermoelement as a result of the effect of the temperature difference ΔT.

The total signal of two thermopiles E_{Σ}, connected in back-to-back series, according to an electrical signal and in parallel with respect to the heat flux, is calculated by the formula (1):

$$E_{\Sigma} = E_1 - E_2 = R_T \cdot q \cdot (z_1 \cdot S_1 - z_2 \cdot S_2) = R_T \cdot q \cdot S_{\Sigma} \quad , \qquad (1)$$

where E_1, E_2 – signals of individual thermopiles; R_T – thermal resistance of the sensor between the planes of the thermocouple junctions; q – heat flux density; S_1, S_2, S_{Σ} – sensitivity of individual thermopiles and total sensitivity of two thermopiles; z_1, z_2 – number of thermoelements in thermopiles 1 and 2.

The total sensitivity of the two thermopiles, that is, the total sensitivity of the sensor, is calculated by the formula (2):

$$S_{\Sigma} = z_1 \cdot \frac{\alpha_1}{1 + \dfrac{\rho_3 \cdot f_1}{\rho_1 \cdot f_{3.1}}} - z_2 \cdot \frac{\alpha_2}{1 + \dfrac{\rho_3 \cdot f_2}{\rho_2 \cdot f_{3.2}}} + \alpha_3 \cdot \left(\frac{z_2}{1 + \dfrac{\rho_3 \cdot f_2}{\rho_2 \cdot f_{3.2}}} - \frac{z_1}{1 + \dfrac{\rho_3 \cdot f_1}{\rho_1 \cdot f_{3.1}}} \right) , \qquad (2)$$

where α_1, α_2, α_3 – Seebeck coefficients of main wire materials (chromel and alumel) 1 and 2 and coating material (nickel) 3; z_1, z_2 – number of thermoelements in the first and second thermopiles, respectively; ρ_1, ρ_2, ρ_3 – electrical specific resistivity of main wires 1, 2 and coating 3; f_1, f_2 – cross-sectional area of the base wires of thermoelement spirals; $f_{3.1} = f_3/f_1$, $f_{3.2} = f_3/f_2$ – relative cross-sectional areas of the nickel coating.

When the condition is met $$\frac{z_2}{1+\frac{\rho_3 \cdot f_2}{\rho_2 \cdot f_{3.2}}} = \frac{z_1}{1+\frac{\rho_3 \cdot f_1}{\rho_1 \cdot f_{3.1}}}, \qquad (3)$$

the sensitivity of the sensor does not depend on the properties of the coating material and is calculated using the formula (4):

$$S_\Sigma = z_1 \cdot \frac{\alpha_1}{1+\frac{\rho_3 \cdot f_1}{\rho_1 \cdot f_{3.1}}} - z_2 \cdot \frac{\alpha_2}{1+\frac{\rho_3 \cdot f_2}{\rho_2 \cdot f_{3.2}}}. \qquad (4)$$

That is, if condition (4) is met, the sensitivity of the bispiral sensor does not depend on the properties of the galvanic coating material. Thus, by choosing the parameters of the thermoelement spirals, it is possible to create a bispiral sensor, the sensitivity of which will depend only on the properties of the base wires, namely chromel and alumel. Based on formula (4), when mathematically subtracting the thermo-emf of another galvanic couple from the thermo-emf of one galvanic couple, it is possible to obtain the sensitivity dependences for a sensor containing one thermoelement each of chromel-nickel and alumel-nickel (Fig. 4).

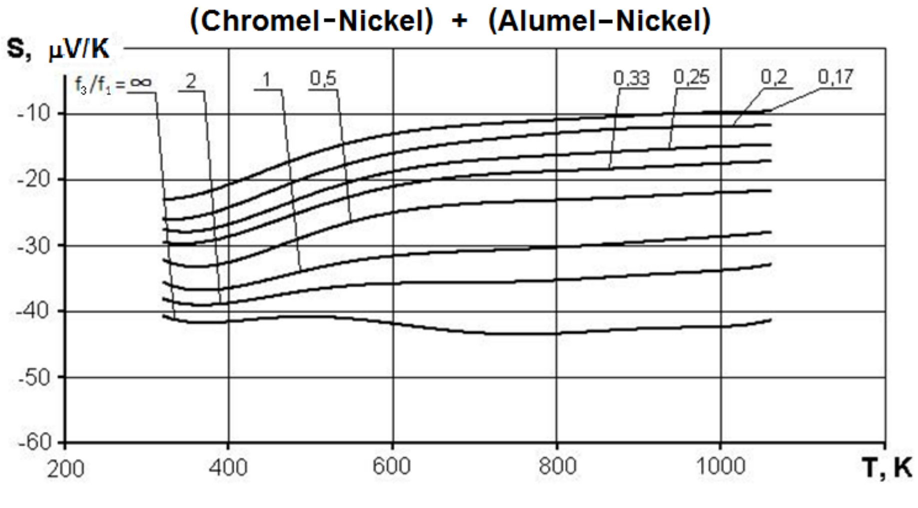


Figure 4 Temperature dependences of the sensitivity of the sensor containing one thermoelement each of chromel-nickel and alumel-nickel.

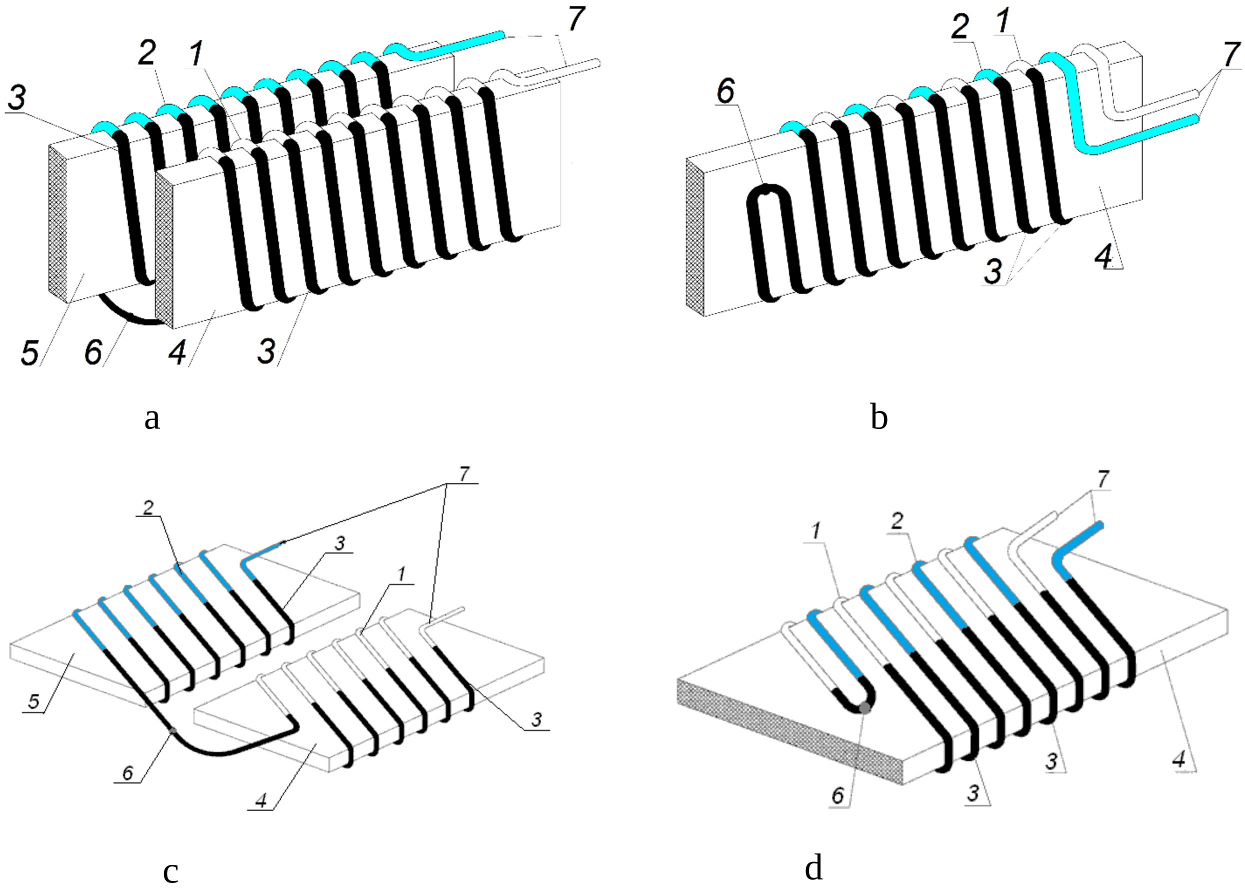
Value f_3/f_1 is the ratio of the cross-sectional areas of the nickel coating and the base wire of chromel and alumel.

From Fig. 4 it follows that the sensor in which the ratio of the cross-sectional areas of the nickel coating and the base wire made of chromel and alumel approaches infinity has the lowest temperature dependence of sensitivity, but in practice the thickness of a high-quality coating applied by an electrolytic method is limited. Therefore, it is advisable to choose the ratio of cross-sectional areas $f_3/f_1 = f_3/f_2 = 2$. That areas can actually be achieved using known technology, ensuring a relatively insignificant temperature dependence of the sensitivity of the spiral sensor, namely no more than ± 10% in the temperature range from 300 K to 1070 K.

Based on the results of the studies, it can be stated that special selection of the parameters of the bie-spiral sensor makes it possible to achieve that its sensitivity will not depend on the thermoelectric properties of the coating material of the main wires. Due to the fact that even a specially selected couple of thermoelectrode materials of base wires, namely chromel and alumel, has some temperature dependence of the Seebeck coefficients, the sensitivity remains to some extent a temperature-dependent value.

The results of studies of the temperature dependence of the sensitivity of thermoelements made of thermoelectrode materials (Fig. 2 and Fig. 4) make it possible to select the coating thickness and other parameters of batteries of thermoelements that will ensure minimization of the temperature dependence of the sensitivity of a sensor based on chromel and alumel with a nickel coating.

When manufacturing a spiral sensor, several design solutions are possible, which are schematically shown in Fig. 5. Options a and b refer to the case where the junctions are located on the edge of the supporting frame spiral tape, and options c and d refer to the case with the junctions on the flat edge of the tape.



1 – main thermoelectrode wire of the first spiral; 2 – thermoelectrode wire of the second spiral; 3 – electrolytic coating of the corresponding half-turns of each spiral; 4, 5 – frame insulating tapes; 6 – junction connection of spirals; 7 – output wires of thermocouple batteries.

Figure 5 Options for the design of a thermopile of thermoelements of a bispiral sensor (a, b – junctions on the edge of the frame tape; c, d – junctions on the flat edge of the tape).

According to the first version of the HFS design (Fig. 5, a) both spirals, which are made of main thermoelectrode wires 1 and 2 with an electrolytic coating of 3 half-turns, are wound on separate frame tapes 4 and 5. These tapes are made of strips of electrical insulating material of the same height and are arranged in parallel in such a way that the upper junctions of both spirals are in one plane and the lower junctions are in another one. The planes of the junctions are parallel and spaced at the height of the thermopile. Both spirals in junction 6 are connected in series and fixed into a single structure with a compound electrical insulating material or by other mechanical methods, for example, by inserting in the gap between two elements, sealing with electrical insulating material or backfilling (not shown in Fig. 5). The spiral sensor signal is output through lead-out wires 7.

The design of the HFS according to the version shown in Fig. 5, b, differs in that both spirals are located on a common frame tape 4, while the thermoelectrode wires 1 and 2 are wound in parallel and offset from each other with an insulating gap that does not allow electrical contact between the thermoelements.

Sensor designs with junctions on the flat edge of the tape (Fig. 5, c, d) can also be made in two similar options described above. That is, the sensor consists of two spirals, with each spiral placed on an individual carrier tape (option c) or on a common tape (option d), but with an offset to prevent the turns of one spiral from touching the turns of another spiral.

Options shown in Fig. 5 b and d are more convenient when forming a single calorimetric sensor, since one tape is used, from which it is easy to form a separate sensor or calorimetric covering. At the same time, the options shown in Fig. 5, a and b, provide more opportunities for varying the parameters of thermoelement spirals to ensure condition (3), i.e. it is possible to choose different and unequal values for the number of thermoelements and coating thickness.

It should be noted that at high temperatures, the mutual diffusion of materials at the point of contact is significantly accelerated, which leads to a change in the sensitivity of all thermoelectric devices. An experimental test of the stability of the sensitivity of the bispiral sensor was carried out by keeping it at a temperature of 520 K for 20 hours. After this, the sensitivity of the sensor remained stable within the measurement error. However, studying the stability of the characteristics of a bispiral sensor at high temperatures requires additional research.

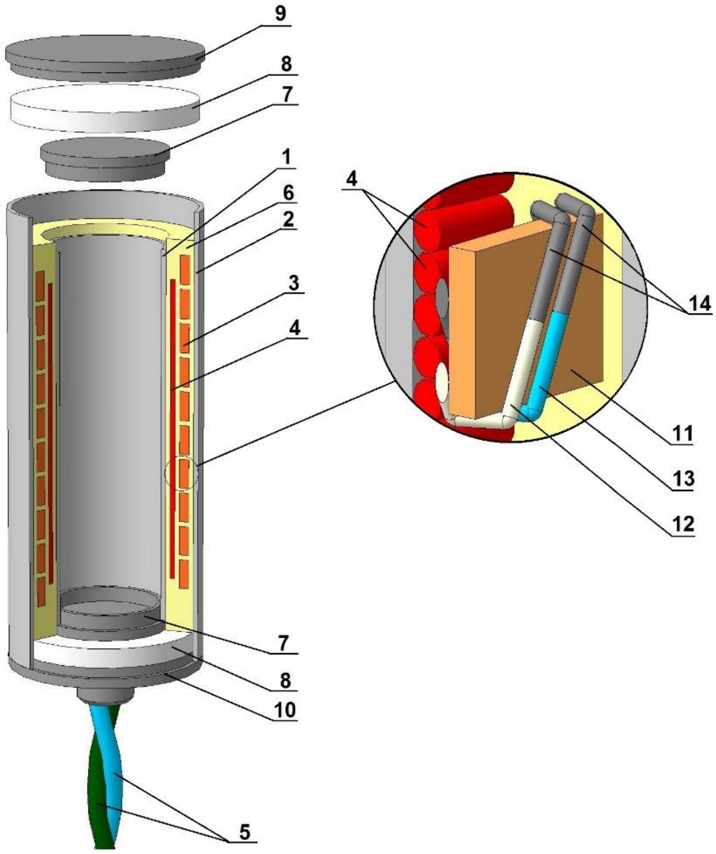
As mentioned above, bispiral thermopile sensors based on wires, which are made of chromel and alumel with a nickel coating, are promising for creating in-reactor calorimeters on their basis. Such measuring instruments are designed for measuring and operational monitoring of radiation heat release in structural materials that are irradiated in the channels of nuclear reactors and at the same time disintegrates or absorb radiation. At the Institute of Engineering Thermophysics of NAS of Ukraine, in collaboration with the Institute for Nuclear Research of NAS of Ukraine, a system of in-reactor calorimeters was developed, built on the basis of multilayer sensors with welded thermoelements from chromel and alumel, manufactured using labor-intensive and low-productivity technology [212, 220]. Typically, a system of in-reactor calorimeters consists of several (4–5 pieces) identical integral heat flux calorimeters. One or two calorimeters do not contain samples and are used to measure background heat generation in the calorimeter itself. Other calorimeters contain samples of the investigated materials.

The design of the proposed internal reactor calorimeter (Fig. 6) consists of two coaxial cylinders, namely, internal 1 and external 2, made of aluminum, which is a stable material under conditions of ionizing radiation.

Inner cylinder 1 forms a calorimetric cell in which the samples to be studied are placed. The ends of the cell cylinder are closed with aluminum caps 7 and heat-resistant ceramic washers 8, which act as thermal insulation. The edges of the outer cylinder of the housing are closed by an upper cover 9 and a lower one 10 with an outlet pipe.

In the internal space between the coaxial cylinders there is a thermopile 3 and an electric heater 4, to the ends of which lead wires 5 are connected. To impart solidity, the thermopile and electric heater are filled with electrically insulating silicone varnish KO-08 filled with corundum 6, which is also resistant to ionizing radiation.

The double spirals of the thermopile are wound on a fiberglass tape 11, while in one branch of the thermopile a chromel wire is used as the main thermoelectrode 12, and a nickel coating 14 is applied as a thermoelectrode couple. In another branch of the thermopile, alumel wire is used as the main thermoelectrode 13, and the coating 14 is also made of nickel. To carry out calibrations of the device, a layer of electric heater made of nichrome or chromel wire in fiberglass insulation 4 is evenly wound onto the inner cylinder 1. The outer diameter of such a calorimeter is 10-20 mm, and the length is 30-50 mm, depending on the requirements for the samples being studied, the design and heat exchange conditions in the measuring channel of a nuclear reactor. The measured thermal power is up to 20 W.



1 – inner cylinder (cell); 2 – outer cylinder; 3 – thermopile; 4 – electric heater; 5 – output wires; 6 – organosilicon varnish with corundum filler; 7 – cell covers; 8 – ceramic thermal insulation; 9 – upper cover of the calorimeter; 10 – lower cover of the calorimeter; 11 – frame tape; 12 – base wire made of chromel; 13 – base wire made of alumel; 14 – nickel coating.

Figure 6. Design of an in-reactor calorimeter with a bispiral sensor.

This design combines a number of advantages compared to the known ones, namely: the materials used in the manufacture of the spiral sensor do not change their physical characteristics under the influence of radiation; the sensitivity of such a measuring device is practically independent of temperature over the entire operating temperature range; during production, the traditional manufacturing technology is retained, which is used for the manufacture of standard HFSs and is well established.

Conclusions. Bispiral HFSs with galvanic depostiton of nickel on half a turn of chromel and alumel wire spirals are proposed and justified for use in harsh operating conditions, namely at elevated temperatures and nuclear radiation.

The developed design of the bispiral HFS for measuring heat release under harsh conditions of ionizing radiation in a wide temperature range allows for reliable recording of the measured parameter. Such a primary sensor can be used in in-reactor calorimeters, which will provide more accurate measurements.