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DEVELOPMENT AND CREATION OF A SELF-POWERED DETECTOR FOR THERMAL NEUTRON FLUX MEASUREMENTS

S.O. Sokolov[1], O.V. Rybka[1], O.O. Pudov[1,*], O.L. Ulybkin[1], O.V. Kosinov[2], V.E. Kutny[1], K.V. Kovtun[2], Ye.O. Bohdan[1], L.O. Pyrozhenko[1], A.I. Pikalov[1], R.V. Azhazha[1]

[1]National Science Center "Kharkiv Institute of Physics and Technology", Kharkiv, Ukraine;

[2]State Enterprise "Scientific Technological Center "Beryllium" of NASU", Kharkiv, Ukraine

****E-mail: pudov@kipt.kharkov.ua***

Self-Powered Neutron Detectors (SPNDs) with a hafnium metal emitter have certain advantages compared to rhodium SPNDs, and are promising both for the upgrades of existing WWERs and for new generation reactors. The hafnium SPND is an emission type inertia-free detector (the so-called "Compton" detector), and can be used in such reactor operation modes, in which it is necessary to obtain data on the neutron field distribution instantly. Hf has a suitable initial nuclide composition (a sequence of nuclides with similar cross-sections in the (n, γ) reaction), which allows to increase the neutron irradiation time significantly, and, consequently, to increase the detector's service life time. The paper outlines the main approaches to the selection and creation of materials and elements for the design of an SPND with a hafnium emitter, designed to measure the neutron flux density in the core of a WWER-type reactor.

INTRODUCTION

Self-powered neutron detectors for the energy release monitoring in the core of a WWER nuclear reactor. The desire to increase the efficiency of nuclear reactors has led to the fact that many parameters of the processes and the elements of the reactor core (RC) have become close to critical (limit) values. To operate in a WWER-1000 reactor, materials must function under irradiation with neutron fluxes of $10^{12}…10^{14}$ $cm^{-2}·s^{-1}$ and a temperature of 320 °C [1, 2] (at the same time, the materials must remain in working condition even at 700 °C and more). Reactor operation near the limit values leads to increased requirements for the measurement procedures and equipment. As for neutron field intensities, the accuracy and efficiency of their determination become extremely important for maintaining the required level of safety of operation of nuclear reactors.

The neutron flux control equipment (NFCE) is a system that, based on the neutron flux, implements control of the power, period, reactivity and other local parameters of the reactor. The NFCE also controls the temperature and pressure of the coolant, and the position of the protection system control elements. Among the NFCE neutron detectors are those that are responsible for the reactor start-up mode, overload mode (i.e., intermediate mode) and operating mode. These are mainly ionization chambers of various designs located outside the reactor. The In-Core Control System (ICCS) is responsible for controlling the energy release levels. This system processes data from NFCE sensors, thermocouples, hydraulic sensors, intra-zone SPNDs, etc. [3–7].

Structurally, the SPNDs have a coaxial geometry, in which the emitter and collector are separated from each other by an insulator layer (Fig. 1).

The emitter of such a detector is made of a metal, the nuclides of which have sufficiently high values of cross section of radiation capture of thermal neutrons. At present time, β-emission SPNDs with emitters made of Rh are used at WWER-1000 type of reactors. The diameter of the emitter of the in-core SPND can be in the range of 0.5…2 mm, which depends on the selected materials and the operation conditions.

As the SPND's insulator, a pressed ceramic powder made of aluminum oxide (Al_2O_3) or magnesium oxide (MgO) (although historically crystalline insulators, such as SiO_2, were used first) is typically used. The insulator of in-core detectors serves to prevent the formation of track breakdowns, i.e. radiation damages of the insulator, leading to local losses of its insulating properties, which can quickly disable the entire device.

The collector is usually made of stainless steel or an Inconel alloy. The collector thickness usually does not exceed 0.25 mm.

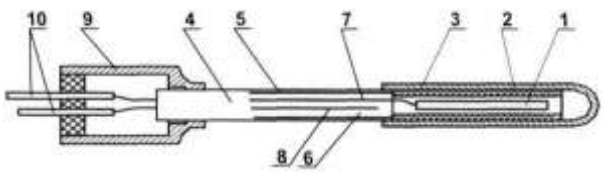

Fig. 1. SPND design: 1 – emitter; 2 – insulator; 3 – collector; 4 – communication line; 5 – shell; 6 – cable insulation; 7 – signal wire; 8 – background wire; 9 – hermetic seal; 10 – feedthroughs

The signal cable of the SPND has a design, which is similar to the detector design – the contact wire is separated from the outer sheath by a layer of powder insulator (usually also aluminum oxide or magnesium oxide). The electrical contact to the wire is usually realized by welding or brazing. It is also obvious that it must have low resistance and maintain operability in the reactor conditions.

So, simple at first glance, the design of an SPND is actually quite complex from the point of view of manufacturing technology. The detector must

simultaneously satisfy a number of requirements regarding the tightness and stability of the design, the absence of "harmful" impurities in the materials, sensitivity to n- and γ-fields, as well as the level of induced activity in the detector materials. All this together makes the SPND manufacturing technology quite complex and laborious.

The basis of the operation of the "emission-based" SPNDs is β-decay (for "β-emission" or "activation-based" detectors)

$$ {}^{A}_{Z}X + {}^{1}_{0}n \rightarrow {}^{A+1}_{Z}X^{*} \rightarrow {}^{A+1}_{Z+1}Y + \beta^{-} + \bar{\nu}_{e}, \qquad (1) $$

and (n, γ)-reaction of radiative absorption of a neutron (for "inertia-free" or "Compton" detectors)

$$ {}^{A}_{Z}X + {}^{1}_{0}n \rightarrow {}^{A+1}_{Z}X^{*} \rightarrow {}^{A+1}_{Z}Y + K \cdot \gamma, \qquad (2) $$

where X is the nuclide interacting with the neutron n; X^* is the newly formed excited compound nucleus; Y is the new nuclide; $\bar{\nu}_e$ is the electron antineutrino; Z and A are the nuclear charge and atomic mass of the nuclide; γ is the γ-quantum; K is the coefficient corresponding to the multiplicity of γ-quanta (the discharge of an excited newly formed compound nucleus usually requires the emission of an entire cascade of photons; as a result, γ-quanta from different energy ranges can be formed over a certain time).

In other words, atomic nuclei in the materials of emitters of both β-emission and Compton SPNDs go through the compound nucleus stage, but then discharge their excitation through fundamentally different processes:

– β-emission detectors – through the emission of an electron and an electron antineutrino. In this case, although there is a signal delay due to the presence of a certain half-life, the emission current is directly proportional to the neutron flux, and therefore to the local reactor power.

– Compton detectors – through the emission of a cascade of γ-quanta. Then these γ-quanta are scattered in the emitter material, generating a cascade of electrons, the kinetics of which subsequently causes the emergence of a useful signal.

In general, in each detector type, both types of reactions (1 and 2) are present in different ratios. In the β-emission detector, up to 97% of the signal arises due to β-emission, while in the Compton detector, the fraction of the signal due to β-decay usually does not exceed several percent, and the main part of the signal is formed due to the conversion of γ-quanta into electrons via Compton effect [3, 4].

The SPND is a current generator if its internal resistance is several orders of magnitude higher than the load resistance. In this case, the current generated as a result of the interaction of the products of the neutron capture reaction with the atomic nuclei of the emitter material will flow through the load resistance. The voltage drop in this case can be amplified and processed by the electronics. The amplitude of the generated signal will be proportional to the number of neutron capture reactions in the emitter material. During the measurements of this type, the electrical properties of the insulator must be stable at high temperatures and ionizing radiation fluxes, which affect the dynamic and noise characteristics of the output signal.

The sensitivity of a detector is determined as the current in amperes generated by a detector emitter of mass 1 g in a flux of thermal neutrons with a unit flux density and a Maxwellian velocity distribution. In a neutron flux of density $\approx 10^{13}$ $cm^{-2} \cdot s^{-1}$ in a detector with a mass 1 g emitter, the atomic nuclei of which have a neutron absorption cross section of 100 barn, the current will be $\approx 10^{-7}$ A, which corresponds to a detector sensitivity in the range $10^{-19} \ldots 10^{-20}$ $A \cdot g^{-1} \cdot cm^{-2} \cdot s^{-1}$.

One of the most common emitter materials in β-emission SPNDs is rhodium. It has a sufficiently large value of the microscopic cross-section (140 barn) for thermal neutron capture and high energy of β-particles emitted in the β-decay process, which determine the high sensitivity of rhodium SPNDs. Also, rhodium has a high melting point (1960 °C) and, as a noble metal, high corrosion resistance.

The use of silver is limited by its relatively low melting point (961 °C) and much lower sensitivity. Due to its low sensitivity, vanadium SPNDs have also not gained widespread use, although vanadium has a high melting point (1920 °C).

During the SPND operation, a part of the emitter nuclei "burns out" – that is, after the capture of a neutron and subsequent transformation, the final formed element no longer takes part in the formation of a useful signal. For example, a rhodium SPND operating in a neutron flux with a density of $\approx 10^{14}$ $cm^{-2} \cdot s^{-1}$ burns out by 34% per year, compared to 19% for an SPND with a silver emitter [8].

Each WWER reactor uses several hundred self-powered activation neutron detectors [9]. Taking into account the generally accepted trends of gradually increased radiation doses and operating temperatures for the materials used in the reactors, the output signal delay of rhodium SPNDs and their relatively short service life time [9–11] lead to the question: is it sufficient, from the point of view of the reactor operation safety, to use the inertial β-emission detectors as the only detectors to monitor the reactor operation conditions?

The main motivation for the research presented in this paper is the increasing requirements for the safety and efficiency of reactors when creating new nuclear power plants, as well as updating existing water-water reactors with a thermal neutron spectrum.

The idea of using Hf as a neutron-sensitive material is not new. For example, in RBMK ("reaktor bolshoy moshchnosti kanalnyy" in Russian) reactors, also called High-Power Channel-Type Reactors, SPNDs with an emitter made of HfO_2 powder have been used. However, for WWER-type reactors, in which the spectrum hardness is significantly higher than in RBMK, the use of SPNDs with an emitter made of HfO_2 is less effective compared to metallic Hf [12].

The main advantages of an SPND with a metallic Hf emitter, in contrast to rhodium and other β-emission detectors, are practically instant action (very short response time) and a fairly long service life time (the Hf

burn-up rate is 3.5% per year at a neutron flux of $\approx 10^{14}$ $cm^{-2} \cdot s^{-1}$ [12]). The absence of inertia is associated with the short times of the occurrence of (n, γ) and (γ, e) processes, which underlie the operation of such a detector [13].

Hafnium has a unique set of values of microscopic cross sections of neutron capture and concentrations of nuclides, which applies to both the natural composition and the one that is formed due to radiation transformations. The comparable (n, γ)-reaction rate values, the consequent series of transforming nuclides and the production of transmutants, which are close in their properties to Hf, ensure the continuous "transformation flow" of atoms of one nuclide into another. Due the combination of the listed processes, Hf retains its basic characteristics for a long time as a material sensitive to neutron radiation.

Improvements in the efficiency of reactor operation, related to achieving a higher level of the nuclear fuel burn-up, are linked to either the increased operation power or the increased lifespan of the reactor. Due to its qualities, a neutron detector with a metallic hafnium emitter is completely suitable in both cases. In addition, the price of Hf presently is ~120 USD per 100 g, while, for example, those of Rh and Pt are ~13,000 USD per 100 g [14].

This work is dedicated to the development of an inertia-free neutron detector based on metallic Hf. The article presents the results of experimental material studies on the selection and manufacturing of materials and construction elements of the designated detector. The current research was founded on the rich previous work experience, especially that with pure metals, including hafnium [15, 16]. Also, this study was preceded by a significant amount of earlier computational work [17, 18].

1. EXPERIMENTAL

1.1. SELECTION AND MANUFACTURE OF SPNDS' STRUCTURAL MATERIALS AND ELEMENTS

Solving the problem of the development of any device for the use in the core of a nuclear reactor is associated with taking into account the following factors:

– the magnitude of the neutron flux (it is important to know the energy spectrum of the thermal and fast neutron flux, as well as the dose rate – this parameter significantly affects the mechanical properties of materials);

– the magnitude of the γ-quanta flux;

– the operating temperature range of the device (this is important from the standpoint of the electrical and mechanical properties, as well as the nuclear properties – due to the change in the neutron absorption cross section in the reaction (n, γ) [21]).

1.1.1. Emitter of metallic hafnium

The most well-known materials used for emitters of Compton neutron detectors are Cd, Co, Er, Hf, and Pt. The nuclide transformation chains for these materials have been compiled and studied in detail, and the cross sections of (n, γ) reactions of nuclides (the initial ones and the formed ones) have been calculated [19]. Based on the studied factors: (a) the elemental composition; (b) the ability to absorb thermal neutrons; (c) the induced activity arising from the interaction with the reactor neutron flux; (d) the signal level, and (e) the market price, it was concluded that the metallic Hf is one of the most "suitable" candidates for the role of the Compton SPND emitter material.

In the process of manufacture of hafnium SPND samples [20], metallic hafnium of the GFE-1 grade, after undergoing the electron beam re-melting, served as the blank. The chemical composition of the initial Hf, which meets the requirements of TUU 143 12708.183-95, is given in Table 1.

Table 1

Chemical composition of the initial hafnium

Element	Requirements for the chemical composition of GFE-1	Determined from the analysis
	Impurity mass fraction, not more than, %	
O	0.05	0.05
Zr	1.0	0.33
N	0.005	0.0035
C	0.01	0.008
Si	0.005	0.005
Al	0.005	0.0014
Ni	0.02	< 0.001
Fe	0.04	0.0023
Ti	0.005	< 0.001
Cr	0.003	< 0.0001
Mn	0.0005	0.00015
Cu	0.005	0.00071
Ca	0.01	0.0024
Mo	0.01	0.0028
W	0.01	< 0.001
Mg	0.004	0.004
Nb	0.01	< 0.001
Content of Hf, not less than, %	98.81	99.6

For the detector emitter, a hafnium wire with a diameter of 1.5 mm was produced by using the process of multiple hot pulling. Further preparation of the wire consisted of chemical surface cleaning (chemical polishing) and annealing for an hour at a temperature of 850 °C in vacuum. The last stage was the additional chemical cleaning and activation of the Hf surface before creating an insulation layer on it by applying a magnesium oxide suspension.

For the high-purity Hf surface etching, a polishing solution containing HNO_3, HF and ethylene glycol was used. The polishing process goes quite intensively in this solution. Processing allows to clean the surface and make it chemically passive. After such processing, the wire is ready for the application of a suspension onto its surface to form an insulator layer.

On the 250-mm long and 1.5-mm in diameter emitter samples, a small pad for the welding with a signal cable was also formed by the electroerosion processing method.

1.1.2. Selection of insulator material

As for the principles of choosing the insulator material, it should be based on "transparency" for neutron and γ-quantum fluxes. The less the insulator interacts with neutrons, the longer it retains its original properties and does not distort the signal with the radiation produced by the newly formed transmutants.

As for the interaction with γ-quanta, it should also be minimized, because this type of radiation effectively destroys covalent bonds in oxides, and, therefore, reduces the resistivity of the insulator material.

The most suitable, due to their thermal stability, chemical neutrality and electrical resistance, are the oxides of aluminum, magnesium and beryllium. From the point of view of neutron absorption, it is convenient to compare these oxides with each other in terms of the macroscopic cross section Σ for the reaction (n, γ):

$$\Sigma = \sum_k \sigma_n^k \cdot N_k, \quad (3)$$

where σ_n^k is the microscopic cross section of the interaction of neutrons with nuclei of type k; N_k is the number of nuclei of type k in 1 cm^3. In essence, the macroscopic cross section is a quantitative characteristic of the probability that a neutron interacts with an atom of type k per unit length of its trajectory. Thus, the value $1/\Sigma$ is the average neutron path length in the material [22, 23].

Considering that the detector is planned to be used in WWER type of reactors, it is possible to calculate the specified values taking into account the processes of neutron absorption in the thermal and epithermal regions of the energy spectrum [5, 24]. In this case, the density of the considered insulating materials is taken to be equal to 2 g/cm^3, keeping in mind that the density of the insulators, which are made by compressing finely dispersed powders, is exactly at this level. As a result, we have the following values characterizing the interaction of reactor neutrons with oxides (Table 2).

Table 2

Macroscopic cross-section and average neutron path length for WWER-1000 conditions

Material	Σ, cm^{-1}	$1/\Sigma$, cm
Al_2O_3	0.00479	208.77
MgO	0.00169	591.72
BeO	0.00032	3125

It can be seen that BeO has the largest average neutron path length, and therefore has the weakest absorption properties. The value of $1/\Sigma$ for magnesium oxide, in turn, is almost three times larger than that of aluminum oxide.

From the point of view of interaction with γ-quanta, all of the mentioned oxides have very similar properties (Fig. 2) in the range of γ-quanta energies of 10^{-3}…10 MeV [25]. Although it is clear that beryllium oxide scatters γ-quanta somewhat weaker. This means that, due to (γ, e) processes, fewer electrons will be formed in the insulator. As a result, the volume charge amount will also be smaller, and this, in turn, determines the height of the barrier that the electrons, which have left the emitter, must overcome in order to contribute to the detector signal.

Regarding the effect of temperature on the performance of the insulator, the electrical resistance of the dielectric of the in-core detector usually has approximately the following behavior shown in Table 3.

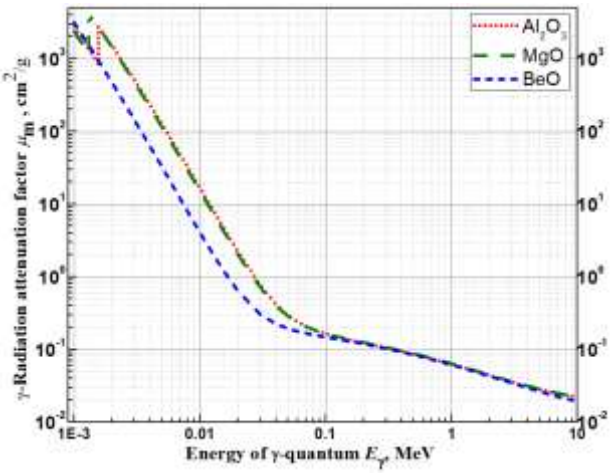

Fig. 2. The mass coefficient of the attenuation of γ-quanta μ_m for Al_2O_3, MgO and BeO [25]

Table 3

The value of the electrical resistance of the pressed Al_2O_3 powder insulator of the Compton neutron detector based on HfO_2 powder in the RBMK reactor [26]

Temperature, °C	Electric resistance, Ω	
	Without irradiation	With irradiation in n and γ fluxes
20	$\approx 10^{12}$	$\approx 5\cdot10^8 \ldots 8\cdot10^8$
400	$\approx 2\cdot10^{10}$	$\approx 8\cdot10^7 \ldots 6\cdot10^8$
700	$\approx 10^7$	$\approx 5\cdot10^5 \ldots 5\cdot10^6$

The table shows the data for a Compton SPND insulator with a HfO_2 emitter and an Al_2O_3 insulator. Unfortunately, there is little publicly available data on the behavior of beryllium and magnesium oxides under reactor conditions.

Thus, it is clear that BeO would be a good insulator material, however, this material is extremely toxic. It is also worth considering the materials' prices. Aluminum and magnesium oxides are available at a price of ~1…5 USD per gram (presently, depending on their purity and dispersion), while BeO powders cost ~80…100 USD per gram. Therefore, based on the sum of the factors, it was decided to take MgO as the insulator material for hafnium SPND [27].

During the SPND development, two methods of the detector manufacturing were tested.

The first method is analogous to the process of manufacture of heat-resistant wires (the so-called cable technology), which involves filling the magnesium oxide powder into the gap between the emitter and the

collector, and the subsequent extrusion to the desired detector diameter. During the extrusion, the emitter diameter is reduced, and the MgO powder is simultaneously compacted.

The second method is based on the chemical formation of the insulator – by applying a MgO suspension onto the emitter. The procedure of applying the suspension is repeated multiple times to obtain an insulation layer of the required thickness. The resulting insulation-covered wire, at this stage, does not have an outer sheath, and requires further heat treatment.

To create a suspension for application onto the emitter surface, aqueous solutions of magnesium chloride, nitrate, and orthophosphate were tested [20]. A magnesium compound based on magnesium oxide, which is mixed with a solution of magnesium salts, has high hardness but low electrical resistance due to the presence of water molecules in the structure. When annealing, the compound decomposes into magnesium oxide and an acid residue, which, in turn, forms a volatile gas. Therefore, at the end of annealing, it is possible to obtain pure magnesium oxide.

Several magnesium salt options were considered. Taking into account the temperature of decomposition of magnesium salts, magnesium chloride and nitrate were recognized as the most promising.

The densification of the deposited MgO layer was carried out by the process of radial compression of the collector-insulator-emitter structure by pulling through dies, and conducting long intermediate anneals in forevacuum at a temperature of 115 °C. At the final stage, a finishing annealing was carried out at a temperature of 730 °C in a residual Ar environment. According to this scheme, samples were manufactured for various electro-physical tests (Fig. 3).

Fig. 3. Detector samples with a diameter of 2.5 mm for testing

1.1.3. Collector

As noted before, all of the SPND structural elements must maintain their operability in the conditions of the nuclear reactor core. At the same time, it is also important to take into account certain technological features of the manufacturing process of these elements.

The material of the collector of the in-core SPND is usually a stainless steel with a sufficiently large share of nickel in the composition, for example, Kh18N10T or Inconel-600. These alloys are often used in the nuclear industry as structural elements of the reactor. Inconel better withstands high doses of radiation for a long time, and does not create an undesirable additional background due to the absence of cobalt in the composition. In addition, its plasticity significantly facilitates mechanical processing.

For the manufacture of SPND collectors, the methods of chemical and electrochemical preparation of pipes made of Kh18N10T and Inconel-600 were developed. Each of these materials has its own peculiarities during the electrochemical treatments. When choosing the polishing electrolytes, it was taken into account that the processing should be carried out on the inner surface of the pipe with an inner diameter of 6…8 mm and a wall thickness of 0.25…0.3 mm.

Inconel-600 contains ~72% nickel, 14…17% chromium and up to 10% iron. For polishing such samples, an electrolyte containing H_3PO_4, acetic acid, and glycerin was selected. The processing was carried out at room temperature and a current density of 1.5 A/dm^2.

SPND collector samples 250 mm long were manufactured and annealed at 750 °C in a vacuum furnace.

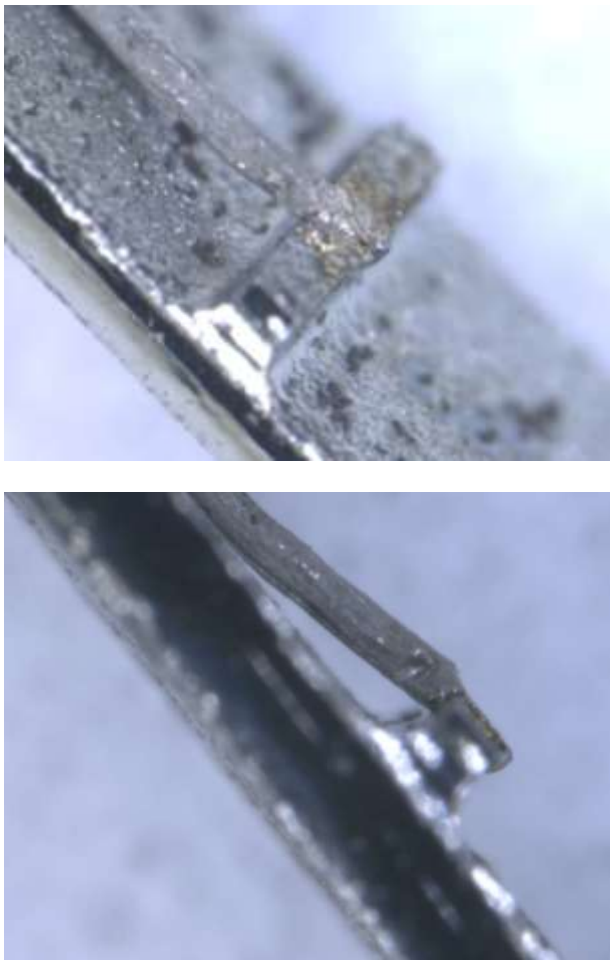

Fig. 4. Welding of a Hf emitter sample with a 0.28 mm diameter signal wire of a coaxial cable

1.2. WELDING OF A SIGNAL WIRE WITH THE EMITTER

A high-resistance shielded cable, the length of which can reach 25 m, is used for the connection of the SPND to the measurement instruments. As a rule, the communication lines at NPPs are KTMS-2 brand cables with magnesium oxide mineral insulation and a sheath of a stainless steel or an Inconel-600 alloy. The current-carrying part is composed of two single-wire conductors. The conductors can be made of chromel and alumel.

Welding of heat-resistant hafnium (M.P. ~ 2220 °C)

is associated with certain difficulties – it needs chemical cleaning of surfaces of the parts being welded and protection of the welding area from oxidation. According to the results of the conducted research, the method of capacitor welding in a pulse mode in an environment of excess argon was chosen for welding. Welding of the hafnium emitter samples with a diameter of 1.5 mm to the signal wire of a coaxial cable with a diameter of 0.28 mm was carried out. The result of welding of one of the twisted-pair conductors of the signal cable to the contact pad on the surface of the emitter is shown in Fig. 4.

1.3. MEASUREMENTS OF THE ELECTRICAL CHARACTERISTICS OF THE SPND SAMPLES WITH METALLIC HAFNIUM EMITTERS

Fig. 5 shows the measured dependence of an SPND sample electrical resistance on the applied voltage. The effect of the non-sealed ends of the sample is also shown.

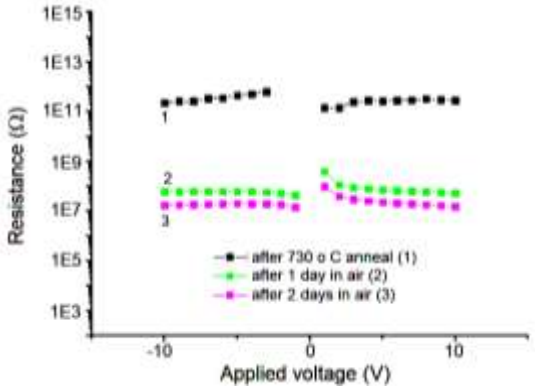

Fig. 5. The dependence of the insulator resistance on the applied voltage. The influence of the unsealed sample ends is also shown

After the sample annealing, the electrical resistance of the insulator was observed to be in the range of $2…8·10^{11}$ Ω depending on the applied voltage, which is consistent with the literature data (see Table 3). Studies of the temperature and irradiation influence will be carried out at a next stage of work.

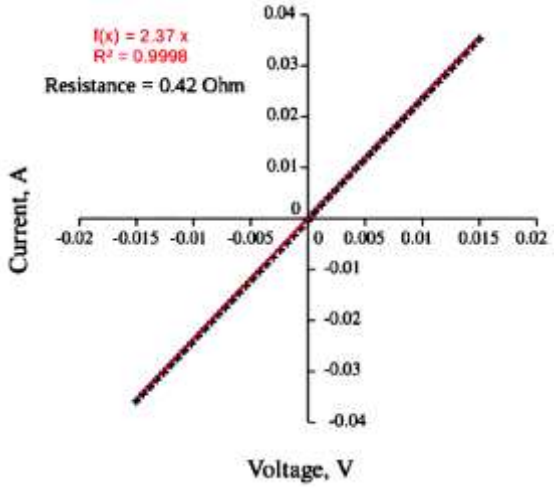

Fig. 6. Current-voltage characteristic of the contact of the welded elements

The fact that the insulator resistance of the SPND samples with unsealed ends decreases rapidly demonstrates how the formed ceramic absorbs water vapor from the air.

Also, the electrical conductivity of the welded joint of the signal wire and Hf emitter was measured. In Fig. *6*, the current-voltage characteristic of the welded joint is shown.

The value of the electrical resistance of the welded joint is in the range of 0.4…0.8 Ω, and the obtained characteristic has a linear dependence. Also, the samples were annealed in air at +250 °C, after which the contact current-voltage characteristics did not change.

CONCLUSIONS

The conditions for using in-core SPNDs were considered, and the approaches to the selection of the structural materials for such detectors' manufacturing were analyzed.

The use of metallic hafnium as an emitter material is advisable for several reasons: 1) its nuclide composition is advantageous from the point of view of nuclear transformations, i.e. the emitter material contains a series of consecutive nuclides that have similar initial concentrations and cross sections in the (n, γ) reaction of neutron capture; 2) the absence of inertia of the output signal in the presence of a changing neutron flux; 3) the possibility of prolonged time of irradiation in the reactor conditions; 4) relatively low cost.

Taking into account the extreme radiation and temperature conditions of operation of the reactor core, as well as the characteristics of materials and the peculiarities of the respective technological processes during the manufacture of the elements of the inertia-free SPNDs, metallic hafnium for the emitter, magnesium oxide for the insulator, and Inconel-600 alloy for the collector were selected.

The technologies for processing the metal elements have been developed: hot pulling, forging, annealing, cleaning and activation of surfaces, and contact welding.

A technology for creating an insulator layer by forming a number of separate layers from a suspension with the subsequent processing of the insulator has been developed.

Measurements have been carried out to confirm the proper quality of the insulator and the welded emitter-signal wire connection.

REFERENCES

1. Tongyuan Cui, Yigang Yang, Hongyuan Xue, Hongbo Kuang, A Monte-Carlo simulation method for the study of self-powered neutron detectors // *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment.* 2020, v. 954, p. 161383; https://doi.org/10.1016/j.nima.2018.10.061

2. S.I. Azarov, A.V. Taranovski. Use of detectors for reactor in-core monitoring // *International Nuclear Safety Journal.* 2014, v. 3, issue 2, p. 12-20; https://nuclearsafety.info/international-nuclear-safety-journal/index.php/INSJ/article/view/27/pdf

3. W.H. Todt, Sr. Characteristics of self-powered neutron detectors used in power reactors // *Proceeding of specialists' meeting "In-core instrumentation and core assessments"*, Mito-spi, Japan, 14-16 Oct. 1996. Publisher: Paris – Nuclear Energy Agency: Organization for Economic Co-operation and Development, 1997, p. 181-190.

4. P.E. Blomberg. Reactor physics problems concerning the startup and operation of power reactors: *Technical reports series N143 "Developments in the Physics of Nuclear Power Reactors"*. Vienna, 1973, IAEA, p. 183-199.

5. H. van Dam, T. van der Hagen, J. Hoogenboom. Nuclear Reactor Physics. Delft University of Technology // *Physics of Nuclear Reactors. Lecture notes AP3341*. 2005, v. 132, p. FILE.

6. S.N. Pelykh, M.V. Maksimov, V.E. Baskakov. Grounds of WWER-1000 fuel cladding life control // *Annals of Nuclear Energy*. 2013, v. 58, p. 188-197; DOI: 10.1016/j.anucene.2013.03.020

7. Elmer E. Lewis. *Fundamentals of Nuclear Reactor Physic.* Academic Press, 2008, 293 p.; DOI: 10.1016/B978-0-12-370631-7.00011-5

8. В.И. Калашникова, М.С. Козодаев. *Детекторы элементарных частиц.* М.: Издательство «Наука», 1966.

9. V.I. Borysenko, Yu.F. Piontkovskyi, V.V. Goranchuk. Model of formation of in-core neutron detector signal // *Nucl. Phys. At. Energy*. 2016, v. 17, issue 4, p. 364-373; https://doi.org/10.15407/jnpae2016.04.364

10. В.І. Мітін, В.Ф. Шикалов, С.А. Цимбалов. Експериментальне дослідження струмоутворення в детекторах прямої зарядки з емітером з родію // *Атомна енергія.* 1973, т. 34, с. 301-303.

11. B.A. Shilyaev et al. Compton detector of neutrons for the energy yield control in the active zone of WWER // *Problems of Atomic Science and Technology*. 2017, N 2(108), p. 75-82; https://vant.kipt.kharkov.ua/ARTICLE/VANT_2017_2/article_2017_2_75.pdf

12. A.L. Ulybkin et al. Compton-emissive hafnium detector of neutrons for in-core monitoring // *Nuclear Physics and Atomic Energy*. 2018, v. 19, issue 3, p. 237-243; DOI: 10.15407/jnpae2018.03.237/

13. Knoll, Glenn F. *Radiation Detection and Measurement*. Sec. ed., Inc. New York: John Wiley & Sons, 1989, 754 p.

14. Periodic Table of Elements and Chemistry. URL: https://www.chemicool.com/elements/.

15. О.Е. Дмитренко, В.М. Пелих, М.М. Пилипенко. Рафінування гафнію методом електронно-променевої плавки // *Питання атомної науки і техніки. Серія «Фізика радіаційних пошкоджень і радіаційне матеріалознавство» (85).* 2004, № 3, с. 112-115.

16. Р.В. Ажажа, К.В. Ковтун, М.П. Старолат, І.Н. Чепурна. Дослідження структури та властивостей дроту з гафнію // *Металофізика та новітні технології.* 2013, т. 35, № 5, с. 677-682.

17. Б.А. Шиляєв, О.Л. Улибкін, О.В. Рибка, В.Є. Кутній, К.В. Ковтун. *Послідовне перетворення ізотопів гафнію при опроміненні в активній зоні ядерного реактора ВВЕР-1000:* Препринт ННЦ ХФТІ, ХФТІ 2017-1. Харків: ННЦ ХФТІ, 2017, 32 с.

18. A. Ulybkin et al. Radiation-induced transformation of Hafnium composition // *Nuclear Engineering and Technology.* 2019, v. 51, issue 8, p. 1964-1969; https://doi.org/10.1016/j.net.2019.06.007

19. A. Ulybkin et al. Compton (prompt-response) neutron detectors: Comparison of emitter materials through the nuclear transmutation model: *Sensors International 1*, 2020, p. 100020; https://doi.org/10.1016/j.sintl.2020.100020.

20. E.A. Bohdan et al. Mineral Insulators for Compton Detectors of Neutrons with a Metal Hafnium Emitter // *Problems of Atomic Science and Technology.* 2020, N 1(125), p. 211-214; URL:https://vant.kipt.kharkov.ua/ARTICLE/VANT_2020_1/article_2020_1_211.pdf

21. C.H. Westcott, W.H. Walker, T.K. Alexander. Effective Cross Sections and Cadmium Ratios for the Neutron Spectra of Thermal Reactors. Conference 2. *United Nations International Conference on the Peaceful Uses of Atomic Energy*, Geneva (Switzerland): Technical Report. 1958, 18 p.; https://www.osti.gov/servlets/purl/4279663

22. D. Reilly, N. Ensslin, H. Smith Jr., S. Kreiner. *Passive nondestructive assay of nuclear materials*. United States, 1991. Web. NUREG/CR-5550. LA-UR-90-732 ON: TI91016546. ISBN: 0-16-032724-5. 723 p.; URL: https://www.nrc.gov/docs/ML0914/ML091470585.pdf

23. *Nuclear physics and reactor theory*. V. 1 of 2. DOE fundamentals handbook. Dept. of Energy, Wash., D.C. DOE-HDBK-1019-1-93. 1993, p. 133; URL: https://sites.ntc.doe.gov/partners/tr/Training%20Textbooks/10-Nuclear%20Physics-Reactor%20Theory/0-Intro%20to%20Nuclear%20Physics%20and%20Reactor%20Theory.pdf

24. А.Д. Галанін. *Введення в теорію ядерних реакторів на теплових нейтронах.* М.: «Енергоатомвидат», 1984, 416 с.

25. National Institute of Standard and Technology, Physical Measurements Laboratory, XCOM Photon Cross-Sections Database; URL: https://www.nist.gov/pml/xcom-photon-cross-sections-database.

26. І.Я. Ємел'янов, Ю.І. Володько, О.К. Єгоров та ін. Радіаційно-термічні випробування комптонівських емісійних детекторів нейтронів з емітером, що містить гафній // *Атомна енергія*. 1983, т. 54, в. 3, с. 189-192.

27. https://www.ottokemi.com/.

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РОЗРОБКА І СТВОРЕННЯ КОМПОЗИТНОГО ДЕТЕКТОРА ПРЯМОГО ЗАРЯДУ ДЛЯ ВИМІРЮВАННЯ ПОТОКУ ТЕПЛОВИХ НЕЙТРОНІВ

С.О. Соколов, О.В. Рибка, О.О. Пудов, О.Л. Улибкін, О.В. Косінов, В.Є. Кутній, К.В. Ковтун, Є.О. Богдан, Л.О. Пироженко, А.І. Пікалов, Р.В. Ажажа

Детектори прямого заряду (ДПЗ) з емітером із металевого гафнію мають певні переваги у порівнянні з родієвими ДПЗ, і є перспективними як при модернізації існуючих ВВЕР, так і для реакторів нового покоління. Гафнієвий ДПЗ є емісійним безінерційним детектором (так званий «комптонівський») і може бути застосований у режимах роботи реактора, коли необхідно миттєво отримувати дані щодо розподілу нейтронного поля. Hf має зручний вихідний нуклідний склад (неперервна послідовність нуклідів з близькими величинами поперечних перерізів у (n, γ)-реакції), що дозволяє суттєво збільшити час опромінення нейтронами, а, отже, і строк використання детектора. Загалом, у роботі окреслено основні підходи щодо вибору та створення матеріалів і елементів для конструкції ДПЗ з емітером із гафнію, призначеного для вимірювання потоку нейтронів у активній зоні реактора типу ВВЕР.