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Development of a fiber-optic system for monitoring the state of oxygen activity in the current flow of the coolant

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Abstract. The need to develop an optical system for remote monitoring of the state of the coolant in the current flow in the first circuit of the nuclear reactor of a nuclear power plant has been substantiated. A method for monitoring the state of the coolant by changing the nature of the evolution of oxygen activity is presented. A fiber-optic system has been developed to study the nature of the change in the evolution of the oxygen activity of the coolant in the current flow. The results of the study of the evolution of oxygen activity in the current flow of the coolant are presented. The nature of the change in the evolution of oxygen activity in the event of the ingress of foreign particles into the coolant (carbon steel particles from welded joints) is determined.

Keywords: fiber-optic system, oxygen activity, coolant

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Разработка волоконно-оптической системы для контроля состояния кислородной активности в текущем потоке теплоносителя

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Аннотация. Обоснована необходимость разработки оптической системы дистанционного контроля состояния теплоносителя в текущем потоке в первом контуре ядерного реактора атомной электрической станции. Представлен метод контроля состояния теплоносителя по изменению характера эволюции кислородной активности. Разработана волоконно-оптическая система для исследования характера изменения эволюции кислородной активности теплоносителя в текущем потоке. Представлены результаты исследования эволюции кислородной активности в текущем потоке теплоносителя. Определен характер изменения эволюции кислородной активности в случае попадания инородных частиц в теплоноситель (частицы углеродной стали со сварных соединений).

Ключевые слова: волоконно-оптическая система, активность кислорода, теплоноситель

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Introduction

In the context of increasing consumption of electrical energy, improving the efficiency of various power plants is one of the tasks of applied physics [1–6]. Currently, four types of power plants (hydroelectric power plants (HPP), thermal (CHP), nuclear (NPP) and solar (SPP)) and solar (SPP) are mainly used for the production of electrical energy in the world.) [2, 3, 6–9]. The share of other types of power plants in the world and electricity production is insignificant [10, 11].

For the sustainable development of nuclear energy, it is necessary to solve a large number of problems [12–15], which are related to the improvement of methods and devices for controlling chain reactions, in the development of new devices for monitoring the operation of nuclear reactors, etc. The solution of these problems required conducting studies of the evolution of oxygen activity in the flow of various liquid media used as a coolant in nuclear reactors at nuclear power plants [15–18].

Oxygen activity $^{16}O(n,p)^{16}N$ is associated with the interaction of oxygen nuclei that are part of one of the parts of the coolant - water with neutrons with an energy of more than 9 MeV, which are present in the reactor zone due to the flow of a chain reaction Currently, in systems with nuclear reactors, monitoring of the state of oxygen activity in the current flow of the coolant is not implemented. The content of ^{131}I is controlled. This characterizes the poisoning of the reactor zone with xenon. In some cases, the activity of corrosion products is monitored. In new models of reactors, reference nuclides, primarily ^{60}Co, are controlled, as this characterizes the tightness of the fuel. In some models of nuclear reactors, the activity of nuclear reactors is implemented continuous monitoring of the amount of coolant leakage from the first circuit to the second outside the central protective system of the reactor based on the registration of gamma radiation of the isotope ^{16}N in the pair. This allows in some cases to prevent an emergency situation.

Therefore, the aim of the work is to develop a method for studying the evolution of oxygen activity arising in the current flow of the coolant, and its practical implementation.

Features and a new method for studying the evolution of oxygen activity

A feature of oxygen activity is that it occurs only when a nuclear reactor is operating at high capacities and subsides immediately after the chain reaction stops. Therefore, without the use of a working nuclear reactor, it is impossible to conduct its research.

Another feature of the studies of the evolution of the oxygen activity of the coolant in the current flow is that they need to be carried out for a long time within the central protective zone of the reactor. For this reason, special ionization chambers, which are located inside protective lead collimators, designed for research in laboratories, are almost impossible to use in the reactor compartment, since they have significant dimensions and have high requirements for protection against temperature, electromagnetic interference, etc. Several of these factors also exclude the use of devices that record γ radiation in steam.

Taking into account these features, we have developed the following method to study the evolution of oxygen activity. It has been established that under the influence of γ radiation, the optical fiber darkens (radiation-induced losses αs increase) [19–21]:

$$\alpha_s = -10\lg(P_{out}/P_{in})/l, \quad (1)$$

where P_{in} is the laser power introduced into the optical fiber, P_{out} is the power at the output of the optical fiber, l is the length of the optical fiber.

The effect of increasing α_s is based on the formation of electron-hole pairs. Knocking out oxygen, the electron takes its place in the cyclic spatial structure [19–22]. Various centers of coloration and 'electronic' connections with different lifetimes are formed [19–25].

Studies [19–27] have shown that if the exposure dose of radiation is low, then the number of formed color centers and 'electronic' compounds is not large. Destruction in the glass mesh does not occur. Transparency (one of the main properties of optical fibers) persists for a long time. The fiber darkens weakly. With an increase in the exposure dose of irradiation, the number of these formations increases, the rate of darkening of the fiber increases. Losses increase.

Fig. 1 presents the results of studies of the change in α_s from time t when exposed to γ radiation duration of 4–6 s (exposure dose of radiation 162.3 Gy) for different composition of the core of the optical fiber.

The results obtained show that by changing the percentage of doping of the core of an optical fiber (for example, with germanium oxide GeO_2), it is possible to change its sensitivity to the effects of γ radiation. Establish a working point when recording γ radiation at the $\alpha_s(t)$ dependence site with the maximum steepness of the slope (Fig. 1). This will make it possible in some cases to record bursts of oxygen activity from the decay of a small number of nuclei of ^{16}N. After recording bursts of oxygen activity, it is necessary to quickly restore the optical properties of the fiber. Natural processes proceed extremely slowly [19-25, 28, 29]. Therefore, we propose to use additional laser radiation with λ = 547 nm to clean the fiber. Fig. 2 shows an example of a process for controlling the relaxation processes of the color centers and 'electronic' compounds in the optical fiber after the cessation of exposure to γ radiation with an exposure dose of 162.3 Gy while maintaining a radioactive background.

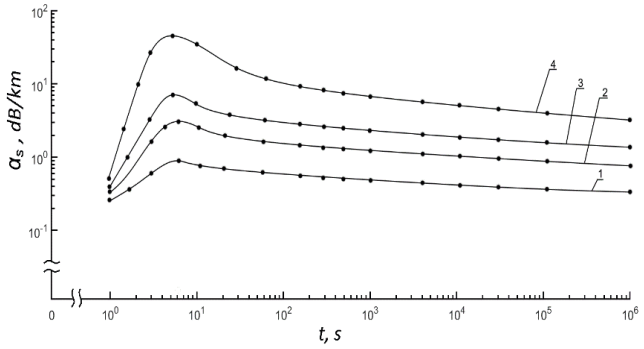

Fig. 1. Dependence of change in α_s on time t at wavelength λ =1310 nm for single-mode fiber at T = 296.4 K
Graphs *1*, *2*, *3*, and 4 correspond to different types of optical fiber core:
pure quartz SiO_2; SiO_2–GeO_2 (doping 3.5 %); SiO_2 – GeO_2 (doping 15 %); SiO_2 – GeO_2 (doping 25%)

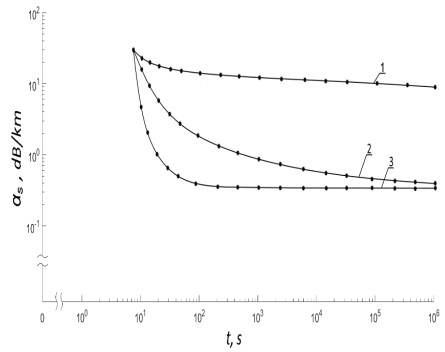

Fig. 2. Dependence of change in losses α_s on time t at wavelength
λ = 1310 nm for single-mode fiber with a core SiO_2–GeO_2 (doping 15.0 %) at T = 296.4 K
Graphs *1*, *2* and *3* correspond to the power of pulsed laser radiation at wavelength λ = 547 nm in mW: 0; 120; 500

The results obtained show that optical fiber restores its optical properties. The transparency of the optical fiber is restored. The number of color centers decreases - the fiber brightens. The absorption of laser radiation at the color center becomes smaller. The output power is increased. This is one feature. The Rayleigh scattering of laser radiation by color centers, which makes the main contribution to the power loss of laser radiation at a wavelength of 1550 nm, is also significantly reduced. Second characteristic.

Since we use low-power laser radiation at 1550 nm, absorption losses are not considered, since they are small compared to scattering losses in this wavelength range.

Let us assume that during the decay of the nucleus ^{16}Nγ-quanta are emitted in all directions in the same way. In addition, in the first approximation, in accordance with quantum theory [30, 31], when one γ-quantum interacts with an optical fiber, one center of color or one 'electronic' compound is formed. In this case, the value of E is spent on the formation of N. The centers of color can be calculated using the following ratio:

$$E = S{\cdot}N{\cdot}h\nu/\sigma = S{\cdot}N{\cdot}h{\cdot}c/(\lambda{\cdot}\sigma) \qquad (2)$$

where σ is the cross-section of the interaction (scattering) of the γ-quantum on oxygen atoms O_2 in the optical fiber, S is the area of interaction of the optical fiber with the γ-quanta, N is the number of emitted γ-quanta, λ is the wavelength of radiation γ – quantum from decay of ^{16}N.

In the decay of a nucleus of ^{16}N, the emission of γ-quanta corresponds to 7F of the spectrum line (λ = 0.254 nm). Then the value of N can be determined using the following relation:

$$N = \sigma{\cdot}\lambda{\cdot}t_{\gamma}{\cdot}(P_{in} - P_{out})/(S{\cdot}h{\cdot}c) \qquad (3)$$

The values of laser radiation power P_{in} and P_{out} are measured. The value of the σ is set experimentally, since it depends on the percentage of doping of the core of the optical fiber with germanium oxide GeO_2, as well as on the temperature of the optical fiber T_c. The value of the exposure time γ-quanta the optical fiber is defined by the following formula: $t_{\gamma} = \pi L_s d_p^2/4q$, where d_p is the inner diameter of the pipeline, coolant flow rate is q, L_s is the distance between the protective screens. Therefore, the measurement function q it is also necessary to implement in the fiber-optic system we are developing. To do this, we have previously developed a method for measuring q [32, 33].

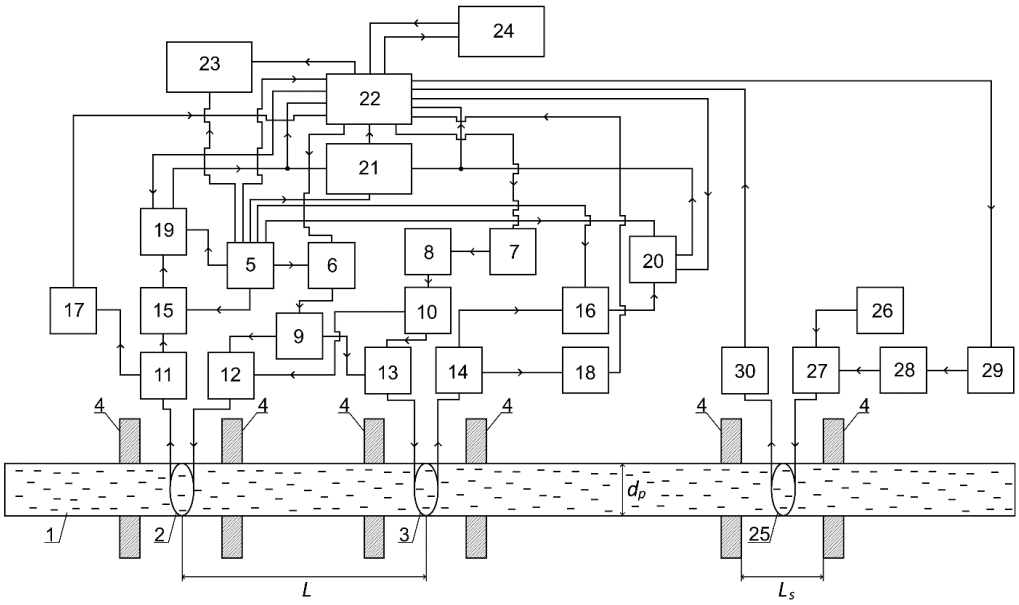

Fig. 3. Structural diagram of the fiber-optic system: pipeline with coolant *1*; coils *2*, *3* and *25* with optical fiber (sensors); protective radiation shields *4*; multifunctional power supply driver *5*; transmitting optical module *6* and *26*; multifunctional power supply driver *7* and *29*; semiconductor laser *8* and *28*; optical dividers *9* and *10*; multiplexers *1:2*; *11*, *12*, *13*, *14* and 27; photodetectors *15*, *16* and *30*; optical power meters *17* and *18*; comparators *19* and *20*; logical device *21*; processing and control device *22*; display device *23*; central computer *24*

Fiber-optic system and the results of experimental studies of the evolution of oxygen activity

Fig. 3 presents a structural diagram of the developed fiber-optic system, which takes into account the features of the study of the evolution of oxygen activity established by us.

To do this, in the developed system (Fig. 3) three coils 2, 3 and 25 with optical single-mode fiber are used, placed at a distance of 3 and 1.5 m from each other (Fig. 1). It should be noted that in the operating conditions of nuclear power plants, the distances of L and L_1 are extremely difficult and not always expedient to change. The function of changing L and L_1 is necessary in the case of various studies on the experimental model of the reactor, since the value of the flow rate of the coolant q during the conduct and a number of experiments must be changed over a large range (at least two orders of magnitude).

We note the main points of the work of the fiber-optic system developed by us. From the transmitting optical module 6, radiation with $\lambda = 1550$ nm (radiation power P_m is regulated from 0.1 to 20 mW) through the optical divider 9 ($N = 2$) enters the inputs of multiplexers 12 and 13. Wavelength $\lambda = 1550$ nm for measuring loss $\alpha_s(t)$ Laser radiation is selected for the following reasons. In addition, the 'tails' of phonon and electron absorption in the wavelength region of 1.0–1.6 μm do not make a significant contribution to optical losses, the data on which are used to study changes in the nature of the oxygen activity of the coolant.

The other inputs of these multiplexers are supplied with laser radiation with $\lambda = 457$ nm from the diode-pumped semiconductor laser 8 (SSP-ST-457-F). Theradiation content of P_L is adjustable from 1 to 1000 mW. The multifunctional power supply driver 7 allows the laser 8 to operate in both continuous and pulsed modes. The wavelength from the range of laser radiation 440-485 nm (blue part of the spectrum) to control the relaxation rate of the color centers and «electronic» connections is chosen for the following reasons. On the one hand, with longer optical fiber lengths, it is necessary to ensure the lowest value of the Rayleigh scattering coefficient (CRC) so that the additional laser radiation carries out the maximum cleaning of the glass. On the other hand, the lower limit of laser radiation at a temperature of $T = 307$ K for effective purification of E' centers is $\lambda = 217$ nm [22]. All other color centers that change the optical properties of laser radiation passing through the fiber have loss regions in the longer wavelength part of the spectrum [19, 34, 35]. When cleaning the fiber, it is desirable to reduce losses of all kinds. Given the fact that our temperature is much higher than in [22], laser radiation with $\lambda = 457$ nm was chosen, since it is likely that it can touch the 'tail' of the spectrum of E› centers, since at high temperatures it shifts and expands.

In Fig. 4, as an example, the dependence of the change N in the coil location zone 25 on time t for various values q. A solution ($H_20 + H_3VO_3$) with plutonium nitride filling at a temperature $T_G = 960$ K was used as a coolant.

The analysis of the results obtained in Fig. 4 shows that the oxygen activity in the coolant is distributed in time randomly. By adjusting the flow rate of the coolant q, it is possible to partially control the N distribution function in the registration zone of γ-quanta coils with optical fiber.

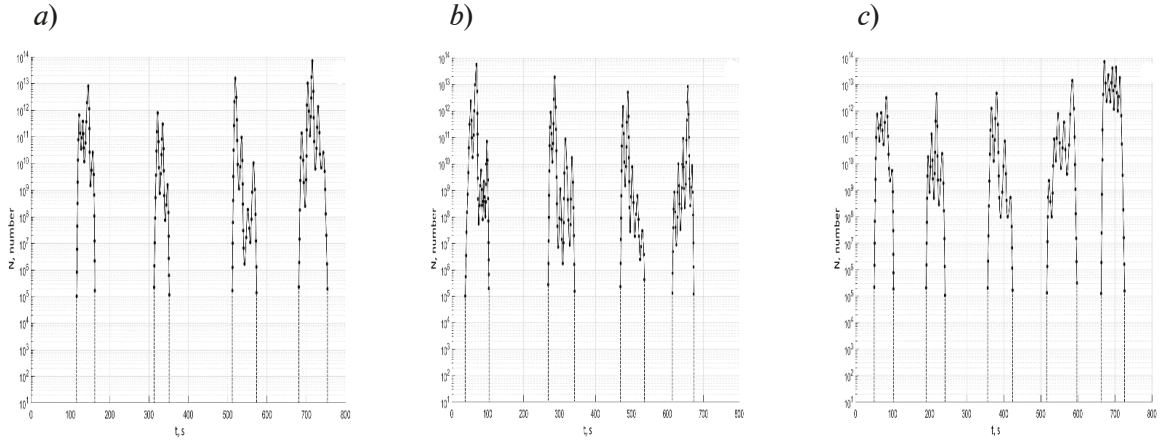

Fig. 4. Dependence of change N on time t
Curves in (*a*), (*b*) and (*c*) correspond to q in m³/s: 0.169; 0.339; 0.678

Conclusion

The results obtained showed the reliable operation of the developed design of the fiber-optic system to control the evolution of oxygen activity in the current flow of the coolant.

It is established that increasing the sensitivity of the new method of studying the evolution of oxygen activity, it is necessary to use laser radiation of wavelengths of the UV range.

In the case of additional calibration, it is possible to use the developed fiber-optic system to control the radiation level in the central zone of the reactor. This is necessary to ensure the independence of measurements when using devices with photoelectronic multipliers (PMFs) to solve these problems.

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