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The ion-thermal deactivation technology of the metal structures surface of nuclear reactor plants

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The actual problem in nuclear energy is the deactivation of the first loop of reactor during decommissioning and during planned repairs of nuclear reactor plants. We are developing a fundamentally new „dry“ ion-thermal technology for the deactivation of metal structures and reactor graphite. This paper is presents the results of numerical calculations of the temperature distribution in the first loop of high-power channel reactor (RBMK) in the process of applying ion-thermal technology.

Keywords: nuclear reactor plants, ion-thermal deactivation technology, decommissioning, deactivation of metal structures surface.

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1. Introduction

The search for an effective technology for deactivation of internal surfaces of equipment and pipelines of the primary circuit of reactor plants (RP) remains one of the actual problems of nuclear energy. Radiactive contamination of the internal surfaces of RP pipelines consists of activated corrosion products of structural materials, as well as fission products of nuclear fuel that appear due to the damage of fuel elements. The chemical composition of radioactive contamination and the amount of activity depend on the time and operation modes of RP and its type. For example, during RP long-term operation at least 90% of the total activity of the radionuclide layer on the surface is the ^{60}Co isotope, which is formed by the interaction of neutrons with the stable ^{59}Co isotope, which is included in the corrosion products of stainless steel containing nickel 10% with a large natural admixture of cobalt.

Currently, chemical technologies and various reagent-free methods combining ultrasonic, electrolytic, shock wave effects [1–8] are used to decontaminate the pipeline equipment of RP, leading to an increase in the volume of liquid radioactive waste (LRW) and metal corrosion. Laser methods for decontamination of metal surfaces of RP [9] are relatively expensive, ineffective and labor-intensive to implement. In this article we propose a fundamentally new method to the decontamination of in-circuit equipment of RP — ion-thermal technology.

2. Basic principles of technology

Ion-thermal technology is based on the use of a microplasma discharge (the length of the discharge gap is about $1-5$ mm) in an inert gas (argon) at a pressure of $0.1-1$ atm for the deactivation of any radioactively contaminated conductive surface, including pipeline equipment of RP. A microplasma discharge is ignited between the deactivated surface (cathode) and the electrode — collector (anode) of the sputtering device installed in parallel to the cathode surface, while the transverse dimensions of the anode are much larger than the gap between the cathode and the anode. Surface deactivation is carried out through ion and thermal sputtering of the radioactive deposit layer of any chemical composition from the conductive metal surface of RP with the diffusion transfer mode of sputtered atoms and deposition in the solid form on the anode surface of the sputtering device, while the sputtered atoms do not form chemical compounds with the inert gas. For example, to decontaminate the internal surface of RP pipeline, the replaceable electrode-collector of the sputtering device is a plate similar in shape to the internal surface of the pipeline. To control the temperature and the deposition process of sputtered atoms on the collector-electrode, the latter can be equipped with a cooling system. The operating parameters of ion-thermal technology were obtained experimentally on model samples of metal alloys: voltage at the discharge gap $100-1000$ V, inert gas (argon) pressure $0.1-1$ atm., current density $0.1-1$ A/cm^2, discharge gap $1-5$ mm. The sputtering rate and thickness of the sputtered layer of radioactive deposits are controlled by the power input into the discharge and the exposure time of the microplasma discharge. Ion-thermal technology allows decontamination to be carried out directly inside RP until it is completely disassembled: the sputtering device on the manipulator moves sequentially, step by step, along all internal surfaces of the reactor primary circuit. A more detailed description of the technology and sputtering device is presented in our patent with the State Atomic Energy Corporation „Rosatom“ [10].

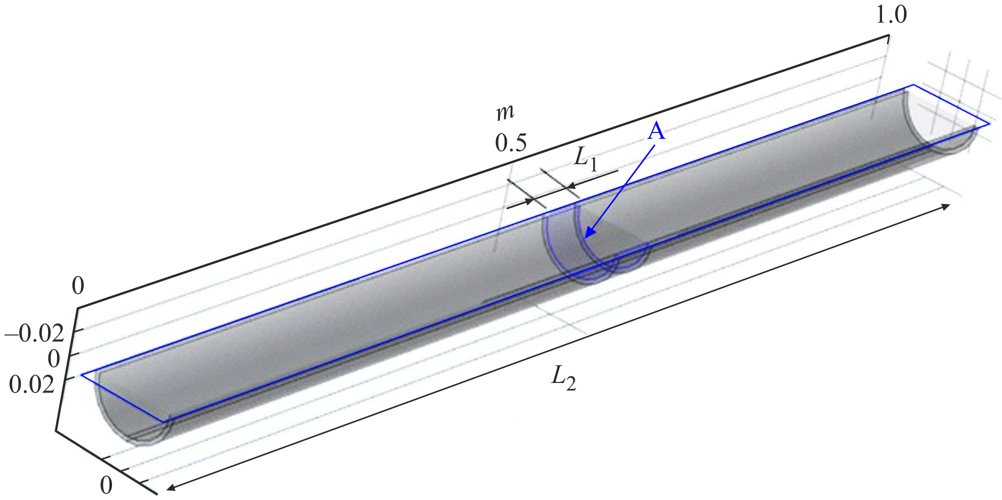

Figure 1. Diagram of pipeline section with the anode located in the form of a chute.

3. Results of temperature regimes calculation of ion-thermal technology

To prevent overheating of the decontaminated fragment of RP pipeline, select structural materials for the manufacture of the sputtering device and determine the temperature values of the decontaminated surface of RP pipeline, the problem of thermal conductivity was solved at different values of power input into the microplasma discharge. When a microplasma discharge is ignited, all value of power put into the discharge is released in the cathode region, so the heat source can be set on the area of the deactivated surface of the pipeline. In this case, the side ends of the pipeline are maintained at the fixed temperature of 300 K. The boundary condition on the outer surface of the pipeline is cooling with an air flow at a speed $u = 10$ m/s perpendicular to the surface of the pipeline. The heat exchange process between the pipeline filled with argon, the sputtering device and the inner surface of the pipeline can be described by the equation for heat flow: $Q' = \langle\alpha\rangle\delta TF$, where $\langle\alpha\rangle$ — average heat transfer coefficient over the heat exchange inner surface of the pipeline walls, δT — temperature difference between the pipeline walls and argon, F — heat exchange surface. A fragment of the pipeline for which the calculation was carried out, indicating the anode position, is shown in Figure 1. The calculation was performed for section of the first loop of the RBMK reactor $L_1 = 1$ m long, made of stainless steel 12Kh18N10T nickel-chromium steel, with the internal radius of 36 mm and the thickness of 4 mm. The anode is made in the form of the chute $L_2 = 4$ cm long and with radius of 35 mm (the anode is indicated in blue), the distance between the anode and the treated surface is — 1 mm. The sputtered area of the inner surface of the pipeline is located directly under the anode. Similar calculations can be performed for the decontamination of pipelines of any geometry.

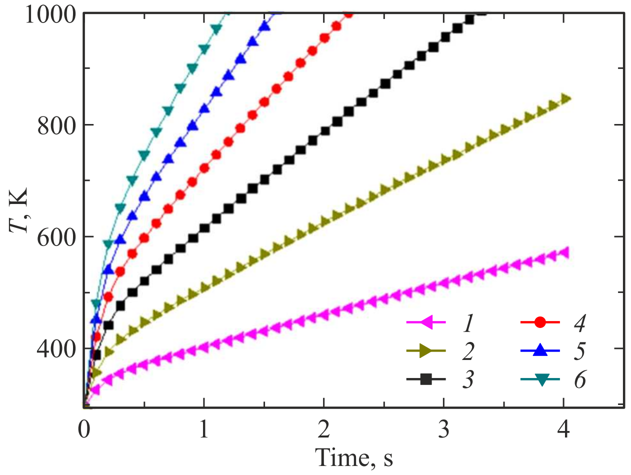

Figure 2. Dependence of heating rate of the inner surface of the pipeline wall.

Figure 2 shows the time dependences of the temperature of the inner surface of the pipeline wall during the first 4 seconds of the microplasma discharge treatment of th surface section located directly under the anode, at different values of the power input to the discharge. Numbers of curves *1, 2, 3, 4,5* and *6* correspond to power values $1 \cdot 10^6$, $2 \cdot 10^6$, $3 \cdot 10^6$, $4 \cdot 10^6$, $5 \cdot 10^6$ and $6 \cdot 10^6$ W/m^2. According to the data obtained, the optimal pulse discharge mode is at power of $6 \cdot 10^6$ W/m^2 (for example, at a voltage of 600 V and discharge current density of 1 A/cm^2) with pulse duration of maximum 1–2 s. When the discharge power is less than $6 \cdot 10^6$ W/m^2, the duration of the discharge pulse increases, at which the selected maximum permissible temperature of the sputtered surface is reached.

The sputtering rate at cathode current density of 1 A/cm^2 will be 0.7 μm/s, while the required decontamination time for a given area of the reactor metal structure is calculated taking into account the thickness of radioactive deposits, positioning speed of the manipulator with the sputtering device and the anode area. The characteristic cooling time of the heated walls 4 mm thick of the first loop of the RBMK reactor is equal to (36.2 ± 1.4) s. The characteristic cooling time allows you to select the sequence of the sputtering device movement along the decontaminated surface (for example, in a staggered order) so that, if it is necessary to repeatedly treat the same surface area, its temperature has time to drop to 300 K.

4. Conclusion

This paper proposes a fundamentally new approach to the deactivation of RP internal circuit equipment, based on sputtering radioactive deposits of any chemical composition from the cathode surface by microplasma discharge of atmospheric pressure in inert gas with the sputtered atoms transfer in the diffusion mode and their condensation on the anode-collector. The thickness of the sputtered layer is controlled by the discharge power and its exposure time. To prevent overheating, as an example, the time dependences of the temperature of the internal surface of RP pipeline wall were calculated depending on the discharge power, and the characteristic cooling time of the pipeline walls was also found. Recommended mode of ion-thermal technology: discharge power $6 \cdot 10^6$ W/m^2, discharge pulse duration maximum 1–2 s at the selected maximum permissible temperature 1000 K. When the discharge power is less than $6 \cdot 10^6$ W/m^2 the width of the discharge pulse increases and the productivity decreases. At higher decontamination temperatures (for example, graphite), it is recommended to make the anode from a refractory metal (for example, Ta) and equip the sputtering device with ceramic thermal insulation (for example, ceramics based on Al_2O_3 or ZrO_2). The advantages of ion-thermal decontamination technology are: the absence of liquid radioactive waste, sputtering of radioactive surface contamination of any chemical composition, collection of sputtered radioactive contamination on replaceable anode-collector in the solid form. The basic principles of ion-thermal technology are applicable for the decontamination of irradiated reactor graphite [10] and the effective spent-fuel reprocessing [11].

Conflict of interest

The authors declare that they have no conflict of interest.

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