Studies of the internal structure of electrical devices and the archaeological heritage by the method of neutron radiography and tomography

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В работе представлены результаты исследования серии объектов электрических устройств и археологического наследия методом нейтронной радиографии и томографии (диод ВЛ-10, свеча зажигания, колокол, древнее кольцо, камень). Показано, что метод нейтронной радиографии и томографии достоверно работает на образцах, изготовленных из различных материалов. Нейтронно-радиографические и томографические исследования диода ВЛ-10 дали преставление о внутренней структуре диода. Эксперименты со свечой зажигания позволили выявить причины его неисправности. По томографическим результатам колокола, кольца и камня выявлены неоднородные участки во внутреннем объеме этих объектов. Полученные результаты являются основой для дальнейших исследований в области археологического наследия и технических устройств особого назначения.

Ключевые слова: нейтрон, томография, радиография, исследовательский ядерный реактор, поток тепловых и эпитепловых нейтронов, сцинтиллятор**,** устройство с зарядовой связью (ПЗС), рассеяние, поглощение, сечение, изображение.

The paper presents the results of the study of a series of objects of electrical devices and archaeological heritage by the method of neutron radiography and tomography (VL-10 diode, spark plug, bell, ancient ring, stone). It is shown that the method of neutron radiography and tomography reliably works on samples made of various materials. Neutron radiographic and tomographic studies of the VL-10 diode gave an idea of the internal structure of the diode. Experiments with spark plugs have revealed the causes of its faulty function. According to the tomographic results of the bell, ring and stone, the heterogeneous areas in the internal volume of these objects were revealed. The results obtained are the basis for further research in the field of archaeological heritage and technical devices for special purposes.

Keywords: neutron, tomography, radiography, research nuclear reactor, thermal and epithermal neutron flux, scintillator, charge coupled device (CCD), scattering, absorption, cross section, image.

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I. Introduction

During operation, the technical condition of the equipment, its elements deteriorate due to the formation of various defects and destruction of their structure. Non-destructive analysis allows you to detect defects and damage formed during the operation of the equipment. There are various methods of non-destructive analysis: ultrasonic radiography, flaw de-

tection, magnetic particle flaw detection, eddy current method, neutron radiography and tomography [1].

Neutron radiography and tomography makes it possible to obtain complete information about the internal structure of an object with a high resolution from deep layers of the object under study due to the electrical neutrality of the particle [2].

It is known that the neutron flux passing through a substance is weakened as a result of absorption or scattering of neutrons on the atomic nuclei of the medium, and their intensity decreases along straight paths. The attenuation of the neutron flux intensity by the sample is described according to the Beer-Lambert law [2].

In neutron radiography and tomography, thermal and epithermal neutrons are mainly used, the main role here is played by the absorption and scattering of neutrons. Cold neutrons obtained after neutron moderation with liquid deuterium are also used in neutron radiography and tomography [3].

Taking into account the advantage of the non-destructive research method, in recent years a large number of experiments in biology [4-7], geophysics [8-10], engineering [11-13], paleontology [14-17], archeology [18-22], etc. In [23, 24], the possibilities of neutron radiography and tomography for visualizing the presence of organic substances inside metals are presented. The results of studying the internal macrostructure of a garnet crystal in a matrix of mica, mollusk shells, as well as visualization of a turbine blade model are presented in [25, 26]. In [27], the presence of fillings of the internal volumes of a gold vessel and an encolpion cross made of copper-based alloys was established.

Archaeological finds, pieces of glass from around the 1st-2nd century AD and polychromatic marble [28] were investigated using a neutron tomography facility, areas with high neutron absorption were discovered, and voids and defects in glass material were quantitatively analyzed [28].

The method of neutron radiography and tomography is especially important in the study of cultural heritage. Due to the need to study the internal structure, identify the presence of internal defects and, in many cases, find out the original figure, which may be hidden due to the presence of rust, fossils of substances adhered to them (after their manufacture), formed over time.

Another important possibility of the method is to study the internal structure, the presence of internal defects in electrical installations, parts of electronic equipment made of various materials to identify the causes of their failure and optimize their production technology.

Thus, the purpose of this work is to study the internal structure, integrity and presence of defects in archaeological objects found in Uzbekistan and electrical devices at the neutron radiography and tomography installation of the INP AS RUz.

II. Objects of study and experimental technique

The objects of research are electrical devices and archaeological finds. The VL-10 diode and car spark plugs were chosen as electrical devices to visualize their internal structure and analyze the cause of their malfunction. The internal structure, homogeneity of the following archaeological sites: bell, ceramic stone and ancient ring will be investigated. The origin of the archaeological finds probably dates back to the ancient period, when the first urban planning activity began in Bukhara. To date, in the Varakhsh massif of the oasis, as a result of archaeological research, many archaeological excavations have been discovered. Among them there are more than 100 metal artifacts of copper, bronze, silver and lead dating back to the XI-XII centuries [29-31].

The studies were carried out on a neutron radiography and tomography unit installed on the fifth horizontal channel of the WWR-SM reactor of the INP AN RUz with a neutron flux of ~9×10^6 neutrons/cm^{2}s and a resolution of ~ 280 μm (L/d~600) [32]. In neutron tomography, a controlled goniometer rotates the sample 180 degrees during an experiment [32].

The 6LiF/Zn(Cd)S:Ag screen is used as a scintillation detector to convert neutrons passing through the sample into visible light with a wavelength of 380 nm to 760 nm. The highly reflective light emitted by the scintillator using mirrors 200×280×3 mm is directed into a ProLine PL09000 CCD camera [32]. The rotation step was 0.45°, the total number of measured projections was 401. The exposure time for each position of the object was 3 s, and the final measurements lasted 34 min.

The obtained experimental data were processed with special software. Neutron radiographic images were corrected for the background noise of the detector system, the contrast of all images was corrected, normalized to the intensity of the incident neutron beam, and the required area of radiographic images was “cut out” using the ImageJ software package [33]. After processing the radiographic images with the

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ImageJ program, the resulting cropped radiographic images were processed with the SYRMEP Tomo Project (STP) software [34] to create a 3D tomographic image from individual angular neutron projections using mathematical operations. SYRMEP Tomo Project (STP) is designed with a clear distinction between a graphical user interface and basic functionality. Depending on the experimental conditions, various methods are proposed for reconstructing a three-dimensional image of the object under study [35-38]. For visual viewing, analysis and processing of the obtained three-dimensional data, the Avizo™ software package is used [39].

III. Experimental results and their discussion

As a result of neutron-radiographic and tomographic studies of the VL-10 diode, it was found that the characteristics of the neutron radiography and tomography unit of the INP of the Academy of Sciences of Uzbekistan make it possible to visualize its internal structure. From the radiographic and tomographic data obtained below (Fig. 1), it can be concluded that a diode consisting of an external flexible terminal (1), a glass insulator (2), an internal flexible terminal (3), a housing (4), crystalline semiconductor silicon (5), bases (6) and pins (7) for fastening to the radiator were visualized with good contrast, no damage was found. It can be seen from the tomographic images (Fig. 1) that each element of the diode gives a separate contrast, and the connecting solders also have a “kind” of contrast. From the radiographic sections in Fig. 1 it can be seen that the semiconductor crystal attached to the diode anode has a more "hazy" contrast compared to other elements and the diode body.

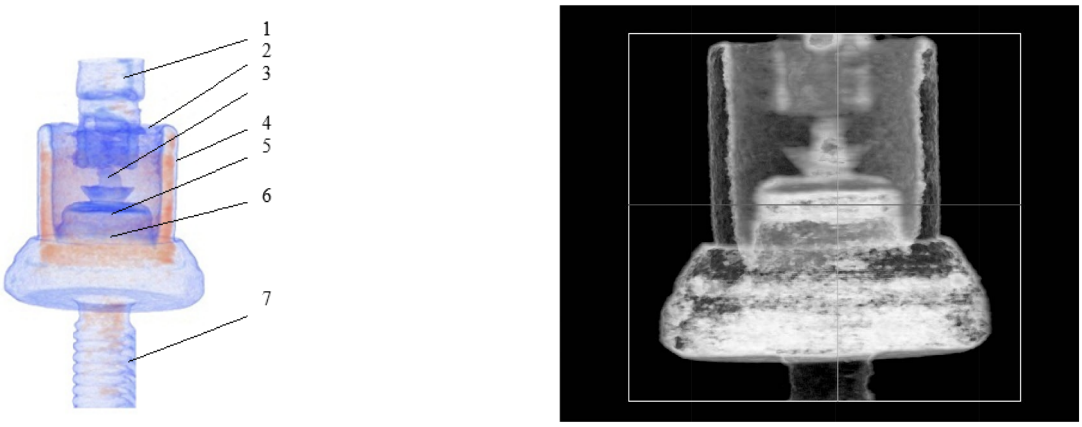


Figure 1. Tomographic view and radiographic section of the diode. 1 - external flexible lead, 2 - glass insulator, 3 - internal flexible lead, 4 - case, 5 - semiconductor silicon crystal, 6 - base, 7 - stud for fastening to the heatsink.

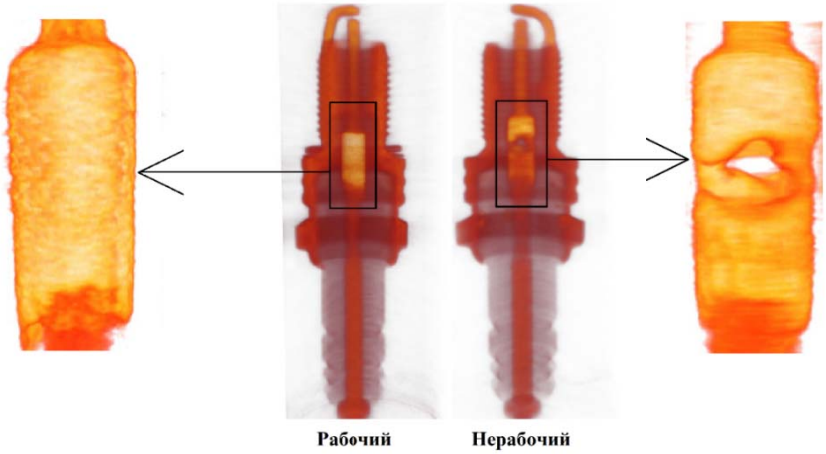


Figure 2. A visual comparison of the internal structure of a working and non-working spark plug. The arrows indicate the conductive section in the center rod of the spark plug.

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On the installation of neutron radiography and tomography, a three-dimensional image of the internal structure of a BRISK L15YCY automotive spark plug was obtained. Experiments were carried out first with a working spark plug, and then with a non-working spark plug of the same brand. As a result of processing, visual 3D images were obtained (Fig. 2). Based on the results obtained, it was found that the conductive sealant connecting the upper and lower rods melted in an idle spark plug at "strong" heating. The length of the molten portion of the conductive sealant is approximately 3.7 mm. Based on the results obtained, it can be concluded that in an inoperative spark plug, the malfunction is most likely due to strong heating of the conductive material.

The archaeological site of the bell is mainly composed of a copper compound. The bell has the shape of a truncated cone with an elliptical base (Fig. 3 (a)). The bell surface is uneven and dark red. As a result of processing the experimental data, it turned out that the bell has an uneven thickness throughout its volume. The tomographic images show (Fig. 3) that on the lateral surfaces of the bell there are thinned areas up to 2.55 cm high (Fig. 3b), 1.53 cm (Fig. 3c), 3.88 cm (Fig. 3d) and width up to 3.01cm (Fig.3b), 1.24cm (Fig.3c), 0.89cm (Fig.3d). This thinning of the side surface of the bell can be caused by corrosion from oxidation of the copper compound in the bell material. Corrosion of metals is a normal process, since archaeological finds are mainly found in humid places underground, in the ground.

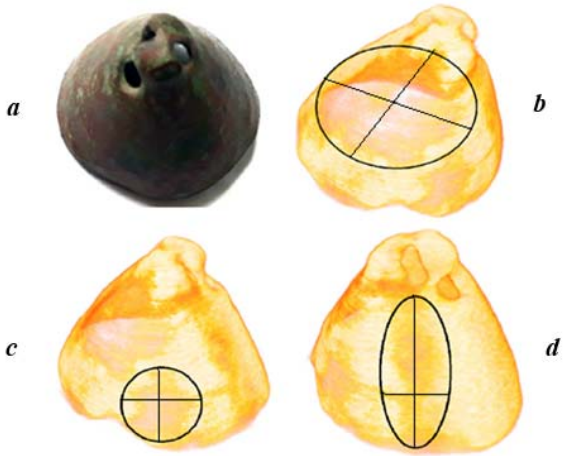


Figure 3. Photo (a) and radiography (b, c, d) of the bell.

The next object of cultural heritage research is an ancient ring, consisting mainly of iron, on the surface of which there is rust (Fig. 4). As a result of severe corrosion, the ring surface has deep cracks of 2.7 mm in size. The ring has a peculiar shape, consists of an incomplete round shank and a cylindrical caste. Approximately one fourth of the ring was “lost” as a result of the collapse. Fig. 4 (b, d), it can be seen that the ring of an unusual shape has an inhomogeneous internal structure, as evidenced by the area with a darker reflection of the internal structure of the ring in the caste part. It can be assumed that the inhomogeneous internal structure was formed as a result of “incorrect” solidification of the substance forming it upon cooling after the ring was cast. The dimensions of this area are approximately: height 0.33 cm, width 0.69 cm. In the whole volume of the ring, no defects, cracks or the presence of other metals were found.

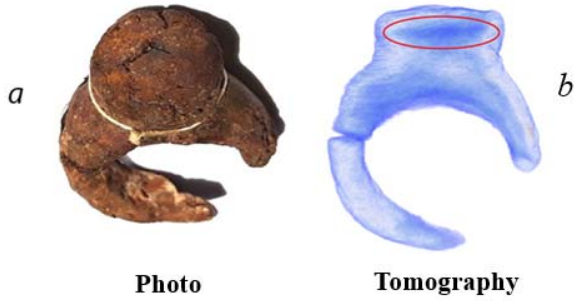


Figure 4. Photo (a) and tomographic image (b) of the ancient ring.

The archaeological object made of "stone" has an elliptical shape with an uneven white-yellow surface and a hole in the center, which in ancient times was most likely intended for household work. From the radiographic and tomographic results, it can be seen (Fig. 5) that the object has an inhomogeneous shape throughout the entire volume. Visual tomographic images of the inner layers showed that an area with a high neutron attenuation is located closer to the outer surface of the stone, which may be associated with a high content of elements with a large neutron absorption cross section (B, Cd, Li, etc.). The dimensions of this area of the stone are 0.50 cm long and 0.53 cm wide. Tomographic images of the stone have shown that it mainly consists of two areas. The first area is the outer disk, which is rendered with good contrast, and the inner area, which has darker contrast. Since the stone is composed of different elements and therefore neutrons are mainly attenuated in the outer layers of the stone, and a small amount of neutrons pass through the inner layers of the stone, and for this reason it is quite difficult to

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visualize the complete internal structure of the stone with good contrast. Below is (Fig. 5) a visual representation of the stone in various positions.

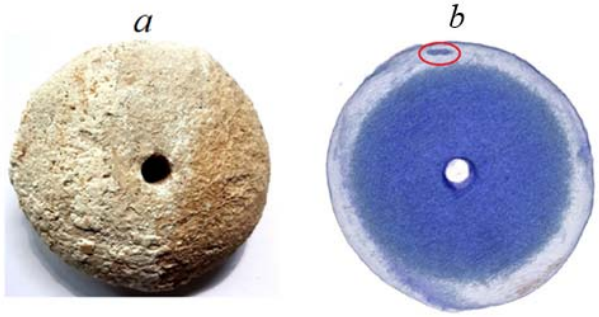


Figure 5. Photographic (a) and tomographic (b) images of the stone in different positions.

IV. Conclusion

The internal structure of the VL-10 diode and BRISK L15YCY brand spark plugs was obtained by research on a neutron radiography and tomography installation. The obtained radiographic and tomographic pictures show that each material of which the VL-10 diode and the spark plug are composed gives a kind of contrast, and from these pictures it is possible to distinguish the materials of which they are composed.

Possible causes of malfunction of an inoperative spark plug are identified and a molten conductive section of a malfunctioning spark plug with a size of ~ 3.7 mm is shown.

It was found that the ancient bell has an inhomogeneous internal structure, that is, there are thinned areas on the bell body with a width of up to 3.01 cm and a height of up to 3.88 cm. These areas are associated with corrosion of the bell material, a picture of the distribution of corroded areas in the volume of the bell metal was obtained.

In the inner structure of the ring, a region with a high attenuation of neutrons was found, which manifests itself in a darker contrast of this region. The discovered inhomogeneous region 0.33 cm high and 0.69 cm wide in the inner structure of the ring was apparently formed as a result of improper solidification of the ring after its casting; deep cracks of 2.7 mm in size were found on the surface of the ring.

In the image of the stone, closer to the surface, there is a section with dimensions of 0.5 cm in length and 0.53 cm in width, which is caused by a high content of elements with a high degree of neutron attenuation.

The studies carried out demonstrate the effectiveness of using neutron radiography and tomography to study the internal structure of complex objects, such as objects of cultural and historical heritage and various electrical devices.

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Электр қурилмаларини ва археологик мерос-ларни нейтрон радиографияси ва томография-си усули билан ички тузилишини ўрганиш

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Мақолада нейтрон радиографияси ва томографияси усули билан айрим электр қурилмалар ва археологик топилмаларни (ВЛ-10 русумли диод, ўт олдириш свечаси, қўнғироқ, қадимги узук, тош) ўрганиш натижалари келтирилган. Нейтрон радиографияси ва томографияси усули ёрдамида турли материаллардан тайёрланган намуналар ички тузилишини юқори аниқлик билан тадқиқ қилиш мумкинлиги кўрсатилган. Тадқиқотлар натижасида ВЛ-10 русумли диоднинг ички тузилиши ҳақида маълумот олинган. Ўт олдириш свечаси билан ўтказилган тадқиқотлар унинг носозлик сабабларини аниқлашга имкон берди. Қўнғироқ, қадимги узук ва тошнинг томографик натижалари эса, ушбу объектларнинг ҳажмида айрим нуқсонлар ва қалинлиги турлича бўлган қисмлар мавжудлигини кўрсатди. Олинган натижалар археологик топилмалар ва махсус мақсадлар учун қўлланиладиган техник қурилмалар тузилиши соҳасидаги кейинги тадқиқотлар учун асос бўлиб хизмат қилади.

Калит сўзлар: нейтрон, томография, радиография, тадқиқот ядро реактори, термик ва эпитермал нейтрон оқими, сцинтиллятор, зарядли боғланган қурилма (ССД), сочилиш, ютилиш, кесим, тасвир.

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