https://doi.org/10.46813/2023-145-076

MATHEMATICAL MODELING OF NEUTRON RADIOGRAPHY PROCESSES

S.I. Prokhorets, M.A. Khazhmuradov
National Science Center "Kharkov Institute of Physics and Technology",
Kharkiv, Ukraine
E-mail: khazhm@kipt.kharkov.ua, sprokhorets@gmail.com

A goal function is formulated and parameters for neutron radiography setup optimization are determined. The results of calculation of neutron passing through formation system are given.

PACS: 28.20.Pr, 29.85.-c, 29.90.+r

The problems of improving the quality, reliability and durability of technical products, machines, parts, materials and complex structures are of particular importance in modern conditions. Solving these problems largely depends on the availability of effective methods of control. The greatest interest in industry is represented by methods of non-destroying control. Such methods include flaw detection of materials and products using gamma and X-ray radiation or bremsstrahlung radiation from electron accelerators. One of the new methods of non-destructive testing, which is intensively developing in many industrially developed countries of the world, is neutron radiography. Currently, there is no radiographic installation in Ukraine, although its implementation would allow to keep pace with the global development of science and technology.

The practical implementation of the neutron radiography method will allow to create in Ukraine a new tool for non-destructive analysis of critical products of the nuclear industry. The introduction of radiography, and then tomography, in neutron beams will provide a new toolkit for inspection of a wide range of products containing both light and heavy elements and their isotopes.

This work considered the models and features of the main systems of the neutronographic installation on the electron accelerator.

The main systems (elements) of the installation include: a radiation source – a source of accelerated electrons that produce neutrons as a result of interaction with the target material, a neutron-producing target, a system for forming a neutron flow and a position-sensitive detector of neutron imaging (Fig. 1).

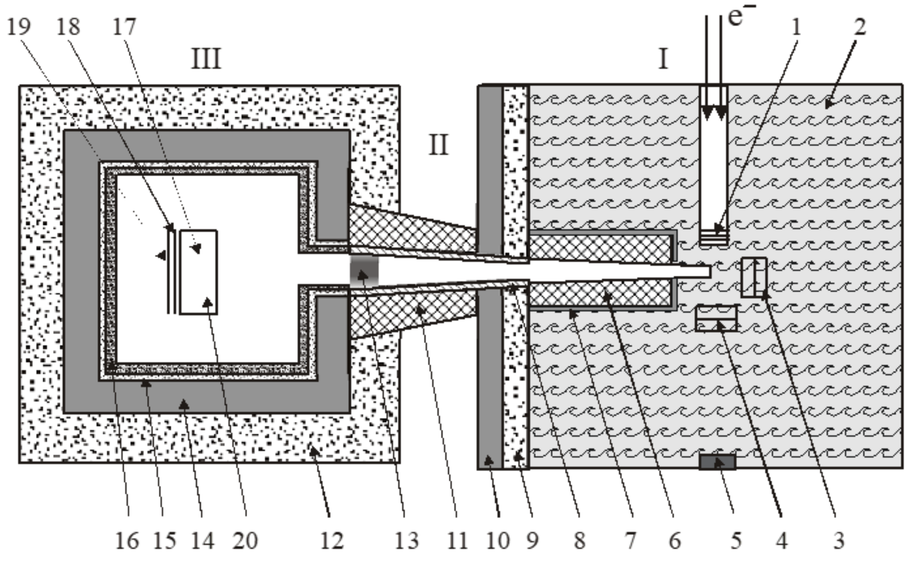


Fig. 1. Scheme of the NR-facility model:
I – neutron producing target; II – system of formation of a beam of slowed neutrons;
III – neutron radiography chamber;1 – Ta-tarhet; 2 – a tank with moderator;
3, 4 – beryllium reflectors; 5 – beam monitor; 6 – collimator; 7 – Pb-shield around the collimator;
8 – Cd layer; 9, 12 – borated polyethylene; 10, 11, 14 – Pb;
13 – gamma-filter; 15 – Sn; 16 – Ni(Cr); 17 – beam purity indicator (BPI);
18 – convertor Gd(Dy); 19 – x-ray film; 20 – ShD-1 device

This presentation of the neutronographic facility allows you to present its structural scheme in the form of a set of subsystems or aggregates and the relationships between them. An electron accelerator is used as a source of radiation, as a result of which neutrons interact with matter. Interconnections in such a system are the interaction of an electron beam with a certain energy and current with a neutron-forming target and the passage of emerging neutrons and gamma quanta sequentially through the path of neutron formation and the research object to the detector. In the first approximation, the functioning of any of the subsystems in the considered system does not depend on the subsequent one, therefore mathematical modeling to optimize their characteristics is reduced to autonomous modeling of subsystems. Therefore, the simulation can be started from any subsystem, the input of which receives information from only one source. In the presented system, such a case can be realized if it is assumed that the gamma background from the neutron target is negligibly small, that is, the influence of the gamma background on further subsystems can be ignored. Such a presentation of a complex system allows you to use information in the form of tables, graphs, etc., to characterize the subsystems entering it and mathematical modeling.

The physical processes underlying the production of neutrons at an electron accelerator were briefly considered priviously. It was shown that the yield of neutrons depends on many controlled parameters, the most important of which are the energy and current of accelerated electrons, the distance from the center of the neutron-generating target to the forming collimator, the length of the forming collimator, the thickness and atomic number of the target material. To simulate the neutron output depending on the controlled parameters, programs have been developed based on the MCNPX code that take into account the processes of neutron production $e^- \rightarrow \gamma + n$ and $e^- \rightarrow \gamma + 2\,n\;n$ in a neutron-forming target made of heavy chemical elements: lead, tungsten, tantalum, uranium. The simulation was carried out under the condition that an electron beam with an energy in the range from 20 to 150 MeV falls normally into the center of the end face of a cylindrical target or plate. As a result of the simulation, it is shown that the neutron output depends slightly on the thickness of the target, starting from 3…4 cm, and on the electron energy, starting from 30…40 MeV. The dependence of the neutron yield on the electron energy almost disappears when the energy of these particles exceeds 100 MeV. The yield of neutrons from uranium is almost twice that of tungsten at the optimal target thickness. The simulation made it possible to estimate the output of neutrons from the target. For a lead target, for example, at an electron beam energy of 20 MeV, it is $2 \cdot 10^{-3}$ for one electron falling on a lead target.

Simulation results show that an increase in neutron flux can be achieved by using a subcritical assembly driven by an electron accelerator. This control determines the course of the neutron propagation process only in the presence of external illumination by particles from the accelerator. A subcritical assembly controlled by an electron accelerator has two main components – a neutron-generating target, the parameters of which are discussed above, and a reactor assembly in which the flow of neutrons from the target is amplified. The subcritical assembly works on the basis of the division of the substance included in its composition. Calculations of the neutron flow enhancement were carried out for homogeneous and heterogeneous assemblies with a multiplication factor of 0.95…0.97, which corresponds to an increase in the neutron flow from the target by 20…30 times.

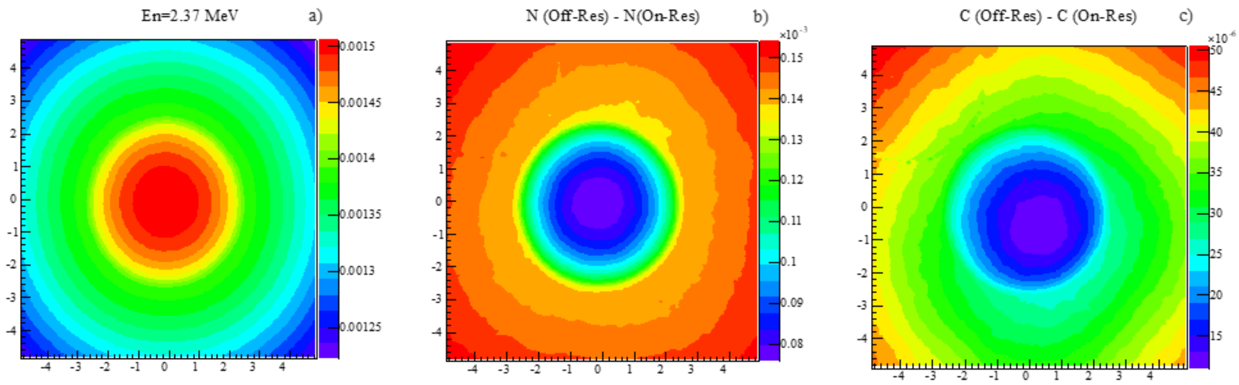
Given that thermal neutrons are used for non-destructive testing of various objects, the collimator-former for modeling is presented in the form of a long hollow cylinder with a lid located on the side of the neutron-forming target. The peculiarity of this neutron flow formation scheme is that neutrons not only move in a slowing medium, but also pass from one medium to another, experiencing reflections. Thus, the neutron experiences a chain of interactions, so its history is considered on the basis of calculations of a number of processes (elastic and inelastic interactions, capture, etc.) using programs developed on the basis of the MCNP-4C code. When conducting optimization calculations of the neutron flow forming system, the neutron flow in the thermal range of energies at the exit of the collimator-former and at the research object was considered as a quality criterion.

As a result of the work performed, mathematical models were developed that describe the physical processes of the interaction of neutrons, electrons and gamma quanta with the substance of the neutron-generating target, which together with the electron accelerator is a source of neutrons, and the path of formation of the flow of thermal neutrons. Mathematical models describe the geometrical parameters of the neutron-forming target, the path of the formation of the neutron flux in the form of a hollow cylinder with a front cover and a cadmium insert. They also take into account the chemical composition of both the neutron-generating target (tantalum, tungsten, lead, uranium) and the simple device that forms a flow of thermal neutrons, a long polyethylene cylinder. Mathematical models formalize the process of birth and transport of neutrons in a thick target. They provide an opportunity to consider the process of neutron birth (electron $\rightarrow$ photon $\rightarrow$ neutron) and its transport, taking into account elastic and inelastic interactions with the environment. The geometric block of the software complex determines the location of the particle after interaction and traces its trajectory in a three-dimensional object. MCNP-4C, MCNPX and GEANT4 software codes were used to develop mathematical and physical models of three-dimensional objects.

RESULTS

Spheres with a diameter of 5 cm were considered for modeling. The composition of objects was considered as follows: hydrogen (H) – 1.0 g, carbon (C) – 7.1 g, nitrogen (N) – 7.1 g, oxygen (O) – 12.3 g; This can be considered as a simulation model of an explosive. Input neutron energies for modeling were 2.37 MeV, 5.36 MeV (carbon resonance energy), 2.23 MeV (nitrogen resonance energy), 3.43 MeV (oxygen resonance energy) and 0.01 MeV (oxygen valley energy O).

At Fig. 2 the results of modeling of the NR- images obtaining for location of a sphere with a diameter of 5 cm in the soil at a depth of 1 cm are shown.



a *b* *c*

Fig. 2. The results of modeling of the NR- images obtaining

CONCLUSIONS

In the work, the objective function is formulated, the parameters that allow optimizing installations for neutron radiography are defined. It is shown that this problem belongs to the class of multi-connected systems with distributed parameters. It is shown that the location of the research object near the collimator is the most rational.

REFERENCES

1. V.G. Batiy, S.I. Prokhorets, M.A. Khazhmuradov, et al. Development of mathematical and experimental model of neutron radiography setup // *Problems of Atomic Science and Technology. Series "Nuclear Physics Investigations".* 2003, N2 (41), p. 116-117.
2. N.P. Buslenko. *Modeling of complex systems*. M.: "Nauka", 1968, 356 p. (in Russian).
3. L.M. Dykhnenko, I.V. Kuzmin, E.G. Petrov, et al. *Fundamentals of modeling complex systems*. Kyiv: "Vyscha shkola", 1981, 360 p.
4. S.I. Prokhorets, I.M. Prokhorets, M.A. Khazhmuradov. Mathematical models of neutron passing through matter // *Radioelectronics and Informatics*. 2003, №1, p. 124-128.

Article received 01.02.2023

МАТЕМАТИЧНЕ МОДЕЛЮВАННЯ ПРОЦЕСІВ НЕЙТРОННОЇ РАДІОГРАФІЇ

С.І. Прохорець, М.А. Хажмурадов

Сформульовано функцію мети та визначено параметри оптимізації установки нейтронної радіографії. Наведено результати розрахунку проходження нейтронів через систему формування.