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ENGINEERING DESIGN OF NUCLEAR PHYSICAL EQUIPMENT

Application of the Tagged Neutrons Method for the Analysis of Material on a Conveyor

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Abstract—In this paper, we discuss the results of applying a tagged neutron method for a remote nondestructive analysis of the elemental composition of matter on a conveyor. The tagged neutron method consists in irradiating the test substance with fast neutrons with an energy of 14 MeV, followed by recording the characteristic radiation of gamma quanta. Neutron tagging is carried out by an alpha detector built into the neutron generator.

Keywords: fast neutrons, tagged neutron method, portable neutron generator, conveyor analyzer, elemental analysis

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INTRODUCTION

The tagged neutron method (TNM) is widely used for a remote nondestructive analysis of the elemental composition of various objects [1–4]. In this paper, we discuss the use of the TNM to determine the elemental composition of mineral raw materials transported on a conveyor. To control the composition of raw materials, samples are usually taken off the conveyor and their chemical analysis is performed. The main disadvantage of this method is that the result of the analysis becomes available in a few hours, which makes it difficult to perform any corrective actions on the composition of the transported raw materials. At the same time, for many production processes, such as agglomerate sintering for iron smelting or cement production, it is important to maintain a constant elemental composition of raw materials on the conveyor within certain limits. Any deviation beyond these limits leads to unnecessary consumption of fuel, production reagents, and environmental problems. The TNM allows a real-time analysis of the elemental composition of raw materials on the conveyor without any sampling. Information about the elemental composition of raw materials can be provided every 40 s.

TAGGED NEUTRON METHOD

The tagged neutron method consists in irradiating the test sample with fast neutrons with energy of 14.1 MeV, which are formed as a result of the reaction:

$$d + {}^3\mathrm{H} \rightarrow {}^4\mathrm{He} + n. \quad (1)$$

Helium nuclei (alpha particles) are registered by a multichannel alpha detector, owing to which we know the number of emitted neutrons, as well as the direction of their momentum, since in binary reaction (1), a neutron and an alpha particle scatter in opposite directions (at the deuteron energy of $T_\mathrm{d} = 50$ keV, the expansion angle is in the range of 174°–180°). This procedure is called neutron tagging (Fig. 1).

Due mainly to inelastic scattering reactions of the $(n, n'\gamma)$ type, fast neutrons excite the nuclei of the substance under study. This excitation is removed by gamma radiation characteristic of each chemical element, which makes it possible to identify it.

An important feature of the TNM is that gamma quanta are registered only within the coincidence window, which opens at the moment of the appearance of a signal that an α particle hits the corresponding section of the alpha detector. This makes it possible to select only those γ quanta that are emitted by the nuclei of the studied substance. As a result, the signal-to-background ratio in the TNM is improved by a factor of almost 200 compared to conventional neutron analysis methods.

DESCRIPTION OF THE CONVEYOR INSTALLATION

The conveyor installation is a hardware–software measuring complex designed to analyze the elemental

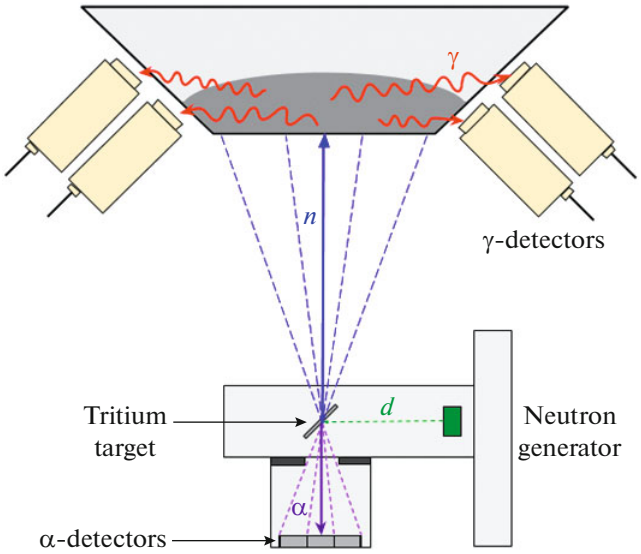

Fig. 1. Scheme of the tagged neutron method.

composition of a substance on the conveyor in real time. The general view of the installation is shown in Fig. 2. The neutron module of the installation is located between the operating and return conveyor belts and is a frame on which a neutron module, that is, a neutron generator, a system for detecting γ quanta, and biological shielding are mounted.

Portable neutron generator ING-27 manufactured at Dukhov VNIIA produces a continuous flux of neutrons with energy 14.1 MeV and intensity $I = 5 \times 10^7$ s^{-1}. Alpha particles from reaction (1) are registered by a built-in silicon alpha-detector consisting of 9 pixels, forming a 3 × 3 matrix. The pixel size is 10 × 10 mm.

To measure the energy spectra of γ quanta from inelastic neutron-scattering reactions, detectors based on large (∅76 × 65 mm) BGO scintillation crystals and R6233-35 photomultipliers manufactured by Hamamatsu according to special technical requirements are used. BGO-based γ-ray detectors used at the facility have a sufficiently good energy resolution, no worse than 10% on the $E_\gamma = 662$ keV line from a ^{137}Cs radioactive source.

The main advantage of BGO crystals is a large effective atomic number ($Z = 74$) and high density ($\rho = 7.13$ g/cm^3). However, a significant disadvantage of BGO is the strong temperature dependence of the light output: 1.2%/°C and so to stabilize the light output, it is necessary to thermostat the crystals.

The γ-ray detection system of the facility consists of two blocks of seven detectors based on BGO crystals. To stabilize the light output of the BGO crystals, the detectors are placed in thermostats, which are located on different sides of the conveyor. The thermostats maintain a temperature of 25 ± 0.1ºC.

Figure 3 shows a typical time distribution of signals from γ quanta. The spectrum was collected in a 100-ns-width coincidence window, which opens at the moment of arrival of the α particle. It can be seen that the time spectrum consists of a plateau of random coincidences and a peak of γ quanta from the studied object. The zero-reference point is chosen on the time spectrum so as to coincide with the maximal peak of the signals from the studied object.

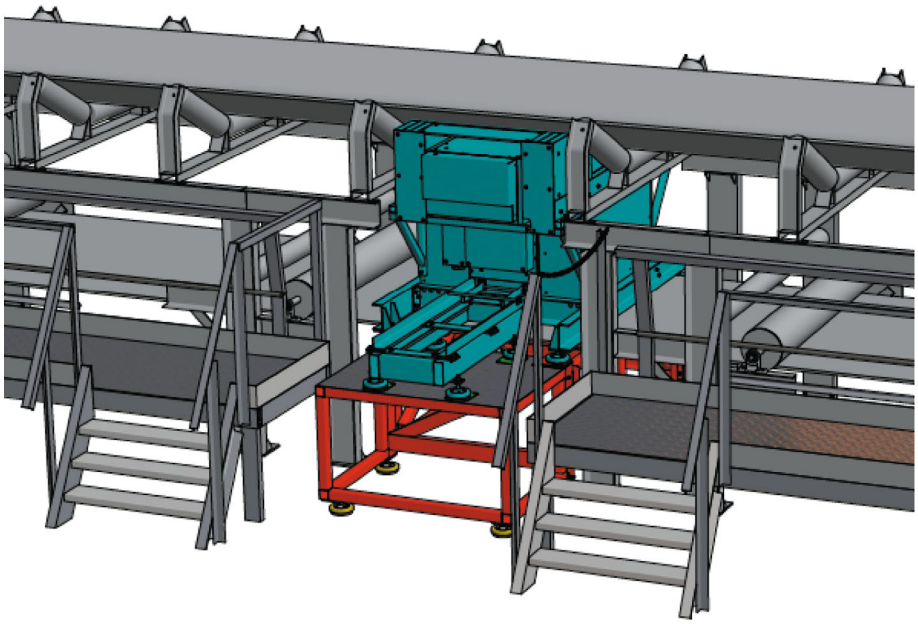

Fig. 2. General view of the conveyor installation for the analysis of the elemental composition of a substance on the conveyor.

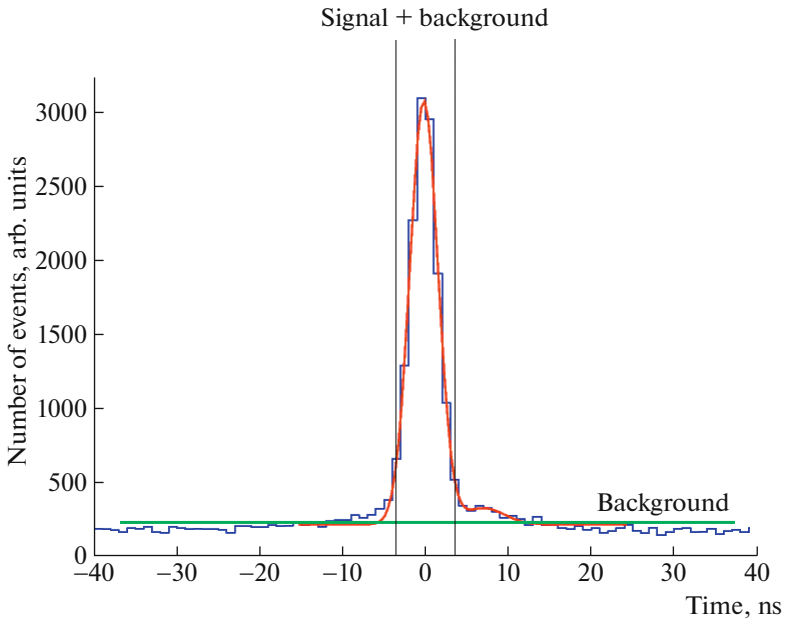

Fig. 3. Time spectrum of gamma quanta.

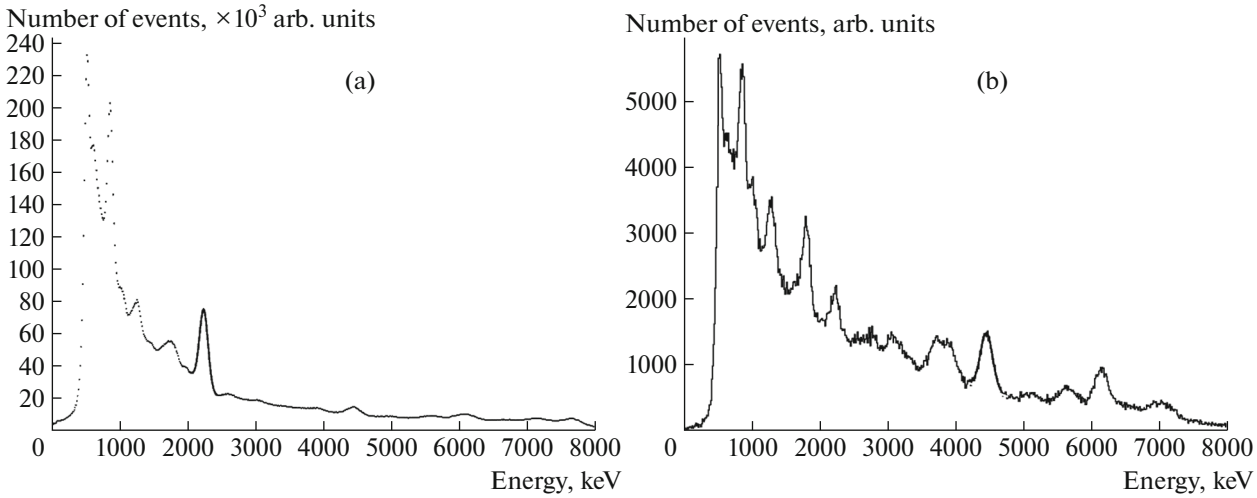

Fig. 4. Energy spectrum of γ quanta from (a) the region of random coincidences and (b) the region of signals from the studied object.

Figure 4 shows the energy spectra of γ quanta corresponding to (a) the region of random coincidences and (b) the region of signals from the studied object.

It can be seen how strongly the energy spectra of the region of random coincidences and the region of signals from the object differ. In the first case, the energy spectrum clearly shows a peak at energy of 2.23 MeV due to the capture of thermal neutrons by hydrogen. Thermal neutrons are produced by moderating 14-MeV neutrons in biological protection elements made of polyethylene. Many lines from various elements present in the composition of the studied substance are visible in the signal area.

RESULTS

We consider the operation of the installation using the example of measurements of the energy spectra of a sinter on a conveyor. Figure 5 shows a typical energy spectrum of gamma quanta of the sinter. The spectra were processed according to the procedure described in detail in [5, 6]. The gamma spectrum of the sinter was deconvoluted into separate components by fitting

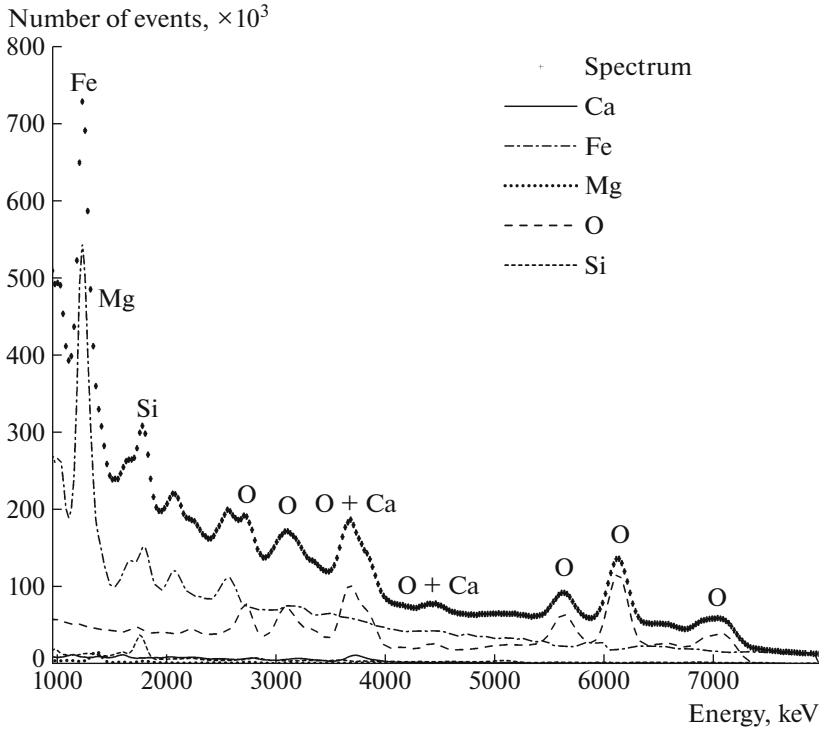

Fig. 5. Energy spectrum of gamma quanta of a sample of sinter. The dashed line shows the contribution from oxygen, the dashed line shows the contribution from iron, the dotted line shows the contribution from magnesium, the short-dashed line shows the contribution from silicon, and the solid line shows the contribution from calcium. Points with errors show the measurement results.

it with the sum of the reference gamma spectra from seven elements C, O, Al, Mg, Si, Ca, and Fe, which were previously measured. For comparison with the chemical analysis, for some components, the concentrations of chemical elements were recalculated in the concentrations of Al_2O_3, MgO, SiO_2, and CaO oxides.

Figure 6 shows how the basicity of the sinter, defined as the ratio of CaO/SiO_2 concentrations changes transported along the conveyor for several hours. The manufacturing process requires that the basicity of the sinter be kept within 1.6 ± 0.1. The results of the chemical analysis at this production facility are available in four hours. As can be seen from the data in Fig. 7, the basicity of the sinter can change from 1.8 to 1.2 and back in half an hour. These sharp fluctuations in basicity can be corrected, for example, by adding CaO, but this requires knowledge of the behavior of basicity in real time.

Figure 7 shows the comparison of basicity values obtained by the chemical analysis and the tagged neutron method. The data cover the measurement period over a month.

A good agreement between the data of the chemical analysis and the TNM can be seen. In Table 1, the mean values of the data of the chemical analysis and the TNM are compared for this monthly period.

We checked the presence of systematic deviations of the TNM results from the chemical analysis ones. The fulfillment of Student's criteria (t-statistic) and Fisher's (F-test) for the mean values of the results of the TNM and the chemical analysis (CA) was verified.

t-statistics were determined by the formula:

$$t = |\overline{\xi}|\sqrt{n}\sqrt{\sum_{i=1}^{n}(\xi_i - \overline{x})^2/(n-1)}, \quad (2)$$

$$\xi_i = C_{\mathrm{TNM}} - C_{\mathrm{CA}}, \quad (3)$$

where C_{TNM} and C_{CA} are the results of measurements of the ith sample (interval) according to the TNM and CA data, respectively, $\overline{\xi} = \sum_{i=1}^{n}(C_{i\mathrm{TNM}} - C_{i\mathrm{CA}})/n$, and n is the number of samples in the corresponding class.

Table 1. Comparison of average values of basicity and mass concentrations of SiO_2, CaO, MgO, and Fe_{tot}

	Basicity	SiO_2, %	CaO, %	Fe_{tot}, %	MgO, %
TNM	1.62	5.77	9.36	57.48	2.62
Chemical analysis	1.62	5.72	9.27	57.26	2.62

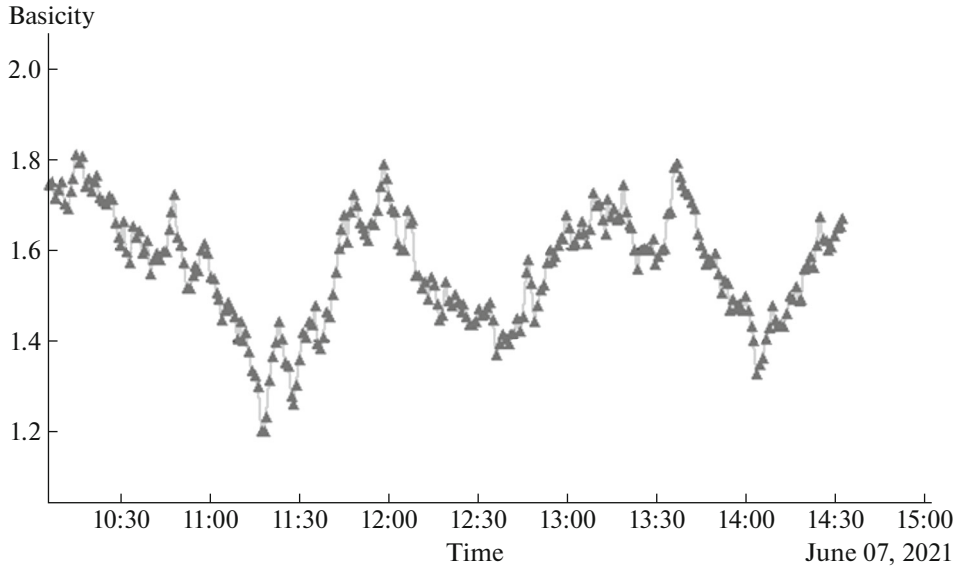

Fig. 6. Change in the basicity of the sinter.

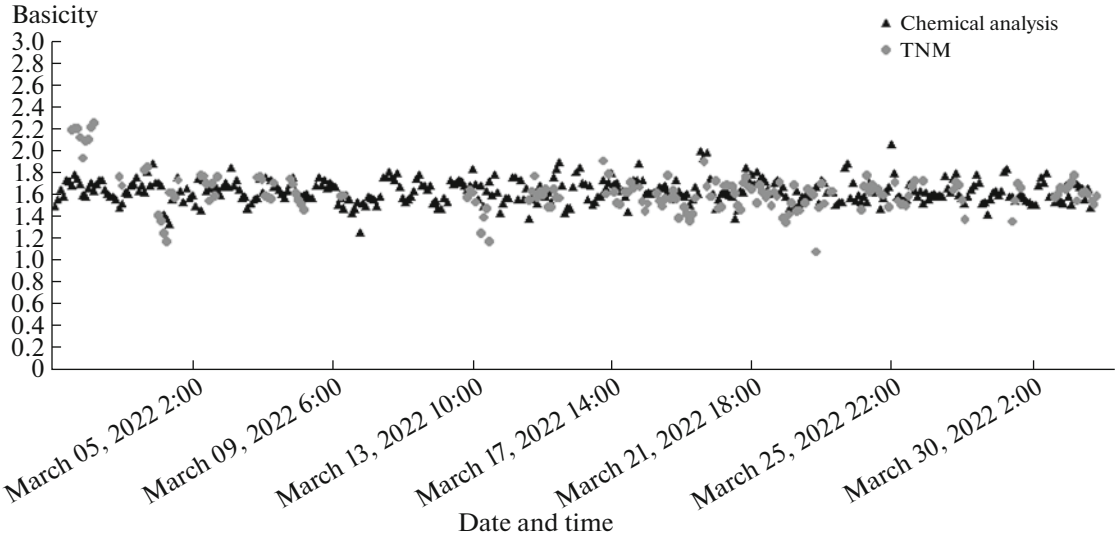

Fig. 7. Comparison of data of the chemical analysis and TNM.

F-statistics were calculated using the following formulas:

$$F = S_1^2/S_2^2, \tag{4}$$

$$S_1^2 = \sum_{i=1}^{n} \xi_i^2/n, \tag{5}$$

$$S_2^2 = \sum_{i=1}^{n} (\xi_i - \overline{\xi})^2/(n-1). \tag{6}$$

The systematic discrepancy was calculated from the difference between the average contents of the element:

$$\overline{\xi} = \overline{C_z} - \overline{C_x}, \tag{7}$$

$$\overline{C_z} = \left(\sum_{i=1}^{n} C_{zi}\right)/n, \tag{8}$$

$$\overline{C_x} = \left(\sum_{i=1}^{n} C_{xi}\right)/n, \tag{9}$$

where C_{zi} and C_{xi} are the results of measurements of the ith sample using the TNM and CA data, respectively; $\overline{C_z}$ and $\overline{C_x}$ are their average values, and n is the number of matched pairs.

Table 2. Comparison of *t*-test and Fisher's test calculated from experimental data and tabular values at $n = 125$

	Basicity	SiO_2	CaO	Fe_{tot}	MgO
t-criterion	0.07	1.62	1.15	1.16	0.16
t-criterion, table value	1.98	1.98	1.98	1.98	1.98
Fisher criterion	0.99	1.01	1.00	1.00	0.99
Fisher criterion, table value	1.35	1.35	1.35	1.35	1.35

$TNM_{av}(\overline{C_z})$ is the average value of the element content when analyzed using TNM, CA_{av} $(\overline{C_x})$ is the average value of the element content when analyzed using the chemical analysis, t is the value of t-statistics for the specified class of contents $(t = |\overline{\xi}|\sqrt{n}/\sqrt{\sum_{i=1}^{n}(\xi_i = C_{zi} - C_{xi} - \overline{\xi})^2/(n-1)})$, t_{table} is the critical tabular value of t-statistics for the number of elements equal to n and a confidence level of 0.95 ($n = 125$)

We see that for all concentrations and basicity, the calculated values of the *t*-criterion and *F*-criterion do not exceed the tabular values. This indicates the absence of systematic deviations from the chemical analysis data.

CONCLUSIONS

An analyser to control the elemental composition of mineral raw materials on a conveyor was created based on the tagged neutron method. The installation makes it possible to determine the elemental concentrations of raw materials on the conveyor in real time without sampling. The results of measurements of the mass concentration of individual elements and oxides that are performed at the analyser are compared with the results of the chemical analysis. Student and Fisher criteria tests showed the absence of statistically significant systematic deviations of the results of the installation from the data of the chemical analysis.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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