

Figure 1 shows the ranking diagram for  $y_3$ , together with the corresponding  $y_1$ ; it and Table 2 show that the release of  $\text{NO}_x$  directly into the gas and the accumulation in the solution vary considerably with the etching conditions, probably because of differences in the mechanisms for the interaction of the  $\text{NO}$  with  $\text{HNO}_3$ , as affected by concentration [5, 6].

These regression equations and the ranking diagram provide scope for reducing the release of oxides of nitrogen during etching zirconium-alloy tubes.

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#### NUCLEAR-PHYSICAL CHARACTERISTICS OF NATURAL RADIONUCLIDES

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One of the purposes of setting standards for the radioactivity of building materials is to limit the population exposure to gamma radiation from natural radionuclides [1]. The dose rate produced by a layer of material uniformly saturated with radionuclides is proportional to their effective specific activity

$$C_{\text{ef}} = C_{\text{Ra}} + a_1 C_{\text{Th}} + a_2 C_{\text{K}}, \quad (1)$$

where  $C_{\text{Ra}}$ ,  $C_{\text{Th}}$ , and  $C_{\text{K}}$  are the specific activities of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ , and  $^{40}\text{K}$  (the radionuclides of the uranium and thorium families are assumed in radioactive equilibrium);  $a_1$  and  $a_2$  are the ratios of the dose rates produced in an infinite cavity by equal specific activities of  $^{232}\text{Th}$  and  $^{226}\text{Ra}$ , and of  $^{40}\text{K}$  and  $^{226}\text{Ra}$ , respectively. These factors depend on the gamma energy and quantum yield of the radionuclides. The values stated in various sources show appreciable differences. In the NRB-76 radiation-safety standards for building materials, for instance,  $a_1 = 1.43$  and  $a_2 = 0.072$  [2]. A 1982 UNSCEAR report gives  $a_1 = 1.55$  and  $a_2 = 0.101$  [3]. In an earlier analysis of published data on the gamma spectra of natural radionuclides, we obtained  $a_1 = 1.26$  and  $a_2 = 0.086$  [4].

Some recently published handbooks recommended by the State Standard Reference Data Service [5, 6] provide the necessary data for calculations. The factors  $a_1$  and  $a_2$  were calculated from the formula for the dose rate in an infinite cavity [7], i.e.,

$$P = \sum_i E_i n_i \gamma_i^{\text{air}} / \gamma_i, \quad (2)$$

where  $E_i$  is the photon energy,  $n_i$  is the quantum yield, and  $\gamma_i^{\text{air}}$  and  $\gamma_i$  are the mass energy-transfer coefficients in air and the material (concrete). The coefficients were taken from [8, 9]. The calculation results were practically independent of the values used for  $\gamma_i$ . With the results obtained, Eq. (1) becomes

$$C_{\text{ef}} = C_{\text{Ra}} + 1.31 C_{\text{Th}} + 0.085 C_{\text{K}}. \quad (3)$$

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TABLE 1. Specific Activity of Natural Radionuclides

Nuclide	Half-life, years	Atomic abundance, %	Mass number, amu	Specific activity, Ci/g
<sup>238</sup> U	4,4683·10 <sup>9</sup>	99,275	238,02892*	3,337·10 <sup>-7</sup>
<sup>235</sup> U	7,038·10 <sup>8</sup>	0,720	238,02892*	1,537·10 <sup>-8</sup>
<sup>226</sup> Ra	1,608·10 <sup>3</sup>	100	226,02541	0,9836
<sup>232</sup> Th	1,40·10 <sup>10</sup>	100	232,03805	1,101·10 <sup>-7</sup>
<sup>40</sup> K	1,262·10 <sup>9</sup>	0,0117	39,09830†	8,477·10 <sup>-10</sup>

†\*Natural mixture of uranium isotopes.

†Natural mixture of potassium isotopes.

The natural-radionuclide content of rocks is often measured in mass units (g/g). In order to compare the measurement results with building-materials radioactivity standards, it is necessary to convert the measurements to specific-activity units, i.e.,

$$C = 3,575 \cdot 10^9 R / (MT_{1/2}), \quad (4)$$

where C is the specific activity of the nuclide in Ci/g, M is the mass number of the element in amu, R is the atomic abundance of the radionuclide in the natural isotope mixture in percent, and  $T_{1/2}$  is the half-life in years. Table 1 gives the initial data and the calculated activities of natural radionuclides. The half-lives are taken from [5, 6], the atomic abundances from [10], and the mass numbers from [11].

The calculation accuracy of  $a_1$ ,  $a_2$ , and the dose rates was checked against dose-rate measurements taken on cylindrical models (120 × 120 cm) of uranium, thorium, and potassium saturated layers. The measurements were made with an MAV-604 detector (whose response is energy-independent) at a point on the model axis 5 cm above its surface. The radionuclide content of the models in mass units was known to ±2%. The effective specific activities calculated from the tabulated data and Eq. (3) were 59.03, 49.76, and 11.64 pCi/g for uranium, thorium, and potassium models, respectively. The dose rates measured on the models, corrected for the dose rate in a background (practically radionuclide-free) model, were 92.4, 79.5, and 18.6 μR/h. The ratios between dose rate and effective specific activity were equal to 1.57, 1.60, and 1.59. The spread of these values is within ±1% and does not exceed the error involved in the radionuclide content or the dose-rate measurements. This indicates that the error in the coefficients used to calculate the effective specific activity of the natural radionuclides lies within ±1-2%.

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#### SOME SOURCES OF ERROR IN SODIUM-STEEL THERMOELECTRIC CONVERTERS

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Sodium-steel thermoelectric converters used for measuring the temperature of sodium have low inertia, a fact confirmed by reactor and test-stand experiments [1, 2]. At the same time, experience indicates that in steady-state and transient regimes the readings of sodium-steel converters may show substantial deviations from the true temperature. We shall consider the possible reasons for these distortions for various schemes of connecting the converters. The steel electrodes of the converter's differential sensor may be immersed inside a protective jacket into the sodium or may be welded to the external wall of a vessel or pipe. One of the electrodes (the signal electrode) is connected to the point being monitored, while the second (the reference electrode) is placed in a volume with a steady-state temperature. If the converter is connected externally, a reduction in the useful signal is caused by shunting through the wall. In the case of immersed electrodes, the signal is distorted by the potentials induced in the measuring segment between the electrodes by the thermo-emfs that arise at the interface between the sodium and the steel structures of the installation. The influence of the thin protective jacket in this case is only secondary. In order to estimate these distortions, we shall consider a simplified model of the measuring segment (Fig. 1), which consists of two rectangular strips of sodium and steel, of length  $L_1$  and  $L_2$ , respectively, which are in contact with each other; the electrodes may be connected to various points of the segment. On the interface we are given the law of variation of the thermo-emf  $\varphi(y)$ , which, for simplicity in calculation, is chosen to be symmetric with respect to the X axis. In the calculations we use values of the electrical conductivity  $\sigma$  which correspond to the average temperature of the materials. The distribution of the potentials in the sodium and the steel is described by the Laplace equation  $\Delta U = 0$  with the boundary conditions

$$U_2 - U_1|_{x=0} = \varphi(y);$$

$$\sigma_1 \frac{\partial U_1}{\partial x} \Big|_{x=0} = \sigma_2 \frac{\partial U_2}{\partial x} \Big|_{x=0}$$

and additional boundary conditions determining the absence of current at the external boundaries; the function  $\varphi(y)$  can be represented, taking account of the aforementioned symmetry, in the form of a Fourier cosine series. The solution of the Laplace equation for this geometry is known; the number of terms of the series for the numerical calculations was chosen in such a way that the deviation of the potential difference at the interface from the exact value was less than 1% of the maximum potential drop. The nature of the distribution of currents and potentials for linear increases and decreases in  $\varphi(y)$  corresponding approximately to the heating and cooling of the coolant as it moved along a vertical axis is shown in Fig. 1. In the case considered here, the parasitic potential difference induced in the sodium between the levels 0 and H by the thermo-emf at the boundary with the steel wall varies between 0.1304  $\varphi(0)$  and 0.1126  $\varphi(0)$  as the point considered moves away from the interface; this amounts to more than 10% of the measured thermo-emf difference in the sodium. Variant calculations indicate that when  $L_1/H$  and  $L_2/H$  are less than 0.1, the parasitic potential induced in the sodium on a segment with linear variation of  $\varphi(y)$  can be satisfactorily approximated by

$$\frac{\delta U}{\delta \varphi} = \frac{\sigma_2 L_2}{\sigma_1 L_1 + \sigma_2 L_2},$$

$\sigma_1/\sigma_2 \approx 6$  for  $T = 550^\circ\text{K}$ . It should be noted that when  $L_1/H, L_2/H < 0.1$  on the segment with linear variation of  $\varphi(y)$ , we have an extended "plateau" in the current distribution. Here the integral currents in the steel and in the sodium are practically constant and identical in magnitude but opposite in sign:

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