RESEARCH ARTICLE | MARCH 09 2023

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AIP Conf. Proc. 2700, 050017 (2023)
https://doi.org/10.1063/5.0125107

Calculation and Instrumentation Method of Assessment of Radioactive Nitrogen $^{16}N_7$ Leaks in Steam Generators Applied at KLT-40 Type Nuclear Reactors

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Abstract. The paper studies a primary-to-secondary leak of nitrogen radionuclide $^{16}N_7$ ($T_{½}$=7.11 s, $E_{\gamma,max}$= 6.134 MeV, $\nu_{\gamma,max}$ = 69%) through a steam generator in a KLT-40 type reactor (used in ice breakers and floating power units, FPUs) with an ingress of water of P_v pressure and T_v temperature heated by a follow-up radioactive steam generation which is released under high pressure P_p through a helical steam duct of the steam generator. Content of the specified radionuclide in steam can be found and estimated by use of methods of gamma-spectrometry, measurement of γ-activity concentration of steam and γ-radiation dose rate through the use of a simple physical and mathematical model allowing to specify the reason and to define area of a leakage on a helical steam duct. The paper specifies main areas in the structure of steam generators where radiation characteristics may be measured, and their assessment techniques may be applied. Fig. 8, Table 4, ref. 17.

INTRODUCTION

The effect of radionuclide release from the primary to the secondary circuit was observed in the operation of reactors of KLT-40 type as well as some other water-moderated water-cooled reactors in line with the nuclear safety regulations of ship nuclear installations, specifically, in the turbine compartment, under normal operation of a facility under monitoring (turbine) as well as under increased radiation level conditions. This effect, called later "a leak," was studied in the following papers [1-3] suggesting a model and methodology to diagnose leaks of $^{131-135}I$, ^{24}Na, ^{42}K, $^{16}N_7$, and other radionuclides from the primary coolant into boiler water of steam generators of nuclear power plants with VVER-440 and VVER-1000 type reactors.

The physical meaning of the model and methodology is the assessment of how said radionuclides get into the boiler water of the secondary circuit steam generator and the level of their accumulation. The model suggests a natural linear relation of the activity concentration of said radionuclides from the reactor power. The cumulative activity of said radionuclides in the boiler water of the steam generator was measured by the identification of activity of the filters. However, filters do not entrap radioactive gas, for example, $^{16}N_7$, and it escapes with steam, while iodine isotopes stay in the water (over 99%) [1]. The disadvantage of the methodology is that it only allows stating a leak by the activity of isotopes settling on the filters and by the activity of radioactive nitrogen $^{16}N_7$ in the turbine compartment when the steam is released to the turbine. In a best-case scenario, the density of γ-quanta, β-radiation, and activity concentration of a radionuclide can be assessed by scintillation detectors' readings. The methodology does not allow getting information about the area (on the helical steam duct) of leak occurrence, dynamics of its development which will obviously linearly depend on the reactor power variations, its dimensions and intensity of $^{16}N_7$ release from the primary into the secondary circuit. With this information absent, it is impossible to give an unambiguous answer to what caused the leak, to analyze the metal of the water and steam line, its physical and mechanical properties, and

Proceedings of the IV International Scientific Conference on Advanced Technologies in Aerospace, Mechanical and Automation Engineering
AIP Conf. Proc. 2700, 050017-1–050017-15; https://doi.org/10.1063/5.0125107
Published by AIP Publishing. 978-0-7354-4412-6/$30.00

their changes caused by the impact of ionizing radiation; to study specifics leading to occurrence of micro cracks where through the leak occurs to prevent such effects, as well as to forecast the size of an inhalation dose which the personnel working with the steam generator and turbine may get, and all this leads to the non-conformance with the requirements (see [4], Chapter 3, para 3.1.6).

Based on this, today the operation of steam generators is prohibited if the gross specific activity of radionuclides in blowdown water reaches 370 Bq/kg ($1\cdot10^{-8}$ Cu/kg). The admissible specific activity of ^{131}1I in the blowdown water of each steam generator − shall not exceed 740 Bq/kg ($2\cdot10^{-8}$ Cu/kg), the admissible average specific activity of ^{131}I in all the steam generators of the unit shall not exceed 185 Bq/kg ($5\cdot10$-$^{-9}$ Cu/kg). Herewith, primary coolant leak into the boiler water of each steam generator shall not exceed 5 kg/h [1]. In this respect, the development of a methodology to assess leaks becomes of vital importance, in particular, development of a correct model that allows finding causes of a leak, its area in a steam generator, and thus, answering the questions raised.

As for the methodology under review, for the assessment of a primary leak of radioactive nitrogen $^{16}\mathbf{N}_7$ into the steam generator of KLT-40 reactor, the effect disco-vered was that a steam jet of the steam generator going to the turbine, contained a ra-dionuclide of radioactive nitrogen $^{16}\mathbf{N}_7$ ($T½$ = 7.11 s, with the energy of γ-radiation equal to $E_{\gamma,max}$ = 6.134 MeV and quantum yield equal to $\nu_{\gamma,max}$ = 69%; energies of β-radiation equal to $E_{\beta,1}$ = 4.288 MeV, and release of β-particles equal to $n_{\beta,1}$ = 68%; $E_{\beta,2}$ = 10.419 MeV, $n_{\beta,2}$ = 26%) (see Fig.1) whose presence in the steam is a sign of depressurization in the water and steam pipe of the SG secondary circuit. And its presence was identified through the use of scintillation detectors with a crystal of NaJ(Tl) due to the high energy of γ-β-radiation, steam generation effect, steam release to the turbine.

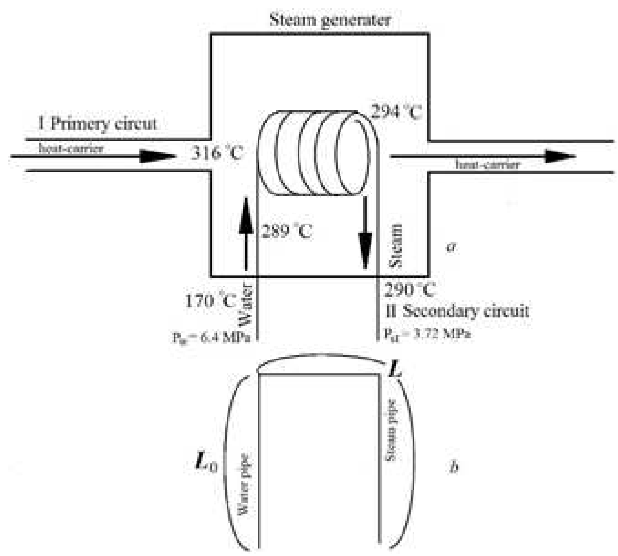

FIGURE 1. This figure shows the issue of a leak of $^{16}\mathbf{N}$ from the primary to the steam duct of the secondary circuit – (a). This is for the calculation of steam density $\rho_s(x)$ and activity concentration $Q_N(x, t)$ of $^{16}\mathbf{N}$ in the turbine steam duct – (b); l_{vr} stands for the width of the leak area. The energy characteristics of steam and water are taken from papers [1, 2].

Let us consider the general operation principle of a nuclear reactor at a nuclear power installation (NPI) and the principle diagram of the steam generator which stands vertically at a nuclear installation; these all are shown in Fig. 2. Pressurized water P_w (left part of Fig. 1 a) with temperature T_w gets into the secondary circuit of the SG by the water line; it is heated up with steam formation whose release through N helical steam ducts of the same inner diameter occurs at the temperature of T_s under high pressure P_s [5, 6]. When water passes through the water line, water in steam generator warms up to the steam saturation temperature under respective pressure, it evaporates on the inner surface of steam generator pipes, and thus, an effective boundary area of water-vapour is created, and finally, it gets to the turbine in the form of superheated steam. Thus, high-pressure steam which is superheated as compared to the saturation temperature, gets to the inlet of the turbine.

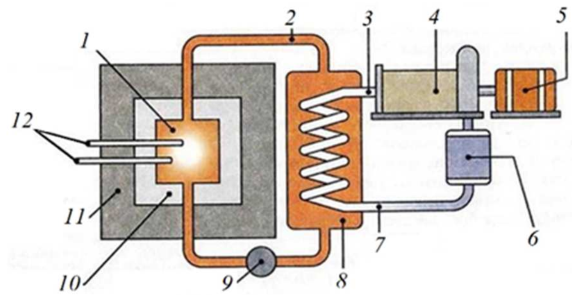

FIGURE 2. Scheme of a nuclear power installation. *1* — Nuclear fuel and sours of neutrons; *2* — Coolant; *3* — Steam; *4* — Turbine; *5* — Generator; *6* — Condenser; *7* — Water; *8* — Steam generator; *9* — Pump; *10* — Reflector; *11* — Containment; *12* — Control rods.

Table 1 shows the relation between the water boiling temperature (steam formation) and its pressure. By using the property of water as an ideal liquid and by considering the fact that the process of water-vapour balance regulation in the water and steam line is automated, and by using the feedback, we conclude that the steam pressure excess leads to some displacement of water against the equilibrium position in the water-vapour boundary area where the temperature will be measured in accordance with the temperature of a respective medium.

The automatic regulation of the SG water feeding up process which is performed with the help of water getting from the compensating tank [5], leads to the water pressure rise in the water line and reverse water displacement into its initial position. This fluctuation process nearby some equilibrium position in the said water-vapour boundary area will occur with certain frequency.

TABLE 1. Water boiling temperature - pressure relationship P.

P		**t_k,°C**	**P**		**t_k,°C**
kPa	**kPa**		**kPa**	**kPa**	
0.981	0.01	6.698	196.1	2.0	119.62
1.961	0.02	17.20	245.2	2.5	126.79
3.923	0.05	28.64	294.2	3.0	132.88
9.807	0.1	45.45	392.3	4.0	142.92
19.61	0.2	59.67	490.3	5.0	151.11
29.42	0.3	68.68	588.4	6.0	158.08
39.23	0.4	75.42	686.5	7.0	164.17
49.03	0.5	80.86	784.5	8.0	169.61
58.84	0.6	85.45	882.6	9.0	174.53
68.65	0.7	89.45	980.7	10.0	179.04
78.45	0.8	92.99	1961	20.0	211.38
88.26	0.9	96.18	2452	25.0	222.90
98.07	1.0	99.09	4903	50.0	262.70
101.3	1.033	100.00	9807	100.0	309.53
147.1	1.5	110.79	-	-	-

Thus, the temperature mode will constantly change in the boundary area of the water and steam line. The latter will automatically lead to a similar change in the frequency of mechanical stress of water and steam line in this area, further metal fatigue and probable generation of micro cracks which may be the path for radionuclide $^{16}N_7$ to get from the primary into the secondary circuit, which creates so called **leak**. Since the steam density is crucially less than that of water, radioactive nitrogen will spread into the steam phase area, including the steam outlet to the turbine, as stated above. The latter may be identified in steam, with radioactive decay taken into consideration, in the target point of the steam duct by the measured value of γ-β-radiation of $^{16}N_7$ flow density or by the dose rate of the ionizing radiation caused by said radionuclide. Thus, to assess the values under consideration within the conditions of the steady process, it is necessary to know the density of water distribution $\rho_w(T)$ which enters the steam generator water line, as a function of temperature during its transfer along the x axis of the steam duct (see Fig. 3), steam density $\rho_s(T)$ as a temperature function (see Fig. 4) or distance x in case of its transfer along the x axis of the steam duct (see Fig. 1b) when its helical part is rectified by the length of L with the internal radius of R_0=1.5–2.0 cm ($0 \le r \le R_0$). Herewith, the water line length (vertical area in the left part (Fig. 1b)) will be L_0 ($L_0 < L$), while the general length of the water and steam line ($L+L_0=L_s$) is known and it may reach ~ 10—20 m depending on the model type of the steam generator. It is worthwhile noting that the nature of water and steam density relation as temperature functions differs significantly: water density falls against temperature rise, while steam density grows, and the pressure of water or steam changes accordingly. With temperature growth in the steam and water line taken as proportional to x, then, we will find that pressure of steam and water can be balanced under certain x_L. Then, it is this value of $x_L = L_0$ which will determine the effective length of the water line in whose boundary area a leak will occur.

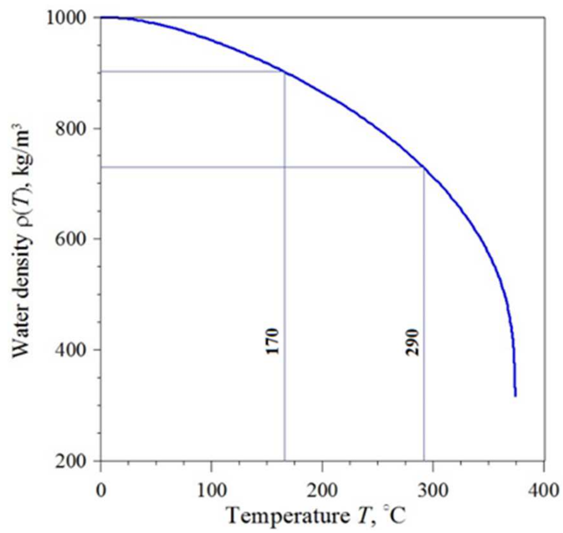

FIGURE 3. Relation of water density ρ(T) and temperature. The curve area between the marks approximates with a relative error of $\delta = 1.16\cdot10^{-2}$ % by a parable of the following type: $\rho(T) = -0.002315\cdot T^2 - 0.39345\cdot T + 1033.79$ [kg/m³].

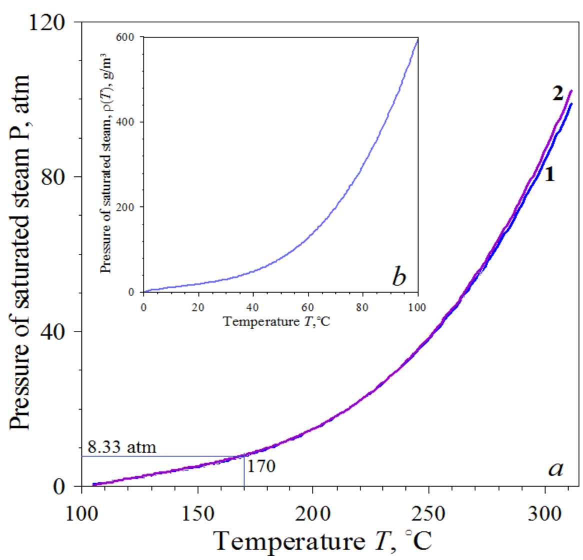

FIGURE 4. The relation of pressure (a) and density (b) of saturated steam as temperature functions. Curve 1 (Fig. 4 a) is given in units (atmosphere), while curve 2 is in kg/cm². The data marked are used to assess initial steam density ρs(T0), T0 = 170 ◦C.

Let us consider the specifics of the physical process of water transfer which is supplied to the SG water line under initial pressure equal to $P_{bnd} \approx 6.1 - 6.4$ MPa. As a result of heat transfer from the primary coolant, water in the SG pipeline is heated additionally, and it leads to its decreased density, evaporation, and formation of saturated steam whose pressure grows together with the temperature, i.e. with the growth of x. Thus, when formulating the problem of water transfer in the pipeline, its flow at a specified speed (it is found by the initial flow and density), reduced water density alongside its temperature rise, and its evaporation shall be taken into consideration. Therefore, if the lateral water transfer speed to the pipeline walls is zero, then, the steady linear equation which takes into consideration these physical processes for a water particle with weight equal to $m = \rho(T)V_w$ and volume $V_w = \pi R^2_0 L_0$, will be as follows in the cylindrical geometry.

$$\bar{v}_w \frac{d\rho_w}{dx} = \frac{G}{V_w} - u_s(T)\frac{S_w}{V_w},$$

Where $\bar{v}_w$ stands for the average speed of water transfer along the water pipe; G stands for water generation (pressurized water injection, see Fig. 1a, G = const.), [kg/s], which is identified in poin $T|_{x=0}T(0)$ by the following expression: $G = S\sqrt{2\rho_w(T_0)P_{bnd}}$; $u_s(T)$ stands for the speed of water evaporation or the speed of steam formation, [kg/m^{2}s]; $S_w = 2\pi R_0 L_0$ is the area of water evaporation. Since the area of water evaporation S_w and the volume V_w it takes are characteristics of the same medium volume, their relationship is $S_w/V_w = 2/R_0$. If the steam duct helix is represented in the form of a horizontal area (see Fig. 1b), while the temperature changes in the medium of the secondary SG circuit is approximated by certain linear function which depends on x.

METHODS, RESULTS AND DISCUSSION

$$\mathrm{T}(x) = T_0 + b_t x/L_s\ ^\circ\mathrm{C}, \tag{1}$$

where T_0 = 170 ºC, b_t = 120 ºC, and x satisfies the inequality $0 \le x \le L_s$. Since $\rho_w(T(x))$ is a composite function of x, then, $d\rho_w/dx = (d\rho_w/dT)(dT/dx) = (d\rho_w/dT)(b_t/L_s)$, and we will write over the equation given above in the following way:

$$\left(\frac{d\rho_w}{dT}\right) = \frac{L_s}{b_t\bar{v}_w}\left\{\frac{G}{V_w} - u_s(T)\frac{S_w}{V_w}\right\} \tag{2}$$

by formula (1). At the same time the input condition determining water temperature at $x = 0$ will be to correspond to temperature of its entrance to the steam generator (see Fig. 1 a), and its density $\rho_w(T)$ in allocated temperature range will be defined by the dependence presented in Fig. 3 at T_0 temperature.

The assessment of water transfer speed by mass m through the water line can be obtained from the condition of the equality of kinetic and potential energy of water pressure at the inlet to the secondary circuit of the SG $P_{bnd}\,V_w/N = m\bar{v}_w^2/2$ where N stands for the number of water lines in a set. Let us clarify the physical meaning of this equality. Potential energy may be used for the following: to work against water friction force on the water line pipe walls, for kinetic energy in the liquid (water) particles transfer inside the water line at the flow rate of $\bar{v}_w$ and to change internal energy of a medium (water again), for example, as a result of changing its temperature due to friction, except for potential energy of water column in the water line with the height of L_0, i.e.: $P_{\mathrm{bnd}}V_w = A_{\mathrm{fr}} + E_{\mathrm{kin}} + U_{\mathrm{ext}} + mgL_0$. However, since the primary coolant temperature is much higher than that of the water at the inlet to the secondary circuit (see Fig. 1*a*), since water in the pipes of the secondary circuit evaporates nearby the walls, and the bulk of water is in a thin steam film and it is transferred without frictions, hence, the first addend may be disregarded. The same reason may be applied to disregard the third addend, considering the fact that inner energy of water is measured mainly due to heat transfer by the coolant from the primary to the secondary circuit (see Fig. 1*a* and Fig. 2). As for potential energy of the water column in the water line mgL_0, the assessment performed shows that in case of the maximum water density of ρ = 1 kg/m^3, $P_{bnd} \approx$ 6 MPa, L_0 =10 m and N = 10, $E_{kin} >> mgL_0$ by four folds. Said equality appears herefrom. Therefore, considering the feature of water as an ideal liquid, let us consider its speed in each pipe of the water line as a constant determined by the following expression:

$$\bar{v}_w = \sqrt{2P_{bnd}\Big/\left[(N/L_0)\cdot\int_0^{L_0}\rho_w\big(T(x)\big)dx\right]} = \sqrt{2P_{bnd}/N\bar{\rho}_w}. \tag{3}$$

In formula (3) $\rho_w(T)$ within the range of temperatures $170 \le T \le 290$ ºC, it will be determined by the relation given in Fig.3 which is approximated by parable $\rho_w(T) = a\cdot T^2 + b\cdot T + c$, [kg/m^3]: ($a$, b, c are coefficients of respective dimensionality) with relative error δ = 1.16 %, while the temperature measurement is approximated with distance x by formula (1). Therefore, the mean value of density given in the denominator of subradix notation in formula (3) will be written as follows:

$$\bar{\rho}_w(L_0) = \frac{1}{L_0}\int_0^{L_0} \rho_w\big(T(x)\big)dx = \frac{a}{3}\left[3T_0^2 + 3b_t T_0 \frac{L_0}{L_s} + b_t^2 \frac{L_0^2}{(L_s)^2}\right] + \frac{b}{2}\left[2T_0 + b_t \frac{L_0}{L_s}\right] + c \quad (4)$$

where a = –0.002315; b = –0.39345; c = 1033.79.

Paper [7] shows the relation of evaporation speed as a function of temperature $u_s(T)$ kg/m2·s, which determines in equation (2) the reduction of water mass or its density within the temperature range of 29 ≤ T ≤ 100 ºC. In a wider range, the relation $u_s(T)$ may be obtained with the help of Clausius-Clapeyron relation (5) [8] (see Fig. 5). According to the relation, sharp drop $u_s(T)$ in the area of high temperatures is caused by the reduction of specific heat of steam formation Λ(T), which also depends on temperature (see Table 2).

$$u_s(T) = u_s(T_0) \cdot exp\left[-\frac{\Lambda(T)}{R}\left(\frac{T_0 - T}{TT_0}\right)\right] \quad (5)$$

where T_0 stands for initial temperature. The full relation Λ(T) within the temperature range of 0 ≤ T ≤ 374 ºC is given in Table 2.

TABLE 2. The value of specific heat of water steam formation as a function of temperature.

Temperature ºC	Specific heat of steam formation Λ(T), MJ/kg	Temperature, ºC	Specific heat of steam formation Λ(T), MJ/kg
0	2.45	250	1.71
50	2.38	300	1.38
100	2.26	350	0.88
150	2.12	374	0
200	1.96	-	-

As input values in formula (5), T_0 = 72 ºC and $u_s(T_0) = 1.375 \cdot 10^3$ kg·m^{-2}·s^{-1} [7] may be assumed for assessment of $u_s(T)$ within the temperature range of interest. By inserting expression (3) into formula (2), after simple transformations relatively to ρ_w, we will get a linear equation

$$d\rho_w = \frac{L_s}{b_t}\sqrt{\frac{N\bar{\rho}_w}{2P_{bnd}}}\left\{\frac{G}{V_w} - u_s(T)\frac{S_w}{V_w}\right\}dT, \quad (6)$$

whose solution is determined by the expression

$$\rho_w(x,T) = \frac{L_s}{b_t}\sqrt{\frac{N\bar{\rho}_w}{2P_{bnd}}}\left\{\frac{G}{V_w}T(x) - \frac{S_w}{V_w}\int_{T(0)}^{T(x)} u_s(T')dT'\right\} + C, \quad (7)$$

where constant C is found through input condition (3), i.e. by the value of water density from Fig. 3 at $T = T_0$, $x = 0$ or by the parabolic relation of water density and temperature $\rho_s(T)$: $\rho_w T(0) - L_s/b_t\sqrt{N\bar{\rho}_w/2P_{dnb}}\,G/V_w\,T(0) = C$. The temperature relation as expressed by water evaporation speed $u_s(T)$ and specific heat of steam formation identified by formula (7) and data from table 2 and coordinate x are represented by formula (2). It follows from Fig. 3 and 5 that the water evaporation speed in the temperature range from 100 to 200 ˚C rises sharply, while its density falls rapidly. Then, assuming that the water transfer in the water pipe is constant as it oc- curs with no friction (it is stimulated by the steam formation processes on the inner surface of the SG pipes), in the view of x grown, i.e., with the growth of temperature determined by equation (2), water pressure will reduce proportionally to steam density, while that of steam will rise. Water pressure in water line can be represented by the formula.

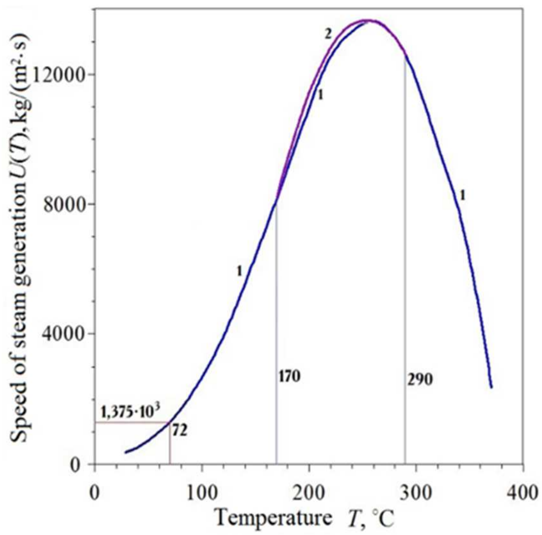

FIGURE 5. The relation of evaporation speed of distilled water vapour and temperature (1). The results of the calculation in area $T \leq 100$ ºC correlate well with the data of the experiment found in [7], (2) stands for the approximation of the highlighted area of temperatures$170 \leq T \leq 290$ ºC by the parable: $a_s T^2 + b_s T + c_s$ with $a_s = -0.7921$; $b_s = 401.0046$; $c_s = -37083.2407$.

$$P_w[T(x)] = \rho_w[T(x)]\, \bar{v}_w^2/2, \tag{8}$$

When formulating the equation for steam transfer in the steam duct, let us neglect the diffusion term characteristic for a turbulent flow, assuming that when steam transfer is along the steam line axis which we have shown by a straight interval located horizontally, its advection component of the transfer speed will be much higher than that of the diffusion one [8]. Thus, if steam mass is specified through $m_s = \rho_s \cdot V_s$, where V_s stands for the inner volume of the steam duct ($V_s = \pi R^2{}_0 \cdot L$), then the equation of transfer for steam density within the steam duct at its radial (lateral) speed equal to zero will be as follows.

$$\frac{d\rho_s}{dt} + v_s \frac{d\rho_s}{dx} - u_s \frac{S_s}{V_s} = -\frac{\rho_s}{\tau_s}, \tag{9}$$

where v_s stands for the longitudinal speed of steam transfer in the steam duct; u_s stands for the steam generation speed found above with formula (5); S_s stands for the steam formation area ($S_s \approx 2\pi R_0 L_0$); $\tau_s = L/v_s$ stands for the steam "life" time in the steam duct; L stands for the length of the steam duct. The input condition is found based on the following assumptions.

Steam density value in the boundary area $\rho_s(L_0)$, i.e. with $x = L_0$, can be found with the help of the conditions of equal water and steam pressure in this area at a specified temperature, i.e. $P_w|_{x=L_0} = P_s|_{x=L_0}$. Since water pressure in view of identified relation of water density and temperature as well as x coordinate is determined by expressions (1), (7), (8), then, assuming steam to be an ideal gas and using the Mendeleev-Clapeyron equation, we will find out that

$$\rho_s[T(x)]|_{x=L_0} = \rho_w[T(x)]\bar{v}_w^2/2\, RT(x)|_{x=L_0}, \tag{10}$$

Where $\bar{v}_w = const.$ determined by formula (3), relation $T(x)$ determined by expression (1), and $\rho_w[T(x)]$ determined by formula (7). Below, we show how condition (10) can be used to determine values $x = L_0$. Disregarding the heat loss in the metal pipe of the steam duct, let us assume that the temperature distribution in the steam of the steam duct will be determined by the distribution of type (1) which in its turn will identify the temperature dependence of steam. Thus, assuming, the steady nature of the steam transfer instead of equation (9), considering the expression for the steam density, we will get the following equation for its density:

$$v_p(T)\frac{d\rho_p}{dx} = u_p(T)\frac{S_p}{V_p} - \frac{\rho_p}{L} v_p(T), \tag{11}$$

where the speed of steam transfer v_s as well as its generation (in case of water evaporation) u_s depends on its temperature and pressure. Saint-Venant's formula can be used to assess steam transfer speed as it identifies the gas flow from the tank into the atmosphere as a function of its temperature and pressure [9, 10].

$$v_s(L) = \sqrt{[2k/(k-1)]RT_s(L)[1 - P_{atm}/P_s]^{(k-1)/k)}}, \quad (12)$$

where k stands for the constant of water steam adiabat; R stands for the gas constant (J/kg∘K); $T_s(L)$ stands for the steam temperature at the steam duct outlet (∘K); P_{at} stands for the atmospheric pressure; P_s stands for the steam pressure at the steam duct outlet, MPa. The overall diagram of $v(T)$ relation is in Fig. 6.

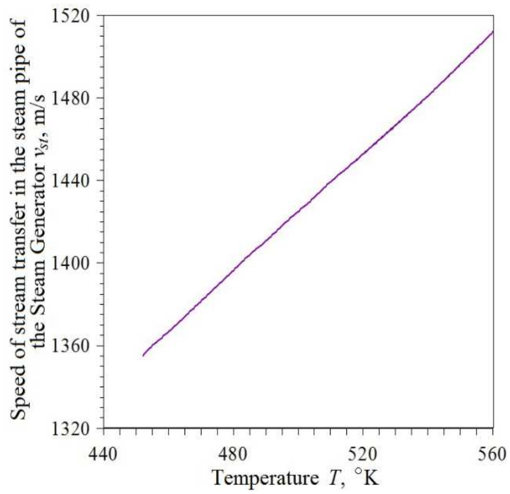

FIGURE 6. The temperature relation of steam transfer speed $v_s(T)$ in the SG of KLT-40 type reactor.

Since steam density is a complex function of temperature caused by temperature relation of water evaporation speed $u_s(T)$, (5) and speed of steam transfer in the steam duct $v_s(T)$, (12), which in their turn depend on x-coordinate, then solving equation (11), let us do the same way as for the solution of equation (2), i.e. let us write.

$d\rho_s/dx = (d\rho_s/dT)(dT/dx) = (d\rho_s/dT)(b_t/L_s)$. Then, considering the fact that the relation of said functions $\varphi(T) = u_s(T)/v_s(T)$ also depends on temperature (see Fig.7), equation (11) may be rewritten in the following way:

$$\frac{d\rho_S}{dT} = \varphi(T)\frac{S_S \cdot L_S}{V_S \cdot b_t} - \frac{\rho_S \cdot L_S}{(L_S - L_0)\cdot b_t}. \quad (13)$$

Function $\varphi(T)$ can be approximated by parable $\varphi(T) = a_f T^2 + b_f T + c_f$ with a relative error of temperature relation in the range of interest of at least 1% (see Fig. 7), where $a_f = -0.5524 \cdot 10^{-3}$; $b_f = 0.2717515$; $c_f, = -24.13\ 445$. Such procedure enables to simplify significantly the solution of equation (13) and to find quite a simple analytical expression to analyze its solution.

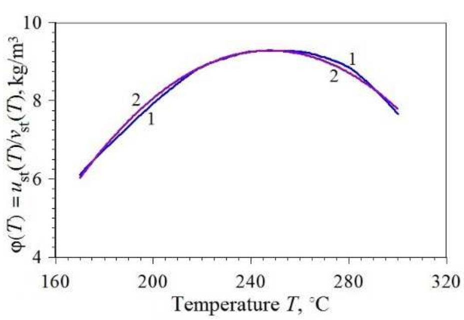

FIGURE 7. Temperature relation of functions $\varphi(T) = u_s(T)/v_s(T)$ (1), kg/m³; approximation of the relation with parable (2).

$$\rho_s(T) = \frac{2L_0}{R_{0(L_s-L_0)}}\frac{L_s}{b_t}\left\{\begin{matrix} a_f\left[\frac{T^2}{\alpha}-\frac{2T}{\alpha^2}+\frac{2}{\alpha^3}\right]+b_f\left[\frac{T}{\alpha}-\frac{1}{\alpha^2}\right]+\frac{c_f}{\alpha}-a_f\left[\frac{T_0^2}{\alpha}-\frac{2T_0}{\alpha^2}+\frac{2}{\alpha^3}\right]+exp[\alpha(T_0-T)] \\ -b_f\left[\frac{T_0}{\alpha}-\frac{1}{\alpha^2}\right]exp[\alpha(T_0-T)]-\frac{c_f}{\alpha}exp[\alpha(T_0-T)] \end{matrix}\right\}+, \quad (14)$$
$$+\rho_s(T_0)exp[\alpha(T_0-T)]$$

where $\alpha = L_s/[b_t \cdot (L_s - L_0)]$, and formula (2) and $T_0 \equiv T(x = 0)$ determines relation $T(x)$.

For assessment of initial steam density $\rho_s(T_0)$ T_0(°K), let us use Mendeleev-Clapeyron equation and data from Fig.4, which give use $\rho_s(T_0) = P(T_0+273)/RT_0 = 4.135$ kg/m^3. Thus, for $x = L_0$, according to formula (2) and solution (14), we get an expression for steam density value $\rho_s(L_0)$ in the boundary area. This allows us to write the final equation for the boundary condition (12) and, finally, to find the value of L_0 parameter we have been looking for which determines x-coordinate of a possible leak in the SG steam duct.

$$R\rho_s(L_0)\cdot\frac{(T_0+273)\cdot L_s+b_t\cdot L_0}{L_s}+\frac{L_s}{R_0 b_t}\cdot\sqrt{\frac{N\bar{\rho}_w}{2P_{dnb}}}\int_{T_0}^{T(L_0)}u_s(T')dT' = \sqrt{\frac{P_{bnd}}{2N\bar{\rho}_w}}\cdot\frac{G}{\pi R_0^2}+\frac{P_{bnd}}{N\bar{\rho}_w}\cdot\rho_w(L_0). \quad (15)$$

Figures 5, 7, 8, respectively, provide temperature dependency relation of functions $u_s(T)$, $v_s(T)$ and their relationship $\varphi(T) = u_s(T)/v_s(T)$ within the range of $170 \le T \le 290$ °C. It implies from fig. 5 that the growth of temperature identifies two areas where steam generation speeds differ significantly. The generation speed grows with the temperature rise in the range of $30 \le T \le 240$ °C, and it reaches its maximum and then decreases, and it is caused by a sharp fall of specific heat of water steam formation $\Lambda(T)$ within the range of temperatures $230 \le T \le 380$ °C. Therefore, the most significant steam generation area from among the specified area of temperatures is the range of 440 – 530 °K.

For the practical use of formula (15), it is necessary to calculate steam formation speed integral $u_s(T)$, whose value has been found with the help of approximation of said curve with parable (see Fig. 5) within the temperature range of interest of $170 \le T \le 290$ ºC. To simplify calculations, the following coefficients were found: $a_s = -0.7921$; b_s=401.0046; $c_s = -37083.2407$, it made possible to have the calculation made with the precision of at least 1% and get calculated function:

$$\int_{T_0}^{T(L_0)} u_s(T')dT' = b_t\cdot\frac{L_0}{L_s}\cdot\left\{\frac{a_s}{3}\cdot[T(L_0)^2+T(L_0)\cdot T_0+T_0^2]+\frac{b_s}{3}\cdot[T(L_0)+T_0]+c_s\right\}.$$

The equation (15) was solved with the graphic method by making diagrams of relations of the functions of the left $U_l(L_0)$ and right $U_r(L_0)$ parts which are identified by the following expressions, respectively:

$$U_l(L_0) = \rho_s(L_0)\cdot R\cdot\frac{(T_0+273)\cdot L_s+b_t\cdot L_0}{L_s}+\frac{L_s}{R_0 b_t}\cdot\sqrt{\frac{2P_{bnd}}{N\bar{\rho}_w}}\int_{T_0}^{T(L_0)}u_s(T')dT'$$

and

$$U_r(L_0) = \sqrt{\frac{P_{bnd}}{2N\bar{\rho}_w}}\cdot\frac{G}{\pi R_0^2}+\frac{P_{bnd}}{N\bar{\rho}_w}\cdot\rho_w(L_0).$$

It is worth noting that $U_r(L_0)$ is practically a constant depending on water pressure parameter P_{bnd}. Therefore, the abscissa of the point of intersection of the diagrams identified the value of parameter L_0 and the length of water part of the SG. The results of the calculations for SG with different total length L_s are given in Fig.8. The figure shows curves 1, 2, 3 which determine the relation of function $U_l(L_0)$ with P_{bnd}= 6.4 MPa and total length of the SG L_s which is 20 m (1), 15 m (2), and 10 m (3), while function $U_r(L_0)$ (4) is a value which slightly varies with the growth of L_0 from $2.098\cdot10^7$ ($L_0 = 0.1$) to $2.101\cdot10^7$ ($L_0 = 0.9063$).

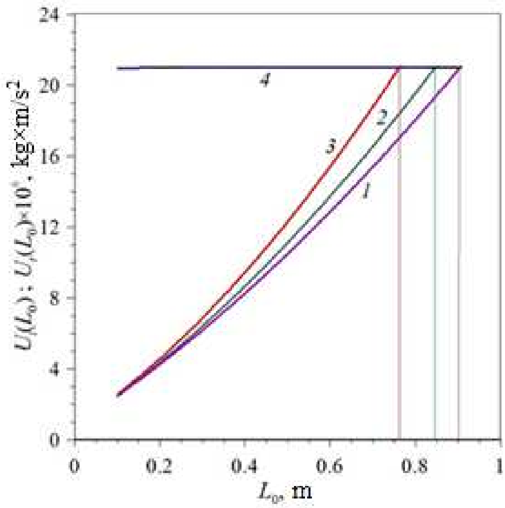

FIGURE 8. The effective length of the water part in the SG of the secondary circuit of KLT-40 type reactor. Functions $U_l(L_0)$ for L_s = 20 (1), 15 (2), 10 (3) m and $U_r(L_0)$ = const (4); *Pbnd* = 6.4 MPa.

With the growth of water pressure P_{bnd} in the secondary circuit, function $U_l(L_0)$ also increases and it decreases with the pressure fall (see Table 3), the value of constant $U_r(L_0)$ also changes respectively, but the nature of the solution stays the same.

TABLE 3. The length of water area of SG L_0, m.

P_{bnd}, MPa		6.24	6.4	6.56
L_s, m	10	0.7534	0.7636	0.7739
	20	0.8944	0.9063	0.9124
Maximum difference of water "flow" in the water and steam line ΔL_0, m				
L_s, m	10		0.0205	
	20		0.024	

Pressure variation was identified by its fluctuation and was ± 2.5% $\bar{P}_{bnd} = 6.4 \cdot 10^6 Pa$ Since $^{16}N_7$ has quite a short half-life, when formulating the equation for transfer of radioactive nitrogen $^{16}N_7$ in the steam duct, it is necessary to consider it through time, taking into account local generation in the water-vapour boundary area, decrease as a result of radioactive decay and, moreover, presence of radioactive nitrogen in the steam spread previously in the steam. Herewith, the value of steam density is determined by solution (14) of equation (11). The activity value of radioactive nitrogen ^{16}**N** present in the steam phase and released to the turbine $Q_N(L)$ can be found by its measurement at the inlet over specified time period τ_s during which steam outflow m_s (water) is found. Then, relation $Q(L)/m_s(L) = \alpha_N$ will determine dimension factor α_N (Cu/kg) in the area where steam goes to the turbine, i.e. x = *L*.

Generation of radioactive nitrogen, similar to releases of IRG releases into the atmosphere out of the vent stacks [11], can be represented by a dose rate of a "release" of $^{16}N_7$ in the steam phase which is determined by the following expression:

$$P_w = Q_V \cdot G_N, \quad (16)$$

where G_N stands for a "injection" flow rate per second [m^3/s]; Q_V stands for activity concentration of radioactive nitrogen [Cu/m^3]. The flow rate per second G_N of "injection" of radioactive nitrogen ^{16}**N** into the steam phase in the boundary area of water-vapour region is a multiplication of the area of the steam duct boundary area $S_{SG} = 2\pi R_0 l_{vr}$, where $l_{vr} = \Delta L_0$ stands for the width of the water-vapour region (see Table 3),and the speed of release of radioactive nitrogen from cracks U_{bnd}, which is the value we are looking for:

$$G_N = 2\pi R_0 l_{vr} \cdot U_g. \quad (17)$$

As you can see in table 3, value l_{vr} can be assessed by the readings of the flow-rate indicator, i.e. by the value of water advance in the water line pipe at its initial area in case there is water pressure fluctuation which can also be found through the measurement of water pressure by the readings of pressure meter and the use of the calculation algorithm given. Indeed, when measuring water pressure with due consideration of its fluctuations $\bar{P}_{bnd} \pm \Delta P$, value $l_{vr} = \Delta L_0 = L_{0,\max} - L_{0,\min}$ will depend on the difference of measured water pressures. Herewith, the value of activity concentration of radioactive nitrogen $^{16}\boldsymbol{N}$ Q_{V0} (Cu/m^3) in case of its generation through microcracks occurred in the water-vapour boundary area of the steam duct will be found by the activity concentration in the SG (see Fig. 1). Since value Q_{V0} is also unknown, then the general product found by formula (16) will represent in a general case constant P_w which is sought for. In this case, transfer of radioactive nitrogen $^{16}\boldsymbol{N}$ in the steam duct can be described by the following equation

$$\frac{dQ_N}{dt} = P_w\{\eta[x-(L_0-l_{vr}/2)] - \eta[x-(L_0+l_{vr}/2)]\} - \bar{v}_s V_s \alpha_N \frac{d\rho_s}{dx} - \lambda Q_N, \tag{18}$$

where L_0 stands for the water line length. The first term in the right part of equation (18) describes the generation of radioactive nitrogen $^{16}\boldsymbol{N}$ in water-vapour boundary area with the width of $l_{vr} << L_0$; $\eta(x)$ stands for a unit function; the second is the decrease of radioactive nitrogen contained in steam due to its release in the steam duct to the turbine; the third one is decrease of the radionuclide due to radioactive decay of $^{16}\mathbf{N}$ with decay constant λ.

The release of radioactive nitrogen by steam from the steam duct represented by the second term in equation (18) depends on the advectional speed found by formula (12) and, strictly speaking, it should be different from steam for nitrogen as adiabat's constant in formula (12) is different for nitrogen and steam [12, 13] (see Table 4). The value of adiabat's constant for the specified range of temperatures was obtained by extrapolation with the help of parable relation $k(T)$ for which steam data from table 4 were approximated, and the average value of adiabat's constant was $\bar{k} = 1{,}303$ Since formula (12) has steam pressure (see Fig.1), which is much higher than the atmospheric one, then the speed of release of steam and nitrogen 16N will be generally identified by their temperature and value of constant adiabat.

TABLE 4. Indicators of adiabat k for different temperatures and gases [12, 13].

temp.	**gas**	**k**	**temp.**	**gas**	**k**	**temp.**	**gas**	**k**
−181 °C		1.597	200 °C		1.398	20 °C	NO	1.400
-76 °C		1.453	400 °C	dry air	1.393	20 °C	N_2O	1.310
20 °C		1.410	1000 °C		1.365	−181 °C	N_2	1.470
100 °C	H_2	1.404	2000 °C		1.088	15 °C		1.404
400 °C		1.387	0 °C		1.310	20 °C	Cl_2	1.340
1000 °C		1.358	20 °C		1.300	-115 °C		1.410
2000 °C		1.318	100 °C	CO_2	1.281	-74 °C	CH_4	1.350
20 °C	He	1.660	400 °C		1.235	20 °C		1.320
20 °C	H_2O	1.330	1000 °C		1.195	15 °C	NH_3	1.310
100 °C	saturated water	1.324	20 °C	CO	1.400	19 °C	Ne	1.640
200 °C	steam	1.310	−181 °C		1.450	19 °C	Xe	1.660
-180 °C	Ar	1.760	-76 °C		1.415	19 °C	Kr	1.680
20 °C		1.670	20 °C	O_2	1.400	15 °C	SO_2	1.290
0 °C		1.403	100 °C		1.399	360 °C	Hg	1.670
20 °C	dry air	1.400	200 °C		1.397	15 °C	C_2H_6	1.220
100 °C		1.401	400 °C		1.394	16 °C	C_3H_8	1.130

Therefore, using the data given in Table 4 for nitrogen and saturated steam under T = 20 ºC (H_2O) and T =15 ºC (N_2), we will find out that the relative error of the release speed of $^{16}\boldsymbol{N}$ relatively to steam will not exceed 7%, i.e. it will be within the error margin of the steam release speed measurement. The latter allows assuming that this difference is negligible and considering that the release of radioactive nitrogen $^{16}\boldsymbol{N}$ from the steam duct occurs at the steam release speed. Plugging the right part of equation (13) into equations (18), we will get the final equation for the nitrogen activity $Q_N(x, t)$.

$$\frac{dQ_N}{dt} = P_w\{\eta[x-(L_0-l_{vr}/2)] - \eta[x-(L_0+l_{vr}/2)]\} + \frac{\bar{v}_s V_s \alpha_N}{(L_s-L_0)}\left[\rho_s(T) - \varphi(T)\frac{2L_0}{R_0}\right] - \lambda Q_N, \tag{19}$$

whose solution will be as follows in case $L_0 \le x \le L_s$

$$Q_N(x,t) = \left\{P_w\{\eta[x-(L_0-l_{vr}/2)] - \eta[x-(L_0+l_{vr}/2)]\} + \frac{\bar{v}_s V_s \alpha_N}{(L_s-L_0)}\left[\rho_s(T) - \varphi(T)\frac{2L_0}{R_0}\right]\right\} \frac{[1-exp(-\lambda t)]}{\lambda} + Q_N(L_0)exp(-\lambda t), \tag{20}$$

where temperature depends on x as per formula (2), while constant $Q_N(L_0)$ is to be found. When steam activity function Q_N(x, t) is found as well as steam density determined by formula (18), it is reasonable to specify parameter α_N introduced earlier, which can be obtained when steam is released from the steam duct in point $x = L_s$ ($T_s = T_0 + bt$ ◦C), except for the leak $P_w(x) \notin [(L_0 + l_{vr}/2) \le x \le L_s]$ since in a moment corresponding to the steam release out of the steam duct under $t = \tau_s = (L_s - L_0)/\bar{v}_s$ P_{bnd} = 6.4 MPa, L_s = 20 m, L_0 = 0.9063 m, $\bar{k} = 1.303$ and

$$\bar{v}_s = \frac{2}{3}\left[\frac{(T(L_s))^{3/2} - (T(L_0))^{3/2}}{T(L_s) - T(L_0)}\right] \cdot \sqrt{\frac{2\bar{k}}{\bar{k}-1} \cdot R \cdot \left[1 - \frac{P_{at}}{P_s}\right]^{\frac{\bar{k}-1}{\bar{k}}}} = 1.415 \cdot 10^3\ m/s: \tag{21}$$

$$\alpha_N = \frac{Q_N[(L_s-L_0),\tau_s]}{m_s(L_s-L_0)} = \frac{\frac{\bar{v}_s V_s \alpha_N}{(L_s-L_0)}\left[\rho_s(T) - \varphi(T)\frac{2L_0}{R_0}\right]}{V_s \cdot \rho_s(T_s)} \frac{[1-exp(-\lambda\tau_s)]}{\lambda} + \frac{Q_N(L_0)exp(-\lambda\tau_s)}{V_s \cdot \rho_s(T_s)}, \tag{22}$$

where v_s is determined by formula (12), $\bar{v}_п$ with the average value, $\rho_s(T_s)$ by formula (18), L_0 by solution of equation (15), while constant λ is determined by the half-life period of ^{16}N $\lambda = 0.693/T_{½}$. Formula (22) allows us to find expression for parameter α_N [Cu/kg] which helps finding the value of nitrogen activity $Q_N(L_0)$ in the water-vapour boundary area of the steam duct.

$$\alpha_N = Q_N(L_0)exp(-\lambda\tau_s) \Big/ \left\{V_s\rho_s(T_s) + \frac{\bar{v}_s V_s}{(L_s-L_0)}\left[\varphi(T_s)\frac{2L_0}{R_0} - \rho_s(T_s)\right]\frac{[1-exp(-\lambda\tau_s)]}{\lambda}\right\}, \tag{23}$$

Two ways can assess the value of parameter α_N: 1— directly find steam volume, its mass and activity concentration by measuring the count rate of registered γ-radiation of ^{16}N after steam has been released into the air during a certain time period; 2— assess dose rate caused by γ-radiation of ^{16}**N**, find through its mathematical expression activity concentration and then find said parameters. Let us take the second option, i.e. find the dose rate of γ-radiation of ^{16}**N** when steam is released into the air environment with the generation of a spherical cloud whose diameter is $l = v_0 \cdot \tau_s$, where v_0 stands for the speed of steam spread in the air which is from 6 to 50 m/s as per measurements; τ_s stands for the time of steam passing in the steam duct whose length is $L = L_s - L_0$, and whose assessment by formula (12) is $\tau_s \sim 13 \cdot 10^{-3}$ s. For this purpose, let us use the formula of dose rate from the virtual globular source with evenly spaced isotropic point sources with specific activity Cu/m^3 with no account of multiple spread providing that $\mu r << 1$, μ stands for linear attenuation factor of γ-radiation; $r = l/2$ stands for the radius of the sphere; $D'_{sf} = 2\pi K_\gamma Q_V(L) \cdot 1$ [14], where D'_{sf} is a measurable value of the dose rate (mSv/h) in a specific spherical volume of radioactive steam $V_{sf} = \pi l^3/6$; K_γ = 14.652 [mSv·m^2/h·Cu] – γ-constant of $^{16}N_7$ [15], $Q_V(L)$ stands for virtual activity concentration of ^{16}N radionuclide (Cu/m^3) at the outlet of the steam duct which appears over the specific time period τ_s and defined by the following relation: $Q_V(L) = D'_{sf}/2\pi K_\gamma \cdot l$. Using solution (14), we find the value of steam density ($\rho_s(L)$ = 509.87 kg/m^3), and its mass at the outlet of the steam duct in point $x = L$ is defined in the following way $m_s(L) = V_s \cdot \rho_s(L) = \pi R_0^2 L \cdot \rho_s(L)$, ($m_s(L)$ = 10.905 kg). Herewith, parameter α_N (Cu/kg) whose estimate was obtained by measuring dose rate of ^{16}N γ-radiation found in the steam cloud, will look the following way:

$$\alpha_N = Q_V(L) \cdot V_{sf}/m_s(L) = D'_{sf} \cdot l^2 \Big/ \left(12\pi K_\gamma \cdot R_0^2 \cdot L \cdot \rho_s(L)\right). \tag{24}$$

If we assume that due to a leak, radioactive steam released from the steam duct creates a dose rate comparable with the radiation background of the reactor and equal to 500 mcR/h, then with the other parameters specified and v_0 = 50 m/s, the value of α_N will be $1.102 \cdot 10^{-6}$ Cu/kg, and it will increase or reduce linearly depending on the reactor power. The estimate of steam mass released from the steam duct can be obtained through other assumptions as well by determining the value as average mass of steam m_{sav} with average density ρ_{sav} and volume of $\pi R_0^2 \bar{v}_s \cdot \tau_s$, released from the steam duct over time τ_s with average speed $\bar{v}_s$= 1415 m/s. In this case, steam mass will be 6.976 kg while α_N value will increase up to $1.723 \cdot 10^{-6}$ Cu/kg, i.e. effective value of α_N parameter will be within the range of $1.102 \cdot 10^{-6}$ - $1.723 \cdot 10^{-6}$ Cu/kg. Thus, by applying value α_N determined by formula (24), the formula (23) can be used to find the value of total activity of ^{16}N in the steam duct boundary area $Q_N(L_0)$ whose average value in case of specified parameters will be $1.728 \cdot 10^{-5}$ Cu, while activity concentration will be $Q_V(L_0) = Q_N(L_0)/\pi R_0^2 l_{vr} = 0.55$ Cu/m^3.

Measurement of steam radioactivity at the radiation background of the reactor requires γ-detectors to be applied. Such detectors should be based on the differential method of ionization currents of the instrumentation devices, including, for example, a flow-type and non-flowing ionization chambers [16], one of which will measure the radiation background of the reactor, while the second will register the radiation back ground of the moving radioactive medium (radioactive steam) as well as the radiation background of the reactor.

The difference in readings of the instrumentation devices will identify the share of the radiation background of the moving radioactive medium within the range of its transfer speeds from 0.2 to 10 – 12 m/s [11, 16]. The other method allowing allocating the information regarding the steam radiation caused by γ, β-radiation of ^{16}N can be one based on the tungsten, lead and bismuth filtering of radiation [8].

On the other hand, if $\rho_s(x)$ stands for the density of steam spread in the steam duct, while $Q_N(x, t)$ is the function of activity spread in the steam duct, then, the value of dose rate created by a set of steam ducts with radioactive nitrogen ^{16}N in certain point $P(x_0, y_0, z_0)$ will be determined by the functionality specified in the decision field in relation to the spread of radioactive impurity with due consideration of the steam density correction in energy transfer and linear attenuation factors, and it will contain the dose rate of the "injection" of ^{16}**N**, i.e. (**leak**) P_w (Cu/s).

$$D'_N(x_0, y_0, z_0) = \Phi(E)\int_V Q_V(x,t) B\left[E_{\gamma,N}, R\right] \frac{exp\left[-\mu\left(E_{\gamma,N}\right)R\right]}{R^2} dV,$$

where $\Phi(E) = KE_{\gamma,N}\nu_N\left(E_{\gamma,N}\right)\mu_a \cdot (\bar{\rho}_s/\rho_{air})S_s$; K — stands for the dimension factor ($K = 1.456 \cdot 10^3$ mSv/h); E_N — stands for energy of γ-radiation (MeV); ν_N — stands for the quantum output of γ-radiation of ^{16}N; μ, μ_a — stands for the linear coefficient and γ-radiation energy transfer coefficient (m^{-1}), respectively; $B(E_N, R)$ — stands for γ-radiation accumulation factor; x, y, z — stand for the current coordinates; x_0, y_0, z_0 — stand for the observation point coordinates; $dV = dxdydz$; V stands for the function domain; $R = \sqrt{(x-x_0)^2 + (y-y_0)^2 + (z-z_0)^2}$ (m). We will find the leak value P_w by comparing the measured value of the dose rate caused by γ-radiation of ^{16}N in certain point $P(x_0, y_0, z_0)$ at the point of steam release to the turbine as well as its mathematical expression defined by the latter formula. If the dose rate can be assessed in the point of steam release out of the steam duct with $x = L_s$, $y = 0$; $z = 0$, then the accumulation factor $B(E_{\gamma,N},R)$ may be assumed as equal to 1, $R = x - L_0$, $dV = S_s dx$; $S_s = \pi R^2_0$; $L_0 - l_{vr}/2 \le x \le L_s$; for $t = \tau_s = L/\bar{v}_s$, then, we will get the following expression:

$$D'_N(L, L/\bar{v}_s) = \Phi(E)\int_{L_0 - l_{vr}/2}^{L_s} Q_V(x,t) \frac{exp[-\mu \cdot (\bar{\rho}_s/\rho_{air})(x-L_0)]}{(x-L_0)^2} dx, \quad (25)$$

where $Q_V(x, t) = Q_N(x, t)/\pi R_0^2 L$ is defined by formula (20), where $Q_N(L_0)$ is found with formulas (23) and (24), while facto $(\bar{\rho}_{steam}/\rho_{air})$ with the factors of linear attenuation μ and energy transfer μ_a in formula (25) takes into consideration specific features of steam transfer of γ-radiation when it passes the steam duct $\tau_s = L/\bar{v}_s$. With the average steam density $\bar{\rho}_s = \left(\int_0^L \rho_s(x)\, dx\right)/L$in the steam duct, when we replace $x - L_0 = U$, $a = \mu \cdot \bar{\rho}_s/\rho_{air}$, $b = 1/L$, we will get the following:

$$\frac{D'_N(L, L/\bar{v}_s)}{\Phi(E)} = P_w \cdot B_1 \cdot A_1 + B_2 \cdot A_2 + B_3 \cdot A_3, \quad (26)$$

where

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$$A_1 = \left\{-\frac{exp[a(l_{vr}/2)]}{l_{vr}/2} + aEi[a(l_{vr}/2)] - \frac{exp[-a(l_{vr}/2)]}{l_{vr}/2} + aE_1[-al_{vr}/2]\right\};$$
$$A_2 = \left\{\frac{exp[(a+b)(l_{vr}/2)]}{-l_{vr}/2} + (a+b) \times Ei[(a+b)(l_{vr}/2)] - \frac{exp[-(a+b)L]}{L} + (a+b)E_1[(a+b)]L\right\};$$
$$A_3 = \left\{\frac{exp[a(l_{vr}/2)]}{-l_{vr}/2} + aEi[a(l_{vr}/2)] - \frac{exp[-aL]}{L} + aE_1[aL]\right\}; B_1 = \left\{\frac{1 - exp(-\lambda L/\bar{v}_s)}{\lambda \cdot \pi R_0^2 L}\right\};$$
$$B_2 = \left\{\bar{v}_s \alpha_N V_s \frac{[1 - exp(-\lambda L/\bar{v}_s)]}{\lambda \cdot \pi R_0^2 L(L_s - L_0)}\left[\bar{\rho}_s(T) - \bar{\varphi}(T)\frac{2L_0}{R_0}\right]\right\}; B_3 = [Q_N(L_0)/\pi R_0^2 L] \cdot exp(-\lambda \cdot L/\bar{v}_s)$$

helps finding the value of injection rate of P_w of $^{16}N_7$ into the secondary steam duct

$$P_w = \left\{\frac{D'_N(L, L/\bar{v}_s) \cdot (L_s - L_0)}{\Phi(E)} - (B_2 \times A_2 + B_3 \times A_3)\right\} / (B_1 \cdot A_1). \quad (27)$$

On the other hand, P_w is found by formula (16), (17): $P_w = Q_V(L_0) \cdot 2\pi R_0 l_{vr} \cdot U_g$. The latter expression, provided $Q_V(L_0)$ is found, helps easily to find the value of a flow rate per second ($G_N = 2\pi R_0 l_{vr} \cdot U_g$) or "injection" speed of U_g of $^{16}\boldsymbol{N}_7$ from the primary to the secondary circuit. When calculating parameter P_w, the width of the leak l_{vr}, as stated above, is found by the difference of water "flow" ΔL_0 with the readings of the flow meter or pressure meter (see the calculation results in Table 3), while the initial activity concentration $Q_V(L_0)$ of $^{16}\boldsymbol{N}_7$ in the area of its generation – is calculated by formulas (23), (24) in the assessment of parameter α_N. The calculated estimates of "injection" rate P_w within the model under consideration provide the value of $P_w \approx 2.0 \cdot 10^{-4}$ Cu/s. Then, if the activity concentration in the leak area $Q_V(L_0)$ is 0.55 Cu/m^3 the flow rate per second or "injection" of radioactive nitrogen into the boundary area of the steam generator will be $G_N = P_w/Q_V(L_0) = 3.64 \cdot 10^{-4}$ m^3/s, while $U_g = 0.116$ m/s.

Similarly to paper [1], assuming the presence of the linear relation of activity concentration of ^{16}N leak and reactor power, we note that the results of measurements of dose rate D'_N caused by radioactive nitrogen $^{16}\boldsymbol{N}$ in case of its release to the turbine, will also have said feature, therefore, P_w parameter found will also have this feature.

Since the measurement of dose rate D'_N induced by radioactive nitrogen ^{16}N when it is released to the turbine, is one of the key procedures performed in the leak assessment, such measurements have to be conducted with the help of γ-radiation detectors with a high temperature range of performance [8], and this will allow decreasing the measurement error of said value, and hence, the "injection" rate P_w. Let us note that the estimates of leak given are true only for the type of SG specified in Figs. 1 and 2.

However, the assessment method suggested can be used for other SG types as well, after it has been respectively adjusted.

Thus, measuring a dose rate when steam is released to the turbine and measuring the activity concentration of ^{16}N at that point as well as the steam mass over the time of passing τ_s through the steam duct, identifying the width of the boundary area l_{vr} by the flow meter readings as well as pressure, steam and water temperature, can be used to assess based on the suggested model and calculation method the leak of $^{16}\boldsymbol{N}$ from the primary into the secondary circuit, to identify the size of the release of radioactive nitrogen $^{16}\boldsymbol{N}$ to the turbine under any reactor power rate, to minimize the leak by selecting respective alloys used for steam ducts in steam generators, and finally to develop respective radiation protection measures [17]. It is possible to make the calculation results given in this work more precise by using the genuine measurement results which in their turn require experimental surveys. However, expenses to conduct such surveys will definitely pay off as they will allow determining work conditions that are safe from the point of view of specialists who are in charge of the radiation safety rules being met at facilities and respective transportation means where such reactors are used.

CONCLUSION

The results of this paper may be of interest for structural divisions involved in radiation safety issues at nuclear facilities, design organizations that develop designs of SGs for NPPs and watercrafts with similar nuclear reactors. In view of the importance and topicality of this paper due to the upgrade of the icebreaker fleet in Russia, the authors find it to be reasonable to conduct simulated experiments that would allow refining a number of dosimetry features to specify design parameters of the model.

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