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ELECTROMAGNETIC FIELDS EXCITED BY NEUTRONS IN AIR

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It is well known [1] that γ radiation emanating into air excites in the space around its source electromagnetic fields. Other authors [1, 2] have calculated fields in the current zone and in the wave zone for the case of a γ radiation pulse decaying exponentially with time while the distribution of emitting currents has a weak spatial asymmetry. Neither the character nor the origin of this asymmetry have not been dealt with specifically in [1, 2]. In another study [3] there has been solved the model problem of fields excited by a transient source of γ radiation on the plane boundary between an ideal conductor and homogeneous air. In still another study [4] the field problem was considered for the case of an isotropic source in nonhomogeneous air, without taking into account the effect of a ground surface. In all these studies [1-4] the air was assumed to be of standard or nearly standard density. An electromagnetic pulse, as theoretically calculated in [1-4], is characterized by half-periods several microseconds long and by a total duration of the order of ten microseconds. The ratio of amplitudes of the field intensity in different half-periods is of the order of 10. In a further study [5] the vertical component of the electric field intensity was recorded as a function of time at a distance of 44.6 km from the source. A comparison of theoretical data [1-4] and experimental data [5] indicates appreciable quantitative discrepancies between them [6], and experimental pulse of electric field intensity having a characteristic time of the order of ten microseconds and a ratio of amplitudes in the first few half-periods of the order of 1:1, with a total duration of the order of a hundred microseconds. Since none of the possible physical modifications of the emission mechanism considered in studies [2-4] seems to bring theory and experiment closer together, it has been proposed in study [6] that emission of an electromagnetic pulse such as in [5] is due not only to Compton electron currents but also to an effect of another nature, associated with evolution of a heat wave and its transformation to a shock wave. The total signal is regarded there as a result of addition of two signals, one of them (the shorter) emitted by Compton electron currents flowing from the pulse of γ radiation [2, 3] and one (the longer) emitted by currents flowing along the front of the heat wave. The orders of magnitude of the amplitude and of the characteristic duration of the emitted signal according to the estimates in [6] agree with experimentally measured values. The nature of a signal extracted in [6] from a recording of a signal in [5], with a characteristic duration of the order of tens of microseconds, will in this study be attributed to γ radiation initiated in air by neutrons of less than 14 MeV energy [7]. The corresponding processes here will be seen as process with a threshold, then threshold energy being 3 MeV [8]. The time of neutron retardation from 14 to 3 MeV is approximately 50 μsec so that a pulse of initiated γ radiation as well as Compton

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electron currents excited in air and an emitted electromagnetic pulse will all also have characteristic times of the order of tens of microseconds. On the basis of the solution to the simplified-model electrodynamic problem, we will calculate fields excited by a pulse source of neutrons which is located on the plane boundary between an ideal conductor and homogeneous air. The purpose of these calculations is to quantitatively compare and interpret the basic amplitude-time parameters of an electromagnetic pulse such as in [5].

1. We consider the nonsteady space-energy distribution of fast neutrons retarded in air, information about which is needed for calculating the space-energy distribution of sources of secondary γ radiation. It is well known [8] that retardation of 3-14-MeV neutrons in air occurs as a result of elastic and inelastic collisions with nuclei of nitrogen and oxygen atoms. Inasmuch as the cross section for inelastic scattering of neutrons with energy $\varepsilon \lesssim 14$ MeV in air is much smaller than that for their elastic scattering [8, 9], further calculations will be simplified by combining both processes and assuming that a single collision characterized by a cross section $\Sigma = \Sigma_S + \Sigma_{in}$ causes a neutron with energy ε to lose, on the average an amount of energy

$$\Delta(\varepsilon) = \frac{\Sigma_S^{(O)}}{\Sigma}\Delta_S^{(O)} + \frac{\Sigma_S^{(N)}}{\Sigma}\Delta_S^{(N)} + \sum_k \left[\frac{\Sigma_{in,k}^{(O)}}{\Sigma}\Delta_{in,k}^{(O)} + \frac{\Sigma_{in,k}^{(N)}}{\Sigma}\Delta_{in,k}^{(N)}\right], \tag{1.1}$$

where $\Delta_S^{(N,O)}$ are the mean losses suffered by neutrons as a result of single elastic collisions with nuclei of, respectively, nitrogen and oxygen atoms; $\Delta_{in,k}^{(N,O)}$ are the mean energy losses suffered by neutrons as a result of single inelastic collisions accompanied by excitation of the k-th level in nuclei of, respectively, nitrogen and oxygen atoms; $\Sigma_{in,k}^{(N,O)}$ are the cross sections for the corresponding inelastic processes; $\Sigma_S^{(N,O)}$ are the cross sections for elastic scattering of neutrons by nuclei of, respectively, nitrogen and oxygen atoms; $\Sigma_S = \Sigma_S^{(O)} + \Sigma_S^{(N)}$; $\Sigma_{in} = \sum_k [\Sigma_{in,k}^{(O)} + \Sigma_{in,k}^{(N)}]$.

Calculations according to Eq. (1.1) with the aid of data on cross sections [8, 9] and data on the anisotropy of elastic scattering [10] reveal that at energy levels $\varepsilon \lesssim 14$ MeV the relative energy losses due to collisions are small, i.e., $[\Delta(\varepsilon)/\varepsilon] \ll 1$. This makes it permissible to calculate the neutron distribution function $f(\varepsilon, t, r)$ on the basis of the age approximation, which establishes a unique dependence of the neutron energy on the retardation time [11]. Using this approximation, we obtain

$$f(\varepsilon, t, r) = N\delta\left[\varepsilon - \varepsilon_m(t, \varepsilon^+)\right]\exp\left[-\mathcal{J}(t)\right]\frac{\exp\left[-r^2/4\tau(t, \varepsilon^+)\right]}{\left[4\pi\tau(t, \varepsilon^+)\right]^{3/2}},$$

where $\varepsilon_m(t, \varepsilon^+)$ is the mean energy of retarded neutrons, as determined from the relation

$$t = \int_{\varepsilon_m}^{\varepsilon^+} \frac{d\varepsilon}{v\Delta(\varepsilon)\Sigma(\varepsilon)};$$
$$\tau(t, \varepsilon^+) = \int_{\varepsilon_m}^{\varepsilon^+} \frac{d\varepsilon}{3\Delta(\varepsilon)\Sigma(\varepsilon)\Sigma_{tr}(\varepsilon)} \tag{1.2}$$

is the "age" of neutrons; the function

$$\mathcal{J}(t, \varepsilon^+) = \int_{\varepsilon_m}^{\varepsilon^+} \frac{d\varepsilon}{\Delta(\varepsilon)}\frac{\Sigma_a(\varepsilon)}{\Sigma_{tot}(\varepsilon)} \tag{1.3}$$

characterizes the subsidence of neutrons with time; N is the total number of neutrons emitted by a monoenergetic source with energy ε^+; Σ_a is the cross section for neutron absorption; $\Sigma_{tr} = [\Sigma_{tot} - \overline{\mu_O^{(\pi)}}\,\Sigma_S^{(O)} - \overline{\mu_N^{(\pi)}}\,\Sigma_S^{(N)}]$ is the cross section for transport ($\Sigma_{tot} = \Sigma_S + \Sigma_{in} + \Sigma_a$); $\overline{\mu_{(O,\,N)}^{(\pi)}}$ are the mean cosines, in the laboratory system of coordinates, of the angle at which neutrons are scattered by nuclei of, respectively, oxygen and nitrogen atoms; and $\delta(x)$ is the Dirac delta function.

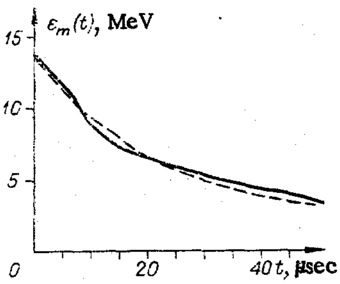

Fig. 1

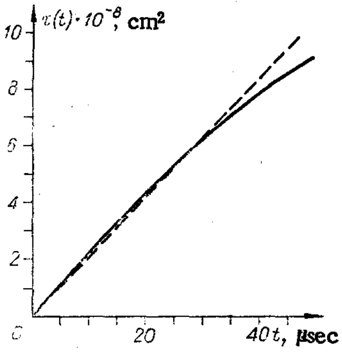

Fig. 2

In order to conceptualize both time and space scales of this phenomenon, we will thoroughly examine the time dependence of the mean neutron energy $\varepsilon_m(t)$, of the neutron age $\tau(t)$, and of the relative number of neutrons ($\exp[-\mathcal{I}(t)]$). Graphs of these quantities as functions of time, based on relations (1.2) and (1.3) as well as on data in [8-10], have been plotted in Figs. 1-3 (solid lines). The curves here can be closely described by the approximate analytical expressions (dashed lines)

$$\varepsilon_m(t) = \frac{14}{[1+2.18\cdot 10^{-2}t]^2}, \quad \tau(t) = 2.12\cdot 10^7 t,$$
$$\exp[-\mathcal{I}(t)] = \frac{1}{[1+2.18\cdot 10^{-2}t]^{2.26}}. \tag{1.4}$$

According to the graphs in Figs. 1-3, neutrons with an energy of 14 MeV which have been promptly emitted by a monoenergetic point source will, as a result of elastic and inelastic collisions, slow down to an energy of 3 MeV within 50 μsec and then form a cloud in space with a diameter of ≈700 m. During this time their total number will, as a result of entrapment processes, have been reduced to approximately one-fifth of the original one.

2. Secondary γ radiation, initiated by neutrons in air, builds up during the processes of inelastic neutron scattering and of neutron entrapment, generally with a threshold. The main kinds of reactions between neutrons and nuclei of nitrogen and oxygen atoms during which emission of γ quanta occurs are listed in [8].

Knowing the neutron distribution function, one can calculate the sources of secondary γ radiation, namely the number of γ quanta emitted by nuclei of the atoms of ambient elements per unit time and per unit volume as a result of interaction with nuclei characterized by cross section $\Sigma^i_{n\gamma}$:

$$\tilde{q}_i(r,t) = \int_0^\infty d\varepsilon v \Sigma^{(i)}_{n\gamma}(\varepsilon) f(r,\varepsilon,t) = N\frac{\Sigma^{(i)}_{n\gamma}(\varepsilon_m)}{\Sigma_{n\gamma}(\varepsilon_m)} f(t)\frac{\exp\{-r^2/4\tau\}}{(4\pi\tau)^{3/2}},$$

where $\Sigma_{n\gamma} = \sum_i \Sigma^{(i)}_{n\gamma}$ is the total cross section for yield of γ quanta and

$$f(t) = v_m(t)\Sigma_{n\gamma}(\varepsilon_m)\exp\left\{-\int_{\varepsilon_m}^{\varepsilon^+}\frac{d\varepsilon}{\Delta(\varepsilon)}\frac{\Sigma_a(\varepsilon)}{\Sigma_{tot}(\varepsilon)}\right\}. \tag{2.1}$$

Function f(t) characterizes the change, with time, of the total (over all reactions and the entire volume) γ radiation intensity. A graph of this function, based on expression (2.1) and data on cross sections [8], is shown in Fig. 4 (solid line) along with a curve (dashed line) representing the simple interpolation for f(t)

$$f(t) = 0.861\cdot 10^5 \exp(-t/b), \; b = 12 \text{ μsec}, \tag{2.2}$$

which quite accurately describes the change with time of the quantity (2.1).

The total number of γ quanta emitted by nuclei of nitrogen and oxygen atoms during their interaction with neutrons is

$$N_\gamma = N\int_0^\infty f(t)\,dt. \tag{2.3}$$

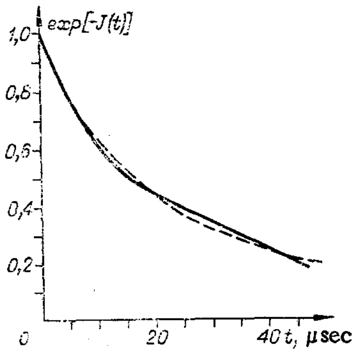

Fig. 3

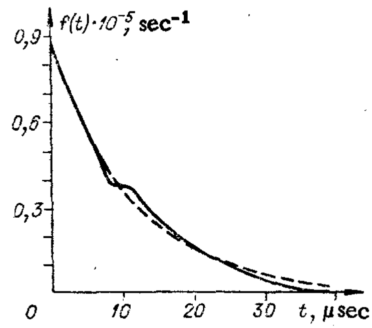

Fig. 4

Inserting expression (2.2) into expression (2.3) yields $N_\gamma = 1.03N$. Accordingly, during the retardation of neutrons from 14 to 3 MeV their interaction with nuclei of nitrogen and oxygen atoms produces, on the average, one γ quantum per neutron emitted by the source. The energy spectrum of generated γ quanta ranges rather widely from 1.6 to 10 MeV [8]. The dependence of the average energy of a γ quantum on the energy of a neutron can be described by the expression

$$\overline{\varepsilon_\gamma(\varepsilon)} = \frac{1}{\Sigma_{n\gamma}(\varepsilon)} \sum_{i=1} \Sigma_{n\gamma}^{(i)}(\varepsilon)\,\varepsilon_\gamma^{(i)}. \tag{2.4}$$

With the aid of expression (2.4) and data on cross sections [8], one can ascertain that the average energy of γ quanta does not change much (from 4 to 2 MeV) while the energy of neutrons changes from 14 to 3 MeV. In view of this, for the purpose of simplifying further calculations, we assume that during retardation of neutrons in air from 14 to 3 MeV their interaction with nuclei of nitrogen and oxygen atoms produces one 3-MeV γ quantum per neutron emitted by the source. For the space–time distribution of sources of secondary γ radiation we then obtain

$$\tilde{q}(r, t) = Nf(t)\frac{\exp(-r^2/4\tau)}{(4\pi\tau)^{3/2}}, \tag{2.5}$$

where for further calculations of f(t) and τ(t) we use the analytical expressions (1.4) and (2.1) accurately enough describing the time dependence of these quantities.

3. A γ quantum with an average energy of 3 MeV imparts, as a result of the Compton effect, on the average 82% of its energy to an electron [12]. In this case the space–time distribution of electron sources, determined by the distribution of absorbed γ radiation energy, as well as the Compton electron current will almost entirely (to the extent of 82%) depend on the unscattered radiation.

Furthermore, inasmuch as the characteristic activity time of a source of secondary radiation (2.5) is approximately 12 μsec (2.2), we can disregard the effects of delay of γ quanta in the system. Indeed, the characteristic range within which sources of γ radiation are active is of the order of 700 m (Fig. 2). The delay time of γ quanta during their motion through this distance is only 2.3 μsec.

On the basis of these data, for Green's function of γ radiation one can use the steady-state relation

$$G(\mathbf{r}, \mathbf{r}') = \frac{\exp[-\mu|\mathbf{r}-\mathbf{r}'|]}{4\pi|\mathbf{r}-\mathbf{r}'|^2}, \tag{3.1}$$

where μ^{-1} is the mean free path of a γ quantum relative to Compton scattering. For $\varepsilon_\gamma = 3$ MeV in air of normal density we have $\mu^{-1} = 217$ m [12]. Considering that a γ quantum loses 82% of its energy during its first collison, we will use for μ^{-1} in expression (3.1) the value $\mu^{-1} = 217/0.82 = 264$ m.

With relation (3.1), the space–time distribution of sources, of secondary and Compton electron currents j can be represented as [13]

$$q(R, t) = N\nu\varepsilon_\gamma\mu f(t)I_1(R, t);\ j(R, t) = Ne\mu l f(t)I_2(R, t), \tag{3.2}$$

where

$$I_1(R,\ t) = \int d\mathbf{r}\, \frac{\exp\left[-\mu\,|\mathbf{r}-\mathbf{R}| - \frac{r^2}{4\tau}\right]}{4\pi\,|\mathbf{R}-\mathbf{r}|^2\,(4\pi\tau)^{3/2}}; \tag{3.3}$$

$$I_2(R,\ t) = \int d\mathbf{r}\, \frac{\exp\left[-\mu\,|\mathbf{r}-\mathbf{R}| - \frac{r^2}{4\tau}\right]}{4\pi\,|\mathbf{r}-\mathbf{R}|^2\,(4\pi\tau)^{3/2}}\, \frac{\mathbf{R}\,(\mathbf{R}-\mathbf{r})}{|\mathbf{R}|\,|\mathbf{R}-\mathbf{r}|}; \tag{3.4}$$

where $\nu = 3\cdot 10^4$ is the number of ion pairs generated in air per 1 MeV of absorbed energy [3]; e is the charge of an electron; and l = 10 m is the mean free path of a Compton electron.

It is not possible to express the integrals in relations (3.3) and (3.4) through elementary functions at any values of R and t. However, it is possible to obtain rather simple expressions for these quantities at small and large distances from the source. Collocation of these expressions will yield quite simple and comprehensive (although not exact) results for I_1 and I_2 over the entire space.

Following this procedure, we represent functions I_1 and I_2 in the form

$$I_1(R,\ t) = \frac{\exp\left\{-\frac{1}{(4\tau/R^2)+(1/\mu R)}\right\}}{\{8\pi\tau\,(1+\mu\sqrt{\pi\tau})+4\pi R^2\}}\,\Psi_1\,(R,\ t); \tag{3.5}$$

$$I_2(R,\ t) = \frac{\exp\left\{-\frac{1}{(4\tau/R^2)+(1/\mu R)}\right\}}{\left\{\frac{3}{R}\,(4\pi\tau)^{3/2}\,(1+2\tau\mu^2)+4\pi R^2\right\}}\,\Psi_2\,(R,\ t), \tag{3.6}$$

with the matching functions Ψ_1 and Ψ_2 selected so as to yield the closest numerical agreement between values of functions I_1 and I_2 based on relations (3.5), (3.6) and on relations (3.3), (3.4), respectively. The permissible error of approximately describing the functions I_1 and I_2 by expressions (3.5) and (3.6) respectively, does not at time $t \le 30$ µsec, exceed 17% at distances smaller than $4\mu^{-1}$ and 50% at distances from $4\mu^{-1}$ to $15\mu^{-1}$. The values of these functions I_1 and I_2, meanwhile, change by ten orders of magnitude as the distance increases to $15\mu^{-1}$.

4. We will now solve the simplified model problem of electromagnetic fields excited by transient source of neutrons and prompt γ radiation located on the plane boundary between air of normal density and an ideally conducting half-space. In the subsequent analysis of this problem we will assume the radiation source to be an isotropic point source. Conduction and extraneous currents excited in air will be assumed the same as in the vicinity of an isotropic source in homogeneous air without a ground surface.

In a more rigorous calculation of fields excited by a pulse of neutrons one must include a transverse θ-component of the extraneous current, in addition to its radial component, as well as changes in the ionization distribution over the air space due to a ground surface near the bulk source of secondary γ radiation. However, as will be demonstrated here, the shape of the electromagnetic pulse in the wave zone (calculation of which is the main object of this study) depends little on the space distribution pattern of currents and air ionization near the sources.

In a spherical system of coordinates with the origin at the source our problem reduces to determining the nonzero field components E_r, E_θ, H_φ, which in the upper half-space satisfy the Maxwell equations

$$\frac{1}{c}\frac{\partial E_r}{\partial t} = \frac{1}{r\sin\theta}\frac{\partial}{\partial\theta}(H_\varphi\sin\theta) - \frac{4\pi}{c}[\sigma(r,\ t)\,E_r - J\,(r,\ t)];$$
$$\frac{1}{c}\frac{\partial E_\theta}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}(rH_\varphi) - \frac{4\pi}{c}\sigma(r,\ t)\,E_\theta,\quad \frac{1}{c}\frac{\partial H_\varphi}{\partial t} = \frac{1}{r}\frac{\partial E_r}{\partial\theta} - \frac{1}{r}\frac{\partial}{\partial r}(rE_\theta), \tag{4.1}$$

where c is the velocity of light; σ(r, t) is the space–time distribution of the electrical conductivity of air; $J = j(r,\ t) + j_1(r,\ t)$; j(r, t) is the current of Compton electrons appearing due to γ radiation initiated by neutrons (3.2); and $j_1(r,\ t)$ is the current of Compton electrons appearing due to prompt γ radiation [3].

For solving this problem we will use the method of images [3], i.e., replace the problem in a half-space with the problem of fields in the full-space, assuming that in the lower half-space the electrical conductivity is the same and the currents are of opposite polarity as in the upper half-space. Such a premise automatically satisfies the condition that the tangential field component be zero at the boundary of an ideally conducting surface ($E_r(r, \theta = \pi/2) = 0$).

For separating the angular distributions we again, as in [3], expand functions $J(r, \theta, t)$, $E_r(r, \theta, t)$ into series of Legendre polynomials

$$J(r, \theta, t) = J_0(r, t) \sum_l c_l P_l(\cos\theta), \quad E_r(r, \theta, t) = \sum_l E_{rl}(r, t) P_l(\cos\theta),$$

and functions $E_\theta(r, \theta, t)$, $H_\varphi(r, \theta, t)$ into series of associated Legendre polynomials

$$E_\theta = \sum_l \frac{1}{r} E_{\theta l}(r, t) P_l^{(1)}(\cos\theta), \quad H_\varphi = \sum_l \frac{1}{r} H_{\varphi l}(r, t) P_l^{(1)}(\cos\theta).$$

Inserting these series into the system of equations (4.1) and then changing to dimensionless variables and functions, we obtain a system of equations for the coefficients of the polynomial series into which the field components have been expanded

$$\frac{\partial \tilde{E}_{rl}}{\partial y} = \frac{l(l+1)}{x^2} \tilde{H}_{\varphi l} - \frac{4\pi}{\mu_1 c}\left\{\sigma(r, t) \tilde{E}_{rl} + \frac{c_l}{E_0} J_0\right\},$$
$$\frac{\partial \tilde{E}_{\theta l}}{\partial y} = -\frac{\partial \tilde{H}_{\varphi l}}{\partial x} - \frac{4\pi}{\mu_1 c}\sigma(r, t) \tilde{E}_{\theta l}, \quad \frac{\partial \tilde{H}_{\varphi l}}{\partial y} = -\frac{\partial \tilde{E}_{\theta l}}{\partial x} - \tilde{E}_{rl}, \tag{4.2}$$

with

$$c_l = [1 - (-1)^l] \frac{\sqrt{\pi}(2l+1)}{4\Gamma\left(\frac{2-l}{2}\right)\Gamma\left(\frac{3+l}{2}\right)}; \quad x = \mu_1 r; \quad y = \mu_1 ct; \; \tilde{E}_{rl} = E_{rl}/E_0;$$
$$\tilde{H}_{\varphi l} = \mu_1 H_{\varphi l}/E_0; \; \tilde{E}_{\theta l} = \mu_1 E_{\theta l}/E_0; \quad E_0 = \mu_1 l_1 c/\nu k_e; \; \mu_1^{-1} = 250 \text{ m and } l_1 = 3$$

are the mean free paths of, respectively, a prompt γ quantum and a Compton electron the latter has knocked out [3]; and k_e is the electron mobility in air.

A solution to system (4.2) in the $(x, \tilde{y})$-plane ($\tilde{y} = y - x$), within the rectangle ($x_0 \le x \le x_1$, $0 \le \tilde{y} \le \tilde{y}_1$) has been obtained by numerical integration. The unique solution to system (4.2) within this region has been determined under the boundary conditions

$$\text{at } x = x_0 \quad \tilde{E}_{\theta l} = 0,$$
$$\text{at } \tilde{y} = 0 \quad \tilde{E}_{\theta l} = \tilde{E}_{rl} = \tilde{H}_{\varphi l} = 0,$$
$$\text{at } x = x_1 \; \tilde{E}_{\theta l}(x_1, \tilde{y}) - \tilde{H}_{\varphi l}(x_1, \tilde{y}) = \frac{1}{2}\int_0^{\tilde{y}} d\tilde{y}' \exp\left\{\frac{\tilde{y}' - \tilde{y}}{x_1}\right\} \tilde{E}_{rl}(x_1, \tilde{y}'). \tag{4.3}$$

The first condition signifies that the source is surrounded by an ideally conducting sphere with a radius x_0, the second condition signifies zero initial values. As the third boundary condition (at $x = x_1$) served the relation between electric and magnetic field intensities in free space at any distance from a radiating oscillator (strictly speaking, this relation holds true only for $l = 1$). This relation is obtained from the well-known exact solution to the field problem of a nonsteady dipole [14]. The choice of a boundary condition in this form was dictated by the fact that the maximum distance to which calculations were carried corresponded to $x_1 = 140$, too short for analysis of pulses with a duration $\tilde{y} \approx 30$ (as will be shown subsequently). At such distances the condition $\tilde{E}_{\theta l} = \tilde{H}_{\varphi l}$, used in [3] and corresponding to the wave zone, may not yet be satisfied.

A complete stipulation of system (4.2) requires still an expression for the space–time distribution of the electrical conductivity of air, which is well known to be

$$\sigma(r, t) = e[k_e n(r, t) + k_- N_-(r, t) + k_+ N_+(r, t)],$$

where n, N_+, N_- are the concentrations of respectively electrons, positively charged ions, and negatively charged ions; $k_e \approx 10^6$ (CGSE units) is the electron mobility, $k_+ \approx 4.11 \cdot 10^2$ is the mobility of positive ions, and $k_- \approx 5.67 \cdot 10^2$ is the mobility of negative ions [15].

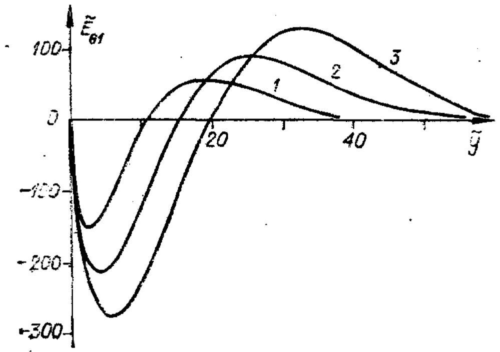

Fig. 5

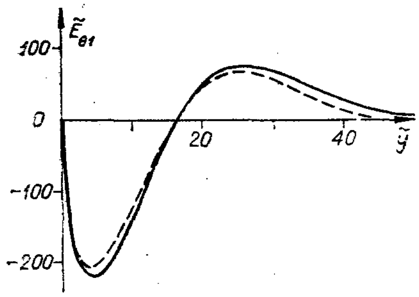

Fig. 6

For calculating an electromagnetic pulse generated by a pulse of γ radiation longer than 1 μsec, one needs to consider only the electronic conductivity of air [3]. The ionic conductivity of air can be disregarded also in our case of field excitation by a pulse of neutrons. Indeed, estimates based on the equation of balance relative to charged particles indicate that during the period of time $t \leq 30$ μsec at distances $R \leq 1000$ m the contribution of ions to the electrical conductivity is negligible when $N = 2 \cdot 10^{23}$, inasmuch as then $(N_{\pm}/n) \ll k_e/k_{\pm} \approx 0.2 \cdot 10^4$. As the total yield of neutrons N increases, the ratio N_{+}/n will decrease still further. It is also to be noted that taking into account the ionic conductivity of air would result in larger time scales of the electromagnetic signal and thus amplify rather than attenuate the subsequently considered effect of a longer duration of the electromagnetic pulse.

Accordingly, we will disregard the contribution of ions to the electrical conductivity of air and will regard the latter to be everywhere due to electrons, with the time dependence of the electron concentration described by the equation

$$d\tilde{n}/dy + \tilde{\gamma}\tilde{n} = \tilde{Q}, \tag{4.4}$$

where

$$\tilde{n} = n/n_0;\ \tilde{\gamma} = \gamma/\mu_1 c;\ \tilde{Q} = Q/(n_0\mu_1 c);\ n_0 = \nu\varepsilon_\gamma^{(1)} N_1 \mu_1^3 \frac{e^{-x}}{4\pi x^2};\ \gamma \simeq 1.1 \cdot 10^8 \text{ sec}^{-1}$$

is the coefficient of electron adhesion to negatively charged oxygen molecules [16]; N_1 is the total yield of prompt γ quanta and $\varepsilon_\gamma^{(1)}$ is their energy [3]; $Q = q + q_1$; q is the source of electrons generated by γ radiation initiated by neutrons (3.2); and q_1 is the source of electrons generated by prompt γ radiation [3].

The problem regarding excitation of electromagnetic fields has thus been reduced to the solution of Maxwell equations (4.2) for the boundary conditions (4.3) and of Eq. (4.4) for zero-value initial conditions. As the function f(y) in expression (3.2) was used

$$f(y) = \frac{1}{B} \frac{y \exp(\Lambda y)}{A + y \exp[(\Lambda + \lambda) y]}, \tag{4.5}$$

with

$$B = \int_0^\infty \frac{dy\, y \exp(\Lambda y)}{A + y \exp[(\Lambda + \lambda) y]};\ A = 3.75 \cdot 10^{16};\ \Lambda = 250,\ \lambda = 0.07.$$

Expression (4.5) takes into account that neutrons are not generated instantaneously but within a finite period of time [7] and that the subsidence of γ radiation with time follows relation (2.2).

The curves in Fig. 5 depict the vertical component $\tilde{E}_{\theta 1}$ of the electric field intensity in the wave zone (at x = 140), as a function of time, according to a numerical solution of Eqs. (4.2) and (4.4) for $N = N_1 = 2 \cdot 10^{23}$, $2 \cdot 10^{24}$, and $2 \cdot 10^{25}$ (curves 1-3), respectively. The results indicate that increasing the total yield of prompt γ quanta and neutrons through two orders of magnitude will approximately double both the duration and the amplitude of the signal.

The curves in Fig. 6 depict $\tilde{E}_{\theta 1}$ at x = 60 as a function of time, according to a solution of Eqs. (4.2) and (4.4) either with spreading of the neutron cloud taken into account, i.e.,

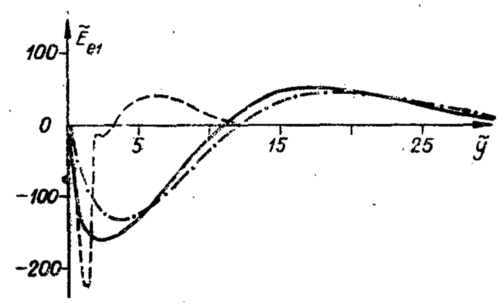

Fig. 7

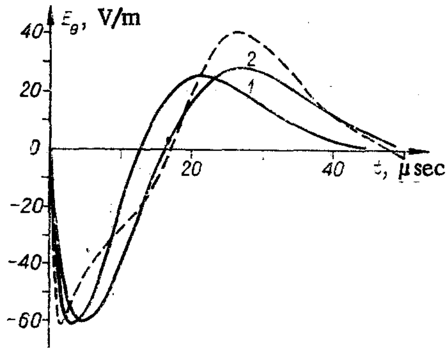

Fig. 8

with the aid of expressions (3.2) (solid line) or on the assumption of a point source of γ quanta initiated by neutrons (dashed line for $N = N_1 = 2 \cdot 10^{23}$). The results indicate that both the amplitude and the shape of the signal in the wave zone depend little on the space distribution pattern of sources of secondary γ radiation (which was noted earlier).

The curves in Fig. 7 depict $\tilde{E}_{\theta 1}$ at x = 60 as a function of time, according to a solution of Eqs. (4.2) and (4.4) either with prompt γ radiation as well as γ radiation initiated by neutrons taken into account (solid line), or with one prompt γ radiation taken into account (dashed line), or with only γ radiation initiated by neutrons taken into account (dotted line). The source of γ radiation initiated by neutrons was regarded as a point source. The graphs in Figs. 5-7 indicate that taking into account γ radiation due to neutrons will increase the time scales characterizing the electromagnetic signal and decrease the differences between the amplitudes of field intensities in different half-periods. The results also show that the intensity of the electric field excited by both prompt γ radiation and γ radiation initiated by neutrons is not equal to the sum of intensities due to each factor individually. This can be explained by the dependence of the electrical conductivity of air on both modes of γ radiation. During the initial period of time (at $\tilde{y} < 0.5$) the absolute magnitude of the electric field intensity rises as it does with prompt γ radiation only. At $\tilde{y} > 0.5$ the changing of the electric field intensity with time departs from this trend toward lower absolute magnitudes, which is attributable to an additional increase in the electrical conductivity of air due to γ radiation initiated by neutrons. At still later periods of time, when the source of prompt γ radiation has almost completely ceased to be active, the electric field intensity changes with time almost as it does with only γ radiation initiated by neutrons. It is noteworthy that the total signal becomes nearly equal to the signal due to neutrons after a time. This suggests that, for extracting from the total signal its component not associated with prompt γ radiation by the method of analytic continuation [6], one should start at a point on the recorded signal sufficiently far on the time scale. It is, furthermore, necessary to make allowance for the nonadditivity of signals due to prompt γ radiation and γ radiation initiated by neutrons during the early period of time.

The curves in Fig. 8 depict the change, with time, of the vertical component of the electric field intensity at a distance of 44.6 km from the source, as has been recorded in study [5] (dashed line) and calculated upon normalization with respect to the amplitude of the first half-wave in the recorded pulse (curve 1 for $N = N_1 = 2 \cdot 10^{24}$, curve 2 for $N = N_1 = 2 \cdot 10^{25}$). The duration of theoretically calculated signals is approximately equal to that of a recorded pulse. A similar agreement is found between the amplitudes of the electric field intensity in various half-periods. On the whole, the results in Fig. 8 indicate a rather close agreement between theoretical and experimental data on the pulse form. It is to be noted that the signal recorded experimentally has an inflection point at t = 3 μsec. During the period t < 10 μsec, moreover, the signal is narrower than according to theoretical calculations. A better congruence of the signal pulse forms can be achieved by shifting, within permissible limits, the maximum neutron yield to later instants of time and adjusting the relative yields of neutrons and γ quanta so to emphasize the signal due to prompt γ radiation.

Theory gives a higher (approximately 6 times) absolute value for the signal amplitude than does experiment. This difference is attributable to several causes, foremost among them being inaccurate values used for the physical constants unavailability of precise data on the energy spectrum of neutrons emitted by the source as well as on the location of that source relative to the ground surface, and on its conduction characteristics far from those of an ideal conductor assumed in the calculations.

In summary, taking into account γ radiation generated in air by interaction between neutrons of energies higher than 3 MeV with nuclei of nitrogen and oxygen atoms will result in a radio pulse similar in total duration and overall form to the actually measured one. Further refinement of the calculated data requires that into account be also taken the effect of the ground surface on the neutrons retardation process, the correct spatial distribution of sources of secondary γ radiation, and the currents flowing on the ground surface itself under these conditions. It is necessary, moreover, to include during the earlier period any nonlinear (with respect to the field intensity) effects which may occur in the current zone [17] and during the later period the electrical conductivity of air due to ions.

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