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EVALUATION OF MALIGNANT ANTHRAX SPORE DISPERSION IN HIGH-RISE BUILDINGS

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Analysis of the dispersion of malignant anthrax spores in a 50-story tower block after a terrorist act has been carried out. A computer model of the aerosol dispersion in the case of intensive small-scale convection equalizing the concentration of malignant anthrax spores in separate rooms of the building has been developed. The model permits predicting the time interval needed for the spores to disperse. It has been shown that the release of even a relatively small amount of malignant anthrax spores can lead to a dangerous contamination of the whole building.

The application of agents of biological weapons for committing a terrorist act jeopardizes public safety. As a biological weapon, many microorganisms that cause dangerous diseases or produce toxins (i.e., viruses, bacteria, fungus spores, etc.) can be used. Soil microorganisms *Bacillus anthracis,* whose metal protease is the cause of the dangerous disease known as "malignant anthrax," have been identified as a probable bacteriological threat. The etiological agent of malignant anthrax is a rather large gram-positive bacterium having the form of a rod. Spores of size 1–5 μm effectively penetrate into the lungs. Investigations on primates have shown that 3–5 spores can initiate an infection. Eight thousand spores are enough to cause the death of a human if no therapeutic intervention had been used before the process of exotoxin formation began. When spores are inhaled and get into the organism, bacilli multiply rapidly and, as a result, bacteria and toxins get into the human circulatory system [1]. Before the advent of antibiotics (1938), inhaling malignant anthrax was very dangerous. Even at the present time its danger is still rather high. For instance, for patients who had not begun treatment before signs of strong intoxication appeared, mortality during the American epidemic in 2001 was 45% [2].

Because of their virulence and elasticity, malignant anthrax spores are extremely attractive as bioterrorist agents, since they can easily be obtained both under laboratory conditions and from natural sources. Grown and purified spores are very small particles that are absorbed with a high probability in human alveolae. Spores can be released into the atmosphere with the help of various devices, including the simplest devices for powder sputtering [3].

The spreading of malignant anthrax spores by mail that took place in the United States of America in October–November of 2001 demonstrated that the bioterrorist threat may become reality. The analysis carried out in the present paper permits estimating the dispersion and the inhaling dose of malignant anthrax spores after a terrorist act in a 50-story tower block.

Methodology. The computer model used is based on ideas first presented in [4], where the dispersion of spores was described for the case of intensive small-scale convection that equalizes their concentration in the premises of the building. The time interval needed for removing suspended spores from the building was estimated from the point of view of a multichamber model describing the air exchange between different rooms and permitting estimation of the inhaling dose in the case of the release of malignant anthrax spores in a terrorist act committed in a high-rise building.

In modeling, the following values of the quantities determining the air exchange and the spore transfer in the building were given:

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1. The total number of spores $N = 3.2 \cdot 10^{12}$ and the mean value of the mass of one spore $m_0 = 7 \cdot 10^{-16}$ kg. The total mass of all suspended spores $Nm_0 = 0.0002$ kg. The initial release of spores occurs on the ground floor of a typical 50-story building.

2. The total volume of all rooms on each floor connected to the ventilation system of the building is equal to 2000 m^3. Every 24 hours the air on each floor is renewed five times due to the active ventilation system. As a result, the rate of air exchange on each floor is 417 m^3/h, i.e., such a volume of air enters a room and the same volume of air leaves the room every hour through the ventilation system.

3. In the process of circulation, 25% of the air (renewal coefficient) is removed from the building and replaced by fresh air. The rate of air exchange in the building is 5212.5 m^3/h (417 m^3/h × 50 floors × 0.25).

In describing the dispersion of malignant anthrax spores, it was assumed that:

1) the particles are uniformly distributed between separate rooms (chambers) of the building, except for the boundary layer near the walls;

2) among particles of one class of sizes there are no differences in the composition;

3) the characteristics of a particle are a function of its size and density, which can vary depending on the composition;

4) the transfer coefficients (as well as the form factor, the boundary-layer size, etc.) are independent of the particle size;

5) internal mixing among particles of the same class of sizes occurs because of the gravitational and Brownian (thermal) coagulation;

6) the spatial homogeneity in the control volume is maintained by small-scale atmospheric convection.

The model describes the processes of spore sedimentation (gravitational and diffusion sedimentation), the interaction of suspended spores (Brownian and gravitational coagulation), and the processes of particle transfer between rooms of the building (sources and drains of spores arising as a result of the inflow and removal of spores through the ventilation system).

Sedimentation of Spores. The model of the process of removal of aerosols under mixing is well known [5–9]. The rate of change in the concentration of spores is determined by the dependence

$$\frac{dc\,(r)}{dt} = -\,c\,(r)\,U\,(r)\,\frac{A}{V}, \tag{1}$$

where the rate of spore sedimentation is calculated as

$$U\,(r) = FB\,(r)\,. \tag{2}$$

The mobility of a spherical spore is found by the Stokes formula

$$B\,(r) = \frac{\mathrm{Cn}\,(r)}{6\pi\eta r}, \tag{3}$$

where Cn(r) is the empirical Cunningham correction factor, calculated by the widely known expression [10]

$$\mathrm{Cn}\,(r) = 1 + 1.246\,\mathrm{Kn} + 0.42\,\mathrm{Kn}\exp\left(-\frac{0.87}{\mathrm{Kn}}\right). \tag{4}$$

In the numerical simulation, it is convenient to use, as the particle size, the radius averaged over its volume.

In a gravitational sedimentation the rate of motion of a spore is determined by the expression

$$U_{\mathrm{g}}\,(r) = \frac{2\rho_{\mathrm{eff}}\,g}{9\eta}\,r^2\,\mathrm{Cn}\,(r)\,, \tag{5}$$

and the surface area A is the sum of areas of the horizontal projections of all floors of the room. For all the other processes of sedimentation the orientation of the room floors is of no importance.

Large-size pores ($r \geq 7$ μm) in the absence of artificial mixing are not deposited on the vertical walls at all and the inertial deposition on the flat walls of a room is extremely small. Thus, in the case under consideration the main mechanism of aerosol deposition on the vertical walls is the diffusion mechanism, which, along with the gravitational sedimentation, leads to the deposition of spores on horizontal and inclined walls and areas of rooms. Since the spores are supplied to the walls by convective diffusion and are deposited as a result of the molecular diffusion in the thin boundary layer, the deposition rate of spores can be estimated proceeding from the equation

$$U_{\mathrm{d}} \sim D(r)\, \nabla_{\mathbf{n}} c(r, t)\,. \tag{6}$$

Since the law of change in the convective diffusion coefficient as the wall is approached is unknown, one has to strongly simplify the problem and assume that in the boundary layers of thickness δ_{d} only the molecular diffusion is acting and outside this layer the convective diffusion is so intensive that the aerosol concentration outside the layer is constant. In this case, the deposition rate will be expressed by the formula

$$U_{\mathrm{d}}(r) = \tilde{D}(r)/\delta_{\mathrm{d}}\,, \tag{7}$$

where $\tilde{D}(r)$ is the molecular diffusion coefficient, which is related to the particle mobility by the relation

$$\tilde{D}(r) = kTB(r)\,. \tag{8}$$

The portion of spores settled on the walls as a result of collisions depends on the adhesive properties of suspended spores. The quantity δ_{d} determines the deposition rate of spores upon collisions of the spores with the walls. The small-scale air convection in the rooms of the building equalizes their volume concentration. As a result of the convection, the spores are uniformly distributed between separate rooms of the building. The deposition rate of spores can be estimated with fair accuracy by choosing the spore density, the form factor, and the boundary-layer size δ_{d} [11].

Thermophoresis. In the presence of a temperature gradient in the atmosphere of the room a force directed oppositely to the gradient acts on the spores. In the case where the spore size considerably exceeds the mean-free path of the surrounding gas molecules (and, consequently; the continuous medium model can be used), the rate of motion of suspended spores as a consequence of the thermophoresis can be estimated as

$$U_{\mathrm{t.ph}} \sim \nu \frac{1}{T}\frac{\partial T}{\partial x}\,, \tag{9}$$

where the quantity $[(1/T)(\partial T/\partial x)]^{-1} \sim L_T$ defines the characteristic size of the temperature change. Substituting expression (9) into Eq. (2) for the Stokes force acting on a suspended spore in the gas flow, we obtain the following estimate for the thermophoretic force:

$$F_{\mathrm{t.ph}} \sim 6\pi\nu^2\rho_{\mathrm{gas}}\, r \frac{1}{T}\frac{\partial T}{\partial x}\,. \tag{10}$$

For the characteristic values of the quantities $\nu \sim 0.1$ cm^2/sec and $L_T \sim 10$ m, the deposition rate of spores under the action of the thermophoretic forces is $U_{\mathrm{t.ph}} \sim 10^{-4}$ cm/sec. This is much smaller than the gravitational sedimentation rate for spores with a radius $r \geq 0.1$ μm and the diffusion sedimentation rate for spores with a radius $r < 5$ μm. Thus, in the region of parameters $r \sim 0.1$–5 μm the spore sedimentation due to the phenomenon of thermophoresis is negligibly small.

Turbulent Convection. In describing the motion of spores under the conditions of a developed small-scale convection, one can use an effective diffusion model based on the introduction in the near-wall region of a turbulent flow of the effective diffusion coefficient of particles, taking into account both the possible inertial sedimentation of spores as a result of the turbulent pulsation and the action on the spores of the "turbophoretic" forces [12]. In a shear turbulent flow, as in the presence of a temperature gradient in the gas, the pulses received by a suspended particle from the carrier medium from the wall, where the rate of turbulent pulsations of the gas is lower, are weaker than the

pulses received from the flow core. This leads to the fact that the particle is subjected to the action of an additional force directed to the wall of the room. Without going into details of the estimation of the influence of this effect on the spore sedimentation, we note that the characteristic values of the Reynolds number Re at which the "turbophoretic" mechanism of sedimentation is decisive are of an order of magnitude $\mathrm{Re} \geq 10^4$. It should be noted that the process of sedimentation of the coarse fraction of spores undergoes the most dramatic change.

Interaction of Spores. Collisions between the spores determine the nonlinear dynamics of the spore sedimentation in the case of a large concentration of spores. The collision frequency of particles in Brownian motion is determined by the expression

$$K_{\mathrm{B}}(r_i, r_k) = 4\pi kT (r_i + r_k) (B(r_i) + B(r_k)), \tag{11}$$

where r_i and r_k are the radii of colliding spores. As a result of a collision, two particles coalesce to form a new particle (r_j), whose mass and volume are equal to the sum of the masses and volumes of the colliding spores:

$$m_j = m_i + m_k, \quad V_j = V_i + V_k, \quad r_j^3 = r_i^3 + r_k^3.$$

In the case of gravitational coagulation, the frequency of collisions is calculated as

$$K_{\mathrm{g}}(r_i, r_k) = \pi\varepsilon (r_i + r_k)^2 \left| U_{\mathrm{g}}(r_i) - U_{\mathrm{g}}(r_k) \right|. \tag{12}$$

To calculate the collisional efficiency, one can use the well-known expression [13] defining the dependence of this parameter on the sizes of colliding particles:

$$\varepsilon = 0.5 \left[\frac{r_i}{r_i + r_k} \right]^2, \quad r_i < r_k. \tag{13}$$

The collision frequency as a result of the gravitational and Brownian coagulation $K(r_i, r_k)$ is the sum of frequencies that are found by expressions (11) and (12):

$$K(r_i, r_k) = K_{\mathrm{g}}(r_i, r_k) + K_{\mathrm{B}}(r_i, r_k). \tag{14}$$

In the proposed physical model, different sedimentation and coagulation processes are considered to be additive. Combining the expressions for individual physical processes permits obtaining the following equation:

$$\frac{\partial c(r, t)}{\partial t} = S(r, t) - Q(r, t) - [\alpha_{\mathrm{d}}(r) + \alpha_{\mathrm{g}}(r)]\, c(r, t) +$$

$$+ \int_0^r K((r^3 - r'^3)^{1/3}, r')\, c((r^3 - r'^3)^{1/3}, t)\, c(r', t) \frac{r^2}{(r^3 - r'^3)^{2/3}}\, dr' - c(r, t) \int_0^\infty K(r, r')\, c(r', t)\, dr', \tag{15}$$

where $\alpha_{\mathrm{d}} = kTB(r)A_{\mathrm{d}}/(\delta_{\mathrm{d}}V)$; $\alpha_{\mathrm{g}} = \left[\frac{4}{3}\pi\rho_{\mathrm{s}} r^3 gB(r)A\right] \Big/ \mathrm{V}$; and $c(r)$ is the concentration of suspended particles with a radius from r to $r + dr$.

The specification of the sources and drains is given below in the section discussing the numerical model.

Qualitative Analysis. Before proceeding to the discussion of the numerical simulation, it is useful to analyze the physical processes leading to the spore sedimentation on the internal walls of the rooms in the building. The time in which a constant sedimentation rate is established can be found from the equation

$$\frac{4}{3}\pi r^3 \rho_{\mathrm{s}} U_{\mathrm{g}} = 6\pi\nu\rho_{\mathrm{gas}} U_{\mathrm{g}} r, \tag{16}$$

where the time is equal to

$$\tau_{st} \sim \frac{2\rho_s}{9\rho_{gas}} \frac{r^2}{\nu}. \tag{17}$$

For the characteristic values of the quantities $\rho_s/\rho_{gas} \sim 10^3$, $r \sim 10^{-4}$ cm, and $\nu \sim 10^{-1}$ cm^2/sec, the time in which the velocity becomes constant is $2 \cdot 10^{-5}$ sec. Since this time interval is small compared to the lifetime of spores in the room atmosphere, we will assume the spore velocity to be constant during the whole time the particle stays in the room atmosphere. The mean velocity of a spore is determined as

$$U_g \sim \frac{2\rho_s}{9\rho_{gas}} \frac{gr^2}{\nu}. \tag{18}$$

For the above example, U_g = 0.002 cm/sec. The characteristic rate of diffusion sedimentation $U_d \sim D/\delta_d$.

The diffusion coefficient of spores $D = kTB$ can be estimated from the expression for the spore mobility $B = U/F \sim (\nu\rho_{gas} r)^{-1}$:

$$U_d \sim \frac{kT}{\nu\rho_{gas} r\delta_d}. \tag{19}$$

For the values of the quantities $\delta_d \sim 10^{-2}$ cm, $T \sim 3 \cdot 10^2$ K, $\nu \sim 10^{-1}$ cm^2/sec, $\rho_{gas} \sim 10^{-3}$ g/cm^3, $r \sim 1$ μm, and $U_d \sim 5 \cdot 10^{-4}$ cm/sec. It should be noted that $U_d \sim 1/r$. Taking into account the gravitational deposition $U_g \sim r^2$, the gravitational sedimentation becomes the basic process of spore removal, beginning with some radius $r > r^*$ (where r^* corresponds to the condition $U_g(r^*) = U_d(r^*)$). As to the order of magnitude, the particle size r^* is determined by the expression

$$r^* \sim \left(\frac{kT}{\rho_s \delta_d g}\right)^{1/3}. \tag{20}$$

In high-rise buildings, under conditions characteristic for the release of malignant anthrax spores, r^* = 0.3 μm. This is exactly why, for an adequate description of the process of dispersion of pores with $r \sim$ 0.1–1.0 μm, it is necessary to take into account both the gravitational and the diffusion (Brownian) sedimentation. Small spores with a radius $r << r^*$ settle on the walls due to the diffusion, and large spores ($r >> r^*$) settle on horizontal and inclined areas due to the gravitational sedimentation. For example, for a room with a characteristic size $L \sim 5$ m and malignant anthrax spores with a mean radius $r \sim 1$ μm, the removal time τ_{sed} is

$$\tau_{sed} \sim L/(U_g + U_d) \sim 5 \cdot 10^4 \text{ sec} \sim 12 \text{ h}.$$

Collisions between suspended spores leading to their coalescence markedly change the size distribution function of the spores, which affects the sedimentation process. From expressions (11) and (12) the following estimates can be obtained for the collision frequencies in Brownian K_B and gravitational K_g coagulation:

$$K_B \sim \frac{kT}{\nu\rho_{gas}}, \qquad K_g \sim \frac{2}{g} \frac{\rho_s}{\rho_{gas}} \frac{gr^2}{\nu} \frac{\Delta r}{r} r^2. \tag{21}$$

Assuming that the variance of the spore radius Δr coincides in order of magnitude with the mean radius of the particle ($\Delta r \sim r$) and setting $r \sim 1$ μm [14–16], we obtain $K_B \sim 5 \cdot 10^{-10}$ cm^3/sec and $K_g \sim 10^{-10}$ cm^3/sec ($\nu \sim 10^{-1}$ cm^2/sec, $\rho_s/\rho_{gas} \sim 10^3$, $T \sim 3 \cdot 10^2$ K). These estimates show that if the particle concentration is rather high, then it is necessary to take into account the collisions resulting from both the Brownian motion and the ordered motion due to gravity. It should also be noted that because of the strong dependence of the collision frequency K_g on the particle size ($K_g \sim r^4$, $\Delta r \sim r$), the gravitational coagulation becomes dominant for particles with a radius $r \geq 3$ μm. Unlike K_g, the frequency of Brownian coagulation K_B is independent of the spore radius. Comparing the mean time between col-

lisions of spores, which in order of magnitude is equal to 1/(K·sec), and the spore removal time τ_{sed}, one can estimate the particle concentration $C^* \sim c\Delta r$, beginning with which collisions between the spores markedly influence the size distribution function of spores:

$$C \geq C^* \sim \frac{1}{K\tau_{sed}} \sim \frac{1}{5\cdot 10^{-10}\cdot 10^5} \sim 2\cdot 10^4 . \tag{22}$$

If the concentration of spores $C \sim 10^4$ spores/cm^3, then the Brownian coagulation leads to a considerable evolution of the function $c(r)$. If the spore concentration $C >> C^*$, then the mean time between collisions turns out to be much smaller than the time of spore sedimentation on the room walls.

The volume density ratio of the spores and the gas, which is the relative concentration of spores, is equal to the mass ratio of the spores and the gas phase. For a room atmosphere containing suspended spores with a mean radius $r_m \sim 1$ μm, a relative concentration of spores equal to one corresponds to the calculated concentration

$$C^* = \rho_{gas} \Big/ \left(\frac{4}{3}\pi r^3 \rho_s\right) \sim 3\cdot 10^8 . \tag{23}$$

In this case, the volume concentration of particles is $\sim 10^{-3}$ and the volume concentration of the gas phase is ~0.999. It is customary to assume that under these conditions the density of air is equal to its true density. It should be remembered that in calculating this density, it is necessary to perform averaging over the volume. For the gas under normal conditions a volume containing $\sim 10^4$ molecules provides a change in the density by less than 1% and is equal to ~0.1 μm^3 [17]. At a relative concentration of suspended particles equal to one, the edge of the cube a containing 10^4 particles is determined by the formula

$$a/(2r) \sim \left(\frac{\rho_s}{\rho_{gas}}\cdot 10^4\right)^{1/3} \sim 10^2 . \tag{24}$$

Thus, the size of the region for which averaging should be performed upon introduction of the volume density of particles is $a \sim 10^2$ μm at a mean radius of suspended particles of 1 μm. In analyzing the aerosol behavior in the room, this size a is much smaller than the characteristic sizes of the flow and it can be considered as a point. It is also possible to estimate the concentration of spores corresponding to a dense set of particles. In a gas flow with a nondense set of particles, the motion of spores is determined by the aerodynamic forces. In a gas flow with a dense set, the motion of spores is due to the collisions between them. The difference in the description of flows with a dense and a nondense set of spores can be established by means of the parameter $\psi = \tau_a/\tau_c$, where τ_a is the aerodynamic relaxation time; τ_c is the time between collisions of spores. The collision frequency between the spores depends on their concentration and can be estimated by the expression

$$\tau_c \sim \frac{1}{(K_g + K_B)} \sim \begin{cases} \dfrac{\nu\rho_{gas}}{kTC}, & r >> r^* ; \\ \dfrac{9\nu\rho_{gas}}{2\rho_s g r^3 \Delta r C}, & r << r^* . \end{cases} \tag{25}$$

The aerodynamic relaxation time is determined by the time a particle at rest needs to acquire a velocity of the order of 0.5–0.7 of the flow rate. Since the carrier-phase velocity $U \sim$ 10–30 cm/sec, for spores with a characteristic size of ~1 μm the Reynolds number Re << 1 and the formula for the aerodynamic drag force transforms into the known expression for the drag force in the Stokes approximation (Stokes formula). The aerodynamic relaxation time can be estimated in this case as the time during which the spore attains a constant velocity at gravitational sedimentation:

$$\tau_a \sim \frac{2\rho_s}{9\rho_{gas}} \frac{r^2}{\nu} . \tag{26}$$

Using the expressions for the aerodynamic relaxation time (26) and the time between collisions (25), we obtain the following expression for the parameter Ψ:

$$\Psi \sim \left(\frac{\rho_s}{\rho_{gas}}\right)^2 \frac{gr^6 C}{\nu^2}\frac{r}{\Delta r}, \quad r << r^*;$$

$$\Psi \sim \frac{\rho_s}{\rho_{gas}}\frac{r^2 kTC}{\nu^2 \rho_{gas}}, \quad r >> r^*. \tag{27}$$

Thus, if $\Psi < 1$, the spore has enough time to acquire a velocity comparable to the carrier-phase velocity, and its motion is determined by the aerodynamic forces. This condition characterizes the motion with a nondense set of particles. On the other hand, if $\Psi > 1$, then the spore in the time between collisions has no time to get entrained in the flow and its motion is determined by the collisions with other spores. Such a motion is characteristic of a gas with a dense set of particles.

For the air with suspended spores in the ventilation duct, the condition $\Psi = 1$ is attained at the spore density

$$C_\Psi \sim \left(\frac{\rho_{gas}}{\rho_s}\right)^2 \frac{\nu^2}{gr^6}\frac{\Delta r}{r}, \quad r \sim r^*. \tag{28}$$

For the characteristic values of the quantities $\nu \sim 10^{-1}$ cm^2/sec, $\rho_{gas}/\rho_s \sim 10^3$, $g \sim 10^3$ cm/sec^2, $r \sim 10^{-4}$ cm, and $\Delta r \sim r$, the parameter is $C_\Psi \sim 10^{14}$ cm^{-3}. Analysis of the possible scenarios for a terrorist attack on a high-rise building shows that the concentration of spores rarely does not exceed values of $\sim 10^{14}$ cm^{-3} and, consequently, the set of spores is nondense.

An important parameter characterizing the motion of suspended spores in the gas is the Stokes number, which is determined as the ratio of the aerodynamic relaxation time τ_a to the characteristic flow time τ_c:

$$\mathrm{St} = \tau_a/\tau_c. \tag{29}$$

Since the characteristic air-flow rate in the ventilation-duct system usually does not exceed values of 1–3 m/sec, the velocities of the malignant anthrax spores and the carrier phase coincide. As a result, the air flow can be considered as a flow of a one-phase medium with drains and sources. And since the suspended spores represent a nondense set ($\Psi << 1$), their relative concentration in the ventilation system does not exceed unity. Moreover, at low values of the Stokes number ($\mathrm{St} \le 1$) the trajectory methods (sometimes referred to as the methods of sources in cells) can be used to estimate the dispersion of spores, taking into consideration the mass balance of the spores and the air.

Exposure and Estimation of Risk. It is interesting to estimate the exposure and the risk of people getting infected depending on the total number of spores released into the atmosphere in a terrorist act. If the source of malignant anthrax spores is located in the ventilation duct of the building, then a high probability that people will get infected arises only at a certain power of the source, since the increase in the concentration of spores in the rooms of the building due to the continuous action of the source will be compensated by their deposition on the walls of the rooms and removal due to the forced ventilation.

The total number of malignant anthrax spores that get into the human organism in a high-rise building in the case of a terrorist act can be estimated on the basis of the data on the total number of spores released and the exposure time. If the time dependence of the concentration of malignant anthrax spores has been determined, then the mean inhaling dose can be estimated for each floor by the expression

$$d \approx \int_0^\tau dt \int_0^{+\infty} \gamma V_t c\,(r, t)\, dr. \tag{30}$$

If only one microorganism is needed to initiate infection, the dose-response function can be given in the following form [18]:

$$P_i = 1 - \frac{\mathrm{B}(\alpha, \beta + i)}{\mathrm{B}(\alpha, \beta)}, \tag{31}$$

where P_i is the probability that the individual who has inhaled a certain amount of microorganisms "i" will be infected; $B(\alpha, \beta)$ is the beta function. The dose-response function has been obtained with allowance for the distribution of survival probabilities among various microorganisms and the differences in survival probabilities inherent in different individuals [18]. The total number of people that will be infected with malignant anthrax in a terrorist act can be estimated as

$$M \sim \sum_i M_i P_i . \tag{32}$$

The maximum concentration of spores in the building is determined by the mass balance between the spores that enter a room and those removed through the ventilation system and settling on the walls. In the case of a continuously operating source of spores, as a result of the competing processes, after a certain time a constant concentration of spores is established. The maximum spore concentrations and inhaling doses can be estimated using the equation

$$\frac{\partial C}{\partial t} = -(\alpha_\Sigma + \xi) C + \tilde{Q}, \tag{33}$$

where $\tilde{Q}$ is the pore-source power, i.e., the number of new spores entering a room of the building in 1 sec on a per-unit volume basis; $(\alpha_\Sigma)^{-1}$ is the characteristic sedimentation time, determined by the processes of gravitational and Brownian sedimentation; ξ^{-1} is the characteristic time of removal of the spores due to the forced ventilation depending on the air-exchange multiplicity in 1 day (usually 5–6 days) and the portion of the fresh air inflown in each cycle (20–25%, as a rule). As is seen from the given equation, the concentration of spores in a room that has reached a steady-state value with time is determined by the expression

$$C = \tilde{Q}/(\alpha_\Sigma + \xi) . \tag{34}$$

The maximum dose absorbed by an individual during the time τ is approximately

$$d_{\max} \sim \frac{\gamma V_t \tau \tilde{Q}}{\alpha_\Sigma + \xi} . \tag{35}$$

The solution of Eqs. (31), (32), (35) permits estimating the inhaling dose and the number of infected people in a high-rise building.

Numerical Investigation of the Spore Dispersion. The integral equation (15) can be solved only numerically. To this end, it is necessary to represent the size distribution of particles $c(r)$ as a set of monodisperse fractions (form of histograms). This procedure makes it possible to reduce the integral (as to the particle size) equation (15) to a system of coupled (time) differential equations for particles in each class of sizes:

$$\frac{\partial c(r_k, t)}{\partial t} = S(r_k, t) - Q(r_k, t) - [\alpha_\mathrm{d}(r_k) + \alpha_\mathrm{s}(r_k)] c(r_k, t) -$$

$$- c(r_k, t) \sum_{i=1}^{N_0} K(r_i, r_k) c(r_i, t) + \frac{1}{2} \sum_{i=1}^{k-1} K(r_{k-i}, r_k) c(r_{k-i}, t) c(r_i, t), \quad k = 1, ..., N_0 . \tag{36}$$

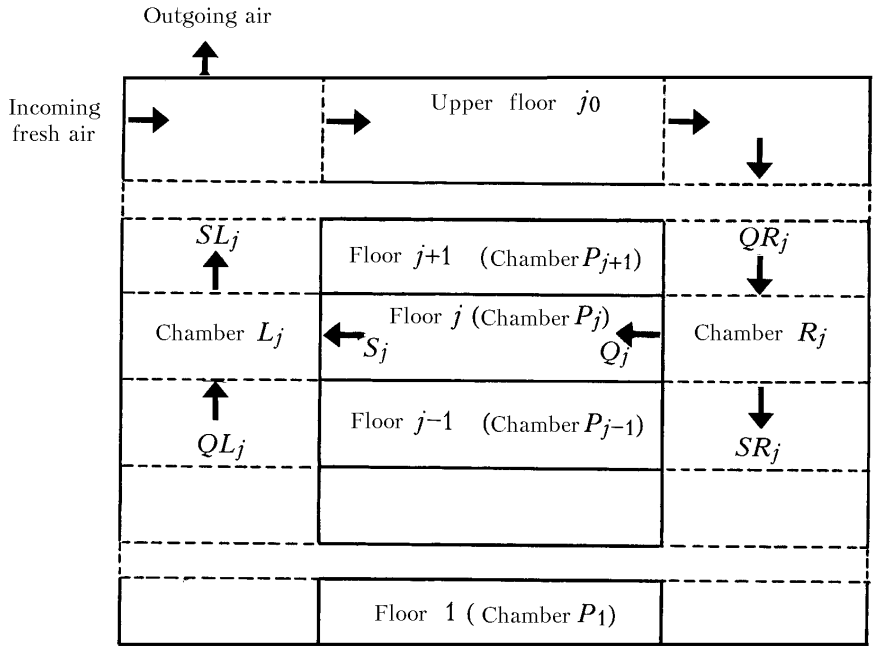

Fig. 1. Scheme of the air circulation in a high-rise building with an active ventilation system.

The system of equations (36) can be solved by the Euler–Cauchy method through a standard program realization. To preserve the numerical stability, the time integration step is calculated in a special subprogram by estimating the values of the first- and second-order time derivatives of the particle concentration. This method is used mainly for controlling the processes of coagulation and removal of spores.

Figure 1 illustrates the air volume in a high-rise building. The air pit can be considered as a set of separate chambers. Each chamber has an air exchange with adjoining chambers and serves as a source or a drain for the others. The source Q_j for the chamber P_j is a drain for the chamber R_j, the drain S_j for the chamber P_j is a source for the chamber L_j. The proposed model permits describing the process of spore spreading in the building no matter the location in the building where spores were released. For each room on the floor there is an air exchange with the outer atmosphere (these air flows are not shown in Fig. 1). Its influence on the total mass balance is minimum when the windows are closed tight. For the results described below, the following estimates were used: the effective density $\rho_{eff} \approx 0.5$ g/cm^3; $\delta_d = 0.01$ cm; the volumes of the air-ventilation chambers were equal to 24 m^3, the air exchange between the chambers L_j, P_j, R_j = 417 m^3/h, and the air exchange with the outer atmosphere for the chamber P_j was equal to 20 m^3/h.

Since all floors of the high-rise building are connected with one another through the ventilation system, the use of an aerosolizer seems to be the most probable way of malignant anthrax spore sputtering. It could be installed in both the air pit and one of the rooms of the building. In the process of circulation, part of the air is replaced by fresh air, as a result of which the recirculating and the fresh air form a downward flow directed to the ground flow. This process of air circulation in the building can be described by means of a number of sources and drains for each floor. Complete renewal of air on each floor occurs approximately five times a day, and the portion of fresh air in each cycle is equal to 25%. The total volume of rooms connected to the air pit is 2000 m^3 for each floor.

The mean logarithmic diameter of malignant anthrax spores used in the numerical simulation was assumed to be equal to 1.18 μm (with a standard deviation of ~1.0 μm) [19, 20]. In the calculations made, it was considered that the initial release of malignant anthrax spores occurs in one of the rooms situated on the ground floor and then the spores spread through the ventilation system and contaminate the building. The initial concentration of malignant anthrax spores on the ground floor was equal to $1.6 \cdot 10^8$ spores/m^3.

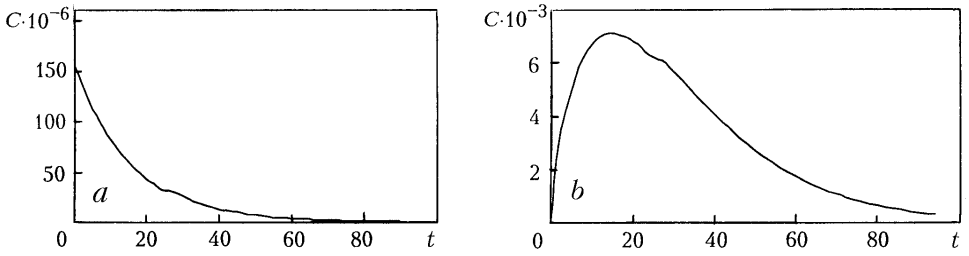

Fig. 2. Time dependence of the concentration of malignant anthrax spores: a) ground floor; b) 50th floor. C, m^{-3}; t, sec.

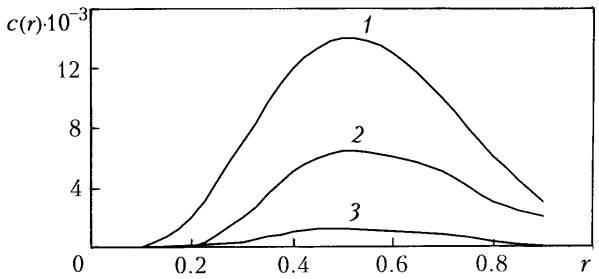

Fig. 3. Time evolution of the spore size distribution function: 1) t = 10; 2) 50; 3) 100 h. $c(r)$, m^{-4}; r, μm.

Figure 2 shows the time dependences of the spore concentration for the rooms situated on the ground floor and the 50th floor. Malignant anthrax spores arrive at the upper floors through the ventilation system, and their concentration on the upper floors is three orders of magnitude lower than on the ground floor. The marked difference between the concentrations of spores on the floors is due to their deposition on the walls and their removal through the ventilation system in the air circulation process. The spreading of spores throughout the building also leads to a decrease in their concentration.

Figure 3 shows the size distribution of spores for different instants of time. As mentioned above, spores with large and very small radii settle on the walls much faster. Thus, the size distribution function of spores changes with time as particles propagate from floor to floor.

The multichamber model used to simulate the spore spreading throughout a high-rise building is based on the assumption of a uniform distribution of spores in each room of the building [4, 20]. While multichamber models are the simplest, they can be used to describe the spreading and sedimentation of aerosols with a fair degree of accuracy. The experiments show that with a proper choice of the form factor of particles, the effective density, the boundary-layer thickness, etc., multichamber models are able to adequately describe the behavior of aerosol [11].

CONCLUSIONS

1. The results of the simulation presented in this paper point to the fact that the differences in the spore sizes and concentrations strongly influence the exposure value and the probability of infection on different floors of the building.

2. In the case where the initial release of spores occurs on the ground floor, their concentration in the rooms on the upper floors is three orders of magnitude lower than on the ground floor. The concentration of spores on the upper floors decreases due to the processes of sedimentation and removal of the spores through the ventilation system of the building. An increase in the volume of the rooms as the spores are spreading throughout the building also favors a decrease in the spore concentration.

3. The time interval needed for rooms to get contaminated increases with the distance of the floor from the site of release of the malignant anthrax spores. And the contamination with spores in the rooms of the building is such that it can infect people. Thus, effective detection of the spores released and timely intervention can considerably restrict the spreading of spores throughout a high-rise building.

4. Treatment of the building with the use of chemical disinfectants, ozone or UV radiation can considerably decrease the contamination of the building. However, the spore resuspension will make disinfection of the building much more difficult and favor a long-term contamination, to overcome which large economic expenditures are required.

5. The analysis performed shows that even a relatively small mass of malignant anthrax spores scattered during a terrorist act in the form of suspended particles has the potential to spread throughout a high-rise building and create such a concentration of spores that it causes infection of people.

6. Taking into account the probable delay in diagnosing the inhaling of malignant anthrax caused by intentional exposure, it is highly probable that infection of people will lead to a high mortality rate. The number of lethal cases will depend on the actual number of infected people and the time that will pass before the beginning of effective medical treatment.

NOTATION

A, area of all surfaces of a room, m^2; A_d, area of horizontal projections of a room, m^2; $B(r)$, spherical spore mobility; $C(r)$, concentration of spores, m^{-3}; $c(r)$, concentration of spores with a radius from r to $r + dr$, m^{-4}; $D(r)$, diffusion coefficient of a spore of size r, m^2/sec; d, mean inhaling dose; F, force acting on the spore, N; g, acceleration of gravity, m/sec^2; k, Boltzmann constant; K, collision frequency of particles; M_i, number of people in the building who have inhaled the ith number of microorganisms, persons; M, total number of infected people, persons; Kn, Knudsen number (Kn = l/r); l, mean-free path of surrounding gas molecules, m; L_j, left air-ventilation chamber; L_T, characteristic size of the temperature change, m; m_i, particle (spore) mass, kg; N_0, total number of fractions of sizes; P_j, central chamber; $Q(r, t)$, source of spores; QL_j, source of the left air-ventilation chamber; QR_j, source of the right air-ventilation chamber; r, spore radius, m; R_j, right-air ventilation chamber; Re, Reynolds number; $S(r, t)$, spore current; SL_j, drain of the left air-ventilation chamber; SR_j, drain of the right air-ventilation chamber; $U(r)$, sedimentation rate of spores; V, volume in which malignant anthrax spores are contained, m^3; V_i, particle volume, m^3; V_t, pulmonary activity determined as the air volume getting into the human lungs per unit time, m^3/sec; T, surrounding gas temperature, K; t, time, sec; x, direction of temperature change; γ, absorption coefficient of spores; δ_d, boundary-layer size, m; ε, collisional efficiency of spores; η and ν, dynamic and kinematic viscosity of the surrounding gas, kg/(m·sec) and m^2/sec; ρ_{gas}, gas density, kg/m^3; ρ_s, spore-material density, kg/m^3; ρ_{eff}, effective density of a spherical spore, kg/m^3; τ, exposure time, sec. Subscripts: a, aerodynamic; B, Brownian motion; c, collision; d, diffusion; sed, sedimentation; g, gravity; gas, gas; eff, effective; i, k, particle (spore) size class numbers; j, floor number; max, maximum; t.ph, thermophoresis; s, spore; st, stationary; m, mean; **n**, normal to the surface.

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