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The Effects of Explosively Venting Aerosol-Sized Particles Through Earth-Containment Systems on the Cloud-Stabilization Height

George W. Dyckes
Transportation Division II. 1714
Sandia National Laboratories
Albuquerque, NM 87185

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Abstract

A method of approximating the cloud stabilization height for aerosol-sized particles vented explosively through earth containment systems is presented. The calculated values for stabilization heights are in fair agreement with those obtained experimentally.

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Introduction

Models for predicting the atmospheric dispersion of radioactive aerosols released from a point source rely heavily on some knowledge of the cloud's stabilization height. In the case of a mixture of radioactive and earth particles of similar size propelled vertically into the atmosphere, the stabilization height is largely dependent upon the thermal and kinetic energy components imparted to the particles by the explosive. Thus, it is important to know the contribution of each component to the total energy of the particles.

Some insight concerning the kinetic energy can be gained by treating the earth and radioactive particles as giant molecules (approximately 10 μm dia) suspended in a gaseous medium. Since in this case we are concerned with very small particles having low Reynolds numbers, the principles for viscous flow (Stokes Law) and accompanying drag phenomena apply. Because the number of particles generated is small compared to the number of gas molecules, their effect on the viscosity of the gases is quite small. It also follows that the mean free path of significance is essentially that determined for the gases. Since the effects of atmospheric turbulence may vary greatly with time and location they were not considered in this work.

The thermal energy component contributing buoyancy to the particles can be approximated by using a simple adiabatic expansion of the gases generated by the explosive (neglects cooling by the earth) and calculating the resulting temperature using the ideal gas law. To illustrate the utility of the above methods for evaluating the kinetic and thermal energy *effects on the cloud stabilization height, 0.1 lb of* explosive was used to disperse 200 g of plutonium under conditions of a single vertical vent through an earth cover 3 ft thick at an exit overpressure of 4 psi. In this case, it was found that the temperature environment for the particles was not high enough to have *a significant effect on the cloud's stabilization height.*

Calculations

Since the exit pressure is known (Figure 1), the initial particle velocity, V_o, of the particle/gas mixture can be calculated from[1]

$$V_o = \frac{C_o P_1}{\gamma P_o}\left[1 + \left(\frac{\gamma + 1}{2\gamma}\right)\left(\frac{P_1}{P_o}\right)\right]^{-1/2}, \qquad (1)$$

where C_o is the sound velocity in air, P_o and P_1 are the ambient and exit pressures, respectively, and γ is the ratio of specific heats for air (1.4). If $P_o = 14.7$ psi (one atmosphere), the initial velocity is 2.1×10^4 cm/s.

Once the initial velocity is determined, the particle travel distance in the atmosphere, S, can be found from the Stokes equation:[2]

$$S = \frac{V_o C D^2_{\rho_p}}{18\eta}, \qquad (2)$$

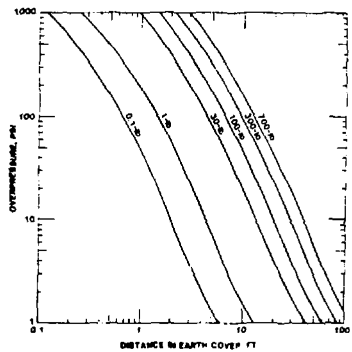

Figure 1. Overpressure in Earth Cover vs Distance from the Explosive (Ref 3)

where C is the slip correction derived from the empirical expression

$$C = 1 + K\left[1.257 + 0.4 \exp \frac{1.1}{K}\right], \qquad (3)$$

D is the mean particle diameter, ρ_p is the particle density, η is the viscosity of the gas/particle mixture, and K is derived from the mean free path particle diameter relationship

$$K = \frac{2\lambda}{D}. \qquad (4)$$

The mean free path, λ, can be approximated as follows:

$$\lambda = \frac{\eta}{\rho_g}\left[\frac{\pi m}{2NkT}\right]^{1/2}, \qquad (5)$$

where ρ_g and m are the density and molecular weight of the gaseous mixture, respectively (chosen values for air), N is Avogadro's number, k is the Boltzmann constant, and T is the temperature of the mixture. As shown below, T was calculated to be 346 K and the constants η and ρ_g were 2×10^{-4} g/cm-s and 2×10^{-3} g/cm^3, respectively, which are slightly higher than the values commonly used for air. This gave a mean free path value of 3.96×10^{-6} cm. The constant K in Eq (4) is found to be 7.92×10^{-3} and the slip correction (Eq (3)) is 1.01; this shows that C for this case is relatively independent of λ.

Although the particle travel distance can be estimated directly from Eq (2), it is also of interest to evaluate this entity as a function of Reynolds number, Re_o (Figure 2):

$$Re_o = \frac{DV_o\rho_g}{\eta}. \qquad (6)$$

Since the Stokes equation (Eq (2)) neglects the increase in drag due to turbulence, it may overestimate the particle travel distance and can thus be considered an upper bound. The work of Bird, et al,[4] which includes turbulence effects, was chosen for a lower bound. Fuchs' analysis of Ingebo's data[5] gives values intermediate to these boundaries.

For approximations of the temperature used in Eq (5), a simple adiabatic expansion of the gases generated by the explosive was done (906 cc/g) using a value of 1.4 for γ:

$$\frac{P_1}{P_2} = \left(\frac{V_2}{V_1}\right)^{\gamma}. \qquad (7)$$

This calculation gave 16.1 L of gas (corrected for the oxygen deficiency of the explosive) at 4 psi overpressure. The exit temperature, calculated using the ideal gas law, was 346 K.

For estimates of the cloud stabilization height, all of the plutonium was considered to be converted to PuO_2 at a particle density (ρ_p) of 11.46 g/cm^3. The Reynolds number for these particles (Eq (6)) is 210. From Figure 2, $\rho_g S/CD\rho_p$ has the following values (solving for S gives the estimated cloud stabilization heights based on the particle travel distance):

	$\rho_g S/CD\rho_p$	S
Upper Limit	11.8	68.2 cm (2.2 ft)
Intermediate	5.2	30.1 cm (1.0 ft)
Lower Limit	3.0	17.[illegible] cm (0.6 ft)

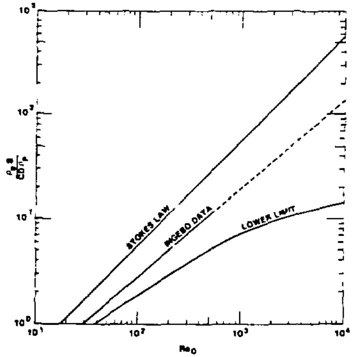

Figure 2. Particle Travel Distance vs Reynolds Number

Experiment

Several experiments[6] were conducted to characterize the pressure attenuation properties of lightly compacted earth of various hemispherical thicknesses placed over hemispherical surface charges of composition C-4 explosive (Figure 3). Several of these experiments vented explosive decomposition products and earth vertically into the atmosphere. The puffs generated in these instances only traveled a few feet (3 to 6) before most of the material fell back on the mound. The fine particles that remained suspended in the atmosphere moved laterally away from the mound before ascending slightly and dispersing into the atmosphere. The behavior of the vented material indicated the suspended particles had very little thermal or kinetic energy, as shown by the previous calculations. However, the temperature used in the calculations needed experimental verification.

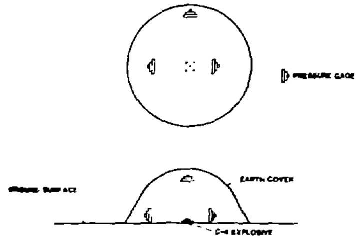

Figure 3. Earth Containment Test Configuration

A simple experiment (Figure 4) was devised where temperature measurements could be taken as a mixture of gas/earth/simulated PuO_2 was propelled into the atmosphere by composition C-4 explosive. One-mil-diameter chromel/alumel thermocouples were placed at three stations in the vent tube to provide information on the temperature gradient developed as the mixture moved out into the atmosphere. After installing the thermocouples, the tube was carefully filled with oven-dried alluvium which had been passed through a 0.5-in. mesh screen. Red iron oxide powder (100 g) which had an average particle diameter of 0.06 μm was placed on top of the explosive to simulate the plutonium oxide along with 100 g of copper powder which was used as a tracer material for air sampling. A cascade impactor air sampler array was placed several feet downwind from the experiment for estimating the cloud density. Neutron activation was used to analyze the amount of tracer collected on the filters. A 45.4-g (0.1-lb) hemispherical charge of explosive was centered underneath the vent tube. After bolting the aluminum hemisphere/vent tube assembly to a concrete pad, an earth cover 3 ft thick was placed over the assembly to hold it down. The temperature data were recorded on a multichannel tape recorder having a 1.5-MHz direct record capability.

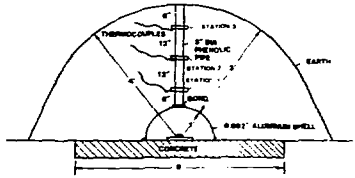

Figure 4. Dispersal Test Configuration

Results

At detonation, a slender plume of C-4 decomposition products and earth with tinges of red color was expelled into the atmosphere. Most of the material fell back to its original location, and only a very low density cloud of small particles drifted into the air sampler. Analysis of the filters revealed a few micrograms of tracer material present.

Temperature measurements at the three stations on the vent tube were as follows:

Station	Temperature (K)
1	392
2	379
3	353

The temperature (346 K) derived from the adiabatic expansion of the gases from the explosive was close to the temperature (353 K) measured near the exit point into the atmosphere. Both temperatures are too low to impart significant thermal buoyancy to the particles. Since temperature has only a small effect on the slip correction in Eq (2), the previous estimates of the cloud stabilization height based on the particle travel distances are essentially unchanged. However, these numbers are not as high as expected based on experiments[6] cited previously which gave cloud heights of 3 to 6 ft at venting pressures between 5 and 6 psi.

Conclusions

A method for approximating the cloud stabilization height based on calculations of the particle travel distance was developed for the case of venting through a fairly large body of earth. Compared with experimental measurements, the mathematical model gives values which are somewhat low (2.2 ft for the worst case obtained from the model). Further refinements in the model will be made as a better understanding of the particulate behavior under venting conditions is developed.

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