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AN UNDERGROUND
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WITH EJECTION OF
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GEOPHYSICS

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Abstract

Full Text

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GEOPHYSICS

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**CONDITIONS FOR THE FORMATION OF
RADIOACTIVE FALLOUT PARTICLES AND
ISOTOPE FRACTIONATION IN AN UNDER-
GROUND NUCLEAR EXPLOSION WITH
EJECTION OF SOIL**

(Presented by Academician E. K. Fedorov, 9 XI 1965)

The conditions for the formation of radioactive fallout particles in an underground nuclear explosion with ejection of soil, and their isotopic composition, differ substantially from those in surface and air bursts (¹⁻⁵). This is due to the distinctive features of the temperature regime in the cavity of an underground nuclear explosion during its development and venting (for a shallow depth of burst), as well as in the radioactive cloud, which lead to changes in the fractionation coefficients.

In an underground nuclear explosion, by the end of the hydrodynamic phase (several tens or hundreds of milliseconds after the explosion (^{2,6})) the cavity walls are covered with molten rock (500-600 tons per 1 kt of explosive yield (^{2,6,7})). The temperature in the cavity at this time is higher than the melting temperature of the rock and lower than its boiling temperature (^{4,6}).

In an explosion near a free surface, at the moment t_g (Fig. 1) the layers of rock located between the cavity and the ground surface acquire additional acceleration (the gas-acceleration phase). At $t_v \approx 1-2$ sec after the explosion (for a scaled depth of burst of $40-60 \text{ m/kt}^{1/3.4}$ and a yield of 1-100 kt), gases break through into the atmosphere (^{2,8}). The gas-acceleration phase is especially important in the case of an explosion in rocks with a high water content, for example, in alluvium and tuff.

Let us estimate the change in volume, pressure, and temperature in the venting cavity for a 100-kt nuclear explosion in alluvium with a scaled depth of $50 \text{ m/kt}^{1/3.4}$ (of the "Sedan" type) (²). The water content in such rock is taken to be 10% (by weight).

The radius of the cavity (the lower part of the hemisphere) is calculated on the basis of a one-dimensional hydrodynamic model of the response of an elasto-

Figure 1

Figure 1: Figure 1

plastic geological medium to an explosion ⁽⁷⁾. The configuration of the cavity above the explosion horizon and the topography of the free surface during the gas-acceleration phase are determined on the basis of a calculation of the motion (acceleration) of elementary volumes (masses) of soil in accordance with Newton's second law, taking friction forces into account, calibrated for the 0.5-kt "Scooter" chemical explosion ⁽⁸⁾.

In the calculation, assumptions stated in various works were adopted:

- a) about half of the explosion energy (32-47%) is spent on heating and melting the rock ^(4,6);
- b) melting and vaporization of the soil (and, consequently, of the water contained in it) occur mainly within the initial cavity (at the moment t_c) ⁽⁸⁾;
- c) the temperature and pressure are the same at every point of the cavity ⁽⁸⁾;
- d) the rock above the cavity has the properties of a homogeneous incompressible liquid ⁽⁸⁾;
- e) the melting temperature of rocks is about 1500°C; for a water content in the rock of 15%, the enthalpy for the molten state is 700 cal/g ⁽⁶⁾.

In addition, by analogy with a surface burst (4), we assumed the presence of thermodynamic equilibrium between the liquid and vapor phases and the validity of Raoult's law inside the cavity.

According to the calculation, the radius of the initial cavity reaches 45 m after several hundred milliseconds, and the volume $V_c = 3.9 \cdot 10^5 \text{ cm}^3$; the cavity walls will be covered with $6 \cdot 10^4$ tons of molten rock (2), and there will be $6 \cdot 10^3$ tons of water in the evaporator cavity.

By the time the gases break through (1.7-2.0 sec), the volume reaches $V_v = 1.1 \cdot 10^7 \text{ m}^3$, and by the time of maximum rise of the rock fragments due to the spalling action and gas acceleration to a height of 130-150 m—about $1.8 \cdot 10^7 \text{ m}^3$ (V_{\max}).

Fig. 1. Dependence of the vertical velocity of ascent of soil particles at the earth's surface at the epicenter of an underground explosion on the time after the explosion. 1—"Scooter," alluvium, $E = 0.5 \text{ kt}$; 2—"Sedan," alluvium, $E = 100 \text{ kt}$; 3—"Danny Boy," basalt, $E = 0.42 \text{ kt}$

The calculation of the temperature regime in the cavity was carried out under the assumption that the gas expands adiabatically during the time interval Δt , but at the same time, owing to heat inflow from the molten soil, it is heated to

the temperature of the latter. The polytropic exponent during gas expansion, according to the data of work (8), is $\gamma = 1.03$. According to the data of work (9), in the temperature and pressure interval under consideration the ratio of the heat capacities of water vapor is $c_p/c_v = 1.2$. The pressure in the cavity, taking account of the thermal expansion of the gases, at the moment t_c will be 125 bar, and at the moment t_v —about 5 bar (for $\gamma = 1.03$).

The work performed by the gas in the cavity during its adiabatic expansion (over successive time intervals Δt) from the initial volume V_c to the maximum V_{\max} is about $1.9 \cdot 10^{20}$ erg (for $\gamma = 1.03$) or $1.4 \cdot 10^{20}$ erg (for $\gamma = 1.20$), and, taking into account the breakthrough of gases beyond the cavity at the moment t_v , still less. On the other hand, during solidification of the molten rock (owing to the latent heat of fusion) more than $2 \cdot 10^{20}$ erg of energy will be released (even if the temperature at the moment t_c is no more than 1500°C). In this connection, the temperature of the incandescent gases during expansion of the cavity to the volume V_{\max} will not fall below 1500°C , since heat losses in the cavity due to radiation and thermal conduction are insignificant (6).

Such constancy of temperature before the breakthrough of the cavity will occur for underground nuclear explosions with ejection of soil over a wide range of yields (up to 100 kt), conducted in rocks with a water content of approximately up to 10–15%. It was precisely this feature of the temperature regime that was not taken into account in predicting the rise height of the cloud in the “Sedan” explosion; it was assumed that the temperature of the gases at their breakthrough would be considerably lower. In this connection the predicted cloud height proved to be 4 times less than the actual one (3).

After breakthrough into the atmosphere, the incandescent gases begin to rise. The rate of ascent of the gas bubble due to Archimedean buoyancy will exceed the rate of rise of the rock 4–5 sec after the explosion. Final separation of the bubble will occur after the rock fragments fall downward and a significant part of the gas volume located inside the cavity is released (i.e., 6–14 sec after the explosion), after which cloud formation will begin.

The cloud will rise analogously to the rise in surface or air bursts. The change in temperature in the cloud, calculated

according to the scheme proposed in [10], is shown in Fig. 2. Approximately 5 min after the “Sedan” explosion the cloud stabilized, reaching an altitude of 4000–4500 m [2]. Unlike an air burst, the cloud of an underground explosion with ejection of soil, especially in its lower part, contains an enormous amount of dust and soil particles, which impedes the removal of heat from the cloud by radiation (although it may lead to a lowering of temperature through mixing with dust particles). The base surge, overtaking the lower part of the bubble of hot gases, also helps to maintain a high temperature for a long time.

Thus, the base surge and the lower part of the cloud constitute a zone in which, for a long time—no less than 5–10 sec for explosions with yields of 1–2 kt and

Fig. 2. Change in temperature in the cloud of an underground explosion with time after the explosion

Figure 2: Fig. 2. Change in temperature in the cloud of an underground explosion with time after the explosion

6–14 sec for an explosion with a yield of 100 kt (i.e., considerably longer than in a surface burst)—a temperature on the order of 1500°C is maintained.

Fig. 2. Change in temperature in the cloud of an underground explosion with time after the explosion

Under the temperature regime described, the molten rock inside the cavity, entraining radioactive products, may break up into separate molten particles; from it there may form individual slag-like formations in the zone of the explosion crater and, probably, finer particles of irregular shape. If thermodynamic equilibrium is maintained in the cavity, it should be expected that in such particles the radioactive products will be distributed uniformly throughout the volume. Soil particles at temperatures close to 1500°C may melt or soften somewhat and firmly entrain the more refractory isotopes. In such particles the radioactive products will be concentrated in the outer volume layer. Volatile isotopes will be deposited on the surface of particles that remained in the cloud or in the base surge after their cooling.

In accordance with the calculated temperature, it is possible to estimate the fractionation coefficients in the various zones for an explosion of the type described in [11, 12].

The estimates made show that the greatest fractionation will be observed in the upper part of the cloud (and it is enhanced there when large particles fall out); less fractionation may be expected on the near trace, and the minimum—in the crater zone, where fallout occurs from a zone that retains a high temperature for an especially long time.

The limited experimental material available confirms these conclusions. In fallout near the crater (up to 5.7 km from the epicenter) from the “Sedan” explosion, no substantial fractionation was detected. In this fallout the activity is practically proportional to the mass, especially for particles larger than 100 μ [13]. A large enrichment in volatile isotopes, especially I^{131} , is observed in the explosion cloud [14–16]. Samples taken in the cloud during the “Danny Boy” explosion (from 8 min to 2 h after the explosion) indicate a steadily increasing enrichment with time of Sr^{89} , Sr^{90} , Cs^{137} in comparison with refractory isotopes, which testifies to a higher fallout rate of refractory products; the enrichment coefficient of products in the cloud by the isotope I^{131} at a distance of about 100 km from the epicenter reached a value of 2–6 [16]. In [16] it is stated that in local fallout there is enrichment in volatile isotopes, compared with refractory ones, by a factor of 3–5.

For comparison, we note that the enrichment coefficients of isotopes, for radionuclides having volatile precursors, in the local fallout from surface megaton explosions reached the following values: for Te^{132} 6, Ba^{140} 12, Sr^{90} 30, Sr^{89} and Cs^{137} 60 [17], i.e., they had significantly larger values than in analogous zones for an underground nuclear explosion.

Thus, the calculations carried out in the present work have shown that, in the breakthrough cavity of an underground nuclear explosion with ejection of soil, for a long time (considerably longer than in the fireball of a surface explosion) a high temperature is maintained, equal to the melting temperature of the soil (1500°C). This explains the weak fractionation of the radioactive products of an underground explosion with ejection of soil in local fallout.

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