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DTRA FOIA
Case Number
02-050

JUN 2 3 2005

Mr. John Greenewald, Jr.
[redacted]

Dear Mr. Greenewald:

This is in response to your April 25, 2001 Freedom of Information Act (FOIA) request to the Defense Technical Information Center (DTIC), which was transferred to the Defense Threat Reduction Agency (DTRA), who transferred it to Department of Energy (DOE), for review. Because the record that you requested potentially concerns weapons of mass destruction or could be related to homeland security, DTRA forwarded it to this Office for review on May 10, 2004.

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FOIA Office
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Ft Belvoir, VA 22060-6201

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Sincerely,

C. Y. Talbott
Chief

Enclosures:
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A SEARCH FOR CONFINED FIREBALLS IN THE ATMOSPHERE (U)

PLESSET (E H) ASSOCIATES INC SANTA MONICA CA

05 DEC 1962

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by

Harris Mayer
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Prepared for
Department of Defense
Defense Atomic Support Agency
Washington 25, D. C.

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TABLE OF CONTENTS

ABSTRACT

The rise of bomb debris from a nuclear explosion at between 50 and 150 kilometers altitude has been studied for the purpose of ascertaining whether the fission fragments can be effectively confined so as to cause presistent local radar blackout as a penetration aid. There are four different cases of debris rise depending on differences in the important mechanism of energy deposition, in bomb debris mixing with ambient air, and in the heated air rise.

1.) Low altitude. Total bomb energy is deposited locally, the initial expansion is spherical, cloud rise is determined by late buoyancy, fission products rise and are mixed in cloud.

2.) Altitudes 60 - 90 km. Total bomb energy is deposited locally. The initial expansion is very assymetric, a shotgun effect ejecting a fraction of the heated air upwards at high velocity. The fission products are almost all in the ejected material. The velocity of ejection increases with increasing altitude. Confinement is not achieved.

3.) Altitudes of 100 - 125 km. Only hydrogynamic energy, about 1/4 of bomb yield, is deposited locally. The mechanism of cloud rise is similar to 1.

4.) Altitudes of 125 - 150 km. Hydrodynamic energy only is deposited locally. Initial expansion assymetric. The shotgun effects ejects a portion of the fission products upwards with high velocity, the velocity increasing with increasing altitude of the burst point. The remainder of the heated air containing a significant factor of the fission products has an initial downward acceleration. The later distribution of this portion of the cloud is not treated in this report, but appears to be the one possibility for causing local blackout of long duration.

SECTION 1

INTRODUCTION

An important ICBM penetration aid is the radar blackout caused by the ionization produced by the beta rays emitted by the fission products of a nuclear explosion. Quantitatively the problem is not well understood; what is least known is the location and motion of the bomb debris, which motion determines the extent, intensity, and duration of the blackout effect. The experimental investigation of this effect has been carried out through several high altitude nuclear tests in the Pacific, including TEAK and ORANGE in 1948, and BLUE GILL, STARFISH, and KINGFISH in the current 1962 series.

Historically the physics concepts of blackout have developed in the following manner. [redacted] The initial ionization intensity was more than sufficient to produce the effect; in fact some betas were simply wasted by overionization in small regions. The debris cloud both rose with a rather rapid velocity (about 2 km per sec) up to an altitude of 500 km., and expanded laterally during its rise so that its radius was also about 500 km. After this rise the ionization was spread over so large an area that it was not sufficiently intense to cause effective radar blackout.

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b(3)

In order to produce radar blackout more effectively by, (1), using the betas more efficiently, (2), preventing local over-ionization initially, and (3), avoiding the rapid rise and dispersion of the debris which lead to under-ionization at later times, A. Latter and R. Lelovier at Rand conceived the "Pancake" configuration, which was tested in STARFISH. Although the specific STARFISH event failed to form a pancake due to assymmetry in the nuclear explosion, the test did not disprove the logic of the Pancake concept, which says that for a shot high enough in the atmosphere, the bomb debris initially will expand unimpeded so that in less than a second the lower hemisphere of debris will be deposited in a layer or pancake in the atmosphere at a depth corresponding to the range of the debris ions. The initial wide distribution of debris avoids local over-ionization and results in an energy deposition which may be low enough so that the pancake will not expand hydrodynamically to any great extent, thus preventing underionization at late times.

The significant question which should be examined, however, is whether or not there is a type of atmospheric explosion intermediate in character between TEAK and the Pancake, which combines the most effective features of both to cause local but long lasting blackout. LeLevier reasons that a small enough explosion at the appropriate altitude, probably above TEAK but in the 110 - 130 km. range, would be confined by the atmosphere initially, but would deposit energy with so low a density that late hydrodynamic motion would not be able to disperse the debris cloud. The fission products would remain localized, causing high ionization immediately below at 60 to 90 km. altitude, and would remain for a few minutes, which is long enough to be an excellent penetration aid.

In this paper the possibilities and effects of such an atmospheric explosion are explored, from the theoretical point of view. All the work reported here was carried out before the 1962 Pacific tests, and it was done not so much to resolve the question, as to determine promising altitudes and yield. As a result the calculations are quite crude. With the limited effort which it was possible to put into this work, a definitive answer was not obtained. The calculations themselves show that a portion of the debris cloud always expands and rises rapidly, and in most cases this portion contains all the fission fragments. For explosions in which the local energy deposition is due to the bomb debris themselves, at altitudes in the neighborhood of 125 km, a portion of the cloud which contains a large fraction of the fission products may remain relatively stationary. However the numerical calculations were not directed towards following this portion of the cloud. Therefore the validity of the conclusion is in doubt. However, the work does indicate that some of the effects in the debris rise are relatively unimportant and may be helpful in that sense to persons interested in more elaborate calculations.

SECTION 2

PHYSICS OF THE CLOUD RISE

2.1 Inadequacy of Equilibrium Treatment

Depending on the altitude of the explosion, a variety of mechanisms account for the manner in which a nuclear bomb deposits energy in the surrounding atmosphere. After the energy is deposited and distributed the resulting heated air must rise to its equilibrium position in the atmosphere, and the altitude to which it will rise, as determined by equilibrium considerations for an adiabatic expansion, will depend upon the manner in which the atmosphere deviates from the adiabatic gradient. The heated air produced in the lower stratosphere has a large rise, because it originates in a region of dry adiabatic equilibrium and therefore of neutral stability, but in the higher stratosphere, where because of the absorption of solar energy the temperatures are greater than those present under conditions of the true adiabatic gradient, the rise is less.

Although the equilibrium argument is sufficient to explain the cloud rise for most sea level explosions, a more detailed treatment of the actual processes of expansion and rise is necessary to describe correctly the radar blackout effect from high altitude explosions. For this case the scale of the entire phenomena is so large, and the significant time intervals so long, that the rate of cloud rise, particularly if slow, is more important than the ultimate location of the cloud. One must then reformulate the question so as to ask not for the ultimate destination of the bomb debris but rather whether the bomb debris remain fairly localized long enough so that the local blackout is effective as a penetration aid. The conclusion to be drawn, therefore, is that the detailed aerodynamic motions of the cloud, which are exceedingly violent in the initial stages, must be studied. Furthermore, with the low atmospheric densities and high initial temperature of the bomb heated air, radiative transport becomes an important mechanism, and because the cloud rise is not purely adiabatic, a discussion based upon an adiabatic assumption will be misleading.

2.2 Energy Deposition and Early Expansion

The major fraction of the energy of a nuclear explosion is emitted in the form of soft X-rays in the 1 to 10 kev energy range. These soft X-rays are absorbed by air molecules, with absorption lengths of about a meter at sea level, a few hundred meters at the altitude of ORANGE, and a few kilometers at TEAK altitude, and they escape to large distances for explosions above about 100 km. Wherever the absorption of energy is great the air is heated and reradiates. Most of the remaining energy of the explosion is kinetic energy of the bomb materials. Below about 150 km. the bomb particles snowplow into the air, causing a strong hot shock which reradiates X-rays of lower energy than the initial bomb X-rays. Above 150 km. the particles are unimpeded by the air. Therefore, below 100 km. essentially all of the bomb energy is rapidly converted into soft X-rays which, as a radiation front, eat into the cold atmosphere, creating an isothermal region behind the front due to the very rapid radiative transport there. This phase persists until the temperature of the isothermal region becomes low enough so that the opacity behind the front rises and stops radiative transport, or until the emissivity drops to a low enough value so that not much energy is converted into radiation. Only then does hydrodynamic expansion begin to play a role.

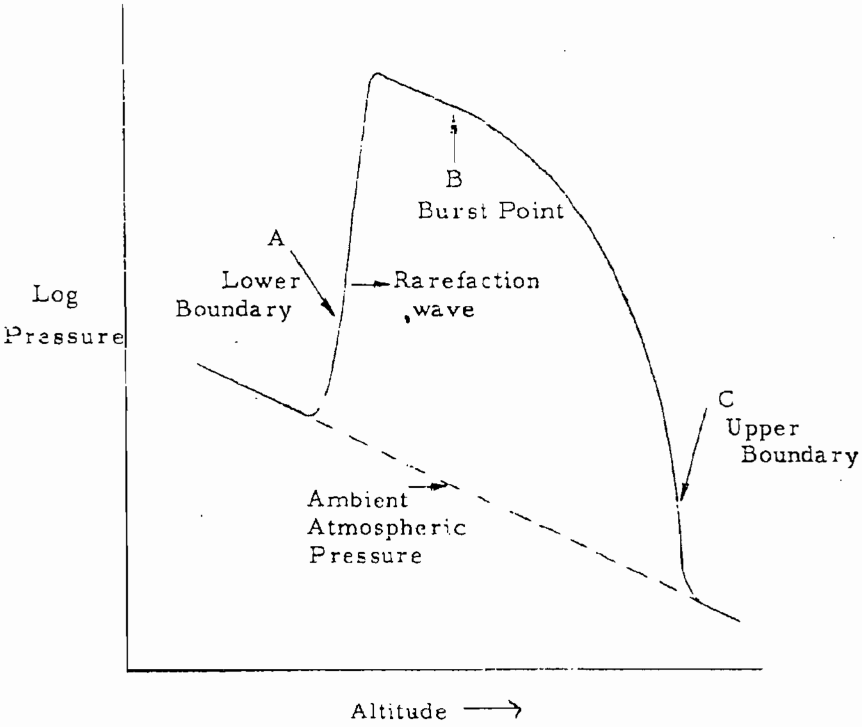
For explosions between 100 and 150 km., the energy of the initial bomb X-rays escapes, but the energy from the bomb debris is distributed in the same fashion as is the total energy for the lower altitude explosions. Above 150 to 200 km., the bomb debris do not interact locally with the atmosphere. In the upward hemisphere the debris escape the atmosphere, but those which are ionized are controlled in their motion by the geomagnetic field. In the downward hemisphere the debris are trapped by the atmosphere at about 150 km. Since the initial dispersal of the debris is not limited by atmospheric interactions, it occurs very rapidly. The entire range of effects of this type of above-the-atmosphere explosion is outside the subject of this report.

Even at the highest altitude considered here of 150 km., the later stages of the bomb expansion are truly hydrodynamic, since the dimensions of the isothermal region are much greater than the mean free paths of the air molecules. Much of the phenomena then is common to all types of expansions. A strong divergent shock develops around the isothermal region, and particle velocities behind the shock are high, causing a region of density lower than ambient to be formed inside the shock.

Initially the expansions are almost spherical in most cases. For altitudes considerably below about 100 km., the X-ray mean free path is less than the atmospheric scale height so that energy deposition and therefore pressure are spherically symmetric. Somewhat above 100 km. but below about 150 km. the X-rays escape the atmosphere, but the range of the bomb debris is then less than the scale height, and the configuration and motion are again quite spherical. At intermediary altitudes, say 80 - 100 km. or 130 - 150 km., where there is considerable variation in ambient density in the region of energy deposition, decidely non-spherical expansion occurs.

2.3 Assymetric Motions - The Shot Gun Effect

When the energy deposition from the nuclear explosion covers an altitude range comparable to the atmospheric scale height, the expansion will be very assymetric. Immediately after the energy deposition the pressure vs. altitude profile is as follows (See Sketch). Far below the explosion the pressure is ambient. At about one energy deposition length below the burst point, (one effective X-ray mean free that below 100 km. explosions or one mean range for debris material above 100 km. explosions) the pressure will increase very rapidly to a high peak. From this point upwards for a considerable distance, the temperature attained by the heated air will be equalized by rapid energy transport and the pressure will decrease exponentially with altitude because the density, still at ambient values, decreases exponentially. Temperatures of the order of 1 volt occur, compared with ambient temperatures of 1/50 volts, so that the pressures are



about 50 times the ambient. Beyond a similar length above the burst point, the pressure will start to return to its ambient value.

Except near the lower boundary of the deposited energy, the pressure gradient will cause particles to be accelerated initially upward. Near the lower boundary, however, (point A of the Sketch) the material will accelerate downward and a rarefaction wave will propagate upward, reducing the pressure as it proceeds. The direction of acceleration of a particle is reversed when it is overtaken by the rarefaction. The reverse acceleration lasts until the upward moving rarefaction meets its counterpart moving downward from the expansion of the upper boundary, point C. As a result the lower regions will experience the upward acceleration for a short time, the downward for a longer time and hence then will acquire a net downward velocity.

For the upper regions the initial pressure gradient causing upward acceleration is reduced by the rarefaction eating in from above, so that the accelerations at a point last only as long as the sound transit time from the upper boundary to the point in question. Therefore the debris at some point in the interior, probably in the neighborhood of the burst point, will receive the highest upward velocity and be projected up and out of the immediate surrounding atmosphere. This phenomenon has been termed the "shot-gun" effect.

Alternatively, the shot-gun effect may be understood by considering the conservation laws. In the early expansion, the bomb generated pressures in the atmosphere are so high compared to ambient, that the reaction of the outer atmosphere can be neglected. In the subsequent motion of the heated air, its center of gravity remains fixed, and the lower portion containing most of the mass moves downward. The upper portion, which contains little mass, but which, significantly, contains the important bomb debris for X-ray deposition explosions, is shot upward, in accordance with momentum conservation. Because of the lesser mass, the velocities upward are much higher.

2.4 Analytic Treatment of the Shotgun Effect

A rough analytic formulation can be given for the shotgun acceleration and the velocity attained by the debris. Consider motion in the verticle Z direction only. Then the hydrodynamic equation of motion is

$$\ddot{Z} = -\frac{\partial P}{\partial Z} - \rho g \qquad (1)$$

where ρg is the body force due to the acceleration of gravity g. As discussed above, the pressure after energy deposition will be much higher than the ambient pressure P_a, but will vary exponentially with altitude in the region of the burst point with the ordinary atmospheric scale height H.

Then

$$\frac{dP}{dZ} = -\frac{P}{H} \tag{2}$$

The density ρ has not had time to change from ambient. For the undisturbed atmosphere in hydrostatic equilibrium where equation(1) also applies, but with $\ddot{Z} = 0$,

$$\frac{dP_a}{dZ} = -\rho g. \tag{3}$$

But similar to (2)

$$\frac{dP_a}{dZ} = -\frac{P_a}{H} ,$$

so that

$$\rho = \frac{P_a}{Hg} . \tag{4}$$

Then substituting from (2) and (4) into (1) the acceleration becomes

$$\ddot{Z} = \frac{P}{P_a} g - g , \tag{5}$$

Usually P/P_a is very much greater than unity and the second term will be neglected in what follows.

The very hot air behaves like a polytrope gas with

$$\frac{P}{\rho} = (\gamma - 1)\varepsilon \tag{6}$$

where ε is the internal energy per unit mass. If a fraction f of the total yield of the bomb W is deposited or distributed by transport in a sphere of radius R_o, the average energy per unit mass will be

$$\varepsilon = \frac{Wf}{\frac{4}{3}\pi R_o^{3}\rho} . \tag{7}$$

The acceleration is then

$$\frac{\ddot{Z}}{g} = (\gamma - 1)\frac{\varepsilon\rho}{P_a} = \frac{(\gamma - 1)}{P_a}\,\frac{Wf}{\frac{4}{3}\pi R_o^{3}} \tag{8}$$

The acceleration lasts a time τ of the order of the sound transit time across the typical dimension of the system R_o so that the shotgun velocity will be

$$v = \ddot{Z}\tau = \ddot{Z}\frac{R_o}{a} \tag{9}$$

where a is the sound velocity in the heated air. Now

$$a^2 = \gamma\frac{P}{\rho} = \gamma(\gamma - 1)\varepsilon. \tag{10}$$

Therefore

$$v = \frac{g\rho}{P_a}\left\{\frac{(\gamma - 1)\varepsilon}{\gamma}\right\}^{1/2} R_o = g\,\frac{\rho}{P_a}\left\{\frac{\gamma - 1}{\gamma}\,\frac{Wf}{\frac{4}{3}\pi\, R_o}\right\}^{1/2} \tag{11}$$

By the perfect gas law $\rho/P_a = \overline{M}/RT_a$, where $\overline{M}$ is the mean molecular weight and T_a the ambient temperature. This factor varies by only a factor of two or three over the entire altitude range considered.

In some cases, particularly for small yield weapons, the quantity ρR_o is the inverse mass absorption coefficient for the initial energy deposition. This is independent of altitude, except insofar as the agency of importance for energy deposition, X-rays, or bomb debris, is different at low than at high altitudes. One concludes therefore that for a particular bomb the shotgun velocity itself is approximately a constant well below 100 km. where the X-rays are important, and is also constant but considerably larger well above 100 km. where bomb debris are important. But nowhere does there exist a region where the shotgun velocity is very small.

In the more important case, however, which occurs for large yields, the energy initially deposited is rapidly spread by radiative transport, which continues until the temperature or energy density per unit mass ε reaches a characteristic value ε_o, which determines the initial radius R_o to which the shotgun calculation applies. From (7) then

$$R_o = \left(\frac{Wf}{\frac{4}{3} \pi \rho \varepsilon_o} \right)^{1/3} \qquad (12)$$

and from the first equality in (11)

$$v = g \frac{\overline{M}}{RT_a} \left(\frac{\gamma - 1}{\gamma} \right)^{1/2} \varepsilon_o^{1/6} \left(\frac{Wf}{\frac{4}{3} \pi \varepsilon_c} \right)^{1/3} \qquad (13)$$

Equation (13) exhibits a decided dependence of the velocity on altitude through the $\rho^{-1/3}$ factor. The velocity in this case increases exponentially with increasing altitude of the detonation.

2.5 Location of the Debris in X-Ray Deposition Explosions

Initially the bomb debris are at a higher temperature and higher density than the surrounding air; the acceleration of the debris is therefore Taylor stable and mixing with the air does not occur. An expansion of the debris to a density lower than the air rapidly occurs, however, and a Taylor instability develops. A mixed air-debris region is then formed. But this condition for mixing also is short lived. The debris-air mixture is decelerated in its outward expansion by the heavier air, again a case of Taylor stability. Decidely incomplete mixing results.

At somewhat later stages, the material near the vertical axis of the cloud containing the bomb-debris is accelerated upward by the "shot-gun effect" discussed in Section 2.2 Velocities on the axis will be highest, becoming progressively less off-axis, and as a consequence, there will be a shear between layers. The shear flow will develop Helmholtz instability, and air free of bomb debris will be entrained with the central core containing the debris as the latter rises. The mixing of fission products with the air, started by the early Taylor instability, will now be carried on very much further, but is no doubt incomplete. For total mixing to take place it requires the formation of a complete vortex, a still later development.

For explosions for which the X-ray energy escapes, the bomb debris are intimately mixed with the entire mass of initially heated air, since of course the debris themselves are the cause of the heating. The material projected upward in the shot-gun effect consists of air mixed with debris, although a large fraction of the total debris is not contained in the shotgun jet, but remains behind. Furthermore the mechanism of Helmholtz instability and vortex formation will cause the entrainment of additional air, further diluting the bomb debris, in accordance with the mechanism just discussed for X-ray deposition explosions.

2.6 Later Stages of Expansion - Buoyancy Effect

There is no definite termination to the shock expansion stage described in Section 2.2. The shock grows weaker as it diverges; the temperature behind the shock is not greatly above the ambient, and the outward velocity behind the shock decreases. The very sharp boundary of the fireball so apparent to the observer denotes nothing more than the position where the shock is no longer strong enough to heat the air to reradiation in the visible. Finally the shock degenerates to sonic, and no further energy is deposited by it. The boundary of the mass of hot, low density air which is involved in the cloud rise is some indefinite region beyond the visible fireball, but not extending out as far as the radius at which the shock is sonic.

The prevailing radially divergent motions of the air cease soon after the internal pressures are reduced to ambient. At this time a large region of air is in hydrostatic pressure equilibrium with the surrounding atmosphere, but is below ambient density. The ordinary buoyancy effect will cause this air mass to rise.

This buoyant rise is not a simple adiabatic expansion, however. In some cases, the shot gun effect causes a volume of material to be ejected upwards with high velocity in addition to the major mass of heated air. In all cases, the rise will cause turbulence at the boundaries resulting in entrainment of cooler high density air. The turbulence itself will increase the effective drag forces at the boundaries of the rising air mass, and the entrainment will change its total mass, volume and density, thus affecting the buoyant force and the buoyant acceleration. The rise is further complicated by the vortex motion of the cloud, which results in a circulation with upward motion in the center, downward motion on the outside. The relative velocity of the boundary of the cloud and the ambient air is thus much lower than the relative velocity of the center of the cloud. In many cases, radiation will play a significant role in cooling the air as it rises, in addition to the usual adiabatic expansion. It appears hopeless to include these effects accurately in any purely theoretical computation. As a result, data from test explosions are used to find an effective drag coefficient for the buoyant rise. The value found is one tenth rather than the value of unity suggested by the model of a rising sphere of air.

SECTION 3

CALCULATIONS AND RESULTS

3.1 Machine Calculations

Using the ideas discussed in Section 2, a relatively crude calculation of the rate of rise of the central portion of the bomb fireball was made. This calculation, done on the IBM 1620 computer with a code appropriately called Snuffy Smith, was to establish the approximate variation in fire ball rise rates with detonation altitude, initial fireball radius, and yield. This analysis probably gives the right magnitude to peak rise velocity for the detonation altitude range of 50 to about 120 km., and has been used as high as 150 km.

The assumption used in Snuffy Smith include the following:

(1) A uniform temperature spherical fireball is formed instantaneously.

(2) The fireball is assumed to contain the air originally present in the calculated initial radius.

(3) Fireball size as a function of time is as predicted in the report,"The Blast Wave in Air Resulting from a High Temperature, High Pressure Sphere of Air", by H. L. Brode, RM-1825-AEC.

(4) The motion of the fireball through the atmosphere can be treated like a sphere going through a fluid. Newton's law, the "shotgun" acceleration, buoyancy, and drag are used to calculate the rate of rise.

(5) The 1959 ARDC model atmosphere was assumed, as reported by Minzer et al, "The ARDC Model Atmosphere, 1959", AFCRC-TR-267.

(6) The distribution of the total yield energy in the X-rays and in the debris was assumed to be 75 percent and 25 percent, respectively.

(7) No consideration was given to magnetic braking.

The majority of the assumptions are clearly non-ideal, but probably adequate. The third assumption is highly questionable, because Brode's study was conducted for a quite low altitude explosion. However, the buoyancy and drag effect on the peak rise rates proved to be quite insignificant at high altitudes, so that relatively little error was introduced by the use of Brode's low altitude fireball expansion data in the high altitude regime studied.

The equations integrated by the machine code are

$$M \ddot{Z} = F_1 + F_2 - F_3 - F_4 \tag{14}$$

where $M = M(t)$ is the total mass of the heated air at any time, the F's are the various forces acting on this mass, and Z is the altitude coordinate of the mass followed in the calculation.

The forces F_1 and F_2 are the surface forces for inviscid flow fluid dynamics. Ideally the Z component of these forces is

$$F_1 + F_2 = \int_{\text{Surface}} P \cos \Theta \, d\sigma \tag{15}$$

where Θ is the angle between the inward drawn normal to the surface element $d\sigma$ and the Z axis. As the discussion of Section 2 indicates, at early times the pressures P are very large and directed outward so that the heated air does work on the ambient atmosphere. The center of gravity of the mass, however, actually moves very little under the resultant force. But an important fraction of the mass will be ejected upward by the shotgun effect. To follow the motion of this mass, the actual surface force is replaced by a fictitious surface force F_2 giving the shotgun acceleration to the entire mass M_o initially in the volume now occupied by the heated air. This force operates only for the sound transit time $\tau = R/a$. From equation 5, one finds

$$F_2 = M_o g \frac{P}{P_a} \tag{16}$$

It is correct to omit the extra term in (5) for the body force is taken care of by the term F_3.

At late times F_2 disappears. But now expansions have slowed sufficiently so that a quasi-static equilibrium exists. Then the surface integral (15) gives the ordinary buoyant force F_1,

$$F_1 = M_o g \, . \tag{16a}$$

Since F_1 is very small for early times, it is included for calculation at all times even though strictly it should be used only for late times.

The body force F_3 is

$$F_3 = Mg, \tag{17}$$

while the drag force is

$$F_4 = \frac{1}{2} \rho_a v^2 C_D A \tag{18}$$

From Brode's work, one can obtain the volume of the fireball V(t) at any time and the mass M(t) within the fireball by assuming that the entire previous expansion took place at the altitude the fireball occupies instantaneously. Then the quantities needed in the above equations are

$$M_o(t) = \rho_a \; V(t) \; ; \quad V(t) = \frac{4}{3} \pi R^3(t) \; ; \quad A = \pi R^2(t)$$

Snuffy Smith was used to study fireball rise characteristics of 1 and 4 MT detonations at altitudes between 75 and 150 km. Because of the uncertainties in the initial fireball size, the calculations were conducted parametrically with several values of initial radius. The values of initial size used are of the right order for the cases run at 120 km. or below, but are probably too small at 135 and 150 kilometers. The essential input numbers and results are shown in Table 1. Resulting peak rise rates are the right order of magnitude but several times high at the Teak datum point. Table 1 indicates that rise velocity increases with a decrease in ambient density (increase in altitude) at constant fireball size. Although fireball size really increases with increasing altitude, even when this factor is considered as discussed in Section 2, equation (13) fireball velocity increases with increasing altitude.

Drag braking was observed to be very slow in all of the problems run, with the fireball rising to very great altitude in every case. Further examination of Table 1 indicates that the precise value of drag coefficient, which was varied from .1 to .8 for the 75 km detonations, has comparatively little effect on the calculated velocity, but that fireball size and energy content are quite significant. The detonation altitude also seems fairly significant. Drag coefficient was taken as .1 for cases 5 through 13 on the basis of the drag insensitivity observed on the first five cases. The insensitivity of the calculated peak velocity to drag coefficient raises the suspicion that buoyancy forces are also quite unimportant in determining peak velocity, and suggests the use of an even further simplified calculation for predicting trends. Such a simplified analysis was actually run to permit more direct observation of the trends, without the frequent reprogramming required to study the many effects separately on the computer.

3.2 Shotgun Effect Only

The simplified analysis considered only the shotgun velocity given by equation (11) which was put in the form

$$v = \frac{g\overline{M}}{RT_a} \left\{ \frac{\gamma - 1}{\gamma} \; \frac{Wf}{\frac{4}{3}\pi \rho R_o} \right\}^{1/2} \qquad (19)$$

Now assume the following values:

$W_f = 4.18 \times 10^{22}$ Yf ergs, where Y is now the yield in MT.

$\gamma = 1.4$ for moderately heated air

$\rho R_o = 6 \times 10^{-5} \frac{gms}{cm^2}$ for light debris nuclei

$\overline{M} = 29$ gms/mol

$g = 980$ cm/sec^2, neglecting altitude effect

$R = 8.33 \times 10^7$ ergs/mol ^oK

Then v in km/sec is

$$v = \frac{23,500 \sqrt{Yf}}{T_o} \quad \text{km/sec} \tag{20}$$

At somewhat lower altitudes, where X-ray heating is dominant, ρR_o should be replaced by the mean free path for X-ray absorption, taken as 2×10^{-2} gm/cm^2. Then the velocity expression becomes

$$v = \frac{1280 \sqrt{Yf}}{T_o} \quad \text{km/sec.} \tag{21}$$

Equations 20 and 21 were used to estimate velocity for cases 21 to 25 (Table 2). Both equation (20) and (21) assume that the initial radius of the fireball to be used in the shotgun calculation is determined by the energy deposition from the bomb. In cases where radiative transport redistributes the energy before hydrodynamic motions occur, one should use an initial fireball radius given by equation (12) leading to a velocity of rise given by equation (13). The appropriate temperature at which radiative transport becomes unimportant at these altitudes is about 8000 ^oK which may be used to determine $\mathcal{E}_o$ by the caloric equation of state.

The results can be expressed in the approximate form

$$v = 10\,(Yf)^{1/3} \exp \frac{\Delta Z}{27} \ \text{km/sec} \tag{22}$$

where Y is the yield in megatons and ΔZ is the height of burst above 100 kilometers in kilometers. For bursts below 100 km ΔZ is negative and the equation still applies. Equation 22 was used to calculate the last two cases in Table 2.

Results calculated by equations (20), (21) or (22) agree very well, within about 10 percent, with the more detailed calculations of Snuffy Smith given in Table I. Valid conclusions for a wide range of cases can therefore be obtained from these simple equations. In particular equation (22), which holds in most cases of interests, predicts rise rates of 1.5 km per second for one megaton even as low as 60 kilometers. In 100 seconds, the duration required if radar blackout is to be effective as a penetration aid, the cloud would rise 150 kilometers, expand to a radius of about 150 kilometers and be unable to cause severe ionization and blackout. Detonations at higher altitudes will be even less effective since the velocity of rise increases with altitude. Detonations of lower yield and lower altitude will not cover a wide enough area initially to be a reasonable penetration aid.

It must be remembered that the numerical work here treats only the motion of a centrally positioned mass of air. When X-ray energy deposition is important this mass will probably contain almost all of the fission products, and the source of ionization for blackout will not remain localized for long. When bomb debris energy deposition is all important, the bottom portion of the debris cloud, which is not considered in the present calculations, may remain relatively stationary, and therefore be significant for blackout.

3.3 Work of Other Authors

Superficially, the conclusions of C. G. Davis et al, "Theoretical Studies of the Motion of Bomb Debris" SWC TR 61-89, appear to differ in some respects from these reported here. Davis points out that for a certain combination of altitude and yield parameters, the analysis which he reports is not strictly valid. This combination includes yields of 100 kt or greater at 100 km or higher, 1 MT or greater at 80 km or higher, and 10 MT at 60 km or higher. Davis points out that for this high yield and high altitude regime, the shotgun effect is dominant, and his model is not ideal. In any event, Davis' studies do not offer hope of a low velocity detonation altitude either.

G. Plass et al, "Final Report, Theoretical Study of the Motion of Bomb Debris", SWC-TR-61-20, report rise velocities of the order of several km/sec for detonations at 100 km, but does not indicate the expected variation with altitude.

R. H. Christian et al, "Final Report, Research Studies in Nuclear Effects in the Upper Atmosphere", AFSWC-TR-60-29, treats the more general problem. Christian concludes that detonations at altitudes from 40 to 300 km probably will cause significant blackout effects. Christian also concludes that the rate of rise is very large and increasing with altitude for detonations at about 110 km, but that magnetic trapping probably will occur. Christian discusses several different models for predicting the debris motion at altitude, and reports results varying from 2 to 50 km/sec. at altitudes above 100 km.

Both the current study and the literature in the field confirm the need for more work in the vicinity of 100 to 200 km. In particular, magnetic braking effects need much more study. No great hope is held for an altitude region of startlingly low fireball rise rates. It is to be hoped that the 1962 Pacific test series provides valuable new data.

TABLE 1

SNUFFY SMITH CASES

Case	Altitude (Km)	Fireball Yield (MT)	Initial Radius (Km)	Drag Coefficient	Peak Rise Velocity (Km/Sec)
1	75	1	10	.1	3.8
2	75	1	10	.2	3.7
3	75	1	10	.4	3.5
4	75	1	10	.8	3.1
5	75	4	11.4*	.1	6.9
6	100	4	11.4	.1	56
7	100	4	50	.1	24
8	120	.25	40.5	.1	16
9	120	.25	40.5	.1	17
10	120	.25	50	.1	16.
11	125	1	84*	.1	25.1
12	135	.25	10	.1	50
13	135	.25	50	.1	21
14	150	.25	50	.1	26

* Initial radius chosen by equation 12 with initial fireball temperature 8000 °K.

TABLE 2
SIMPLIFIED ANALYSIS

Altitude (Km)	Ambient Temperature (^oK)	Ambient Density (g/cm^3)	Yield (MT)	Initial Radius cm		Shotgun Velocity (km/sec)	
				Debris	X-Ray	Debris $f = .25$	X-Ray $f = 1.0$
75	188	4.82×10^{-8}	4	12.4×10^2	4.15×10^5	125	14
100	199	3.73×10^{-10}	4	16.0×10^4	5.36×10^7	118	13*
120	477	1.48×10^{-11}	1	40.5×10^5	1.35×10^9	25	
135	758	4.15×10^{-12}	1	14.4×10^6	4.83×10^9	16	
150	1031	1.76×10^{-12}	1	34.0×10^6	11.4×10^9	11	
75			4		11.4×10^5		6.3
125			4	83.9×10^5		25	

* This figure should be corrected downward to 7.5 to allow for the fact that Δp is not $>> p_o$ in this case.

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