APPROVED FOR PUBLIC RELEASE

UNCLASSIFIED

CIC-14 REPORT COLLECTION
REPRODUCTION
COPY

[redacted]

Classification changed to UNCLASSIFIED
by authority of the U. S. Atomic Energy Commission,
Per J. H. Kolm / ltr dtd 9-11-58
By REPORT LIBRARY M. Martinez 9-17-58

LA - 577 C.3

[redacted]

June 18, 1946 This document contains 16 pages

FORMATION AND RISE OF SMOKE CLOUDS FROM EXPLOSIONS

WORK DONE BY:

Samuel Cohen
Joseph O. Hirschfelder
Mac Hull
John L. Magee

REPORT WRITTEN BY:

Samuel Cohen

PUBLICLY RELEASABLE
LANL Classification Group
M. Pauwkratz 2/26/96

LOS ALAMOS NATIONAL LABORATORY
3 9338 00349 5859

UNCLASSIFIED

~~...ment contains inf... ing of the ... of the Uni... transmission ... 50 31 ... its ...ion of its contents in any manner ... is prohibited by law.~~

[redacted]

APPROVED FOR PUBLIC RELEASE

APPROVED FOR PUBLIC RELEASE

UNCLASSIFIED

[redacted]

Abstract

In this report, a method to determine the formation and rise of the smoke cloud produced by an explosion in the earth's atmosphere has been developed. Using this method, calculations were made to forecast the developement of the cloud under "Crossroads" atmospheric conditions for a nuclear explosion releasing the energy equivalent of 20,000 tons of TNT.

LOS ALAMOS NATL. LAB. LIBS.
3 9338 00349 5859

UNCLASSIFIED

APPROVED FOR PUBLIC RELEASE

APPROVED FOR PUBLIC RELEASE

UNCLASSIFIED

[redacted]

Formation and Rise of Smoke Clouds from Explosions

The methods we have used in considering the formation and rate of rise of smoke columns are based on a treatment by G. I. Taylor (LA 236 and LA 270). In report LA 270, Hirschfelder predicted that the cloud from the Trinity shot would rise 15,000 feet. The actual rise was about 60,000 feet, and observational agreement on this height was found at Nagasaki. The disagreement was a result of two factors: (1) The moisture content of the air was neglected, so that the smoke puff lost heat more rapidly than actually happened. (2) A reworking of Taylor's equations in LA 236 showed that he assumed that conservation of volume implied conservation of mass (section I, LA 236). Since density changes in the puff accompany volume changes, this is not true although the effect is not excessively large. When this is realized, we see that a proportionality constant between mass and velocity is needed, which turns out to be half Taylor's constant between volume and velocity.

With the indicated corrections, the calculated height of the Trinity cloud is $>50,000$ feet, in agreement with the observations. This corrected theory should then apply to the air-burst shot at Crossroads.

The theory has developed in the following round-about fashion. The pattern of turbulent convection above a steady line source of heat (such as a long hot wire) has been determined by Schmidt. The derivation, however, is too complicated to apply to other examples such as the turbulence above a steady point source of heat. For this reason, G. I. Taylor (LA 236) developed an approximate method which agrees with Schmidt's results in the case of a steady line source of heat and which may be applied to much more complicated problems. Taylor makes the following assumptions:

UNCLASSIFIED

1. The turbulent column is sharply defined. Within this column the air rises with a velocity, u, which is a function of altitude

[redacted]

APPROVED FOR PUBLIC RELEASE

APPROVED FOR PUBLIC RELEASE

UNCLASSIFIED

[redacted]

but not a function of horizontal distance.

2. The rate of taking air into the turbulent column is proportional to the velocity of rise of the air within the column at the height in question. That is, the volume of air taken into the smoke column in an element of height, δh, in unit time is $\alpha u A$, where A is the cross-sectional area of the column and α is a constant. In Goldstein's "Modern Developments of Fluid Dynamics", the work of Tollmien (Ziet.f.angew.Math.u.Mech. 468 (1926)) is cited which shows that $\alpha = .172$ for the turbulent spreading of jets. Undoubtedly, G. I. Taylor had other evidence when he asserted that α is usually in the neighborhood of 0.2. As we have said, we do not assume that conservation of volume implies conservation of mass, so we take $\alpha = 0.1$. This brings our calculations into agreement with the observed rate of rise of the cloud in the early stages after the Trinity shot, and with the observed height of rise.

3. The problems are further specified by including the usual equations of conservation of energy and the equation of motion. The equation of motion is just the Law of Archimedes for the static lift of a gas balloon. The lifting force is just equal to the difference in the weight of the air within the column and the outside air which it displaces.

Our problem differs from the steady state problems which have been studied experimentally. However, for lack of better information or mathematical skill we apply essentially the same procedures. It is necessary to make one additional assumption with regards to our smoke puff:

4. Instead of the smoke rising in a column, we idealize the situation by assuming that the heated air is originally in the shape of a sphere and that it remains spherical as it rises and expands. A further idealization consists in assuming that the temperature of the air

[redacted]

UNCLASSIFIED

APPROVED FOR PUBLIC RELEASE

APPROVED FOR PUBLIC RELEASE

UNCLASSIFIED

[redacted]

and the upward velocity is constant throughout the sphere.

After the explosion, shock waves pass out through the air dissipating energy as they progress. The air through which these shock waves have passed is left heated. The air in the center is at first much hotter than the air further out (see LAMS-380) but this difference in temperature is soon equalized by turbulent convection and radiation. If an atomic bomb is burst in air and releases the energy equivalent of 20,000 tons of TNT, 75% of the energy of the explosion is left by the shock waves within the first 400 yards. Part of this 75% is radiated away so that we may conservatively estimate that 50% of the explosion energy remains within a radius of 400 yards. Originally after the shock wave has passed by, the temperature at 400 yards is only 350°K but the average temperature for the material within 400 yards is 770°K. Thus in spite of the ball of fire in the core which remains at temperatures of the order of 20,000°K, the largest percentage of the bomb energy is dissipated in very low grade heating of from one hundred to one thousand degrees.

I. INITIAL CONDITIONS.

First of all, we are given complete meteorological information as to the atmospheric pressure, temperature, and mixing ratio (ratio of the mass of water vapor to the mass of dry air) as a function of altitude. Experimentally we know that the wind velocity as a function of altitude is important but we do not know how to use such information in our calculations. The moisture in the smoke puff condenses when the temperature drops and releases its energy of condensation which helps the cloud rise higher than it otherwise would. The water vapor also helps to make the cloud rise because its density is lower than that of dry air under the same conditions

[redacted]

UNCLASSIFIED

APPROVED FOR PUBLIC RELEASE

APPROVED FOR PUBLIC RELEASE

UNCLASSIFIED

 [redacted]

of temperature and pressure.

Secondly, we are given the energy of the explosion, the height of burst and whether the explosion took place over land or water. We shall assume that 50% of the energy of the explosion goes into the formation of the initial smoke puff. The initial composition of the smoke puff depends on the conditions of firing. For example, in the first Cross-Roads where the explosion takes place 600 feet above the water, a lot of spray will be thrown from the surface of the water and carried by strong winds into the smoke puff. Roughly we can estimate that 1500 tons of water will go into the starting smoke puff and approximately 5% of the energy of the explosion will go into vaporizing and heating it.

Since we assume that the temperature of the puff is uniform, we have considerable latitude in choosing our initial temperature. If we take the initial temperature too low, the initial radius will be too large and the smoke puff will not rise quite as high as it should. In LAMS-380 we have seen that most of the heating has taken place by the time the average temperature is down to 770°K, (if we take the energy required to vaporize and heat the spray into consideration this temperature is reduced to around 600°K). Although these temperatures are somewhat arbitrary they are sufficiently accurate for our purposes

The initial pressure of the puff is atmospheric since the shock wave has passed long before the smoke puff has formed.

With this preamble, it is clear that we can determine the initial density and radius of the puff. Let:

UNCLASSIFIED

E_o = Energy which goes into forming the smoke puff, i.e. 50% of the energy of the explosion.

T_o = Initial temperature of the smoke puff, we assume that T_o = 600°K.

[redacted]

APPROVED FOR PUBLIC RELEASE

APPROVED FOR PUBLIC RELEASE

UNCLASSIFIED

[redacted]

p_o = Initial pressure in the smoke puff. If the explosion occurs at sea level, $p_o = 1$ atm = 1.03 bars
ω_o = Ratio of mass of water vapor to mass of dry air initially in the smoke puff.
T_{oo} = Temperature of atmosphere at height of explosion
$C_{p,a}$ = specific heat of dry air at constant pressure = 1.004×10^7 ergs/gm°C
$C_{p,wv}$ = specific heat water vapor at constant pressure = 1.911×10^7 ergs/gm°C
k_a = gas constant of dry air = 2.87×10^6 ergs/gm°C

ρ_o = Initial density of air in puff
R_o = Initial radius of smoke puff

Then the initial density of the air in the smoke puff is given by the equation:

$$\rho_o = p_o\left[T_o k_a(1 + .61\omega_o)\right]^{-1} \qquad (1)$$

And the initial radius is given by the equation:

$$R_o = E_o^{1/3}\left[\tfrac{4}{3}\pi\rho_o(C_{p,a} + \omega_o C_{p,wv})(T_o - T_{oo})/(1 + \omega_o)\right]^{-1/3} \qquad (2)$$

The initial mass of the smoke puff is then

$$M_o = \tfrac{4}{3}\pi R_o^3\rho_o \qquad (3)$$

It is somewhat difficult to obtain a reasonable value for the initial velocity of the smoke puff. G. I. Taylor advises (see LA-236) the use of the following trick which he has used successfully to calculate the rate of rise through water of the bubbles formed by underwater explosions. Consider a spherical bubble of density, ρ_o, rising with a velocity, u, through a medium of density, ρ_{oo}. Then assuming that the fluid is non-viscous we get from classical hydrodynamics (see Leigh Page, "Introduction to Theoretical Physics", page 199 (Van Nostrand, 3rd printing, 1930)) the pressure on the surface of the spherical bubble at an angle θ from the vertical:

$$p_\theta = \tfrac{1}{2}\rho_{oo}u^2\left[(1 - \tfrac{9}{4}\sin^2\theta) + R_o\cos\theta\,\frac{du}{dt}\right] + g(\rho_{oo} - \rho_o)(h_o - R_o\cos\theta) \qquad (4)$$

Here g is the usual gravitational constant; R_o is the radius of the bubble; and h_o is the height of the center of the bubble. The bubble soon reaches a steady velocity so that du/dt becomes negligibly small. Furthermore,

[redacted] UNCLASSIFIED

APPROVED FOR PUBLIC RELEASE

APPROVED FOR PUBLIC RELEASE

UNCLASSIFIED [redacted]

the mass increment always remains sensible. The maximum height of rise of the cloud is very sensitive to the value of alpha. The volume of the cloud and its rate of rise as functions of time are insensitive to the detailed mechanics of the calculations provided that the energy in the puff and its height of rise are fixed.

The change of velocity of the puff is given by the Archimedes equation:

$$\frac{d}{dt}(Mu) = \frac{4}{3}\pi R^3(\rho_{atm} - \rho)\, g \qquad (8)$$

The actual mechanics of getting a point-by-point solution to the motion of the puff is somewhat complex. For convenience, in the subsequent equations we shall use the subscript h to indicate the quantity at the end of the interval and the subscript o to indicate the quantity at the beginning of an interval. A bar above a quantity indicates that it is averaged throughout the interval. The work proceeds in the following fashion. First, Eq. (7) can be integrated approximately over a small height increment to give:

$$M_h = M_o + 4/3\,\pi\,\bar{\rho}_{atm}\left[(\alpha h + R_o)^3 - R_o^3\right] \qquad (9)$$

In our calculations we will use this value for M_h as a first approximation in order that we may find ρ_h and R_h as follows:

For the early stages of the ascent the water vapor in the puff is in the unsaturated state, so we may use the equation of the dry adiabatic for the ascent, namely,

$$T_{h,1} = T_o\left(\frac{p_h}{p_o}\right)^{\gamma_1}, \text{ where} \qquad (10)$$

UNCLASSIFIED

$$\gamma_1 = \frac{(1 + .61\omega_o)\, K_{air}}{(1 + .90\omega_o)\, C_{p,air}} \qquad (11)$$

[redacted]

APPROVED FOR PUBLIC RELEASE

APPROVED FOR PUBLIC RELEASE

UNCLASSIFIED [redacted]

the bubble changes its shape until the pressure on its surface is independent of position. Experimentally it has been found that the bubble flattens out like the head of a mushroom but the top part may still be regarded as a segment of a sphere. For small values of θ, equation (4) still applies. Expanding p_θ in powers of θ neglecting the term in du/dt:

$$p_\theta = \tfrac{1}{2}\rho_{oo}u^2 + g(\rho_{oo} - \rho_o)\,(h_o = R_o) + \theta^2\left(-\tfrac{9}{8}\,\rho_{oo}\,u^2 + \frac{gR_o}{2}\,(\rho_{oo} - \rho_o)\right) \qquad (5)$$

The stability of the bubble depends on p_θ being independent of θ. The requirement in the neighborhood of $\theta = 0$ where the above equation applies, is that the term involving θ^2 must vanish or

$$u^2 = \frac{4}{9}\,gR_o\left(1 - \frac{\rho_o}{\rho_{oo}}\right) \qquad (6)$$

We take the value of u given in Eq. (6) as the starting velocity, u_o.

II. Motion of the Smoke Puff

Having these initial conditions, we proceed to find the motion of the puff as follows. Since the temperature, water vapor content and density structure of the atmosphere cannot conveniently be represented as mathematical functions, we follow the motion of the smoke puff over a number of small increments of height and assume average values for the atmospheric conditions within these intervals.

The fundamental assumption which we make is that the rate of change of mass in the puff with height is proportional to the surface of the puff and the density of the atmosphere. Thus:

UNCLASSIFIED

$$\frac{dM}{dh} = \alpha\, 4\pi R^2 \rho_{atm} \qquad (7)$$

This equation is similar to Eq. (21), Part I, LA-236 but it differs in treating M rather than R as the dependent variable. We prefer to consider the changes in mass rather than in radius as fundamental because the radius changes in a peculiar fashion when the water vapor condenses, etc. whereas

[redacted]
APPROVED FOR PUBLIC RELEASE

UNC

 [redacted]

This process is used until the temperature of the puff falls sufficiently so that saturation occurs and energy of condensation will be released. When saturation does occur, we must use the equation for the saturation adiabatic process. The convenient form for this may be written as a differential equation

$$-L d\omega_s = \left[1 + 1.90\omega_s + 4.17(\omega - \omega_s)\right] C_{p,air}\, dT - (1 + 1.61\omega_s)K_{air}T \frac{dp}{p} \qquad (12)$$

where L is the latent heat of condensation = 2.50×10^{10} ergs/gm. (For reference see Dynamic Meteorology-Holmboe, Sect. 3.34). An expression for $d\omega_s$ can also be obtained and can be written as

$$d\omega_s = \omega_s(1 + 1.61\omega_s)\left(\frac{.622L}{K_{air}} \cdot \frac{dT}{T^2} - \frac{dp}{p}\right) \qquad (13)$$

and thus we have,

$$-L\omega_s(1 + 1.61\omega_s)\left(\frac{.622\,L}{K_{air}} \cdot \frac{dT}{T^2} - \frac{dp}{p}\right) \qquad (14)$$

$$= \left[1 + 1.90\omega_s + 4.17(\omega - \omega_s)\right] C_{p,air}\, dT - (1 + 1.61\omega_s)K_{air}T \frac{dp}{p}$$

For a small rise, where the changes in pressure, temperature and mixing ratio are also small we can write for the change in temperature of the puff, the following:

$$\delta T = \frac{\frac{\delta p}{p}\left\{(1 + 1.61\omega_s)(L\omega_s + K_{air}T)\right\}}{\frac{.662\omega_s L^2(1 + 1.61\omega_s)}{K_{air}\,T^2} + \left[1 + 1.90\omega_s + 4.17(\omega - \omega_s)\right] C_{p,air}} \qquad (15)$$

Since the puff takes in atmospheric air as it rises, we must devise a method for obtaining the new properties of the puff at the end of the interval. This is done as follows:

First we raise the puff having the properties p_o, T_o, ω_o a distance "h" (along a dry or a saturation adiabatic, as the case may be), thus giving us a new set of properties $(p_1 T_1 \omega_1)_h$. We then raise an amount of atmospheric air δM having the initial properties $(p_o, T_o, \omega_o)_{atm.}$ a distance "h/2" to the same level as the raised puff, which gives us the new properties $(p_2, T_2, \omega_2)_h$.

DECTHO

UNC[redacted]FIED

APPROVED FOR PUBLIC RELEASE

UNCLASSIFIED

 [redacted]

We then mix the two masses of air at constant pressure, p_h, and obtain the new properties of the puff p_h, T_h, ρ_h, R_h at the end of the interval of rise, "h". Since our equation for the saturation adiabatic is approximate we will have the puff arrive at the end of the interval in a non-saturated condition, and also since the atmospheric air that we mix it with is far below saturation (at these levels) and will thus even lower the mixing ratio of the puff still further, we can safely assume (and this turns out to be the case) that no further condensation will occur when we mix the two raised parcels of air.

For mixing in the early (no condensation) stages, the resulting temperature of the puff, T_h, is

$$T_h = \frac{M_o(1 + 1.90\omega_1)T_1 + \delta M\,(1 + 1.90\omega_2)T_2}{M_o \times (1 + 1.90\omega_1) + \delta M \times (1 + 1.90\omega_2)}\text{, and also} \qquad (16)$$

$$\omega_h = \frac{M_o\omega_1 + \delta M\omega_2}{M_h}\text{, } (M_h = M_o + \delta M) \qquad (17)$$

For mixing in the later stages of the ascent where water vapor has already condensed out and is in either the form of water ($T > 0^\circ C$) or ice ($T < 0^\circ C$), we have

$$T_h = \frac{M_o\left[1 + 1.90\omega_1 + \Delta(\omega - \omega_1)_1\right] T_1 + \delta M\left[1 + 1.90\omega_2 + \Delta(\omega - \omega_2)_2\right]T_2}{M_o\left[1 + 1.90\omega_1 + \Delta(\omega - \omega_1)_1\right] + \delta M\left[1 + 1.90\omega_2 - \Delta(\omega - \omega_2)_2\right]} \qquad (18)$$

$$\omega_h = \frac{M_o\omega_1 + \delta M\omega_2}{M_h}\text{, } (M_h = M_o + \delta M) \qquad (19)$$

(By the symbol ω in this equation and also in the saturation adiabatic equation, we mean the total amount of water in any form, vapor, liquid, ice, expressed in grams per gram of dry air)

where

$$\Delta = 4.17,\ T > 0^\circ C \qquad (20)$$

$$\Delta = 2.052,\ T < 0^\circ C \qquad (21)$$

UNCLASSIFIED

[redacted]

APPROVED FOR PUBLIC RELEASE

For raising the parcel of atmosphere, δM, we use the dry adiabatic equation, namely,

$$T_{h,2} = T_{o,atm}\left(\frac{p_h}{p_{o,atm}}\right)^{\gamma_2} \tag{22}$$

$$\gamma_2 = \frac{(1 + .61\omega_{o,atm})\, K_{air}}{(1 + .90\omega_{o,atm})\, C_{p,air}} \tag{23}$$

We can now find the density, ρ_h, and the radius, R_h, by means of the following formulae:

$$\rho_h = \frac{p_h}{K_{air}\,(1 + .61\omega_h)\, T_h} \tag{24}$$

$$R_h = \left(\frac{M_h}{4/3\,\pi\rho_h}\right)^{1/3} \tag{25}$$

Using the afore-described process, we can now lift the puff another distance "h", and obtain its new properties. To find out if the puff is saturated, so that we will know when to use the saturation adiabatic equation, we can use the formula

$$\omega_{s,h} = \frac{.622\, e_{s,h}}{p_h - e_{s,h}} \tag{26}$$

, where e_s is the saturation vapor pressure, and can be computed from the empirical formulae

$$\log e_s = 8.4051 - \frac{2353}{T}\ , \quad T > 0^{\circ}C \tag{27}$$

$$\log e_s = 9.5553 - \frac{2667}{T}\ , \quad T > 0^{\circ}C \tag{28}$$

When the temperature of the puff falls to $0^{\circ}C$, we have the so-called "hail stage", where the temperature of the puff remains constant until all of the existing liquid water has frozen out. The equation for this process is

$$\log(p_1 - e_s) - \frac{59.71}{p_1 - e_s} = \log(p_o - e_s) - \frac{52.39}{p_o - e_s} - 1.846\omega \tag{29}$$

(Actually this is a very small effect since saturation will first occur quite near to $0^{\circ}C$, so that we will have very little liquid water available for the process.)

APPROVED FOR PUBLIC RELEASE

SECRET

UNCLASSIFIED

To compute the dynamics of the puff, we develop the following equations

$$\frac{d}{dt}(M_h u_h) = 4/3\,\pi R_h^3(\rho_{atm,h} - \rho_h)g \qquad (30)$$

$$M_h u_h \frac{d}{dh}(M_h u_h) = 4/3\,\pi g R_h^3 M_h(\rho_{atm,h} - \rho_h) \qquad (31)$$

$$\left(u_h = \frac{dh}{dt}\right) \qquad (32)$$

$$\frac{(M_h u_h)_1^2}{2} - \frac{(M_h u_h)_0^2}{2} = \int_{h_0}^{h_1} 4/3\,\pi g R_h^3 M_h(\rho_{atm,h} - \rho_h)dh \qquad (33)$$

$$u_{h,1} = \left(\frac{2\int_{h_0}^{h_1} 4/3\,\pi g R_h^3 M_h(\rho_{atm,h} - \rho_h)dh + (M_o u_o)^2}{M_{h,1}^2}\right)^{1/2} \qquad (34)$$

$$t_{h,1} = \int_{h_0}^{h_1} \frac{dh}{u_h} + t_o \qquad (35)$$

III. Prediction of Cloud Formation in Cross-Roads Air Burst

In the first Cross-Roads explosion, we expect that the bomb will burst at a height of 600 feet above the surface of the water and release an amount of energy equivalent to 20,000 tons of TNT (the nominal energy of one ton of TNT is taken to be 4.185×10^{16} ergs). We assume that 1500 tons of spray will be entrapped in the smoke puff before it starts to rise. Thus our starting assumptions are:

E_o = energy going into the smoke puff = 4.2×10^{20} ergs

T_o = initial temperature of puff = 600°K

p_o = initial pressure in puff, 1 atm = 1.03 bars

ω_o = initial mass of water vapor divided by mass of dry air in puff = .030

From the above information, it follows that

ρ_o = initial density of the puff = .00588 gms/cm^3

R_o = initial radius of puff = 417 yards

M_o = initial mass in puff = 1.369×10^{11} gms = 151,000 short tons

u_o = initial velocity of rise of puff = 28.07 meters/sec

SECRET

[redacted]

UNCLASSIFIED

APPROVED FOR PUBLIC RELEASE

APPROVED FOR PUBLIC RELEASE

UNCLASSIFIED

Table I [redacted]

Structure of Atmosphere, Kwajalein, June 3, 1945

height × 1000'	pressure (millibars)	temp. (°A)	mixing ratio ($\frac{\text{gm. water vapor}}{\text{gm. dry air}}$)	density (gm/cm³)	potential temperature
0	1030	303	.020	1.14×10^{-3}	300
1	987	299	.017	1.13	301
3	920	294	.013	1.09	302
5	850	292	.012	1.02	305
7	795	290	.009	.948	310
9	745	287	.005	.897	312
11	690	283	.007	.843	315
13	640	279	.006	.793	317
15	595	276	.003	.750	321
17	555	273	.003	.712	324
19	515	271	.002	.664	328
21	480	267	.002	.625	331
23	445	263	.001	.585	334
25	410	260	.001	.552	336
27	382	256	.001	.520	338
29	350	251	.001	.485	339
31	320	246	.001	.453	341
33	294	241	0	.425	343
35	273	233	0	.408	343
37	249	230	0	.377	343
39	225	223	0	.352	343
42.5	190	[illegible]	0	.311	343

[redacted]

UNCLASSIFIED

APPROVED FOR PUBLIC RELEASE

APPROVED FOR PUBLIC RELEASE

UNCLASSIFIED

[redacted]

The atmospheric conditions were taken to be those of Kwajelein on a typical summer day (June 3, 1945) and the pertinent data is given in Table I. The results of the calculations are shown in Table II. The cloud rises above 50,000 feet in 20 minutes and at that time it occupies 15 cubic miles. The water vapor in the cloud turns to ice above 20,000 feet.

Mean Height of Cloud		Trinity	Calculated $\alpha = .1$	Calculated $\alpha = .2$
1000 ft	Time	5 sec	5.5 sec	6.5 sec
	Radius	380 m	420 m	440 m
2000 ft	Time	13.5 sec	13.1 sec	15.2 sec
	Radius	400 m	470 m	500 m
3000 ft	Time	19.0 sec	19.1 sec	23.2 sec
	Radius	450 m	490 m	560 m
Final Height of Cloud about 60,000'			54,000'	22,000'

From Table II it is obvious that the value of $\alpha = 0.1$ gives results better in agreement with observation than Taylor's cited value (LA 236) of $\alpha = 0.2$. We have indicated the reason for the discrepancy: Our equation (7) would agree with Taylor's Eq (21) if $\frac{dm}{dh} = \frac{d}{dh}\left(\frac{4}{3}\pi R^3\right)$; i.e., if conservation of mass and volume were equivalent. Actually, this equality cannot exist because R changes not only on account of the increase of mass, but also because of the change of density of the puff with height. The appropriate value of α depends on its definition, and our calculation using $\alpha = 0.1$ in Eq (7) of this report roughly corresponds to a calculation using $\alpha = 0.2$ in Taylor's Eq 21 of LA 236.

[redacted]

UNCLASSIFIED

APPROVED FOR PUBLIC RELEASE

Table III

(Assuming

Mean Height of Cloud in 1000 Feet	Time (sec)	Radius (m)	Volume (m^3)	Mass (kg)	Density ($\frac{gm}{cm^3}$)	Temp (°A)	Velocity ($\frac{m}{sec}$)
0	0	3.82×10^2	2.33×10^8	1.37×10^8	$.591 \times 10^{-3}$	600	28.1
2		4.53	3.90	2.94	.755	433	
4	24.7	4.26	6.09	5.02	.825	369	63.1
6		5.99	9.01	7.60	.843	338	
8	45.3	6.74	1.28×10^9	1.07×10^9	.833	318	53.8
10		7.50	1.76	1.43	.812	305	
12	70.3	8.28	2.38	1.85	.778	294	44.3
14		9.07	3.12	2.33	.746	285	
16	101	9.86	4.01	2.87	.715	279	35.8
18		1.07×10^3	5.09	3.47	.681	273	
20	140	1.15	6.43	4.12	.641	269	27.4
22		1.24	8.00	4.84	.604	265	
24	191	1.33	9.82	5.61	.568	261	20.8
26		1.42	1.19×10^{10}	6.44	.536	256	
28	258	1.52	1.47	7.33	.500	251	15.3
30		1.62	1.76	8.28	.468	247	
32	345	1.72	2.13	9.28	.435	243	12.9
34		1.82	2.50	1.03×10^{10}	.410	239	
36	454	1.92	2.96	1.15	.385	234	9.9
38		2.03	3.48	1.26	.362	228	
40	598	2.15	4.16	1.39	.335	222	7.3
44	804					209	4.8
45			6.01×10^{10}			207	4.2
48	1140						3.2
52	1780						1.0
54	2030						0

E = 20,000 tons

[redacted]

APPROVED FOR PUBLIC RELEASE
UNCLASSIFIED
UNCLASSIFIED
UNC

APPROVED FOR PUBLIC RELEASE

DECLAS
[redacted]
SIFIED

UNCLASSIFIED

ENT ROOM

REC. FROM 92

DATE 6/25/46

REC. ____ NO. REC. ✓

UNCLASSIFIED

DECLASSIFIED

APPROVED FOR PUBLIC RELEASE