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CLOUD-CHAMBER EFFECT IN LARGE EXPLOSIONS

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ABSTRACT

Under certain atmospheric conditions a cloud of water droplets will form when an atomic bomb or a large amount ($\gtrsim$ 1000 tons) of TNT is detonated. These conditions are discussed on a semiempirical basis and two experimental verifications of the theory are given:

1. The explosion of ~3000 tons TNT over water,
2. The July 16 nuclear test at Trinity.

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CLOUD-CHAMBER EFFECT IN LARGE EXPLOSIONS

Under certain atmospheric conditions a cloud of water droplets will form in the region having < 15 psi overpressure when an atomic bomb or a large amount of high explosive ($\gtrsim 1000$ tons) is detonated. Assuming an empirical formula for the time variation of pressure exerted by the explosion, it can be predicted that water vapor will condense in the suction phase and a fog will form, providing the relative humidity is greater than 85 percent and there are available sufficient nuclei on which condensation can occur. The lifetime of the cloud increases with the relative humidity of the preshocked air and the energy of the explosive; as the blast tonnage increases, the duration of the pressure pulse and suction phase increases, maintaining for a longer period the conditions which are favorable to condensation. This dependence of the cloud lifetime on the blast tonnage probably accounts for the lack of information on the condensation effect because the enormous number of charges that have been set off in explosives experiments were small (< 10 tons TNT).

Because of the cloud-chamber effect it is possible, providing the very special conditions mentioned above are met, that by observing the region in the vicinity of the bomb immediately after it has exploded we can get a rough measure of blast performance. Since the condensation phenomenon is expected to occur in the region of 5 to 10 psi overpressure, it may offer some measure of blast pressures which are in the range of military importance. Although the formation of a cloud in itself has a limited military application in the production of a carrier of radioactivity, it must be considered quite seriously in planning tests of atomic bombs. A fog blanket would, for example, make

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it impossible to make a continuous observation on the performance of a ship in a blast.

The first part of this report deals with the theory of the cloud-chamber effect. The second section is a discussion of the experimental evidence for the effect.

I. THEORETICAL DISCUSSION

Before describing the effect in detail, it is pointed out that its interpretation depends on the following three factors:

(1) the pressure-vs-time and pressure-vs-distance relationships for explosive,

(2) the relative humidity and air temperature prior to detonation, and

(3) the degree of supersaturation required to cause condensation of dust and other nuclei.

Information of the type listed in (1) is not available in the presence of the ground. The reflection phenomena which occur because of the ground force a semi-empirical approach to this problem. More experiments are probably desirable in this connection. The relative humidity and air temperature can be obtained, even in military target areas, to within about 1 percent and a few degrees respectively. Item (3) can be settled by an appeal to experiment.

In order to see how the cloud-chamber effect operates, let us consider an expanding blast wave. The blast wave proceeds from the region of its origin heating the air irreversibly as it expands. The greater the peak pressure reached in the blast wave, the greater the irreversible heating to be expected. Indeed, if the shock has sufficient strength the irreversible heating which

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results is great enough to overcompensate the temperature drop in the suction phase, thus preventing the air from ever dropping below its unshocked temperature. At some lower value of the shock pressure, the drop in temperature due to the subsequent adiabatic expansion becomes greater than the temperature increase due to irreversible heating, causing the air to drop below its unshocked temperature for some period of time in the suction phase. As the peak overpressure becomes progressively less in the expanding wave, the irreversible temperature increases diminish, and in the limit of small changes in pressure the situation becomes reversible: the temperature returns to its preshock value after the pulse has passed.

Now consider the case in which the unshocked air is completely saturated. In view of the above we can expect condensation to occur first at that value of peak overpressure which is followed in the suction phase by a drop in temperature sufficiently far below that of the unshocked air to cause the degree of supersaturation required for condensation to occur. We should therefore expect that an observer at some distance from the event should see no condensation out to a given radius. From this critical radius (corresponding to a calculable value of the peak pressure) and outwards to a distance which is again determined by the degree of supersaturation necessary to cause condensation, a cloud is expected to form.

If the air is initially slightly less than the saturated, the point at which the cloud starts forming will be somewhat more distant from the point of detonation, the critical radius occurring where the minimum temperature in the blast wave is somewhat below the unshocked temperature. The radius at which the cloud forms is thus seen to be related to the shock pressure and the relative

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humidity in the region of interest.

We now calculate the conditions under which the cloud forms, assuming for simplicity that the degree of supersaturation required to cause condensation is negligibly small.

For purposes of this report, we assume the empirical relationship between overpressure and time for ordinary high explosives,

$$p(t,r) = p_0(r)\left(1 - t/\tau_0\right)e^{-\alpha t} \qquad (1)$$

where t = time in milliseconds measured from the time of arrival of the shock front.

$p(t,r)$ = overpressure, psi (excess over atmospheric pressure) at time t and at distance r from the explosion.

$p_0(r)$ = initial overpressure, psi

$\tau_0(r)$ = duration of the positive pressure pulse in milliseconds.

$\alpha(r)$ = milliseconds^{-1} a constant fixed by the observed positive impulse I where

$$I = \int_0^{\tau_0} p(t)\,dt$$

For air the ratio of specific volumes v_1/v_0 in a shock of strength p_1/p_0 (absolute pressures) is given by

$$\frac{v_1}{v_0} = \frac{6 + y}{1 + 6y} \qquad (2)$$

where $y = p_1/p_0$ and γ, the ratio of specific heats, equals 1.4. Since air in the region of interest ($<$ 10 psi gauge) may be treated as an ideal gas the ratio of temperatures in the shocked and unshocked regions is given by

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$$\frac{T_1}{T_o} = y\,\frac{6 + y}{1 + 6y} \tag{3}$$

where T_1 = absolute temperature immediately behind the shock front

T_o = absolute temperature in the unshocked region.

The expansion after the shock is essentially adiabatic and therefore the time variation of air temperature during this phase is given by

$$\frac{T(t)}{T_1} = \left(\frac{p(t)}{p_1}\right)^{2/7} \tag{4}$$

where p(t) may be obtained from the empirical relationship (1).

We can now make use of the temperature time relationship obtained by combining (1) and (4) to determine the peak over-pressure at which to expect condensation in moist air. Until condensation occurs, the water vapor content of the air represents a thermodynamically unimportant element of the system, e.g., 1 meter^3 of air at 17°C contains only 14.339 gms of water at 100 percent saturation. Under these extreme conditions,

$$\frac{\text{mass of water per meter}^3 \times \text{specific heat of water}}{\text{mass of air per meter}^3 \times \text{specific heat of air}} = \frac{14.339 \times 1}{1270 \times .74} = .047$$

Therefore, we can consider the situation prior to condensation as dealing with dry air which has the simple equation of state

$$pv = n_a RT \tag{5}$$

where p = absolute pressure in psi

v = volume per n_a moles

T-273 = temperature in °C

R = gas constant in mixed units

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It is clear that the liberation of energy due to condensation will tend to decrease the amplitude of the suction phase. This diminution of the suction phase does not affect the point at which condensation starts, but it may decrease the lifetime or the density of the cloud or both and hence make observation of the phenomenon more difficult.

In order to get some idea of the magnitude of the various factors which enter the problem, data from two-ton and four-ton blockbusters (nominal weight) were used to determine the various constants in equation (1) for the 10, 6, and 4 psi pressure levels. The values of these constants scaled to 1 pound of TNT are summarized in Table I.

TABLE I

Initial Peak Overpressure, Positive Impulse and Duration of the Positive Phase at Selected Distances from a One-Pound Charge of TNT

P_o psi	R ft.	I_t psi millisecs	τ_o millisecs	$1/a$ millisecs^{-1}
10	9.7	7.7	2.7	1.35
6	12.3	6.1	3.0	2.33
4	16.4	4.5	3.1	2.94

Fig. 1 shows the excess pressure vs. time and the temperature vs. time for the 4-psi pressure level assuming an unshocked temperature of 290°A and an unshocked pressure of 12.8 psi (approximate Trinity conditions). The curves are insensitive to changes in the unshocked temperature and pressure. Fig. 2 is a plot of the maximum drop of temperature in the suction phase as a function of initial peak overpressure. It shows that at about 10 psi the

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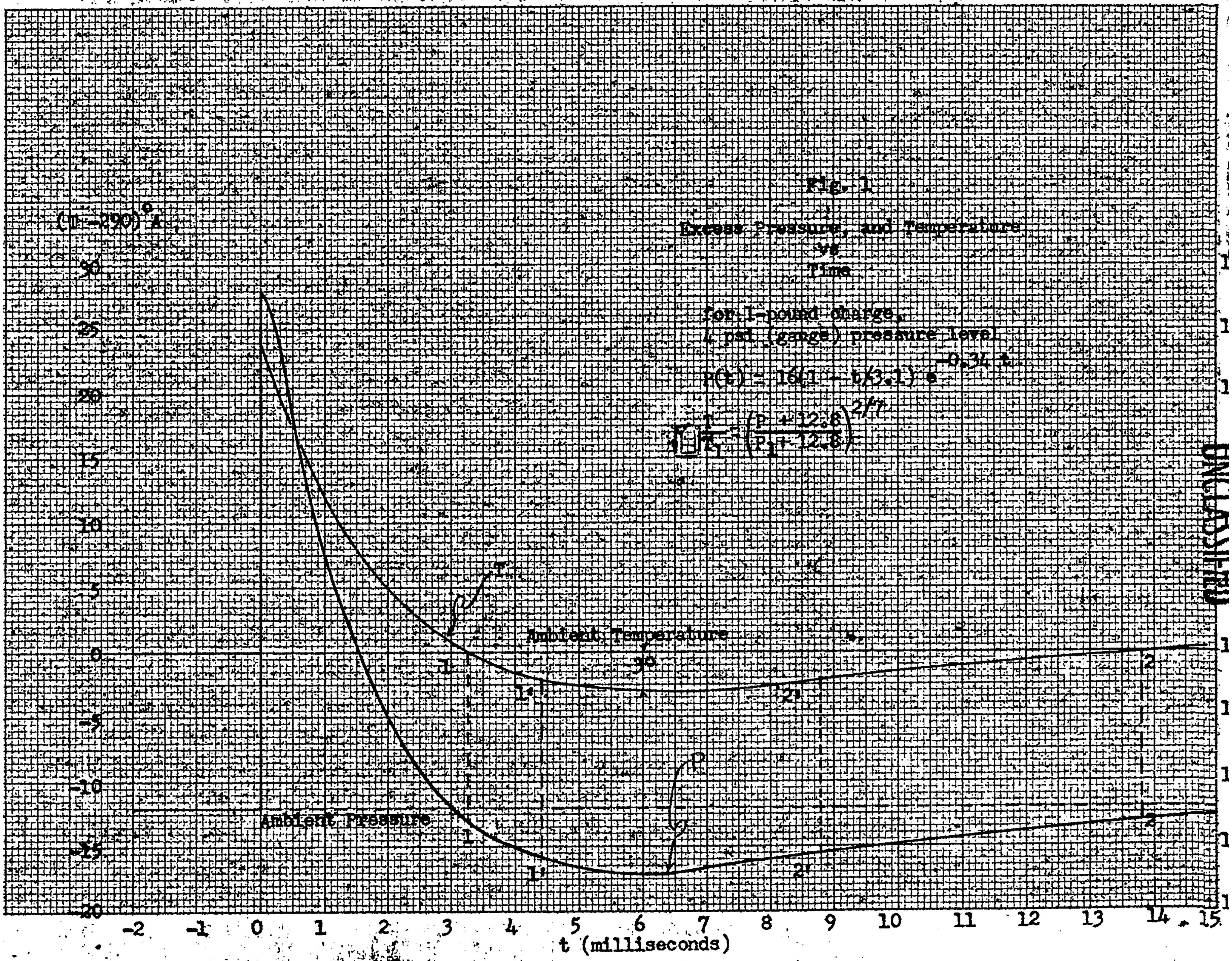

Fig. 1

Excess Pressure, and Temperature
vs
Time

for 1-pound charge,
4 psi (gauge) pressure level

$$P(t) = 16(1 - t/3.1)\, e^{-0.34\, t}$$

$$\frac{T}{T_1} = \left(\frac{P + 12.8}{P_1 + 12.8}\right)^{2/7}$$

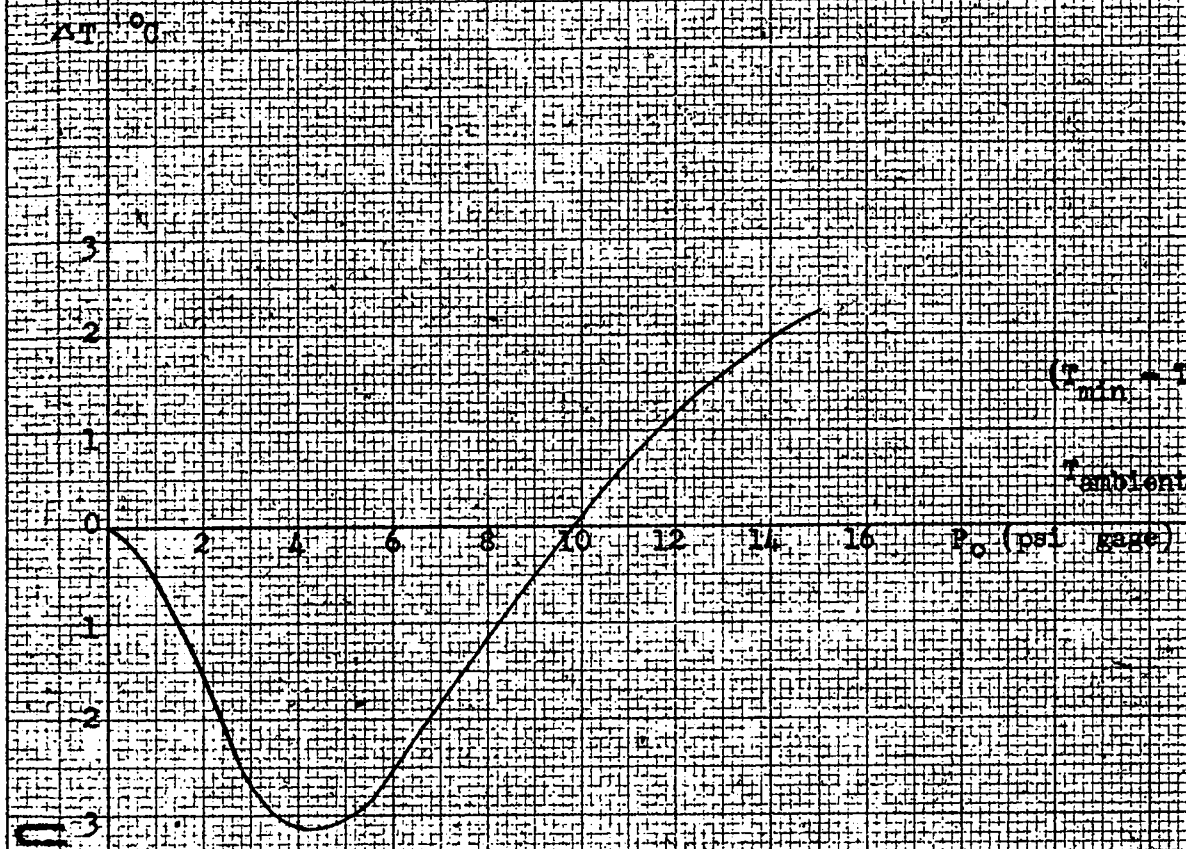

Fig. 2

$(T_{min} - T_{ambient})$ as a function of peak overpressure in the shock.

$T_{ambient} = 290°$ A.

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irreversible heating is sufficient to prevent cooling below the unshocked temperature in the suction phase and that the maximum cooling ~ 3° occurs around 4-psi peak over-pressure. Both curves are for dry air and in view of the above simple calculation which shows that the effect of uncondensed water is negligible, these curves are valid for humid air down the point at which condensation occurs.

Referring to tables (HANDBOOK OF CHEMISTRY AND PHYSICS) of the saturated water vapor content of air at 290° and 287°, we find that an initial relative humidity of 83% (at 290°A) is a lower limit on the value at which we can expect condensation.

For saturated air, Fig. 2 tells us that condensation will start where the initial peak overpressure is slightly less than 10 psi. In the case of initially saturated air Fig. 1 is altered in the region between the points marked 1 and 2. For air which is initially less than saturated the curves are altered in some narrower region, say from 1' to 2'.

Assuming no condensation, the time during which the temperature is below atmospheric at the 4-psi level from 1 pound of TNT is ~ 10 milliseconds. Scaling up to a 5000-ton explosion this time becomes ~ 2 seconds. In view of this great duration the correctness of the adiabatic assumption (4) may seem questionable. However, the extent of the blast wave in space is also scaled up by the same factor and it is considered reasonable that the temperature gradients are sufficiently reduced so that heat transfer is small and the condition is essentially adiabatic.

As was indicated previously, the heat liberated by the condensing water will tend to diminish the density of the cloud and its duration. Out to the radius at which condensation first occurs, the pressure-time curve is unchanged

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from the dry-air pressure-time curve. It is reasonable to assume that in the region of the critical radius, the amount of condensation can be obtained in a rough way by considering the dry air pressure, time curve to be correct.

Even if the condensation in the critical region proves to be sufficient to make a visible cloud, observation of this cloud is limited by the fact that it i not possible to see the inner hole after the cloud has formed. However, we only need to know the position at which condensation started and if it is visible it can be observed quite accurately with a fast motion-picture camera. Incidentally, it is not expected that the ball of fire which was observed to have a diameter of ~100 meters in free air over Japan would interfere either with the occurrence or observation of the fog since its expected radius is ~600 meters and greater.

We will now calculate the expected density of fog in the critical region for a system which is initially saturated. (The modification to be made for other than 100 percent relative humidity is clear.) From the first law of thermodynamics,

$$\frac{dT}{dv} = \frac{p + L(\partial n_w/\partial v)_T}{n_a C_a + L(\partial n_w/\partial T)_v} \tag{6}$$

where the equation of state of air saturated with water vapor is

$$p = \frac{n_a RT}{v} + p(T) \tag{7}$$

and T = absolute temperature °K

L = heat of vaporization of water

v = volume in meters^3 of system having an initial volume of 1 meter^3

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n_a = moles of air in meter^3 at atmospheric pressure prior to the arrival of the shock wave.

n_w = moles of water in meter^3.

Ca = specific heat per mole of air, cal/mole.

C_w = specific heat per mole of water, cal/mole.

and use has been made of the fact that $n_w C_w \ll$ naCa. For the small changes in the suction phase

$$dT/dv \cong \Delta T/\Delta v \tag{8}$$

Δv is obtained by assuming the adiabatic law for dry air,

$$pv^{\gamma} = \text{constant} \tag{9}$$

By using (6) through (9) the change in temperature is calculated. The weight of water condensed per meter^3 is then obtained as the difference between the gm/meter^3 of water in saturated air at the two temperatures. The results are summarized below.

Conditions:

$T = 290^\circ A$, initial peak overpressure = 4 psi

$v = 1$ meter^3, $\Delta v = 0.026$ meters^3

14.339 gm/meter^3 = water vapor content at saturation

$\Delta T \geq .9^\circ C$, ΔT (for dry air) $= -3^\circ C$

Result: ~ 1 gm/meter^3 condenses out.

We are now in a position to discuss whether the condensed vapor should be visible as a cloud. According to Napier-Shaw,* a cloud of fog which lowers visibility to 120 ft can accompany the condensation of 0.87 grams/meter^3. Since an estimated maximum of ~ 1 gram/meter^3 can form into droplets for an atmosphere

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* Shaw, Napier, Manual of Meteorology, Vol. III, p. 342 [illegible] 1942.

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which is initially saturated with water vapor, the prospect of obtaining a cloud sharp enough to measure to within 120 ft is marginal and must be checked experimentally. Some experimental evidence is already available for the formation of a cloud when 3000 tons of TNT exploded on the surface of the ocean, i.e. with almost saturated air initially. This TNT explosion will be discussed in detail in the next section.

Experimental Evidence

I. Large TNT explosion at Sea.

On December 29, 1944 at 2:20 P.M., local time, the Liberty Ship, U.S.S. John Burke, laden with 3200 ± 200 tons of high explosive was blown up by a Kamikaze pilot in the Surigao Straits off Panoan Island in the Philipines. The incident was photographed in color by a medical officer who also served as ship's cameraman aboard the destroyer U.S.S. Bush. The record is of interest to us here because the formation of a cloud and its evaporation was observed, providing experimental evidence for the cloud-chamber effect.

Evaluation of Space, Time Data.

The camera used was a standard Eastman 16-mm Cine Kodak equipped with a fifty-foot magazine and a standard non-telephoto lens with an f-value of 1.9. The focal length of the lens was given by the Kodak Company as 25 mm, the standard value for this model camera. The camera speed used was sixteen frames per second. We are relying on the cameraman's memory throughout for details regarding his camera because all his records were lost.

In addition to data on the camera, we have estimates of the distances involved made by the cameraman and the Commander of the Bush. The cameraman estimates that his distance from the Burke was 3,000 yards, the Com-

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mander estimates it to be about 3,500 yards. Since the cameraman was not particularly experienced in these matters we will discount his guess. The Commander must be considered as fairly reliable because such estimates are important to the operation of his ship. Estimates were also given for the maximum size of the condensed cloud but those must be considered as less reliable than the distance estimates because the need for making such size estimates is much less frequent. In addition, since the size and shape of the cloud was constantly changing the meaning of "maximum size" is not clear. For the record, however, we note that the cameraman estimated the maximum diameter of the cloud to be 700 yards and the Commander estimated the maximum diameter to be somewhat less than 1,000 yards.*

It was observed by the cameraman that the camera shook when it was struck by the air blast. By counting frames from the instant of the explosion to the time when the camera was evidently jarred, as evidenced by a blurred picture, and using a nominal frame speed of 16 frames/sec a value can be obtained for the time required for the shock wave generated by 3,200 tons of TNT to travel from the Bush to the Burke. Frame 187 after the camera catches the spectacle shows such a disturbance. It is not possible to know precisely at which frame the explosion started because the cameraman evidently started photographing the Burke a short time ~1/5 second (~3 frames) after the explosion occurred. This is not a serious correction in view of the relatively great length of time, 11 seconds, required for the blast to traverse the distance from the Bush to the Burke. The distance as reckoned from the time of travel of the

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* There is some confusion as to whether diameter or radius is referred to by these witnesses. Since it is more reasonable in judging the size of an object to give an edge-to-edge dimension, we will assume in the face of this uncertainty that the diameter was estimated.

[redacted]

shock wave is ~ 4500 yards. A lower limit on the size of the dome at frame 20 was obtained by assuming that the radius grew with the velocity of sound, taken as 1100 ft/sec. The value so obtained is a lower limit because a plot of the radius as a function of frame number is described by an equation of the form $r = r_o + vt$ (see Fig. 3). Consideration of all this data and the simple optical relationship

$$(1) \quad p \cong f \frac{L}{\ell}$$

where p = object distance

f = focal length (25 mm)

L = object size

ℓ = image size (6.4 ± .1 mm after 20 frames)

leads us to the conclusion that the distance was >3400 yards. The distance from the Bush to the Burke will be taken as that computed from the shock velocity and time of travel.

$$\text{i.e.} \quad p \cong 4500 \text{ yards}$$

The Commander's estimate of the distance is in fair agreement, 80 percent of the computed distance. From Eq. (1) the maximum diameter of the hemispherical dome was ~1100 yards.

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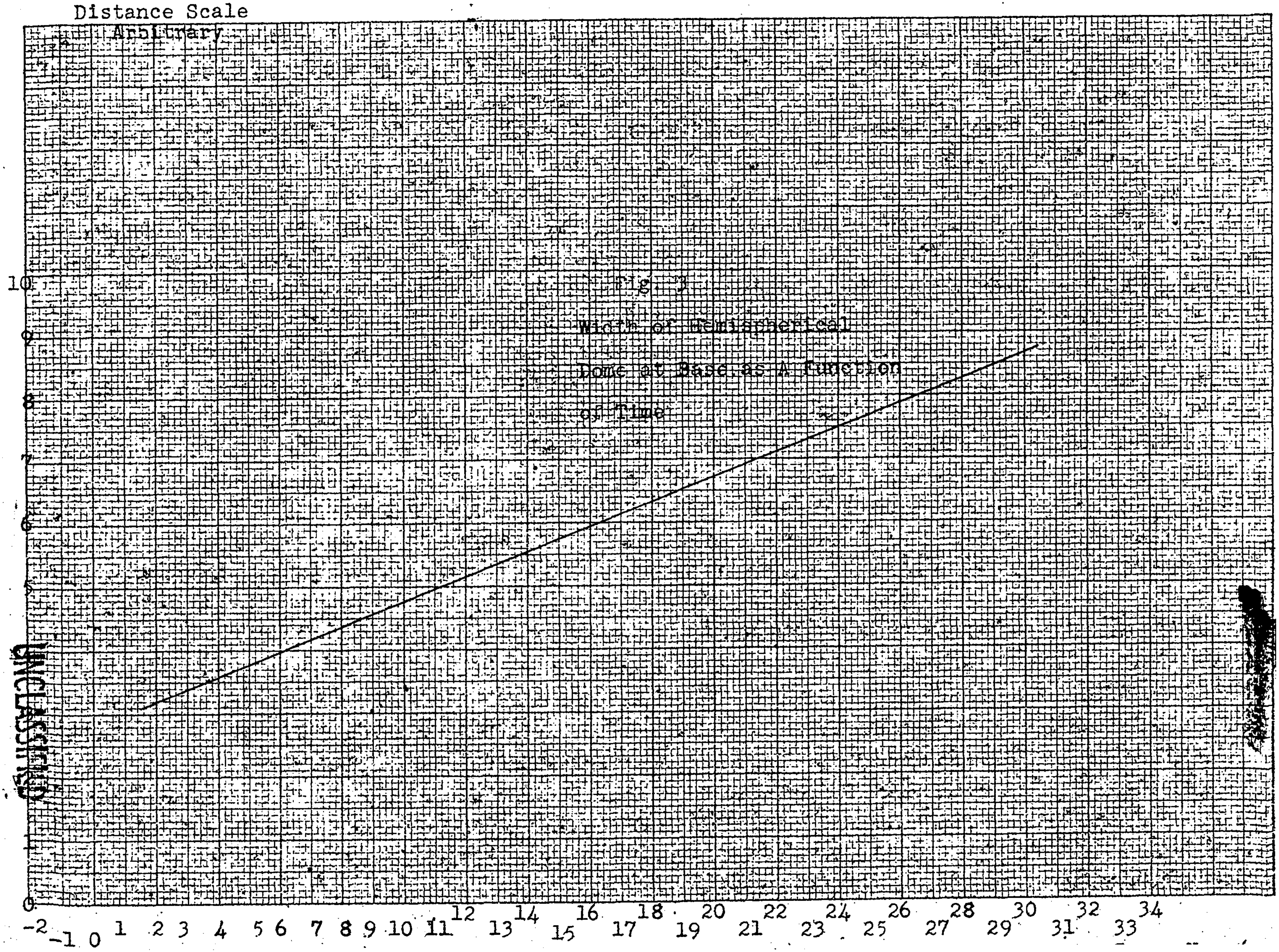

Fig. 3

Width of Hemispherical Dome at Base as A Function of Time

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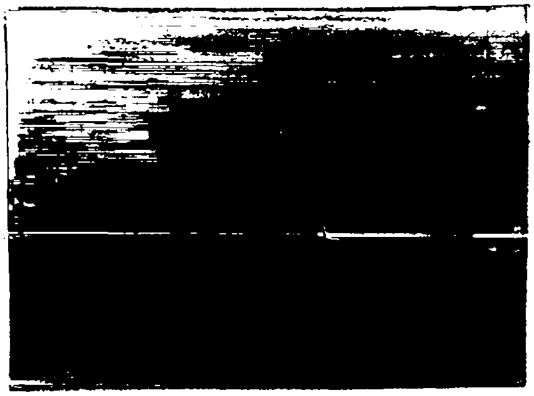

Frame 1 - The explosion is almost off the frame at the right of the picture. Condensation is evident and flame is visible. The original color picture shows the flame very clearly. For reference notice the dark line in the cloud bank behind the explosion.

T=.2 sec

Frame 2 - The entire explosion is now visible. Note the marked assymmetry. Two clouds of about the same size can be seen, a white cloud in the lower left and a reddish-white cloud in the upper right.

T= .25 sec

Frame 5 - The fog now covers the explosion except for some white and black knob-like masses around the hemispherical dome.

T=.4 sec

Frame 7 - In this frame the shape of the cloud seems to indicate the formation of a cylindrical ring at the base of the hemisphere.

T= .5 sec

Distance from camera to explosion: 4,500 yards
Horizontal scale: ⟵——————⟶ 1,000 yards

Fig. 4. Explosion of U.S.S. John Burke

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Frame 8

T = .6 sec

Except for the straight sides the fog is now roughly hemispherical.

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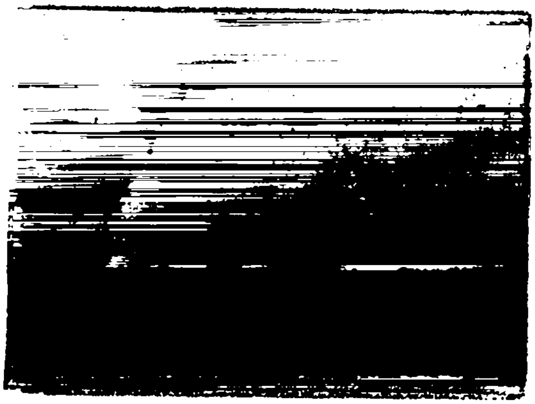
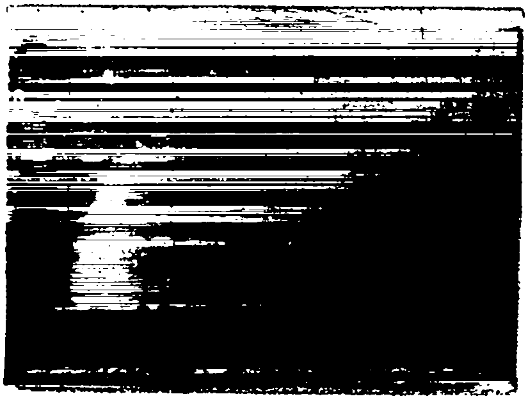


Frame 11

T = .8 sec

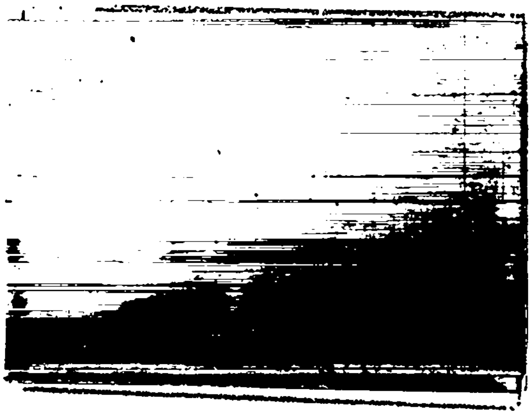
At this stage the explosion is completely obscured by the cloud. The boundaries of the cloud are quite sharp (< 30 ft). Note the spray on the surface of the ocean, and the lack of huge surface waves.



Frame 18

T = 1.2 sec

The cloud is now losing its hemispherical shape and clean-cut edges. The top of the cloud has merged with the clouds present in the atmosphere before the explosion.



Frame 29

T = 1.9 sec

This frame shows the cloud as an amorphous mass the outlines of which are barely distinguishable.

Horizontal scale ⟷ 1,000 yards

Fig. 4

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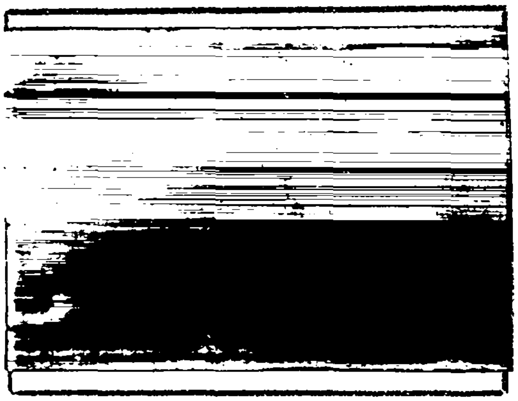


Frame 53

T = 3.3 sec

The cloud has now grown so that it extends outside the camera field.

Frame 72

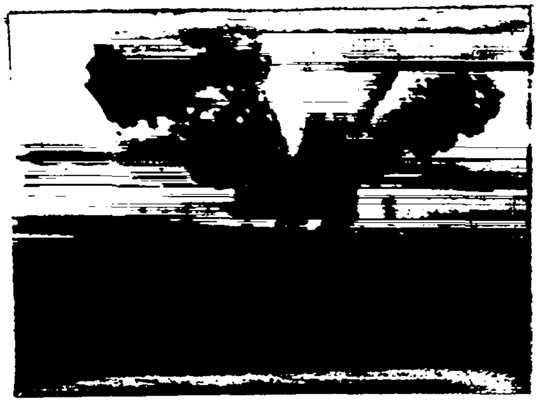
T = 4.5 sec

As the cloud evaporates from the surface of the ocean up, we can see the inner holocaust and various projectiles which comprised part of the cargo shooting into the air.

Frame 99

T = 6.2 sec

The cloud continues to rise disclosing a tremendous smoke column which tops what appears to be a water spout.



Frame 184

T = 11.5 sec

This last frame shows the cloud essentially evaporated. Although not visible here, the original pictures reveal missiles now dropping back to the sea which were originally thrown into the air by the explosive.

Horizontal scale: ⟵——————⟶ 1,000 yards

Fig. 4

[redacted]

Discussion of Results

We will now compare the observed cloud-chamber effect with the simple theory of section I. According to the theoretical calculation, if condensation occurs when the air becomes very slightly supersaturated and if the air is initially saturated, a cloud should first form at 550 yards, the distance at which the overpressure dropped to 10 psi. The observations are not inconsistent with those predictions for ~ 3000 tons TNT but unfortunately they are somewhat incomplete because the beginning of the explosion was not photographed (see frame 1 and compare with frame 2).

It was discovered in the process of abstracting the data that the radius was a linear function of time $r = r_0 + vt$, in the range in which data was available. The reason for $r_0 > 0$ can be seen in the following qualitative way. A blast wave from an explosion travels a certain distance before developing a suction phase. This distance is traversed with a velocity much faster than sound. As the wave proceeds a suction phase develops, and the pressure-time curve crosses the axis and falls below its preshock value. The point in the blast wave which separates positive and negative gauge pressures travels with the velocity of sound in the shocked and heated air. From the distance at which it occurs this "sonic point" which indicates the onset of rarefaction, cooling, and eventually cloud formation, travels outward with a velocity which asymptotically approaches the velocity of sound in unshocked air. Fig. 3 indicates that this limit is practically reached very early in the expansion and hence that the initial higher velocity phase is very short compared to the observed 1-1/4 sec period of expansion.

From its formation to its eventual evaporation, the cloud persisted

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for 11 seconds. When it started evaporating after 3 seconds, it did so from the surface of the ocean upwards. It seems reasonable that the evaporation should have proceeded in this direction because the rate of evaporation depends in an inverse manner on the initial relative humidity of the surrounding air. The absence of a low fog and the presence of clouds higher up indicates that the humidity actually increased with altitude and was somewhat less than saturated near the surface of the water. Very little can be said about the expected lifetime of the cloud since the actual humidity was not known and the results indicate that the lifetime is a sensitive function of the humidity.

The shape of the cloud suggests the formation of a Mach stem. However, a comparison of the height of the cloud's cylindrical section with the distance from the explosion indicates that the straight side is far too short for this to be an example of the Mach phenomenon. The ring may be a shape effect due to the hull of the ship.

In passing, it might also be mentioned that the waves produced by this surface explosion were small (< 50* ft) in the vicinity of the ship ($\sim$500 yds) in roughly accordance with an investigation of Penney and Shapiro.

II. Nuclear Explosion at Trinity, July 16, 1945

The incidence of heavy rain in the night prior to the July 16 test left a few strata of high relative humidity in the air above the bomb. Three consecutive pictures, Figs. 5, 6, 7, obtained by Mack's group indicate the formation of clouds by the blast in these regions of high relative humidity. Hubbard's group found (LA-357) that there were three layers of humidity greater than 95 percent between 4 and 7 kilometers and noted that condensation occurred

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* This is an estimate made by inspecting the pictures in this report.

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in these three layers as the shock wave passed through. Two of these layers are visible in Figs. 6 and 7, taken 12 and 15 seconds after detonation. The average velocity of the blast wave over these great distances is practically the velocity of sound, 1100 ft/sec as expected for weak shocks. In order to make the clouds visible in these pictures, the photographic group found it necessary to adjust the printing time and "burn" the clouds in.

The peak overpressure at 4 kilometers above the explosion was calculated by the IBM to have been ~0.5 psi. The maximum suction was 0.3 psi and it corresponded to a maximum drop in temperature of ~3° C below the pre-shock temperature. A relative humidity in the neighborhood of about 90 percent is sufficient to cause supersaturation under these conditions. This agrees with the observations. The effect of the ground on the blast wave is not expected to alter these rough considerations.

Other Evidence

An examination of the color film taken a few seconds after the Nagasaki drop indicates the formation of a barely visible cloud which traveled out from the explosion. The humidity conditions were probably such that the cloud had an extremely short lifetime and hence existed only in the immediate neighborhood of the suction phase of the expanding blast wave.

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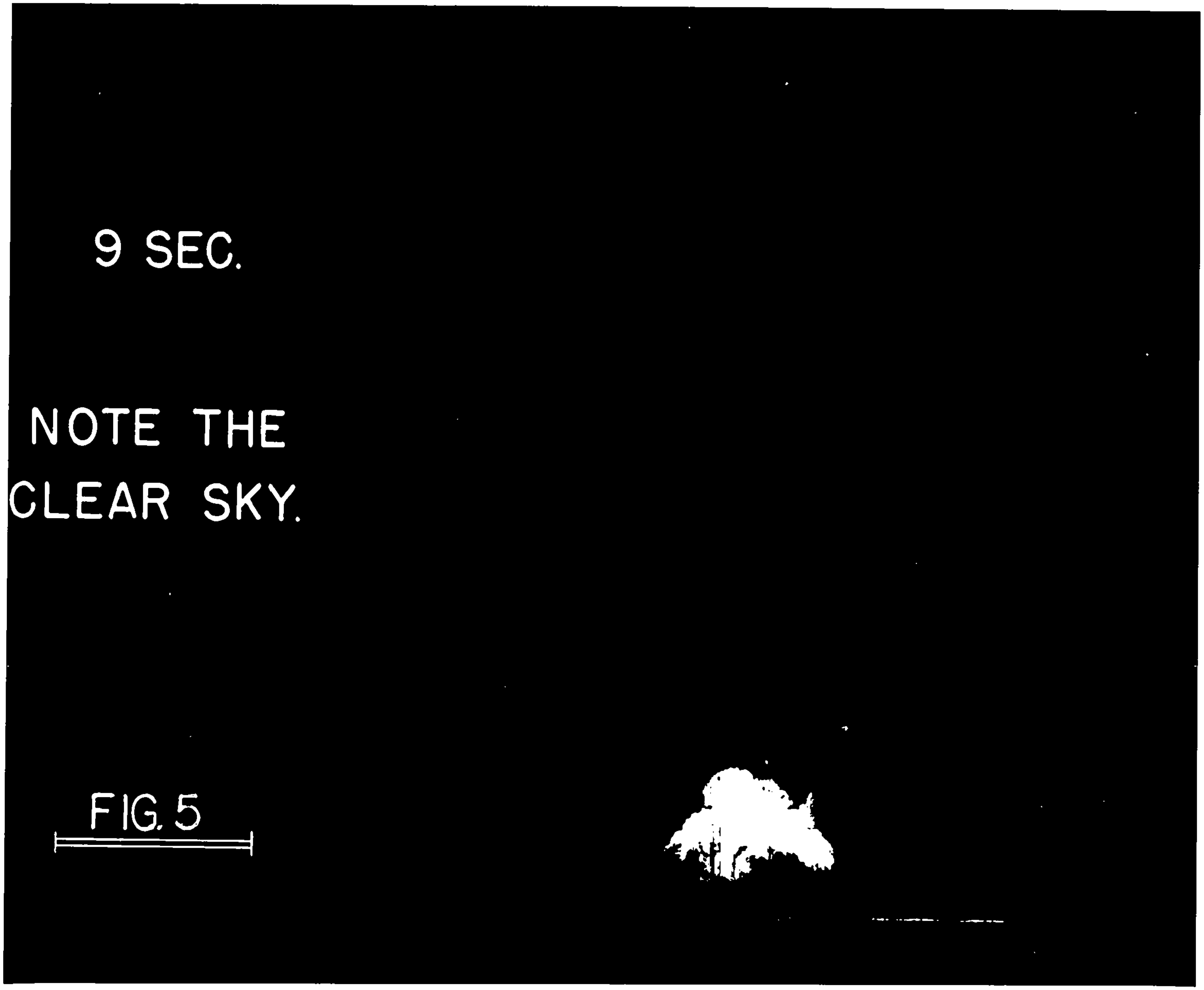
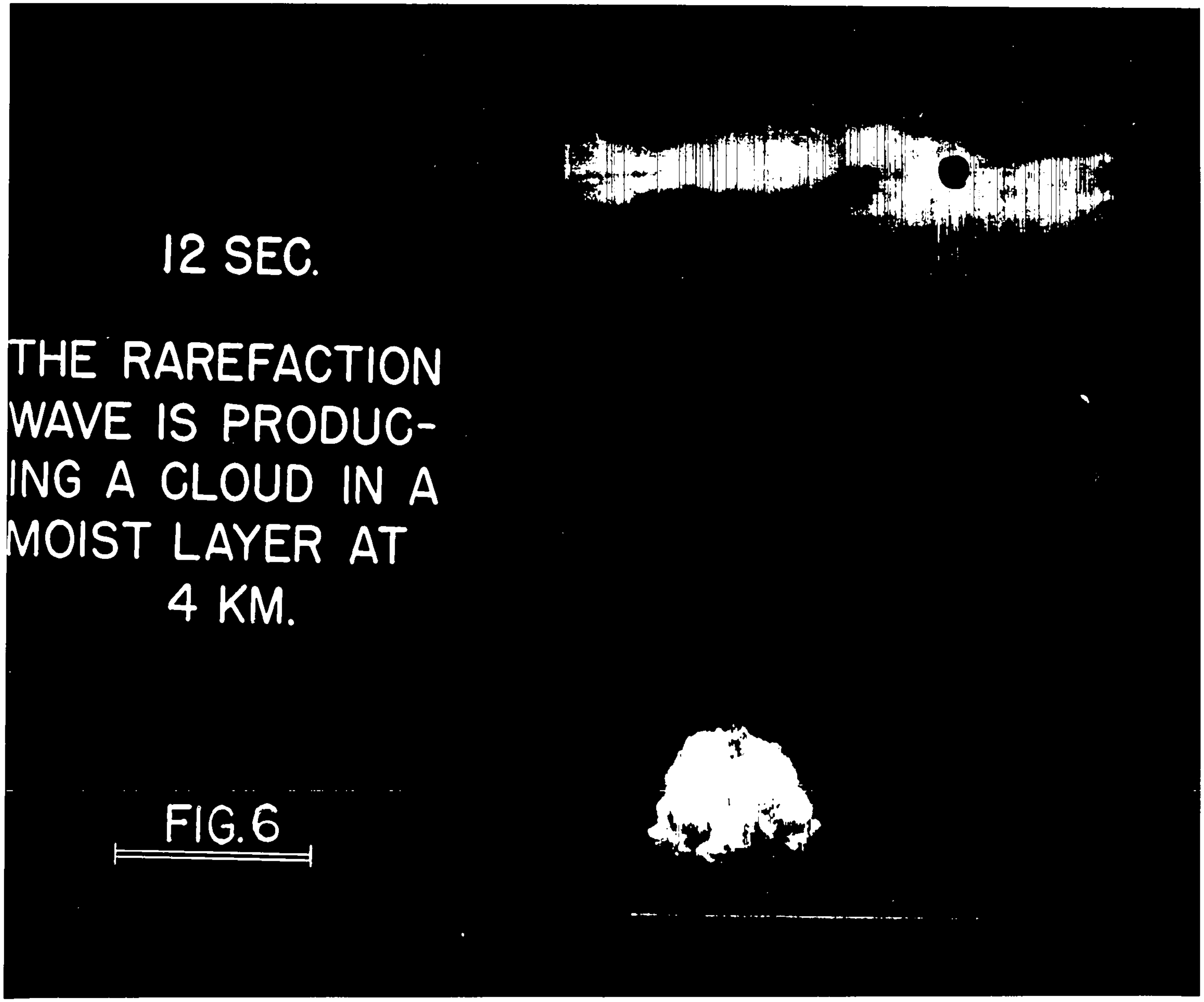


9 SEC.

NOTE THE
CLEAR SKY.

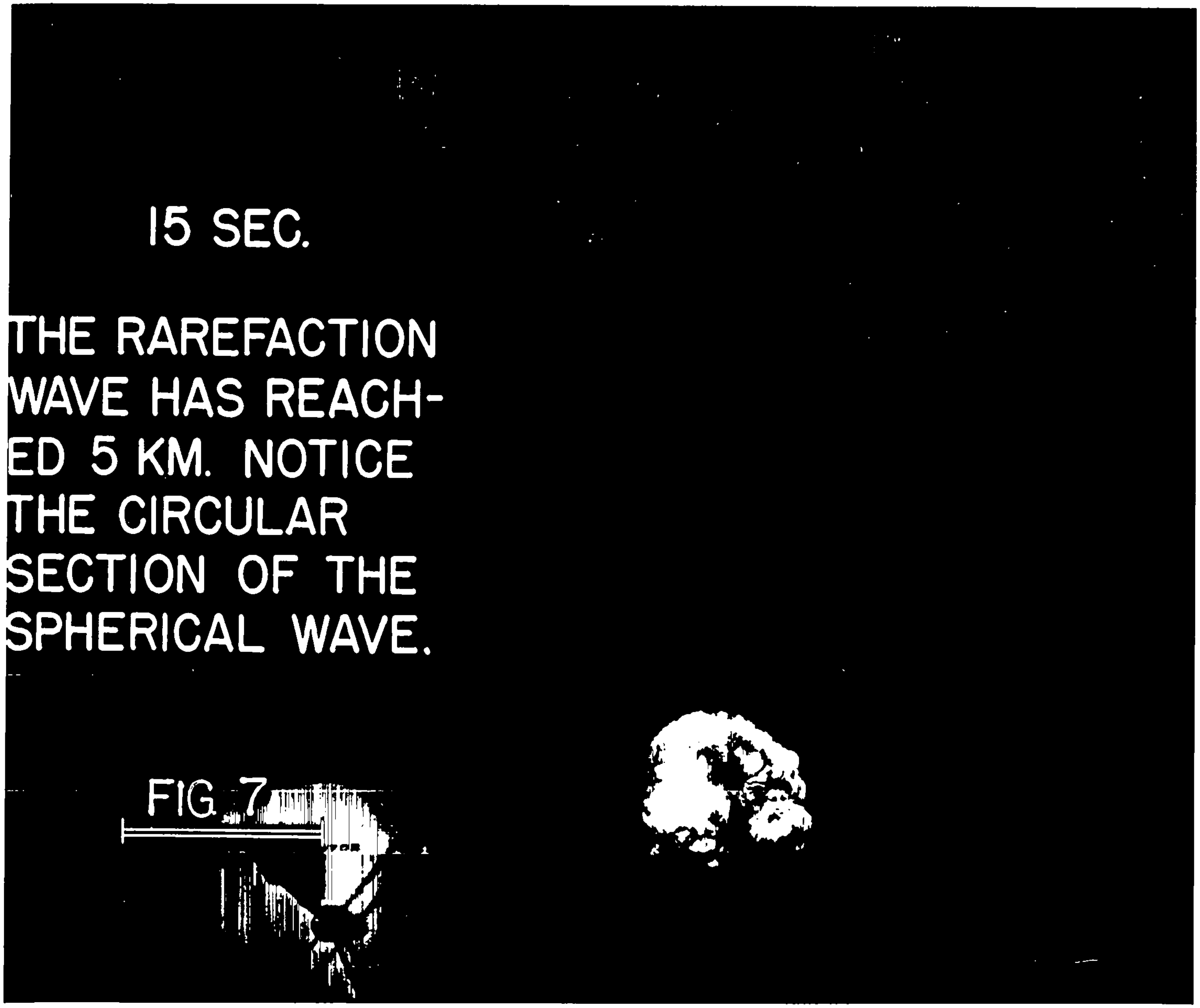
FIG. 5



12 SEC.

THE RAREFACTION
WAVE IS PRODUC-
ING A CLOUD IN A
MOIST LAYER AT
4 KM.

FIG. 6



15 SEC.

THE RAREFACTION WAVE HAS REACHED 5 KM. NOTICE THE CIRCULAR SECTION OF THE SPHERICAL WAVE.

FIG. 7

[redacted]

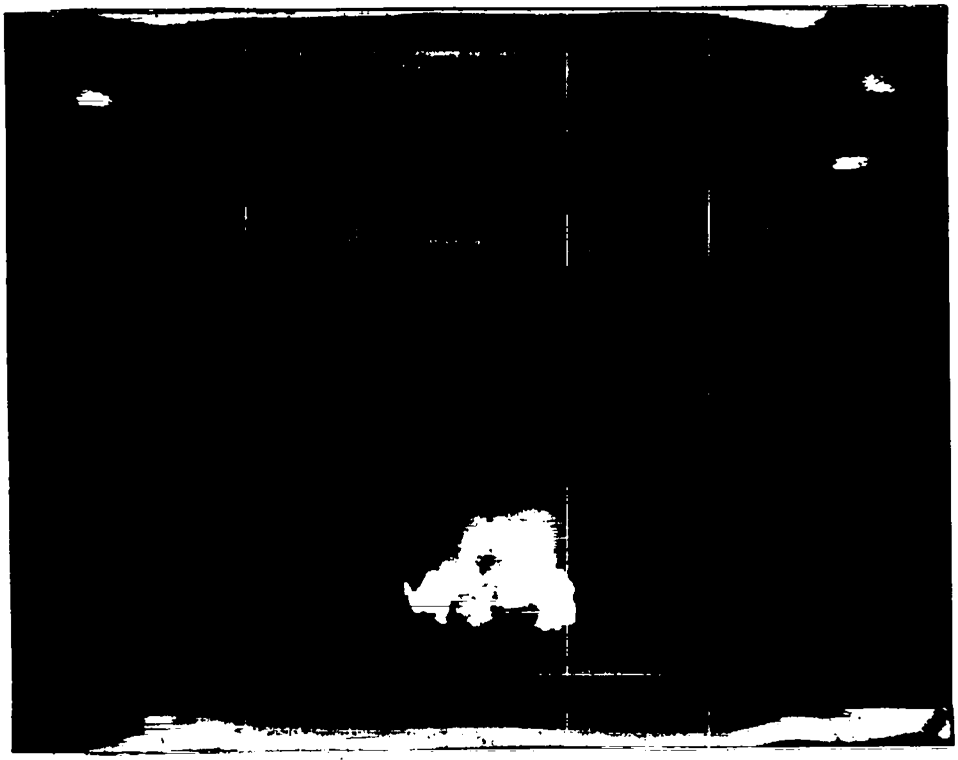


Fig. 8. This color photograph was taken by Jack Aeby about 10 seconds after detonation. Two cloud layers are visible. Color pictures taken a few seconds earlier and later do not show such clouds, indicating the occurrence of the cloud chamber effect. The picture is not retouched.

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