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Air Currents Above Ground Zero Area After a Low Air Burst and Their Relation to Fall-Out

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CURRENTS ABOVE GROUND ZERO AREA AFTER A LOW AIR BURST AND THEIR RELATION TO FALL-OUT

by W. G. Penney

SUMMARY

Both of the Totem shots fused the ground around the tower to a radius of 100 metres. The average depth of the fused layer was judged to be 6 mm. It is estimated that 600-800 calories/cm^2 were left as heat in the fused area when the fire-ball lifted. During the next minute or two, a strong convection jet rose from the fused area. Approximately 100 cal/cm^2 were radiated as heat from the fused area, and the remainder went into the convection jet. From observations on the speed of the jet and from an application of Schmidt's theory of the convection jet from a point source of heat on a horizontal plane, it is shown that the total heat put into the jet was about 1800 cal/cm^2, or 560 tons TNT equivalent for the whole of the fused area. Thus we have obtained as good a balance of the energy equation as we could possibly expect.

The early part of the convection jet sweeps upwards and has enough buoyancy to reach a level of several thousand feet, the exact height depending on the lapse rate. At some level, the top of the jet comes to rest, and spreads sideways, making as it were a small cloud on the stem, well below the main cloud.

The lowest few thousand feet of the stem are of low activity. The Totem II shot, because of the unusual conditions of wind shear prevailing, demonstrated conclusively that much of the activity in the fall-out pattern up to 3 miles distance, came from heights in the air not more than 5,000 feet, and much of this activity came from the first two or three thousand feet. The conclusion is inescapable that activity falls out of the cloud from the very first moment when the cloud lifts and is left in the air around the column which itself is clean. A theoretical formula is devised

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for the concentration of activity left in the air by the rising cloud. The simplest version of the theory, called Theory A, is that particles are sedimenting out of the base of the cloud. Particles of diameter μ leave the base at a rate proportional to V_μ, their free falling velocity in still air. According to this theory, particles of all sizes are left behind in the air but there are relatively far fewer of the smaller particles than there are in the soil material. Even so, a large part of the activity is held on these smaller particles, and this appears to disagree with the Totem II fall-out contours.

A second version of the theory uses the experimental form of the particle size distribution in the soil and assumes that the smaller particles cannot sediment from the base of the rising cloud because the base of the cloud is growing downwards with respect to the air just below by turbulent in-mixing. Only the larger particles can get away. In this form the theory reproduces the main features of the fall-out patterns of Totem II.

Approximately 14% of the total activity of the weapon was distributed over the surface of the soil particles. The rest was in the cloud as very small particles whose activities were proportional to their volume.

Fall-out up to distances of 300 miles would be mainly from the soil particles, and we would therefore expect to find less than 10% of the total activity on the ground up to 300 miles. This appears to be so.

About 1.0×10^{-3} of the total activity of the weapon was left in each 1,000 feet of air as the cloud rose. This result applies up to about 8,000 feet.

If the ideas put forward in this paper stand up to criticism and to further experimental results, a result of the highest importance follows. A weapon in the megaton range gives an enormous cloud which rises and expands with velocities scaling like $(\text{yield})^{1/6}$. Only particles of 700 - 800 microns

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diameter, or larger, will be heavy enough to escape from the rising cloud of a megaton explosion. Since there are hardly any such particles in the soil, the activity in the contamination contours up to 20 miles or more will be only one or two percent of those predicted from the normal scaling laws. At distances 20-50 miles, depending on the mean winds up to cloud height, the normal fall-out scaled contours will apply.

While the surface burst of a weapon in the kiloton range causes one half of the activity to fall on the ground within a few miles of burst, there are reasons for thinking that a surface burst of a weapon in the megaton range will cause relatively small contamination within 20 miles. At greater distances, the fall-out will be severe, but even so not more than about 10% of the total activity will come back to ground within a day.

Introduction

When a weapon of a few kilotons explodes on a tower, or as an air burst, the ground zero region becomes very hot. The cloud rises and leaves a wake behind it. The hot ground near ground zero causes vigorous convection currents which stream up after the cloud, and become mixed with the wake of the cloud.

In this paper, an attempt will be made to discuss the mechanics of the convection currents from the ground zero area. The problem, of course, is one of great physical complexity, and it is impossible to give more than a semi-quantitative discussion.

A point of great practical importance is to know whether the convection currents have much influence on the immediate fall-out pattern near the burst. Even if the effect is not great for bursts in the kiloton range, the situation may be different for megaton bursts. We reach the important conclusion that fall-out in the near vicinity of a low air burst does not come from the stem, or column, as we had hitherto thought. The lower parts of the stem are inactive. Fall-out comes from the base of the cloud as it rises; and the amount of fall-out leaving the cloud as it rises for the first

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few thousand feet is of the order 0.1% to 1%, depending on the height of burst and the yield. A megaton explosion, at the corresponding scaled height of burst would give a near-in pattern of fall-out less severe than predicted from the usual scaling laws.

AIR CURRENTS CAUSED BY THE RISING CLOUD AND BY THE FUSED AREA

When an atomic explosion takes place so far above the ground that the heating of the ground is negligible, the cloud rises without being influenced by the ground. The flow pattern at such high Reynold's numbers, but low Mach numbers, is outside the range of normal experience but there is no doubt about the general characteristics of the motion. These have been described by various authors, notably Sir Geoffrey Taylor.

The air flow pattern around the cloud breaks away from the edge of the cap and there is a vortex sheet enveloping a "wake" leaving the cap. The motion in the wake is extremely turbulent. Just behind the cap is a region of "dead water" in the wake moving with the cap. This turbulence allows the dust from the cap to become diffused through the dead water, and the cap and the dead water thus form the cloud. The tail of the dead water moves away from the stagnant region and forms the stem or column, which therefore is highly radioactive. The wake, however, is wider than the stem and has the approximate width of the cloud itself. At large distances behind the cloud, the wake is wider than the cloud. The first diagram sketches the situation for very high air bursts. Because the wake starts in the air and because the boundary surface is a vortex sheet, we would expect that a high air burst would cause a very large vortex ring.

The main features of the flow pattern caused by a burst near the ground can be more easily understood if the ground is imagined removed, and an image cloud inserted into an image atmosphere. As the cloud and its image move apart, air is drawn in from the sides to fill the vacant space. Some of this air goes into the wakes and it would seem that the inflow of air must "pinch in" the wakes. In the region exactly central between the two clouds, there is a stagnant turbulent region. The speed at which the fireball separates

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flow of the image is severely checked at first because the separation requires the creation of a partial vacuum into which the air must flow. As the two clouds move further apart, each of them begins to establish a "steady state" wake. The pinch effect is less and the wake and column should be wider and nearer to the "steady state" value. The mean velocity in the central stagnant region between the two clouds, representing the region of the ground, should be small and should be quadratic in the distance from the plane of symmetry. The second diagram illustrates the situation.

In the real case, however, the presence of the ground affects the motion through an additional mechanism not so far considered. The ground is left very hot and the hot ground causes a convection current. Near the ground, the velocity at which the air is rising in the stem must be caused mainly by the convection heating. Higher up the stem, and thus nearer to the cloud, the upward streaming of the stem is mainly the wake current caused by the rising cloud.

In the following paragraphs we investigate whether the magnitude of the rising current near the hot ground is roughly in agreement with what we should expect from the amount of heat put into the ground, and we find that this is so. While this result is both interesting and satisfactory, we reach a conclusion of much greater importance. This is that the lowest few thousand feet of the stem made by a tower burst contains little radioactivity. While that part of the stem which is receding from the dead water of the wake is falling behind the cloud, it is still rising rapidly in the atmosphere, and it is being pushed from below by a vigorous convection jet from the hot ground. Later in this paper we shall explain how this deduction compels us to make a new and clearer description of the processes of fall-out from the rising cloud.

A low air burst over the desert fuses the ground over a circular area whose radius is 100 yards or more, depending on the yield and on the height of burst. This fused area, when it has cooled, looks like a dull, green slag or glass. The thickness of the fused material at Totem was in the main variable between

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4 and 7 millimetres. However, there were places where only the first millimetre was fused and there were other places where the material had fused and run into a puddle, with a depth of an inch or more. We assume that the average depth was 6 mm or 1.5 gm/cm^2. The transition from fused material to unfused material was quite sharp, and the radius of the fused area gave a fairly accurate value of the extent of the fireball.

One observation of interest at the Totem experiments was that surrounding the fused area there was a layer, about two inches deep, of extremely fine desert sand which had obviously settled within minutes of the time when burst occurred; but there was no covering of this fine material over the fused area itself. One can be sure that this fine dust settled around the fused area after burst (and was not simply the soil that was there originally, pulverized by the blast), because all sorts of things could be found buried underneath. For example, bits of mulga trees, short lengths of cables, etc., were buried under this fine dust. Unfortunately, we did not take samples of this dust, but the depth was measured at a number of places.

Experiments have shown that the temperature at which the desert material melts and forms a crude glass is about 2,000° K, while the temperature at which it begins to boil is only a few hundred degrees higher. It seems a fair approximation, having regard to the turbulence and the great violence of the motion during the fireball stage, to assume that the fused layer had approximately constant temperature, and that this temperature was about 2,000° - 2,500° K.

One of the problems we wish to consider is how this fused material cooled. There are two principal mechanisms. The first is radiative cooling, the second is convection cooling.

The specific heat of the fused material has been measured as 0.18 calories per gramme at ordinary temperatures, rising to about 0.25 at the melting temperature.

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To get the order of magnitude of the quantities of importance, we may say that the radius of the fused area for both Totem shots was 10^4 cm. The average thickness of the fused area was about 6 mm or 1.5 gm/cm^2. Then the energy required to take the material to the melting point would be about 600 cal/cm^2, and to take the material to the boiling point would require about 800 cal/cm^2. If 1 kT of energy were distributed over a circle of radius 10^4 cm, the energy per unit area would be 3,000 cal/cm^2.

As the fireball rose above the ground, the hot fused area began to radiate heat, without receiving very much in return. Taking the emissivity as 0.4, then at 2,500° K the rate of radiation of energy per unit area is 21 cal/cm^2 sec. Since there was something like 700 calories available in the fused material, then, if it were not for cooling, all the energy would be radiated in 700 ÷ 21, say 35 seconds. Now the rate of emission of radiant heat is proportional to the fourth power of the temperature, and it is therefore clear that radiation cooling alone would be a comparatively slow process, and that the fused area would still be very hot after several minutes. The radiation equation is considered in an Appendix.

We turn now to consider the cooling by convection. The large fused area causes a rising convection current which is fed by air sucked over the fused area from the surrounding atmosphere. Unfortunately there is no experimental or theoretical treatment fully adequate to cover the situation which we are considering. Even the known steady state solutions of certain related heat convection problems are highly idealised. Accordingly, then, we can only treat matters very approximately.

Schmidt (ZAAM 28, 346, 1948) has discussed theoretically the convection jet caused by a line source of heat on a rigid horizontal plane, there being no wind. He also treated the currents caused by a point source of heat on a horizontal plane. He describes experiments which show that his theory gives a reasonable

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[redacted] the convection currents.

The point source of heat analysis is helpful in our problems. Schmidt's results are summarised by the following formulae:-

$$\left.\begin{aligned} W &= 6.9 \times 10^{-6}\, V^3 Z \\ \theta &= 1680\, W^{2/3}\, Z^{-5/3} \end{aligned}\right\} \qquad (1)$$

where the heat source is W calories per second, V cm/sec is the velocity at the centre of the jet at height Z cm above the source and θ is the temperature excess at the centre of the jet in degrees Centigrade, above that of the undisturbed air.

We might apply Schmidt's results to the convection currents above the fused area made by the Totem shots in the following way. The radius of the fused area was 10^4 cm, instead of being a "point source", as in Schmidt's theory. Accordingly, we assume that the convection currents above the fused area were equal, or nearly equal, to those that would have been produced by a point source on ground which was 10^4 cm $\div$ 0.28, the divisor 0.28 being the tangent of the semi-angle of the turbulent convection jet, as measured by Schmidt. In other words, in applying Schmidt's theory, we must suppose that the ground was 350 metres lower than it really was. The use of Schmidt's theory in this way is approximate, for the stream line flow outside the jet is different in the model considered, and in the real case of the finite source; but the numerical values should not be too widely different except near the source.

Rough experiments with the grill plate of an electric cooker indicate that the application of Schmidt's formulae to a finite source on a plane is fairly good at one diameter above the source, provided the theory is applied as we have suggested. The jet velocity and temperature are more evenly spread over the jet, and the average values are as calculated.

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The rate of rise of the convection currents above the fused area decreases as the area cools. Strictly speaking, therefore, we are not entitled to use Schmidt's theory to evaluate the rate of heat release by the source. We must regard the convection currents above the fused area as quasi-steady, i.e. that the current speeds at any time are given approximately, but not exactly, by the heat being released at that time. The errors caused by this approximation are probably no greater than those introduced by other approximations which we have made.

Referring back to Schmidt's formulae, it will be seen that the rate of heat release by the source is proportional to the cube of the convection current at any given height above the source. To find the total heat released by the fused area, through the mechanism of convection, we therefore require time integral of the cube of the current speed.

Cinematic photographs of the Totem explosions enable estimates to be made of the rate of rise of the convection currents above the fused area. The speed of the convection jet 700-2,500 feet above the fused area at Totem varied with time. Details are given later, but for the moment, let us take a value of 2,000 cm/sec. Then using Schmidt's theory, the rate of production of heat to give a speed of 2,000 cm/sec at a height 350 metres is given by

$$W = 3.8 \times 10^9 \text{ cal/sec.}$$

This rate of heat production is the equivalent of the detonation energy of 38 tons of TNT per second.

The rate of heat production distributed uniformly over a circle of radius 10^4 cm (the radius of the fused area) gives a rate of heat production per unit area as follows:

$$\frac{dH}{dt} = 12 \text{ cal/cm}^2 \text{ sec}$$

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Assuming that the heat production lasted one minute, the total amount of heat given to the air by the fused area, per unit area, is given by

$$H = 720 \text{ cals/cm}^2$$

This has to be compared with the estimate made earlier that 700 cals/cm^2 had been left by the fireball in the fused area.

The speed of the convection currents above the fused areas at Totem were erratic and to get really satisfactory values a large number of readings have to be made. The following values can probably be improved and made more self-consistent, by making more measurements, but approximately at any rate, the following values are correct.

Totem I - Velocities 600-800 feet above area

Time after burst seconds	16	24	28	52	60
Speed of rising current cm/sec	2200	1470	1470	1050	420

These results may be fitted to a law of exponential decay, as follows:

$$V = V_o e^{-\alpha t}$$

with $V_o = 3400$ cm/sec and $\alpha = 0.0310$ sec^{-1}.

Now what was measured of course was the upward velocity of the stem at the outside, say 100 metres from the centre. On a Z value of 700 metres, this is an angle $\tan^{-1}(1/7)$. The mean value of $\bar{V}$ over this section of the jet, according to Schmidt, is 0.63 of the value at the centre. We therefore say that the Schmidt equivalent jet speed at the centre is V/0.63 and we call this V_s. Then

$$V_s = 5400e^{-0.031ot} \text{ cm/sec} \qquad (2)$$

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We require the integral of V_s^3 from the time when the fireball lifted, say t = 5 secs.

Then from the formula

$$\int_5^\infty V_s^3 dt = 1.2 \times 10^{12} \text{ c.g.s. units.}$$

Measurements on the Totem II currents are in hand and the currents at 600-1,000 feet above the fused area are roughly equal to those of Totem I. There is a pronounced difference in the behaviour of the currents higher up, due to the considerable difference in the lapse rates at the two experiments.

Taking Schmidt's formula for the velocity at the centre of the jet 700 metres above the source, integrating with respect to time for the exponentially decaying source, we find that for Totem I the total energy put into the heat currents was 5.8×10^{11} calories or 580 tons TNT equivalent. This is 1,850 cal/cm^2 over the fused area, in fair agreement with the value of 700 cal/cm^2 which we had expected from our earlier arguments.

Three further points must be considered. First, the treatment we have given of the convection currents does not allow for the stability of the atmosphere. Second, there is the preheating of the air by the irreversible processes of the shock wave. Third, there is the loading of the air by dust.

To enable the heated air to rise to several thousand feet, the input of heat must be enough not only to give a convection jet as in Schmidt's theory, but also to make up for the difference of potential temperature at ground level and at several thousand feet. Schmidt's theory can only be applied up to heights Z where the rise in temperature θ is several times greater than the potential temperature difference at ground level and at height Z. At greater heights, the condition is no longer satisfied. Due to the stability of the atmosphere, the rate of rise of the convection jet decreases. At some height, the jet comes to rest and spreads horizontally.

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In the Totem I shot, the difference in potential temperature at ground level and at 1,000 feet was 6°C. The rise in temperature due to the heat when the observed speed of the convection jet is 1500 cm/sec at 1,000 feet above the ground is 50°C. Since the air in the jet at this height comes from all heights up to 1,000 feet, the average potential temperature is perhaps one third of 6°C, say 2°C. This is small compared with 50°C, calculated from Schmidt's formula for the point source. Even allowing for the greater spread of the heat from a finite source, the temperature excess is enough to be regarded as large compared with the loss of potential temperature due to the lapse rate in the atmosphere. Thus we have correctly applied Schmidt's theory at least to the stage where the observed speed of the stem at 1,000 feet is 1,500 cm/sec, viz. 25 seconds. The contribution to the integral of V^3 is small for later times.

The early part of the convection jet is formed while the ground is still very hot. This part of the jet will be continuing to rise fast while the lower part of the jet is much slower, due to the cooling. The upper part of the jet will slow down when the temperature excess is about equal to the potential temperature at the height concerned. The jet will stop when the temperature excess is about equal to the average potential temperature between the level of the top of the jet and at ground level. A swelling should occur in the stem at this level. The appearance will be like a second cloud on the stem, below the main cloud. Both Totem I and Totem II showed these swellings, the former at 6,000 feet and the latter at 4,000 feet.

The point which has been raised on the preheating of the air around the explosion due to the irreversible processes of the shock wave is substantial enough to upset the numerical agreement which we have obtained, but not by very much. The irreversible heating by a shock of overpressure 5 atmospheres is 45°C, and this pressure

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Mfeurs at a distance of about 600 feet. The air will move out to about 2000 feet. This air is hot enough to go with the fireball. In fact, the reason why the cloud even after 10 seconds or so is much bigger than the fireball, is due to the hot air around it going with it and mixing in. The cloud "radius" at both Totem shots was about 800 feet at 8 seconds. Since the shock heating falls off so quickly with distance (almost R^{-6}) we see that the pre-heating effect is not negligible. The air that was sucked into the space left by the rising fireball was hot as the result of the shock wave heating. This air must have risen immediately behind the fireball. As time progressed, the air which was sucked in by the convection was colder and for this reason, as well as because of the cooling of the fused area, the convection jet became slower.

The preheating of the air by blast probably made a substantial addition to the strength of the convection jet. To some extent we could argue this from one result that the heat in the jet at Totem appears to have at least twice as much energy as was left in the fused area. Another line of argument, pointing the same way, is that at the Bikini Able shot, there was a powerful convection jet below the rising cloud. The heat from the fireball must have left the top few inches of the sea water boiling and the heat in this layer would give quite a powerful convection jet (the rate of rise of the jet is proportional only to the cube root of the rate of energy release); but the observed jet appeared to be comparable with that over the fused area at Totem. Although no measurements on the Able convection jet are available to the writer and therefore the point cannot be definitely established, it seems likely that the boiling surface of the water at Able could not have given such a powerful convection jet as was observed unless the air being fed into the jet was preheated by the blast.

The convection jet above the fused area at Totem was fed with air loaded with dust. Reference has already been made to the dust

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collar of depth about 2", around the fused area. This dust was in the air, and fell out from about 500 feet of air. The dust loading of the air was therefore very roughly 0.007 gm per litre. This requires the air to have a buoyancy of only 1.5°C to make the air in mechanical equilibrium with ordinary air. Of course, this estimate may be out by a factor 2 or more because not all the dust settled in the collar. The wind blew the air away before all the dust settled. On the other hand, dust was settling all the time that the convection jet was rising.

The reason why the dust collar did not extend over the fused area was that as the convection slowed down, the dust began to settle, but the fused area was still hot enough to prevent any dust from actually falling on to it. The falling dust was swept away at the very last moment, and probably fell on the collar.

The theory developed above enables us to understand one other observation which has always been puzzling. At Hiroshima and at Nagasaki there was a big "smoke column" which came from the ground. From a high air burst, the cloud rises rapidly and leaves its wake. A convection jet comes from the ground, rises to the wake, and probably sweeps the bottom of the wake upwards. The heat put into the ground at both Hiroshima and Nagasaki was at least 2 kT, spread over a circle of radius, say, 2,000 feet. This is enough to give a convection jet which will rise at approximately 100 ft/sec. There was no radioactivity in the lower parts of the stem. The heat currents in fact swept the wakes, with their fission products, to heights of many thousand feet.

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FALL-OUT PROBLEMS

Having now reached the stage where we can get an approximate energy balance for the fused area, and having a grasp of what the currents are like, we now come to a much more important matter affecting fall-out. Perhaps the clearest way of introducing this new point is to summarise earlier ideas on the mechanism of fall-out in the heavily contaminated areas. Having done this, we can make criticisms, in the light of what has been deduced about convection currents, and then see our way to giving a more accurate description.

When an atomic weapon explodes low in the air above the ground, the fireball touches the ground and contaminates it by direct contact. As time proceeds, the fireball starts to rise, and dust is sucked away from the ground, due to the suction caused by the rapidly rising fireball. This dust is soon left behind as the foot of the column or stem. As the fireball, or cloud, rises, a wake is left behind, containing dust and fission products from the cloud. After a few minutes, the cloud and column are fully developed. The radioactivity at this time is to be found in the cloud and in the stem. The fall-out pattern on the ground is determined by particle sizes, winds, Stokes' Law and so on; and the contamination in the heavily contaminated areas comes mainly from the stem. While this description has never been claimed as full or as completely accurate, it was thought to be right in its main contentions.

We now see that the composition and behaviour of the stem have not been accurately portrayed. The stem is formed by a convection current and the dust has come with the air sucked in from outside the fused area. The first air and dust to be swept in and up, at the Totem trials, was taken to a height of about 6,000 feet. The vigour of the convection updraft was surely enough to take with it

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any radioactivity left in the air above the fused area. Hence, the bottom 6,000 feet of the stem contained practically no radioactivity. Later on, the situation changed, for the stem collapses by a type of base surge mechanism. Where then does the contamination in the first mile or two downwind of the fused area originate? There can be only one explanation. The contamination must come from fall-out from the bottom regions of the cloud, outside the region of the stem. This fall-out starts from the moment the cloud begins to rise.

At first sight, this explanation seems unlikely. Some fall-out must take place from the bottom of the cloud, as the cloud rises; but surely, if there were much, one would see it in the photographs. The bottom of the cloud appears to be sharply defined and even close examination of the photograph gives no direct visual evidence of the presence of fall-out from the bottom of the cloud. However, a closer examination by mathematics of the orders of magnitude shows that fall-out must be there, and that there is enough to account for the near-in fall-out pattern. The fall-out cannot be seen because only comparatively few large particles are involved. The matter seems to be definitely settled by the shape of the Totem II fall-out patterns, as described later.

The following argument can be presented in several versions; but the simplest physical assumptions are always preferable, if adequate. The orders of magnitude obtained agree with such facts as we have.

Suppose that at any time during the rise of the cloud, the turbulence is enough to preserve a more-or-less equal distribution of dust particles at all points in the cloud. This applies while the cloud is still rising quickly. Suppose that while the bottom of the cloud is rising from height Z to Z + dZ, some sedimentation is taking place. The bottom of the cloud is rising quickly, but the cloud is increasing in size due to turbulence and entrainment.

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however, the larger particles at least can fall through the turbulence and escape into the colder air below the cloud.

The particles in the cloud consist of very small ones, made by the condensation of the bomb material and vaporised ground and tower material; and of more or less normal soil particles thrown into the fireball by the explosion. We distinguish between these two types.

For the condensed particles, let the distribution function be $f_c(\mu)d\mu$; and for the "normal" soil particles be $f_s(\mu)d\mu$. The functions f represent the total number of particles in the cloud with diameters lying between μ and $\mu + d\mu$.

The activity contained in a condensed particle is proportional to the volume, i.e. to μ^3. The activity contained in a soil particle is proportional to the area, i.e. to μ^2.

The particle size distribution in dusty soils is often such that the mass distribution in any range of μ is constant from small values of μ up to several hundred microns. In such a case, apart from a normalising constant

$$f_s(\mu) = \mu^{-3} \qquad (3A)$$

A particle size distribution curve for Totem was obtained by sieving and sedimentation experiments of a dozen different samples. The scatter was fairly considerable, but the following laws gave a fairly good fit to the average histogram:

$$\left.\begin{aligned} f_s(\mu) &= (300/\mu)^3 \qquad 1 \leq \mu \leq 300 \text{ microns} \\ f_s(\mu) &= (300/\mu)^6 \qquad 300 \leq \mu \end{aligned}\right\} \qquad (3B)$$

This law gives the specific surface correctly for the "fines", gives a good fit to the mass distribution curve from 20 to 300 microns, gives about the right amount in the range 300-1,000 microns, and gives about the right amount over 1,000 microns except for the stones, which were much more plentiful than the law suggests. (It is difficult to get a good experimental value for stones but they did represent a few percent of the total mass.)

When we come to fit the experimental results at Totem, we use the law (3A) and call these results "Theory A"; and whenever we use law (3B) we call the results "Theory B". Figure 6, for example,

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uses this terminology.

Define the activity function g for the two groups of particles. Thus $g_c(\mu)$ represents the total activity contained in particles of the cloud in the diameter range μ to $\mu + d\mu$.

$$g_c(\mu) = A\mu^3 f_c(\mu) \tag{4}$$

$$g_s(\mu) = B\mu^2 f_s(\mu) \tag{5}$$

We do not know the form of $f_c(\mu)$ from experimental evidence; but we could, if required, make a reasonable guess from the theory of coagulation, following Smoloukowski. In the present context we do not need $f_c(\mu)$.

To determine the constant B we assume that a fraction α of the total activity is caught on the soil particles. The fraction α is, of course, a function of the height of burst, the yield and other parameters. For bursts of the Totem type, α appears to be about 0.1 or 0.2.

Thus, B is related to a parameter α by the relation

$$\int_{\mu_{min}}^{\mu_{max}} g_s(\mu)d\mu = \alpha C \tag{6}$$

where C is the total activity of the weapon.

Consider now the rate of escape of particles from the base of the cloud when the base is at height Z. The base of the cloud represents the limit of the fine particles which move with the air. Relative to these, the particle of diameter μ is falling with speed V_μ. Take a vertical cylindrical element through the cloud, of cross section dS and depth h. Then the fraction of the particles of diameter μ to $\mu + d\mu$ in this element which are escaping in time dt is $V_\mu dSdt/\Pi$, where Π is the total volume of the cloud. Integrating over the total cross section of the cloud, the fraction of particles in the range μ to $\mu + d\mu$ which escape in time dt is $V_\mu dt/D_Z$, where D_Z is the volume of the cloud divided by its maximum cross sectional area.

The activity left in the air by the rising cloud between height Z and Z + dZ on particles of diameter μ to $\mu + d\mu$ is therefore

$$B\mu^2 V_\mu f_s(\mu)d\mu dZ/\dot{Z}D_Z \tag{7}$$

If $F(\mu,Z)$ is the activity - particle diameter distribution at

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being left in the air, then we have

$$F(\mu,Z) = B\mu^2 V_\mu f_s(\mu)/\dot{Z}D_Z \qquad (8A)$$

The total activity A(Z) left in the air between heights Z and Z + dZ is simply the integral of $F(\mu,Z)$ with respect to μ.

The above theory is insufficient in one important respect. The boundary region at the bottom of the cloud between the cloud and the outside air is eating into the air by turbulent mixing. If the rate of downward growth of the cloud surface is too fast, it will stop the escape of all those particles not falling fast enough to escape merely by catching any that have escaped. Suppose that the rate at which the boundary region of the cloud is growing downwards due to turbulent in-mixing of air is W. Then we might assume that only particles for which V_μ is greater than W can escape. This however is too drastic an assumption, for the bigger particles as well as the smaller ones are thrown about by the turbulence in the fringe area and the turbulence will throw some of them downwards. We have from physical arguments obtained an upper and lower limit. Particles of diameter μ are not moving away and downwards from the base of the cloud with a velocity as large as V_μ, because the base of the cloud is itself extending downwards by turbulent mixing; but on the other hand, the particles are not moving downwards with a relative velocity to the base of the cloud as small as $(V_\mu - W)$. Let us make the plausible assumption that the average velocity of fall with respect to the cloud base is $(V_\mu - \frac{1}{2}W)$.

According to this approximation, the activity - particle diameter distribution left in the air between heights Z and Z + dZ is

$$F(\mu,Z) = B\mu^2(V_\mu - \tfrac{1}{2}W)f_s(\mu)/\dot{Z}D_Z \qquad (8B)$$

An important consequence of this formula is that the turbulent mixing at the bottom of the rising cloud inhibits the fall-out of the finer particles. Since W must scale the same way as $\dot{Z}$, W scales as the one-sixth power of the yield. Large explosions therefore inhibit the fall-out of larger particles from the rising cloud than do small explosions.

APPLICATION TO TOTEM II FALL-OUT

We now attempt to fit the Totem II fall-out contours by the theory

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developed above. We use two versions of the theory. First, the simplest possible assumptions, using the particle size distribution (3A) for the soil particles and the activity function (8A). Second, we use the more realistic soil distribution function (3B) and the activity function (8B). These two versions we call Theory A and Theory B.

To decide the value of the speed W of turbulent down-growth of the base of the cloud at Totem we argue as follows. Representing the cloud as a sphere of radius R and height of centre Z_o, we measure $\dot{Z}_o$ and $\dot{R}$ from photographs. Over the range of heights where the base of the cloud rose from 3,000 feet to 8,000 feet, we have that $\dot{Z}_o$ was substantially constant at 60 ft/sec and $\dot{R}$ was substantially constant at 17 ft/sec. Part of $\dot{R}$ is due to the expansion of the cloud as it rises due to decreasing atmospheric pressure and we subtract 2 ft/sec from $\dot{R}$ to allow for this. Now the turbulent growth of the cloud is more rapid at the top than at the bottom and we assume that the growth at the two places is in the ratio of the upward velocity at the top and at the bottom, i.e. in the ratio $\dot{Z}_o + \dot{R}$ to $\dot{Z}_o - \dot{R}$. This ratio is 1:0.6. Thus we take W as 0.6 of 15 or 9 ft/sec or 270 cm/sec. This means that no particle can escape unless V_μ is at least 135 cm/sec, the corresponding diameter being 190 microns.

The wind structure at the time of the Totem II shot was quite remarkable. The wind speed from ground level up to 10,000 feet was practically constant in magnitude, but the direction of the wind rotated steadily with height. The winds at 10,000 feet were almost at right angles to the wind near the ground.

The fall-out pattern had a very pronounced elbow, and by integrating up the contamination in various directions from the crater, it was possible to estimate how much contamination came from each height.

No measurements were made of the particle size distribution of the active particles in the fall-out, nor were any measurements made of the activity - particle size distribution. These are important matters and should be measured in future.

To simplify matters somewhat, let us suppose that the activity is initially concentrated in a vertical line source through the point of explosion.

Then the activity - particle diameter distribution function at height Z is the same function $F(\mu,Z)$ that we have used hitherto, for

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example in equations (8A) and (8B). This time, however, we are going to attempt to deduce $F(\mu,Z)$ for a few heights Z from the fall-out pattern, and then compare the results obtained with the theoretical formulae (8A) and (8B).

Suppose that the magnitude of the mean wind from ground level up to height Z is W_z and that the direction of the mean wind, measured from some convenient direction such as north, is ϕ_z.

Then all the particles at height Z move off and gradually fall on to the earth in the direction ϕ_z.

Similarly, all the particles at height Z + dZ all lie eventually along a line on the ground at the direction $\phi_z + \partial\phi_z/\partial Z.dZ$. Of course, due to atmospheric turbulence, the particles fall about their mean lines with some form of Gaussian distribution, but for the near-in pattern of fall-out, the blurring caused by turbulence is small.

The particles of diameter μ, originally at height Z, come to earth a distance

$$R_\mu = ZW_z/V_\mu \tag{9}$$

along the direction ϕ_z.

The particles of diameter $\mu + d\mu$ originally at height Z + dZ come to earth at a distance

$$R_\mu + dR_\mu = \frac{ZW_z}{V_\mu}\left[1 - \frac{1}{V_\mu}\frac{V_\mu}{\partial\mu}\,d\mu\right] \tag{10}$$

Corresponding formulae can be written down for the distances where the particles of diameter μ and diameter $\mu + d\mu$, originating at Z + dZ, fall.

All of the particles in the range μ to $\mu + d\mu$ from Z up to Z + dZ fall in a quadrilateral area, one side of which has the length

$$dR_\mu = \frac{Z\,W_z}{V_\mu^2}\,\frac{\partial V_\mu}{\partial\mu}\,d\mu \tag{11}$$

and whose dimension perpendicular to the side dR_μ is $R_\mu\,\partial\phi_z/\partial Z.dZ$.

/The area

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The area of this quadrilateral is therefore

$$\frac{Z\, W_z\, R_\mu}{V_\mu^2} \quad \frac{\partial V_\mu}{\partial \mu} \quad \frac{\partial \phi_z}{\partial z}\, d\mu dZ \qquad (12)$$

Suppose that the activity measured on the ground at this quadrilateral area is $\Lambda(R_\mu, \phi_z)$. Then we have that

$$F(\mu,Z)d\mu dZ = \Lambda(R_\mu, \phi_z) \frac{Z\, W_z\, R_\mu}{V_\mu^2} \quad \frac{\partial V_\mu}{\partial \mu} \quad \frac{\partial \phi_z}{\partial z}\, d\mu dZ$$

Hence by observing the contamination Λ we can compute the activity - particle diameter distribution function at height Z. We have

$$F(\mu,Z) = \Lambda(R_\mu, \phi_z) \frac{R_\mu^2}{V_\mu} \quad \frac{\partial V_\mu}{\partial \mu} \quad \frac{\partial \phi_z}{\partial z} \qquad (13)$$

where R_μ is given by (9).

In the above formula we must express the contamination as a number per cm^2 times the total activity produced by the weapon. Having evaluated $F(\mu,Z)$ for a few heights Z, we can then make a direct comparison with the theoretical formulae (8A) or (8B), in which the only adjustable parameter is α, which is the fraction of the total activity caught on soil particles, the rest remaining as very fine condensed particles.

From the Totem II contamination contours we have computed $F(\mu,Z)$ from (13). The results are shown in Figure 6, for Z = 1,500 feet, Z = 3,000 feet, Z = 5,000 feet and Z = 7,500 feet.

Figure 6 reveals that the activity - particle diameter function at Totem II at various levels up to 7,500 feet, all show the same general characteristics. Within a factor of two, the amount of activity in any layer, per unit depth of layer, was constant; and in any layer, the activity per unit range of particle diameter showed a fairly sharp maximum for particles in the diameter range 400 to 500 microns. The activity on particles greater than 600 microns diameter falls away with increase of diameter, the explanation

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[illegible] that these larger particles were very infrequent in the soil material.

More striking is the fact that the curves show little activity on particles in the diameter range 200 to 300 microns. No observations corresponding with smaller particles were made, and in any case, the theory as given could hardly be applied to smaller particles.

Figure 6 also shows the theoretical formulae (8A) and (8B), using $\dot{Z}D_z = 1.3 \times 10^3$ cm, taken from the measurements of the cinematic photographs. The value chosen for α was in each case 0.14. For the Theory A, the value of μ_{max} in the soil particles was taken as 800 microns.

The theoretical formula (8A) gives a very broad maximum, and appears to give too much activity on particles of diameter 200-300 microns, and presumably fails badly at smaller diameters.

The theoretical formula (8B) gives a good representation of the experimental results. The maximum in the activity function appears to be at about the right value, and the general shape of the curve closely follows the experimental curves. It is true that the experimental curves for the different heights vary by a factor of two on either side of a mean. The explanation for this may in part be that the mean wind rotation with height was not measured with sufficient accuracy. An error of a couple of degrees on a rotation of a few degrees is enough to account for much of the discrepancy. However, we must not seek to push the theory too far. We have at least achieved a semi-quantitative fit of theory to observations and we appear to have accounted for the broad characteristics of the fall-out patterns.

By integrating the activity curves shown in Figure 6 with respect to particle diameter, the amount of activity left in the air at various levels can be found. The results are as follows:-

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Height of air level feet	3000	5000	7500
Amount of total weapon activity per cm x 10^8	5.3	2.6	1.7

The average activity per centimetre depth of air is 3.2×10^{-8} C, where C is the total activity of the weapon.

Base Surge Mechanism. The Totem stems came to rest approximately three minutes after burst. The lower parts of the stem stopped first. During the next minute or two, downward currents here and there in the stem were observed, of 5-8 ft/sec. These downward density currents were analagous to the base surge at Bikini, but they appeared to be localised.

The air in parts of the stem may have been warmer than the surrounding air and its air density was therefore lower. However, the air was loaded with dust. No doubt, the motion had an overshoot, and each part of the stem may have reached one or two thousand feet higher than its equilibrium level. A density current of 10 ft/sec would imply that the stem at about three or four minutes after burst had an average density about one or two percent greater than the atmosphere at equal levels. The density current resulting would then be about one tenth of the Bikini speed, but the surge would not persist. It would stop when the stem had fallen one or two thousand feet.

With certain types of burst it is possible to imagine the lower parts of the cloud collapsing very much more completely as a density current. The large particles fall from the bottom of the cloud but their places are taken by the larger particles coming from above. At some stage, a large volume of the cloud has an average density big enough to bring the cloud down. If the lapse rate in the air is

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favourable, the density current might fall many thousand feet. Extreme cases of this were the cloud at Baker (Bikini) and the cloud at Monte Bello. The Monte Bello cloud was very much like that of Baker, and there is no doubt that most of the fall-out at Monte Bello came from the cloud. There can be little doubt, therefore, that the fall-out on the ships at Baker came from the cloud and not from the stem or base surge.

A ground burst weapon in the kiloton range would cause these density currents, and thus produce an intense fall-out near the explosion. It is debatable whether a megaton explosion would do the same.

Contamination from a Megaton Burst. Suppose that a weapon in the megaton range were exploded over the desert at the same scaled height as Totem. Let the yield be N times that of Totem.

Then at scaled heights of cloud, the value of $\dot{Z}$ for the megaton weapon would be $N^{1/6}$ times that of Totem.

If the ideas on which formula (8A) was obtained are valid, then the activity left by the rising cloud in the air per centimetre would be $N^{5/6}$ times that at Totem. The fall-out pattern from the megaton burst at distances corresponding with two or three miles at Totem would be similar in shape, and the linear dimensions would be increased by a factor $N^{1/3}$ but the level of contamination would be increased by only a factor $N^{1/6}$. Thus, if N were 1,000, the contamination contours out to 25 miles would be like those scaled from Totem, increased by 10 in linear dimensions, but the contamination levels would be only increased by a factor 3.15, instead of the 10 given by the normal scaling laws.

The above argument, however, still needs modification. We have already given reasons for thinking that as the cloud rises only the larger particles can escape. Those particles which can be

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held in suspension by the turbulence do not fall out, and at Totem only particles bigger than 190 microns in diameter could sediment out of the base of the cloud. The turbulence cut down the flow of 300 micron particles to 40%, and cut down the flow of 500 micron particles to two-thirds.

Now the velocity W at which the base of the cloud is expanding due to turbulent in-mixing of air must scale like $\dot{Z}$ at corresponding heights. We have given plausible arguments for believing that W at Totem was fairly constant at 270 cm/sec as the base of the cloud rose from 3,000 feet to 8,000 feet. Below 3,000 feet, W must have been somewhat bigger. Thus for the burst 1,000 times greater in yield than Totem, at the scaled height, W will be 850 cm/sec when the base of the cloud covers the height range 9,000 feet to 25,000 feet. Actually, the cloud will go up faster than we have assumed and will still be rising very fast at 25,000 feet. It seems very likely that W will be at least 850 cm/sec all the way up to 80,000 feet. The implication is that no particles will sediment from the base of the cloud unless their falling velocity V_μ is at least 425 cm/sec. The corresponding diameter is 550 microns. Even the particles of diameter 800 microns will escape rarely and the sedimentation of these will only be 27% of what they would have been, but for the turbulence at the base of the cloud. Obviously, the fall-out from the rising cloud is going to be restricted to the very large particles and there are few of these. The intense region of fall-out will be due to fall-out from the cloud when it stops rising. We should expect the area of greatest contamination to be where particles of diameter 200-400 microns fall from the cloud when it stops rising, and we should expect to be able to find on the ground only about 5% of the total activity of the weapon within the contours

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representing contamination which fell in the first day.

The fall-out pattern from a megaton explosion on the ground in the desert is difficult to estimate. There is no doubt that a kiloton explosion gives a cloud which is so heavily loaded with dust that the rate of rise of the cloud is considerably slowed down, and downward density currents from the cloud start very early. However, the amount of dust in the cloud from a megaton explosion will not be correspondingly so great. Dust raising is more a surface than a volume effect. It could therefore be argued that the turbulence in the rising cloud will practically inhibit sedimentation and that there will be only slight activity between the burst point and the place where the first large particles from the cloud settle. The total amount of the weapon activity caught on the soil particles is proportional to the total area of the soil particles in the cloud. For a kiloton burst, approximately one half of the total activity is on the soil particles. If, then, for an explosion 1,000 times greater, the total amount of soil in the cloud is only 100 times greater, then only 5% is caught on the soil particles. The amount of dust will be more than the factor 100 assumed, and the linearity relationship assumed for the amount caught on the soil particles cannot be quite correct. Making a reasonable allowance for these two corrections, it still seems likely that only 10% of the total activity will be found on soil particles and only two-thirds of this will fall to the ground in the first day.

Clearly it is of the highest importance to discover whether there really is a "skip distance" in the fall-out from bursts of weapons in the megaton range, exploded within 1,000 feet of the ground. Possibly there is no way other than an actual full-scale test of reaching a conclusion on this point with absolute certainty. The views put forward in this paper would receive

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considerable support by making two types of measurement at kiloton tests. First, one might have an intermittent powerful black smoke generator at the edge of the fireball and watch in the photographs to see how high the black smoke went. Second, one might shoot rockets below the rising cloud and outside the stem to collect the particles that have fallen out of the base of the cloud. An analysis of the particles collected from this "clear air" should establish whether the present paper is correct in its assumption that the fall-out near to the explosion comes from this type of fall-out.

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APPENDIX 1

Cooling of the Fused Area by Radiation

The conclusion was reached in the paper that the cooling of the fused area by radiation was less effective by about one order of magnitude than the cooling by convection currents.

We have solved by numerical methods the cooling of a semi-infinite material initially at one temperature, due to radiation losses from the plane face into a vacuum. The solution will not be given here.

Reasons have been advanced in the paper for assuming that the fused material was at about 2,000-2,500° K when the fireball lifted, and that about 700 calories/cm^2 of heat was contained in the fused material.

During the cooling phase, the temperature of the exposed surface must be less than that anywhere inside the fused material. Suppose that T is the average temperature of the fused material at time t. Then the rate of loss of heat by radiation is less than $\epsilon\sigma T^4$. Let us calculate the temperature at time t assuming that the only loss of heat is by radiation, and that the surface is radiating as if it were at the average temperature of the fused material. Then writing $X = T/To$

$$\frac{dX}{dt} = -\alpha X^4$$

and α is 21/700, for we know that at 2,500° K, 21 calories are radiated per second and there are 700 calories of heat in the fused material. (If the initial temperature was only 2,000° K then α has the value 0.012).

The solution is

$$\frac{1}{X^3} = 1 + 3\alpha t.$$

With the value $\alpha = 0.03$, the temperature falls to half the initial value, i.e. to 1,250° K at time 78 seconds. With $\alpha = 0.012$,

/the temperature

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the temperature falls to half the initial value, i.e. to 1,000° K in 193 seconds. Both of these times are lower limits.

Thus radiation alone can only remove half the heat of the fused layer in about two minutes. Convection is considerably quicker.

Of the 700 cal/cm^2 left in the fused layer, probably about 100 cal/cm^2 are radiated and the remainder is mainly removed by convection.

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APPENDIX 2

When the particle diameter is sufficiently small, the terminal velocity V_μ of a sphere of diameter μ falling in still air is given by Stokes' Law, namely

$$V_\mu = \frac{g \rho_p}{18 \nu \rho_a} \mu^2$$

where ρ_p is the particle density and ρ_a is the density of the air. For particles of specific gravity 2.5, Stokes' Law begins to fail for spheres of diameter 30 microns. At larger diameters, the terminal velocity can be deduced from the observed drag coefficient C_D with Reynolds' number R, where

$$C_D = \frac{4\mu g}{3V_\mu^2} \left(\frac{\rho_p}{\rho_a}\right)$$

and $$R = \mu V_\mu / \nu$$

The values used to construct the following table were taken from Goldstein, "Modern Developments in Fluid Dynamics".

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TERMINAL VELOCITY DATA

μ (10^{-4} cm)	V_μ (cm/sec)	$\int_0^\mu \frac{V_\mu}{\mu} d\mu$ (cm/sec)	$\frac{dV}{d\mu}$ (10^4 sec^{-1})	V_μ/μ (10^4 sec^{-1})
0	0	0	0	0
50	20	10	.700	.400
100	60	36	.830	.600
150	101	68	.857	.673
200	145	103	.860	.725
250	188	140	.851	.752
300	230	178	.837	.767
350	272	217	.821	.777
400	312	256	.794	.779
450	350	295	.768	.780
500	390	333	.740	.779
550	426	372	.712	.775
600	462	411	.682	.770
650	495	449	.652	.762
700	527	487	.621	.753
750	555	524	.590	.740
800	580	569	.558	.725

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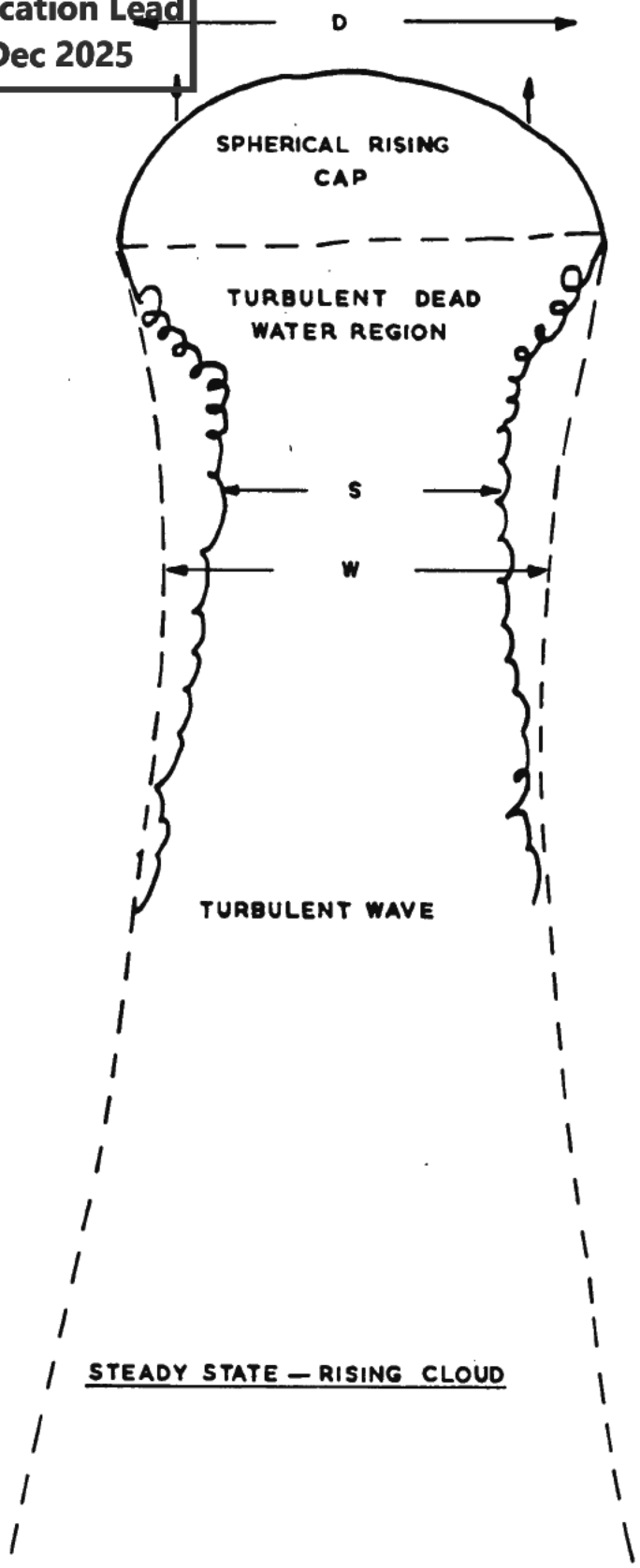

FIGURE 1.

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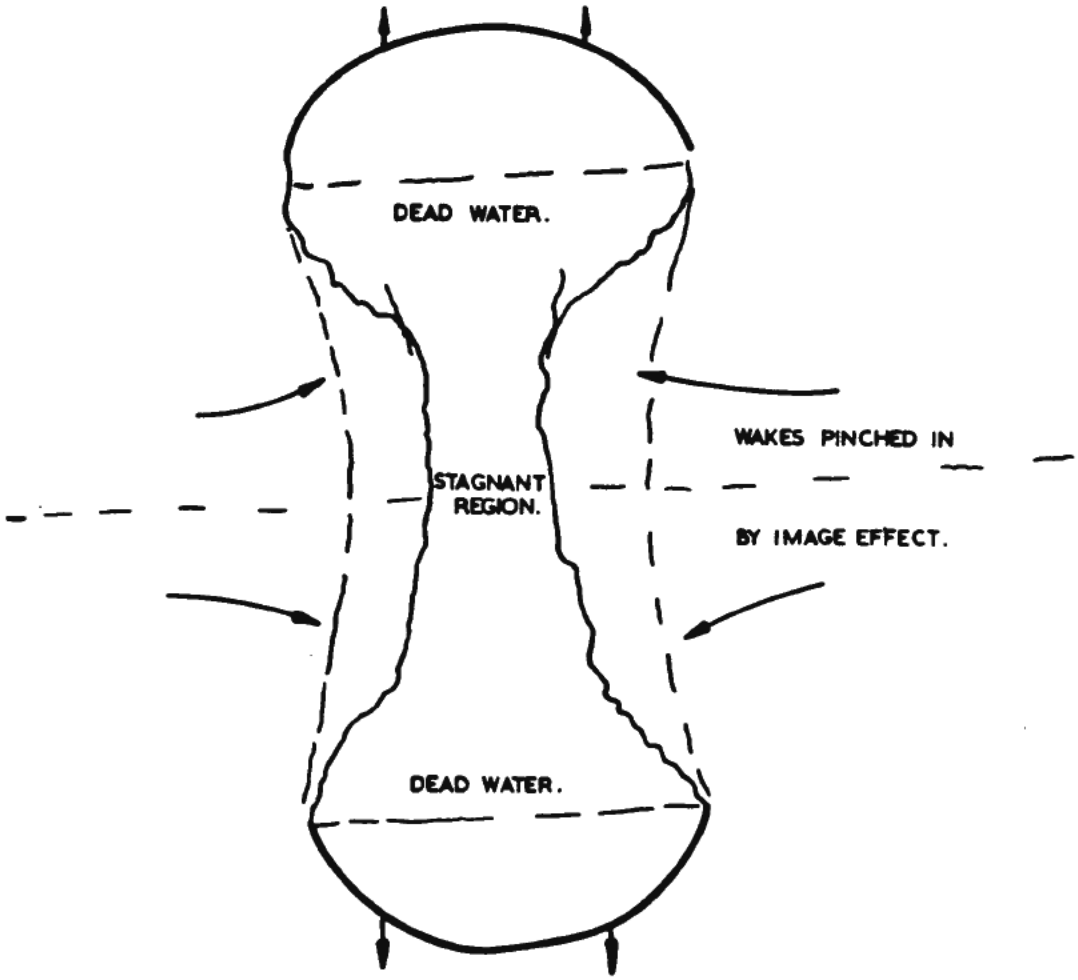

RISING CLOUD AND ITS IMAGE.

FIGURE 2.

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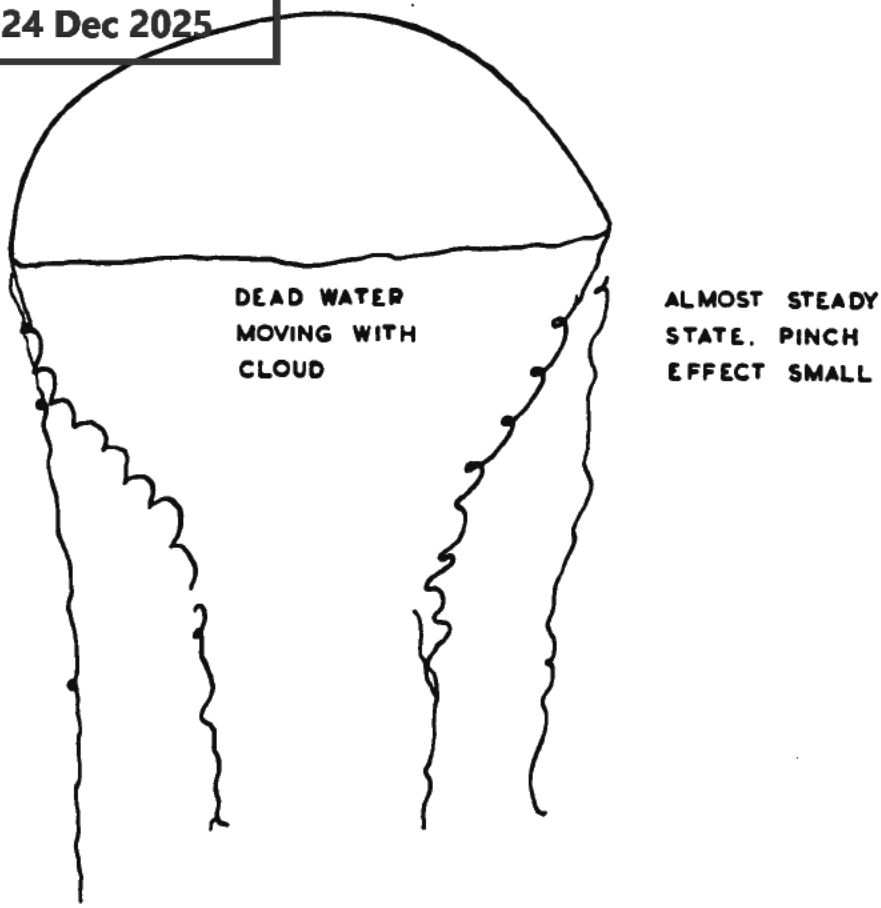

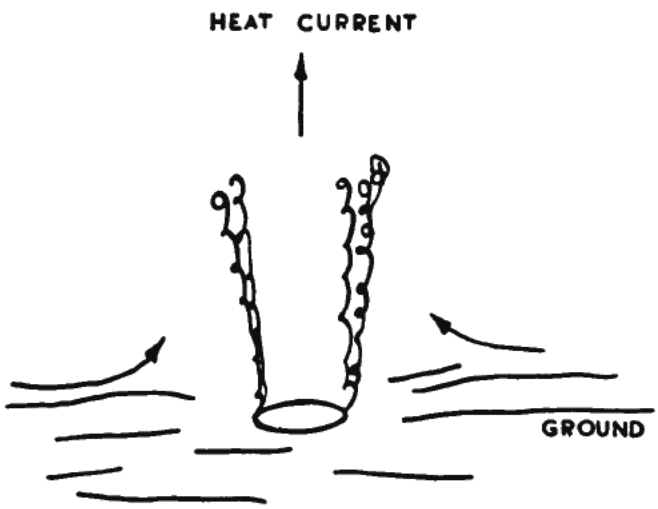

FIGURE 3.

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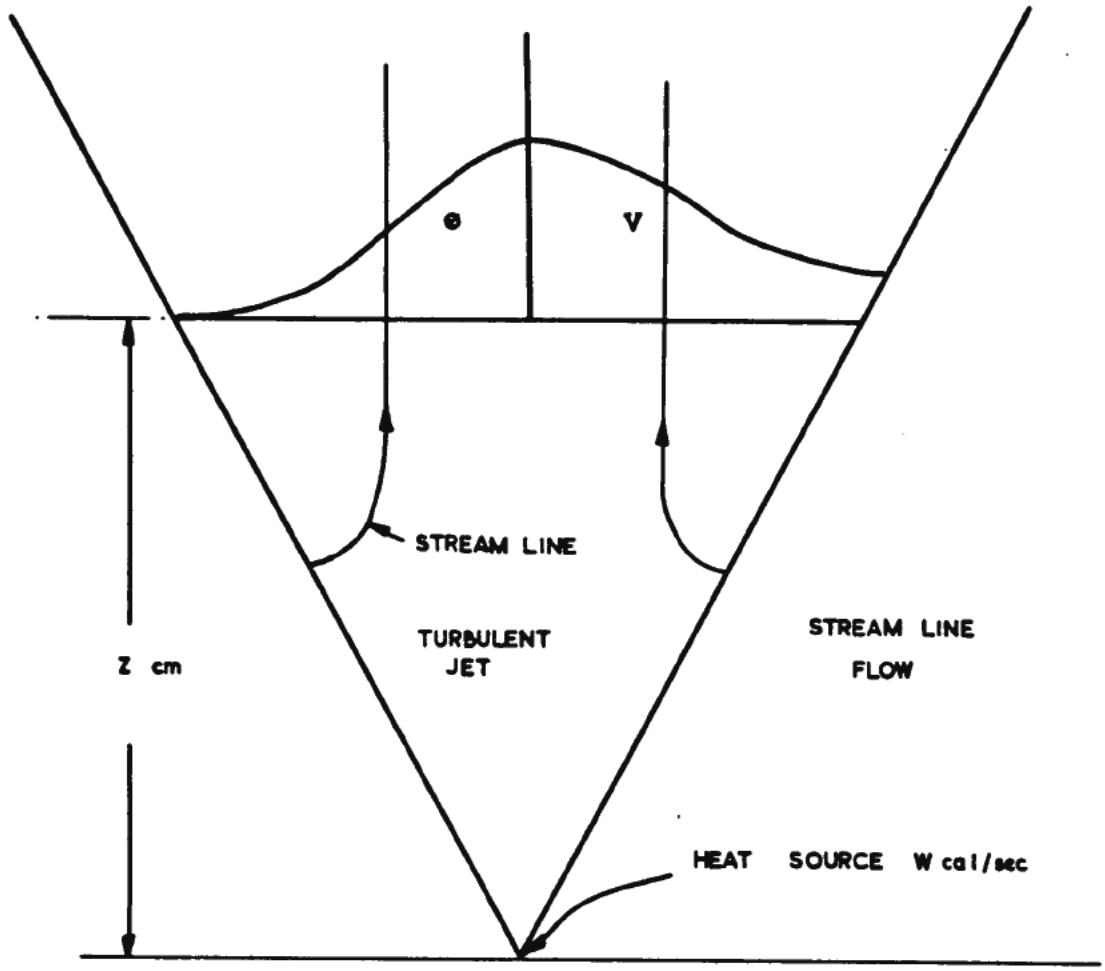

SCHMIDT GIVES AT CENTRE OF JET

$$W = 6{\cdot}9 \times 10^{-6} V^3 Z$$

$$\theta = 1680 \, W^{2/3} Z^{-5/3}$$

FIG. 4

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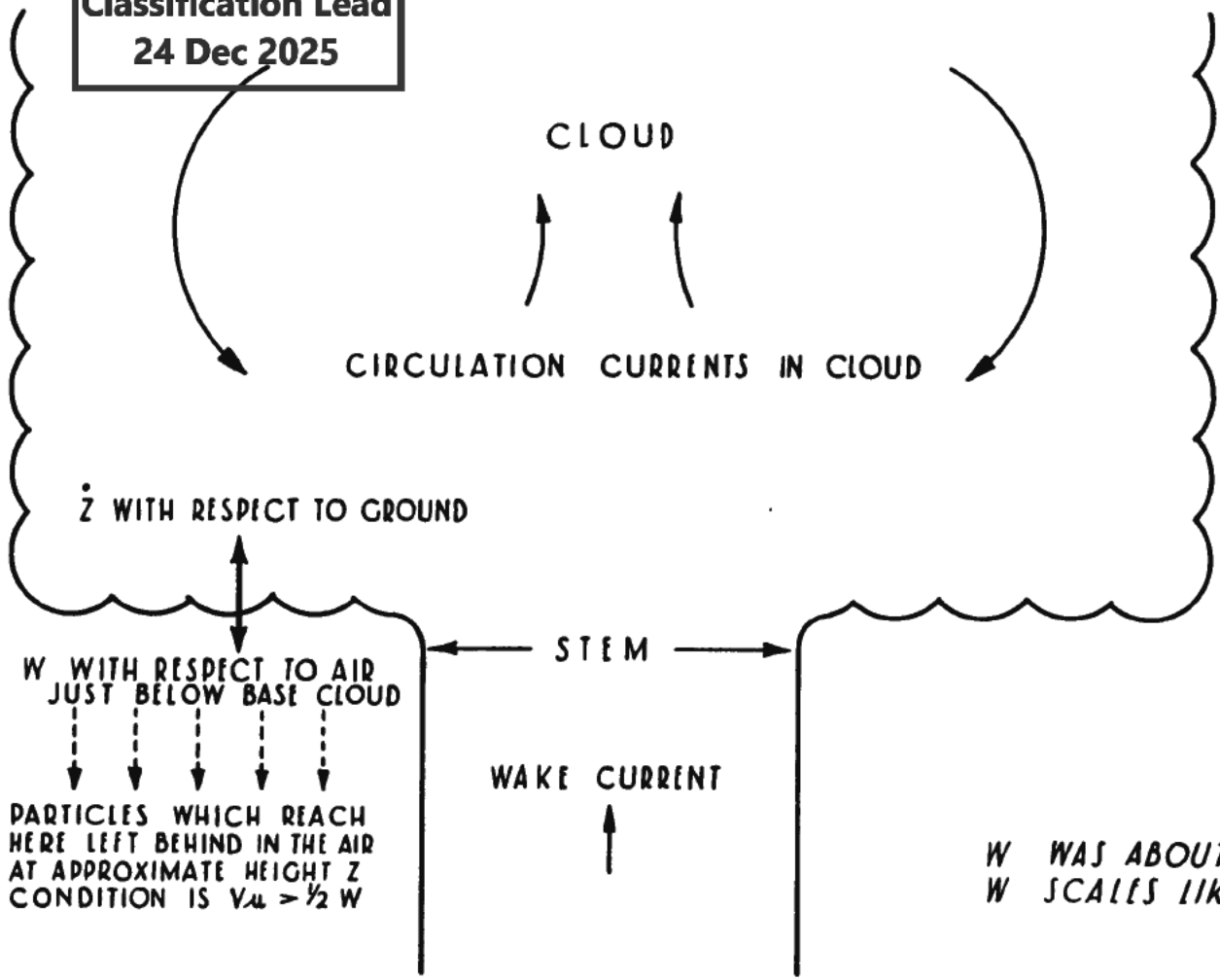

FIG. 5

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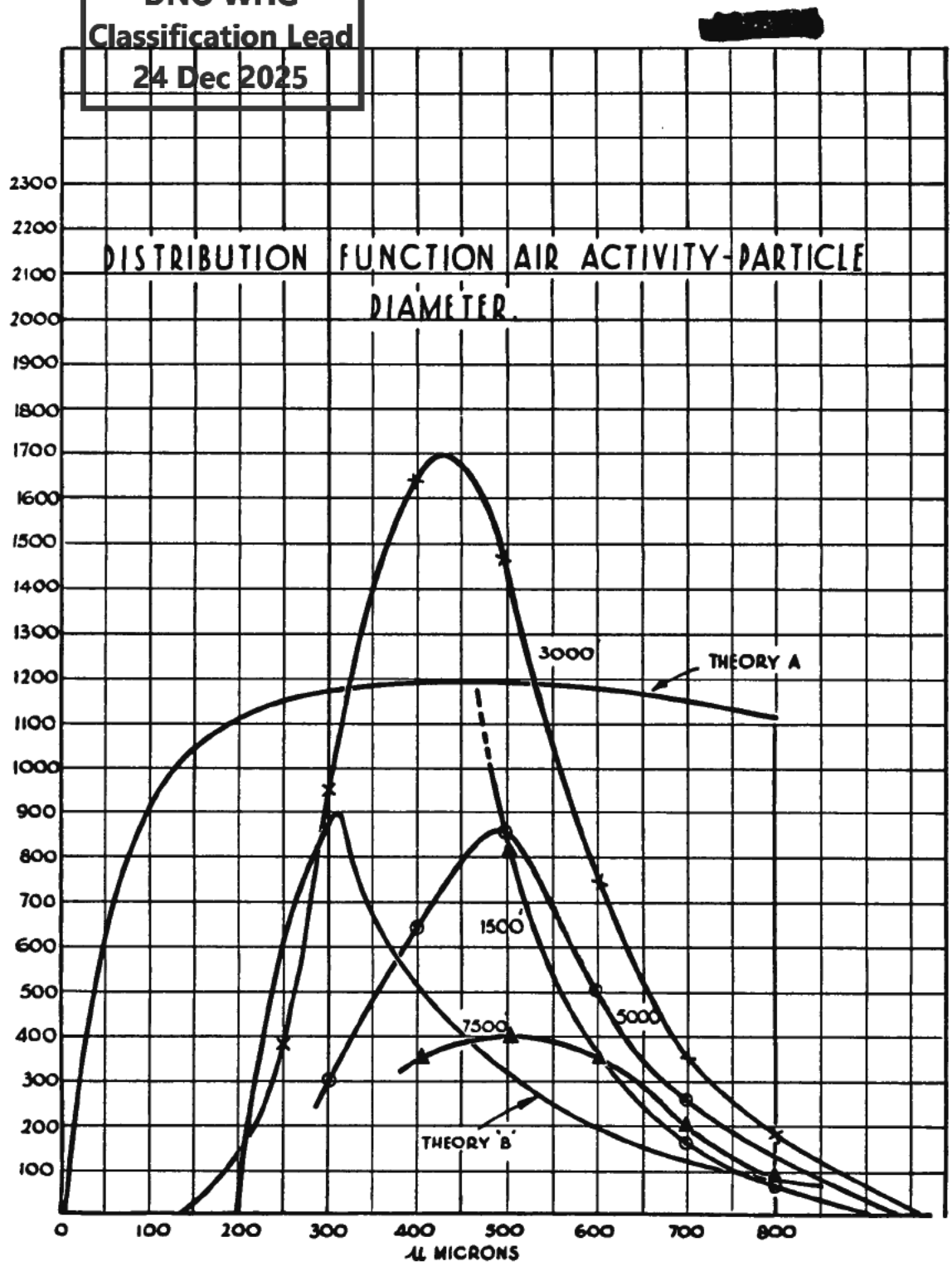

FIG. 6.

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