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THE EFFECT OF ATMOSPHERIC LIQUID WATER ON ATOMIC BOMBS

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ABSTRACT

A method of finding the effect of atmospheric liquid water on the shock wave from an air-burst atomic bomb is presented. The importance of the drop size distribution is emphasized. Using an approach which underestimates the effect, the results show that the effect should not be neglected. Recommendations for future work are made.

PREFACE

The work contained herein was principally accomplished during a period of active duty with AFSWP at Sandia Base ending in August, 1951. The author wishes to thank his present employer, the Los Alamos Scientific Laboratory, for clerical and drafting assistance in the preparation of the manuscript, and permission to issue it as a Los Alamos Report.

Several people have given considerable help in the preparation of this work. I should like to thank the following for their important help: Dr. Frederick Reines and John W. Bond, Jr. , Los Alamos Laboratory, and Drs. C. E. Buell and Thomas B. Cook of Sandia Corporation.

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SYMBOLS

(Some others are defined in the text)

a_i = initial radius of drop before passing through the shock wave

a = final radius of drop, after being subjected to both fracture and evaporation

a_c = radius of largest drop after fracture, at R_c (this drop is then also the largest which could be evaporated at that point)

a_{is} = radius of drop, after being subjected to fracture by the shock wind, and before being evaporated

a_s = radius of largest drop which can be evaporated by a given shock wave

a_t = radius of the largest drop just stable in a given air stream. It will be called the "critical size"

b = surface tension of water

c_i = constant

E_∞ = total energy extracted from the shock wave

E_c = energy extracted from the shock wave inside R_c

E_o = energy extracted from the shock wave outside R_c

$f(a_i)$ = differential frequency of initial drop radii (Ref 1)(aufm Kampe)

L = latent heat of vaporization

P_s = shock overpressure

q = liquid water content of the air in g/m^{+3}

R_c = radius of complete evaporation i.e., radius inside which all water drops are evaporated. It is determined by the point of intersection of the curve for the size to which all drops are reduced by fracture and the curve of the radius of the largest drop which can be evaporated by the shock wave.

R = radius from the origin of the shock

R_e = Reynolds number = $\dfrac{\rho_a \, u \, a_1}{\mu_a}$

t = time of duration of the positive phase of the shock wave

τ = total time or upper limit of t

T_s = shock over-temperature or $(T-T_o)$ where T is temperature after the shock front in the positive phase and T_o is previous ambient temperature

W = yield of bomb in kilotons equivalent

u = shock wind velocity

v = average proportion of evaporation from $x = 0$ to x_1 (or ∞)

W_e = $\dfrac{\rho_a \, u^2 \, a_t}{b}$

x = R/R_c

ρ_a = ambient density of the air

μ_a = air viscosity

[redacted]

1. Introduction and Summary

This paper is a status report on work which had been done as of August 1, 1951, and has been written so that that work would be available to other research workers.

The problem considered is the loss of energy (and overpressure) of an atomic bomb when exploded in an atmosphere which contains liquid water in the form of rain, fog, or cloud.

Although this should be considered a preliminary report,* it is clear from the results that atmospheric liquid water will be of importance in planning atomic missions. Under an extreme condition of liquid water content, a 100 kt. yield weapon could have a loss of area of 40% at the 10 psi level.

The methods used will be discussed in detail and several recommendations will be made as to necessary future work.

The main recommendation is that if liquid water in any form (rain, cloud, or fog) has a good chance of occurring at the strike time, the planned height of burst should be lowered by several hundred feet, for an airburst bomb set to maximize 6 – 12 psi.

2. History

W. G. Penney in LA-721 furnished the first discussion of this problem in a preliminary fashion. Subsequently,[6] he made a more complete study. This study included experimental as well as theoretical evidence. However, his study cannot be used for a practical answer to the problem of airburst bombs, because it applies to a surface burst only,

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* The method has been previously discussed by the present author; see Richard L. Moore, Phys. Rev. 83, 890(A), (1951).

[redacted]

and furthermore, did not consider the important effect of the droplet size distribution.

3. Development of E_o/E_c

The procedure used to attack this problem consists of finding a radius (R_c) inside which all liquid water is evaporated and computing the energy lost (E_c) inside this radius. Through an equation which relates the energy (E_o) lost outside this radius to E_c, the total energy lost E_∞, may be obtained. In this process a number of physical assumptions must be made. The philosophy was adopted that where an arbitrary choice of a particular assumption must be made, it would be made so that the final results would be as conservative as possible. In other words, the effect of arbitrariness would always be in the direction of minimizing the energy loss, and thus the final result will be in the nature of a lower limit.

The physical nature of this problem may be summarized as follows:

1. There is a fog or rain present which has drops of various radii (a_i). For fog (or clouds) these drops have a frequency distribution $f(a_i)$ such that $f(a_i)da_i$ is the proportion of drops whose radii lie between a_i and $a_i + da_i$. The frequency distribution of raindrop sizes will not be needed.
2. The shock wind (of the shock wave) breaks up those drops of water which are bigger than the critical size a_t to size a_t.
3. The drops which are too small to break up, and the broken drops are evaporated under the positive phase of the shock wave because of the increase in temperature. Some are evaporated completely, others only partially. Their final radii are denoted by a.

4. The heat necessary to effect this evaporation is lost to the positive phase thus draining energy out of it and reducing the overpressure.

5. Condensation occurs in the negative phase, but due to the nature of the shock, the feedback of energy is taken to be negligible per the arguments of Penney.[6]

Four main topics must therefore be developed to solve this problem:

a. The frequency distribution of drop sizes.

b. The "radius of the largest drop stable in a suddenly applied air stream".

c. The equation of evaporation of the drops in the positive phase.

d. The variation of the shock properties with time and distance.

a. The frequency distribution of the size of the water drops in rain, fog, or cloud, is important due to the fact, which will be demonstrated, that drops of different size will be affected differently by the shock passage. Therefore, one cannot use an average drop size to obtain correct results. The total effect must be obtaining by averaging the effect over all drop-sizes with the proper relative weight given to the drops of larger mass.

The symbol $f(a_i)$ denotes the distribution function of the drop sizes. Its dimension is $(\text{microns})^{-1}$ where the radius of the drops is given in microns, i.e., $f(a_i)\,\Delta a_i$ gives the fractional number of the drops which have radii between a_i and $a_i + \Delta a_i$. Furthermore, it is implicit that $\int_0^\infty f(a_i)\,da_i = 1$.

The water-drop frequency distribution for clouds has been given by many authors to a greater or lesser precision.[9] However, we have used the data of auf Kampe[1] for our studies. He gives frequency distribution curves

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of drop diameters for several types of clouds.*

A large body of literature shows that rain-drop radii are about 5/10 mm or greater. It will be shown that all drops will be broken to a much smaller size by the shock wind (see Sec. b below). Therefore, the original frequency distribution does not matter and will not be needed for rain.

b. <u>The radius of the largest drop stable in a suddenly applied air stream</u> is given by Eq. (1.2) which was derived by Hinze.[3] He gives a method of determining a_t which is the best available in current literature, although the constant W_e is not yet precisely determined:

$$a_t = \frac{(W_e)b}{\rho_a u^2} \tag{1.2}$$

Penney[6] developed the basis for an estimate of the radius of the largest drop stable in a suddenly applied air stream (shock wind) as

$$\left(a_t = 10^{-1} p_s^{-2} \right).$$

His derivation was similar to that of Hinze. He stated in a longhand note that experimental verification had been obtained. Further details are not available to the present writer.

Following Hinze's approach, we note that the liquid drop is subject to two important pressures: The dynamic air velocity pressure $\rho_a u^2$ and the surface tension pressure b/a. By combining these opposing forces in a dimensionless ratio, one obtains Weber's number $W_e = \rho_a u^2 a_1/b$.

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* These curves have normalized to unity and unlike Ref. 9, the radius used instead of the diameter.

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Splitting of the drop occurs if W_e is greater than a critical value, which must be determined experimentally. In the remainder of this paper we shall use W_e as the symbol for this critical value of Weber's number. The radius of the drops, which are just stable in a suddenly applied air stream of a specified density and velocity, will be given by Eq. (1.2), and the symbol for this radius will be a_t.

Eq. (1.2) which was derived theoretically, has been verified by experiment in which Weber's number was observed to be a constant. It should be noted that the only assumption made in the derivation, which does not strictly hold in our application, is that the Reynolds' number (Re) is large, say equal to 1000. Our values of Re are ordinarily smaller, at least in the neighborhood of R_c the radius of complete evaporation. At this important point, a drop with a radius of 20μ has a Re of 100. By neglecting the effect of the Reynolds' number, we may have obtained an incorrect value for a_t at this point. Also the experimental data which Hinze used to obtain the value of 6 for W_e was not sufficiently precise to fix the value of W_e to better than 25%. For these two reasons, the value of a_t might vary as much as 50%.

The curve of the variation of a_t as a function of P_s has been plotted on Fig. 6.1. Three different curves are displayed:

1. a_t, which was computed using Hinze's value for W_e of 6.0.
2. 1.4 a_t which is 40% greater than a_t to illustrate the effect of increasing W_e by that amount.
3. $a_t(P)$ which is the value computed from Penney's relation, and which is seen to be about 60% of a_t.

The influence of these variations in a_t on the final results will be studied in Sec. 6. It will be seen that it is slight.

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The question now occurs: How long does it take for the breakup to occur? It is well known that the duration of the shock wind is of the order of a tenth of a second for atomic bombs. An estimate of the time of breakup is given by Hinze as $t_b \cong (a_i/u)(\rho_b/\rho_a)^{1/2}$. Taking P_s as 1.8 psi, (certainly a conservative value!) and a_i as 10μ, then ρ_a is 1.2×10^{-3}, ρ_b is 1, u is 3×10^3 cm/sec and $t_b = 10^{-5}$ sec. If a_i were 100μ, t_b would be 10^{-4} sec, a short time indeed compared to the duration of the shock wind of the positive phase. Thus, the breakup of the drops will be completed long before the shock wind has passed, or even dropped appreciably below the peak velocity.

c. Discussion of the evaporation equation. The problem of the radius of a drop as a function of time under the influence of evaporation has been studied for the case of drops at rest by several authors.[4]

The evaporation equation discussed by Houghton[2] is used here as:

$$-2a\,da = c_1 T_s\,dt \qquad (1.1)$$

The determination of the constant in this equation will be given later in this paper, in Sec. 6. The relation given here assumes that the drops are at rest and that the drop radii are comparable to the mean free path of the molecules of the environmental air.

The case where the droplets are not stationary, but exposed to moving air of different velocities, has been studied by Gunn and Kinzer[4] where it is stated that,

"In working out a descriptive theory of the evaporation from a freely-falling spherical drop, it is necessary to solve the problem of the transport of heat and vapor from the drop when it is exposed to moving air of different velocites. Since the details of air flow about a drop are generally unknown, approximations of the kind usually adopted in the problems of aerodynamics are employed. However, the physical basis for the theory has been carefully preserved and it should be directly applicable to actual raindrops falling into a known environment.

"Equilibrium evaporation-rates are calculated by two independent processes. The first, based on the fact that the mass of water evaporated is proportional to the heat transferred to the drop, depends only upon the laws of heat transfer; the second is concerned directly with the transfer of vapor outward from the drop under the influence of vapor-density gradients. The resulting equations must be compatible since they deal with the same evaporation and they may be combined to yield the psychrometric equation for a freely falling drop. This auxiliary equation expresses the equilibrium temperature of the drop in terms of its size and the physical properties of the environment.

"In calculating the rate of transport of vapor or heat, it is noted that the radial gradients surrounding the drop when it is at rest have finite values out to distances large compared to the radius of the drop; but when the drop is falling freely, the vapor and cooled air at its surface are continually replaced by environmental air. The net effect of increasing ventilation is to shrink the boundary of the environmental air closer and closer around the drop, thus augmenting the surface gradients of vapor density and temperature and the rates of transport of vapor and heat. The movement of air near the drop must be examined in order to evaluate the effective gradients at the surface and the dependence of these gradients upon the velocity. A quasi-transient state may now be considered in which the vapor or heat is allowed to diffuse into successive packets of fresh environmental air as each packet comes within the zone of duffusion around the drop for a calculable period of time. This period of effective contact must approximate the diameter of the drop divided by the velocity of ventilation. By summing up the transport to all packets of air making contact, the total exchanged heat or vapor may be estimated and used to determine the equilibrium evaporation-rate and temperature of the drop."

The experimental data of these writers (see Figs. 5, 6, and 7 of Ref. 4) confirms Eq. (1.1) with

$$c_1 T_s = (2K/L)(T - T_a) \quad \text{or} \quad c_1 = (2K/L)\alpha$$

where $\alpha T_s = (T - T_a)$

and T_s = overtemperature in the shock wave

T = actual temperature of the air

T_a = actual temperature of the drop

K = coefficient of heat conduction for air.

The temperature of the drop T_a will be the "Wet Bulb" temperature of the air, and may be obtained from psychrometric tables. T is the temperature of the air in the positive phase of the shock wave. The relation between T and T_a may be seen from Appendix VI. The value of α has been studied as a function of various assumptions as to the initial ambient temperature and relative humidity. The conclusion is that a value of 6/10 for α is the most conservative choice.

For simplicity the discussion to the present point has ignored the increased evaporation due to the rather high ventilation of the drop imposed initially by the shock wind. Kinzer and Gunn derived an equation which considered the increased ventilation of drops due to relative motion, induced in their case, by gravity. This equation (Eq. (29), Ref. 4) may be expressed in our terminology as:

[redacted]

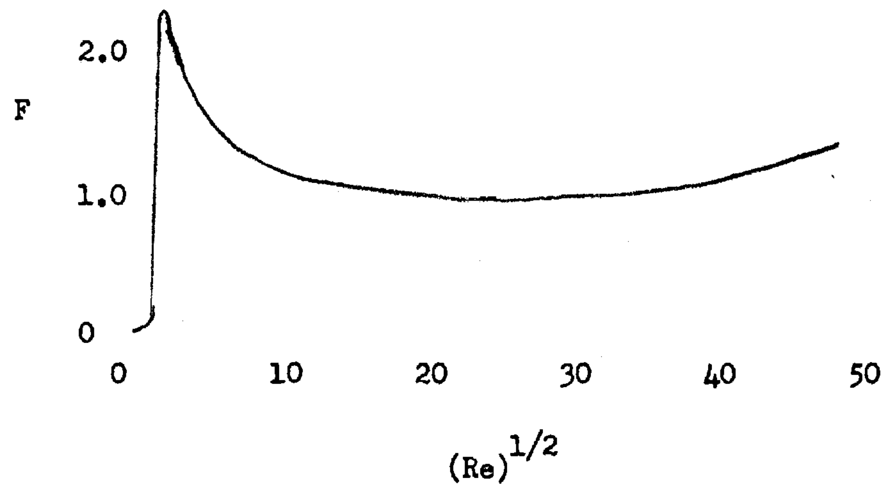

Fig. 3.1

Curve shows dependence of F on square root of Reynolds number, as given by Gunn and Kinzer[4].

$$-2a\,da/dt = (K/L)\Delta T_s(1 + Fa/s')$$

$$\text{where } a/s' \cong 1$$

The added quantity Fa/s' is the correction factor for increased ventilation, and in the physical situation under consideration a and s' are radii which are approximately equal. F is a dimensionless number to be determined experimentally, and is thereby similar to the Weber and Reynolds numbers. Fig. 3.1 (derived from Fig. 7 of Ref. 4) shows F as a function of Reynolds' number.

To study the effect that ventilation has on evaporation, let us assume that a is 10μ, a typical value, and that the shock wind is 100 ft/sec. This wind is associated with a peak overpressure of 1.8 psi; it is therefore clear that any effect obtained with this low value of overpressure will apply a fortiori to higher values of overpressure. In this discussion, the acceleration of the particles to the velocity of the air stream has been neglected; justification for this will be seen presently.

Using the above values for the ventilation effect, it is found that Re is about 45, and thus $Re^{1/2}$ is about 6.7. Fig. 3.1 shows that F must be about 1, and that it is well above the hump in the curve which occurs at about $Re^{1/2} = 3$. If this value of F is used in the preceding equation, the result indicates that the radius of the drop which can be evaporated is increased by a factor of $(2)^{1/2} - 1$ or 40%. This effect is to some extent (not readily computable) negated by the decrease in ventilation due to the acceleration of the drop. The overpressure region where this effect is most important is from about 3 to 10 psi free air overpressure, and it is precisely here that the situation is not clear cut. However, in line with the previously expressed philosophy that the effect will be underestimated wherever it is necessary to make an

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arbitrary choice because of lack of information, it is ultra-conservative to use the non-ventilated case.

It has been shown that for a rather small droplet at a relatively small shock wind, the Reynolds' number is large enough initially to make an appreciable difference in the radius of the drop which can be evaporated because of the ventilation of the drop. The importance of this point is seen when it is considered that a difference of 40% in the radius implies that the mass evaporated is 2.7 times the original, and the corresponding increase in energy loss to the shock wave will occur.

At a point of higher overpressure, and using larger drop radii, the Reynolds' number will be larger, and thus the evaporation greater, at least initially. In any event, any evaporation of liquid water drops obtained by the use of the relation for stationary drops will be too small and thus conservative from our point of view.

d. Variation of shock properties. In order to know the interaction of the shock wave and waterdrops, it is necessary to know the properties of the shock.

The properties were obtained from Ref. 7 and Ref. 8 assuming an infinite homogeneous atmosphere. The particular properties needed have been evaluated empirically in the range of 1 to 10 psi free air overpressure.

Three properties are needed: the impulse in ft. lb. sec.; the square of the material velocity (shock wind) times the density; and the relation of overtemperature (T_s) and overpressure (P_s). The mathematical statement of thse properties and their derived value is shown in Fig. 3.2.

The impulse distance curve is given by Fig. 3.3 and was based on Fig. 8 (Ref. 8). The coordinates are impulse multiplied by $10^3 X(W)^{-1/3}$

[redacted]

Fig. 2.2

VARIATION OF SHOCK PROPERTIES

IMPULSE

$$I = \int_0^t P_s \, dt = \frac{c_2}{R} \quad (2.1)$$

MATERIAL VELOCITY SQUARED, TIMES DENSITY

$$u^2 \rho_a = \frac{c_3}{R^{2.9}} \quad (2.2)$$

OVERTEMPERATURE VS. OVERPRESSURE

$$T_s = c_4 P_s \quad (2.3)$$

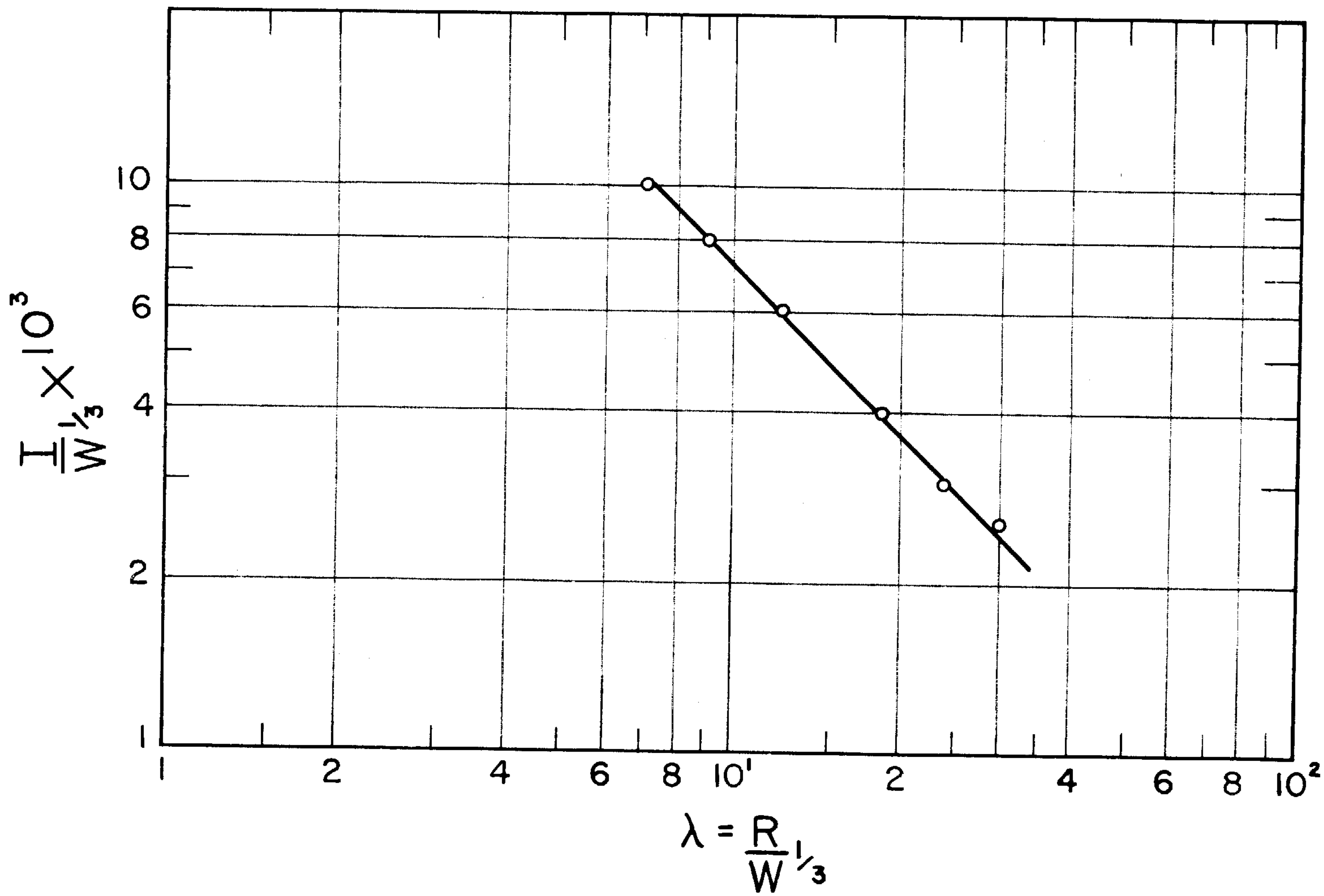

Fig. 3.3. Impulse, I, vs Free Air Distance [illegible]. [illegible] in ft lb sec; [illegible] in kt equivalent. [illegible] in thousands of feet. [illegible] from reference [illegible].

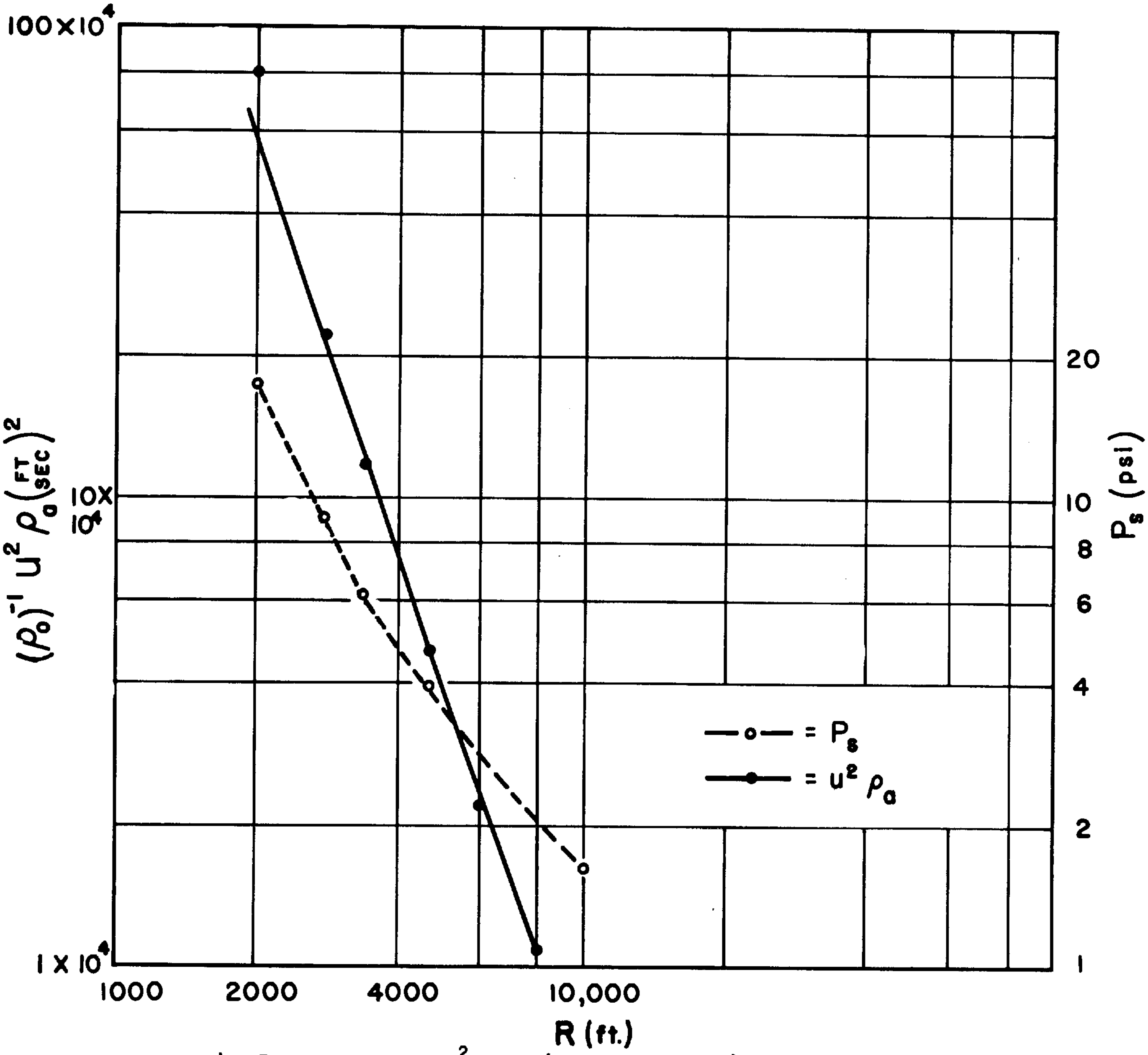

Fig 3.4 Relative value of $u^2{}_a$ vs R (free air distance). This applies to a 20 kt yield airburst bomb. Values of Ps(free air overpressure) apply to right-hand scale. Data from Ref. 7 and 8.

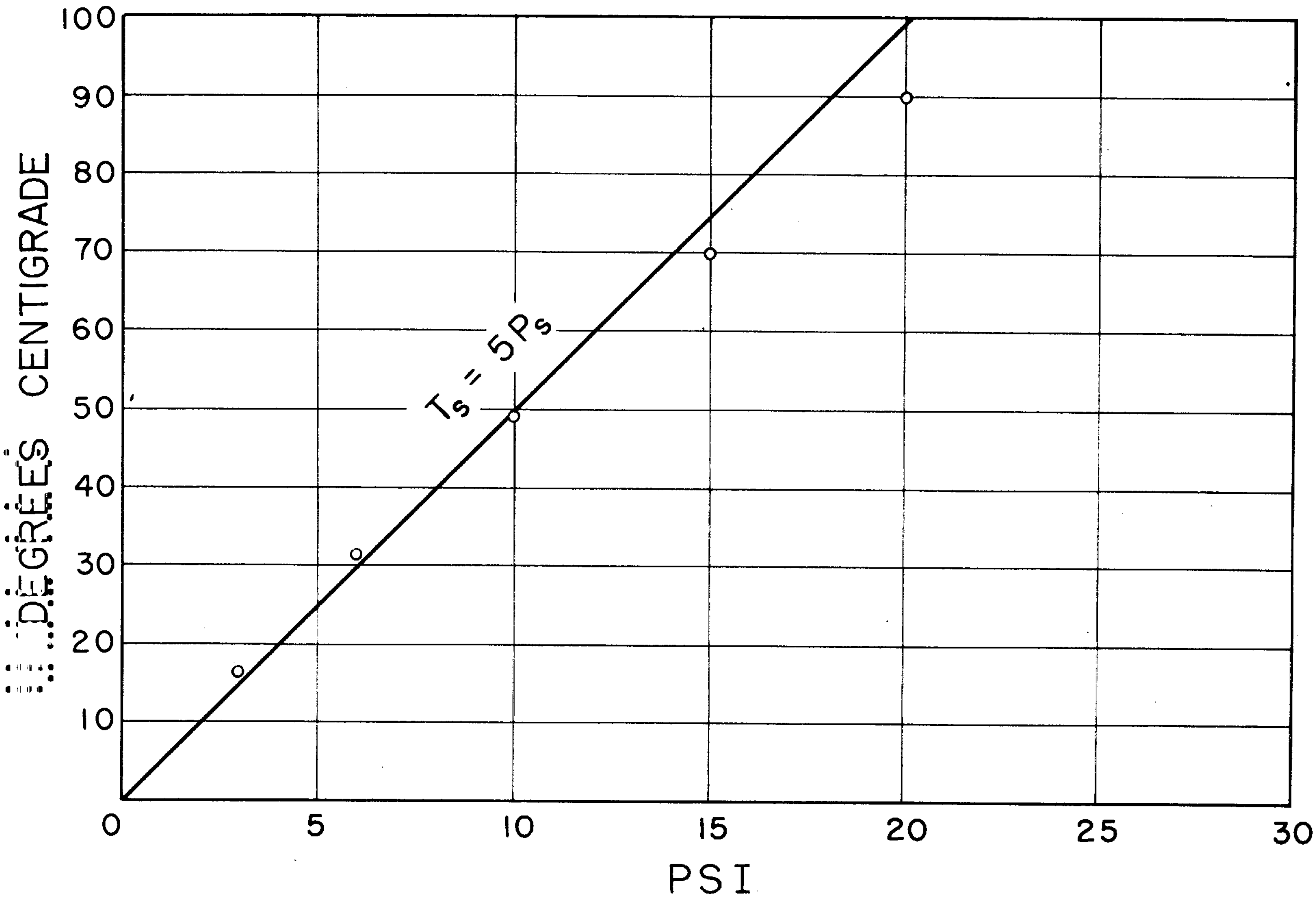

Fig 3.5 Overtemperature T_s vs Overpressure P_s (from Sandstone report (22)).

[redacted]

vs. $\lambda = R(W)^{-1/3}$ where W is yield in kiloton equivalent. Equation 2.1 represented by the straight line is a good fit to the data in the region under consideration where the value of c_2 is $8.4 \times 10^3 \left(\frac{W}{20}\right)^{2/3}$ with I is in psi sec and R in ft.

For determination of a_t (Eq. 1.2) it is necessary to know the quantity $u^2\rho_a$ as a function of R. Fig. 3.4 shows a log-log plot of relative values of $u^2\rho_a$ vs. R as determined from Refs. 7 and 8. This relation assumes a 20 kt. yield bomb. P_s has been plotted vs. R for reference.

A slope of -2.9 on the line for $u^2\rho_a$ leads to Eq. (2.2). The value of c_3 will not be needed but a_t will be computed as a function of overpressure (Fig. 6.1).

To find Eq. (2.3) Fig. 3.5 was plotted from data of Ref. 8. Although the slope of the best fitting line on log-log paper is 9/10, Eq. (2.3) (Fig. 3.2) with $c_4 = 5^\circ C/psi$ is a reasonably good approximation from 1 to 10 psi, and especially so in the region of 0-3 psi which is of importance. It should be noted that the curve for T_s is used for the range 0 to 10 psi instead of 1 to 10 psi as are the others. The reason for this is that T_s must be averaged in time over the entire duration of the positive phase, at a given point.

4. Equation of Energy Loss

The total energy extracted from a spherical shock wave by water drops in the atmosphere may be defined as E_∞. E_c is the energy lost inside R_c; E_o is the energy lost outside R_c.

Then
$$E_\infty = \int_0^\infty 4\pi R^2 qLv \, dR = E_c + E_o \qquad (3.1)$$

[redacted]

[redacted]

and $$E_o/E_c = \frac{\int_{R_c}^{\infty} 4\pi R^2 qLv\, dR}{\int_{0}^{R_c} 4\pi R^2 qLv\, dR} = \frac{3}{(R_c)^3}\int_{R_c}^{\infty} vR^2 dR \qquad (3.2)$$

Note: when $0 \leq R \leq R_c$, $v = 1$

Let $x = R/R_c$, then $$E_o/E_c = 3\int_{1}^{\infty} vx^2\, dx \qquad (3.3)$$

The relation 3.3 may be used to obtain the total energy lost. To do this we must obtain the variation of v with x. Let v be a function of a_i, a, a_{is}. a_i is the initial radius of the drops. a_{is} is the radius after passing through the shock front, and furthermore, a_{is} is equal to the smaller of a_t or a_i. v is the proportion of the mass of the drops which is evaporated at a given value of x. dv is defined as the proportion of the mass (or volume, since the density of water is one) of the drops of water, which have radii a_i to $a_i + da_i$, which is evaporated.

Then $$dv = \frac{\left[\frac{(a_{is})^3 - a^3}{(a_{is})^3}\right] \times \left[(a_i)^3 f(a_i)\, da_i\right]}{\int_0^{\infty} (a_i)^3 f(a_i)\, da_i}$$

Let $$\int_0^{\infty} (a_i)^3 f(a_i)\, da_i = \overline{(a_i)^3}$$

[redacted]

[redacted]

We now integrate and obtain:

$$v = \left[\widehat{(a_i)^3}\right]^{-1} \int_0^{\infty} \left[\frac{(a_{is})^3 - a^3}{(a_{is})^3}\right] (a_i)^3 f(a_i)\, da_i = \left[\widehat{(a_i)^3}\right]^{-1} (A + B + C) \quad (4.1)$$

The above integral has been separated into three separate integrals of value A, B, and C respectively to correspond to three distinct regions of integration, denoted by Region I, II, and III respectively. The reason for the division into the separate regions is that a_{is} has different rules of behavior depending upon the drop size, and so does a.

The condition which defines Region I is that a, the drop radius after evaporation, is always zero, and that the shock wind does not break up the original drops into smaller drops. In other words, they are all less than the critical size a_t. This statement implies that a_{is} equals a_i.

To find the upper limit to this region, let us consider the equation of evaporation (1.1)

$$-2ada = c_1 T_s \, dt$$

At the present, it will not be necessary to determine the actual value of c_1 because it will be absorbed in the value of $(a_c)^2 R_c$.

From Eq. (2.3): $T_s = c_4 P_s$.

Therefore: $-2a\, da = c_1 c_4 P_s \, dt$.

Integration of this equation and use of Eq. (2.1) yields:

$$(a_i)^2 - (a)^2 = (a_{is})^2 - (a)^2 = c_1 \int_0^{t} T_s \, dt = c_1 c_2 c_4 / R \quad (4.2)$$

Since in Region I, $a = 0$, then

$$(a_{is})^2 = (a_i)^2 = c_1 c_2 c_4 / R \quad (4.3)$$

[redacted]

When R is equal to R_c, then by definition, $(a_{is})^2 = (a_t)^2 = (a_s)^2 = (a_c)^2$. And it follows that $(a_{is})^2 = (a_c)^2 = c_1 c_2 c_4 / R_c$.

Or $\quad c_1 c_2 c_4 = (a_c)^2 R_c$.

This value of the constants may be substituted in Eq. (4.3) to give an alternate form of (4.3)

$$(a_i)^2 = (a_{is})^2 = (a_c)^2 \, R_c/R = (a_c)^2 \, (x)^{-1} \tag{4.3}$$

This equation defines the upper limit for the integral of Eq. (4.1) over Region I as x: $a_i = a_{is} = a_c(x)^{-1/2}$ The lower limit is zero, of course.

Thus
$$A = \int_0^{a_c(x)^{-1/2}} (a_i)^3 \, f(a_i) \, da_i \tag{5.1}$$

Region II starts where Region I leaves off. As a consequence the lower limit is the same as the upper limit of Region I. Furthermore, $a_{is} = a_i$ is still a condition. From Eq. (4.2) we now obtain that:

$$(a)^3 = \left[(a_{is})^2 - (a_c)^2 \, x^{-1}\right]^{1.5} = \left[(a_i)^2 - (a_c)^2 \, x^{-1}\right]^{1.5} \tag{4.4}$$

This relation may be substituted in Eq. (4.1) to give B. However, the upper limit of Region II is not yet determined. We define that limit as the place where $a_t = a_i = a_{is}$.

From Eq. (1.2) we know that $a_t = (W_e) b / (\rho_a u^2)$

Substituting in Eq. (2.2), we find that

$$a_t = (W_e) \, b \, (c_3)^{-1} \, R^{2.9}$$

Now by definition, at $R = R_c$, $a_t = a_c = a_{is}$ and therefore ,

$$a_c = (W_e) \, b \, R_c^{\,2.9} / c_3.$$

Substituting this equation in Eq. (1.2) and the condition that at the upper limit $a_t = a_{is}$ gives the result that

$$a_i = a_c \, x^{-2.9} \tag{4.5}$$

[redacted]

Substituting (4.4) in Eq. (4.1) and putting in the proper limits we find that:

$$B = \int_{a_c x^{-1/2}}^{a_c x^{2.9}} \left[1 - \left\{ 1 - (a_c/a_i)^2 \, x^{-1} \right\}^{1.5} \right] (a_i)^3 \, f(a_i) \, da_i \qquad (5.2)$$

In Region III $a_{is} = a_t = a_c \, x^{2.9}$ and Eq. (4.4) may be used to obtain the value for a (note that a_i no longer equals a_{is}) to give

$$C = \int_{a_c x^{2.9}}^{\infty} \left[1 - \left\{ 1 - (a_c/a_{is})^2 \, x^{-1} \right\}^{1.5} \right] (a_i)^3 \, f(a_i) \, da_i \qquad (4.7)$$

Or

$$C = \int_{a_c x^{2.9}}^{\infty} \left[1 - \left\{ 1 - (x)^{-6.8} \right\}^{1.5} \right] (a_i)^3 \, f(a_i) \, da_i \qquad (5.3)$$

Combining Eqs. (5.1), (5.2), and (5.3) and inserting (4.1) into (3.3), the expression for E_o/E_c is found* to be:

$$\frac{E_o}{E_c} = \frac{3}{(\bar{a}_i)^3} \left[\int_{x=1}^{x_1} x^2 \left(\int_{a_i=0}^{a_c x^{-1/2}} (a_i)^3 \, f(a_i) \, da_i \right. \right.$$

$$+ \int_{a_c x^{-1/2}}^{a_c x^{2.9}} (a_i)^3 \left(1 - \left\{ 1 - \left(\frac{a_c}{a_i}\right)^2 x^{-1} \right\}^{1.5} \right) f(a_i) \, da_i$$

$$\left. \left. + \int_{a_c x^{2.9}}^{\infty} (a_i)^3 \left(1 - \left\{ 1 - x^{-6.8} \right\}^{1.5} \right) f(a_i) \, da_i \right) dx \right] \qquad (6.0)$$

[redacted]

[redacted]

* The application of Eq. (1.2) through Eq. (4.6) to Region III tacitly assumes that each drop of radius a_1 will be broken into exactly an integral number of drops of radius a_t, each of which will evaporate according to the given rule. This is not exactly true, for there will nearly always be a residue of drops less than a_t in radius, and as a consequence they should be considered as Region I or II drops. However, the difficulty of expressing this mathematically and getting an answer with a minimum of labor, leads one to treat all the water in the drops in Region III as evaporating under the same law as a_t. This is another assumption which tends to underestimate the total loss of energy, in accord with our basic philosophy of underestimating this effect.

5. Methods of Computation

In application of the shock properties to the problem of interaction with the atmosphere, it was tacitly assumed that they do not change under the influence of the evaporation of the water drops. This assumption is difficult to justify. In actuality, the present method does not depend upon it. There are two separate phases of this problem. The first is the absolute values of the shock properties at R_c; the second is their rate of variation from there out to the limit of integration, x_1.

With regard to the first, the value of R_c can be obtained experimentally. Some data are already available, i.e., Penney's study and the data in Appendix V from the Greenhouse test, which indicate that the estimates of this paper are not too large. The experimental value of R_c will contain the effect on the shock wave due to the liquid water present, and the value of E_∞ will not be in as great an error as it otherwise might be due to the mistaken estimate of R_c.

[redacted]

In estimating the value of E_o/E_c ($x_1 > 1$), the shock properties are assumed, for simplicity, to have the same rate of change they would have without the presence of the liquid water content. There are two reasons why it is felt that this approximation does not introduce a large error.

First, a computation was made under conditions which should show up the difference due to the wrong rate of change. These computations are given in Table 7.2 and 7.3. The computation using the method developed in this paper is #4 of Table 7.2. x_1 is 1.59; the fractional loss in energy is .35. To make a proper comparison, one should find the change in the slope and use it to integrate over the range of x_1 from 1 to 1.59. However, the change in slope is not known to the present writer, so a simpler procedure was devised. It consisted of applying the equation for E_o/E_c in five successive steps of small intervals. At the end of each step the shock wave properties were found from consideration of the energy lost in that step. These new properties were then used to find E_o/E_c at the end of the next step. See Table 7.3 for these computations.

If the original equation for E_o/E_c were greatly in error because the effect of the liquid water on the rate of change of P_s was ignored, this procedure should lead to a significant difference between the two methods of computation. There was no difference. The fractional loss was .35 for the first case and .348 for the second. These results give confidence in the method for $x_1 \lesssim 1.5$.

The second reason why this assumption should not introduce a large error is due to the nature of atmospheric cloud formations. In the most probable case, where these energy losses could occur, there will be a cloud layer between the point of bomb-burst and the target, and a space of more or less clear air between the bomb and the cloud, and less probably, between the cloud and the ground. For convenience, the computation

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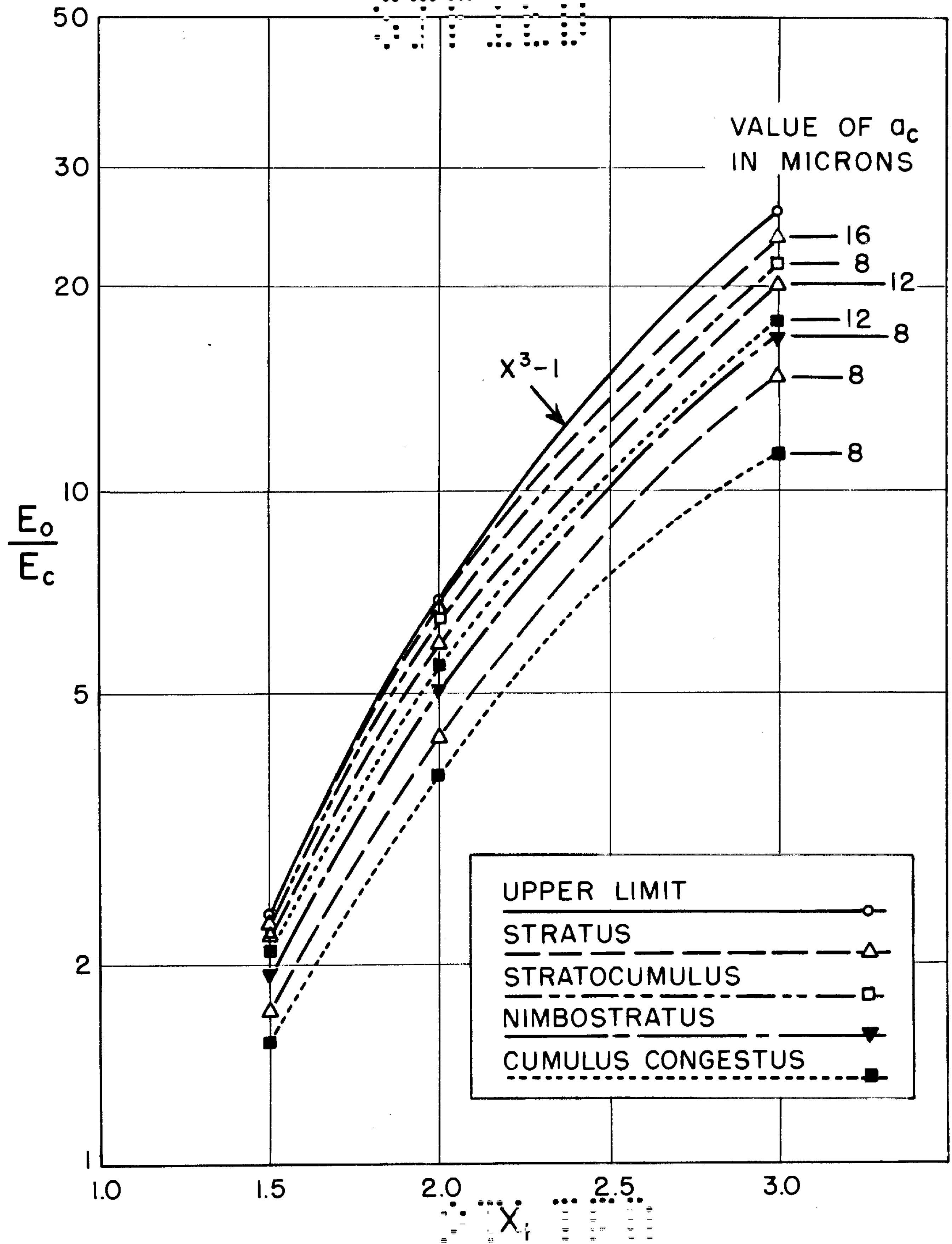

Fig. 5.1 E_0/E_c as a function of X_r. Legend shows the type of cloud and value of a_c which applies to each curve.

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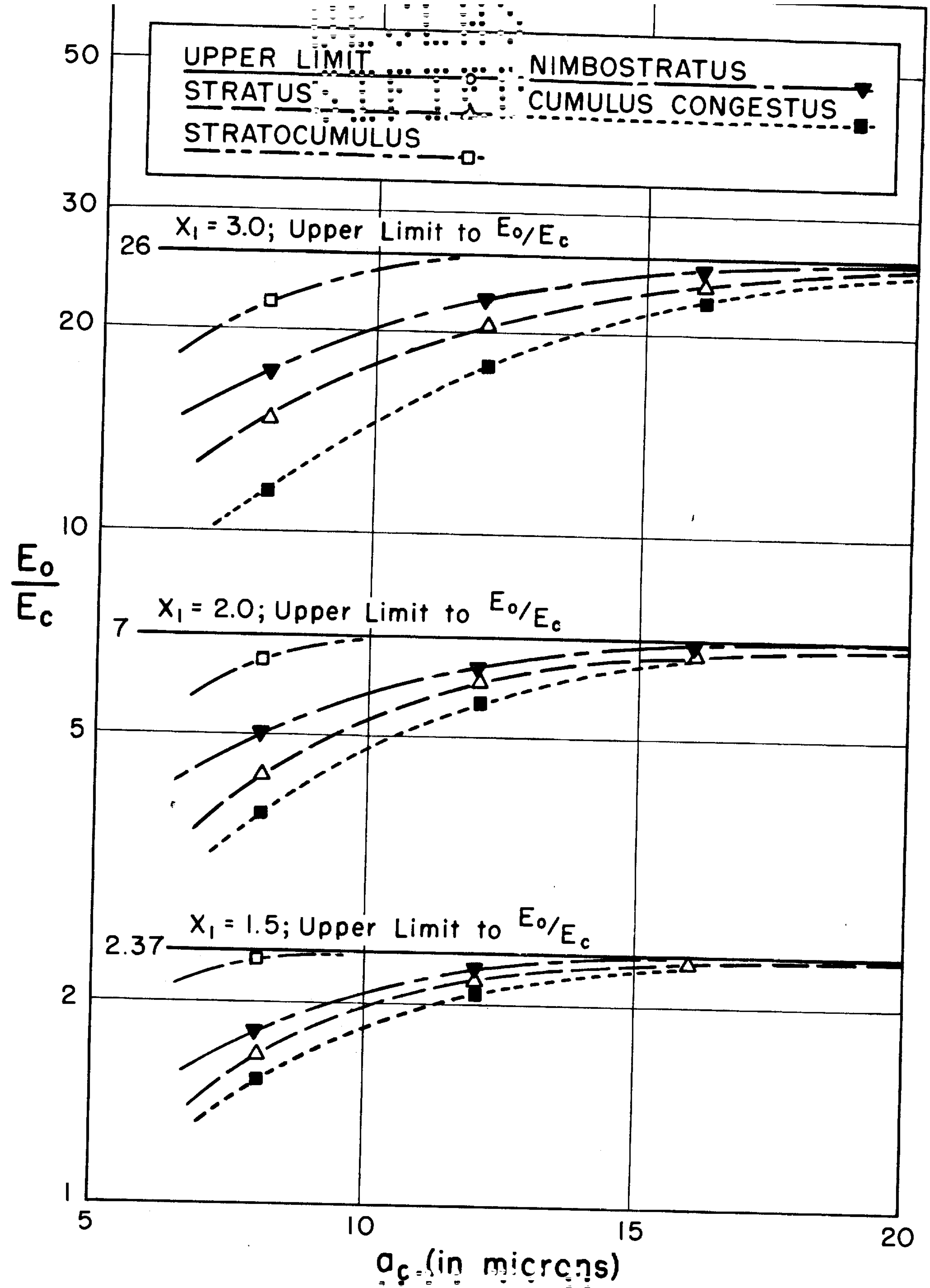

Fig 5.2 E_o/E_c as a function of a_c. Legend shows the type of cloud which applies to each curve. The value of X_1 is shown above each group of curves.

[redacted]

of the energy loss is made in two steps. The computation is first made of the energy loss to the point where the cloud ends, assuming the cloud extends into the point of bomb burst. This computation is corrected by subtracting the energy not lost because of the clear air space. Thus, only the actual cloud thickness attenuates the shock wave. In most practical cases the energy loss will be only slightly overestimated because of the neglect of the variation of the rate of change of the shock properties in the cloud.

a. Evaluation of Integrals

The integrals for E_o/E_c were numerically evaluated by personnel of Division 1613 of Sandia Corporation: Mr. C. Hassel and Mrs. Sutherland. The procedures used will be discussed by them in a separate report. The data on the frequency distribution of a_1 obtained from aufm Kampe were normalized to yield:

$$f(a_1)\ da_1 = 1$$

These values of $f(a_1)$ were then used in Eq. (6.0) to evaluate it for four types of clouds: stratus, stratocumulus, nimbostratus and cumulus congestus. The values of x_1 were 1.5, 2.0, and 3.0. a_c was used as 8, 12, 16, and 2μ.* The results are shown in Figs. 5.1 and 5.2. Smooth curves have been used to connect the points. The upper limit for E_o/E_c is clearly defined as the complete evaporation of all liquid water out to x_1, the limit of the integration. From the geometry, it follows that the upper limit for E_o/E_c is $(x)^3 - 1$.

b. Procedure of Computations

The computation of the energy loss for a particular yield of

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* Some cloud forms were not evaluated for all values of a_c. Whenever E_o/E_c was near the theoretical limit, further computations were omitted.

[redacted]

bomb and a specific height of burst and weather situation is made in several steps. The first step is a basic one which can be used for more complicated situations by appropriate modification. The purpose behind it was to estimate what order of magnitude the maximum effect of cloud might be. If that effect were negligibly small, no further effort would have to be expended on the problem. Therefore, it was decided to make the following assumptions for the basic computation. These assumptions are in addition to the ones already made for the computation of E_0/E_C:*

1. The yield is 100 kt TNT equivalent. The bomb is exploded at a height to maximize the 10 psi level. The energy loss at the 10 psi circle was of prime interest, and therefore, computed.

2. A large liquid water content of $q = 1$ g/m^3 was assumed for convenience. All the liquid water out to the 10 psi circle on the ground was assumed to be evaporated, in order to get an upper limit.

3. The cloud (fog) was considered to extend from the ground to the burst height. This assumption was used only to simplify computational procedure. Computations will be discussed later which utilize more probable cloud distributions.

4. In this step and the remaining steps, the energy loss at a point on the ground was computed assuming that the blast energy which arrived at that point had traveled along an essentially straight line

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* It should be noted that some assumptions had to be made in lieu of better information. Some of these are not wholly defensible, but they were believed to be the best at the time. Since the method does not depend upon these assuptions, the purpose of this paper - to demonstrate the method used - is fulfilled.

[redacted]

from the origin to that point.*

5. Two assumptions were used for the energy of the blast wave. In 1951, when this study was made, that figure had not yet been precisely determined:

a) 87% of yield energy.[8]

b) 55% of yield energy.[9]

Discussion of the results considering these two conflicting figures for blast energy will be given for each specific situation considered.

c. Basic Data

1. From LA-743R the height which maximizes 10 psi for a 1 kt. yield, is 1000 ft, and the 10 psi point on the ground is 1650 ft from ground zero. Multiplying by $(100)^{1/3} = 4.65$ to obtain figures for 100 kt. yield, a height of 4650 ft and a distance of 7,660 ft are obtained.

2. Energy in blast wave of 100 kt. yield bomb is 8.75×10^{13} calories (87% of yield energy).

3. The volume (V) of a sphere of radius R meters is

$$V = 4\pi R^3/3 \ m^3 .$$

4. The energy lost from a shock wave due to evaporation of q grams of liquid water per m^3, whose latent heat of vaporization is L cal/g is qLV calories.

5. The distance from the point of detonation to the 10 psi circle on the ground is 8950 ft (2730 m), and will be denoted as R_{10}.

$$qL(4\pi/3)R_{10}^3 = 5.12 \times 10^{13} \text{ cal.}$$

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* This assumption neglects Mach reflection and flow of energy from one part of the shock wave to another. See Appendix IV for a discussion of this assumption.

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[redacted]

F, fraction of energy lost is ratio of energy lost to the energy in the blast wave.

F is 58.5% for the case where it is assumed that 87% of the energy goes into the blast wave, and 92.5% for the case where 55% of the energy goes into the blast wave.

This energy loss is certainly significant, although it is not presumed to be correct, because the water will not all be evaporated. The conclusion that the effect can not be ignored a priori is justified by the results of this computation, and further refinement must be made to determine the losses to a better approximation.

d. Use of E_o/E_c Curves

For the computation of the energy loss in any specific case, where complete evaporation of all the liquid water was not assumed, the computations in (c) were used to obtain the absolute or relative value of the energy loss in the following manner. The energy lost inside R_c was obtained by using the ratios of q/l, and $(R_c/R_{10})^3$ times 58.5%. This figure gives the percent energy loss inside R_c. Then E_o/E_c was computed. Two figures were obtained for this, each corresponding to the upper and lower limit obtained for R_c (to be discussed in Sec. 6). The total percent energy loss was obtained by multiplying $\left[E_o (E_c)^{-1} + 1 \right]$ times the percent loss in R_c.

Once the percent energy loss at a given point had been determined, then the overpressure which would arrive at that point was determined from LA-743R by assuming a bomb of appropriate reduced energy at the given height.

Thus a 58.5% energy loss for the 100 kt. bomb of the previous example would mean a 41.5 kt. bomb at a height of 4,650 ft. This bomb would

[redacted]

[redacted]

give an overpressure at 7,660 ft from ground zero of 6.2 psi instead of 10 psi. The computations follow:

$(41.5)^{1/3} = 3.45$; $4650\ (3.45)^{-1} = 1350'$ for reduced burst height $7660\ (3.45)^{-1} = 2220'$ for reduced distance out. Thus scaling to a 1 kt. yield bomb at 1350 ft height gives 6.2 psi at 2220 ft from ground zero. Note again that this is an upper limit computation as explained in Sec. c above.

The computations in Table 7.1 which are plotted on Fig. 7.1 were made to show the maximum effect possible of a q of 1 g/m^3. All liquid water from burst point out to the point of computation was considered to be evaporated. Thus the maximum effect of this amount of water is shown in Fig. 7.1. However, the theory developed in this paper has been applied in Table 7.2, which is plotted on Fig. 7.2. This result has been found assuming a R_c of 4800 ft, and a q of 1 gm/m^3. Before discussing these results, it is necessary to evaluate R_c and some constants whose values have not been needed in the discussion heretofore.

6. Evaluation of R_c

In order to evaluate R_c, certain constants must be determined which have been unnecessary for the development of the theory to this point. Table 6.1 shows these constants, the equation in which they occur, and a reference to the literature. a_t according to Hinze's theory, is plotted vs. P_s in Fig. 6.1. a_t being a function of P_s only, it will not change for various yields, except as P_s changes. a_s, however, is a function of yield as well as P_s (see Eq. (4.3)) and has been plotted on Fig. 6.1 according to the theory of this paper (curves labeled '$a_s(M)$'), and according to Penney's theories (curves labeled $a_s(P)$). The 'M' curves are

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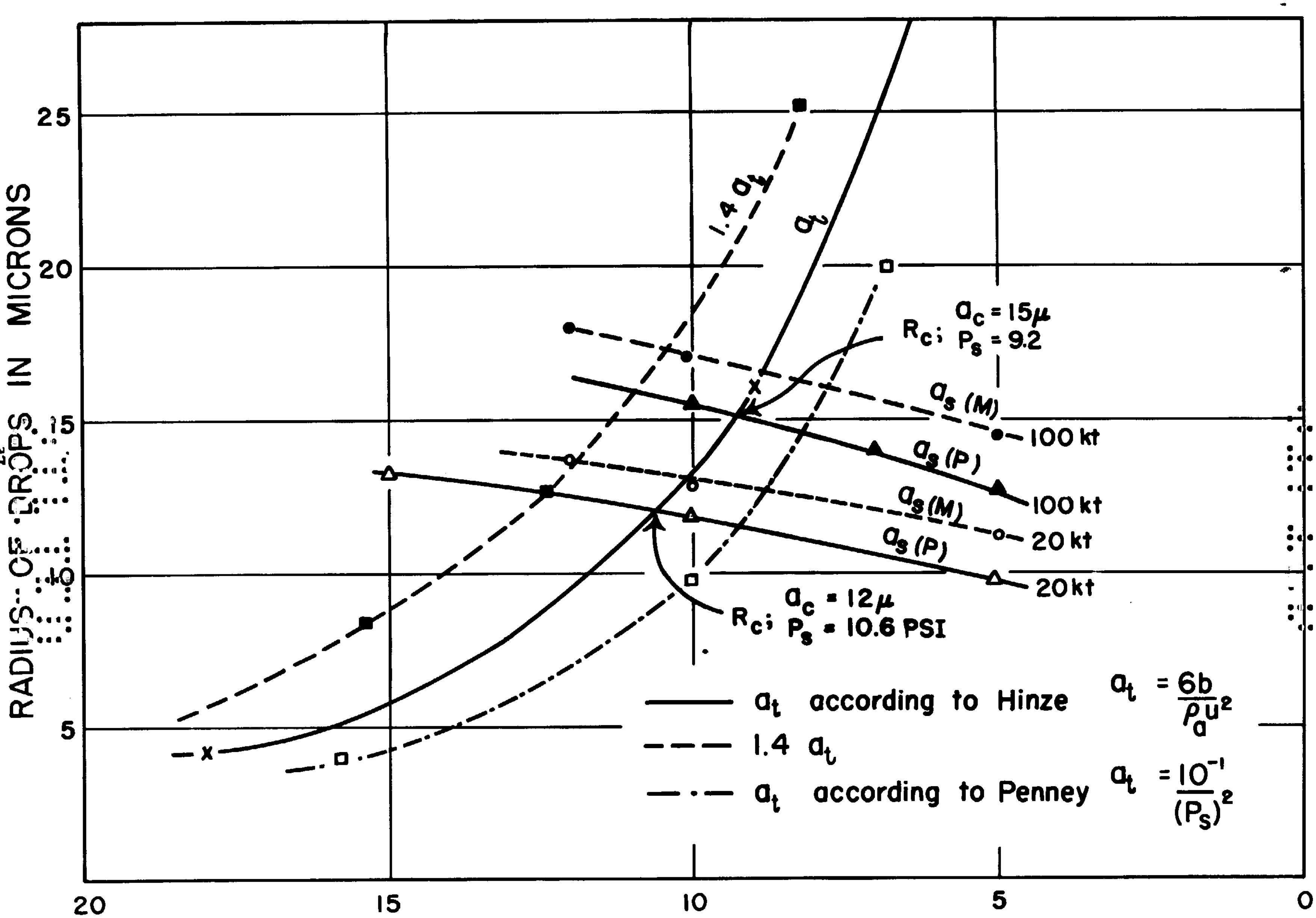

Fig 6.1 Diagram for determination of R_c.

Symbol a_t is the radius of the largest drop left after the passage of shock wind. a_s is the radius of the largest drop which can be evaporated by the corresponding overpressure of a given yield airburst atomic bomb. a_s(P) are the curves according to Penney's work. a_s(M) are from the derivation of this paper. R_c is the point of intersection of a_t and a_s.

essentially of the same family as the 'P' curves but are displaced upward by a constant percentage. Therefore, our basic philosophy of underestimating the effect, required that the 'P' curves be used to determine R_c. These Penney determined by showing that:

$$\int_0^{\tau} (T_s - T)\, dt = 5/12\ (\phi_s)\tau$$

where ϕ_s is the peak overtemperature, and τ the duration. ϕ_s and τ were determined from (7) and (8). It is believed that there is quite good agreement between the 'M' curves and the 'P' curves considering the number of approximations made in deriving them. The slopes of the curves are essentially the same when 100 kt. M and P, and 20 kt. M and P are compared. Therefore, the expression (4.2) should be valid, no matter which curve is used to evaluate a_c and R_c. By using the 'P' curves, one underestimates R_c, which seems reasonable in view of the large loss of energy found with a small R_c, and thus one underestimates the energy loss. As far as a_t is concerned, the W_e number of 6 is probably correct only to ± 40%. Assuming it to be + 40%, R_c corresponds to 11.5 psi for a 100 kt. yield (or a distance of 4300 ft) and a_c corresponds to 16μ.

This R_c, then, is only about 5% smaller than the smallest R_c (4280) which will be used. The increase in size of a_c from 15.5μ, which was used, to 16μ in this case, would no doubt compensate, as far as energy loss is concerned, for the decrease of R_c. If the M curve for 100 kt. were used, R_c would correspond to about 10.5 psi, and a_c would be approximately 17.5μ. R_c would be 4280 (the smallest value) but a_c would be larger, thus increasing the effective loss of energy. Similar reasoning holds for a 20 kt. yield.

[redacted]

TABLE 6.1

NUMERICAL VALUES AND DIMENSIONS OF CONSTANTS USED

Symbol	Eq. No.	Value	Dimensions	References
c_1	1.1	1.12×10^{-7}	$cm^2\ sec^{-1}(^{\circ}C)^{-1}$	2
c_2	2.1	$8.4 \times 10^{+3}(\frac{W}{20})^{2/3}$	(psi)(sec ft)	8
c_3	2.2	This value is not used. a_t is expressed as a function of overpressure. See Fig. 6.1		
c_4	2.3	5	$^{\circ}C\ (psi)^{-1}$	Ref.8 and Fig.3.6
b	1.2	72	dynes/cm	Handbook of Meteorology
W_e	1.2	6	none	3
ρ_o	1.2	1.23	kg/m^3	Handbook of Meteorology
K	(p7)	5.57×10^{-5}	$cal\ cm^{-1} sec^{-1}(^{\circ}C)$	Handbook of Meteorology
L	(p16)	600	$cal(gm)^{-1}$	Handbook of Physics
$c_1c_2c_4$	4.2	$47 \times 10^{-4}(\frac{W}{20})^{2/3}$	$cm^2\ ft$	

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[redacted]

Penney,[6] on page 8 stated in a holographic note that $a_t = \frac{10^{-1}}{P_s^2}$ had been experimentally verified. If this is correct, then the Penney curve for a_t is the correct one. This is the dashed curve on Fig. 6.1. In this case, R_c would correspond to about 5300 ft (7.6 psi) for 100 kt., $a_c = 14.4\mu$; for 20 kt. $R_c = 2950$ ft (8.6 psi) and $a_c = 11.4\mu$. Thus, R_c is only slightly larger than our maximum values of 5200 and 2900 for the respective yields. In order to continue to be on the conservative side, the value of a_t derived in this paper will be used.

Inasmuch as it will be shown that the energy loss is not a very sensitive function* of R_c, if a_c varies in the opposite direction, it is obvious that one need not worry too much in this paper about tieing down R_c more accurately than it has been for the case of fog and clouds.

If, as in Sec. 3c, the values for a_s should be increased by up to 40% due to the ventilation factor, then in the case of a 20 kt. yield using the M curves, R_c would correspond to approximately 9 psi overpressure and a_c equals 15μ. This variation would increase the energy loss although not by 40% (probably in the order of 10 to 20%).

7. Height of Burst vs. Overpressure Curves

This section applies the theory to the case of a 100 kt. airburst bomb. The original burst-height curves of LA-743R have been plotted for the 100 kt. yield directly and will be compared with the curves modified by evaporation of fog drops.

As a check on the theory, and an indication of the upper limit, Fig. 7.1 was computed with the assumption that all the liquid water is evaporated from the burst point to the chosen point on the ground. The

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* For fog and clouds.

TABLE 7.1
COMPUTATION FOR FIG. 7.1

Computation number	Height(ft)	Distance(ft)	R(ft)	R/Ro*	$(R.Ro)^3 = n$
1	3500	8000	8740		.93
2	5000	9000	10300	1.16	1.57
3	3000	9000	9500	1.06	1.2
4	4000	6500	7650	0.855	.63
5	5000	6500	8210	0.915	.77
6	4650	5000	6800	0.76	.445
7	2500	6500	6950	0.78	.472
8	3050	5750	6510	0.728	.385
9	5500	5500	7800	0.872	.66
10	5500	7000	8850	0.99	.97

TABLE 7.2
COMPUTATION** FOR FIG. 7.2

			m	R/R_c	E_o/E_c
1	3500	8000	.57	1.82	4.60
2	5000	9000	.912	2.14	8.40
3	3000	9000	.70	1.97	6.45
4	4000	6500	.365	1.59	2.85
5	5000	6500	.447	1.71	3.75
6	4650	5000	.258	1.42	no
7	2500	6500	.273	1.44	change
8	3050	5750	.225	1.35	discernible
9	5500	5500	.385	1.62	2.95
10	5500	7000	.565	1.84	4.80

TABLE 7.3
CHECK COMPUTATION

	R	n	m	R/R_c	E_o/E_c	x_1^3
1'	4800	.156	.092	1.00	0.	1.0
2'	5500	.231	.149	1.20	.68	1.72
3'	6200	.330	.193	1.38	1.40	2.50
4'	6900	.459	.269	1.62	3.10	4.3
5'	7650	.63	.368	1.85	4.8	6.1

* Ro = 8950 ft

** R_c = 4800 ft
q = 1
P_c = 9.2
Cloud type: Stratus
$a_c = 15\mu$

$R_c = \sqrt[3]{\frac{Y}{22}}$

R_a = free air distance from LA-743R for 22 kt yiel for P_c

R_c = corrected radius of completed evaporation

$n = \left(\frac{R}{R_c}\right)^3$ use R_c from previous computation

= .585n	$k = \sqrt[3]{(1-m)\,100}$	h/k	d/k	OP'	OP
0.57	3.5	1000	2280	6.5	8
0.912	not applicable				8
0.70	3.1	970	2900	3.8	6.2
0.365	4.0	1000	1625	10	12.0
0.447	3.72	1340	1750	6.8	11.0
0.258	4.2	1100	1190	11.0	13.3
0.273	4.16	600	1560	8.9	9.5
0.225	4.26	715	1350	12.0	13.0
0.385	3.94	1400	1400	7.2	9.8
0.565	3.51	1570	1990	5.0	8.8

x^3	z	mz	$\sqrt[3]{(1-mz)100} = k$	h/k	d/k	OP
5.85	.96	.55	3.65	960	2190	6.9
10.0	.94	.86	2.41	2075	3740	4.0
8.0	.93	.665	3.21	935	2800	3.8
4.0	.96	.35	4.05	990	1600	10.4
4.9	.97	.432	3.84	1300	1690	7.1
no change discernible						
4.10	.965	.373	3.98	1380	1380	7.4
6.10	.95	.54	3.58	1540	1960	5.2

$= \dfrac{E_o/E_c + 1}{x_1^3}$	Fractional loss fr. 0 to R	Effective Yield = Y'	P_s	a_c	R_a	R_c
1.0	0.92	90.8	9.5	14	2850	4580
.978	.132	86.8	9.6	14	2830	4470
.960	.185	81.5	9.7	14	2750	4260
.954	.256	74.4	9.7	14	2750	4130
.951	.348					

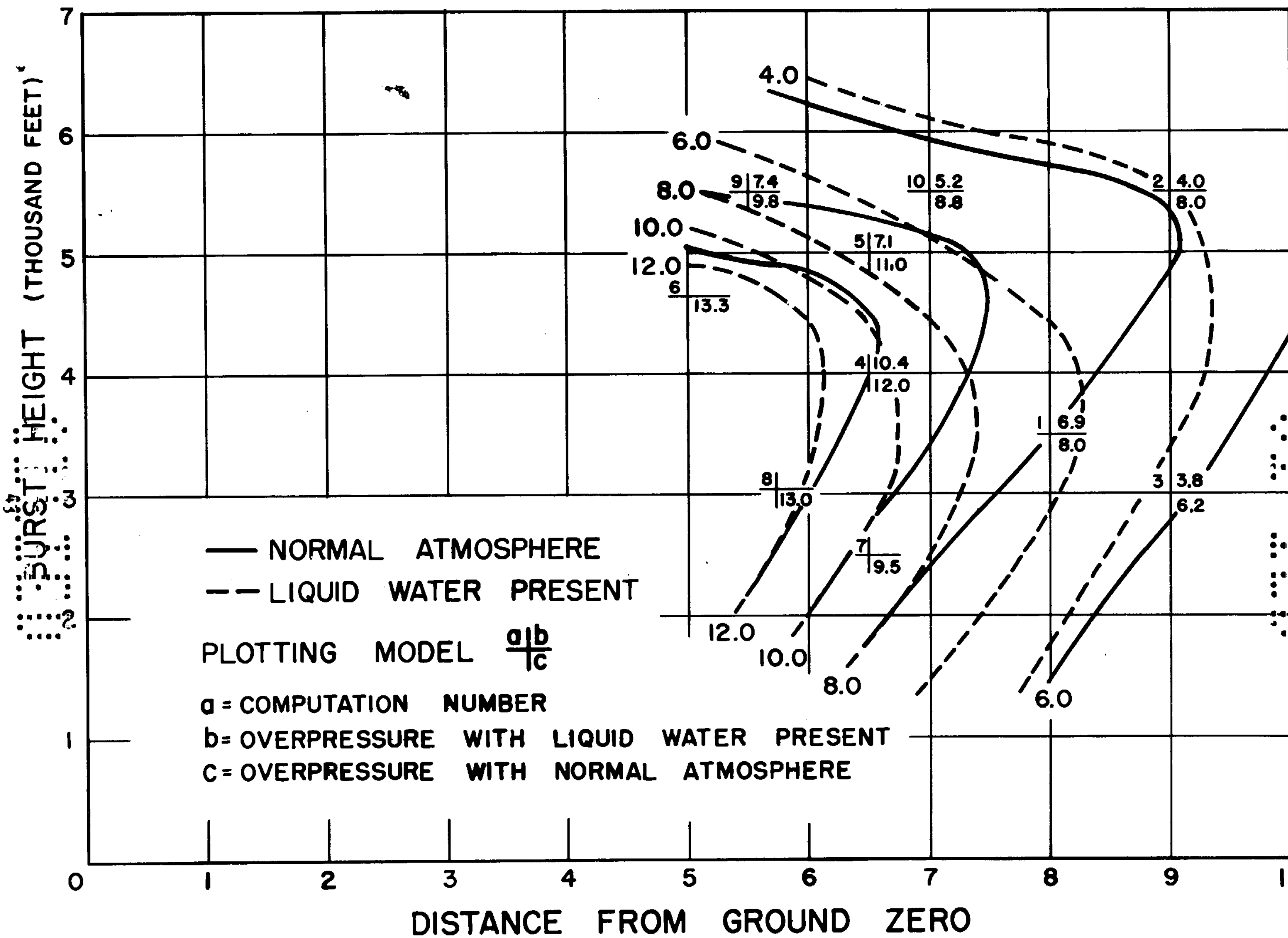

Fig 7.1 Overpressure as a Function of Burst height and distance from ground zero. It is assumed that there is 1 gm/m³ of liquid water present, and that it is completely evaporated. The energy yield is assumed to be 100 kt equivalent. Normal curves from LA 743R

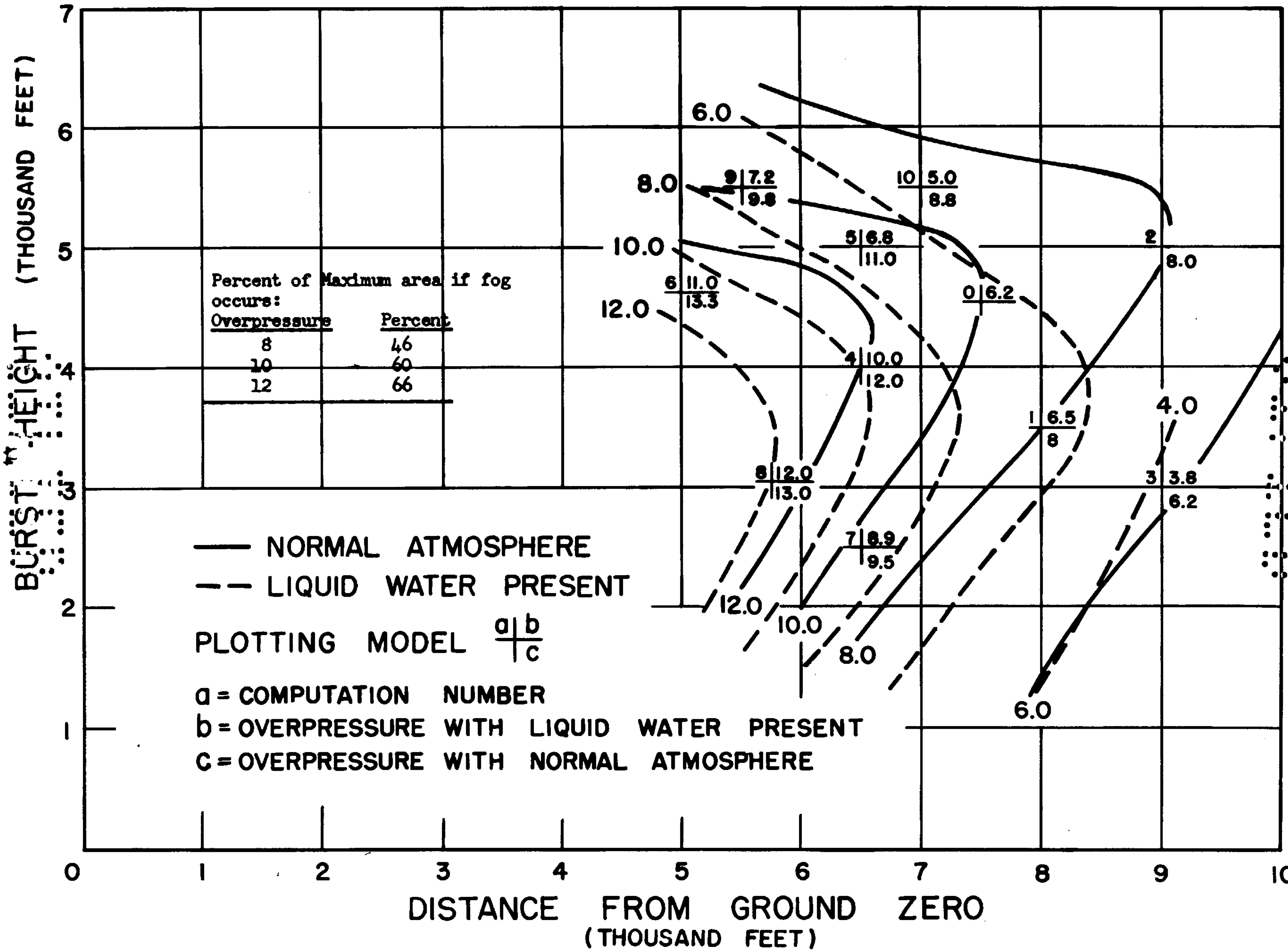

Fig 7.2 Overpressure as a function of burst height and distance from ground zero. It is assumed that q = 1 gm/m^3; R_c = 4800 ft; a_c = 15 μ. Yield: 100 kt. Normal curves from La 743R.

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amount of liquid water is assumed again to be 1 gm/m^3. This computation clearly does not depend upon the theory previously developed (which will be the case in Fig. 7.2). Since Fig. 7.1 is meant for comparison and serves only as an upper limit, its details are not too important and should not be given great weight.

Fig. 7.2 shows the effect of fog (or stratus cloud) with $q = 1\ gm/m^3$; $R_c = 4800$ ft and $a_c = 15\mu$. The fog, as before, is assumed to extend uniformly from the earth's surface to the burst height, but all drops are not completely evaporated.

The computations which are included in Tables 7.1 and 7.2 corresponding to Figs. 7.1 and 7.2 were made as follows:

1. The energy loss outside R_c was evaluated from Fig. 5.1, for $R_c = 4800$ ft and $a_c = 15\mu$ for stratus clouds.

2. The fraction of maximum energy lost (z) is found by $E_o/E_c + 1 = z$.

3. $m = (\frac{R}{8950})^3 (0.585)$ and is the fraction of energy lost from 0 to R if all liquid water were evaporated assuming that 58.5% is the fractional energy lost from 0 to 8950 ft.

4. (1-mz) 100 gives the apparent yield of the bomb.

5. From this yield, the scaling laws, and LA-743R, the expected overpressure is determined at each point.

Considering only 8 psi overpressure at the surface and above, which is the region where the assumptions fit the best, Fig. 7.2 shows that: (1) The optimum burst height for 10 psi overpressure is reduced from 4600 ft to approximately 3600 ft; (2) Greater changes of overpressure occur for heights of burst above 4000 ft than for below; (3) The burst height is no longer so critical for the maximum, i.e., the knee is flattened out; (4) The inset gives the percent of the maximum area obtained if fog occurs,

[redacted]

and the burst height is planned for 10 psi, is 60%. The amount is 66% for 12 psi and 46% for 8 psi.

A comparison of Figs. 7.1 and 7.2 shows that the 12 and 10 psi lines change but little from 7.1 to 7.2. The bigger changes occur farther out. This is because the evaporation is complete out to the 10 - 12 psi region in Fig. 7.1 and almost so in Fig. 7.2.

It is clear, from these figures and from the percent of maximum area obtained, that if the burst height is planned to maximize 10 psi overpressure in a cloudless atmosphere and fog occurs, a large loss will be realized. However, if a lower burst-height, i.e., 3600 ft, were utilized, the loss would not be nearly as great. The area in this instance would be 74% of the maximum obtainable in a clear atmosphere.

It may also be noted that since the "sharpness" of the curve is reduced considerably, if fog or stratus has a fair chance of occurring, a lower burst height should always be chosen, for if the weather is clear, the lower burst will not lose an appreciable amount of area, but if fog is present, the area will be maximized.

Additional charts of this type should be made assuming the various types of weather situations and various liquid water content as has been done for 10 psi (only) in Sec. 9.

8. Atmospheric Water Content

In order to determine what type of atmospheric models to assume, several (Refs. 9 - 11) studies have been made by Hq. Air Weather Service, Andrews Air Force Base.

Ref. 9 gives a quick summary of some of the work which has been done on drop size frequency distributions, and liquid water content of

[redacted]

TABLE 8.1

RECOMMENDED VALUES OF METEOROLOGICAL FACTORS FOR CONSIDERATION IN THE DESIGN OF AIRCRAFT ICE-PREVENTION EQUIPMENT

Class	Item	Air temp. (°F)	Liquid water content (g/m^3)	Mean effective diameter (microns)	Pressure altitude* (ft)	Remarks
I-M Instantaneous Maximum	1	32	5.0	25	18,000 to 20,000	Horizontal extent: 1/2 mile Duration at 180 mph: 10 sec. Characteristic: Very high liquid water content
I-N Instantaneous Normal	6	32	1.0	20	10,000 to 20,000	
II-M Intermittent Maximum	11	32	2.5	20	10,000 to 15,000	Horizonatal extent: 3 miles Duration at 180 mph: 1 min. Characteristic: High liquid water content
	16	32	1.3	30	8,000 to 15,000	
	21	32	.4	50	8,000 to 15,000	
II-N Intermittent normal	26	32	.8	20	8,000 to 12,000	
III-M Continuous Maximum	31	32	.8	15		Horizontal extent and duration: continuous Characteristic: Moderate to low liquid water content for an indefinite period of time
	36	32	.5	25		
	41	32	.15	40	3,000 to 20,000	
III-N Continuous Normal	46	32	.3	15		
IV-M Freezing Rain	50	25	.15	1000	0 to 5,000	Horizontal extent: 100 miles Duration at 180 mph: 30 min. Characteristic: Very large drops at near-freezing

* Altitudes according to aircraft barometric altimeter

the atmosphere.* A complete discussion is beyond the scope of this paper. However, excerpts have been made of pertinent data.

Ref. 12, which is not mentioned in (9), has in its Table I "Recommended Values of Meteorological Factors for Consideration in the Design of Aircraft Ice-Prevention Equipment".

Table 8.1 presents excerpts from Table I. It must be remembered that these values apply only at 32°F. Theory and other measurements show, furthermore, that at higher temperatures and lower altitudes, a higher liquid water content is probable. The measurements of Nyberg[9] show data consistent with Ref. 12. In his data, the liquid water content ranges with visibility as follows:

Mean Value of q	Visibility
0.60 g/m	30-90 meters
0.43 "	200-300 "
0.30 "	500 "
0.21 "	700 "
0.15 "	800 "

Since the other data of (12) gave neither temperature or visibility at time of observations, it is difficult to determine the complete significance of their observations for the present problem.

From Nyberg's data and Ref. 9, one can be justified in associating

---

* Several errors were noted in this paper: (1) Page 4, line 2: the mean effective diameter is the mean volume diameter where a is the diameter of the drops.

$$= \sqrt[3]{\frac{\int a^3 f(a)da}{\int f(a)da}}$$

(2) page 7: See correction in April 1950 Journal of Meteorology; (3) page 7: Table of Average Drop Radius was copied incorrectly.

TABLE 8.2*

FREQUENCY OF LOW CLOUDS AND FOG AT REPRESENTATIVE RUSSIAN CITIES

CITY	TIME**:	07:00		13:00	
	WEATHER TYPES***:	A	B	A	B
1. Moscow		44.5%	17.2%	34.8%	12.1%
2. Kharkov		53.4%	19.2%	55.7%	11.1%
3. Stalingrad		10.8%	22.8%	12.4%	29.8%

* Mr. C. N. Charles of Sandia Corp. kindly pointed out an error in this table in draft form and supplied the correct data.

** Time is local standard.

*** Weather types:

A = Less than 5/8 mile visibility and/or 1000 ft ceiling (or less).

B = 5/8 - 1 1/4 mile visibility and/or 1000 ft to 2000 ft ceiling.

[redacted]

q with visibility according to his table and if there is a dense cloud, say that q is of the order of 8/10 gm/m^3, and thus estimate the liquid water content from visibility and ceiling observations.

If the frequency of low clouds and restrictions to visibility (fog, rain, etc.) is known, one may justifiably infer at least a rough idea of the frequency of high liquid water content.

From Ref. 10, Table 8.2 has been prepared to give an idea of the prevalence of conditions at various representative locations in the USSR, favorable to a high value of q. For condition A, visibility less than 5/8 mile and/or a ceiling of 1000 ft or less, it is estimated that q ranges between 2/10 and 1 gm/m^3. For condition B, it will range around 1/10 or less at the surface up to 6/10 to 1 gm/m^3 in the cloud. A mean surface temperature of between 20° and 30°F has been assumed.

The high percent of observations of conditions A and/or B shown is prima facie evidence that there will be a good probability of losing energy to evaporation of fog and cloud in the winter over the USSR. For example, in Moscow in January at 07:00 LST, a frequency of 53.4% of condition A means that there is a high probability of loss of energy to liquid water for an atomic bomb delivered at this time of day - at random. It is obvious that if a strike should be planned for a day when cloud cover gives maximum protection to the attackers, there is also the maximum probability of loss of energy from the shock wave.

Further studies of weather conditions conducive to large values of q were being conducted by Hq. AWS and a report on these studies should now be available for use in further analysis of this problem.

[redacted]

9. Realistic Atmospheric Models and Their Effects on Apparent Yield

Previous computations have, for simplicity, assumed that the clouds extended from the burst height throughout the lower atmosphere. The weakness of this assumption is recognized and several models of the liquid water content distribution in the atmosphere have been adopted as being more realistic in that they are more frequently observed than the first assumption, but do not interpose undue difficulties of computation.

Four types of atmospheric models will be assumed as shown below:

Type No.	Cloud Type	Height: Base	Height: Tops
I	Fog	0	2500 ft
II	Stratus	1000	2500 for 100 kt yield 2000 for 20 kt yield
III	Fog	0	1500
IV	Fog	0	500

Computations will be made for each of these types of 2/10, 5/10, and 1 gm of liquid water per m^3.

In order to investigate the influence of the fact that R_c is not precisely known, (see Sec. 6), a further refinement is added in that for each case the computations will be made for three sets of values of R_c and a_c, as below, for 100 kt. yield.

	R_c	a_c
a)	4280	15.5μ
b)	4800	15μ
c)	5200	14μ

and for 20 kt. yield

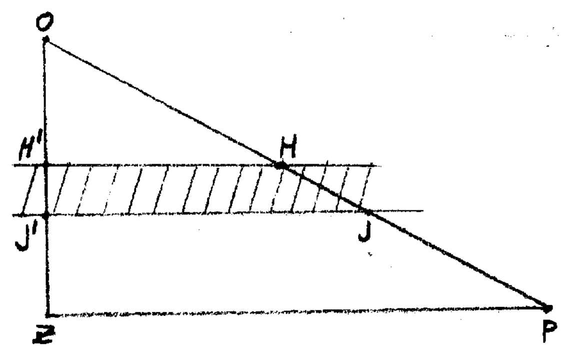
[redacted]

	R_c	a_c
a)	2350	12.6μ
b)	2500	12.0μ
c)	2900	11.6μ

The reasons for this choice of values are discussed in Sec. 6. An example of the computation follows:

Type Weather: II

Yield: 100 kt.



Geometry: OZ = 4650; OP = 8950

H' Z = 2500; J'Z = 1000

H'J' = 1500; OJ' = 3650

$$\left(\frac{OH}{OP}\right)^3 = (.464)^3 = .099$$

$$\left(\frac{OJ}{OP}\right)^3 = \left(\frac{3650}{4650}\right)^3 = (.786)^3 = .49$$

$$OJ = (.786)(8950)' = 7030'$$

	R_c	a_c	OJ/R_c	E_o/E_c	$x_1^3 - 1$	z_1	z_3	E_{hs}
a)	4280	15.5	1.64	2.2	2.3	.94	36	21
b)	4800	15	1.47	1.6	1.65	.97	37.5	22
c)	5200	14	1.35	3.13	3.5	.98	38	22

$$z_1 = \frac{\frac{E_o}{E_c} + 1}{x_1^3} \text{ (for OJ)}$$

$$z_2 = \frac{\frac{E_o}{E_c} + 1}{x_1^3} \text{ (for OH)} \cdots\cdots\cdots = 1 \text{ since } R_c \geq OH$$

E_{HJ} = Energy lost on path HJ

[redacted]

TABLE 9.1

PERCENT LOSS OF ENERGY FOR REALISTIC ATMOSPHERE MODELS

Bomb yield and height		100 kt at 4650 ft			20 kt at 2700 ft		
Weather type		Liquid water content gm/m^3			Liquid water content gm/m^3		
		2/10	5/10	1	2/10	5/10	1
I	a	9.6%	24%	48%	10%	25	51%
	b	9.8	24	49	10	25	51
	c	10.	25	50	10	26	52
II	a	4.2	10.5	21	2.6	7	13
	b	4.2	11	22	2.8	7	14
	c	4.2	11	22	2.8	7	14
III	a	6.0	15	30	9.2	23	46
	b	6.2	15	31	9.2	23	46
	c	6.4	16	32	9.4	23	47
IV	a	1.6	4	8	4.4	11	22
	b	1.8	4.5	9	4.4	11	22
	c	2.0	5	10	4.6	11.5	23

[redacted]

$$E_{HJ} = E_{OP} \left[z_1 \left(\frac{OC}{OP}\right)^3 - z_2 \left(\frac{OH}{OP}\right)^3 \right]$$

$$= 58.5 \left[z_1 (.49) - (1)(.10) \right] = z_3 (58.5)$$

E_{OP} = Energy lost assuming complete evaporation

Using the above computational procedure, and assuming that 87% of the bomb yield goes into blast energy, the percent loss of energy is given in Table 9.1 for various conditions.

By subtracting figures for type IV weather from the corresponding figures for type I or III, one can obtain, if desired, an additional estimate of loss for the cases of:

a) Stratus cloud base, 500 ft tops 2500

b) Stratus cloud base, 500 ft tops 1500

To see the difference that changing the assumption that 87% of the energy goes into blast effects to the one, which is probably of greater validity, (that 55% of the energy goes into blast effects), each of the figures in Table 9.1 should be multiplied by 1.57. This, of course, makes some of them very large indeed and, in fact, it is doubtful if all other assumptions hold good in these cases. However, it is clear that:

a) Varying R_c and a_c in accord with the limits previously assigned has little influence on the loss of energy observed (the comparison of a, b, and c shows no significant difference).

b) In many of the atmospheric cases, such as III, Table 9.1, (with 5/10 gm/m^3 liquid water content with 20 kt. yield) the percent loss in energy (which is 23% on one assumption of magnitude of the total blast energy and 36% on the other) is significantly large.

[redacted]

c) To minimize the loss of energy to liquid water in the atmosphere, until further studies have been made, it is recommended that the desired burst height of a bomb of given yield be reduced by 700 to 800 ft for a 100 kt. bomb when maximizing 10 psi and appropriate values for other yields and desired overpressure.

10. Effect of Rain

The case of rain is essentially simpler than that of fog or cloud, for the size of the drops is much greater. Therefore, in Eq. (6) the first two integrals involving a_i are zero, since $f(a_i)$ is zero over their range. Thus since:

$$\int_{0}^{\infty} (a_i)^3 \, f(a_i) \, da_i = \overline{(a_i)^3}$$

(6.0) becomes

$$\frac{E_o}{E_c} = 3 \int_{x=1}^{x_1} x^2 \left[1-(1 - x^{-6.8})^{1.5} \right] dx \qquad (7.0)$$

This may be evaluated with $x_1 = 2$ as $\frac{E_o}{E_c} = .978$.

It may easily be shown that the major contribution to this integral occurs with $x_1 \leq 1.5$. This means that the total energy loss will be $E_t = (1 + .978)\, E_c = 1.978\, E_c$. For the case of the 10 psi circle and $R_c = 4800$ for 100 kt. yield, the energy loss (E_t) will be $1.978 \left(\frac{4800}{8950}\right)^3 E_e$ where E_e is loss if all water out to a radius of 8950 ft is evaporated. $E_e = 58\%$ for $q = 1$ gm/m^3.

Since q in a heavy rain could be as high as 5 gm/m^3, one could

[redacted]

observe an energy loss of $5(17.4) = 87\%$* if all assumptions made held true. Obviously they would not. However, these figures are given to indicate that the effect would not be a minor one.

Thus, every effort should be made to avoid dropping a bomb of large yield in a rain storm. As shown in Sec. 6, R_c increases more than proportionally to scaling laws for atomic explosions of larger yield. Therefore, work should be done to determine accurately R_c** under rain conditions, so that a more accurate prediction may be made.

11. Summary and Recommendations

Using a method of computation developed in the text, the energy lost by a spherical blast wave outside the radius of complete evaporation has been found, as a function of radius of complete evaporation, cloud type and yield of bomb (through P_s and a_c).

In nearly every instance, the assumptions which were made tended to underestimate the effect upon the blast wave. However, this effect was found to be considerable, depending, of course, upon the particular configuration of bomb and weather conditions.

The effect in rain was found to be great enough so that avoiding such a situation in combat missions is strongly indicated (Sec. 10).

Other recommendations (most of which are in the text) are:

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* These figures are computed on the basis of 87% of yield going into blast energy. If the figure of 55% is true, then the percentage loss would be, respectively, 27% for 1 gm/m^3 and an impossible 138% for 5 gm/m^3.

** If in the case of 100 kt, R_c is varied from 4280 to 5200, the energy loss varies from .71 to 1 to 1.27, where energy loss with $R_c = 4800$ is taken as unity.

[redacted]

a) If fog or stratus has a good probability (order of 25% or more) of occurring at strike time, the planned burst height should be lowered by an appropriate amount to avoid large losses in the area of a given overpressure (Secs. 7 and 9).

b) Curves of E_o/E_c should be recomputed using recently published data on drop-size distribution.

c) Using these curves for E_o/E_c (or the ones in the text), computation of 6, 8, 10, 12, and 14 psi overpressure should be made similar to those for 10 psi in Sec. 9 and using curves of overpressure vs. burst height from LA-1046.

d) Analysis of a report on weather conditions leading to large values of "q" made by Hq. Air Weather Service should be applied to this problem.

e) A suitable experimental program should be planned so that R_c may be verified further under actual atomic bomb (not scaled) conditions.

f) Use other methods to refine computations, such as the application of the work of W. R. Lane, Ind. Eng. Chem. 43, 1312-17 (June 1951), to the determination of W_e.

g) See recommendation in Appendix V.

[redacted]

APPENDIX I

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[redacted]

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APPENDIX II

DIFFERENCES BETWEEN THE PRESENT STUDY AND THAT OF W. G. PENNEY

The fundamental differences between Penney's study: BR/MOS 1/48 and this report are:

1) Recognition of the influence of the frequency distribution of drop size of clouds and fog. W. G. Penney assumed that all drops were greater than a_t. Essentially, he obtained an expression similar to 7.0 for both rain and fog and thus underestimated the effect considerably by neglect of the other two terms of Eq. (6.0).

2) Use of Eq. (1.2) for "radius of largest drop stable in an airstream". The paper from which this was obtained was not available to WGP. He used $(P_s)^2 \, a_t = 10^{-1}$, which is not a bad approximation to the Hinze relation.

3) Use of a different set of shock wave parameters. U. S. data on atomic bomb shock waves, presumably was not available to him, both because of security restrictions and because of the reports which have been published recently.

4) Penney's study assumed a bomb burst at the surface; this report used air burst bombs.

[redacted]

APPENDIX II

EFFECT ON THERMAL RADIATION

It is appropriate at this time to mention in light of Ref. 14 (which emphasizes the number of primary fires which could be started by thermal radiation) that the effect of clouds on thermal radiation (and vice versa) is to reflect nearly all of it back from the face of the cloud. This effect is exactly the same as the solar albedo which has been measured from many clouds and found in accordance with theory,* to be approximately as follows:

Thickness of Clouds	60 meters	100 meters	1000 meters
Reflection	65%	72%	92%
Transmission	32%	22%	2%
Absorption	3%	6%	6%

These figures imply that if the bomb is above the cloud, no thermal radiation will hit the target, but if it is below it, the radiation at the target will be considerably enhanced by reflection from the lower surface of the cloud.

This effect, plus the effect on the blast wave, leads one to say qualitatively that the worst weather situation to use an atomic bomb is when there is fog from the ground extending to about 2000 ft, while the best might be below a cloud whose base is 2000 ft to 2500 ft.

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* See The Handbook of Meteorology.

[redacted]

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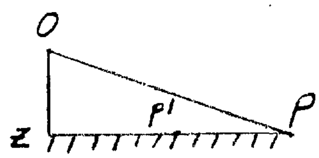
APPENDIX IV

"PATH LENGTH" OF THE SHOCK THROUGH LIQUID WATER

There are two naive ways in which the path length of the shock wave through liquid water may be approached. The first method assumes that the blast energy which arrives at a unit area at P' originates in the solid angle at O which is subtended by the unit area. The blast energy then passes through a segment of a sphere with a radius of OP'. It is clear that the ratio of the energy lost in this segment of the sphere to the incident energy is the same as the ratio of the energy lost in a sphere of radius OP to the total energy of the blast wave. This method would give the average energy lost at point P', except for the fact of Mach reflection, and the energy which is fed through the Mach Stem mechanism from several points between Z and P' toward P.



The second method is to take a cone of revolution OP' about OZ and compare the blast energy going into this cone with the energy required to evaporate all liquid water inside the cone.

TABLE IV-1

Let OP = 8950	ZP	0	2000	4000	6000	7000
OZ = 4650	OP'	4560	4960	6140	7590	8520
	$(\frac{OP'}{OP})^3$	.14	.171	.322	.61	.86

[redacted]

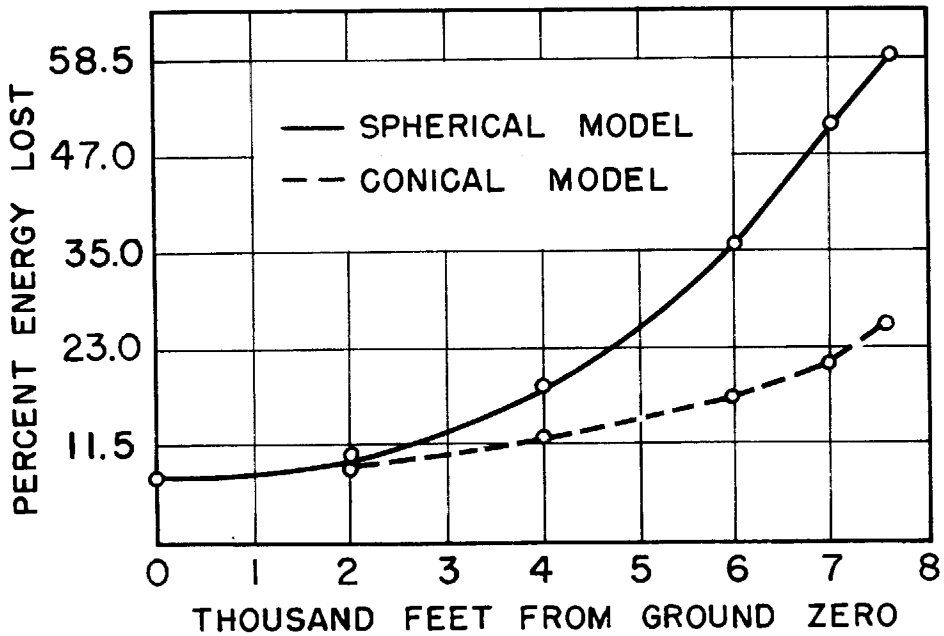


Fig IV-1 Percent of Energy loss compared for spherical model and conical model.

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Fig. IV-1 shows the percent of energy loss at any point on the ground at a distance from ground zero of ZP'. The curve on Fig. IV-1 marked "spherical model" is the percent energy lost, assuming complete evaporation with 1 gm/m^3 of liquid water present. The computations were made assuming that each unit solid angle (Ω) (which is the fractional part of the total solid angle of $\frac{\Omega}{4\pi}$) has incident energy of $\frac{\Omega}{4\pi}$ times the total energy (E_t). Furthermore, no energy is fed into or out of this solid angle. The energy lost to evaporation of liquid water in this solid angle is then $\frac{\Omega}{4\pi}$ times the total energy lost (E_k) or the percent of energy lost in this unit solid angle is:

$$\frac{\frac{\Omega}{4\pi} E_k}{\frac{\Omega}{4\pi} E_t} (100) = 100 \left(\frac{E_k}{E_t}\right) = \text{percent energy lost}$$

It may easily be shown that the conical volume is the fraction $1/2 \left(\frac{OZ}{OP' - OZ}\right) \left(\frac{ZP'}{OP'}\right)^2$ of the spherical volume considered above. Its curve (conical model, Fig. IV-1) is obtained by multiplying the above fraction times the percent energy lost for the corresponding spherical model. It turns out that the conical model at point P' gives the same answer as the average of the spherical model from Z to P'. It is clear that if one is interested in the energy loss at 7600 ft from ground zero, using the mean via the conical model will give an estimate which is much too low, and therefore, the conical model should not be used.

In order to consider the effect of the Mach Stem, consider Fig. IV-2. If this theory is used, then it is clear that the difference between OQ and OP is negligible, and thus the path length through liquid water is approximately the same.

[redacted]

Another way of approaching the problem, and the most conservative way possible, is to consider that ZQ is the distance of the limit of regular reflection. All energy then going into $\angle$ POQ will contribute to the overpressure at P. From LA-743R, ZQ = 1250 ft and P = 1650 ft for a 1 kt. yield or $\frac{ZQ}{ZP}$ = .76. Thus,

$$OQ = \sqrt{(OZ)^2 + (.76)^2(ZP)^2}$$

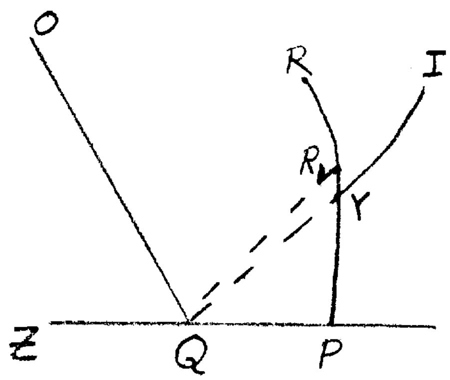
$$= 7400 \text{ ft}$$

$$\left(\frac{OQ}{OP}\right)^3 = \left(\frac{7400}{8950}\right)^3 = .57$$

$$\frac{.57 + 1}{2} = .79$$

The factor (.57) is the ratio of the volume of the sphere with radius OQ to the volume of the sphere with radius OP. If the arithmetical average is used, the energy lost at P will be .79 times the energy loss computed on the basis of the spherical model. Thus, .79 is the lower limit to the correction factor due to different path lengths of the energy through liquid water. However, the above assumption of "average" is certainly not a reasonable one and overestimates the effect of different path lengths. Since this "wild" assumption only makes a decrease of 21%, it is safe to assume, in view of all other uncertainties, that this effect can be neglected.

FIG. IV-2



Y is the triple point.

Q is the point on the ground from which the energy in the reflected shock R at point R_1 (which is a small distance along R from Y), comes.

a) Using the acoustic approximation, $\angle RQP = \angle OQZ$. (It is conservative to take this approximation, as it will give a larger value of QP than shock wave theory for in shock wave theory $\angle R_1QP \leqq OQZ$.)

b) For overpressure at P = 10 psi from a 100 kt. yield bomb at a height of burst of 4650 ft, the Mach stem has a height of 37 ft (LA-743R). Thus, if triangle OQZ is similar to triangle YQP then x is difference in path length through liquid water.

$$\frac{YP}{OZ} = \frac{PQ}{ZQ} \rightarrow \frac{37}{4650} = \frac{x}{ZP - x} \rightarrow \frac{YP}{OZ}(ZP - x) = x \approx 61 \text{ ft}$$

[redacted]

APPENDIX V

R_c AS DETERMINED FROM GREENHOUSE MOVIES

In program 3.33 of the Greenhouse test, a motion picture camera photographed the reaction of an Air Force structure. This camera 302 A (2) was located* so that its field of view faced obliquely toward ground zero. Fig. V-1 shows the location and the geometry involved.

From still enlargements of the film taken, it is clear that a small cloud in the upper right corner disappeared (Figs. V-4 to 8) presumably due to the action of the positive phase of the shock. The angle may be determined to be 40° to the tangent. If one takes a line in that direction, the point nearest to ground zero is at a distance of 5400 ft.

Based on this distance (as a conservative calculation) upon taking the "effective yield" as 75 kt. and scaling from (Ref. 7), the following is obtained:

Observed time of complete evaporation			3.9 sec
Computed time of arrival of positive phase	2.5 sec		
Computed time of positive phase	1.0	=	3.5 sec

Thus, 3.5 sec would be the time of arrival of the negative phase compared with observed complete evaporation at 3.9 sec. The agreement here is very good considering the rough approximations made, for the following errors could easily have occurred:

1. The distance of the cloud is in fact greater than 5400 ft, thus giving a later time of arrival of the positive phase.

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* See Draft of Structures Photography, Program 3, E. G and G, 17 May 1951, pp 31, 32; C36 (1951).

[redacted]

2. The "effective" yield is less than 75 kt, thus giving a later time of arrival.

In any event, it is interesting to compare the R_c, obtained from computations (Sec. 6), with the R_c obtained from this experiment.

1. R_c from this experiment $\geq$ 5400 ft (for a 75 kt. yield)
2. R_c from calculation $\simeq$ 4800 ft (for a 100 kt. yield)*

Thus, the computations of R_c for a 100 kt. yield bomb were very conservative indeed and they by no means over-estimate the amount of water evaporated.

Further studies and interpretation of the enclosed pictures should be made to determine more definitely the conditions which prevailed at the time of the test.

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* A 75 kt. yield bomb on the surface is very roughly equivalent to a 100 kt. free air burst bomb.

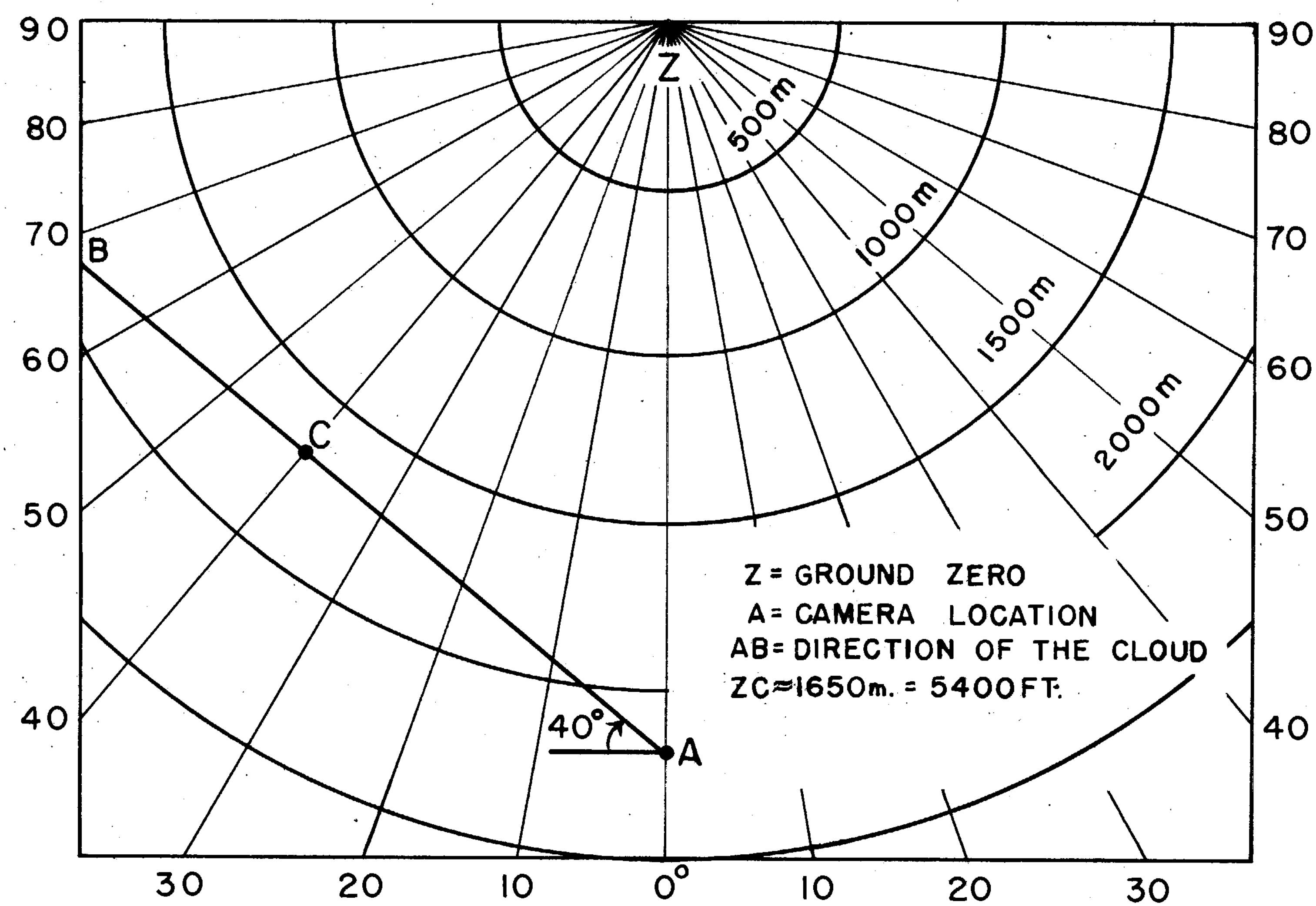

Fig V-1 Position of Camera and Cloud with respect to ground zero.

V-2, 100th frame after zero

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V-3, 120th frame after zero

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V-4, 130th frame after zero

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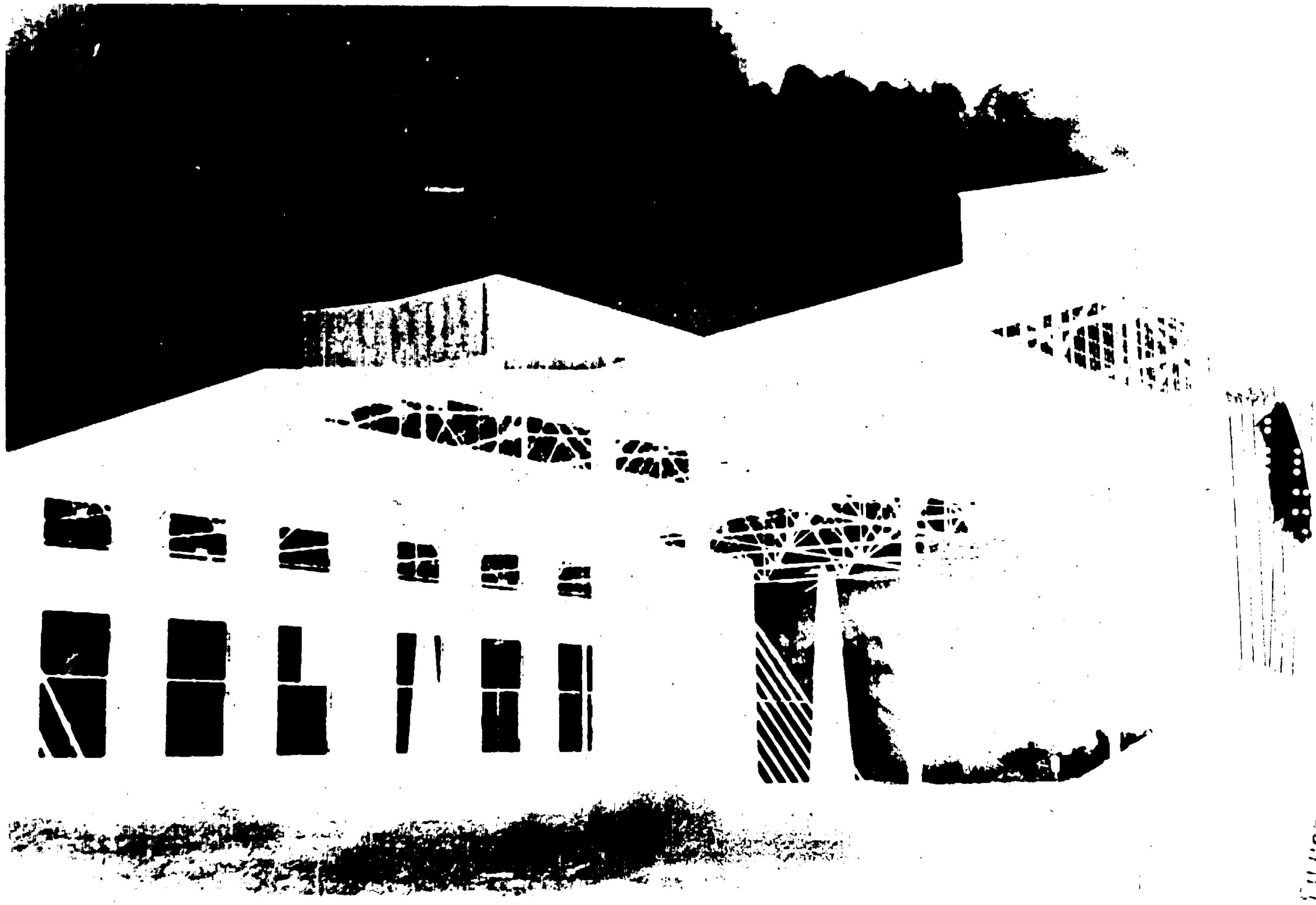

V-5, 135th frame after zero

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V-6, 140th frame after zero

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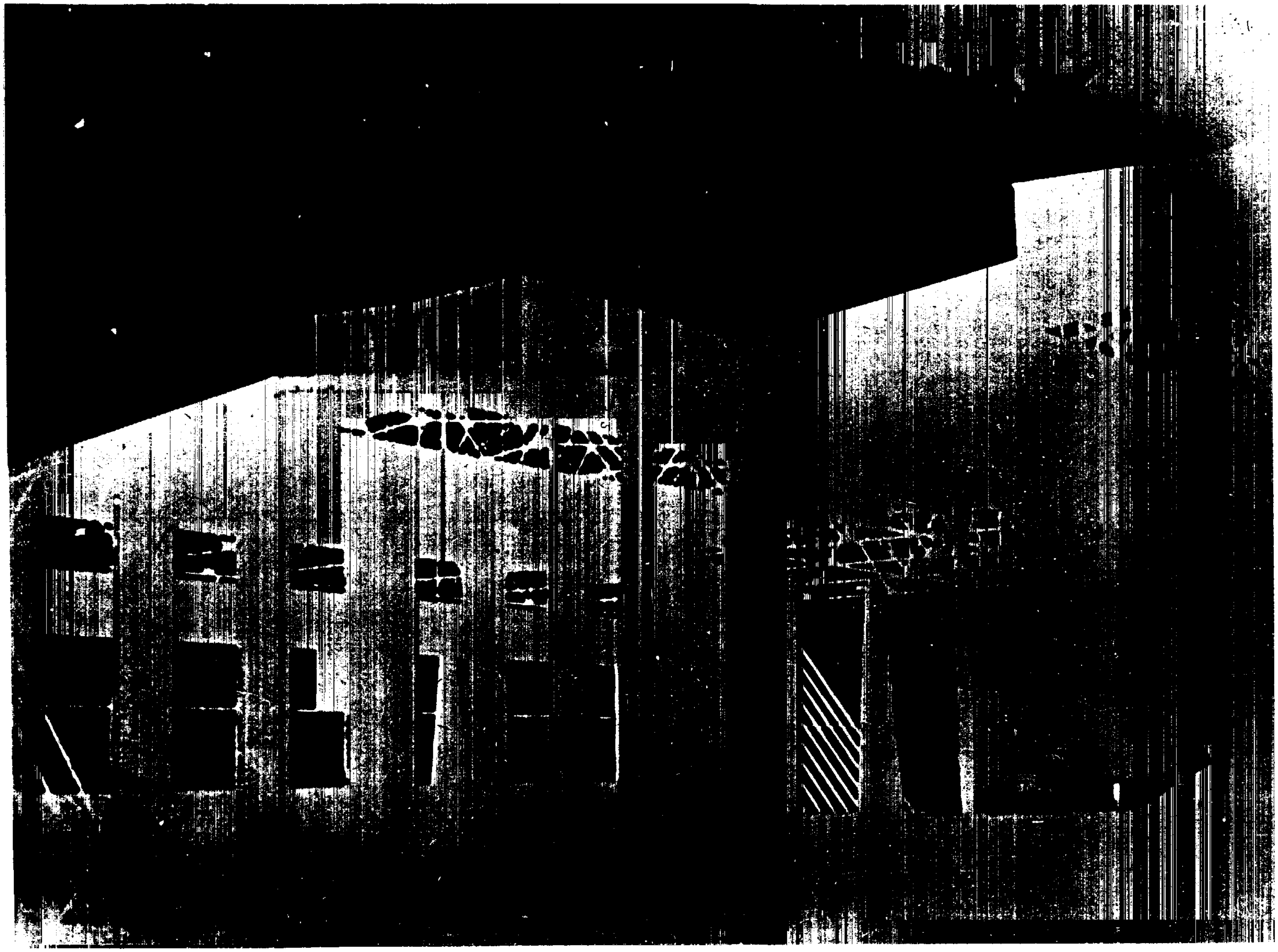

V-7, 145th frame after zero

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V-8, 150th frame after zero

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V-0 155th frame after zero

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V-10, 160th frame after zero

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APPENDIX VI#

THE WET-BULB TEMPERATURE DEPRESSION

The value of α, the relative depression of the wet-bulb temperature is important because the size of drops which may be evaporated depends upon it, through equation (1.1) (see Sect. 3c). Penney and the present writer have used 0.6 as a reasonable approximation to the value of α. Recently, however, Hartmann* has used the value of 0.86.

#This appendix was prepared in April, 1954

*G. K. Hartmann, "The Effect of Rain or Fog on Air Blast," NAVORD Report 2944, 1 Aug. 53.

The purpose of this appendix is to examine critically all assumptions made in obtaining the value of α.

Hartmann, in Sect. 21, derives the following equation which may be used to find $\alpha = (\varphi - \vartheta)(\varphi)^{-1}$:

$$\frac{p_{va}}{1 + \vartheta/T_0} - \gamma p_{vo} = \frac{T_0 \sigma R}{L D M}(\varphi - \vartheta) = A(\varphi - \vartheta)$$

The meaning of the symbols is as follows:

- p_{va} = saturated vapor pressure at the droplet surface at temperature $T_0 + \vartheta$, in mm Hg.
- T_0 = original ambient temperature.
- ϑ = increase of wet-bulb temperature above T_0.
- γ = compression ratio at a given overpressure in the shock.
- p_{vo} = vapor pressure in the air before shock, in mm Hg.
- σ = coefficient of conductivity for air.
- L = latent heat of vaporization for water.
- D = diffusion coefficient.
- M = molecular weight of water, = 18.
- R = gas constant
- A = constant
- φ = shock overtemperature.

A is .54 at T_0 = 298°K, as computed by Hartmann. He then assumed that the <u>original relative humidity in the presence of clouds</u> was 66%. This enabled him to obtain α as a <u>function of ϑ</u>, through the use of psychrometric tables. For ϑ between 5° and 20° C, the value obtained for α was approximately .86.

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He states that the values near $\vartheta = 0$ are sensitive to the assumption made as to the initial relative humidity, but does not justify his unusual choice of 66% relative humidity. Furthermore, he does not mention that the values of α are also sensitive to the assumption as to the initial temperature. He has chosen a rather high ambient temperature of 77°F, which is certainly not representative of atmospheric conditions under which one might expect this type of weapon to be used.

We have studied the relation between φ and ϑ when more reasonable assumptions are made as to the initial conditions and find that the value of 0.6 used by Penney and the present writer is both more conservative and more nearly correct.

In our procedure, the equation given above was separated into functions of φ and ϑ alone with the following results:

$$\left(\frac{p_{va}}{1 + \vartheta/10} + A\vartheta \right) - \left(j\, p_{vo} + A\varphi \right) = \Theta - \Phi = 0$$

The values of Θ and Φ have been plotted on Fig. VI-1 as a function of ϑ and φ. To obtain the value of $(\varphi - \vartheta)$, one choses a value of φ, and finds the corresponding value of Φ. The equal value of Θ is found from the graph, and the corresponding value of ϑ is read off.

Fig VI-1 is based on the same assumptions which Hartmann made, namely, an ambient temperature of 77°F. The curve Φ_1 is based on an assumed initial relative humidity of 66%. The curve Φ_2, on an initial relative humidity of 100%.

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The values of φ which are the most important lie between 0 and 50^{o}C, corresponding to an overpressure of about 0 to 10 psi. This comes about because in regions of higher overpressure, for atomic bombs, the drops will be completely evaporated no matter whether α is .6 or .9. Furthermore, each drop while evaporating, eventually goes through this region of overpressure and temperature as the shock moves by.

One table on Fig VI-1 shows representative value of α obtained in the region of 2 to 8 psi. The values of α agree, within the precision of the present method, with the values obtained by Hartmann for ϑ less than 10^{o}. The value of α for higher values of ϑ and φ is of academic interest only, for this problem. As we have mentioned above, what counts is the value of α in the region of 0- 10 psi. These values of α were obtained considering that the initial relative humidity is 66%. This, according to our philosophy, is not a conservative assumption. Furthermore, it is not a plausible one either. Except in very special circumstances, it is well known that the relative humidity in the air in clouds is 100%, and sometimes, it is greater!

Therefore, the values of α obtained from the assumption of 100% relative humidity before shock are more conservative and more likely. Using the curve labelled Φ_2, we find a value of approximately 0.66.

Now let us see, what effect there may be in assuming a lower, and consequently, more likely ambient temperature. Fig. VI-2 has been derived on the basis of a 5^{o}C (41^{o}F) initial temperature, and 100% relative humidity. As may be seen from the table on Fig VI-2, these assumptions

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lead to a value of α of between .51 and .58 in the region of 0-10 psi.

What value of α should now be used? Considering the result at ambient temperatures of 77° and 41°F, with the most plausible assumption that the initial relative humidity is 100%, the value of 0.6 is a much better figure than 0.86. Furthermore, 0.6 is none too conservative.

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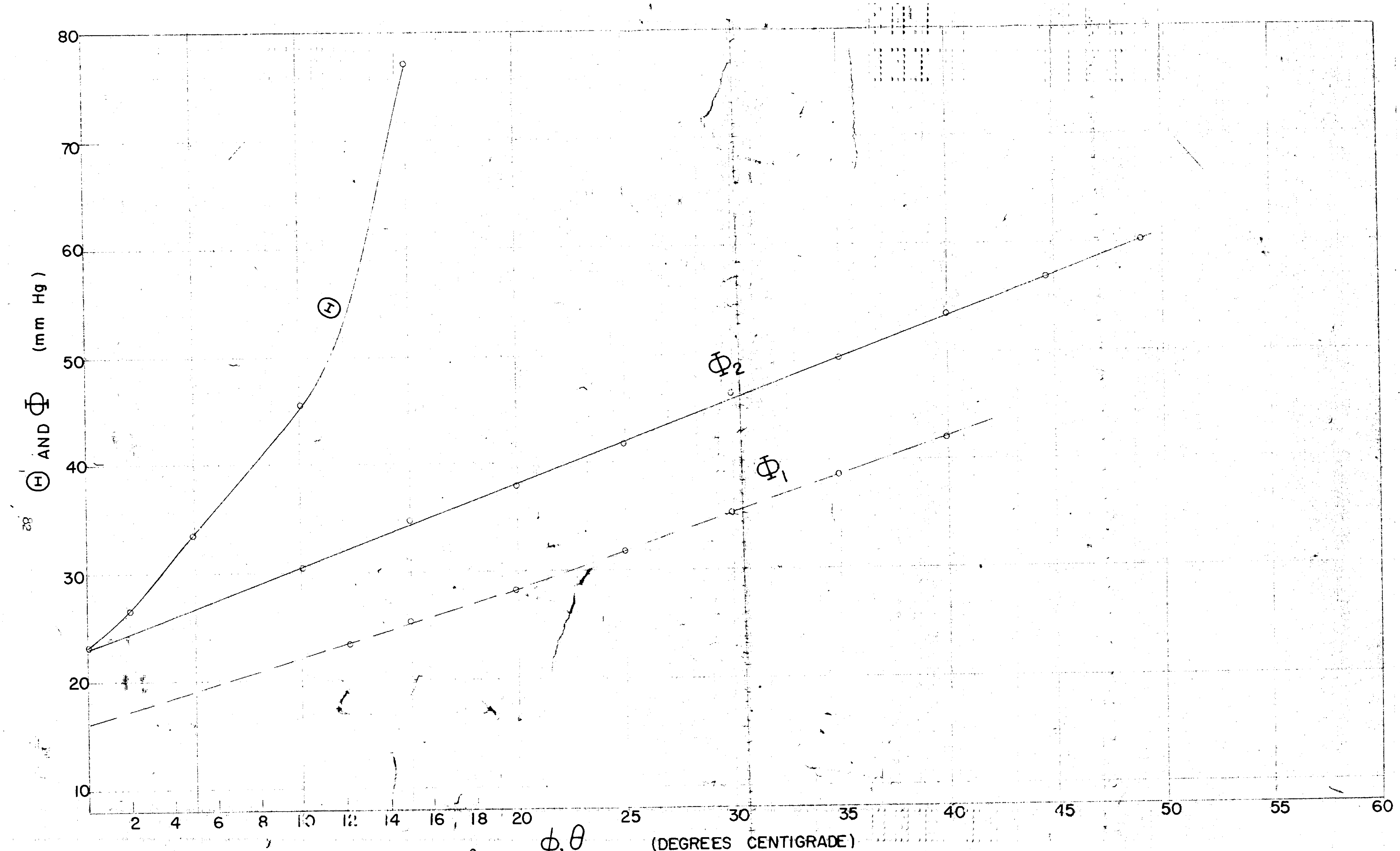

Fig VI-1 Graph for evaluation of α. T_o is assumed 77°F. Relative humidity 66% for Φ_1 and 100% for Φ_2.

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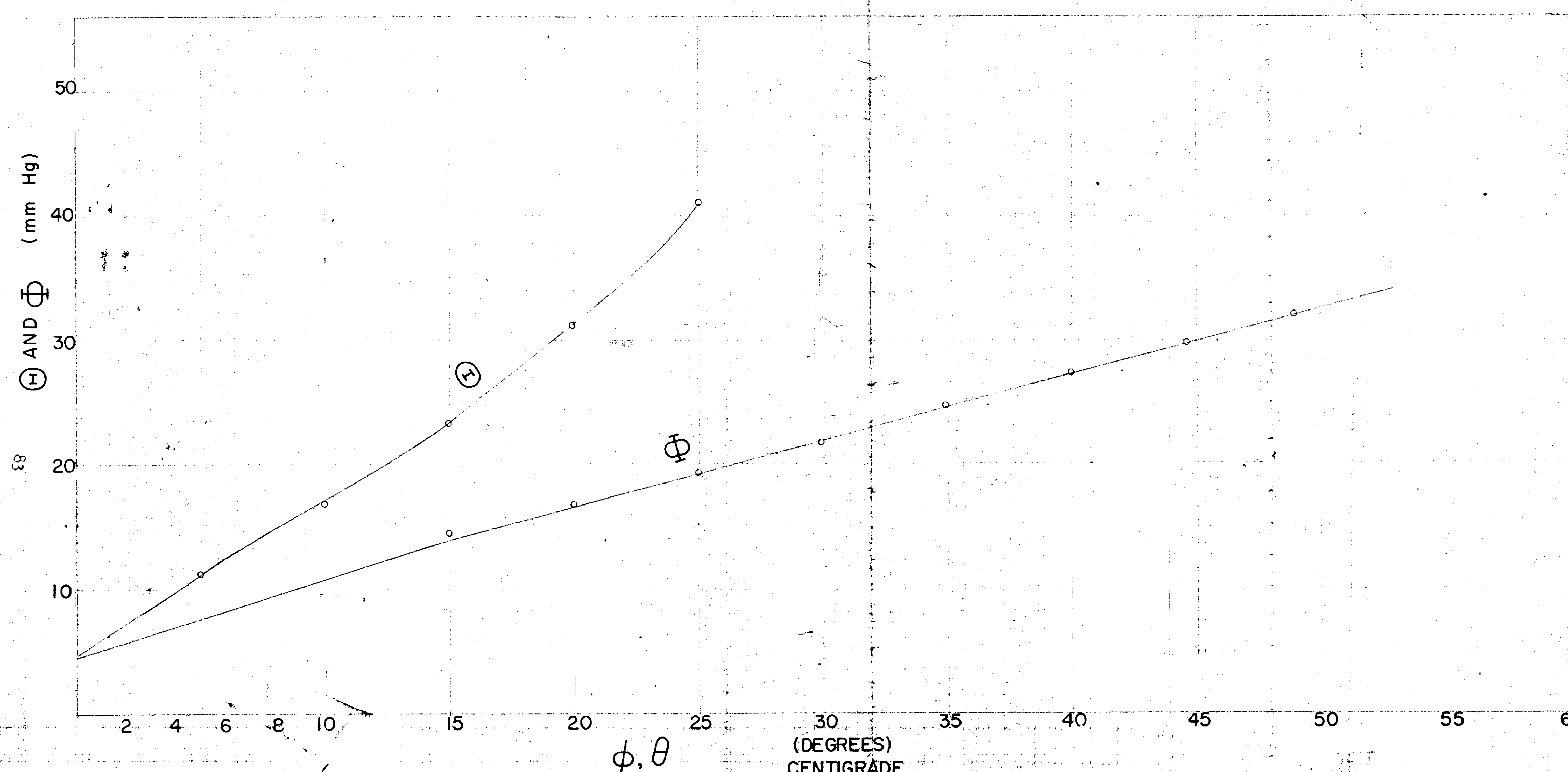

Fig VI-2 Graph for evaluation of ε. T_c is assumed 44° F.
Relative humidity 100%.

Computation from Fig VI-1:

a. Assuming $\Phi = \Phi_1$

ϕ	θ	$\alpha = (\phi - \theta)(\phi)^{-1}$
10	- 0.6	1.06
15	+ 1.2	.92
20	3.5	.82
25	4.0	.83
30	5.5	.82
35	7.1	.80
40	8.6	.78

b. Assuming $\Phi = \Phi_2$

ϕ	θ	α
10	3.5	.65
15	5.5	.63
20	6.8	.66
25	8.4	.66
30	10.0	.66
35	11.3	.675
40	12.2	.70

Computation from Fig VI-2

ϕ	θ	α
5	2.4	.52
10	4.6	.54
20.5	10.0	.51
32.3	15	.53
38.0	17	.55
40	17.7	.56
45	19.4	.57
50	21.2	.58

Fig VI-3 Computation of α.

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