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LA-743 R

Series A

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HEIGHT OF BURST FOR ATOMIC BOMBS

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ABSTRACT

The significant role of Mach reflection and the $W^{1/3}$ scaling law which is used to relate the blast pressures from chemical explosions and nuclear explosions is discussed; the simple scaling law can be expected to fail at distances near the explosions because of the vastly different energy densities involved in the two cases. A new set of values for reflected pressures in the Mach region is presented as a function of incident pressures and angles of incidence. These values are based on Von Neumann's theory of regular reflection, semi-empirical considerations at extremely flat angles, and Taub's experimental data in the region of Mach reflection. An attempt was made to eliminate from the data the effect of certain experimental conditions, such as geometry of charge, a factor recently shown to be of considerable importance. A free air curve is deduced for an atomic bomb and a new set of height of burst curves for atomic bombs is presented. The most striking change in the height of burst tables resulting from ~~the~~ present study arises from the observation that in the region from ~~2~~ 4-20 psi peak overpressure the blast from an atomic bomb of W kilotons total energy release is most nearly equal to the blast resulting from a scaled ~~0.6~~ 3/4 W kilotons of a spherical pentolite charge.(1) The inaccuracies and deficiencies in present data are summarized. The study indicates that a requirement exists for a broad experimental program, prior to and

(1) Since data of the same order of accurracy was not available for spherical TNT charges as it was for pentolite, the latter was chosen as a reference. The difference between TNT and pentolite is possibly of the order of 5% in pressure (15% in blast energy) from two charges of the same weight. In consequence the factor 0.6 would be raised somewhat if TNT were used as the reference chemical explosive.

during future tests of atomic weapons, and the nature of such a program is briefly indicated.

LA-743-R ~~Series B~~ differs from LA-743 ~~Series A~~ primarily in that the free air curve from Bikini Able is ~~as~~ deduced for an atomic bomb somewhat altered in accordance with the reflected pressure data given ~~on~~ in Annex 5 of the Sandstone Scientific Director's Report.

Fig 33

[redacted]

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I. INTRODUCTION.

As is well known the damage area produced by the blast from an atomic bomb can be maximized by choosing the proper height of burst. This report contains the results of a study of the factors which enter into this choice of the burst height with special emphasis on the pressure distribution to be expected from a bomb burst above a rigid surface in the absence of structures.

It is, of course, necessary in applying the results to actual target configurations to allow for the diminution in blast energy at a given position by target destruction and the shielding of one target element by another. There is, at present, no accurate quantitative procedure for making such allowances.

Furthermore, due allowance should be made for the meteorological conditions at the time of delivery since it is known that energy is lost to the blast if the weapon is detonated in rain or fog[2]. The possible importance of the effect of the altitude of the target on the blast wave warrants further study. Finally, the present study is restricted to the blast effects of air burst atomic bombs and does not attempt to deal with Radiological Warfare aspects of the problem.

Start

II. THEORY OF REFLECTION AND SCALING LAWS.

2.1 Mach Reflection

In the region of practical interest (2 to 50 psi) the peak pressures[3] along and near the ground are closely related to the phenomenon of Mach reflection. Intuitively, one might guess that in

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(2) W. G. Penney, LA[redacted]-217. There is recent evidence that this effect is not so important in fog.
(3) Only peak pressures are discussed because of the sole dependence of damage for large explosions on this quantity. Cf reference (2).

[redacted]

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order to maximize the pressure at a target area by means of an explosive charge located at a fixed distance from the target area one should placed the explosive directly above the area to get a "broadside" effect. It is a peculiar consequence of Mach reflection that such is not the case: to achieve maximum effect, one places the charge at an angle θ to the target area (Fig. 1).

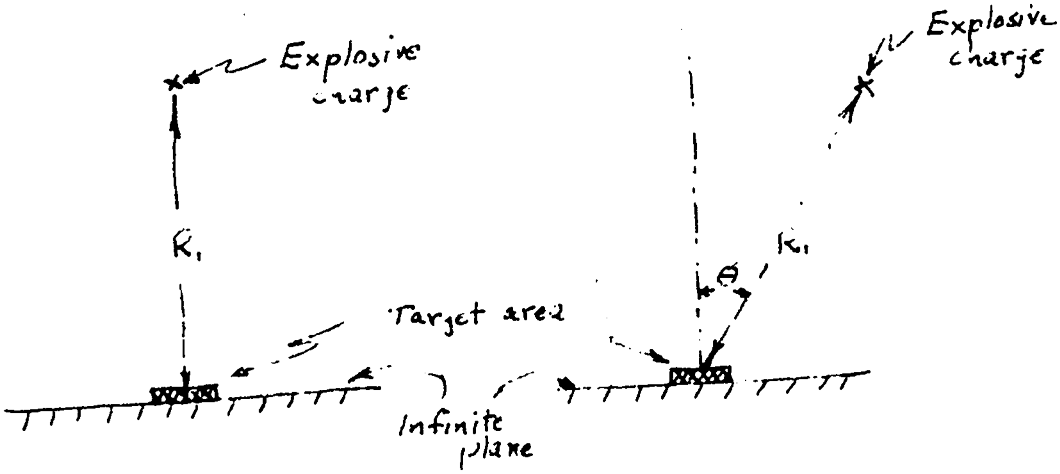

Fig. 1.

This phenomenon has been described in some detail in many previous papers[4]. Briefly the picture is this: Initially a spherical shock wave diverges from the explosive source, followed by the familiar pattern of a reflected wave, illustrated in Figure 2. The region in which the two shocks intersect only on the ground is called the region of regular reflection. The once-shocked air in the region behind the incident wave is heated by the passage of the

(4) e.g. "The Mach Effect and the Height of Burst", J. vonNeumann and F. Reines, Chapter 10, Vol. 7, [illegible] ATS

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incident shock and in consequence, the reflected shock moves more rapidly than ~~an~~ the incident shock. ~~of the same strength~~

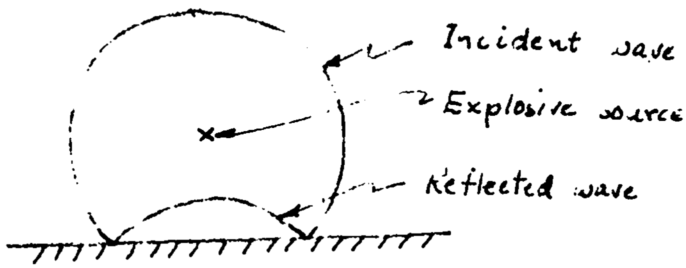

Fig. 2. Regular Reflection of a Shock Wave.

At a certain critical angle of incidence (which is a function of the pressure), the reflected shock actually overtakes the incident shock and the two fuse forming a Y like pattern (Fig. 3). The triple point which limits the fused region continues to rise as the shocks move outward until eventually the incident and reflected waves are everywhere fused into one. The pressure in the fused region behind the stem of the Y, or Mach stem as it is called, is roughly double the pressure behind the incident or reflected wave alone.

Although there is evidence that the pressure may vary along the Mach stem decreasing by $\sim 15\%$ in passing from the ground to the triple point, we neglect this variation in the present discussion. When more accurate data are obtained this refinement might well be made.

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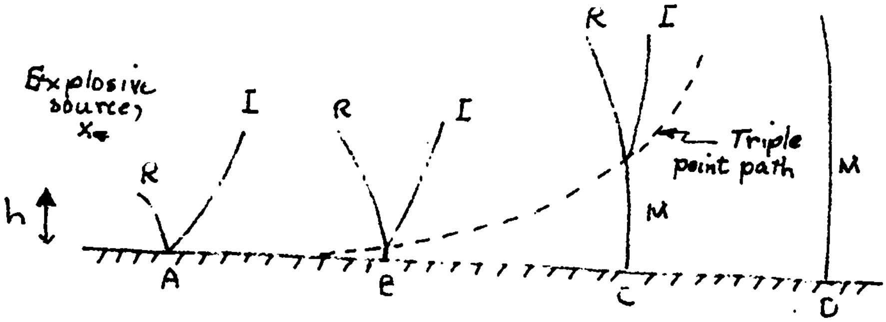

Stages:

A. Regular reflection
B. Mach stem barely formed
C. Mach stem
D. Mach stem completely closed (Fusion complete over hemisphere)

where:

I - Incident wave
R - Reflected wave
M - Fusion wave (Mach stem)

Fig. 3. Development of Mach Pattern.

The pressures recorded at a certain height $\underline{h}$ above the points A, B and C as a function of time, would be somewhat as in Figure 4.

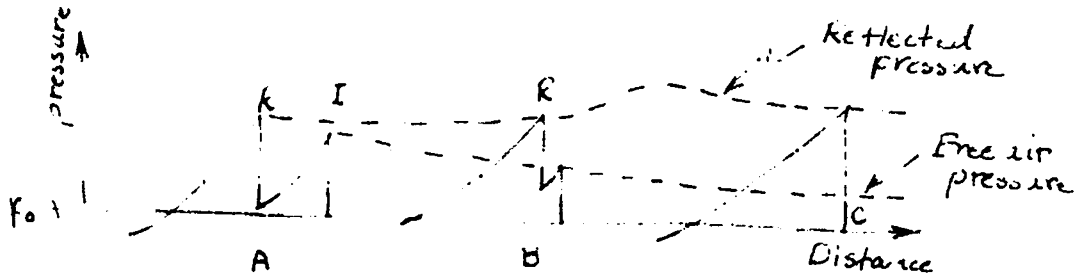

Fig. 4. Pressure Distribution in Reflection Pattern.

[redacted]

The point at which the Mach stem is formed, and at which the advantage of the fused shock is obtained, is very sensitive to the height of burst.

At the present time the relations in the region of regular reflection are reasonably well understood, as a result of the theory of J. vonNeumann(5). Detailed calculations based on this theory were carried out by Polachek and Seeger(6), and tested and verified by Taub(7) and others. However, there is no adequate theory presently available for the region of Mach reflection. In this region, we will depend primarily upon experimental shot data obtained from small scale explosive shots (TNT, pentolite). The work by Taub in this region is based in part on shock data of L. G. Smith(8). There is, however, reason for believing that shock tube results are not generally applicable to explosions because of the one dimensional character of the shock tube data (cf however remarks on page 12 below). Nor is sufficient data available from atomic bombs because of the small number fired and the low height of burst employed. The only possibly reliable existing pressure distance data are from Bikini Able. No free air pressures are as yet available for atomic bomb explosions although it is understood that considerable effort will be put forth to obtain this basic information in the next series of bomb tests.

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(5) "Oblique Reflection of Shocks", J. vonNeumann, Explosives Research Report No. 12, Navy Dept. Board, Oct. 12, 1943, Confidential.

(6) "Regular Reflection of Shocks in Ideal Gases", H. Polachek and R. J. Seeger, Explosives Research Report No. 13, Navy Dept. Board, February 12, 1944, Confidential.

(7) "Peak Pressure Dependence on Height of Detonation", A. H. Taub, NDRC Div. 2, Interim Report No. 1, NDRC A 4076.

(8) "Reflection of Shock Waves in Air", L. G. Smith, PMR No. 5, March 1944, and PMR No. 19, April 1944, Princeton University Station.

[redacted]

A considerable portion of this paper is devoted to an analysis of the available small charge data for Mach reflection, a study of its applicability to atomic bombs, and the making of a compilation designed for use in height of burst charts.

2.2 Scaling Laws

The forced dependence on small charge data attaches a great importance to the so-called $W^{1/3}$ scaling law, which states that start for two explosives of different weight, equal peak pressures are observed when the volumes involved are proportional to the masses and hence to the energy releases W_1 and W_2. From this it follows that the distances R_1 and R_2 are related as the cube roots[9]. That is

$$\left(\frac{R_1}{R_2}\right) = \left(\frac{W_1}{W_2}\right)^{1/3} \tag{1}$$

$$p = \text{constant}$$

Another important scaling law is that which relates the times for similar events to occur e.g. for the pressure to reach a given value.

$$\left(\frac{t_1}{t_2}\right) = \left(\frac{W_1}{W_2}\right)^{1/3} \tag{2}$$

$$p = \text{constant}$$

The fact that the scaling law has been found to be applicable over a considerable range of energy values for two chemically identical geometrically similar explosives is taken as evidence of its validity. In this paper then, the familiar assumption is made that for similar explosive arranged in similar initial Start geometries all details of the shock phenomena both in space and time will scale according to the cube roots

(9) For a discussion of scaling as applied to high explosives see R.H. Cole "Underwater Explosions" Princeton University Press(1948). Vol. II and III of the Scientific Director's Report for Sandstone contain remarks relative to the scaling laws as applied to atomic bombs.

of their weights.

It is instructive in considering the relevance of the scaling of blast from H.E. to atomic bombs to compare the conditions attending the detonation of these two sources of blast.

Assuming a density of 1.6 gm/cm^3 , 20 kilotons of TNT would have a radius of 46 feet. An atomic bomb has a radius of the order of a few feet, the exact size depending on the model. It is clear that the initial energy density in an atomic bomb explosion when the shock has reached the surface of the bomb is something like 10^3 to 10^4 times that in the chemical explosive which liberates the same detonation energy and that the pressures close to an atomic bomb are consequently much greater than those from chemical explosives. Farther out one might hope that the blast waves become more nearly similar in view of the decreasing spatial extent of the chemical explosive relative to the distance from the explosion, i.e., the tendency for the true solution to approach the point source solution.

There is an argument which makes it plausible that energy losses due to surface roughness may be considerable in the case of the small charges at least. The best small charge data has been obtained from charge fired over concrete; it is not uncommon to have projections of gravel as high as 1/16" quite generally Start distributed over the "smooth" surface. For a 20 KT bomb an equivalent roughness would be something like 2 feet. In other words, to obtain comparable conditions, one would have to measure the pressures from an atomic bomb over a field liberally strewn with 2-foot boulders. On this view, the data obtained over a sandy beach at Eniwetok is more typical of a "smooth surface" than the small charge data with which it can be compared.

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III. REFLECTED PRESSURES FOR SMALL CHARGES.

A study was made of the small charge pressure reflection data available to the authors. In order to provide the best possible basis for height of burst charts, an effort was made to eliminate a number of distorting factors which initial study showed to be important.

Recently, Bleakney demonstrated[10] that free air curves differ markedly for different charge shapes rendering invalid the assumption employed in reference (4) that at great distances, any charge geometry can be treated as a point source. Bleakney's curves show that, in general, non-spherical charges cause higher peak pressures close up than do spherical charges, that these pressures later fall to as much as 30% lower (in the case of TNT blocks, in the region of 3 psi) and gradually rise again but are still 20% low in the region of 1 psi. Differences for cylindrical shapes were less marked, some 15% low at 4 psi, rising to about 5% low at 1 psi. Reynolds[11] has shown that the free air curve from a rectangular Engineer block is quite complex, shows two pressure peaks, as a Start result of the merging of different peak pressures from the side and butt ends of the block. Accordingly we have attempted to consider and eliminate, as far as possible, the effects of different free air curves.

The reflected pressure at any point on the ground is a

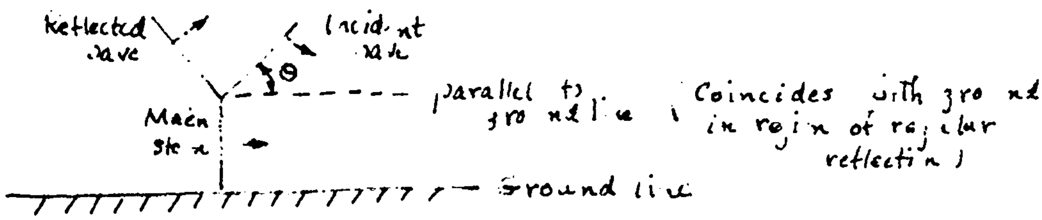

Fig. 5. Mach Configuration.

(10) "Attenuation of Spherical Shock Waves in Air", "Journal of Applied Physics", July 1948, p. 670.

(11) G. T. Reynolds, "... Tests", NDRC, No. 1532.

function of the free air pressure at that point, and the angle of incidence, Θ. (Fig. 5)

It is, of course, recognized that in the region of the Mach effect ~~where~~ the reflection phenomenon does not take place in an infinitesimal region of space but is, as it were, a phenomenon in the large; the pressure on the ground is probably also a function of the past history of the shock pattern and consequently should in principle differ if the pressure versus time start and distance surface differs for the explosions under comparison. The earliest part of the Mach phenomenon is of greatest interest to us[12] and in this region it seems reasonable to expect that "history effects" are small. In addition, we lack experimental information bearing on this question. In consequence we will neglect the differences in these effects in scaling from one explosive to another.

For convenience we define a quantity, M, called the pressure multiplication, as

$$M = \left(\frac{P_r}{P_f}\right)_{r\,=\,\text{constant}} \qquad (3)$$

where:

P_r = reflected pressure measured on the ground

P_f = free air (or incident) pressure

As stated above, we assume that

$$P_r = f(P_f, \Theta)$$

or in view of (3) that

$$M = g(P_f, \Theta) \qquad (4)$$

(12) The scaled stem heights commonly considered as optimal for the production of damage are 100 feet for a 20 kt bomb or ~3".

[redacted]

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Another useful quantity is the reflection factor K, which is defined to be the ratio of the apparent tonnage as indicated start by the reflected pressure distance curve to that indicated by the free air pressure distance curve.

$$K = \left(\frac{R_r}{R_f}\right)^3_{p \,=\, \text{constant}} \tag{5}$$

for a small interval

If the free air pressure distance relationship is of the form

$$P_f = \frac{C}{(R_f)^n} \tag{6}$$

then K and M are related by the equation

$$K = M^{3/n} \tag{7}$$

Experimental data has been compiled on Fig. 6 where the free air pressures are plotted as a function of the reflected pressure and $\cos\Theta$. The bulk of this data, based on the firing 1/2 lb. TNT blocks, is taken from Tables I → IV of Taub's paper[7]. Each rectangle represents the average of the group of shots (2 to 4) in which the data were taken at a certain distance and angle from the charge. These were compared with the free air pressures for 1/2 lb. TNT blocks as given by Taub, and are plotted together with the associated value of $\cos\Theta$. In these experiments the long axis was kept perpendicular to the line of gauges. Reynolds[11] reports that the variation was not very marked along an equatorial plane so that the uncertainties in reflection factors due to charge orientation are judged to be start small. There is considerable difference between the free air curves for TNT blocks as given by Bleakney[10] and Taub[7], but Taub's free air curves were used, despite the fact that Bleakney's

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curves are probably more accurate, because we seek a ratio, M, and it is felt that this quantity is best obtained by using the same experimental techniques in determining the free air and reflected pressures.

As stated previously, regular reflection theory provides a quantitative relationship between the incident and reflected pressures and the angle of incidence, θ. The general features of regular reflection are these. Directly beneath the bomb ($\theta = 0$) the reflected pressures are given by the well known relationship

$$\xi' = \frac{(3\gamma - 1)\xi - (\gamma - 1)}{(\gamma - 1)\xi + (\gamma + 1)} \qquad (8)$$

where:

$$\xi' = \frac{P_r + P_o}{P_f + P_o}, \quad \xi = \frac{P_f + P_o}{P_o}$$

P_o = pressure in the unshocked region (taken = 14.7 psi)

P_f = overpressure in the once shocked region

P_r = overpressure in the twice shocked region i.e. the reflected pressure

γ = 1.4 is the ratio of specific heats for air

VonNeumann's regular reflection theory was used to define the lines of constant P_r in the region of regular reflection. For start each value of P_f there exists a critical angle, θ_c, indicated by the dotted line, beyond which regular reflection ceases and irregular reflection sets in. In the absence of more detailed evidence ~~that~~ than is presently available we take this to be Mach reflection. θ_c approaches a limiting value of 39.97° as the incident pressure increases. The theoretical treatment of regular reflection is verified by experiment and constitutes the boundary conditions at the region where Mach

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reflection sets in. The slopes as well as values were taken to be continuous across the bondary boundary denoted by Θ_c.

For $\Theta = 90^\circ$, another boundary condition was employed. In the reflection from a smooth rigid surface, the reflection factor K should be exactly 2 at large distances, because the energy which would normally have gone into the lower hemisphere is concentrated in the upper hemisphere, with a consequent doubling of the energy density. Since the ground even if substantially rigid is not smooth, energy losses will occur and the reflection factor will be reduced from 2. We make the assumption that the curves P_r = constant are orthogonal to the vertical axis at $\cos\Theta = 0$. This seems reasonable in view of the extent of the fusion of incident and reflected shock waves which has occurred by the time such extreme obliquity has been reached by the expanding shock waves. As can be seen by inspection of Figure 6, there were two experimental points in the neighborhood of Start $\cos\Theta = 0$ and $P_f = 1.75$ psi, i.e. $P_r = 2.0$ at $\cos\Theta = 0.075$ and $P_r = 1.6$ at $\cos\Theta = 0.058$. For the two points mentioned and the measured dependence of P_f on distance r (Fig. 7), we find that

$$K = \cancel{1.56}\ 1.48, \quad \cos\Theta = 0.075$$

$$K = 1.46, \quad \cos\Theta = 0.058.$$

Accordingly it appears that even on the best rigid reflecting surfaces used, smooth concrete, the reflection factor is less than 2 and not far different from 1.5 at these pressures. In other words, about 1/4 the apparent energy of the blast wave has been lost to the reflecting surface.

With the boundary conditions on left and right fixed by regular reflection theory and K = 1.5 respectively, smooth curves

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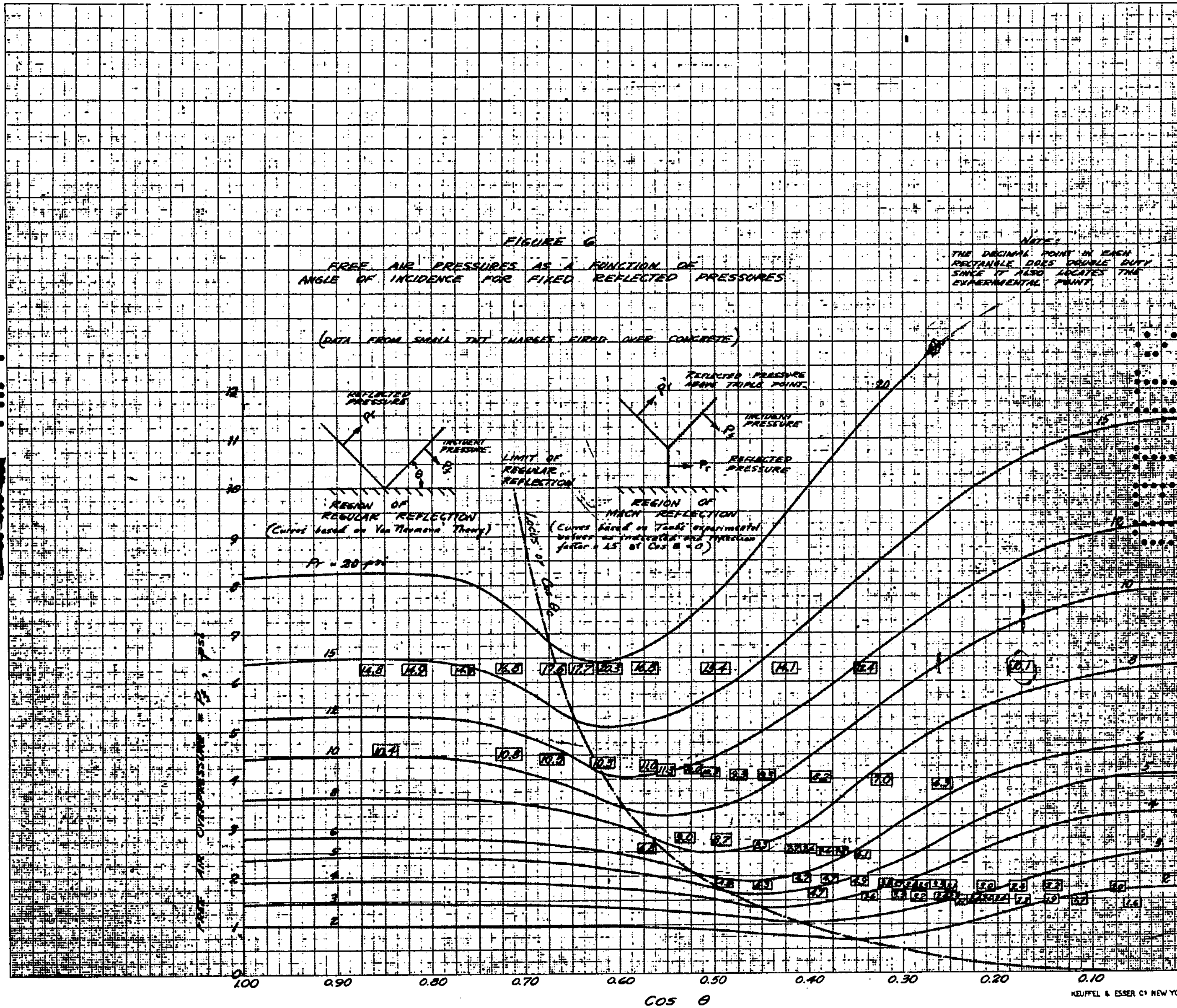

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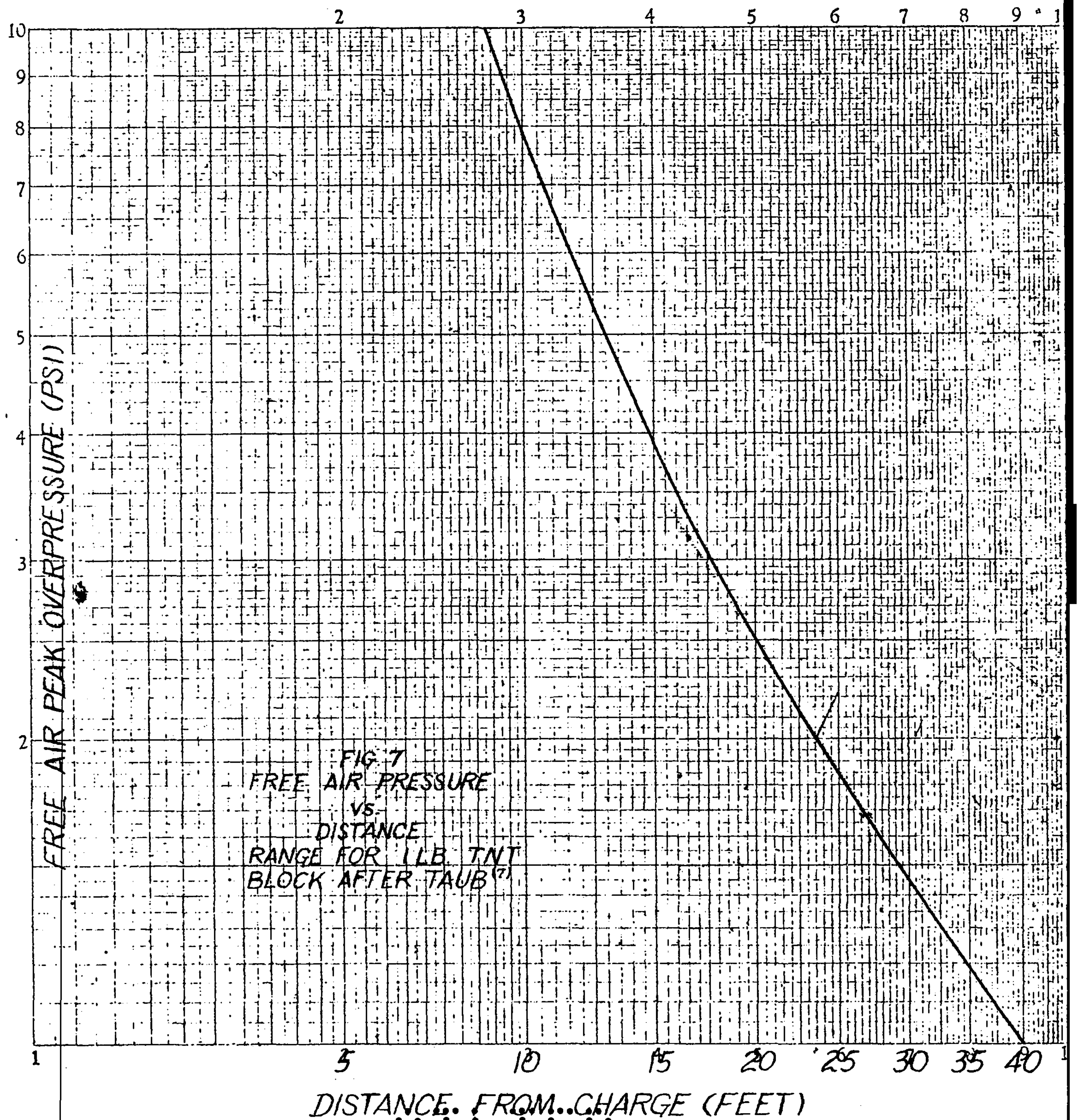

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were passed through the experimental points. This procedure is somewhat arbitrary because of the erratic nature of the experimental values. Some groups of data ~~whole runs~~ seem to be generally low. The fit on the curve which applies to the region just after Mach reflection sets in, is particularly poor; here one notes that some ~~the~~ experimental points in this region, if accurate, would mean that there is practically no increase in reflected pressure over that at $\Theta = 0$.

The Closeness ~~goodness~~ of fit of the curves to the experimental data of Taub was tested in an interval ~~a band~~ from Θ_c to an angle Θ where $(\cos\Theta_c - \cos\Theta) \approx 0.2$. For the 34 experimental points involved, the smoothed curves are 4% higher than the experimental points which had large fluctuations. Taub quotes the overall accuracy of his data to be of the order $\pm$ 5%, and hence the curve can be taken as a fair representation of his data. The probable error of the curves just after Mach reflection sets in, is something like $\pm$ 5% in pressure corresponding in the pressure range studied to $\sim \pm$ 15% in yield. The scarcity of data for more oblique incidence makes a comparison between experiment and the curve even less reliable.

IV. FREE AIR PRESSURE DISTANCE CURVE FOR AN ATOMIC BOMB.

In the attempt to apply the small charge results to the pressure distance curve for an atomic bomb we recognize that as indicated earlier in this report the ratio of energies in the form of blast is different for an atomic and chemical explosion of the same total energy; ~~and that, as indicated earlier in this report,~~ the pressure distance characteristics for the two are also different.

In this section we will give the results of applying the reflection factors given in Figure 6 from small charges to the Bikini

[redacted]

Able peak pressure distance curve (Fig. 8) and deduce a free air curve for an atomic bomb of known yield. Because of the height of burst employed in this case (520') it is expected that relatively little energy was lost to the surface and that the blast energy and hence free air pressure so deduced is in fact related to the total yield in much the same manner as in most combat drops in which burst heights between 1,000 and 4,000 feet are contemplated(13). After the deduction of the free air curve the results are applied to determine the scale factor for pentolite required to produce the best match in the region in which data is available (2-20 psi).

First a statement as to the blast measurements at Bikini Able (Fig. 8). Involved in this data are pressures calculated from shock velocities; these are reasonably dependable but do not go below reflected overpressures of about 7 psi. At lower pressures, no data were available except through such devices as foil gauges. In the region of 2 psi, the pressures can easily be in error by 20%, with a consequent error of about 50% for tonnages deduced from it.

The Bikini Able measurements have been combined with the small charge information of Figure 6 to give the free air curve for an atomic bomb plotted in Figure 9. Bleakney's curve for spherical pentolite has been included for comparison. (Note that two separate distance scales are used, one for the 1 lb. pentolite charge, and one for the Bikini Able bomb.) This is the free air curve for an atomic bomb, assuming that the relative energy loss is exactly the same as that for small charges fired over concrete and that history effects are small.

(13) The Trinity and Sandstone shots were too close to the ground in that the fireball touched it and hence are omitted from the present discussion.

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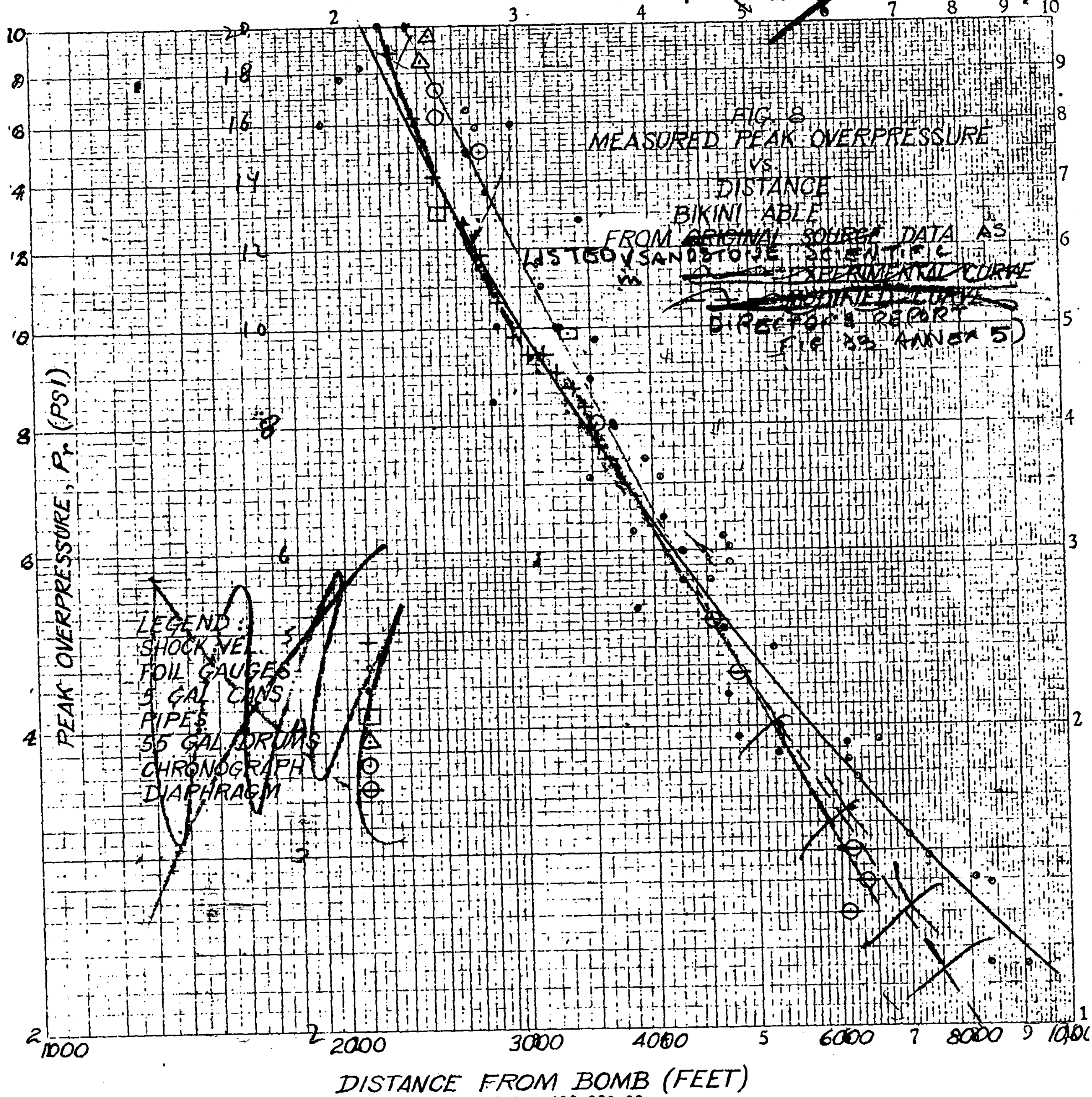

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The blast tonnages indicated at any peak overpressure are readily obtained from Figure 9 and these results are plotted on Figure 10, which gives the indicated tonnage at various reflected pressures ~~for K = 1.5.~~ The fact that the line is not horizontal might be taken to indicate that the free air pressure distance characteristics of an atomic bomb and pentolite spheres are slightly different in the range considered or that the procedure used to derive the atomic bomb curve is in error, except that the difference ~~±10%~~ ± 5% is considered to be within experimental error.

In the region of interest, from ~~6~~ 4 to 20 psi, the average value for the indicated tonnage in terms of pentolite is:

Table I.
Bikini Able

Total Yield Kilotons	22	22
Average Indicated Blast Yield Kilotons Pentolite	~~12.7~~	16.8
Fractional Indicated Blast Yield	~~0.58~~	0.76
High Indicated Tonnage Kilotons Pentolite	13.8	17.5
Low Indicated Tonnage Kilotons Pentolite	11.6	16.0

Following the result indicated in Table I we ~~reduce~~ multiply the expected total yield of an atomic bomb by a factor of ~~0.6~~ 3/4 in scaling up the free air peak overpressure curves of pentolite so that they best match the free air peak overpressure curve from an atomic bomb in the region of interest (20 to ~~8~~ 4 psi reflected overpressures).

If any true free air curves for atomic bombs were available, together with the collected experience of reflected pressure distance curves over many tactical targets, one could, no doubt, use a much more refined procedure than that resulting in the ~~0.6~~ 3/4 factor. Meanwhile, its use permits scaling from small charge data in what seems to

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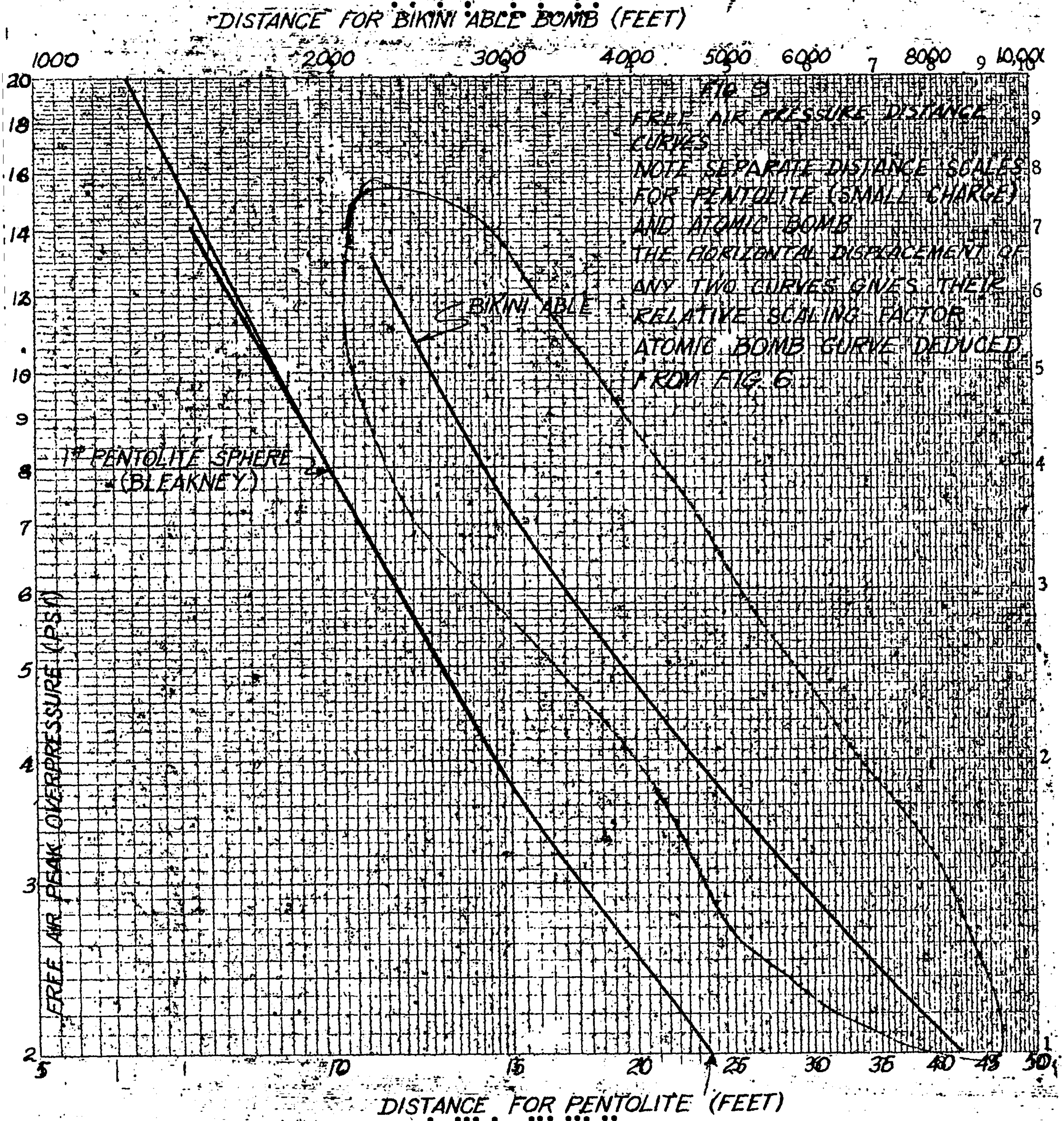

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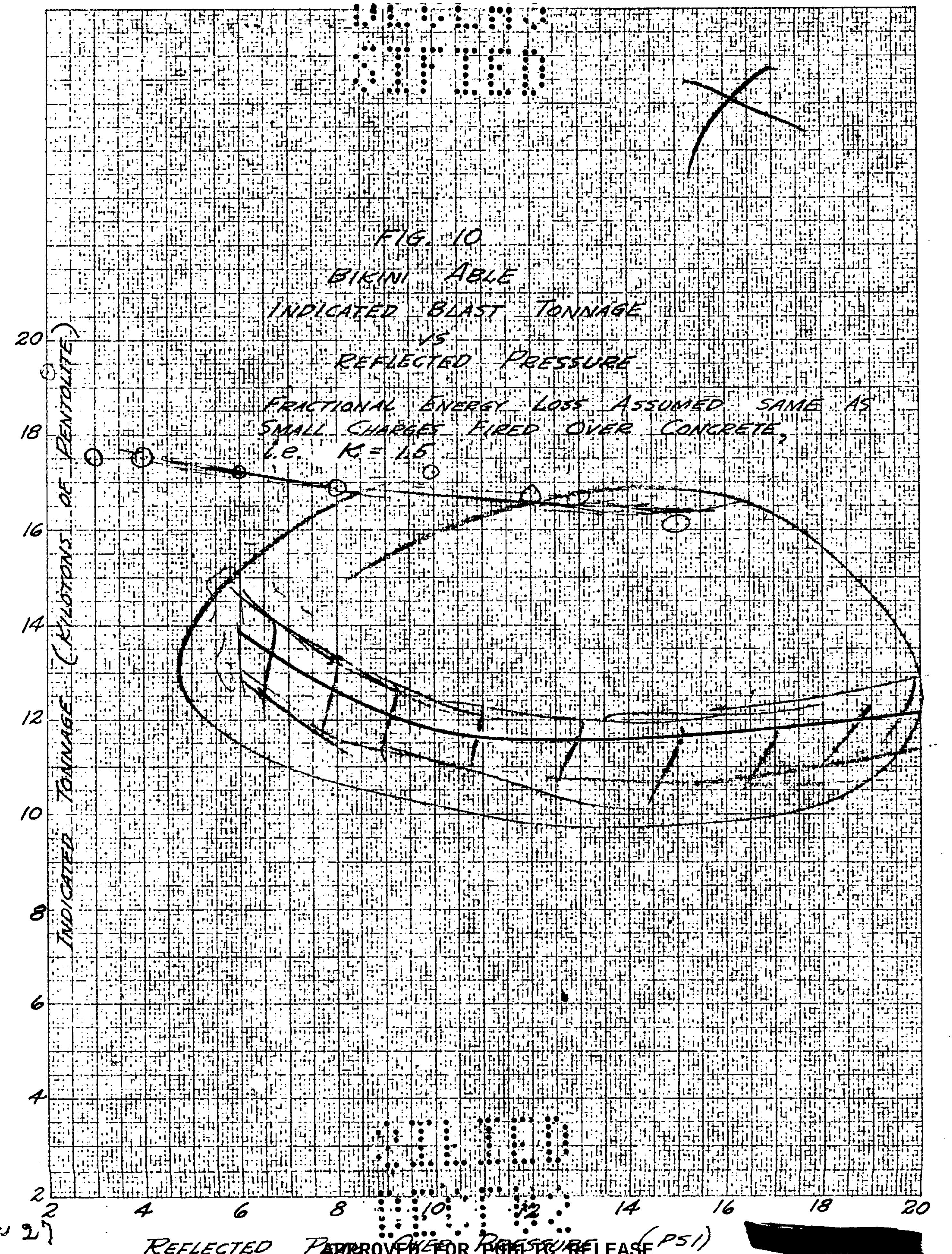
FIG. 10
BIKINI ABLE
INDICATED BLAST TONNAGE
VS
REFLECTED PRESSURE
FRACTIONAL ENERGY LOSS ASSUMED SAME AS
SMALL CHARGES FIRED OVER CONCRETE,
i.e. K = 1.5
INDICATED TONNAGE (KILOTONS OF PENTOLITE)
20
18
16
14
12
10
8
6
4
2
2
4
6
8
10
12
14
16
18
20
REFLECTED PEAK OVER PRESSURE (PSI)

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be a rational manner.

V. HEIGHT OF BURST CHARTS.

5.1 Chart for 1 Kiloton Atomic Bomb

In the practical determination of height of burst, reflected pressures may be presented in a useful form through the parameters, height of burst, h_c, and horizontal distance d. An h_c vs d chart requires the use of a specific free air curve; spherical pentolite was chosen as a useful approximation.

The result of combining Figure 6, with the free air curve for spherical pentolite, Fig. 9, after the transformations are made to h_c and d, and a scale factor $(\frac{3}{4}\ \cancel{0.6} \times 2 \times 10^6)^{1/3}$ was applied, appears as Figure 11. This then is the height of burst chart for an atomic bomb of 1 kiloton total yield. This is the same form of presentation as given previously by VonNeumann and Reines (Fig. 42 reference of footnote 4), and is intended to supercede it.

Included on the chart are curves for several Mach Y stem heights. These were obtained principally from Halverson's work at Woods Hole (14). The data presently available for such low stem heights is extremely meager and inaccurate. The experimental procedure ordinarily used is to place gauges at several heights in a vertical line; the time lag Δt between incident and reflected pressures is measured, plotted against gauge height, and the corresponding Mach stem height found by extrapolating Δt to zero. This procedure is quite satisfactory for high stem heights; a height ~~the line~~ Y = 1.0 agrees within a few per cent with other sources, but on a scaled basis, it corresponds to several hundred feet for atomic bombs. The procedure is not satisfactory for

(14) "The Effect of Air Burst on the Blast from Bombs and Small Charges", R. R. Halverson, Div. 2 NDRC A-323, OSRD Report 4889.

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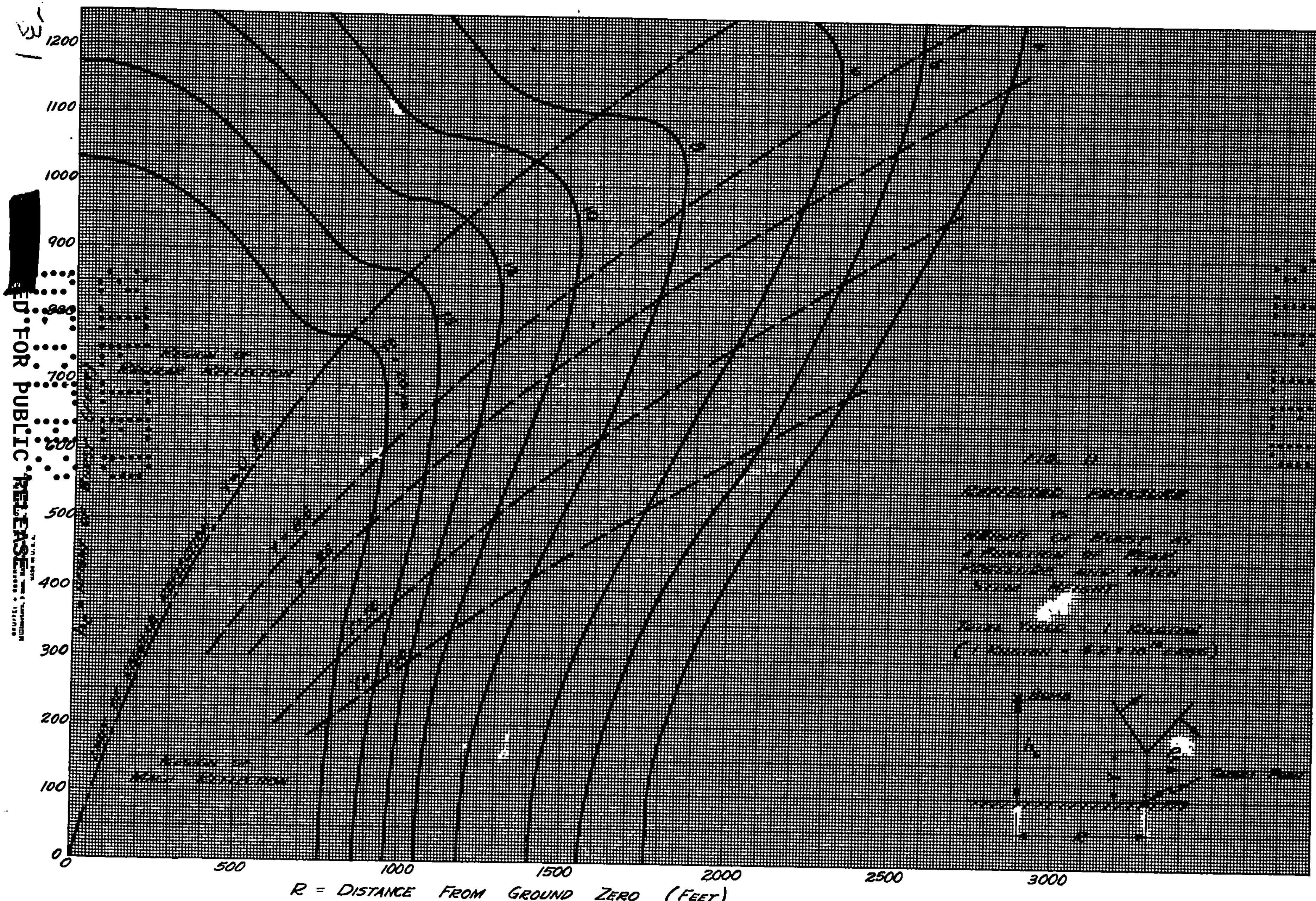

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1st change

very low heights, about 0.05 to 0.08, which when scaled is in the region of interest for atomic bombs. For example, the line Y = ~~0.08~~ 10, Figure 11 may be in error by 50 to 100%.

To apply Figure 11, one merely multiplies all distances by the scaling factor $W^{1/3}$, where W is the total yield in kilotons TNT (1 kiloton TNT is <u>defined</u> as 4.2×10^{19} ergs). We now proceed to give several illustrations of how it can be used, subject of course to the limitations cited in Section 1 of this report.

(1) <u>Maximize the area covered by a certain peak pressure.</u>
This is given by the maximum horizontal distance reached by any of the reflected pressure curves.

(2) <u>Stem height required to cover a structure.</u>
One scales down the height of the structure by the scaling factor, selects the pressure desired in the stem, and reads directly the height of burst which gives this combination, and the distance at which it occurs.

(3) <u>Areas covered by improper heights of burst.</u>
For a given height of burst, and a selected pressure, read the horizontal distance at which this occurs. This can be compared with the distance for the maximum, and squaring the ratio gives the % of maximum area covered.

(4) <u>Small targets.</u>
If a given circular area is to be damaged, and no damage is desired beyond a certain radius from ground zero, one can increase the damage inside that radius, and minimize it outside by suitable adjustment of the height of burst. Reduce the critical radius by the

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scaling factor; at this distance, some peak pressure will be maximized, obtained by interpolation on a line joining all the maxima. A somewhat similar procedure would be used if the pressure outside the critical radius was definitely not wanted to exceed a certain pressure.

Figure 11 shows quite clearly the insensitivity of damage area to height of burst in the region of the maxima. For example, the area covered by ~~8~~ 6 psi is maximized with a height of burst of ~~1025~~ 1250 feet, and the relevant horizontal distance is ~~1850~~ 2500 feet. For a height of burst of ~~[illegible]~~ 1150 feet, ~~[illegible]~~ 8% low, the horizontal distance is changed to ~~1810~~ 2450, a change of ~~2%~~ 2% in radius or reduction of ~~4%~~ 4% in area. On the other hand, an increase in height of burst of ~~11%~~ 8% to ~~1140~~ 1350 feet, decreases the radius to ~~1350~~ 2420 feet by ~~[illegible]~~ 3, a reduction of ~~44%~~ 6% in area. This emphasizes the fact that in general no great accuracy is required in height of burst; ~~but it~~ in general it is considerably better to err in the direction of low heights, than to err in the direction of high heights. Reference is made in this connection to Figs 12 through 15. ~~(cf remarks below relative to the stem height criterion).~~

We note further than the same height of burst is fairly satisfactory for several peak pressures near it; that is, maximizing 8 psi very nearly maximizes both 10 and 6. Also, if Mach stem heights were selected as a criterion, say 30' minimum, for a bomb of total yield = ~~[illegible]~~ 27 KT this scales to Y = 10 ~~[illegible]~~ feet, and such a value passes close to all the maxima in the neighborhood of 8 psi. ~~Furthermore~~ Hence, it is interesting that ~~a 30 kiloton~~ an atomic bomb of such yield has about the correct blast tonnage so that the Y height and peak pressure required to damage the entire face of a structure (requiring ~~4~~ 10 psi) is obtained

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with the same height of burst which would be required simply to maximize the area covered by that pressure.

It is to be noted that the requirement that stem height have a prescribed value is a much more stringent criterion in fixing the height of burst than is the requirement that a given peak pressure be achieved on the ground. In view of this fact it is of interest to inquire again into the validity of the stem height criterion. Furthermore, in view of the considerable experimental error in measuring the low stem heights here employed, it is not felt that a height of burst should be fixed by this criterion except in a rough manner until better experimental evidence becomes available.

5.2 BURST HEIGHTS FOR ATOMIC BOMBS

Figs. 12, 13, 14 and 15 give the height of burst as a function of bomb tonnage for several selected pressures.

The criterion chosen in making up these curves was height of burst which will maximize the area for the particular pressure, as obtained from Fig. 11. The yields shown are the expected rated yield of the bomb. The locus of points for such a proper height of burst is the central 100% line on each graph. As a guide to the accuracy required, lines are also given which show the heights of burst at which only 90 and 80% of that area is covered. On the left margin are also scales for the corresponding horizontal distance in feet for maximum coverage, and the maximum area in square miles. It must be cautioned that the distance and area scales refer only to the 100% lines. For heights of burst which are too high or too low, the % factor for area can be interpolated and applied to the 100% area. The stem heights

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vary from about 10 ft. for the 5 kiloton cases to about 35 ft. for the 50 kiloton bombs, this for the 100% lines.

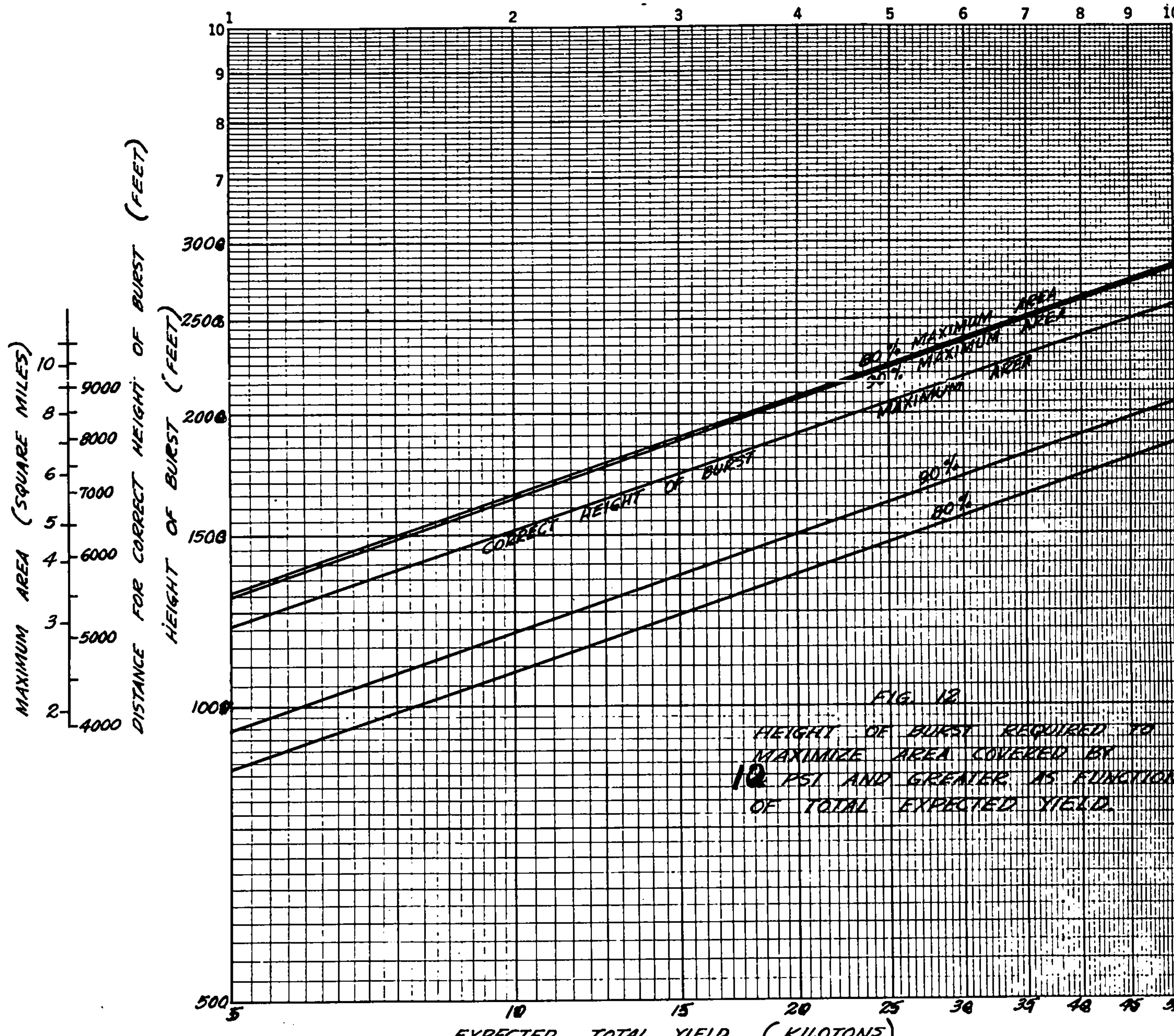

FIG. 12
HEIGHT OF BURST REQUIRED TO MAXIMIZE AREA COVERED BY 10 PSI AND GREATER AS FUNCTION OF TOTAL EXPECTED YIELD.

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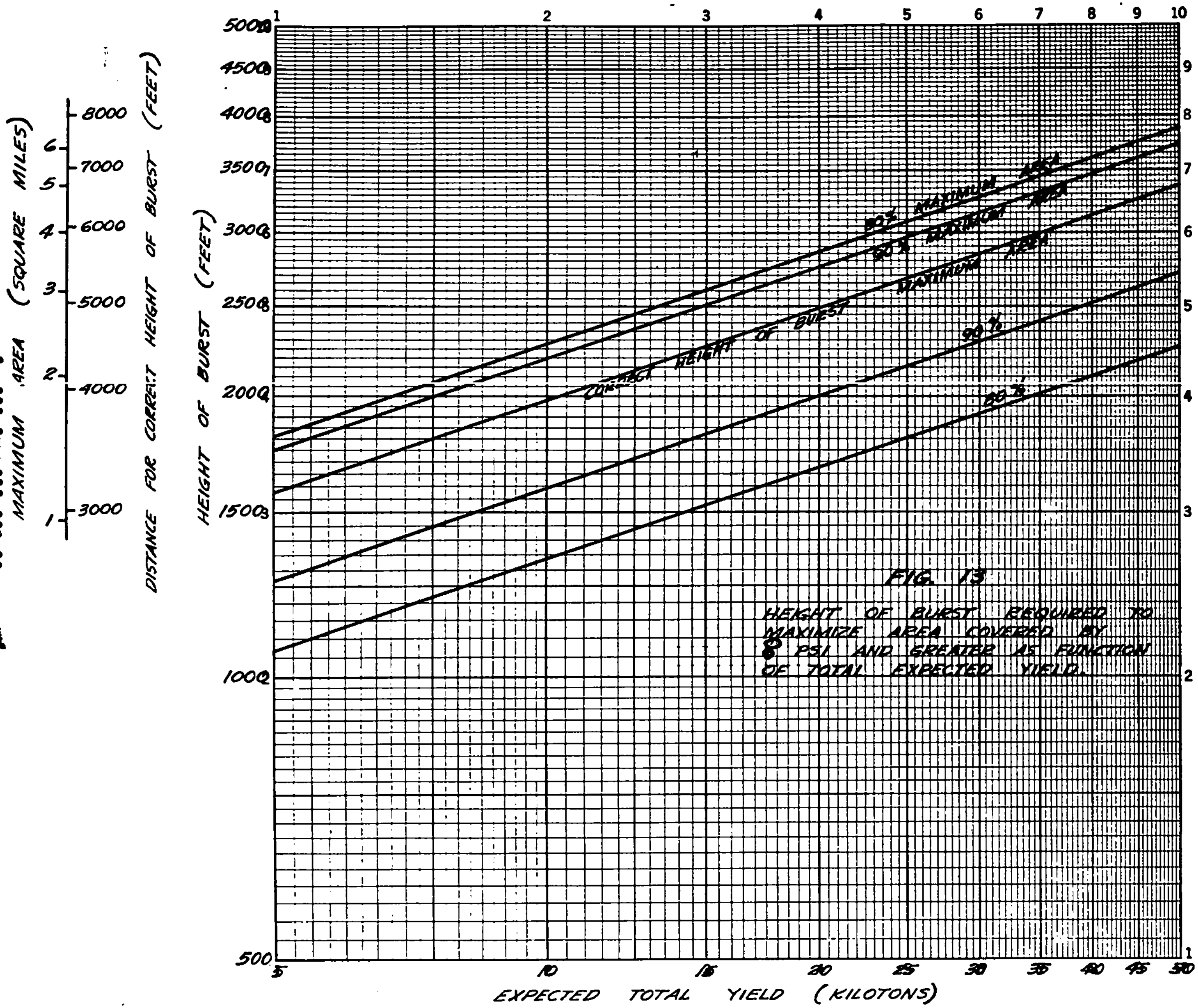

FIG. 13

HEIGHT OF BURST REQUIRED TO MAXIMIZE AREA COVERED BY 8 PSI AND GREATER AS FUNCTION OF TOTAL EXPECTED YIELD.

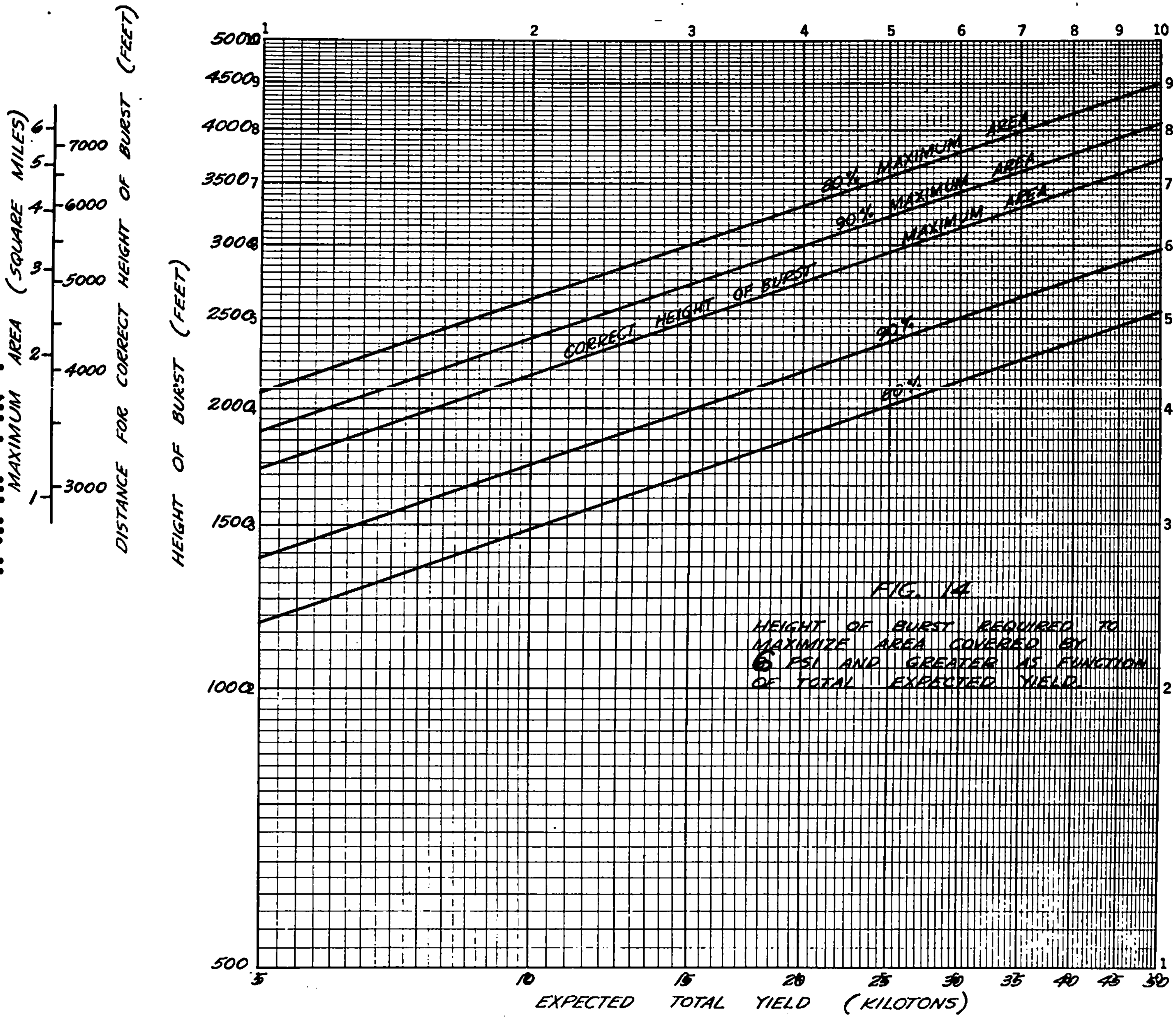

FIG. 14

HEIGHT OF BURST REQUIRED TO MAXIMIZE AREA COVERED BY 6 PSI AND GREATER AS FUNCTION OF TOTAL EXPECTED YIELD.

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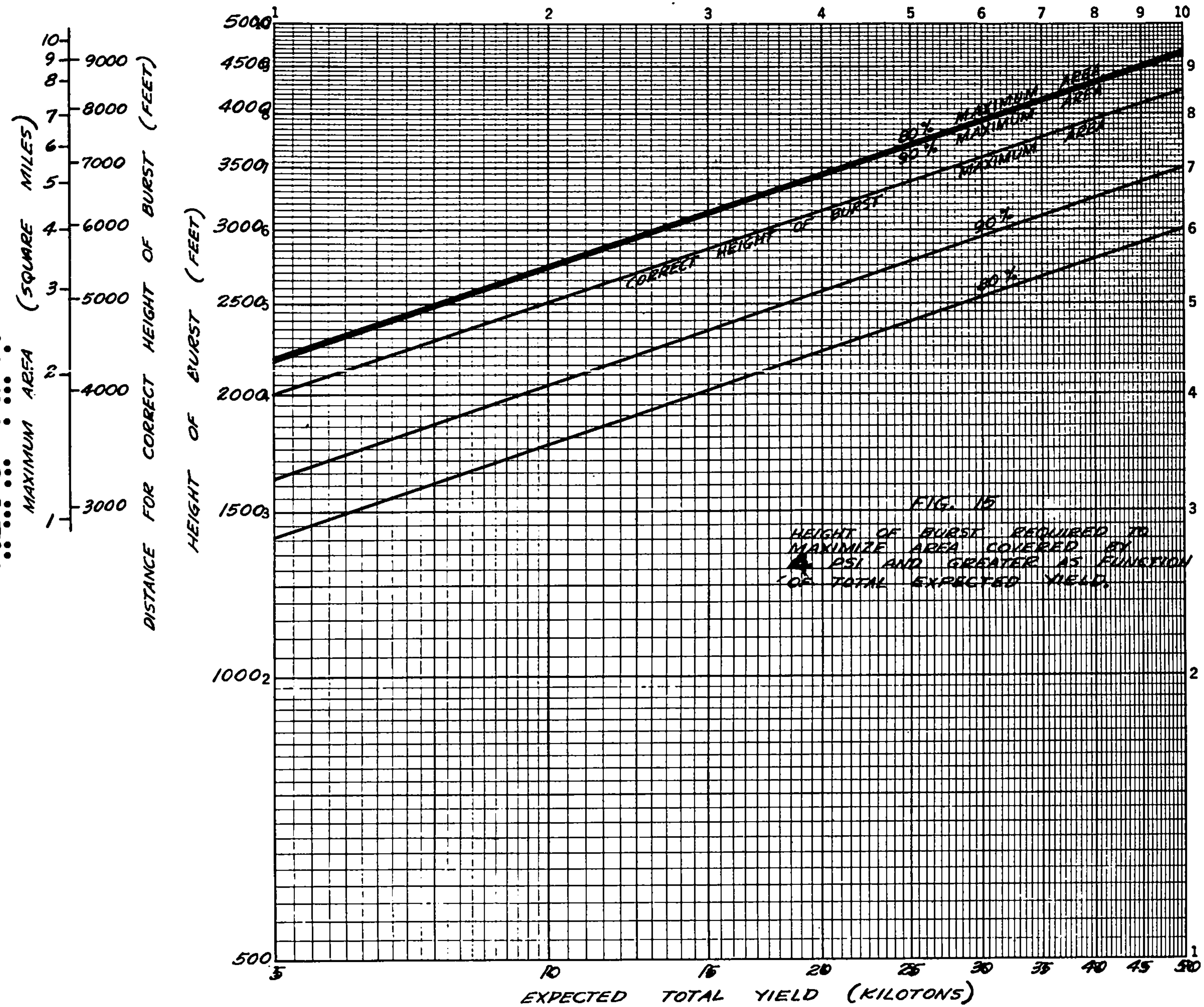

FIG. 15

HEIGHT OF BURST REQUIRED TO MAXIMIZE AREA COVERED BY [redacted] PSI AND GREATER AS FUNCTION OF TOTAL EXPECTED YIELD.

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VI. RECOMMENDATIONS AND CONCLUSIONS

1. It is suggested that experiments designed to measure the reflection pattern be conducted using larger ($\gtrsim$ 500 lbs.) H. E. charges. Larger charges than used in the past are required in order to facilitate measurement of the Mach pattern and minimize the effect of surface irregularities. Charges should be spherical in shape and detonated at the center. The importance of this H. E. program is in part based on economic considerations which will probably always make necessary dependance on scaling on small charge data.

2. In view of the absence of free air pressure-distance curves for atomic bombs, it is suggested that all possible support be given towards measurements of this quantity at Eniwetok in the 1951 tests as well as to calculations which can be carried out in advance of these tests.

3. Measure Mach phenomenon in conjunction with full scale tests of atomic bombs.

4. The role of the Mach stem in the production of damage should be re-investigated, especially in view of our present lack of precise information of stem heights which result in a given burst height.

5. In any practical use of the height of burst curves herein derived one must consider a much more complex situation than that in which a single structure is set by itself on an infinite rigid plane. In an actual target array one has a group of structures, each one in general requiring a different peak over pressure to be destroyed and each one shielding others and absorbing energy from the blast. It is clear that in view of these losses one should optimize higher pressure

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than those felt to be necessary at the target point under consideration. In this connection it might be well to study the target configurations actually encountered in Hiroshima and Nagisaka in the attempt to learn something about the problems of shielding and energy absorbtion by studying the pre- and post-shot photographs that are available. Furthermore, a comparison of the observed pressure curve and curve which can be "predicted" using figure 11 and the height of burst and bomb model employed may give some indication as to the energy loss. Some work has already been done in comparing these pressures.

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