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A METHOD FOR DETERMINING EQUATIONS OF STATE AND REACTION ZONES IN DETONATION OF HIGH EXPLOSIVES, AND ITS APPLICATION TO PENTOLITE, COMPOSITION-B, BARATOL, AND TNT.

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APPENDIX

MEASUREMENT OF FREE SURFACE AND SHOCK VELOCITY IN METALS.

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ABSTRACT

A method, which is here described, has been devised and utilized for the study of detonation waves in high explosives. Those investigated are pentolite, composition - B, baratol, and granular TNT. Pressure - volume data have been obtained for the detonation head and the Chapman - Jouget point. The peak pressure of the detonation head is found to be about 2.5 times that at the Chapman - Jouget point. Furthermore, assuming the adiabatic expansion of the burnt gases can be represented by pv^{γ} = constant, it was found that the mean square deviation of any of the explosives from the value $\gamma = 3$ was about 4 per cent, which therefore makes the formula $p = (\rho_0 D^2/4)$ a useful first approximation in determining the Chapman - Jouget point. If this picture of the detonation head is correct then "abnormal" spall effects, i.e. not present in thicker specimens, should occur in thin plates. These have been observed. Estimates have also been made of the width and duration of the reaction zone. They are found to lie in the intervals 0.8 ± 0.2 mm and 0.2 ± 0.1 microseconds respectively.

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A METHOD FOR DETERMINING EQUATIONS OF STATE AND REACTION ZONES IN DETONATION OF HIGH EXPLOSIVES, AND ITS APPLICATION TO PENTOLITE, COMPOSITION-B, BARATOL, AND TNT.

Hypothetical Considerations.

The conditions under which the tests were conducted are such that the detonation process may be treated as one-dimensional, i.e. the detonation wave moves across the explosive as a series of parallel planes. Furthermore, divensions have been so chosen that the wave has reached a stationary state i.e. the wave velocity is constant in time.

Let

D_1 or D = detonation velocity

D_2 = shock velocity in metal

u = mass velocity

v = specific volume

v_0 = initial specific volume of the solid explosive

$\Delta v = v - v_0$

p = pressure

x = fraction of explosive in which the reaction is complete; fraction of intact explosive = $1 - x$.

E = internal energy per unit mass

$\Delta E = E(p, v, x) - E(p_0, v_0\ x = 0)$

The explosive, in passing from the intact state through the various reaction states, must fulfill the conditions of conservation of mass, momentum and energy. Therefore, neglecting viscosity and thermal conductivity effects,

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for $u_o = 0$ and p_o negligible,

$$u/D = -\Delta v/v_o \tag{1}$$

$$p\, v_o = u\, D \tag{2}$$

$$\Delta E = -1/2 p\, \Delta v = 1/2\, u^2 \tag{3}$$

v_o, p_o, u_o are given, D is an unknown parameter, and p, v, u are unknown functions of x.

A hypothetical set of Rankine-Hugoniot curves in the (p,v)-plane together with the point (p_o, v_o) are plotted in Fig. 1 for different x. The angle between the negative v-axis and the direction $(p_o, v_o) \rightarrow (p, v)$ is denoted by ϕ so that $D = v_o\sqrt{\tan\phi}$ and $D - u = v\sqrt{\tan\phi}$.

While ϕ is undetermined it is not entirely arbitrary since it may be observed to lie in the upper left quadrant from the conditions that $\tan\phi = (D/v_o)^2 >$ and that $p > p_o$, $v > v_o$ because we are here considering detonation and not merely burning. Furthermore the straight line from (p_o, v_o) to (p, v) must intersect the (p, v) curves for all $0 \leq x \leq 1$. Therefore, in Fig. 1, we must have $\phi \geq \phi_\eta$ where ϕ_η is the tangent to the (p, v) curve for x = 1. The Chapman-Jouget hypothesis states that $\phi = \phi_\eta$.

Thermodynamic and hydrodynamic arguments can be propounded to justify this conclusion.

For example, if at x = 1 we have $-(\partial p/\partial v)_s = (p-p_o)/(v_o - v)$ then $D = u + c$ and the condition is fulfilled; c here denotes the sound velocity. If the point lies at "a" in Fig. 2 then $-(\partial p/\partial v) > (p-p_o)/(v_o - v)$ and $c + u > D$. The rarefraction wave will then catch up with the detonation wave and lop it off

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until the point has moved down to "d". But we have hypothecated a steady state to the detonation wave. If the point lies at "b" then $-(\partial p/\partial v) < (p - p_o)/(v_o - v)$ But the entropy of the burnt gases corresponding to state "b" is less than that for state "a", i.e. "a" is more probable than "b"; similarly for all pairs "a" and "b" until a = b = d. Hence "d" is the most probable point.

A discontinuity must of necessity occur at $x = 0$ for increasing x with an immediate jump from the lower intersection point (p_o, v_o) to the upper intersection point (p^o, v^o). Thus the reaction zone sets in as a shock wave with an abrupt increase of p and u and an equally abrupt decrease of v. This is accompanied by a large increase in temperature and a vehement blow of velocity u by the wave head on the intact explosive. This velocity is smaller but of the order of magnitude of the detonation velocity D and it is this discontinuity in material velocity which can provide a mechanism to start reaction. The reaction zone behind the head is able to replenish the head with the necessary energy since inthis region $c + u > D$. The reaction proceeds continuously remaining as an upper intersection point for the curves $0 < x < 1$, and terminates at $x = 1$ as a tangent point. This is followed by an adiabatic expansion of the burnt gases.

Von Neumann (OSRD No. 549) has also presented an alternative argument wherein all the curves for different x intersect each other, i.e. in which endothermic changes of state can occur, and for which the Chapman-Jouget hypothesis would not be valid.

A similar argument could be made for an intermediate situation wherein the Hugoniots for the $x \leq x_o$ form stream lines as in Fig. 1 while the curves for $x > x_o$ intersect one another. Here the envelope of the intersecting curves could be so tight and small that even though the Chapman-Jouget hypothesis be not fulfilled

[redacted]

the deviation from this condition would be negligible. In this case what we observe would not be a function of the reaction zone width but only of that fraction from $x = 0$ to $x = x_0$ the remainder blending in with the indistinguishable from the adiabatic expansion portion of the curve.

This latter concept of Von Neumann does not appear very probable thermodynamically since it implies that a mixture of reacted and unreacted material can do more work than the completely reacted material. If this were true it would be desirable to include an inhibitor which would prevent the reaction from going to completion. As will be seen, it does not agree either with the results obtained herein.

The cross section of the detonation wave will thus appear as in Fig. 3. The shape of the burnt-gas expansion curve will depend upon the confinement. With an infinite amount of explosive this portion of the curve would remain horizontal, provided no endothermic recombinations occur. It should be remembered that no after-burning effects, such as from reaction with surrounding air, will be observable with the method of this paper.

When such a detonation wave impacts on a metal surface a shock wave will be transmitted into the metal with shock velocity D_2 and pressure

$p_2 = p_t$ where [1]

$$(p_2 / p_1) = \frac{2\rho_2 D_2}{\rho_1 D_1 + \rho_2 D_2} \tag{4}$$

1). More correctly $(p_t / p_1) = \frac{\rho_2 D_2}{\rho_1 D_1} \quad \frac{\rho_1 D_1 + \rho_3 D_3}{\rho_2 D_2 + \rho_3 D_3}$

where ρ_3 is the density behind the detonation front and D_3 the reflected shock velocity.

$p_1 = p_i$ denoting the incident pressure in the shock wave, ρ_1 and ρ_2 the initial densities in the high explosive and metal respectively, D_1 and D_2 the detonation and shock velocities respectively. Relations (1), (2) and (3) must also apply for the p, v, u and D in the metal.

A facsimile of the detonation wave modified in amplitude as indicated by (4) is transmitted through the metal. Here however there is no replenishment by reaction and the unloading wave, moving with velocity $u_2 + c_2$ which is greater than D_2, is continually encroaching upon and eroding the peak. c_2 is the sound velocity in the compressed medium behind the shock front.

It was expected therefore that, on impacting the front surfaces of a series of metal plates of varying thicknesses by high explosive detonation waves and measuring the initial surface velocities of the backs of these plates, a cross sectional picture of the detonation wave could be obtained.

From this cross section it should be possible to estimate

(a) the width of the reaction zone

(b) p^o, v^o for $x = 0$

(c) p, v for $x = 1$

provided certain other quantities, such as D_1, D_2, c_2, were also determined.

If <u>a</u> denote the width of the reaction zone and <u>b</u> the apparent width in the metal then

$$a \doteq b \left(\frac{D_1}{D_2}\right) \left[1 - \frac{D_2}{u_2 + c_2}\right] \qquad (5)$$

c_2 being the sound velocity in the compressed medium. For $D_1 > D_2$ there is a foreshortening effect due to crowding of the detonation wave at the metal surface and given by the ratio in parenthesis; on the other hand there is an elongation resulting from the term in square brackets. The reaction time Δt will be given by

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$$\Delta t = (a/D_1)\ (v_o/v) \qquad (6)$$

where the increase in time as represented by $(^{v}o/v)$ results from the fact that the reacting particle is moving at velocity u in the same direction as D.

The impedances ρD of the impacting and impacted materials should be identical. For aluminum and high explosive the ration p_t / p_i as given by (4) is about 1.25. In consequence a pressure wave is reflected back into the explosive which might have an effect in shortening the reaction zone and would therefore constitute a possible source of uncertainty inestimating the reaction zones by this method.

p_1^o and p_1 may be approximated by (4) after the p_2 have been obtained from the velocities D_2 and u_2.

Even with the above approximations and limitiations in mind it was believed that the results obtained by the method of this paper would be able to supply additional justification for the considerations just described or to indicate wherein they might be invalid.

For this purpose it is desirable to use a substance for which mass velocity is a sensitive function of pressure and which would yield a fair "impedance" match with the high explosive. Beryllium, aluminum, and graphite approach these specifications. Aluminum was chosen because it is readily obtained in very homogeneous form and is easily worked.

In order to ascertain further to what extent the measurements may be correlated with particle velocity rather than with momentum transfer from explosive to target for the very thin plates a series of measurements was also made on steel plates.

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The procedure consists in impacting the front surface of a metal plate with a plane detonation wave and obtaining a measure of the initial velocity of the back surface of the plate. This is accomplished by spacing a set - about eight - of electrical contactors in the interval from 0 to 2 millimeters from the back surface of the plate and measuring the times of arrival of the plate at these contactor positions. Details of the technique are given in LA - 384 and with more detail in the appendix to this report.

Calculation of pressure by Eqn. (2) is subject to some uncertainty since the free surface velocity is given by

$$u + \int_{S_2} c \; d \; (\ln \rho) \qquad (7)$$

where c is the sound velocity in the compressed region. Expression (7) has been approximated herein by <u>2 u.</u> The Hugoniots for aluminum and steel are expected to cross over into the liquidus regions for pressures of about 0.6 and 1.7 megabars respectively. No marked discrepancies were observed between results for steel and aluminum. To ascertain what might be expected in the liquidus to vapor region a series of tests was made with lead and with lead backed by 0.125" of steel. The Hugoniot for lead is expected to cross over into the liquidus region at about 0.26 mb and into the vapor region at about 1.25 mb. The data obtained are shown in Fig. 9 where it may be observed that velocities from unbacked lead scatter considerably and for thickness under one inch are about double the values for steel-backed lead.

EXPERIMENTAL RESULTS

The experimental data of surface velocity as a function of thickness of material through which the shock wave has traveled are tabulated for

(A1) Aluminum - pentolite

(A2) Steel - pentolite

(A3) Aluminum - Composition B

(A4) Aluminum - Baratol

(A5) Aluminum - granular TNT

as follows:

TABLE (A1)

Aluminum - Pentolite

Thick Al inches	No. of Observ.	Mean Obs. Vel. km/sec.
1.50	5	2.454 ± .028
1.25	13	2.605 ± .020
1.00	3	2.679 ± .044
0.50	6	2.900 ± .029
0.234	1	2.96
0.220	1	3.11
0.125	2	3.35
0.119	1	3.56
0.087	1	3.34
0.065	1	4.16
0.005	5	6.03 ± .04

The first four points may be represented [illegible] 165 - 2.294 x where y = thickness in inches and x = velocity in km/sec.

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TABLE (A2)

Steel - Pentolite

Thick. Steel, inches	No. of Observ.	Mean Obs. vel. Km / Sec.
2.00	3	0.65
1.50	5	0.964 ± .045
1.00	16	1.376 ± .022
0.50	7	1.628 ± .031
0.49	1	1.668
0.079	1	2.078
0.038	1	2.920
0.016	1	2.781
0.010	1	3.947

The first five points can be represented by $y = 2.962 - 1.483\,x$ where y = thickness steel in inches, x = velocity in km/sec.

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[redacted]

TABLE (A3)

Aluminum - Composition B

Thick Al inches	No. of Observ.	Mean Obs. vel km/sec.
1.50	2	2.818 ± .023
1.00	3	2.979 ±0.29
0.50	3	3.13 ± .018
0.229	1	3.08
0.200	2	3.01 ± .045
0.124	2	3.19 ± .00
0.063	2	3.75 ± .13
0.031	1	3.75
0.016	2	5.26 ± .45
0.011	1	5.52
0.005	1	7.11

[redacted]

[redacted]

TABLE (A4)

Aluminum - Baratol

Thick Al inches	No. of Observ.	Mean Obs. Vel. km/sec.
1.50	2	1.45 ± .01
1.00	2	1.61 ± .01
0.765	2	1.628 ± .04
0.620	1	1.711
0.500	2	1.776 ± .05
0.483	1	1.730
0.250	1	1.905
0.235	1	1.970
0.062	1	2.370
0.031	1	2.758
0.011	2	3.474 ± .06

TABLE (A5)

Aluminum - Granular TNT

Thick Al inches	No. of Observ.	Mean Obs. Vel. km/sec.
1.000	1	1.61
0.500	3	1.67 ± .01
0.250	2	1.72 ± .02
0.125	2	1.84 ± .02
0.062	1	2.63
0.026	5	3.275 ± .01

[redacted]

These results are also shown as graphs in Figs. 4 to 8 inclusive.

From each test the times of arrival of eight contactors, distributed in the interval 0 to 2 millimeters from the back surface of the plate, are recorded and a least square value for the slope is calculated from these points. Even though the mean square deviation of the points from this line may amount to only about two percent, the deviation from shot to shot in repeat tests may be several times this value. The factors which result in the latter spread are due probably to differences in the quality of the high explosive, e.g. from variations in porosity, grain size, segregations, cavities and cracks.

The first set of measurements (LA-384) was made with a lens intended to give a flat wave 3.5" in diameter (the actual wave front was, however, convex, the central axis leading by about 0.2 u sec). To this lens was attached the cylindrical disc 4" diameter by 3" high of the explosive investigated. Thicknesses less than 2" were found to give low values of velocity. Later a lens designed to give a flat wave 6.5" in diameter was made available (the actual wave front was slightly convex the central axis leading the edge by about 0.1 u sec). The cylindrical cake of the explosive investigated was 8" diameter by 3" high. Results with the former lens showed considerably more scatter than was obtained with the latter. In fact the data obtained for thick plates with composition-B cakes and 3.5" lenses had to be discarded entirely because the values of velocity obtained were too erratic and were furthermore consistently lower than those obtained with 6.5" lenses. An adequate explanation for this behavior is not known because the measurements were made within the unperturbed conical region as computed and checked experimentally.

The shock velocity is aluminum and steel was obtained from a series of

[redacted]

14 internally imbedded pins spaced in the interval 1 to 23 millimeters from the front surface of the one-inch thick plate. The shock velocity in aluminum (3.5" lens and pentolite) may be represented by

$$D_2\ (Al) = \frac{d\,x}{d\,t} = \frac{1}{0.1204 + 0.0006336\,x}\ \text{km/sec},$$

where x is distance in millimeters and t time in microseconds, except for the initial high-pressure peak.

The shock velocity in steel (6.5" lens and pentolite charge), from similar measurements, is

$$D_2\ (Steel) = 5.24\ \text{km/sec}$$

and over this interval the mean square deviation of velocity from constancy was less than one per cent. This value is about 5 per cent higher than the figure obtained with 3.5" lenses (LA-384).

The characteristics of the various explosives tested are as follows:

TABLE B

Explosive	Density	D. km/sec	Grain size
Cast pentolite 50/50	1.666	7.500 (stick)	coprecipated product
Cast Comp-B 60/40 RDX/TNT	1.70	7.850 (stick)	RDX 70 microns
Cast Baratol II	2.51	4.850 (stick)	Barium nitrate 12 microns
Granular TNT	1.03	5.250 (flat wave lens)	Spherical granules from 0.3 to 0.5 mm diameter. Grain size small.

[redacted]

 [redacted]

DERIVED QUANTITIES

Equation of State: From these data and the relations which have been presented it is possible to evaluate a p and corresponding v or v/v_0 in the detonating explosive from the initiation to the end of the reaction, i.e. from x = 0 to x = 1. The data are given in the following table.

TABLE C

Reacted fraction	Corr. thick. in aluminum	Pressure Megabars	v/v_0
		PENTOLITE	
x = 0	0	.562	.400
	0.05	.347	.629
	0.10	.308	.672
	0.15	.247	.736
x = 1	0.20	.245	.738
		COMP-B	
x = 0	0	.664	.366
	0.025	.444	.576
	0.05	.293	.721
	0.10	.272	.740
x = 1	0.15	.264	.748
		BARATOL	
x = 0	0.01	.294	.502
	0.05	.201	.659
	0.10	.168	.735
	0.20	.150	.745
	0.30	.141	.761
x = 1	0.40	.136	.769
		GRANULAR TNT	
x = 0	---	(.260?)	(.1 ?)
	0.06	.204	.280
	0.10	.122	.570
	0.13	.107	.622
	0.15	.101	.643
x = 1	0.18	.098	.652

[redacted]

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The peak pressure values will be somewhat uncertain because measurements sufficient to reduce probable errors from random fluctuations are not yet available. The peak pressure in the detonation front, according to the above table is about 2.5 times that at the Chapman-Jouget point.

Reflection of this high peak from free surfaces of thin plates should then be able to produce certain spall effects which would not be observable in thicker specimens. Such "abnormal" spall effects have been observed and therefore offer an indirect confirmation.

H. Jones (BM-647, AC-3641) has computed the (p,v) - adiabatic expansion curve for the reaction products of composition-B. His calculated values for the Chapman-Jouget point are[2] $p = .208$ mb, $(v/v_o) = .79$. These are to be compared with $p = .264$ mb and $(v/v_o) = .75$ of this paper.

A plot of <u>p</u> versus (v/v_o) for these explosives is shown in Fig. 10, the detonation velocity D being given by

$$D = \sqrt{v_o \tan \phi^1}$$

where ϕ^1 is the angle between the line containing the $(p, v/v_o)$ points and the negative (v/v_o)-axis.

It has been shown that at the Chapman-Jouget point

$$-\left(\frac{\partial p}{\partial v}\right)_s = \frac{p - p_o}{v_o - v}$$

Now assume that the isentropic expansion curve of the burnt gas may be represented by

$$P V^{\gamma} = \text{constant}$$

2). These are modifications by Peierls of Jones' original values. Jones calculations are for $\rho_o = 1.5$ whereas the actual initial density is 1.70; furthermore his peak temperature is 3800°K whereas Fox has obtained spectroscopically a temperature of 4800°K for RDX.

 [redacted]

where γ is identified with the ratio of heat capacities (c_p/c_v). Then

$$-\left(\frac{\partial p}{\partial v}\right)_s = \frac{p\gamma}{v} = \frac{D}{v_o}$$

whence by elimination, neglecting p_o, we have

$$1/\gamma = -(\Delta v)/v_o$$

or

$$p = \rho_o D^2/(\gamma + 1)$$

From these relations and the data of Table C we have

TABLE D

Explosive	$\gamma = (c_p/c_v)$
Pentolite	2.82
Comp-B	2.97
Baratol	3.33
Granular TNT	2.88

The mean square deviation of the explosives from the value $\gamma = 3$ is about 4 per cent which therefore makes the relation $p = (D^2 \rho_o/4)$ useful as a first approximation in computing (p, v) at the Chapman-Jouget point for various densities of packing.

Reaction Zone

The reaction zone width and time of reaction may be obtained from the relations (5) and (6). The ratio $D_2/(c_2 + u_2)$ decreases with increasing pressure so that erosion of the peak is more rapid at the higher pressures. Hence the evaluations desired of these functions in expression (5) are those for which $x = 1$.

[redacted]

Furthermore, for shocks of small amplitude (small Δp) c_2 will approximate to D_2, the effect of rigidity being negligible for aluminum at these pressures.

From the plots of u_2 and D_2 as a function of distance in aluminum pressure-volume points are computed for aluminum. c_2 is obtained from the slope of the resultant (p,v) -Hugoniot curve at these points. It was found that in the Chapman-Jouget pressure region for these explosives the ratio $D_2/(u_2 + c_2)$ lay in the interval $0.85 \pm .03$.

The values so obtained for the widths and durations of the reaction zones are as follows:

TABLE E

Explosive	Width a of reaction zone in millimeters	Time of reaction t in microseconds
Pentolite	0.80 ± 0.16	0.14
Comp-B	0.64 ± 0.14	0.11
Baratol	1.12 ± 0.12	0.30
Granular TNT	(0.5)	(0.15)

The reaction zones are therefore of the order of 0.8 ± 0.2 mm wide and durations 0.2 ± 0.1 microseconds.

These values do not agree with estimates made by Eyring and his collaborators (OSRD 3796) from such methods as (a) extrapolation from low temperature rate of decomposition (b) rate at which detonation builds up from low to high order (c) limiting cylindrical diameter for steady state detonation along the uncased stick[3] (d) calculated rate for surface reaction from activation

3). They deduce that the detonation velocity is proportional to ar^{-1} where r is the radius of the stick. Other determinations would indicate that the minus exponent should be about 4.

[redacted]

[redacted]

energy. Their conclusion is that the reaction time for TNT is 1 microsecond and length of about 0.5 cm.

Another method is to relate the width of perturbed region of a detonation wave proceding around a concave arc with the radius of curvature r_1 of the arc by $D = D_\infty \left[1 - (\kappa\, a/r_1) \right]$ where D_∞ is the steady state velocity and κ an unknown parameter. If κ is made unity then a would be the order of 0.4 cm. However, κ should be more than unity and in fact probably a function of r since one component of the vector D will be directed away from the surface.

Herzberg and Walker (BM 1165), from direct observation of the duration of detonation luminosity, found an upper limit to be 0.03 μsec. for RDX - BWX 91-9 pellets and 0.1 μsec for all other explosives investigated (tetryl, NENO, TNT). Corresponding upper limits for lengths of the reaction zones are 0.3 to 0.9 mm. These are in very good agreement with the results obtained by us.

[redacted]

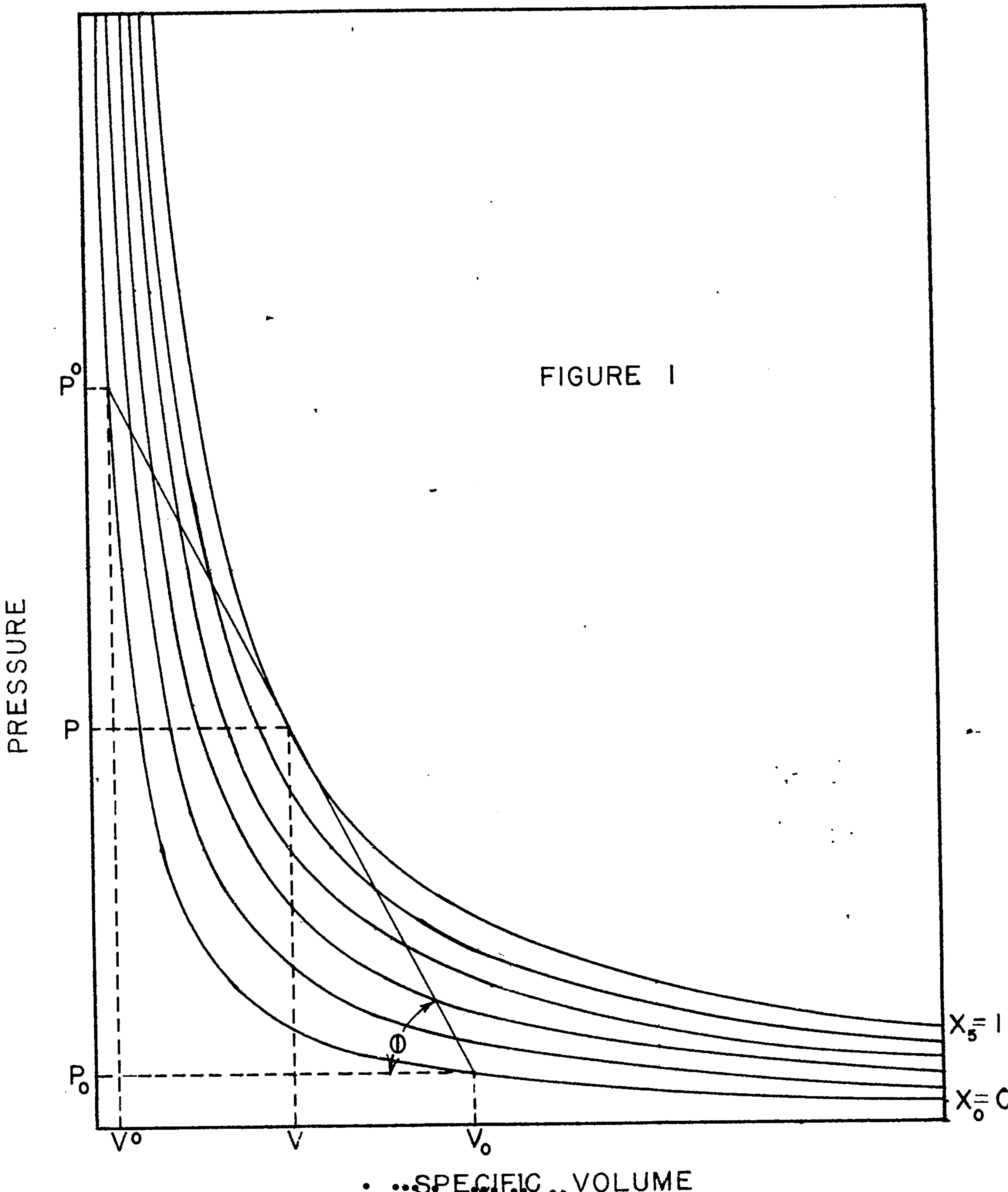

FIGURE 1

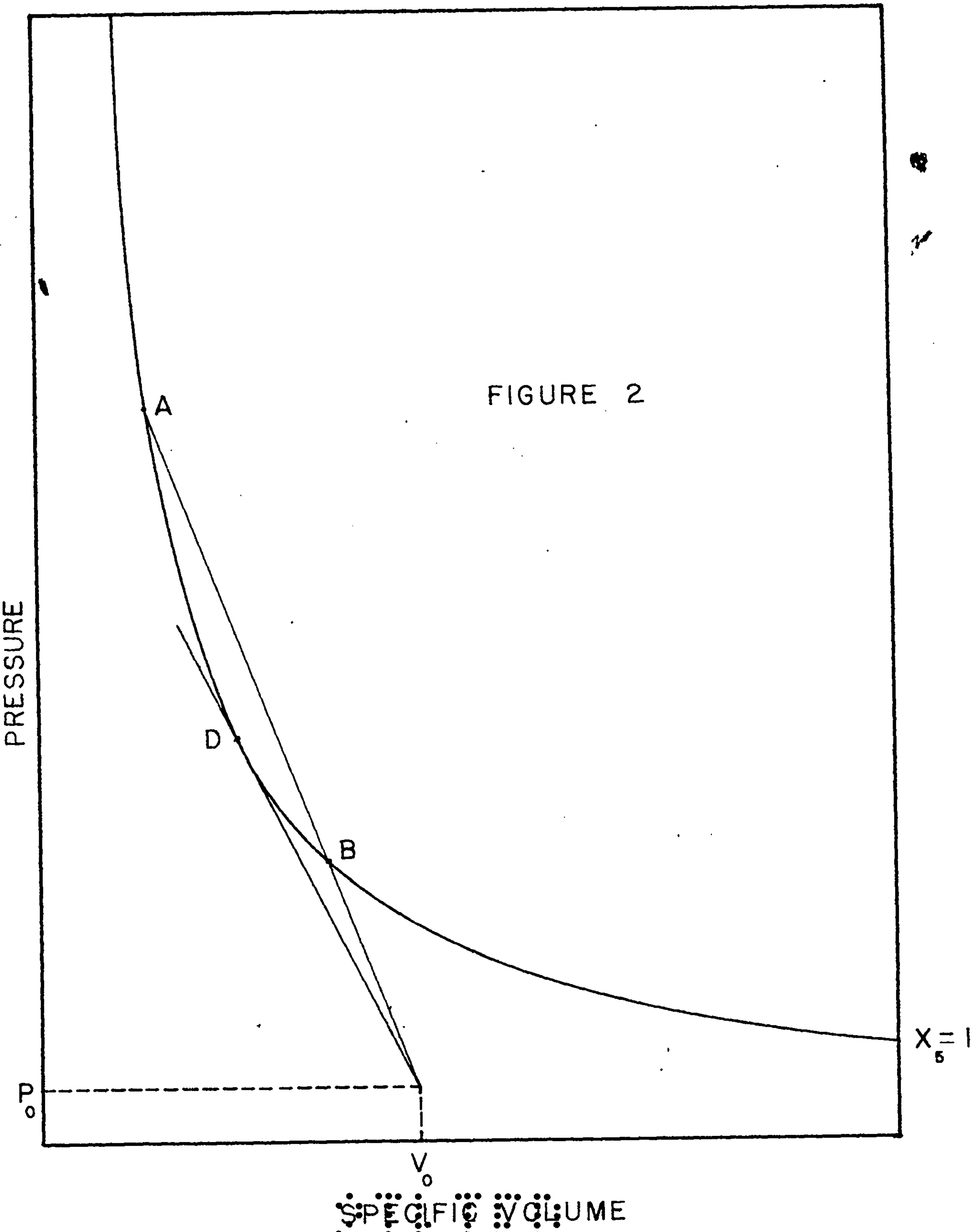

FIGURE 2

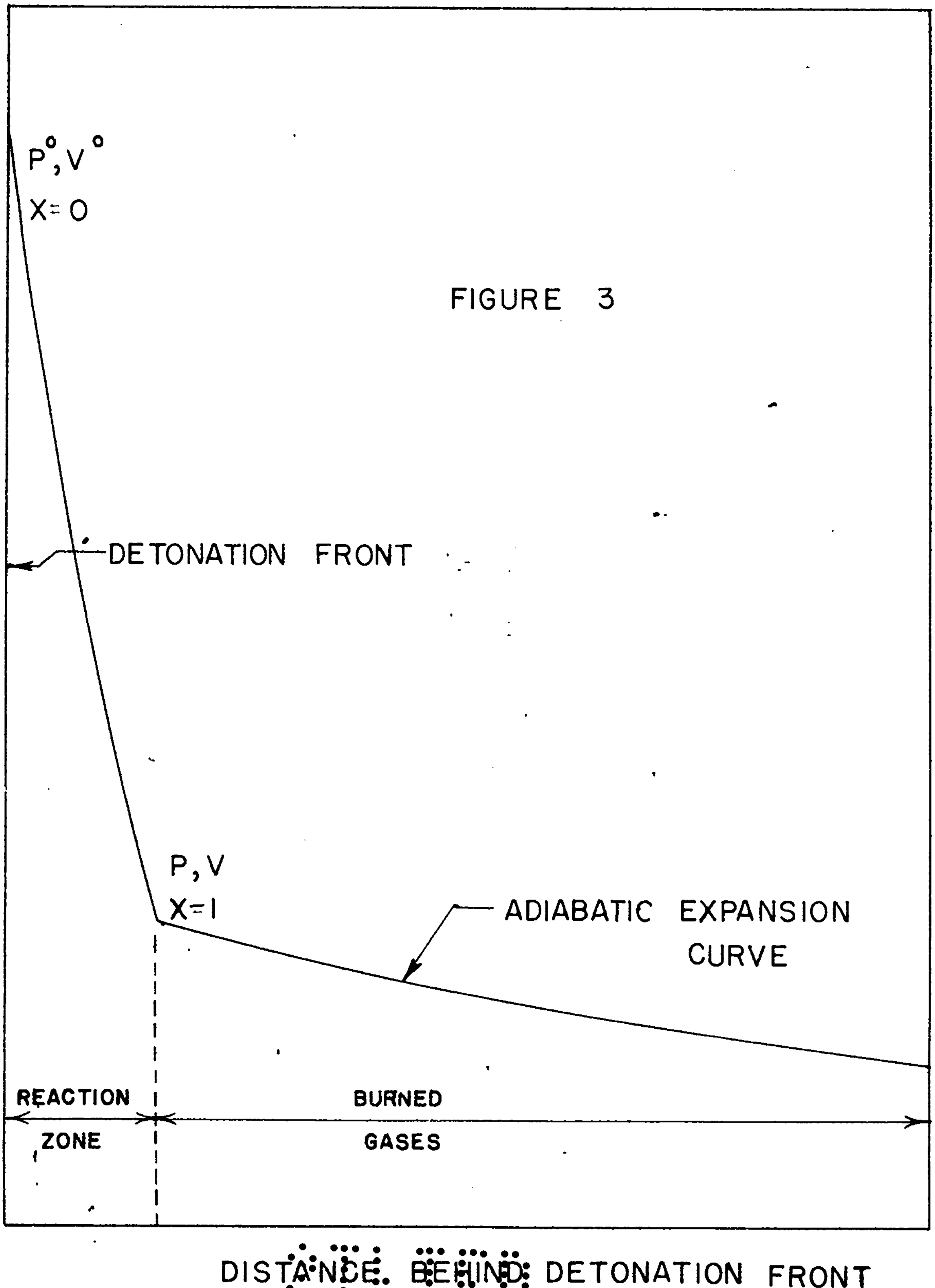
P°, V°
X = 0
DETONATION FRONT
P, V
X = 1
ADIABATIC EXPANSION CURVE
REACTION ZONE
BURNED GASES
DISTANCE BEHIND DETONATION FRONT

FIGURE 3

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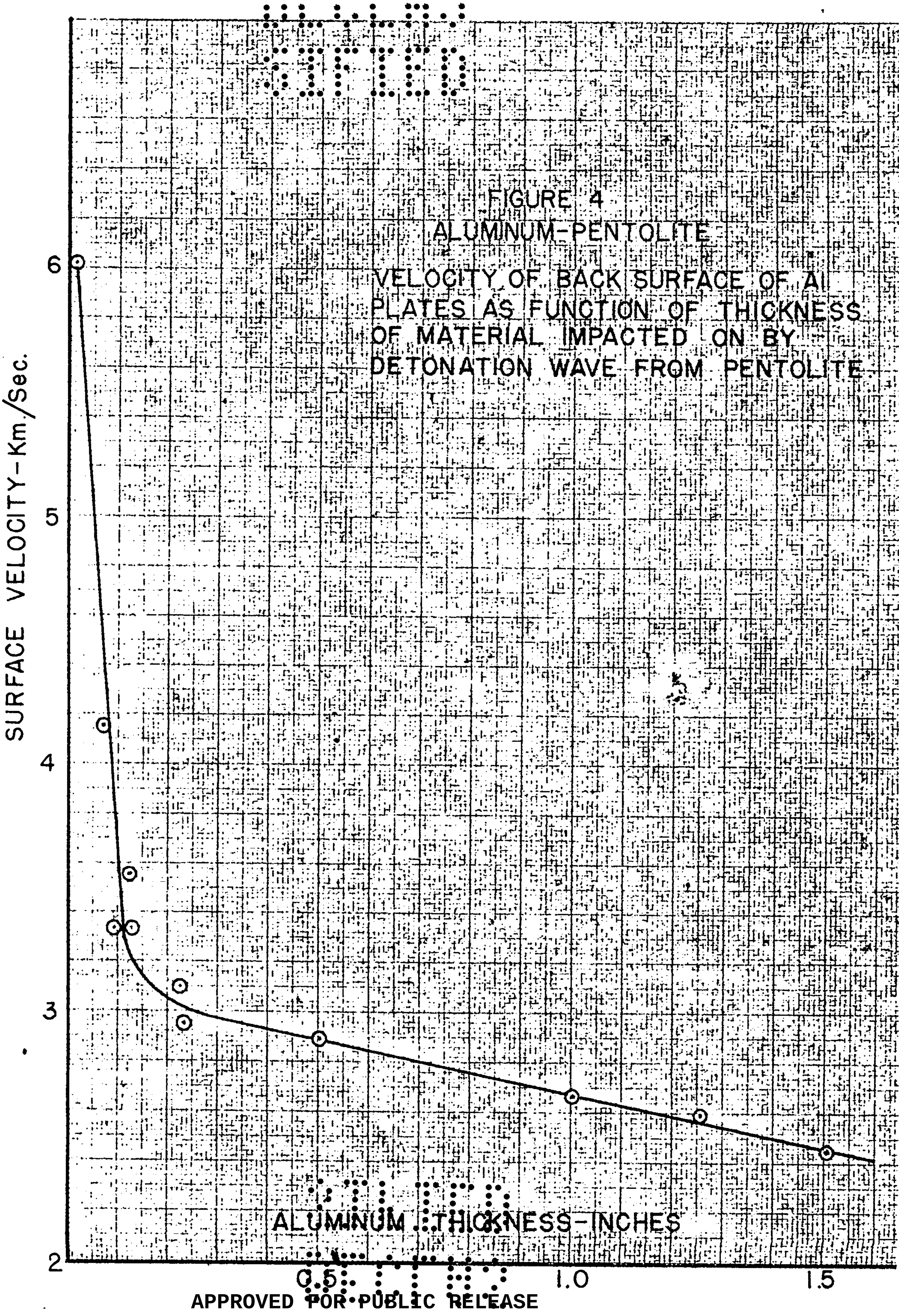

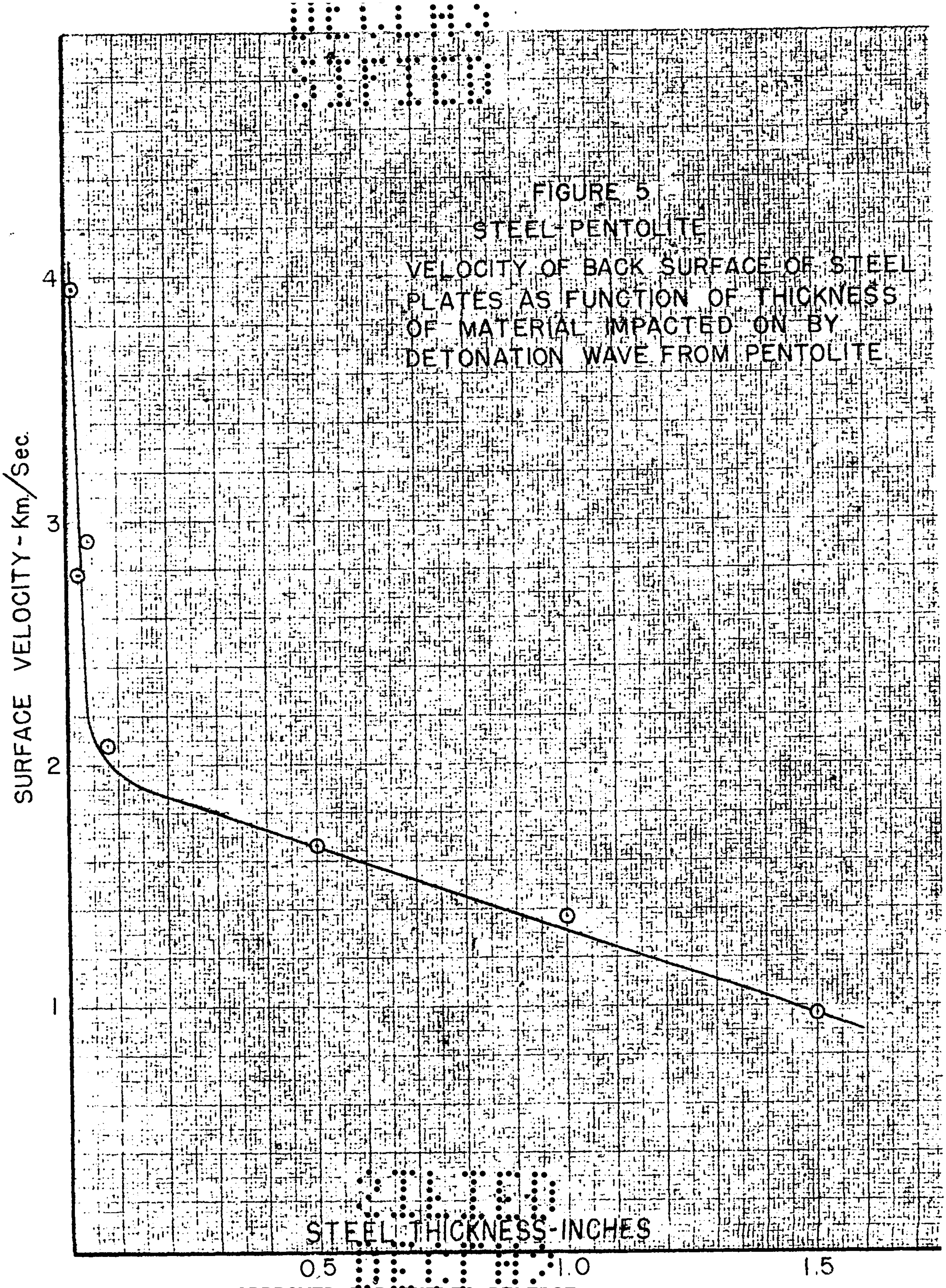
FIGURE 5
STEEL-PENTOLITE
VELOCITY OF BACK SURFACE OF STEEL PLATES AS FUNCTION OF THICKNESS OF MATERIAL IMPACTED ON BY DETONATION WAVE FROM PENTOLITE
SURFACE VELOCITY - Km./Sec.
4
3
2
1
STEEL THICKNESS-INCHES
0.5
1.0
1.5

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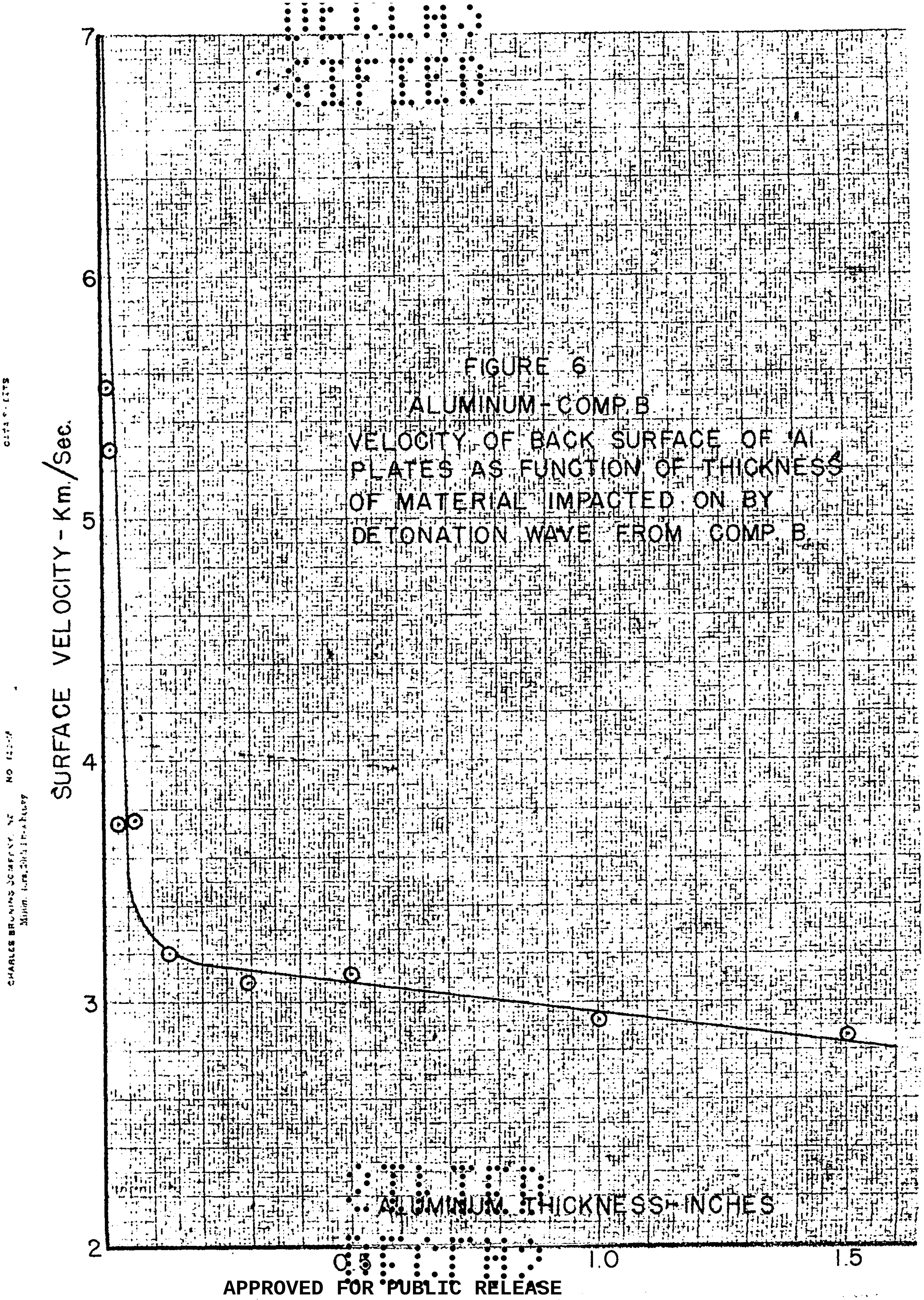

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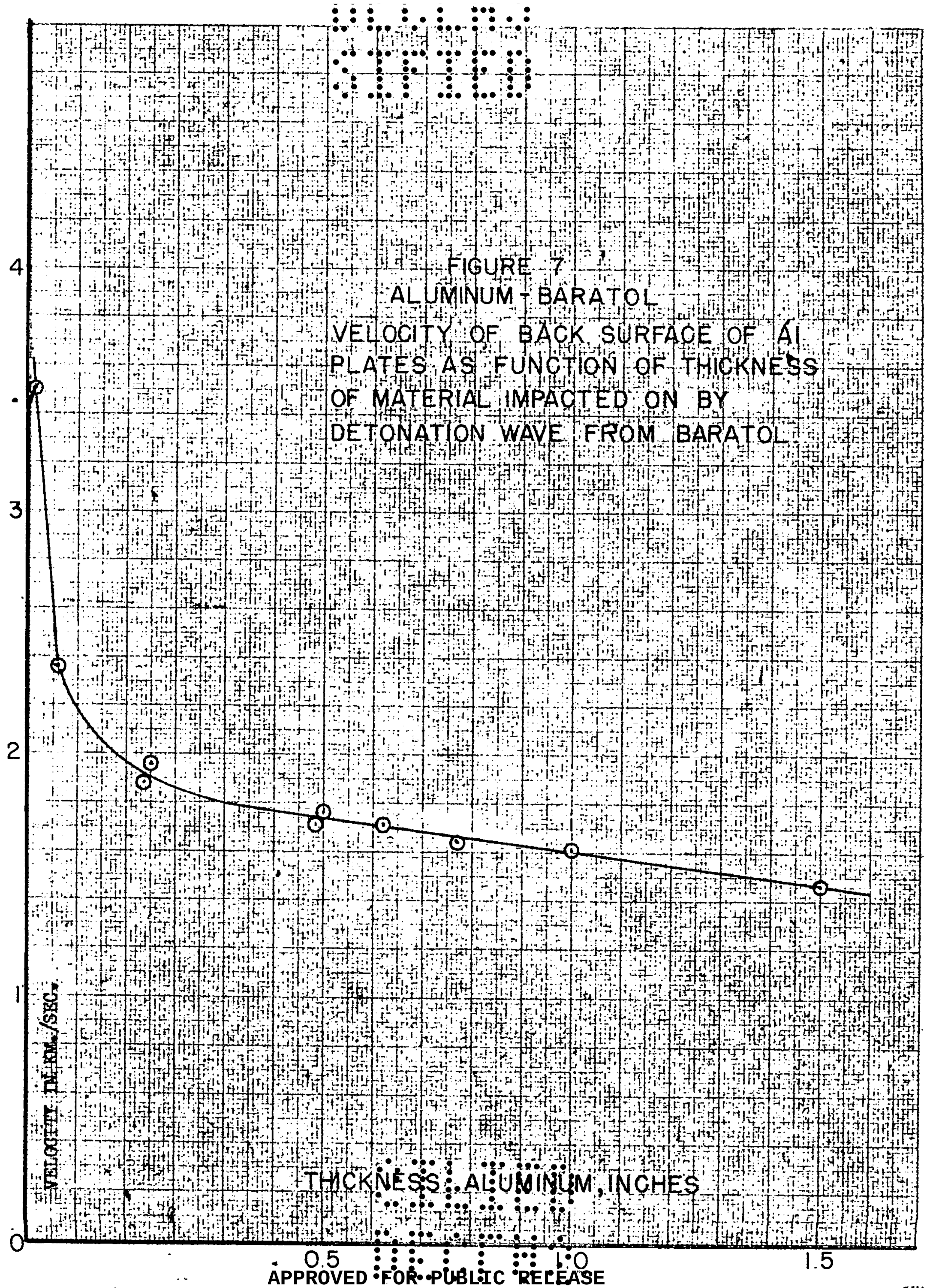


FIGURE 7
ALUMINUM - BARATOL
VELOCITY OF BACK SURFACE OF Al PLATES AS FUNCTION OF THICKNESS OF MATERIAL IMPACTED ON BY DETONATION WAVE FROM BARATOL
VELOCITY IN KM./SEC.
THICKNESS, ALUMINUM, INCHES
0
1
2
3
4
0.5
1.0
1.5

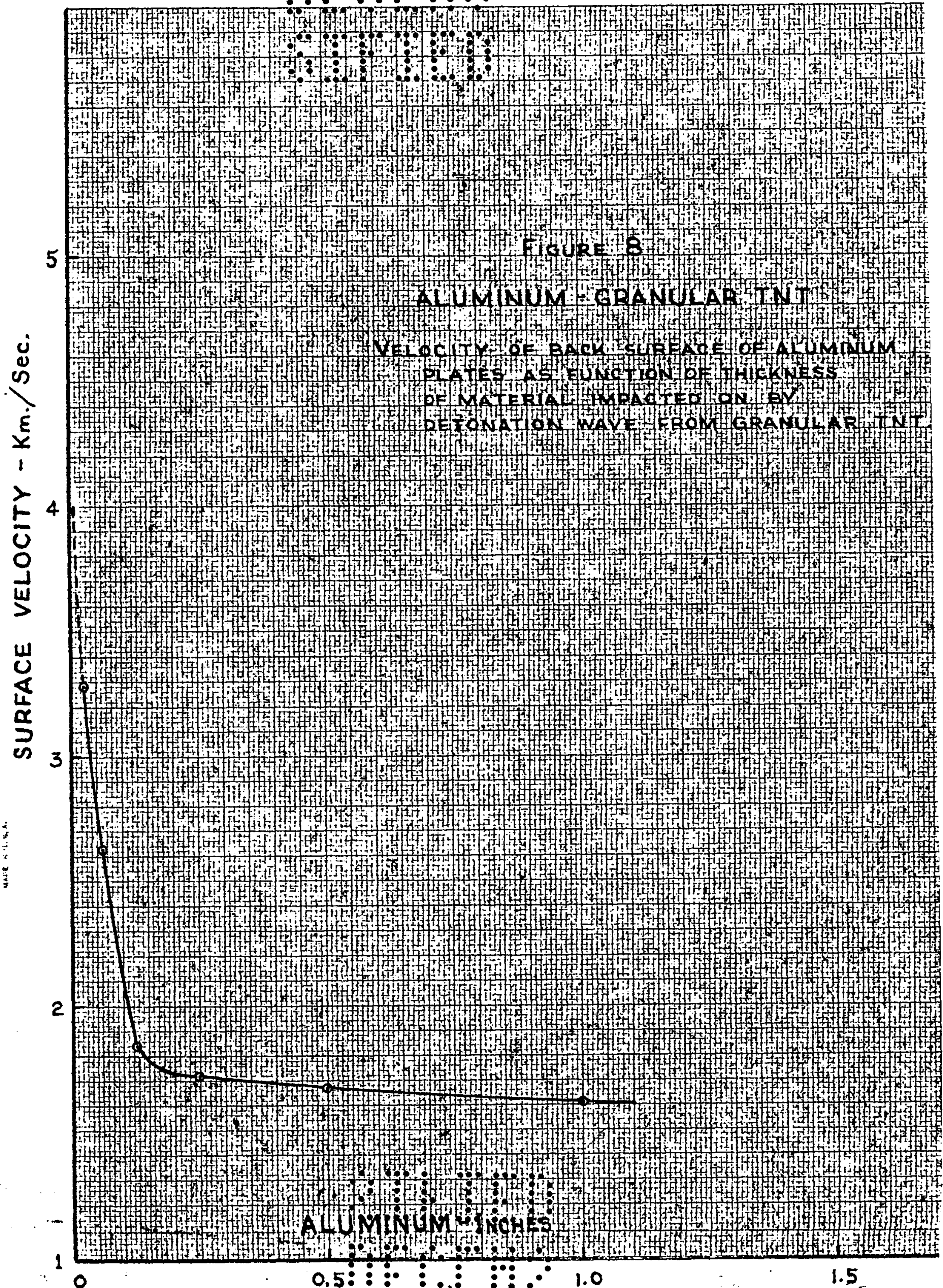
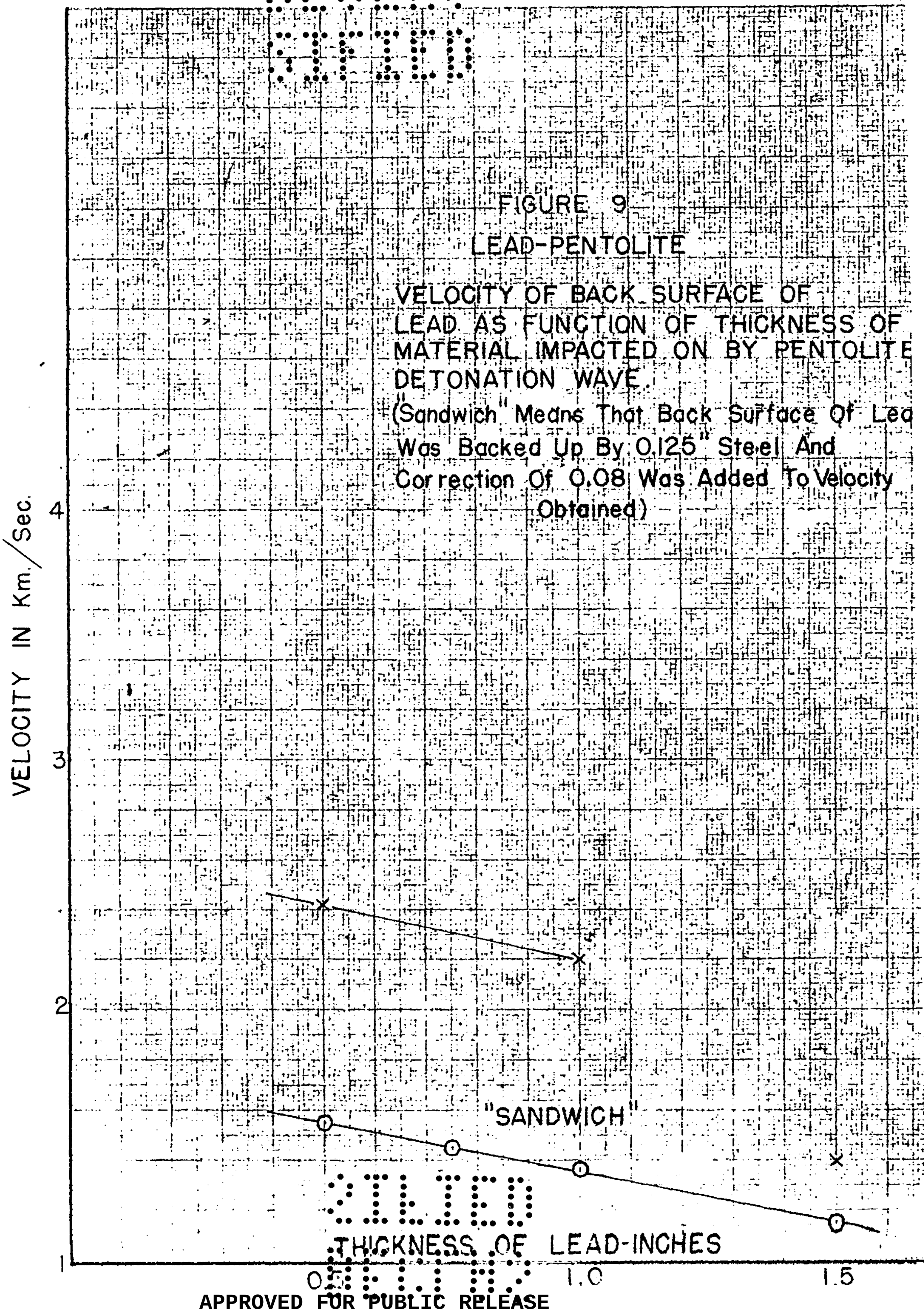


FIGURE 8
ALUMINUM - GRANULAR TNT
VELOCITY OF BACK SURFACE OF ALUMINUM PLATES AS FUNCTION OF THICKNESS OF MATERIAL IMPACTED ON BY DETONATION WAVE FROM GRANULAR TNT
SURFACE VELOCITY - Km./Sec.
ALUMINUM - INCHES
1
2
3
4
5
0
0.5
1.0
1.5



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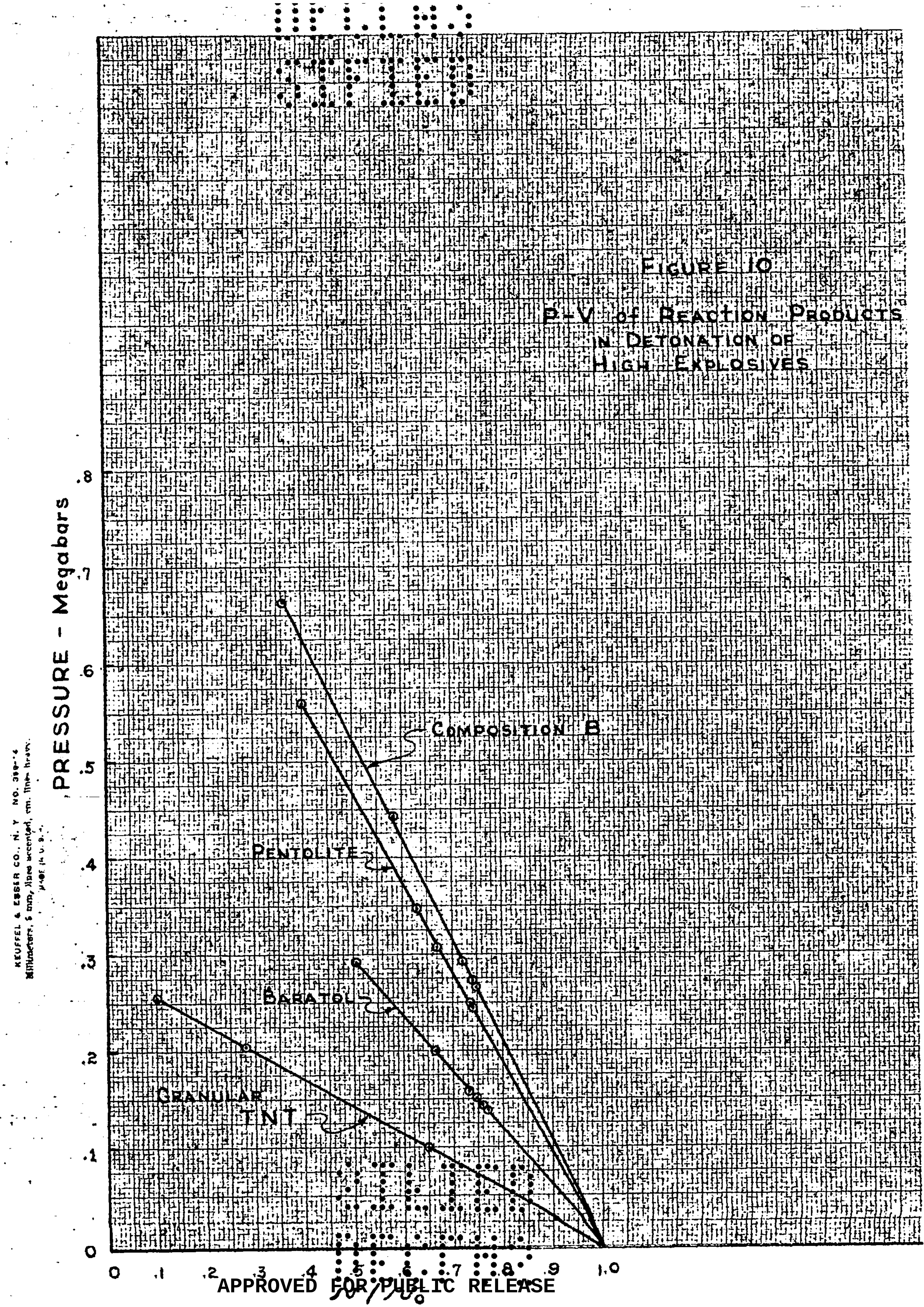
FIGURE 10
P-V of REACTION PRODUCTS
IN DETONATION OF
HIGH EXPLOSIVES
COMPOSITION B
PENTOLITE
BARATOL
GRANULAR
TNT
PRESSURE - Megabars
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
KEUFFEL & ESSER CO., N. Y. NO. 359-4

 [redacted]

APPENDIX

Measurement of Free Surface and Shock Velocity in Metals

For these measurements a technique was adapted from one previously devised[4] for obtaining deflection of plates and structures as a function of time when subjected to high explosive impacts.

This Norfolk technique consisted in arranging a series of suitably spaced probes near the back surface of the target. Each probe was connected directly to the grid of a tube and both charged to a suitable potential through a high resistance. When contact was established with the target the probe became discharged and fired the tube. The plate current flow through a resistor caused a drop in potential across the plates of the cathode ray tube. The resultant oscillograph track thus consisted of a series of steps equal to the number of probes. This was later modified by means of a transformer-type mixing circuit which gave an alternating series of short positive and negative pulses. This circuit has a high-impedence level and was made so because some of the tests involved relatively high contact resistances.

A technique very similar to this has been employed by Froman (LA-182, December 1944; LA-182A, March 1945).

For the measurements of this paper, however, a high-impedence circuit is undesirable. Furthermore the total durations of some of the recordsare less than a microsecond. Consequently time resolutions of the order of a milli-microsecond are needed.

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4). Bureau of Ships Test Memoranda and Underwater Explosion Progress Report for 1943, by R. W. Goranson.

[redacted]

 [redacted]

The measurements of surface velocity were made by arranging a series of external contactors near the back surface of the target (Fig. 11). Seven or eight contacts were set in a circle 3/8 to 1/2 inch in diameter. The points of the contactors were arranged in a double helix, so that any asymetrical variations of surface velocity across the 1/2 inch circle would result in random deviations from a smooth displacement time curve, instead of the regular deviations which might be expected if a single helix were used. The target was grounded electrically, while the contacts were charged to a potential about 45 volts by means of a battery (Fig. 12). In general 7 contacts were used, the most distant one being 2 millimeters from the surface and the closest being 0.2 millimeters.

Photographs of the pin contactor assembly appear in Fig. 13. It will be noted that each contact is insulated along its length by means of a piece of vinylite tubing. The surface of each contact was lacquered and all contacts were tested before use by immersion in water to determine whether or not the insulation was perfect. This precaution was necessary since it was found that ionized air would otherwise slowly discharch the condensers (Fig. 12) before mechanical contact was established, and no clean-cut pulse rise could then be observed. No difficulty was encountered from ionized air for velocities less than 1 km/sec but above this velocity conditions became increasingly bad until at 5 km/sec the lacquer began to fail in an erratic manner and unintelligible records were frequently obtained.

Tripping of the circuits was accomplished by means of a thin piece of insulated metal foil inserted between the target and the charge (Fig. 11). A similar piece of foil was used to record the arrival time of the shock wave at the front surface of the target. In order to record the latter on the oscilloscope, the entire 8 signals from the mixing circuit were delayed by means of a 500-foot

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piece of coaxial cable.

Shock velocity was measured in a similar manner except that the contactors were imbedded in the material and arranged such that no one of them would perturb those behind. Furthermore the front ends of the probes were separated from the target by very thin cellulose acetate films.

The circuit (Fig. 12) used in conjunction with the pin contactors was designed to satisfy the following distinct requirements:

(a) The impedance level of the contact circuit must be low, so that no signal will result from spurious electrostatic effects produced in the detonation of the high explosives and to reduce the possibility of pre-contact discharge. In other words the contacts should carry a relatively high current once the circuit through them is completed.

(b) Each contact should be capable of producing one and only one signal, regardless of whether or not the circuit remains complete after contact is established.

(c) The pulse front produced by closing each contact should be as steep as possible.

(d) The signals resulting from closing the successive contacts should be approximately of equal size and shape. This is in order to minimize systematic errors in determining the beginning of each pulse on the record.

(e) A signal of at least two volts must be delivered to the oscilloscope input. Smaller signals would require excessive amplification which would be difficult to accomplish without affecting the steepness of the pulse front.

(f) The voltage across open contact should be as low as possible in order to avoid premature breakdown of the gap before contact is established

[redacted]

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mechanically.

(g) Any apparatus to be used near the high explosive must be either rugged enough to withstand continued use, or simple enough to be produced in quantity.

In order to satisfy condition (b) it was decided to have each contact discharge a separate small condenser through a resistor, and to observe the voltage across the resistor (Fig. 14). By making the time constant RC short, a brief exponential pulse e (t) will be produced. If on the other hand the time constant R_1 C is long (several microseconds) a signal will be observed only at the initial closing of switch S.

The circuit of Fig. 14 was developed into that shown in Fig. 12, which provides for eight separate contacts, each with its own condenser. In Fig. 12 the values of R_1 and R_3 have been so chosen that the impedance as seen from the cable is about 82 ohms (the surge impedance of the cable is 75 ohms). The characteristics of the circuit are such that even with all contacts closed, there can be no appreciable reflection. When a contact is closed, a signal is delivered to the cable and proceeds to the remote end, which is practically open because of the high input impedance of the oscilloscope. The signal is then reflecte and proceeds back down the cable where it is almost perfectly absorbed. The reflection process delivers to the oscilloscope twice the signal which would be received if the input impedance of the scope were 75 ohms.

The first and last contacts which close will produce the same signals as would the circuits of Figs. 15a and 15b respectively. (Fig. 15b assumes all contacts closed). In Fig. 15a the peak value of e (t) will be about .041 E, which means that if E = 45 volts, a signal of nearly 3.7 volts would be received at the oscilloscope input. The actual peak signal will be somewhat smaller for reasons to be discussed.

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Certain defects of the circuit of Fig. 12 will be obvious from reference to Fig. 15a. In the first place the signals produced by the various contacts grow successively smaller, and what is worse they change in shape. It is reasonably obvious, however that these effects are not large, a conclusion which is supported by reference to actual oscillograms (Fig. 17). But because of this inherent defect it was felt desirable to measure all oscillograms at the initial discontinuity in slope of each pulse (estimating the position by eye as accurately as possible) in order to eliminate any errors which might result from differences in shape of successive pulses such as might occur if, for instance, the position of maximum amplitude were measured.

More important than the defect just noted are the limitations imposed on the steepness and duration of the pulse by residual inductance and capacitance. Consider for example the circuit of Fig. 16 which represents approximately the actual conditions met in practice. L_1 and C_1 are estimated to be 2.0×10^{-6} henries and 10×10^{-12} farads respectively. The duration of the pulse will be controlled by the time constant RC, which should be appreciably less than the rise time of the oscilloscope amplifier, if best results are to be obtained. Thus we must make $RC \leq 0.01 \times 10^{-6}$ seconds. On the other hand the rise time of the pulse cannot be less than (L_1/R) and this too should be of the order 0.01×10^{-6} seconds. This consideration means that $R \geq 200$ ohms. Hence $C < 50 \times 10^{-12}$ farads. Furthermore, R must introduce enough dissipation into the circuit to eliminate objectionable oscillations. If C were infinite, it would be necessary to make $R < 500$ in order to obtain more than one half critical damping. Actually since C is finite R must be appreciably smaller than this upper limit. The actual values used were $C = 30 \times 10^{-12}$ farads, and $R = 260$ ohms. These are probably not quite the optimum

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values, but they have proved adequate.

In order to obtain maximum contrast in photographing the oscillograph trace 103 - 0 spectroscopic plates were used. The schedule of operations was such that they also received a certain amount of prefogging, which increases their sensitivity. Timing intervals were obtained from a 5-megacycle sine wave oscillator constructed for this purpose. The plates were measured with a precision micrometer slide accurate to 0.01 mm. The photographic trace of a two microsecond sweep length is about 3.5 cm so that reproducibility of a milli-microsecond is possible.

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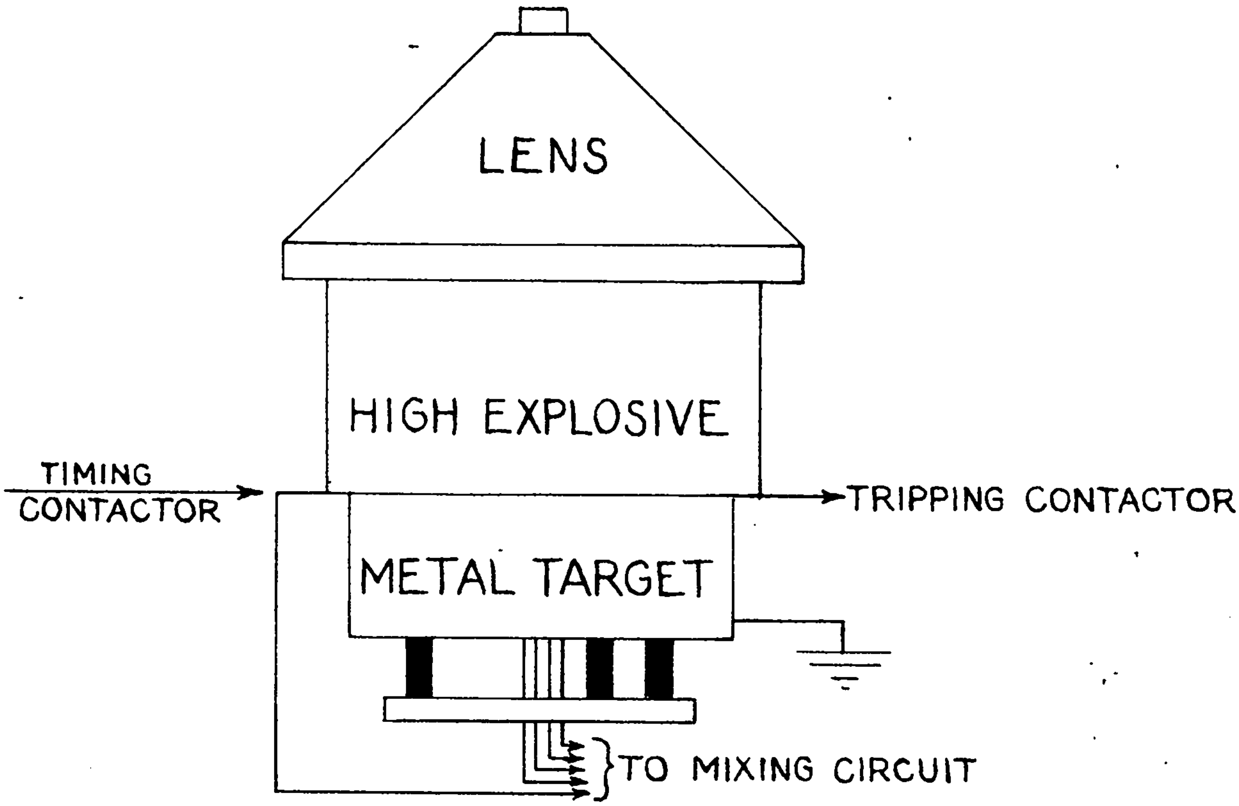

FIG. 11

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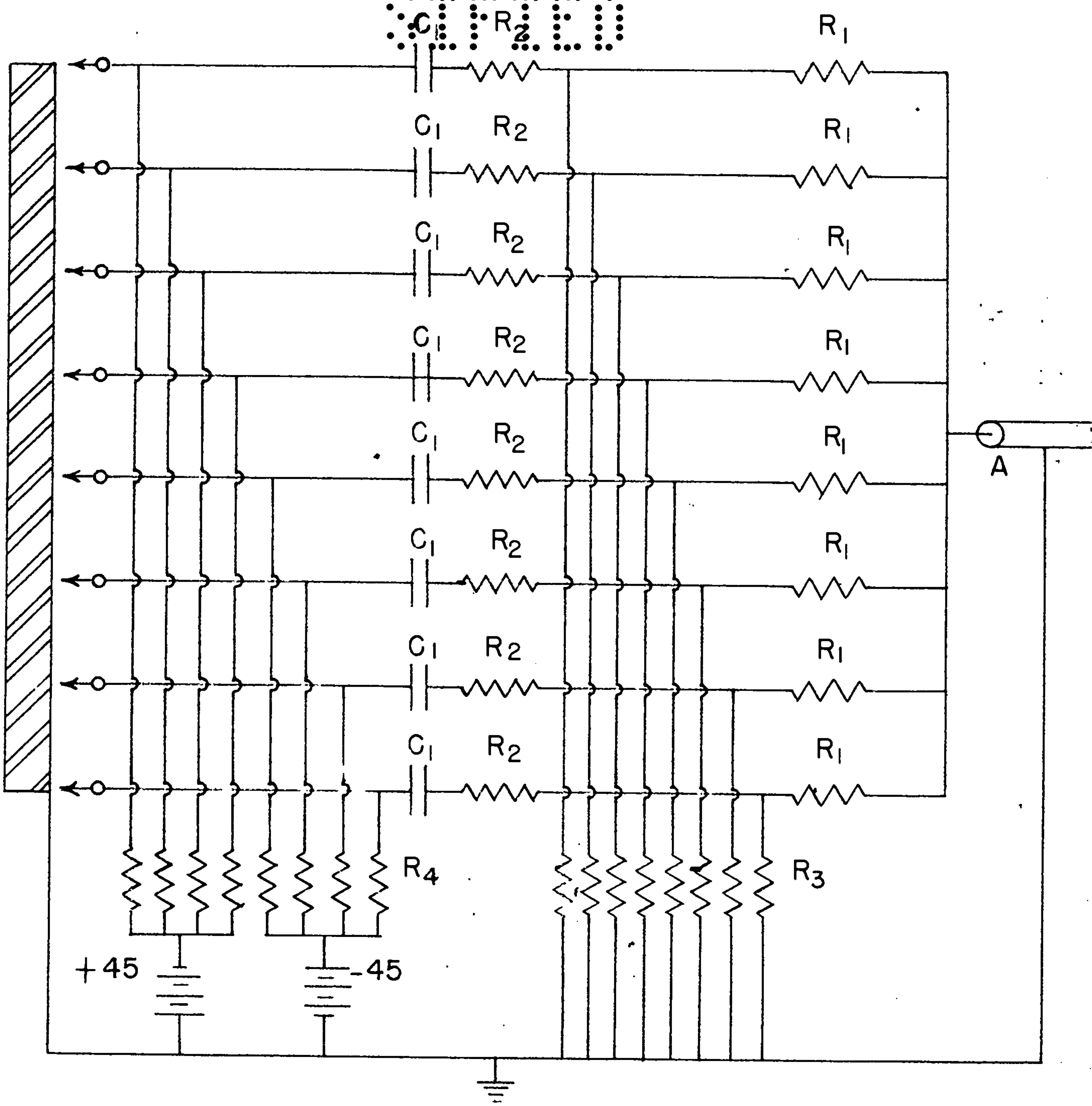

FIGURE 12

CIRCUIT USED TO PRODUCE PULSES WHEN CONTACT WITH TARGET IS ESTABLISHED

$R_1 = 330\Omega$ $R_2 = 100\Omega$

$R_3 = 330\Omega$ $R_4 = 100K\Omega$

$C_1 = 30 \mu\mu fd$

[redacted]

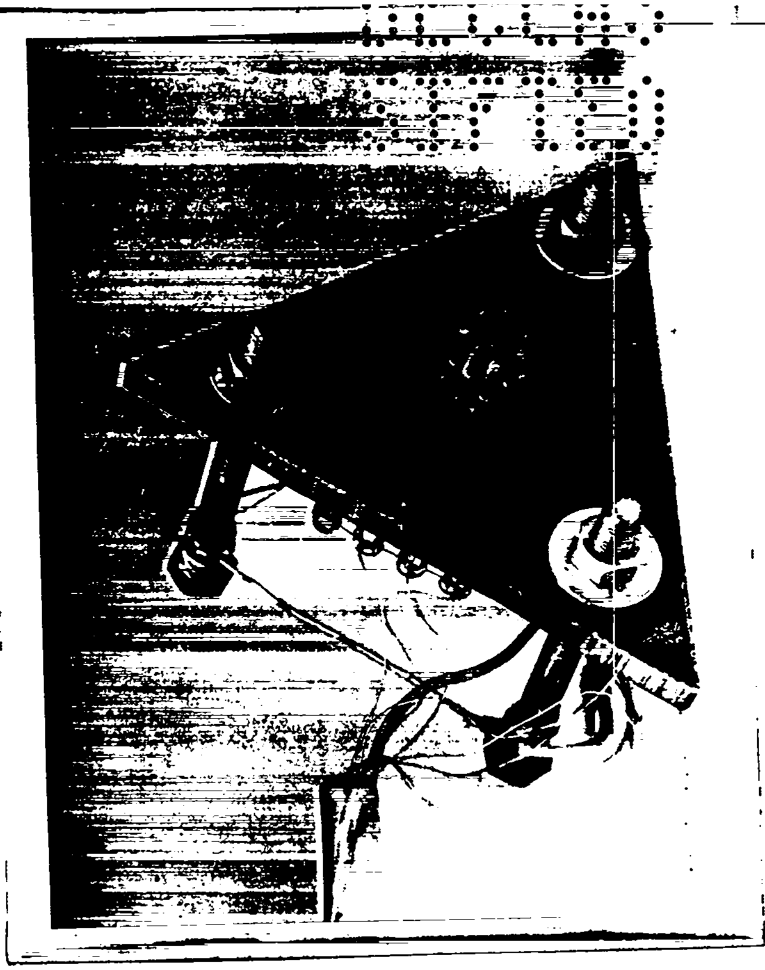

Fig. 13a.

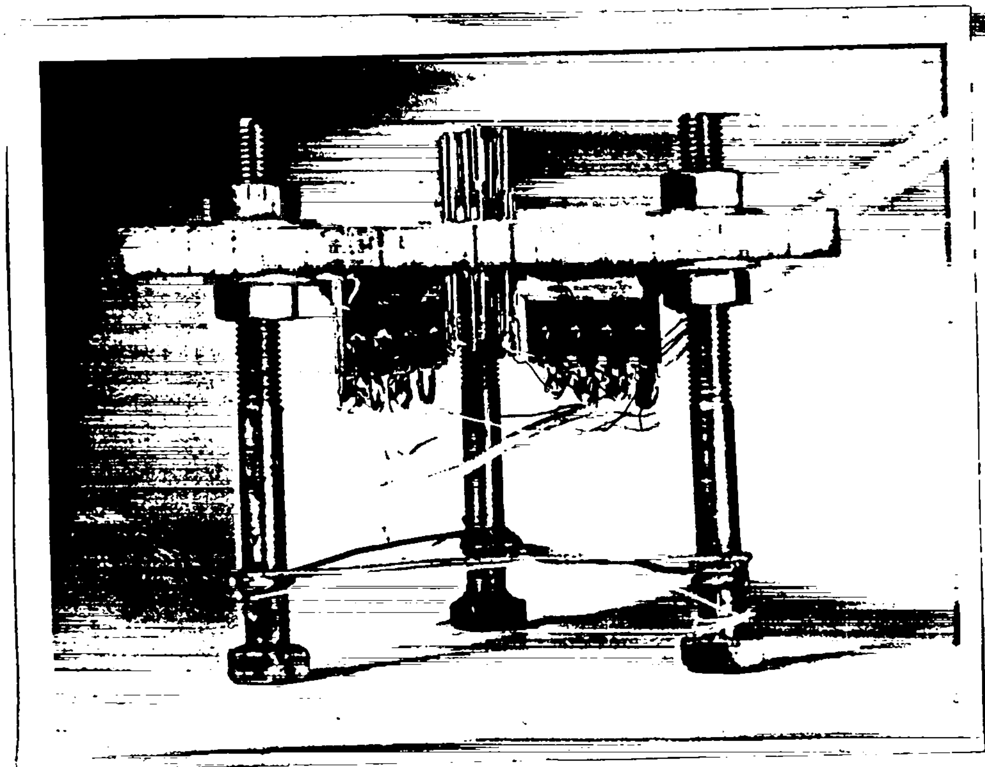

Fig. 13b

Assembly of the pin contactors. The upper ends of the cap screws are lapped smooth. The leads are about 18" long.

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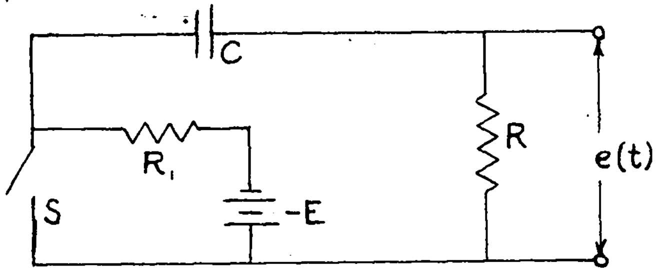

FIG. 14

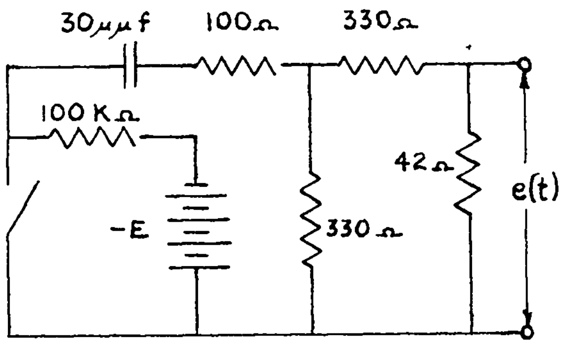

FIG. 15a

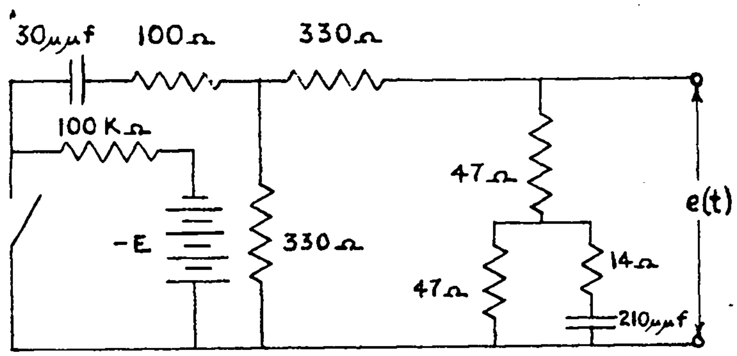

FIG. 15b

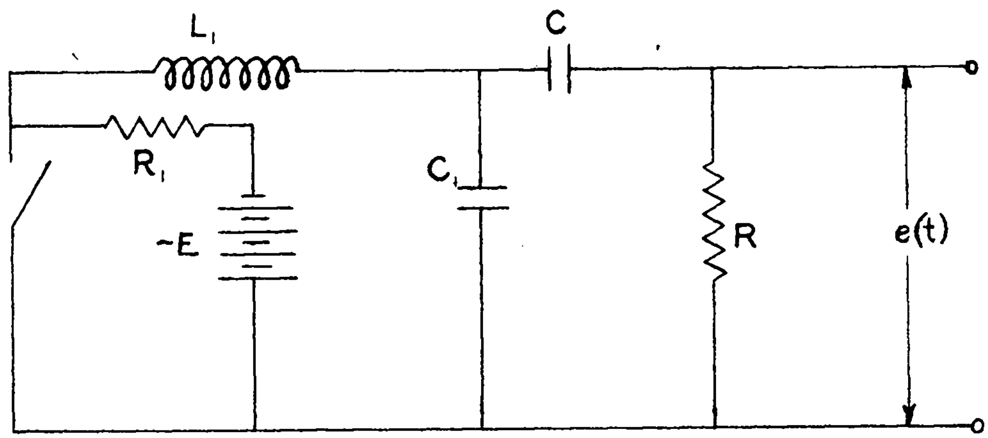

FIG. 16

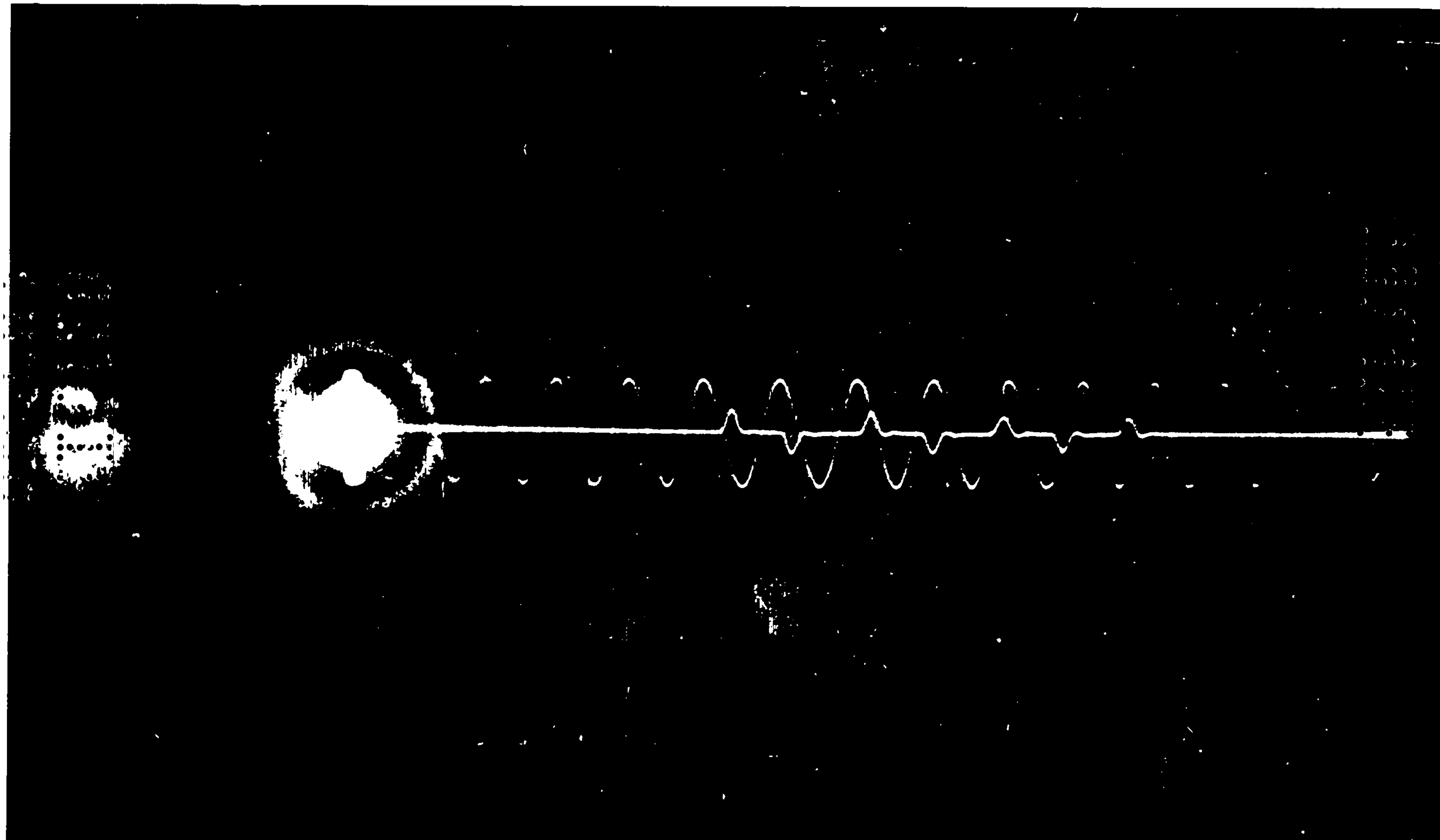

Fig. 17. Enlarged photograph of typical oscillogram trace from a half-inch aluminum target. Total duration of sweep is two microseconds. A five-megacycle sine wave is superimposed on the trace for calibration of time intervals.

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