UNCLASSIFIED

UNCLASSIFIED

CLASSIFICATION CANCELLED
Per DOC
By Jack L. Hite
1-16-73

[redacted]

384

[redacted]

C.3

[redacted]

[redacted]

VERIFIED UNCLASSIFIED
6-11-79 EMS
7-14-80 LMR

SPECIAL RE-REVIEW
FINAL DETERMINATION
UNCLASSIFIED, DATE: 7-14-80

[redacted]

UNCLASSIFIED

UNCLASSIFIED

[redacted]

UNCLASSIFIED

CLASSIFICATION CANCELLED
Per Doc
By [illegible] 1-16-73

LA-384

[redacted]

September 12, 1945 This document contains 32 pages

PRESSURE, COMPRESSION, SHOCK AND PARTICLE-VELOCITY MEASUREMENTS IN THE NEIGHBORHOOD OF ONE-THIRD MEGABAR

PROGRESS REPORT TO AUGUST 15, 1945

WORK DONE BY:	REPORT WRITTEN BY:
S. W. Bale	R. W. Goranson
D. Bancroft	
[illegible] Brockmeyer	
R. W. Goranson	
R. Hirt	
[illegible] Houston	
[illegible] Pierson	
G. Waters	
D. Whyte	

VERIFIED UNCLASSIFIED
Per EMS 6-11-79
By LKolar 5-24-96

PUBLICLY RELEASABLE
Per EMSandoval FSS-16 Date: 8-2-91
By LKolar, CIC-14 Date: 5-24-96

~~to an unauthorized person is prohibited by law.~~

UNCLASSIFIED

[redacted]

UNCLASSIFIED

[redacted]

ABSTRACT

Measurements have been made of pressure, particle velocity, and shock velocity in tuballoy, steel, aluminum, and cadmium under impact by H.E. detonation waves. From these data pressure-volume relations are obtained in the region of 0.2 to 0.4 megabars. The work is continuing on these materials and on others such as beryllium, lead, carboloy. Related quantities for the elastic wave in steel have also been measured. In addition information has been obtained on the shape and pressure of the detonation wave in pentolite. This study will be extended to other explosives such as composition B and baratol.

[redacted]

UNCLASSIFIED

[redacted]

PRESSURE, COMPRESSION, SHOCK AND PARTICLE-VELOCITY MEASUREMENTS IN THE NEIGHBORHOOD OF ONE-THIRD MEGABAR

PROGRESS REPORT TO AUGUST 15, 1945

INTRODUCTION

On the recommendation of personnel of the theoretical groups, experimental work was initiated for the study of physical properties of materials in the pressure range from 0.1 to 1 megabar (10^{12} dynes/cm^2). 0.2 megabars has been attained statically at the Geophysical Laboratory but it is impracticable to do this here because of the elaborate and cumbersome apparatus required and because the measurements are subject to uncertainties resulting from creep distortion. The logical extension, and one particularly suited to the data here desired, is to make the measurements dynamically thereby eliminating the need for elaborate pressure apparatus and inherent creep uncertainties.

An opportunity for developing and testing techniques and methods suitable for this kind of work was afforded by the Bureau of Ships in setting up its experimental program of underwater explosion damage studies in 1942 and 1943.

Four parameters with which we are concerned are the pressure p, compression $-\Delta v/v_0$ the zero subscript referring to the initial state, mass or particle velocity u, and shock velocity D. These quantities are interrelated by the two expressions

$$-\frac{\Delta v}{v_0} = \frac{u}{D}$$

$$P = \rho_0 uD$$

[redacted]

UNCLASSIFIED

UNCLASSIFIED

[redacted]

where ρ_0 is the initial density of the material. These two expressions may be derived readily from the assumptions of conservation of mass and of momentum. Thus only two of these four quantities need be measured. It is also desirable to evaluate the temperature in the shock wave and the drop in temperature due to adiabatic expansion in order to aid in correlating the Rankine-Hugoniot relations with isentropic pressure-volume relations.

Furthermore, in some substances the elastic or ordinary sound wave travels faster than the main shock wave even at pressures of the order of 300 kilobars. For such material it is desirable to evaluate equivalent relations for this compressional wave. The dynamic yield point is known to be higher than its static value but so far no accurate measures of these ratios have been available.

The values of sound velocity ordinarily given in handbooks are for specimens wherein the lateral dimensions are small compared with the longitudinal direction along which the wave is moving, and are thus related to "bar velocity" which is $V_L = \sqrt{E/\rho}$, E denoting Young's Modulus. The values desired here are those for an "infinite medium" which, for an isotropic substance, are given by $C_0 = \sqrt{C_{11}/\rho}$, C_{11} denoting one of the two elastic constants. The ratio C_0/V_L is given by $\left[(1 - \sigma)/(1 - 2\sigma)(1 + \sigma)\right]^{1/2}$ where σ is Poisson's ratio. For $\sigma = 0.27$ this ratio is 1.12.

As the amplitude of the shock is increased it eventually exceeds the elastic limit of the material and two shock fronts are observed: the elastic front moving with velocity $C_0 = \sqrt{\left[K + (4/3)R\right]/\rho}$, K being the bulk modulus and R the modulus of rigidity, and with amplitude equal to the "dynamic yield point"; the other or main shock front moving with velocity $D = v_0\sqrt{-\Delta p/\Delta v}$. D is

[redacted]

[redacted]

initially less than C_0 but eventually overtakes C_0 as the amplitude of the shock continues to increase. For the pressures herein investigated only one front was observed in the case of aluminum, cadmium, tuballoy, and lead, whereas two shock fronts were still observable in steel and carboloy.

It was originally planned to use the impact from a gun projectile to initiate the shock wave in the target. The reasons were (1) that shocks between 0.1 and 0.5 megabars could be expected and (2) that the wave would be flat topped and could be made of sufficient duration that no degradation in pressure would occur as it proceeded into the target. Simultaneous measurements made of mass velocity from projectile velocity, shock velocity and pressure would thus yield a unique point on the pressure-volume curve together with a check on the consistency of the data.

A 6"/47 smooth-bore gun was supplied but the sealing bands on the projectiles designed for us did not function satisfactorily. Leakage of gases past the projectile tripped the electronic circuits prematurely. It is not difficult to design adequate seals and several such designs were submitted to members of the ordnance group. Pending their decision on which to use work was begun with H.E. using lenses to obtain plane waves in conjunction with flat discs of pentolite. Pentolite was used because it could be obtained easily and quickly. PTX - 2 was considered more desirable but the cakes of this material supplied to us had surfaces which were too irregular and too wedge-shaped to be of use. The data presented herein were all obtained in this manner.

The shock wave in the target resulting from impact by the detonation wave in the explosive is not fl~~at topped, the shock front~~ being followed immediately

[redacted]

[redacted]

by a decay which is more or less exponential in form. This unloading wave, moving more rapidly than the shock front, is continually whittling down the peak pressure. In consequence it is necessary to measure the parameters as a function of thickness of the material. In addition repeat measurements are necessary to reduce uncertainties arising from unavoidable statistical fluctuations.

Pressure is determined by means of probes made from X-cut tourmaline discs. The calibration constant of the crystals, for the geometry and conditions of these tests, was determined from measurements of u and D in steel. It is advantageous to make these crystals thin. Ours are thicker, about 0.5 mm, than desired but this choice was dictated by practical considerations of existant constructional limitations. Several reverberations are required for equilibrium to be attained between target and crystal and therefore a useful crystal life of about 0.5 μsec is required. If the crystal becomes shorted before this time a correction factor must be applied for the acoustic mismatch of crystal and target. This factor can be expressed very closely by $2\left[1 + (\rho_2 D_2/\rho_1 D_1)\right]^{-1}$ subscripts 1 and 2 referring to crystal and target, respectively.

Oscillograph records of elastic and shock waves through steel are shown in Fig. 1.

Shock velocity is determined from (a) the transit time between two crystal plates, (b) the transit time between a series of electrical contactors set into the target, and (c) from the arrival times of the shock wave at the front and back surfaces of the targets by means of externally placed electrical contactors. The last method is not as accurate as the first two and is used therefore only as a rough check measurement. The first method may be illustrated by the two crystal records of Fig. 1. The second method is illustrated by

[redacted]

oscillograph records and a plot of the data obtained therefrom in Figs. 2 and 3 respectively, made on an aluminum plate.

Particle or mass velocity of the material was ascertained by means of externally placed electrical contactors. The measure obtained is that of the free surface velocity and hence of $u + \omega$ where $\omega = \int c\,d\rho/\rho$, c being the sound velocity and given by $\sqrt{(\partial p/\partial \rho)_{S_2}}$. At a free surface the pressure wave is reflected back into the material as an equivalent tension wave. The unloading expansion occurs along an isentropic S_2 which is different from that of the original entropy state. For weak shocks the difference is negligible but for very strong shocks S_2 may lie in the liquidus or even gaseous region. In consequence $u + \omega$ may become much larger than the ordinarily assumed approximation $2u$.

It is essential to complete the measurements of this motion before reverberations can occur in the target plate. Otherwise one obtains a measure not of u but of the momentum transfer from explosive to target. In consequence, for our measurements, about eight contactors are spaced in an interval not more than 2 or 3 mm distant from the back surface of the plate. For the very thin plates even closer spacing is desired and time resolutions are being sharpened so that these measurements can be completed in the first millimeter of motion. The positions of the contactor points are measured to 10^{-4} cm and are coated with a non-conductor to prevent pre-contact conduction by ionized gases. Time resolution obtained in these records is reproducible to about a millimicrosecond.

An oscillograph record obtained from a 1.25-inch cadmium plate is shown in Fig. 4. A plot of the data obtained from this plate is given in Fig. 5.

In design and construction of the targets it is necessary to take

[redacted]

into consideration the fact that the wave from the lenses is not flat but slightly convex. Each probe must also be placed in the target such that it lies in a conical region unperturbed by rarefaction waves from the sides of the target and from the other probes. Calculated angles were verified empirically for steel targets.

[redacted]

DAT [redacted]

A. The data on physical properties of materials are tabulated for aluminum, cadmium, steel and tuballoy, as follows:

(1) Surface velocity as a function of thickness of material through which the shock wave has traveled. The values in general represent the mean of several tests in which case mean square deviations are listed. These deviations are not necessarily errors of measurement but include also statistical fluctuations such as might arise from variations in the plane wave lenses, in the pentolite cakes (as nonparallelism of surfaces, imperfect surfaces), in variable distortion of photographic emulsions, in possible damage to targets during transportation. Two and sometimes three oscillographic records are obtained in each test. A least square value of slope is obtained from each record (see Figs. 4, 5).

A plot of surface velocity as a function of thickness for aluminum is given in Fig. 7.

If the elastic wave is observable similar records are obtained for it.

(2) Mean values of the shock velocity over the thickness interval indicated. In general the change in shock velocity over the thickness range here investigated is so small that no serious attempt has yet been made to measure its variation, with the exception of aluminum for which the effect should be most marked. These values have been obtained in the various ways just described (see Figs. 1, 2, 3).

The observed velocity of the elastic wave for steel is listed. It is not known whether the differences indicated for cold rolled (1020) and SAE 4340 have a real significance.

(3) <u>Pressure in the shock wave</u> (and the elastic wave for steel) at one or more points.

[redacted]

[redacted]

(i) as computed from u an

(ii) as measured with the crystal probes using steel as a calibration medium (see Fig. 1).

The computed values (i) will tend to be slightly high at 1.25" and low at 0.25" owing to the fact that the value of D used will correspond to a somewhat higher pressure for the first and lower for the second.

(4) Pressure versus compression.

In addition to the tabulations a plot of these relations is also given in Fig. 6.

B. Explosives

Some of these data may be utilized in studying detonation of explosives, as illustrated by Fig. 7. In this figure free surface velocity of aluminum is plotted as a function of thickness of material through which the shock wave has traversed. The very high peak in the detonation front, about 610 kilobars (kb) in aluminum and corresponding to 470 kb in pentolite, is extremely narrow since it has been completely degraded in moving through a quarter inch of aluminum. The relatively slow decay in the remainder of the shock wave is illustrated by the marked discontinuity in slope. The pressure at 0.25" is about 292 kb, corresponding to an H.E. pressure of 224 kb. The latter figure is the peak pressure one would calculate for the detonation wave assuming the ratio of heat capacities to be three. This is the value ordinarily assumed as peak pressure in the detonation wave since the high narrow peak is not usually observed.

It would seem probable also that this high narrow front could account for certain abnormal spall effects which have been observed in thin plates.

[redacted]

[redacted]

ALUMINUM

Free-Surface Velocity

Thickness 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

$y = 7.165 - 2.294\,x$

y: thickness inches

x: velocity, km/sec.

Shock Wave Velocity

Mean value through 1.25 inches: 7.40 km/sec

Weighted means of three tests (see Fig. 3):

(i) Initial	7.48 ± .17
(ii) At 10 mm thickness	7.385 ± .052
(iii) At 20 mm thickness	7.29 ± .11

Mean value through 25 mm path 7.41

Shock Pressure

Through 0.25" material	From velocities P = 287 kilobars From crystals P = 267 "
Through 1.25" material	From velocities P = 255 " From crystals P = 223 "

[redacted]

[redacted]

ALUMINUM (continued)

Compression

Pressure kilobars	$-\Delta V/V_0$		
	Observed	Theoretical (LA-208)	Theoretical (correcte (LA-385)
(244)	(.167)		
255	.174	.207	.188
(265)	.181		.193
287	.193	.222	.204
(338)	.22		.224

[redacted]

[redacted]

CADMIUM

Free-Surface Velocity

Thickness inches	No. of Observ.	km/sec
1.25	(3)	1.45

Shock Wave Velocity

Mean value through 1.25": 3.96 km/sec

Shock Pressure

Through 1.25" material

From velocities P = 248 kilobars

From crystals P = 231 "

Compression

Pressure kilobars	$-\Delta V/V_0$		
	Observed	Theoretical (LA-208)	Theoretical Corrected (LA-385)
250	.183	.235	.213

[redacted]

[redacted]

STEEL

Free Surface Velocity

(A) SHOCK WAVE

Thickness inches	No. of Observ.	Mean obs. vel. km/sec
2.0	(3)	0.65
1.5	(5)	0.964 ± .045
1.0	(16)	1.376 ± .022
0.5	(7)	1.628 ± .031
0.5		1.668

y = 2.962 - 1.483 x

y = thickness inches
x = velocity, km/sec

(B) ELASTIC WAVE

0.0667

Shock Velocity

Mean value through 1.25" material:

SAE 1020 steel 5.09 km/sec
SAE 4340 HT " 5.10 "

Sound Velocity

SAE 1020 steel 5.85 "
SAE 4340 HT " 5.92 "

Elastic Pressure

From velocities P = 15 kilobars

From crystals P = 15.7 "

[redacted]

[redacted]

STEEL (continued)

Shock Pressure

Through 0.25" material	From velocities	P = 332 kilobars
	From crystals	P = 324 "
Through 1.25" material	From velocities	P = 223 "
	From crystals	(calibration point)

Compression

Pressure kilobars	$-\Delta V/V_0$		
	Observed	Theoretical (LA-208)	Theoretical (Correcte (LA-385)
(130)	(0.064)		
(193)	(0.094)		
223	0.109	0.096	0.091
330	0.163	0.125	0.120

[redacted]

UNCLASSIFIED

[redacted]

TUBALLOY

Free Surface Velocity

Thickness inches	No. of Observ.	Mean obs. vel. km/sec
1.5	(3)	0.839
1.0	(8)	0.950 ± .01
0.5	(8)	0.14 ± .02

Shock Wave Velocity

Mean value through 1.25" material (8 observ.) : 3.37 ± .02 km/sec

Shock Pressure

Through 0.25" material	From velocities	P = 354 kilobars
	From crystals	P = 347 "
Through 1.25" material	From velocities	P = 280 "
	From crystals	P = 289 "

Compression

Pressure kilobars	$-\Delta V/V_0$		
	Observed	Theoretical (LA-208)	Theoretical Corrected (LA-385)
(268)	(.129)		
280	.135	.164	--
355	.169	.194	.187

[redacted]

UNCLASSIFIED

APPENDIX: TECHNIQUES 1)

Crystal Probes and their Associated Circuits. Thin z-cut circular discs made from tourmaline crystals are used in measuring the pressure amplitude in the shock wave. Velocity of this motion is also obtained from the transit times between two crystals placed one in front of the other and offset so that the one in front does not perturb the one in back.

The amplitude of the shock is given by $p = Q/KA$ where Q is the charge developed, K the "calibration constant" and A the area of the plate.

The effective area A is somewhat uncertain because of perturbations from the insulated region. In consequence the value KA was obtained from steel targets under conditions identical with those for the other targets.

The basic circuit used in conjunction with the tourmaline crystals is given in Fig. 9.

It may be shown that if R_1 is made equal to the surge impedanse R_o of the cable and that if $C_1 = 2/Rv_o$, where R is the cable resistance per unit length and v_o the velocity of propagation, then reflections are virtually eliminated at the receiving end of the line. Indeed the value of C_1 for short lengths of cable is not at all critical, and may very by a factor of 5 from the computed value without serious effect. It may be shown further that if $R_2C_2 = R_1C_1$, then an e.m.f. placed in series with C_2 will be received with negligible distortion at the oscilloscope.

---

1) The design and utilization of these piezoelectric crystal and electric contactor circuits were developed elsewhere and described in various Bureau of Ships memoranda (1942-44) and in Progress Report for 1942-43 on Underwater Explosion Tests. The modifications made necessary for this work have been concerned primarily with increasing the time resolution.

[redacted]

The analysis upon which the above circuit is based was tested empirically as shown in Fig. 10. The crystal capacity is neglected in this test which is justifiable, since the crystal capacity C_3 is less than .0005 x 10^{-6} farads whereas C_2 is about .05 x 10^{-6}. S is a mercury switch, which provides rapid and reliable completion of the circuit. C_4 and T furnish an auxiliary pulse to start the sweep. The line to the sweep circuit trip must be shorter than the main transmission line in order that the signal will not arrive at the oscilloscope until the time base is well under way. The square voltage step thus produced at S appears on the oscilloscope with a rise time of about 0.05 µs or less. The general appearance of the transmitted step is shown in Fig. 11. The discrepancy noticed at A in the above sketch can be compensated by shunting R_2 with a small condenser and resistor in series. This refinement was not deemed necessary, however, in practice.

The basic circuit of Fig. 9 was modified to that shown in Fig. 12. The latter provides means for attenuating the signal received and in addition includes a device for calibrating the crystal circuit. This is obtained by impressing a known charge Q_0 upon the system. The attenuator and calibrator switches are ganged together so that the attenuation and calibration are automatically adjusted by merely setting to the charge anticipated.

Velocity measurements. Measurements are also obtained from transit times between a series of appropriately spaced contactors. In this manner surface velocities have been obtained from externally placed contactors and shock velocities from internally placed contactors. Two circuits have been constructed each of which can handle eight probes.

[redacted]

[redacted]

The eight external contactors used to measure the velocity of the back surface of the target were set in a circle one-half inch in diameter. The points of the contactors were so arranged that they lay on a double helix; in this way any assymetrical variation of surface velocity across the half-inch circle would result in random variations 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 each contactor was charged to a potential of about 45 volts by means of a battery. Target and contactors were connected by leads about 18" in length to a massive steel cylinder, which housed the electrical equipment necessary to produce the desired signals and which could be buried near the target. The circuit used appears in Fig. 13. It will be evident upon examination of this diagram that, when any contact is closed, a small pulse of brief duration will be impressed on the coaxial cable. It will also be noted that the mixing network is so designed as to terminate the cable approximately in its surge impedance of about 75 ohms.

Different combinations (A and B) of resistances and capacities were used:

	A	B
R_1	330 Ω	470 Ω
R_2	100 Ω	0
R_3	330 Ω	150 Ω
R_4	100 K Ω	100 K Ω
C_1	30 uufd	100 uufd

[redacted]

[redacted]

The steepness of the pulse is limited by the rise time of the scope amplifier and by the stray shunt capacitances and inductances between the contactor circuits. The latter is being eliminated by a somewhat different circuit arrangement now being investigated. Some progress has also been made in decreasing the rise time of the amplifiers supplied to us.

Design of Crystal Probes

Assembly details of the crystal probes within the target are shown in Figs. 14 and 15. In Fig. 14 the crystal plate (C), together with an anvil (A) in contact with its rear surface, are first installed in the cylinder (S). A and S are of the same material as the target. Cylinder T and disc W of Fig. 15 are of bakelite. T is used to insure that A is centered in S prior to insertion of insulation. The anvil is insulated from the cylinder by a mixture of finely ground aluminum oxide and a silicon resin. This mixture is forced into the annular cavity between A and S under pressure. All parts are very carefully fitted and assembled. After assembly the end of the cylinder and crystal are lapped smooth before being pressed into firm contact with the target. The target and cylinder are connected to the outer conductor (shield) of a coaxial cable. The anvil is connected to the inner conductor of the cable via a resistance-capacity network as described elsewhere.

[redacted]

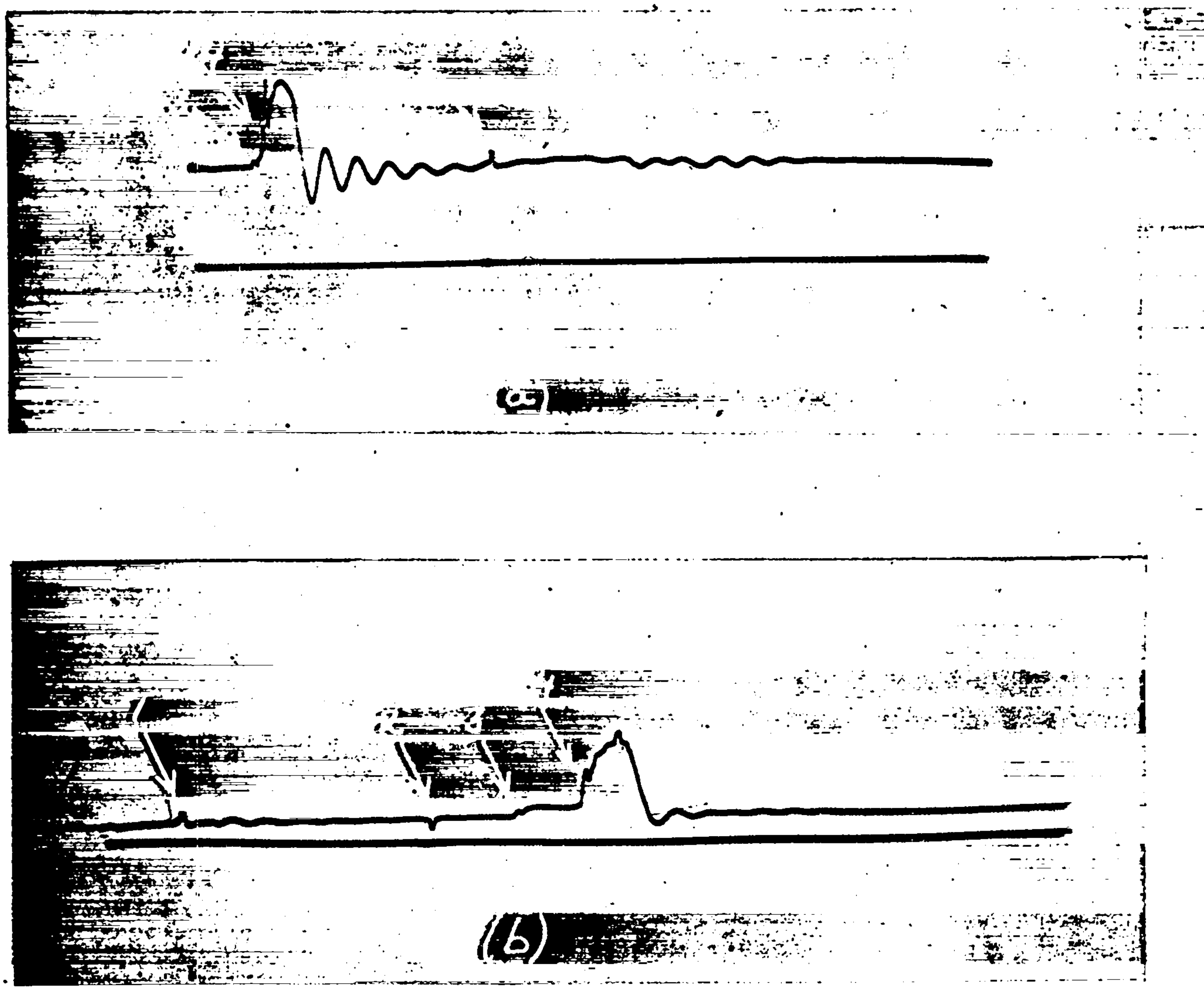

Fig. 1. Oscillograph records of shock-wave profile after moving through (a) 0.25" (b) 1.25" of SAE 4340 steel. (1) is cross talk from (a); (2) is the synchronizing time pip for the two records; (3) is the elastic-wave front; and (4) is the main shock front. Total sweep length is 10 microseconds. Elastic pressure is 15.7 kb; peak shock pressure in (b) is 225 kb; elastic velocity is 5.85 km/sec; and shock velocity is 5.10 km/sec. (Oscillations in shock front are reverberations in crystal probes.)

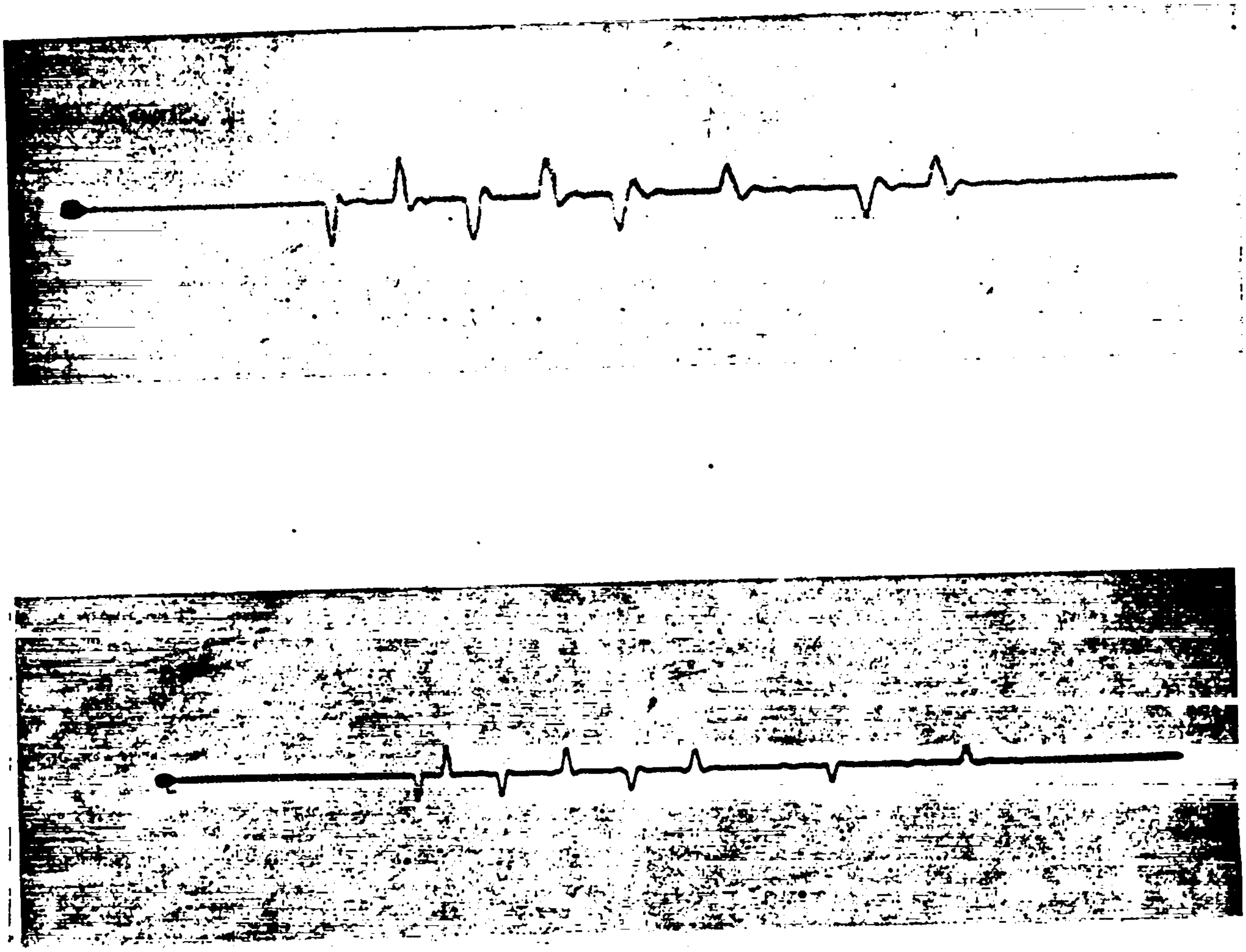

Fig. 2. Oscillograph records of time pips obtained from internally placed electrical contactors in an aluminum target for obtaining shock velocity as a function of thickness of material. The first and last contactors, namely (1) and (14), occur on both records. Total sweep time is 4 microseconds. Total path traveled is 2.9 cm. The composite from these records is plotted as a time-distance curve in Fig. 3.

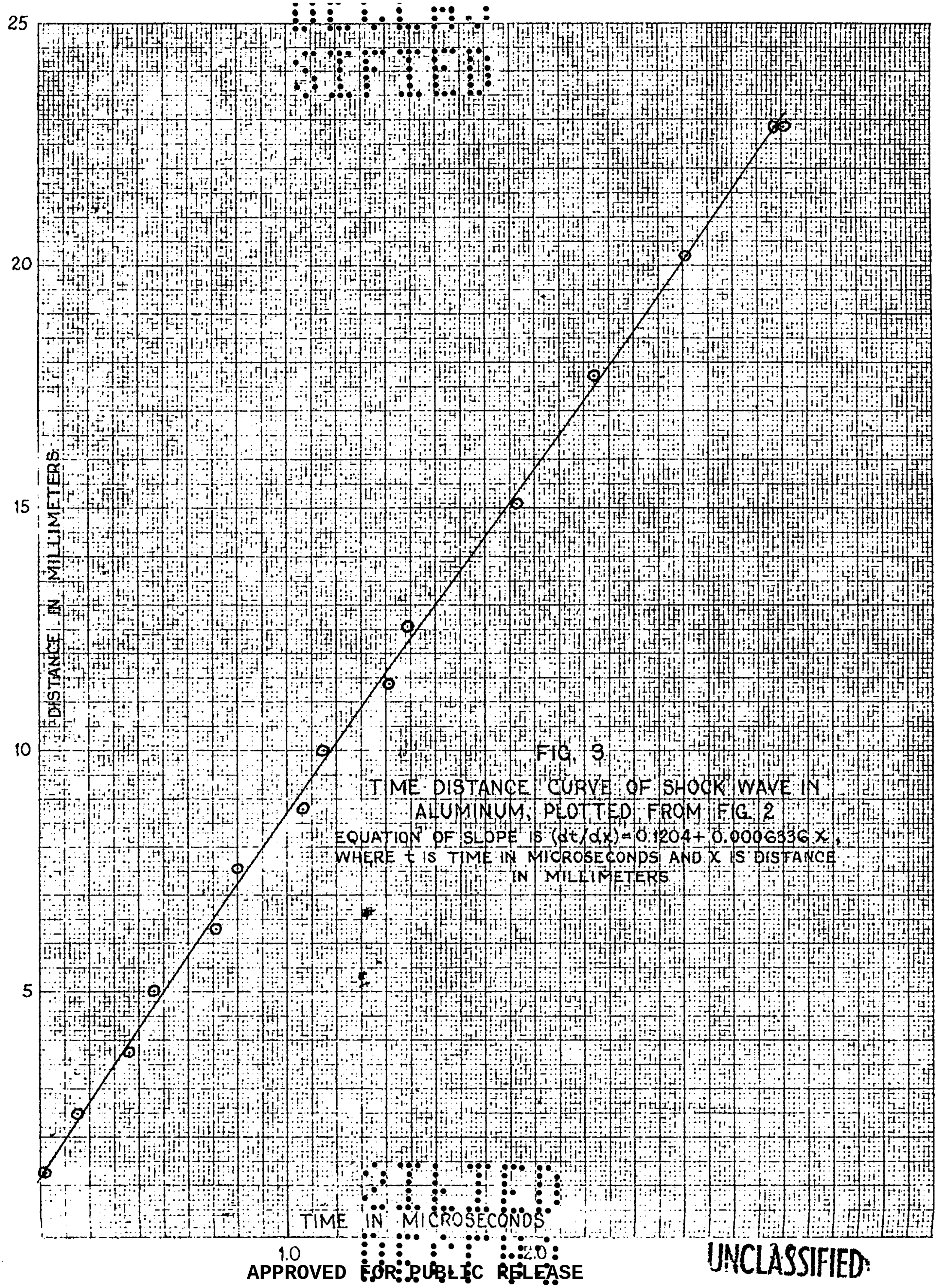

FIG. 3

TIME DISTANCE CURVE OF SHOCK WAVE IN ALUMINUM, PLOTTED FROM FIG. 2

EQUATION OF SLOPE IS (dt/dx) = 0.1204 + 0.0006336 X, WHERE t IS TIME IN MICROSECONDS AND X IS DISTANCE IN MILLIMETERS

UNCLASSIFIED

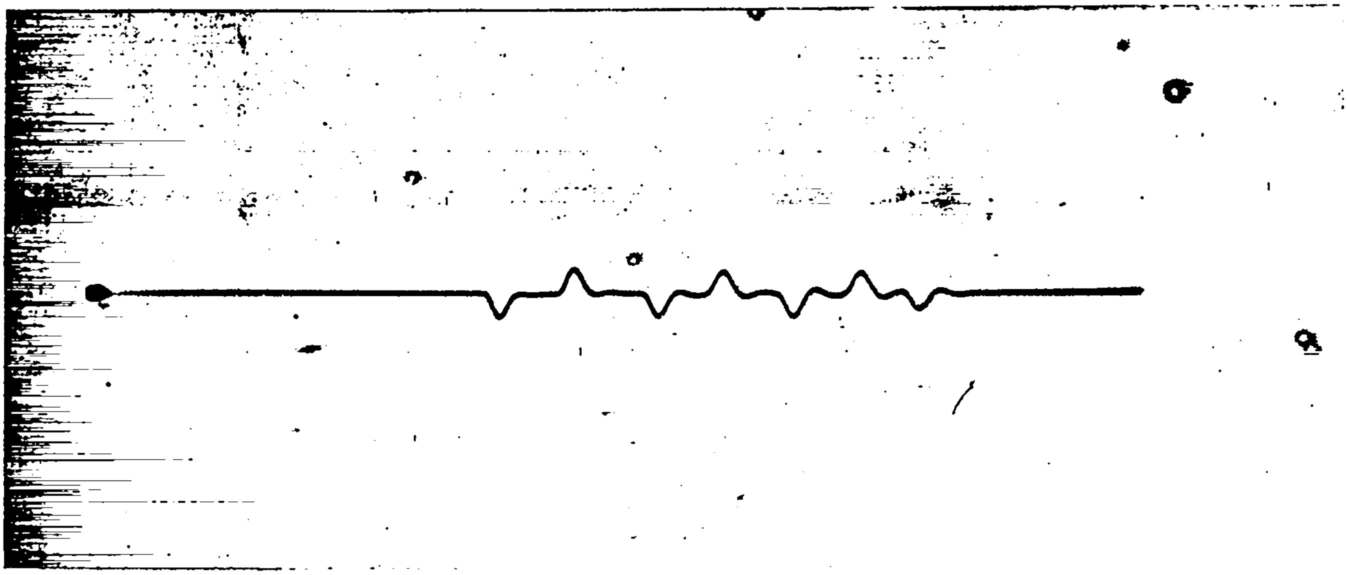

Fig. 4. Oscillograph record of external contactors with 1.25" cadmium target. Total sweep time is 2 microseconds. Total pin spread is 2 millimeters. A plot of the data from this record is given in Fig. 5.

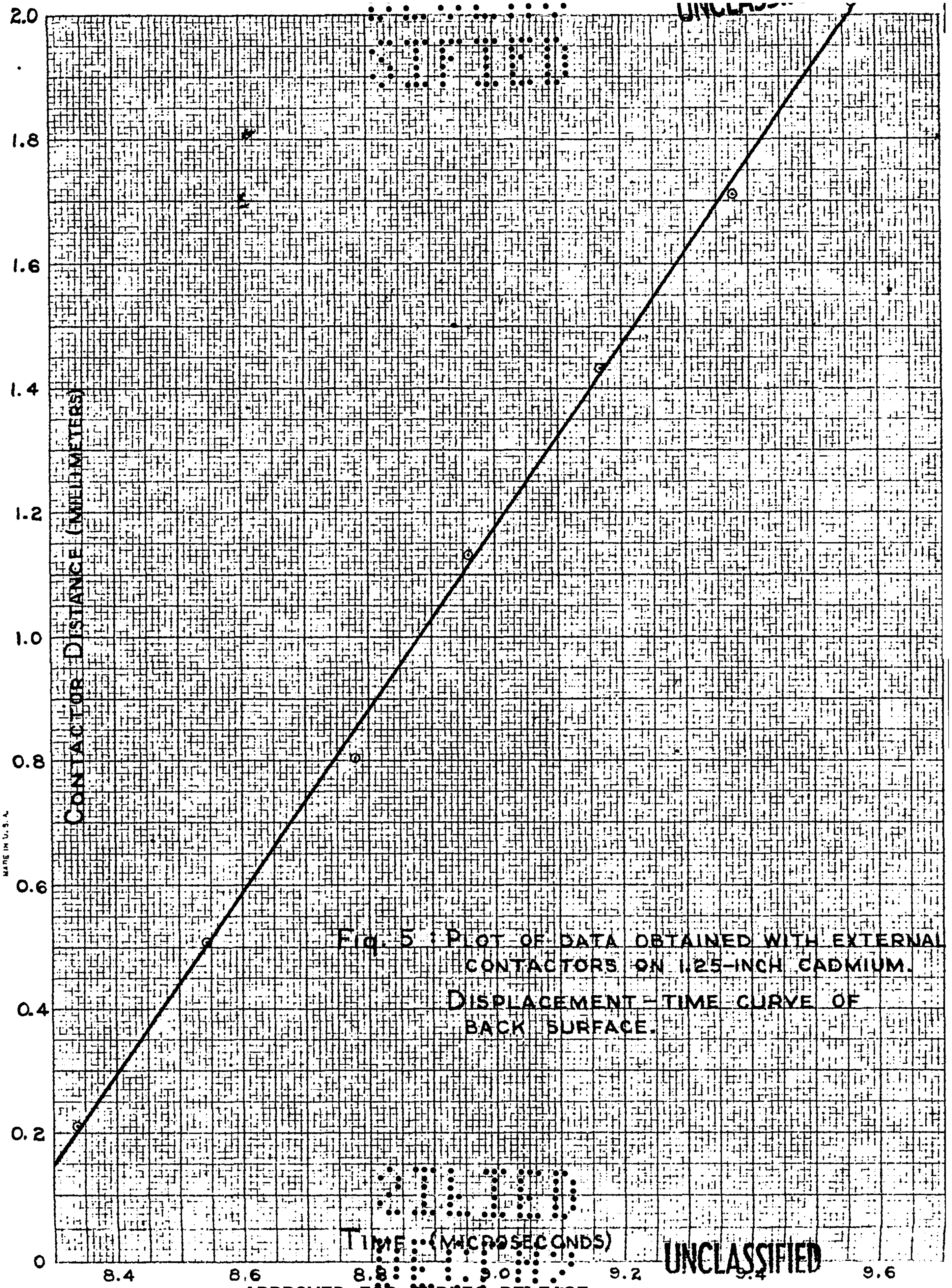

Fig. 5: PLOT OF DATA OBTAINED WITH EXTERNAL CONTACTORS ON 1.25-INCH CADMIUM. DISPLACEMENT-TIME CURVE OF BACK SURFACE.

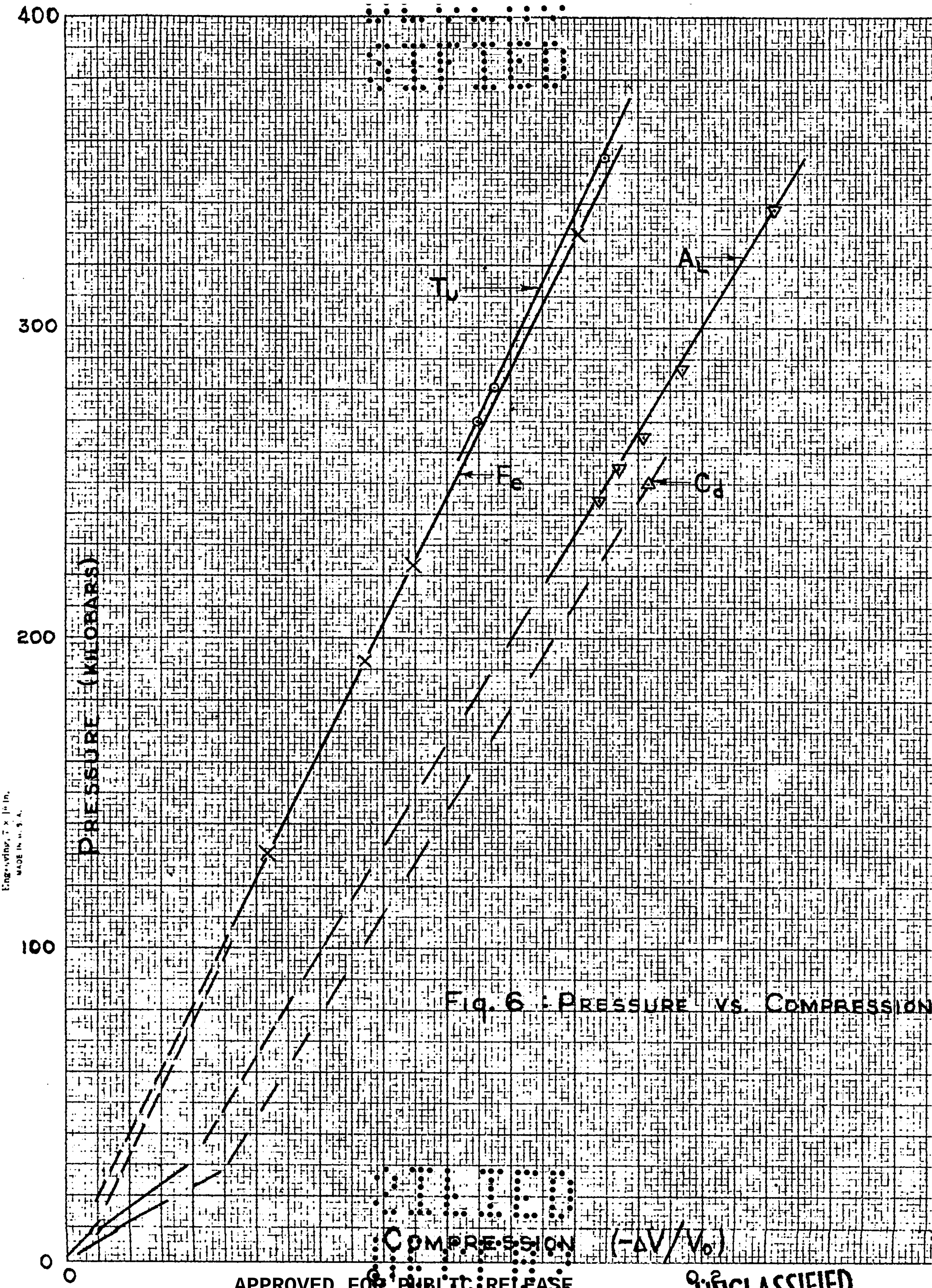

FIG. 6 : PRESSURE VS. COMPRESSION

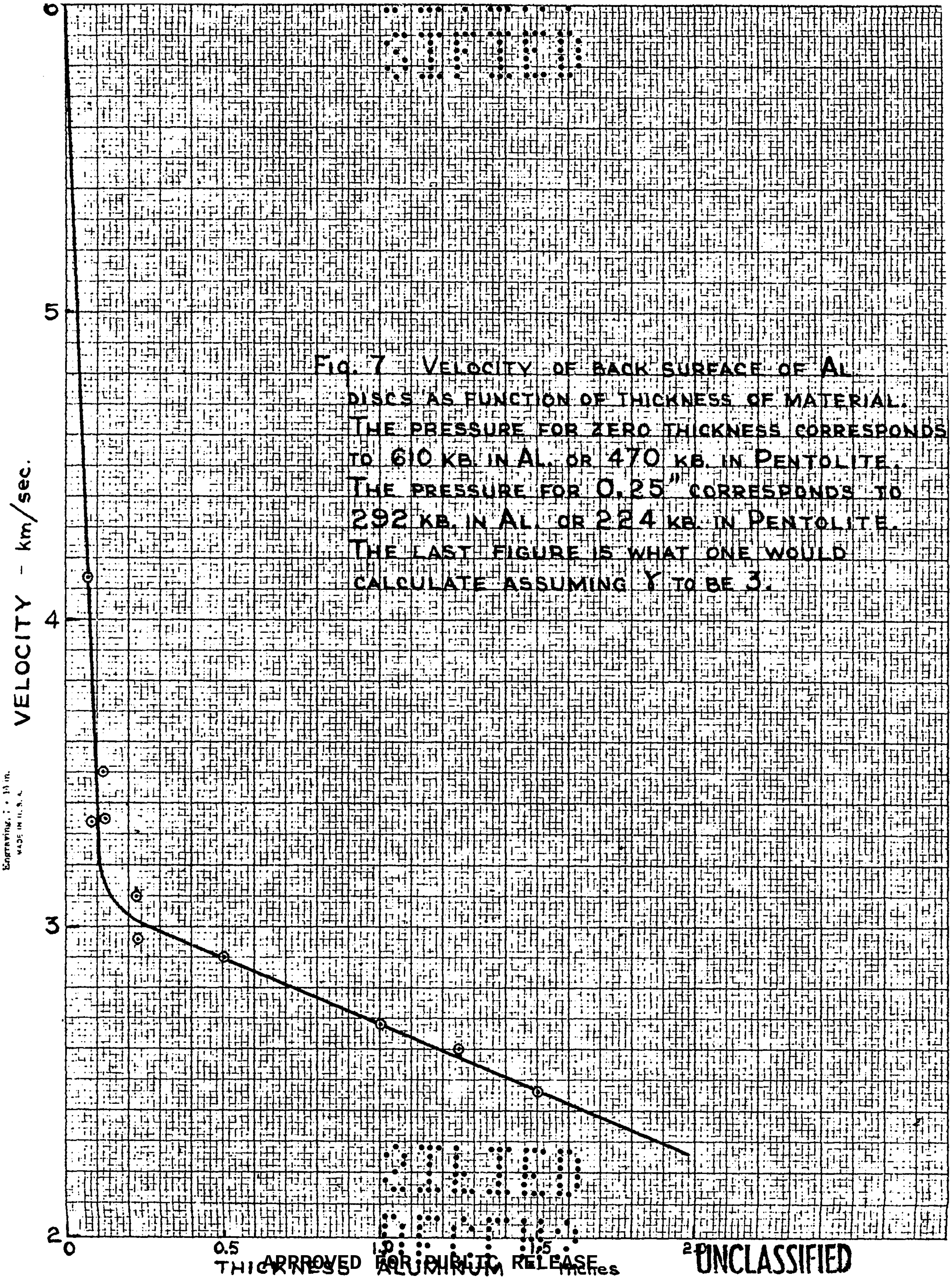

FIG. 7 VELOCITY OF BACK SURFACE OF AL DISCS AS FUNCTION OF THICKNESS OF MATERIAL. THE PRESSURE FOR ZERO THICKNESS CORRESPONDS TO 610 KB. IN AL. OR 470 KB. IN PENTOLITE. THE PRESSURE FOR 0.25" CORRESPONDS TO 292 KB. IN AL. OR 224 KB. IN PENTOLITE. THE LAST FIGURE IS WHAT ONE WOULD CALCULATE ASSUMING γ TO BE 3.

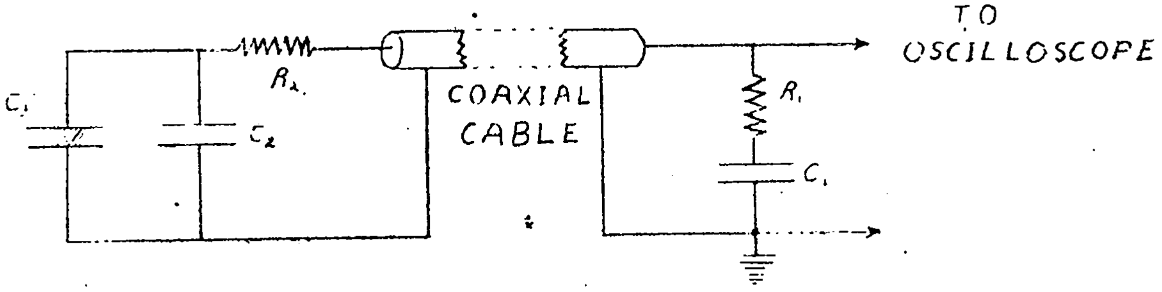

Fig. 9 : Basic crystal circuit.

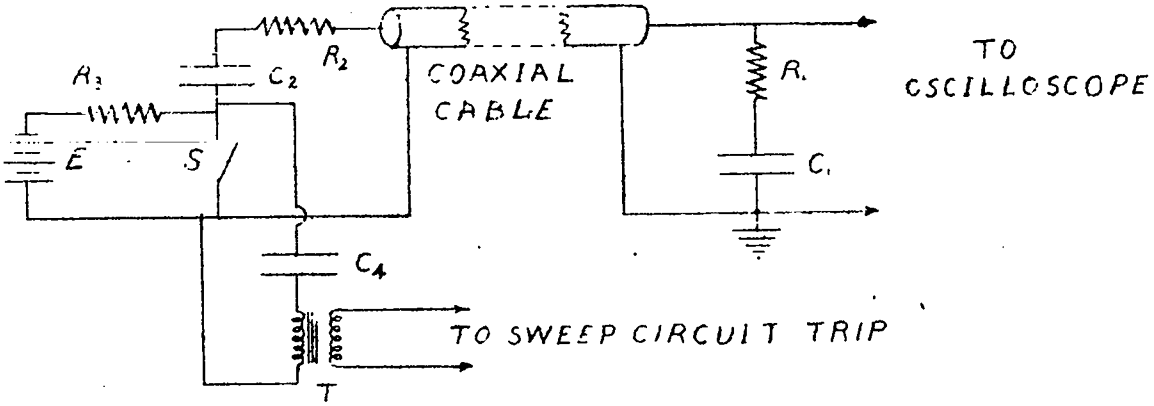

Fig. 10 : Circuit for testing cable distortion.

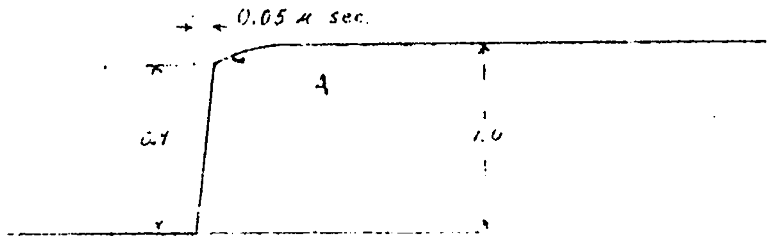

Fig. 11 ; Distortion encountered with circuit of Fig. 10 .

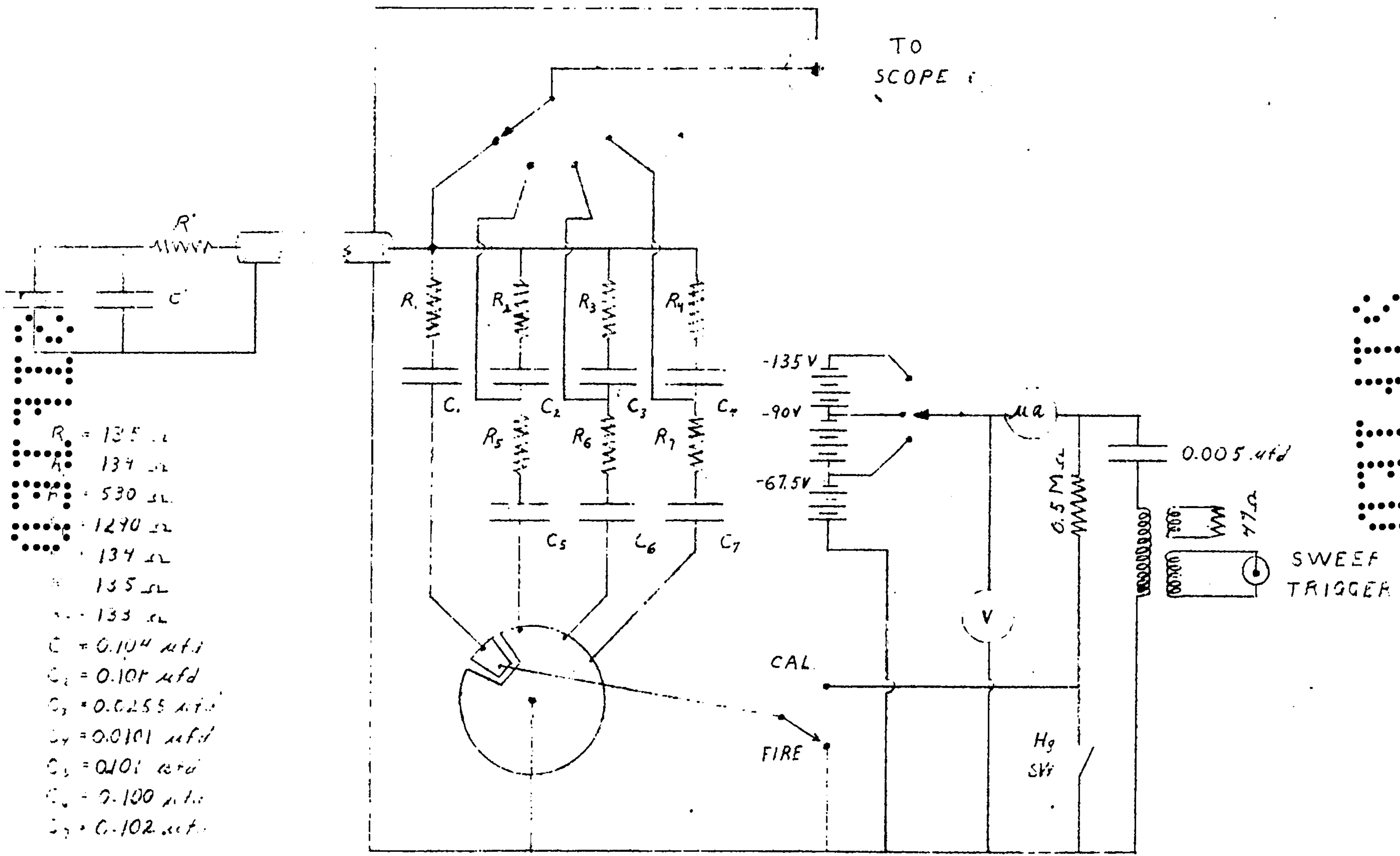

Fig. 12: Crystal circuit with attenuator and calibrator units.

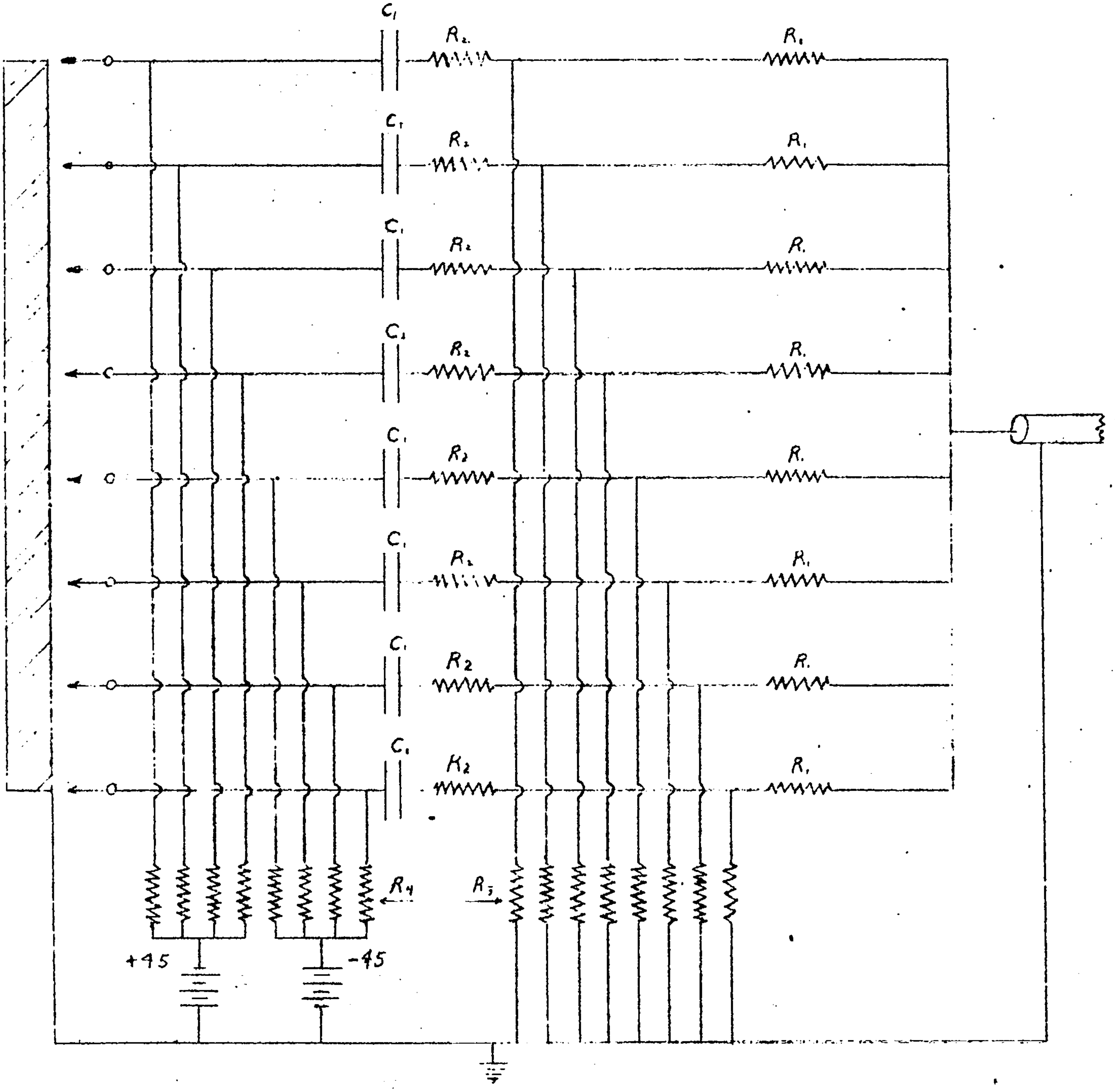

Fig. 13 : Circuit used to produce pulses when contact with target is established.

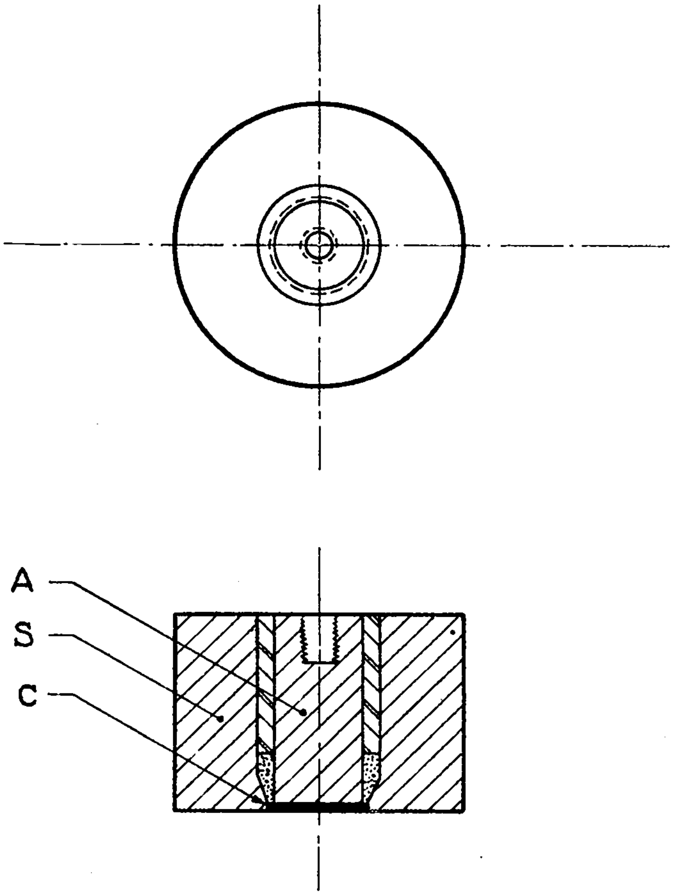

Fig. 14.

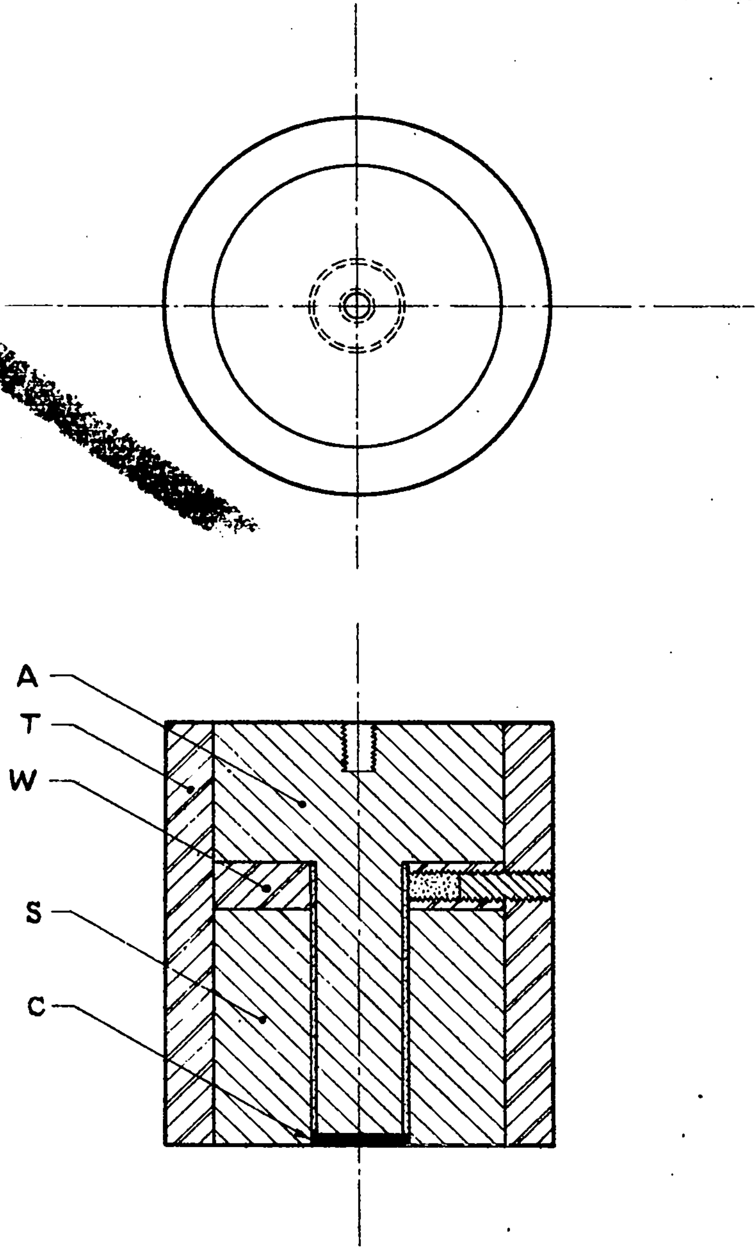

Fig. 15

UNCLASSIFIED

DOCUMENT ROOM

9/14/45 ✓

[redacted]