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SHOCK AND MATERIAL VELOCITIES IN SEVERAL METALS AND NONMETALS

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ABSTRACT

The pin-contact electrical method described by Froman in LA-182 has been developed to measure shock and material velocities in plates of both metals and non-metals. The shock velocity appears to be relatively independent of the shape of the detonation wave and the thickness of the plate but the initial velocity imparted to the far side of the plate varies considerably with thickness. Conical lenses and sufficient H.E. tend to reduce this variation. Material velocities can be approximately deduced from the observed initial velocities on the assumption that they are one-half the initial velocity imparted to the far side of the plate by the first reflection of the shock wave. The following table summarizes the measured shock and initial velocities:

Material	Shock Velocity	Initial Velocity
Metals	km/sec	km/sec
Aluminum	7.1 ± 0.2	3.8 ± 0.2
Cadmium	4.0 ± 0.2	2.9 ± 0.3
Copper	5.3 ± 0.3	1.8 ± 0.3
Lead	3.2 ± 0.2	3.0 ± 0.3
Steel	5.05 ± .05	2.0 ± 0.2
Tuballoy	3.4 ± 0.1	1.2 ± 0.1
Non-Metals		
Pressed calcium Fluoride	4.7 ± 0.4	3.8 ± 0.8
Marble	5.8 ± 0.5	2.5 ± 0.5
Mycalex (transverse)	6.5 ± 0.5	
Mycalex (longitudinal)	6.1 ± 0.5	3.5 ± 0.5
Steatite	5.7 ± 0.5	2.0 ± 0.5
Bonded Tuballoy Oxide	3.4 ± 0.3	2.3 ± 0.5

SHOCK AND MATERIAL VELOCITIES IN SEVERAL METALS AND NONMETALS

I. INTRODUCTION

Since knowledge of the shock and material velocities in certain materials is of direct importance in gadget design, experiments were undertaken to measure them. These quantities are of additional importance because they can be used to check equations of state at points where hitherto the only information to be had was based on long interpolations between experiments up to about 0.03 megabars (Mb) and Thomas-Fermi-Dirac calculations of Metropolis above 30 Mb. The technique developed for the measurement of these quantities is based on the pin-contact method described by Froman (LA-182).

The material velocity can be calculated from the initial velocity imparted to a plate of the material since the first quantity is about one-half the latter. By initial velocity is meant the velocity imparted to the plate by the first reflection of the shock wave at the far face of the plate. For thin plates, therefore, the pins must be all set within a small distance of the surface. Especially for this purpose step gauges were made which permitted accurate setting of ten pins all within the first two millimeters of the surface of the plate.

The shock velocity in a plate can be obtained from a measurement of the time it takes the shock to go through the plate. For metals the arrival of a shock at the face adjacent to the H.E. can be recorded by the shorting of a thin copper foil, originally insulated by a thin insulating foil, to the plate. It is not certain whether the electrical contact is due to the copper foil being pushed through the insulating membrane or that the heat associated with the phenomenon merely breaks down the insulator. The arrival of the shock at the far face can be detected by observing contact with a pin placed very close to the surface (less than 0.001 in.).

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The experiment is complicated by the possibility of a longitudinal sound wave preceding the shock wave to the far surface of the plate. Although the sound wave probably would not carry nearly as much energy as the shock and consequently would not impart a very high velocity to the plate, still for a sufficiently thick plate the sound wave might be responsible for contact with the close pin. It is very unlikely that contacts with pins some tenths of a millimeter or farther away would be caused by the sound wave. This phenomenon could be observed easily experimentally on a distance-time plot of the pin contacts for some types of plates. If all contacts were caused by the shock then all of the points would fall on a straight line but if the first contact were caused by a sound wave, the first point would fall too early in time to be on the line through the other points. Therefore, in order to obtain the true shock velocity one must use as the transit time of the shock through the plate the interval between the foil contact and the time intercept of the extrapolated line through the points on a distance-time plot.

The velocity of the longitudinal sound wave, if it is responsible for the first pin contact, is given by $C = d/(t-\delta/u)$ where d is the thickness of the plate, t the time interval between foil contact and first pin contact, δ the distance from the first pin to the plate, and u the velocity imparted to the plate by the sound wave. Since both δ and u do not lend themselves to easy direct measurement, accurate values for C can be determined most conveniently when δ/u can be neglected relative to t as, for example, when the plate is very thick.

A further complication in the measurement of the shock velocity arises from the possibility that the processes of the foil and pin contacting requires different times. If this is the case, corrections must be applied to the transit time of shock waves through plates, the corrections being more important for the thinner plates. The apparent delay, Δ, of pin contact compared with foil contact was measured, for example,

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for metallic plates by subtracting the transit time for 1/4" plates from twice the transit time for 1/8" plates. (If t is the true transit time for a 1/8" plate $t_{1/4} = 2t + \Delta$ while $2t_{1/8} = 2t + 2\Delta$; therefore, $(2t + 2\Delta) - (2t + \Delta) = \Delta$. For steel plates this quantity was 0.05 microseconds, and for aluminum plates it was 0.1 microseconds. The variation is probably only statistical since the measurement involves determining a small difference of two large terms. Runs on cadmium, lead and copper gave 0.08 microseconds, 0.17 microseconds and 0.07 microseconds, respectively, but the fewer runs available makes these values less reliable than those for steel and aluminum.

II. EXPERIMENTAL PROCEDURE AND RESULTS

A. Metals. 1. Steel - Plates of thicknesses ranging from 1/8" to 2" and transverse dimensions at least four times the thickness were used. The pentolite charges used with plates up to 1/2" thickness of steel were 2-1/2" diameter by 3" high; with plates 1/2" to 1" thickness, 3-1/2" diameter by 5" high; and with plates 1-1/2" and 2" thickness, 6" diameter by 6" high. Most of the early runs were made to measure shock velocity and there was only one pin set closely underneath the plates. The results obtained on these early shots varied from about 5 km/sec for 1/8" and 1/4" plates, to 5.5 km/sec for the 2" plates. Later, when some of the heavier plates were shots with several pins set to obtain initial velocities, it was found that the close pin seemed to be making contact prematurely, falling off the straight line through the other points. A typical distance-time curve obtained with a 2" thick plate 8" by 8" and a 6" diameter by 6" cylindrical pentolite charge is shown in Graph 1. Further shots with fairly thick plates continued to show this phenomenon. By interpreting this effect as due to a weak preliminary wave and using the extrapolated intersection with the time axis as the time of arrival of the shock at the far face, quite consistent values were obtained for the shock velocities in both thin and thick plates.

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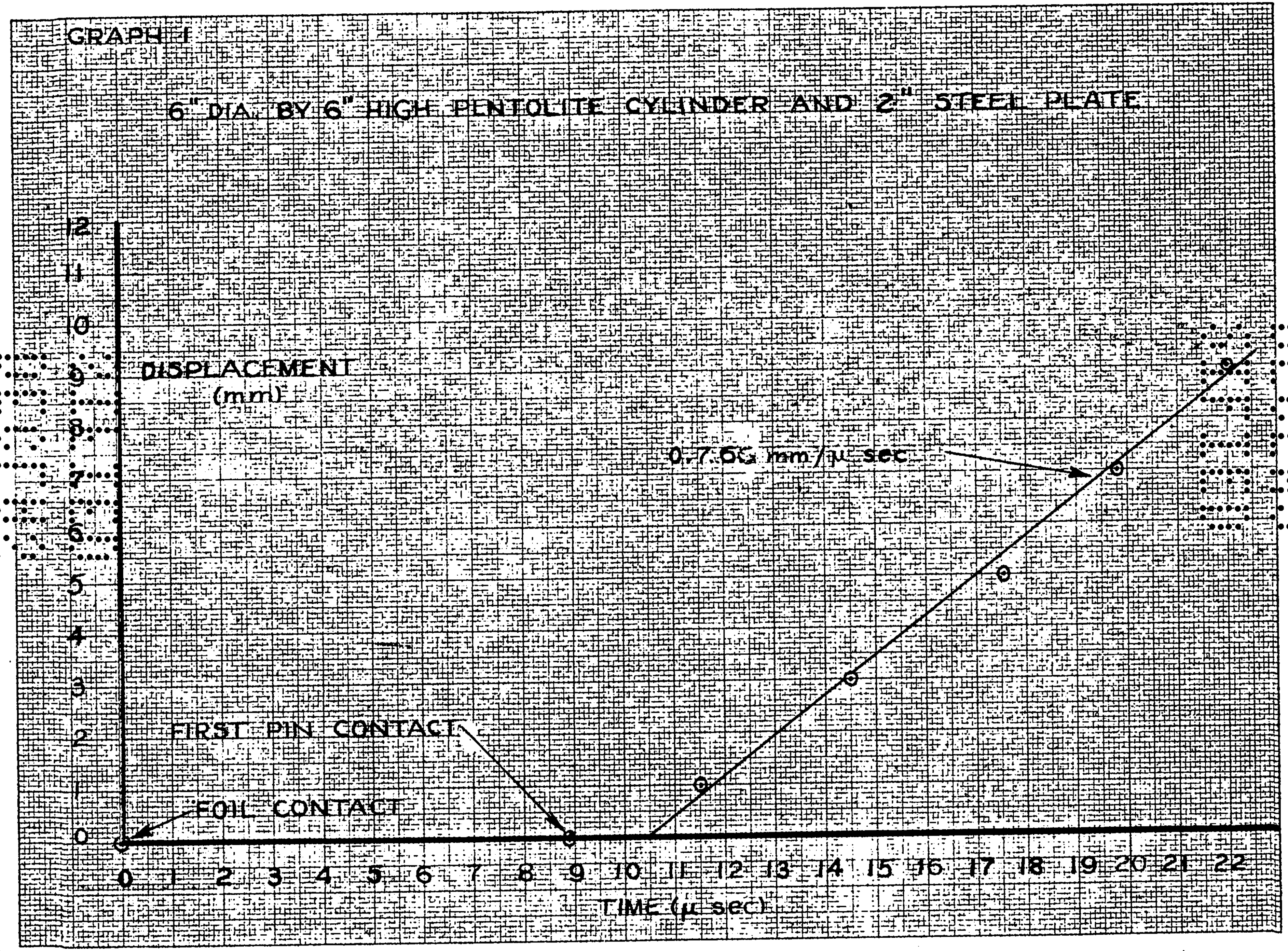

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The average value was 5.04 ± 0.05 km/sec.

Among the various thickness shots, there seemed to be no constancy of the initial velocity imparted to the plates. For a given-size charge the initial velocity dropped with increasing thickness of plate. In order to investigate this apparent attenuation of the divergent shock, a step gauge was made that permitted accurately spacing 10 pins within the first 2 mm of the surface of the plate. It was found that with a 3-1/2" diameter by 5" high pentolite charge, 1/8" plates acquired an initial velocity of 1.3 km/sec while the surfaces of 1" plates acquired an initial velocity of but 0.6 km/sec.

To see whether this attenuation was characteristic of a divergent shock wave, runs were made with conical lenses placed on top of the pentolite cylinders. At first four shots were fired with only one inch of pentolite between the lens and plate, two with 1/8" and two with 1" steel. The same initial velocity was obtained for the 1/8" steel as before, and only a slight increase was observed in the initial velocity of the 1" steel (0.7 km/sec). The experiment was repeated on both thicknesses of steel by placing 5" of pentolite between the lens and the plate. The initial velocity imparted to the 1/8" steel was increased to 2.0 km/sec and in the case of the 1" steel to 1.3 km/sec.

The initial velocity thus depends upon the flatness of the detonation wave and on the amount of high explosive as well as upon the thickness of the plate. However, for otherwise comparable geometries a flatter shock wave tends to reduce the thickness variation in material velocity. Graph 2 shows this effect.

In order to study the motion of the plate between 0 and 0.2 mm from the initial position of the plate, thickness gauges were used to space pins at about 0.06 and 0.12 mm from the plate. Graph 3 indicates that this is considerable acceleration in this region. This implies either that the phenomenon is caused by a broad shock

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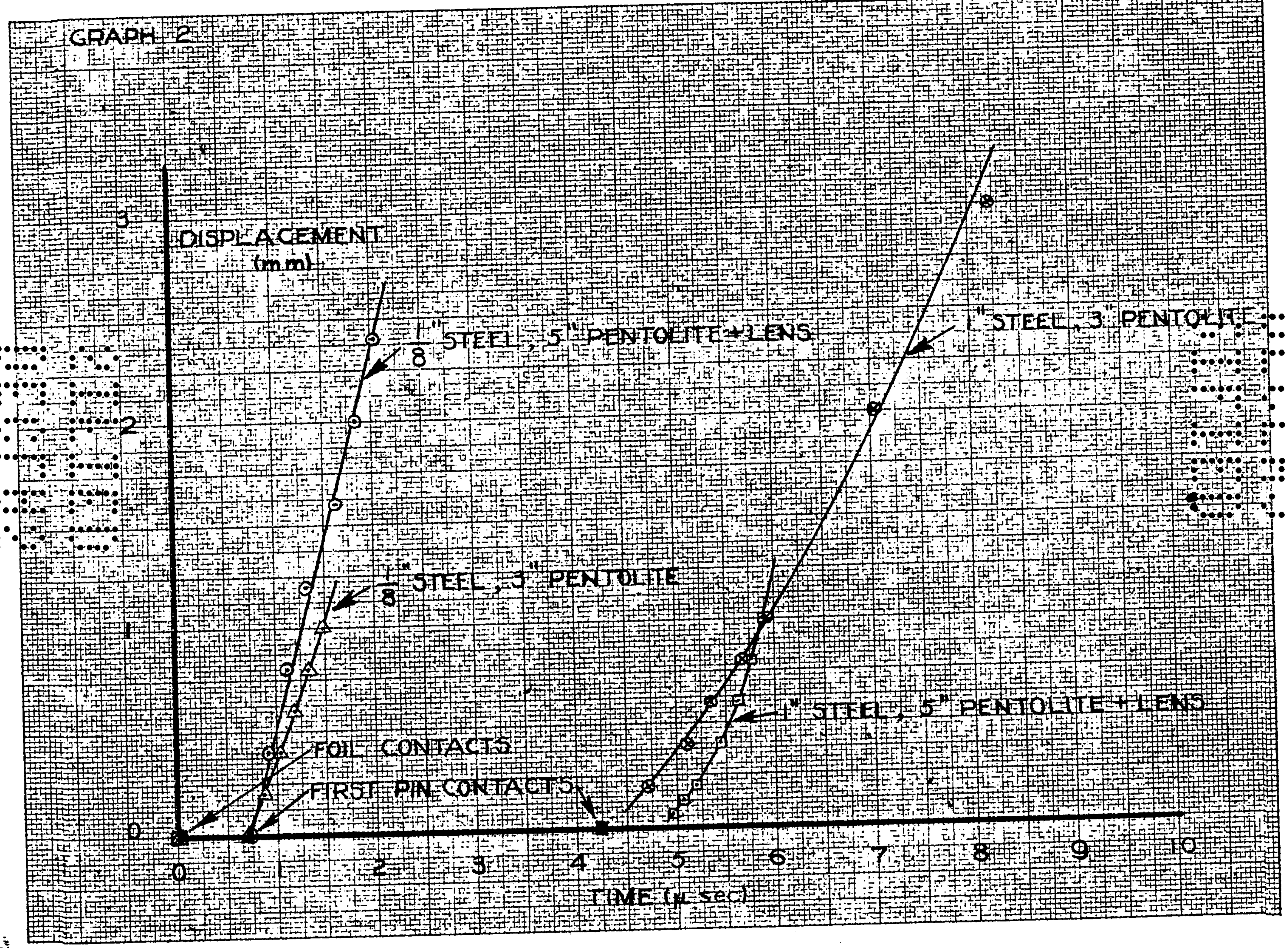

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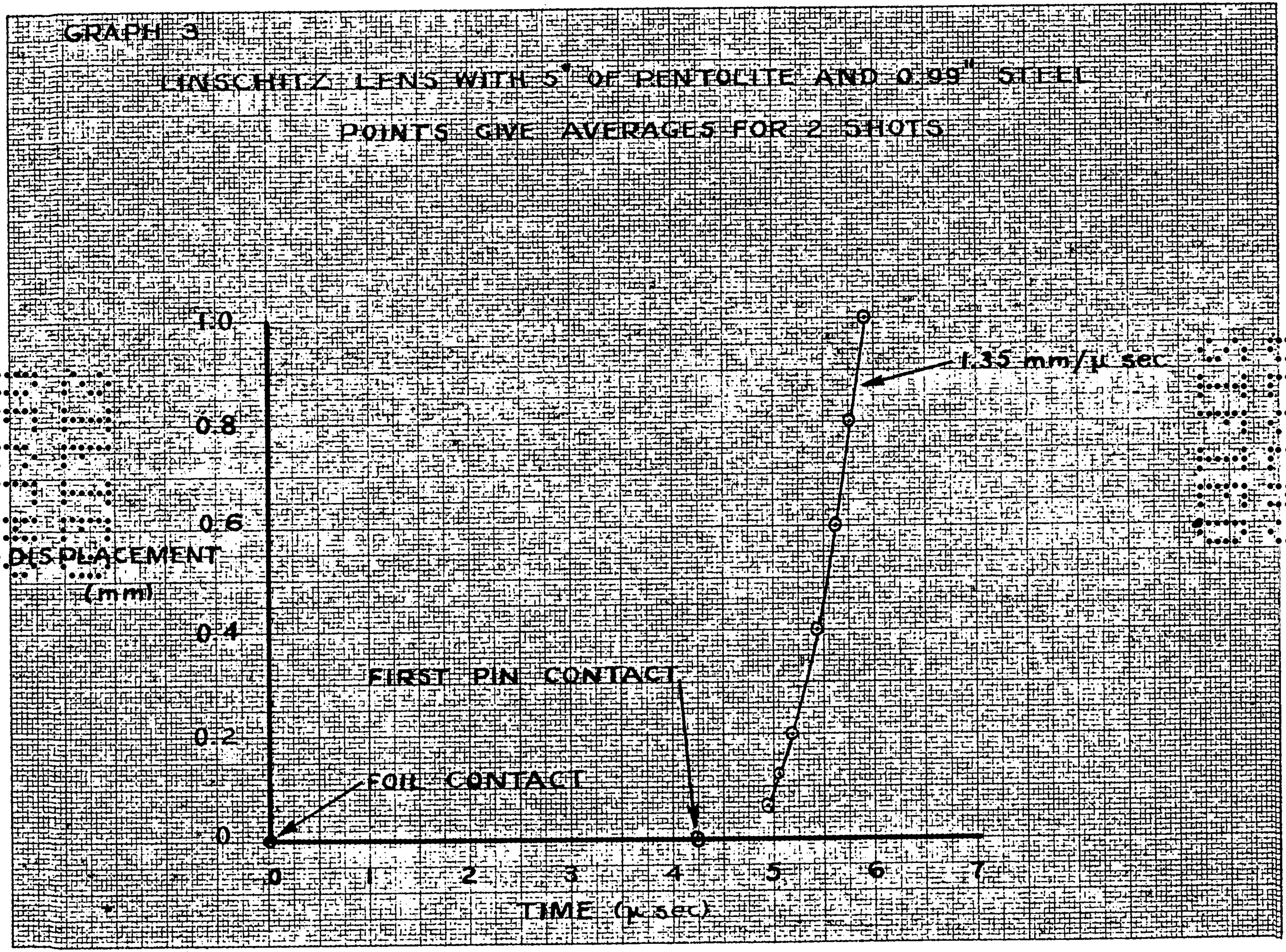

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front rather than by a preliminary sound wave, or that there is a "fuzzy" boundary between the sound wave and the main shock.

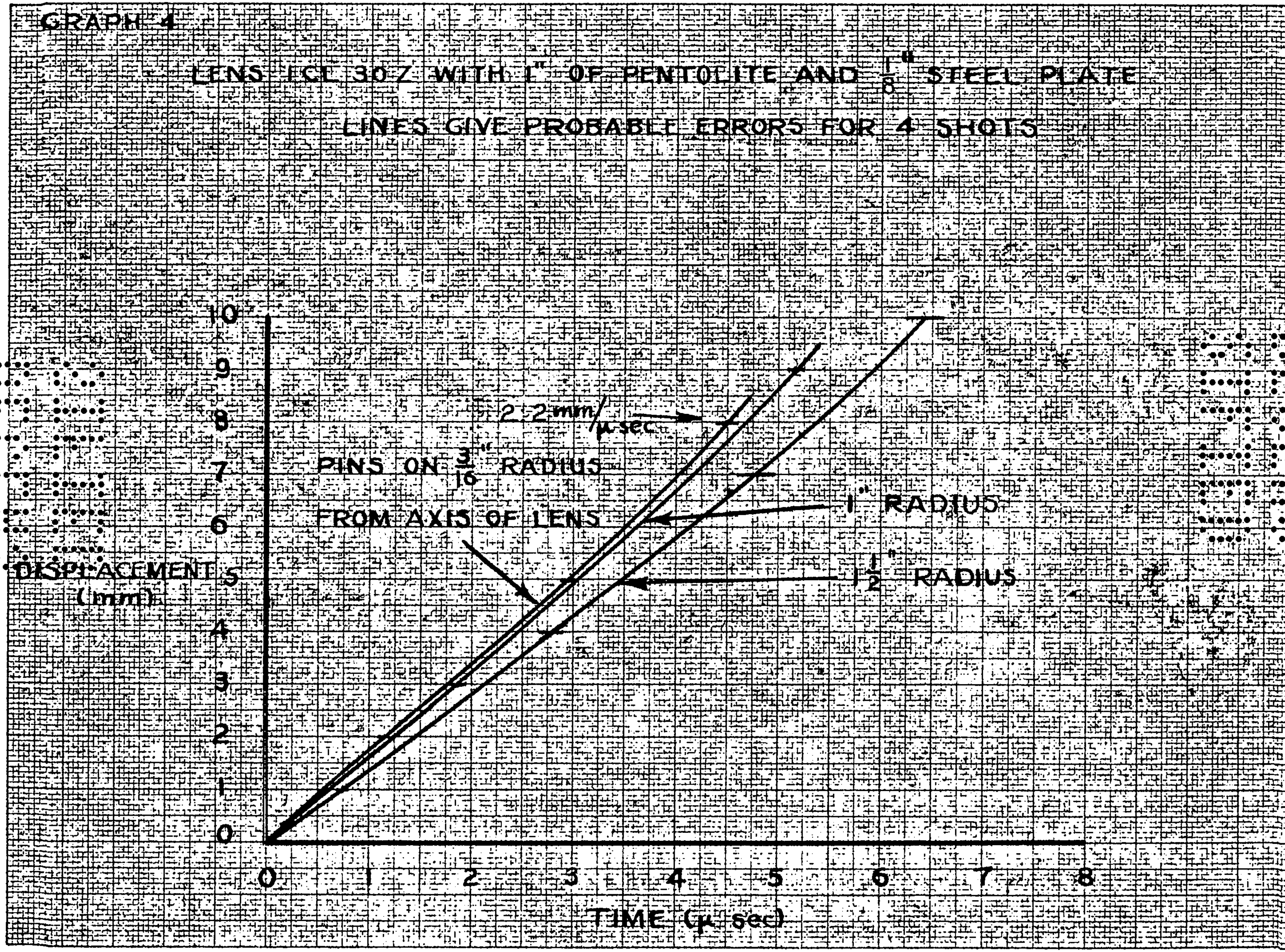
The pin-contact electrical method was used to measure the velocity imparted to 1/8" steel plates under conical lenses of type 1 CL 30 Z during the first 6 microseconds of motion when 1" and 2" of pentolite are placed between the lens and the plate.

Four shots were fired with 1" of pentolite between the lens and the plate. Graph 4 gives the results of these shots. It will be observed that there is considerable lag in the motion of the plate at the 1-1/2" radius; however, this part of the plate was close to the edge of the lens so that the lag is not a significant indication of the quality of the lens. The velocity of 8 mm from the initial position of the plate along the axis of the lens is about 1.8 km/sec.

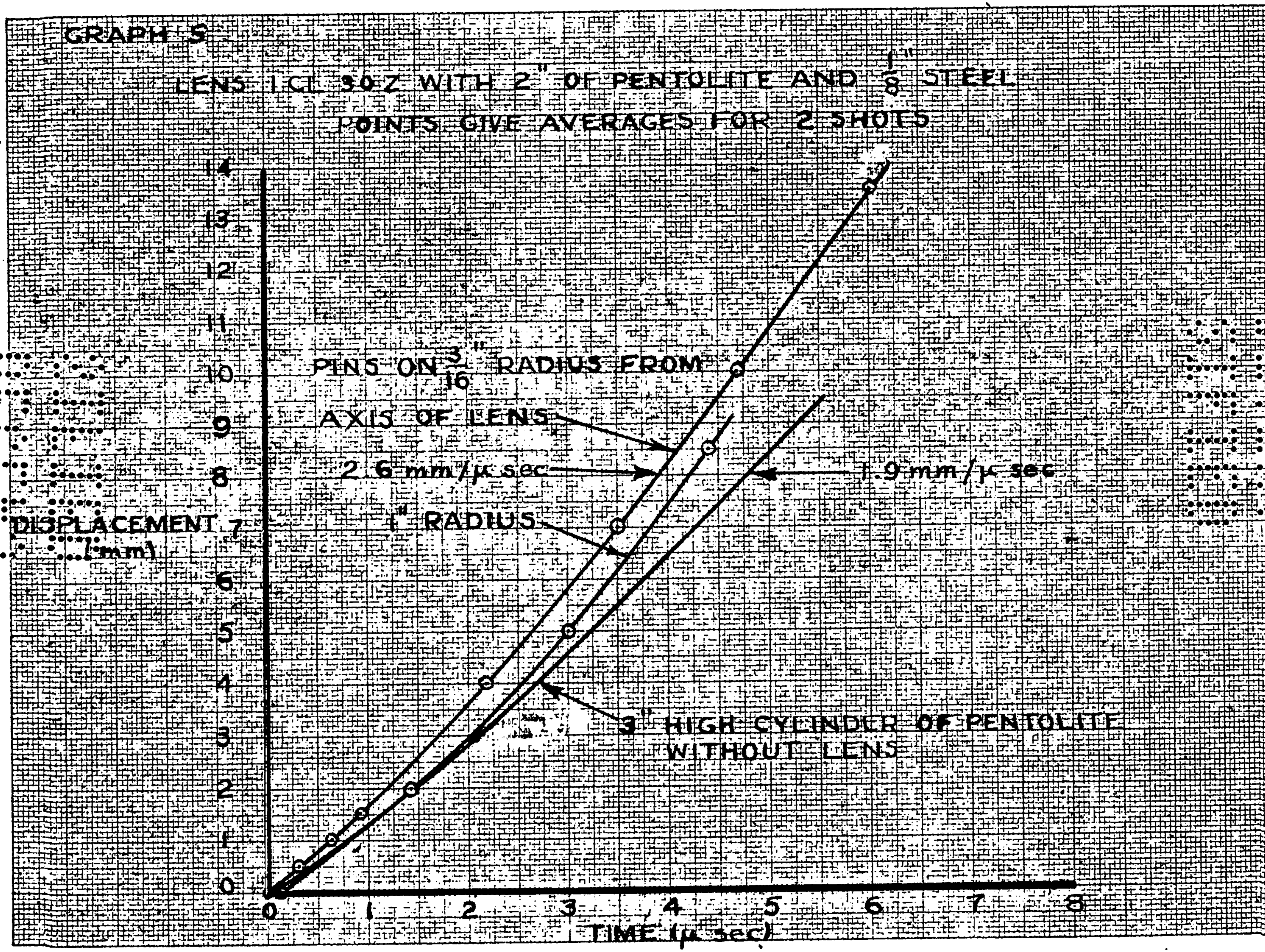
Two shots were fired with 2" of pentolite between the lens and the plate. Graph 5 gives the results. It will be observed that the region of the plate 3/16" from the axis of the lens starts ahead of the region at the 1" radius by about 0.15 microseconds. The velocity of the center is about 2.6 km/sec when the plate has moved 8 mm. Excellent agreement was obtained between the two shots.

In order to show the effectiveness of a lens in increasing the velocity of the plate, Fig. 5 has been reproduced from LA-182 on Graph 5. It will be observed that the velocity at 8 mm is about 1.9 km/sec. Since the charge used for this data was 3" of pentolite without a lens and since the height of 2" of pentolite plus the lens is roughly comparable, the data indicates that the lens increases the velocity by about 35 percent.

2. Aluminum. Some thirty-five runs were made with aluminum plates of various thicknesses. Two-thirds of these runs were made using non-lens charges, usually pentolite cylinders 3-1/2" diameter by 5" high. The remaining runs were made using Tuck conical lenses plus 5" of pentolite 3-1/2" in diameter; the first ones were filled with spherical grained tetryl, and the later ones with spherical grained TNT (special



GRAPH 4
LENS ICL 30Z WITH 1" OF PENTOLITE AND 1/8" STEEL PLATE
LINES GIVE PROBABLE ERRORS FOR 4 SHOTS
2.2 mm/μ sec
PINS ON 3/16" RADIUS
FROM AXIS OF LENS
1" RADIUS
1 1/2" RADIUS
DISPLACEMENT (mm)
0
1
2
3
4
5
6
7
8
9
10
0
1
2
3
4
5
6
7
8
TIME (μ sec)


GRAPH 5
LENS 1 CL 30 Z WITH 2" OF PENTOLITE AND 1/8" STEEL
POINTS GIVE AVERAGES FOR 2 SHOTS
PINS ON 3/16" RADIUS FROM
AXIS OF LENS
2.6 mm/μ sec
1" RADIUS
1.9 mm/μ sec
3" HIGH CYLINDER OF PENTOLITE
WITHOUT LENS
DISPLACEMENT (mm)
TIME (μ sec)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14

type B). Within the experimental error there seemed to be no variation of shock velocity with the types of H.E. charges used nor with thickness of plate after correction was made for the apparent discrepancy of timing of the foil and pin contacting. In this case the correction time used was 0.1 microseconds. In averaging the results, the data from various thickness of plates were weighted by a factor proportional to the thickness of plate since the absolute error in time measurement is probably about constant. This averaged value is 7.1 ± 0.2 km/sec.

It was found that initial velocities varied with thickness and with type of H.E. used. Graph 6 shows the variation of initial velocity with thickness of plate both for lens and non-lens charges. It is seen that the initial velocity increases for decreasing thickness of plate but is higher for a given thickness when lenses, presumably giving plane shock waves, are used. The values of the initial velocity 3.8 ± 0.2 km/sec given in the summary table is the average of the results for 1/8" and 1/4" thick plates. The extrapolation to zero thickness probably cannot be used since the points for greater thickness were obtained with a different type of lens.

3. <u>Tuballoy.</u> Twelve runs were made with tuballoy plates, six of them about 0.2" thick and six about 0.4". All were made with conical lenses plus five inches of pentolite. Three were fired with Linschitz lenses, three with Tuck lenses filled with tetryl, and six with Tuck lenses filled with spherical grained TNT (type B). In the six runs with the last type mentioned, pins were placed at a radius of 3/16" from the axis of the lens and also at 1" from the axis. The contacts at the 3/16" radius were early by 0.05 to 0.3 microseconds but there appeared to be no correlation in the variation of either the shock or initial velocities with the flatness of the detonation wave over this range. There were insufficient data to determine definitely whether or not there was any variation depending upon the type of lens used, but there appeared to be none. The shock velocity for the thinner plates appeared to be a little low as compared with the thicker plates. This could be explained by a pin-foil delay

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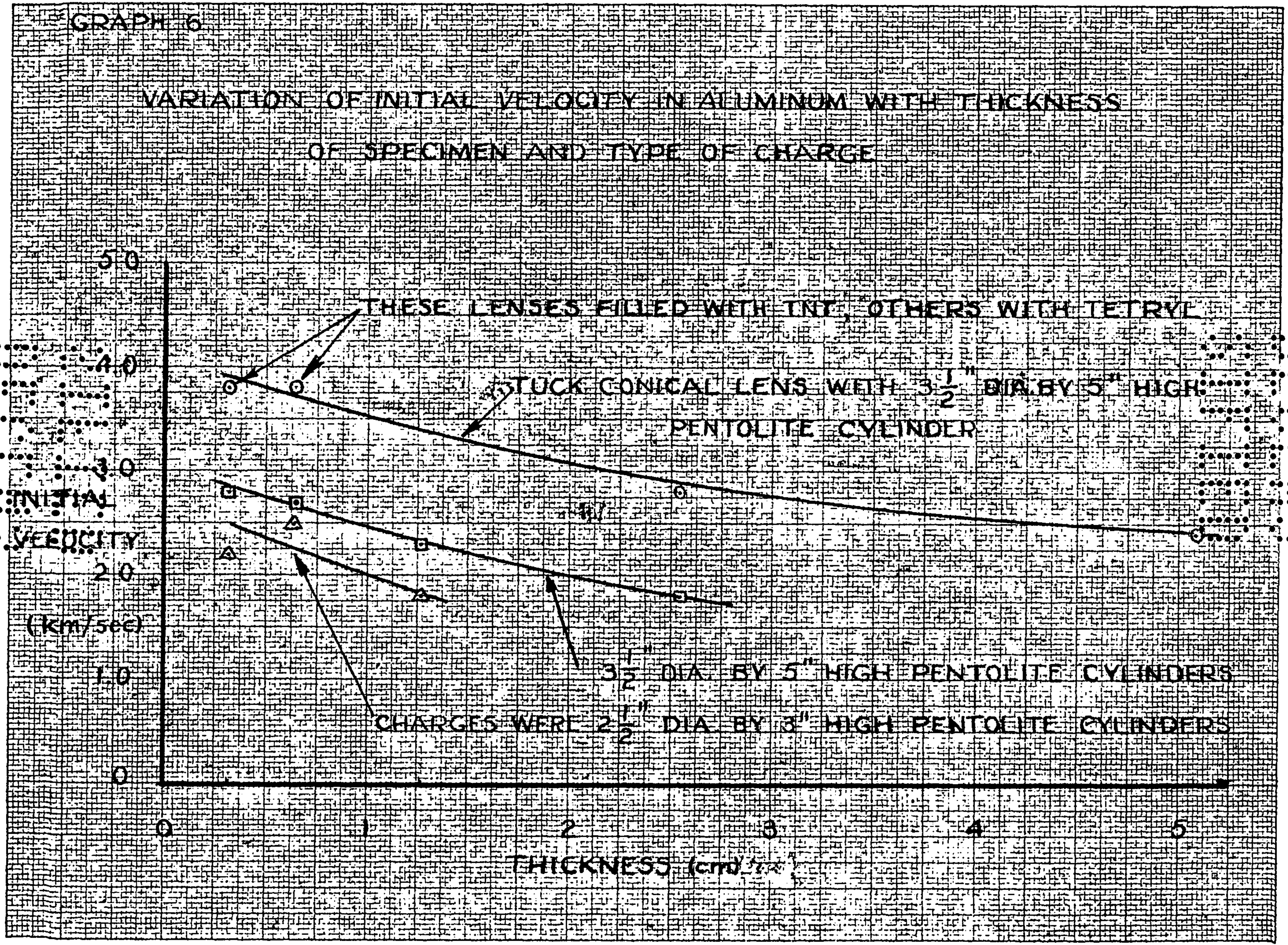
GRAPH 6
VARIATION OF INITIAL VELOCITY IN ALUMINUM WITH THICKNESS
OF SPECIMEN AND TYPE OF CHARGE
THESE LENSES FILLED WITH TNT, OTHERS WITH TETRYL
TUCK CONICAL LENS WITH 3 1/2" DIA. BY 5" HIGH
PENTOLITE CYLINDER
3 1/2" DIA. BY 5" HIGH PENTOLITE CYLINDERS
CHARGES WERE 2 1/2" DIA. BY 3" HIGH PENTOLITE CYLINDERS
INITIAL
VELOCITY
(km/sec)
5.0
4.0
3.0
2.0
1.0
0
0
1
2
3
4
5
THICKNESS (cm)

 [redacted]

of 0.05 microseconds. The average initial velocity of the thicker plates was about seven percent lower than the average for the thinner plates. A typical run is plotted in Graph 7.

The shock velocity for tuballoy after correction for the pin-foil delay of 0.05 microseconds is 3.4 ± 0.1 km/sec. The average material velocity for all twelve runs is 1.2 ± 0.1 km/sec.

4. <u>Cadmium</u>. A dozen plates of Cd in the thickness range 1/8" to 1/2" were shot. An average value of the pin-foil delay of 0.08 microseconds gave $4.0_5 \pm 0.1_5$ km/sec for the shock velocity. There were not enough data in the case of cadmium as compared to aluminum to indicate definitely a trend of initial velocity with thickness. Again, as in the case of the aluminum, only the results obtained with 1/8" and 1/4" plates using Tuck lens-shells filled with spherical grained TNT (type B) were used in obtaining the average value of the initial velocity, viz. 2.9 ± 0.3 km/sec.

5. <u>Copper</u>. Only four shots were fired with copper plates, two using 1/8" thickness and two 1". All shots were with 5" or 6" of pentolite plus a Tuck conical lens (spherical TNT). As for all other metals the shock velocity was apparently smaller for the thin plates which could be explained by a pin-foil time delay of 0.07 microseconds. After applying this correction the shock velocity is 5.3 km/sec. The initial velocity imparted to the 1/8" plates is 1.8 km/sec, and in the case of the 1" plates 1.5 km/sec.

6. <u>Lead</u>. Some ten shots were made with lead plates of thicknesses ranging from 1/8" to 1". In spite of the difficulties in the fabrication of smooth and accurately plane lead plates the results of separate runs were in very good agreement, the averages giving for the shock velocity 3.2 ± 0.2 km/sec and for the initial velocity 3.0 ± 0.3 km/sec. As in the case of cadmium the values of the shock velocity were obtained using an average value of the pin-foil delay of 0.08 microseconds.

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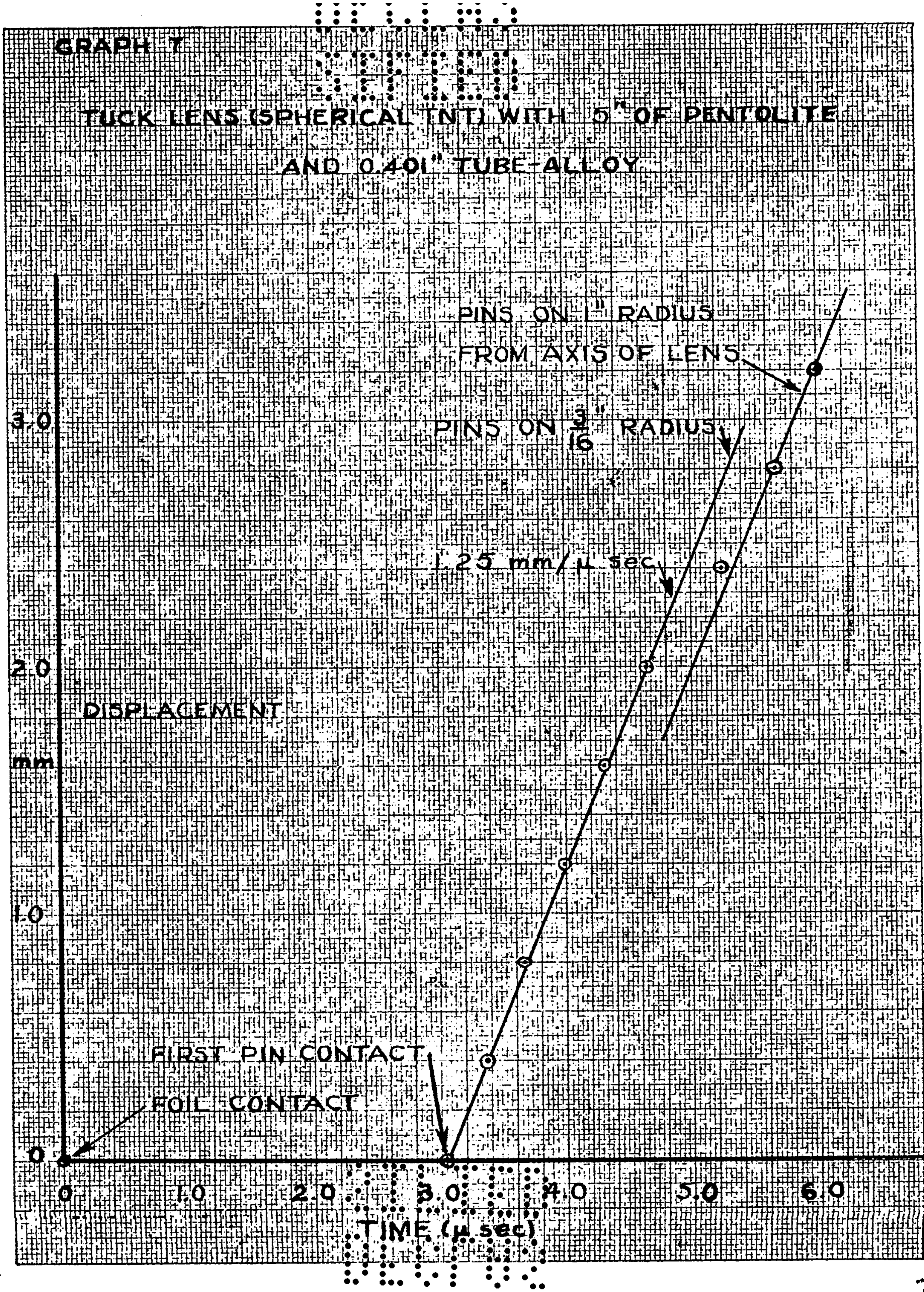
GRAPH 7
TUCK LENS (SPHERICAL TNT) WITH 5" OF PENTOLITE
AND 0.401" TUBE-ALLOY
PINS ON 1" RADIUS
FROM AXIS OF LENS
PINS ON 3/16" RADIUS
1.25 mm/µ sec
FIRST PIN CONTACT
FOIL CONTACT
DISPLACEMENT
mm
3.0
2.0
1.0
0
0
1.0
2.0
3.0
4.0
5.0
6.0
TIME (µ sec)

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B. Nonmetals. At the suggestion of McMillan a study of certain materials was undertaken in the search of a nonconductor with hydrodynamic properties similar to those of aluminum. Such a material would be very useful as an insulator in certain types of assemblies that the magnetic group fires. In order to measure the shock and material velocities of nonconductors a modification of the technique used for metals had to be made.

For the pulse identifying the time at which the detonation wave arrived at the near side of the slab, two 0.0003" copper foils were placed side by side, about 1/32" apart, between the H.E. and the slab. The explosive gases are apparently sufficiently ionized to make a low-resistance contact between the foils. In timing the arrival at the far side of the plate of the first wave traversing it, a grounded 0.0003" copper foil was cemented to the far side, directly under the first pin, which was placed as closely as possible to it without actually making electrical contact.

To measure the material velocity of the substance pins were spaced at 0.2-mm intervals from the far face, and grounded copper foils 0.001" in thickness were suspended between the pins and the slab. When the slab moves sufficiently to drive a foil into the corresponding pin a pulse is obtained.

Since the chief concern at first was measuring the shock velocities, most of the measurements were made with diverging shock waves; i.e., pentolite cylinders without plane lenses were used. Those used were 3-1/2" diameter and 5" high. Since lenses were not used it was not surprising to find large variations in initial velocity with thickness of sample. To afford some basis of comparison of the non-metals with each other the various values listed in the summary table are initial velocities reduced to 1/2" thickness of sample. The values are still not strictly comparable since plane lenses were used with Ca F_2 and Mycalex (longitudinal) but not with the others, so that presumably the initial velocities listed for these materials

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are closer to the infinitely-thin-slab value than those for the other materials.

1. PRESSED CALCIUM FLUORIDE. Two plates 3/4" thick and two 1-3/4" thick were shot with 5" of pentolite and a Tuck lens. The average value of the shock velocity was 4.7 ± 0.4 km/sec. The 3/4" plates gave an initial velocity of 2.8 km/sec while the 1-3/4" plates gave 1.3 km/sec. The value 3.8 km/sec given in the summary table was obtained by extrapolation to 1/2" thickness of plate. The density of this material was about 2.7 gm/cc.

2. MARBLE. Two marble plates 1/2" thick and two 1-1/2" thick were shot. The shock velocity averaged 5.8 ± 0.5 km/sec while the initial velocity was 2.5 ± 0.5 km/sec for the 1/2" plates and 1.6 km/sec for the 1-1/2" plates. These plates were shot with 3-1/2" diameter by 5"-high pentolite cylinders without plane lenses.

3. MYCALEX (transverse). Six plates of mycalex (planes of cleavage perpendicular to the direction of shock) of thickness ranging from 1/4" to 3/4" were shot giving a shock velocity of 5.5 ± 0.5 km/sec. The initial velocity of this material was not measured.

4. MYCALEX (longitudinal). Three plates of mycalex were prepared so that the direction of the shock would be along the planes of cleavage of the material. These plates were shot with 5" of pentolite and Tuck conical lenses. The initial velocity showed no trend between 1/4" and 3/4" thickness averaging at 3.5 ± 0.5 km/sec. The shock velocity averaged 6.1 ± 0.5 km/sec. Graph 8 summarizes these data and is typical of the data obtained on the nonmetals.

5. STEATITE. Five runs were made on steatite, and rather large variations were obtained in the results of both shock and initial velocities. In all runs pentolite cylinders 5" high and 3-1/2" in diameter were used. The steatite slabs varied in thickness from about 0.5" to 1.6". Since the detonation wave was divergent it is not

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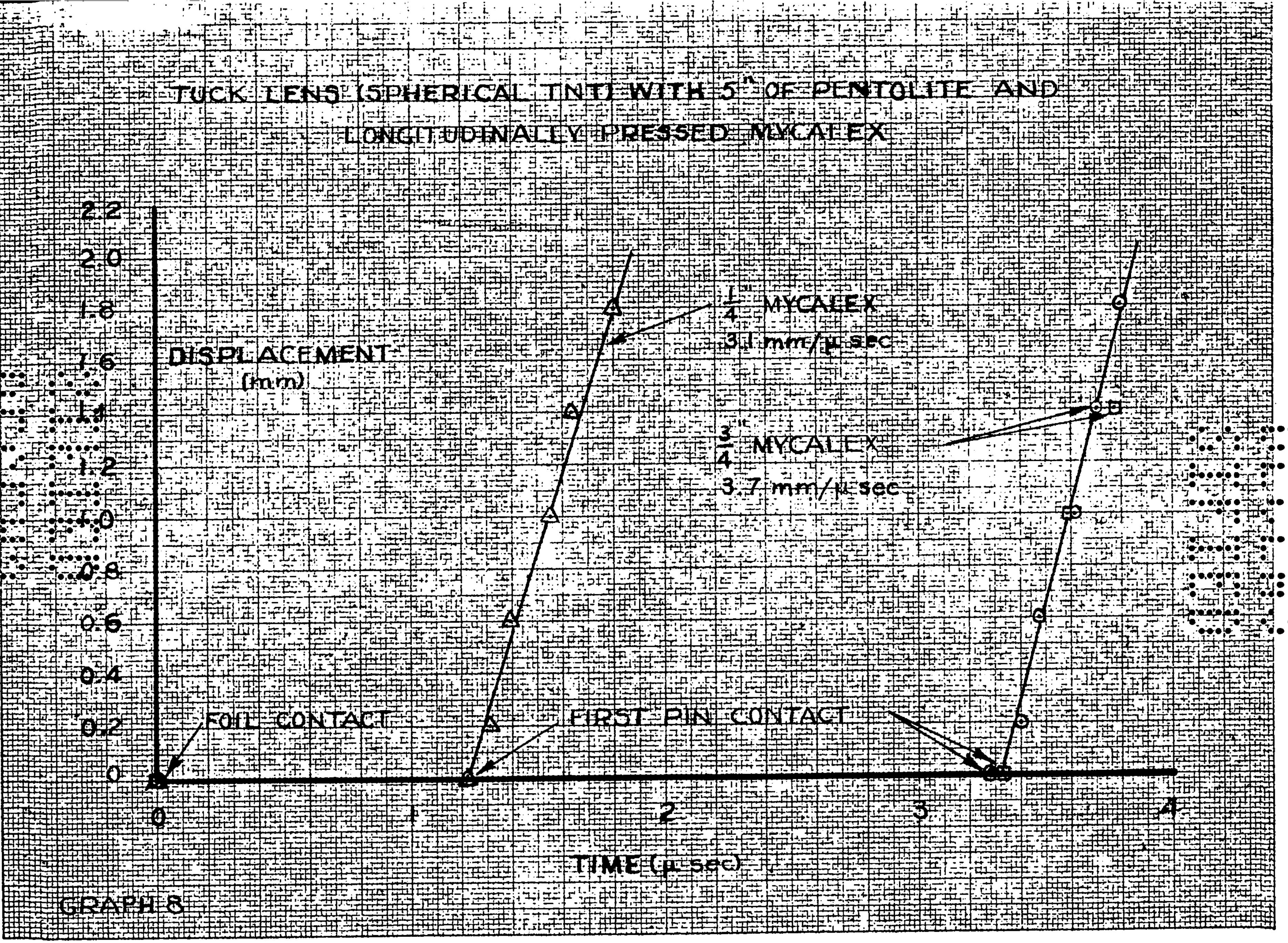

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surprising that the initial velocities for the thick slabs should be much less than that for the thin, but variations independent of thickness were observed. One possible conclusion is that one sample varies from the next and that it is difficult to fabricate the material so that it always has the same hydrodynamic properties. The data obtained are too meager to permit drawing any definite conclusions as to the cause of this variation. The values obtained for the shock velocity vary from 5.0 to 5.8 km/sec, and for the same thickness (1/2") the initial velocity ranges from 0.8 to 2.0 km/sec. This substance shows the peculiarity of steel in that a preliminary shock seems to precede the main shock wave.

6. <u>TUBALLOY OXIDE BONDED IN POLYSTYRENE</u>. Four runs were made on tuballoy oxide bonded in polystyrene. Good records were obtained in only two cases in which good agreement was obtained in the shock velocity. (3.4 km/sec) One slab, 1" in thickness gave a material velocity of 1.2 km/sec, whereas the other, 1/2" in thickness gave a material velocity of 2.3 km/sec. Five inches of pentolite without a lens was used in all shots. The material used was about 45 percent by volume of polystyrene and about 55 percent by volume of UO_2 pressed at 10,000 psi with a resulting density of about 6.1 gm/cc.

<u>GENERAL DISCUSSION OF RESULTS</u>: Since the shock velocities measured for the various substances have on the whole seemed independent of the thickness of sample as well as of the type of charge used it would seem that the numbers obtained are definitely characteristic of the materials studied for either diverging or plane shock waves. The same can not be said for the initial velocities imparted to the various substances; they vary as a very sensitive function of both the type and amount of charge used, as well of the thickness of the sample. However, the variations with thickness of sample are reduced considerably when sufficient H.E. is used in conjunction with plane

detonation waves initiated by conical lenses. When this was done variations in initial velocities imparted to a given metal in thickness range of 1/8" to 1/4" dropped to within 5 percent, the experimental error. All of the values listed in the summary table for the metals are characteristic of 1/8" thick samples of the material shot with 3-1/2" dia x 5" high pentolite cylinders initiated by Tuck conical lens shells filled with spherical grained TNT (special type B).

The values of the initial velocities of the nonmetals cannot be directly compared with those of the metals nor can the values for various nonmetals be directly compared with each other. They were all reduced to the values for 1/2" thickness of sample, but the calcium fluoride and longitudinal mycalex values were obtained with lens charges, while the others were obtained with 3-1/2" dia. by 5" high pentolite charges initiated by singlepoint detonation. Therefore, the values for these two materials are closer to those for the infinitely thin slab, plane-wave values than are the results quoted for the other nonmetals. In comparing the initial velocities of the nonmetal with those of the metals, one must keep in mind that the metal values are characteristic of plane shock waves in every case and also characteristic of 1/8" thick samples of the materials rather than 1/2".

An examination of the various sources of experimental error in these measurements, such as timing errors and errors in spacing pins, indicates that fluctuations from shot to shot in both shock and initial velocities should be well within 10 percent. However, a few shots, identical in every known respect, gave results which were different from each other by as much as 30 percent. These fluctuations as studied in the case of tuballoy seemed not to depend on the flatness of the detonation wave. Apparently qualities not understood, inherent in the H.E. or samples of the substances studied are all that are left to explain these fluctuations. In view of these gross fluctuations in the results for some of the materials the probable errors

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were very conservatively set on all of the values. In most cases the probable errors listed are about twice the probable errors computed in the conventional manner from the data for a single material.

D. K. Froman and A. C. Graves have contributed valuable guidance to the work, and other members of group G-8 have assisted in construction and operation.

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