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Particle Velocity						
C-J parameters						
TNT						
EMV Gage						

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THE MEASUREMENT OF PARTICLE VELOCITY IN CAST TNT

By:

D. J. Edwards and J. O. Erkman

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Details of illustrations in
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Approved by:

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White Oak, Silver Spring, Maryland

NOLTR 71-19 14 June 1971

THE MEASUREMENT OF PARTICLE VELOCITY IN CAST TNT

The work described in this report was carried out under IR 159, Task MAT-03L-000/ZR011-01-01 (Transition from Deflagration to Detonation) of NOL's Independent Research Program.

The work described is the measurement of particle velocity in detonating cast TNT by the electromagnetic velocity gage technique. The results of this study are in agreement with reported Russian values of particle velocity in cast TNT.

The identification of commercial materials implies no endorsement or criticism by the Naval Ordnance Laboratory.

GEORGE G. BALL
Captain, USN
Commander

Albert Lightbody
ALBERT LIGHTBODY
By direction

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INTRODUCTION

The particle velocity (u), vs time (t), behavior of detonating cast TNT has been measured by the electromagnetic velocity (EMV) gage method. This method, which was introduced into the international literature by Zaitsev, Pokhil, and Shvedov[1] in 1960, is a direct application of Faraday's law of electromagnetic induction. The particle velocity in a non-conducting medium can be obtained by measuring the emf developed across the base of the EMV gage which is moving with the medium in a magnetic field. This magnetic field must be oriented normal to the direction of the gage base and the direction of motion. The generated emf across the gage base, in volts, is given by

$$V = H \cdot u \cdot \ell \cdot 10^{-3} \tag{1}$$

where H is the magnetic field in gauss, u is in mm/μsec, and ℓ is the gage base length in cm. The EMV gage method and the necessary instrumentation were described and checked out in a non-conductor (PMMA).[2,3] That work showed that the measured particle velocity agreed, within experimental error, with previous work using a different method on PMMA.

When used to study the flow behind detonation waves, the EMV gage method, in principle, measures not only the u,t behavior of an explosive but can also be used to determine the Chapman-Jouguet (CJ) particle velocity (u_{CJ}) and the reaction time (t_{CJ}) directly and thus the reaction zone width and the CJ pressure (P_{CJ}). All of the reported work[1,4-11] in explosives using the EMV gage method is of Russian origin, mostly by Dremin or his associates. The Russian results of the CJ parameters of several explosives raise the question of misinterpretation of free surface velocity measurements by American researchers. In particular for cast TNT, Dremin[4,7,12] et al, have reported a CJ pressure which is about 15% lower than the findings of Craig,[13] who used the free surface velocity method to obtain the $u_{f.s.}$ vs x curve for Dural on TNT. Dremin has argued that the wrong point was selected in the observed free surface velocity vs distance curve as the value to be associated with the CJ condition. Craig argued that the region between the CJ point he chose and the value chosen by Dremin is a decay zone caused by the divergent flow behind the detonation front. Petrone's paper[14] on nitromethane, which is another explosive whose CJ parameters are also in question, supports Dremin's arguments. Our results in cast TNT, which are preliminary, tend to support Dremin.

Cast TNT was chosen instead of pressed TNT in this study because its reaction time should be greater than the rise time of our recording system, ≈ 0.10 µsec, which is one-third of Dremin's[4] reported reaction time. This situation is necessary to observe any change in slope which might be associated with the CJ point.[3] The present work shows that a single record cannot be used to determine a CJ point in cast TNT; this may be true for other explosives as well. Another approach to the problem, that of using charges of different length and, thus, varying the steepness of the Taylor wave, was used.

EXPERIMENTAL

Setup

The explosive charge and booster configuration used in this work is shown in Figure 1. A Baratol-Pentolite plane wave booster, PWB (50.8 or 63.5 mm diameter), was used in each experiment to initiate either the cast TNT directly or an intermediate layer of a different high explosive which acted as a booster for the TNT. The intermediate layer, when present, was either pressed Pentolite (ρ_0 = 1.56 ± 0.01 gm/cc) or pressed TNT (ρ_0 = 1.60 ± 0.01 gm/cc) pellets which had been machined to 50.8 mm diameter and thickness L. The particle size of the TNT was ~200 microns. The cast TNT was machined from cream cast charges into pellets of 50.8 mm diameter and thickness x. (The TNT was melted, cooled with stirring to 78°C, and then poured into a 15" long heated mold (75°C).) The density of the cast TNT was 1.62 ± 0.01 gm/cc. The reported detonation velocity, D, of the cast TNT is 6.85 mm/µsec, of the pressed TNT is 6.91 mm/µsec, and of the pressed Pentolite is 7.28 mm/µsec. The intermediate layer was necessary because the PWB's were not powerful enough to initiate the cast TNT close to the PWB-cast TNT interface. Jacobs, et al[15],

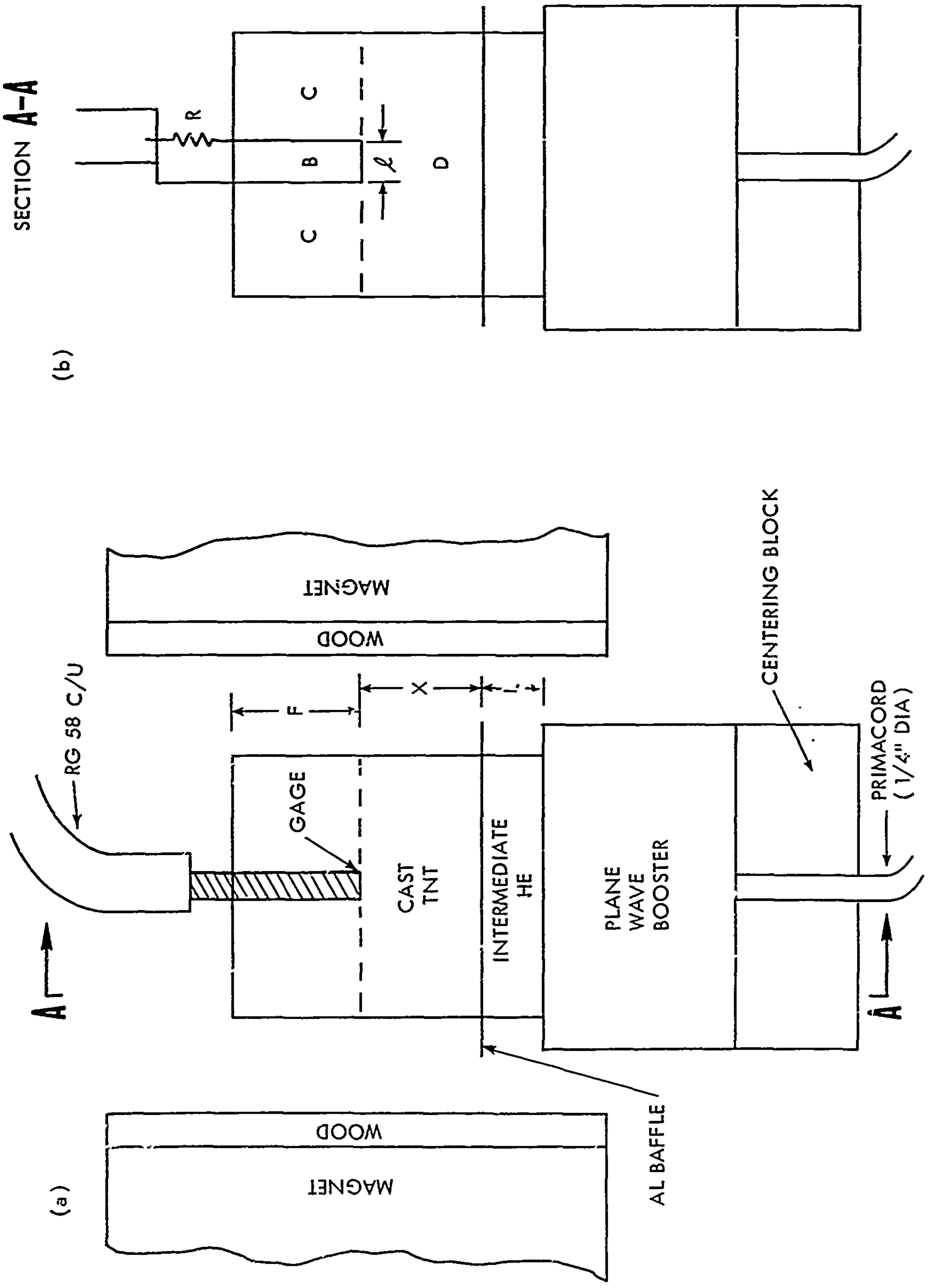

FIG. 1 EXPERIMENTAL SETUP

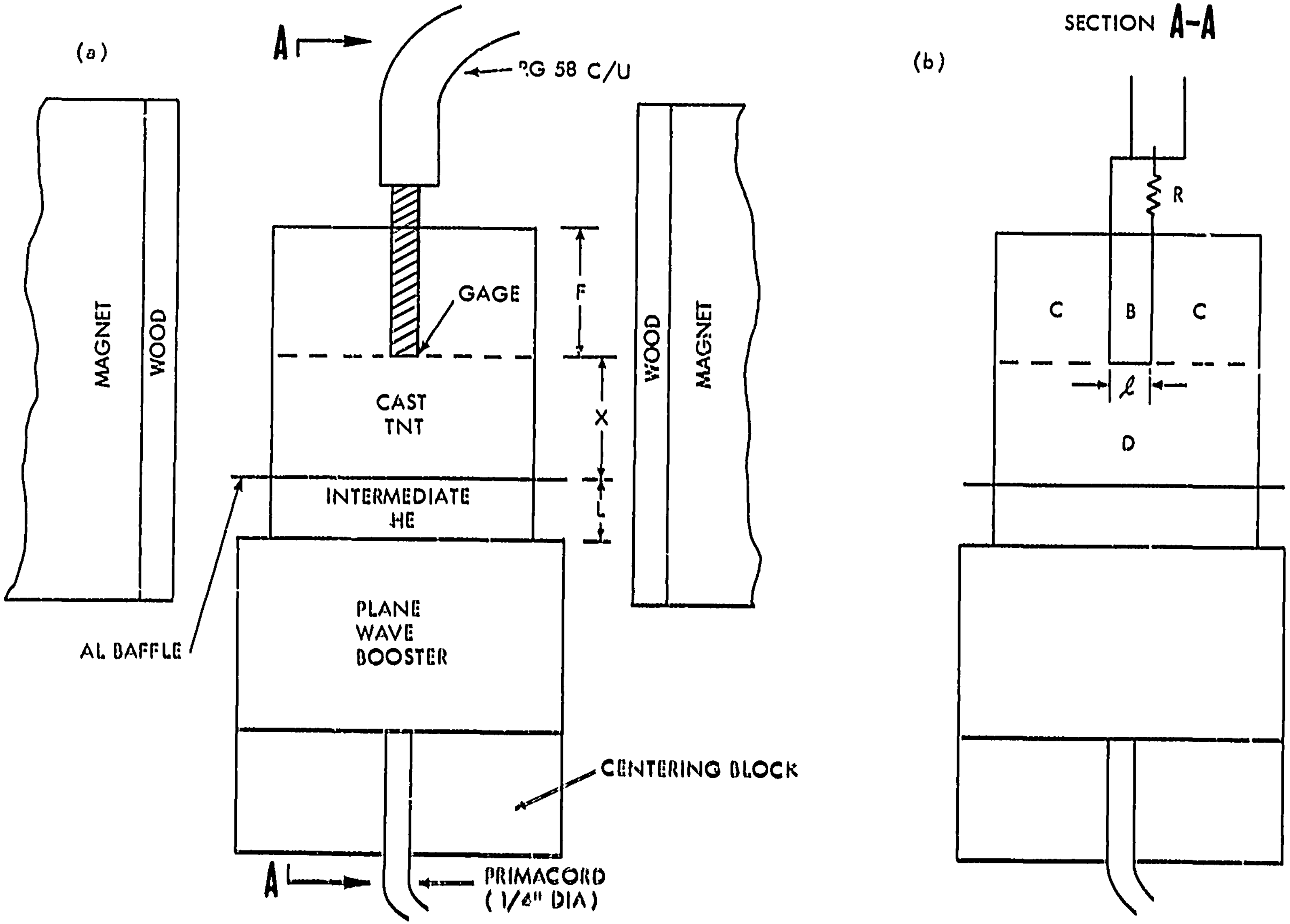

FIG. 1 EXPERIMENTAL SETUP

have shown that cast TNT requires a run length which is related to the initiating pressure to attain steady state detonation; for 75 kb the distance is 20mm and for 137 kb, 6 mm. Because Baratol would induce pressure of about 110 kb, at the interface, the run length to steady detonation this would produce in cast TNT would be intolerable for our purposes. For this reason, an intermediate explosive which would reach steady state detonation quickly was added (see Fig. 1). Pentolite and pressed TNT were chosen because their impedances, $\rho_0 D$, are very close to cast TNT: $\rho_0 D = 11.35$, 11.06 and 11.10 gm-mm/μsec-cc for Pentolite, pressed TNT, and cast TNT respectively.

The PWB was initiated by a primacord lead (120 grain RDX/foot) 30 cm long which in turn was initiated by an exploding bridgewire detonator. The primacord isolates the charge from the detonator to prevent possible stray electrical signals from the firing unit being picked up by the gage.

The usual EMV gage consists of a rectangular loop of aluminum foil 0.13 mm (5 mils) thick, 5 mm wide, and 10 mm long. It is mounted in a cast TNT back-up assembly whose thickness, F, is 25.5 mm (see Fig. 1). The gage is mounted in the cast TNT by shaping the foil around piece B. A thin layer of silicone grease is placed between the pieces except near the gage. Then pieces B, C, and D are placed together and cemented using Duco on the exterior under a slight pressure. The gage circuit is completed by connecting the foil leads (30-55 mm length) to a RG 58 C/U coaxial line (50 ohms nominal impedance) with a resistor, R (50 ohms), in series with the foil.

A 0.05 mm thick, 6.4 cm square aluminum baffle (see Fig. 1) was located in the plane of the HE-cast TNT interface and was grounded. The significance of this baffle will be discussed in the following section.

The magnets and power supplies used in these experiments are discussed in Ref (2) and (3). The magnetic field was measured with a Rawson-Lush Type 824 rotating coil gaussmeter (± 1% accuracy) at the mean position of the gage. Then, with no field present, the charge assembly was placed in position, the current and therefore the magmetic field returned to the same value as before and the shot fired.

Instrumentation

The EMV gage was connected to 15 feet of RG 58C/U (50 ohm nominal impedance) coaxial cable with a 50.8 ± 0.25 ohm resistor in series with the gage to minimize any reflections. The cable was connected to the center lead of a 50 ohm power divider (Tektronix Model 017-0082-00). The other two leads of the power divider were connected to two fast response oscilloscopes, a Tektronix Model 454 (2.4 ns rise time) and a Hewlett-Packard Model 175 (7.0 ns rise time), through 50 ohms terminators (Tektronix Model 011-049-01). Figure 2 is the circuit diagram of this arrangement. The arrangement results in the proper termination of all cables; that is, the coaxial cables see 50 ohms at both ends. This arrangement, however, results in a considerable drop in amplitude of the signal generated by the gage. The 50 ohm resistor near the gage reduces the signal by 50% while the power divider further splits this signal by 54.88% with the net result that each oscilloscope sees only 27.44% of the original voltage.

Voltage calibration marks were placed on all oscilloscope camera records. This voltage was obtained from a power supply, the output of which was measured with a Fairchild Model 7050 Digital Multimeter (±0.1% accuracy). The calibration voltage was placed on the oscilloscope records with the power divider in place; this procedure eliminates any corrections due to imperfect splitting of the signal by the power divider. Time calibration was obtained from a crystal-controlled time mark generator (Tektronix Model 180A) and was placed on separate records because of the limited viewing area of the oscilloscope screen. The oscilloscopes were triggered internally by the output voltage from the gage.

The aluminum baffle shown in Figure 1 was found useful in reducing spurious signals which appeared in the first experiments with cast TNT; this phenomenon also appeared in the work with PMMA[2,3] where this baffle was also employed for the same purpose. (Figure 3

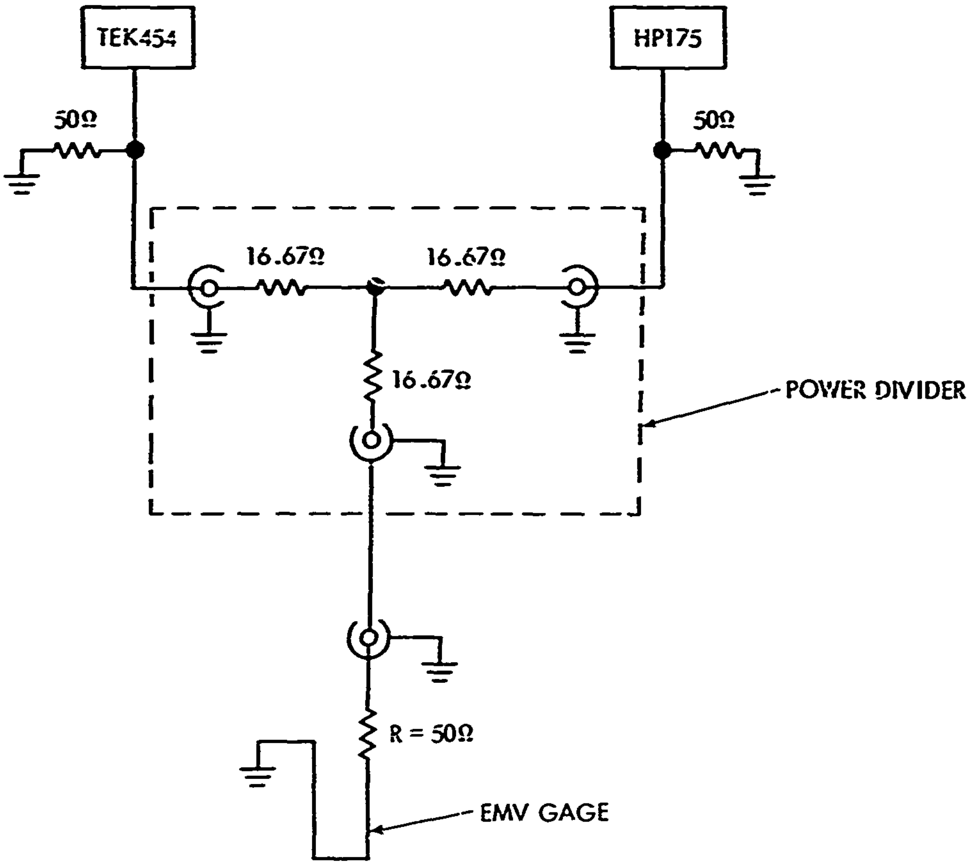

FIG. 2 CIRCUIT DIAGRAM

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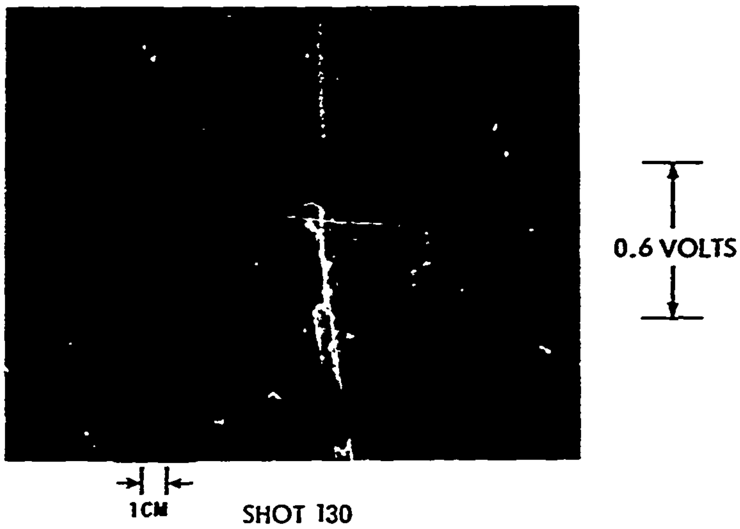


SHOT 130

GAGE LOCATED 50.8 MM FROM PENTOLITE BOOSTER

MAGNETIC FIELD 750 GAUSS

SWEEP SPEED 0.05 μSEC/CM

FIG. 3 EXAMPLE OF A RECORD OBTAINED WHEN NO ALUMINUM BAFFLE WAS USED.

shows an example of the signal obtained without a baffle.) The baffle was grounded to a circuit which was separate from the oscilloscope circuit. This grounded baffle greatly reduced and, in most cases, completely eliminated the spurious signals. A similar type of noise was observed by A. A. Brisn, et al,[10] when the electromagnetic method was used to study conductivity in detonating explosives.

Data Reduction

The oscilloscope records were read on a Universal Telereader with the origin at the point where the trace leaves the baseline. The digital data obtained were then converted to u and t by means of a computer program using eq. (1) and the calibration of the oscilloscope.

FACTORS WHICH AFFECT RECORDS AND THEIR INTERPRETATION

There are several factors which must be considered when interpreting the records. These can be divided into two main groups: (a) those which contribute to the rise time, and (b) those which are connected with the conduction of the plasma.

System Rise Time

There are at least five factors which contribute to the overall rise time of the recording system; they are:

1. wave front curvature,
2. shock impedance mismatch between the gage and the cast TNT,
3. wave front tilt,
4. inherent rise time of the oscilloscopes,
5. electrical impedance mismatch between the coaxial cable and the oscilloscope or the EMV gage.

The first three are connected with the detonation itself, while the last two are electrical. These effects have been discussed in Ref. (2) and (3). The planarity of the wave front after it had traveled from a 50.8 mm diameter PWB through 25.4 mm of pressed TNT and 25.4 mm of cast TNT was examined using a streak camera (writing speed, 4 mm/μsec); the front was plane to within reading error over the middle 20 mm of the charge which allows factor 1 to be neglected, see Figure 4. However, a tilt of 0.2 mm, or 0.02 radians was observed in the region where the gage would have been placed.

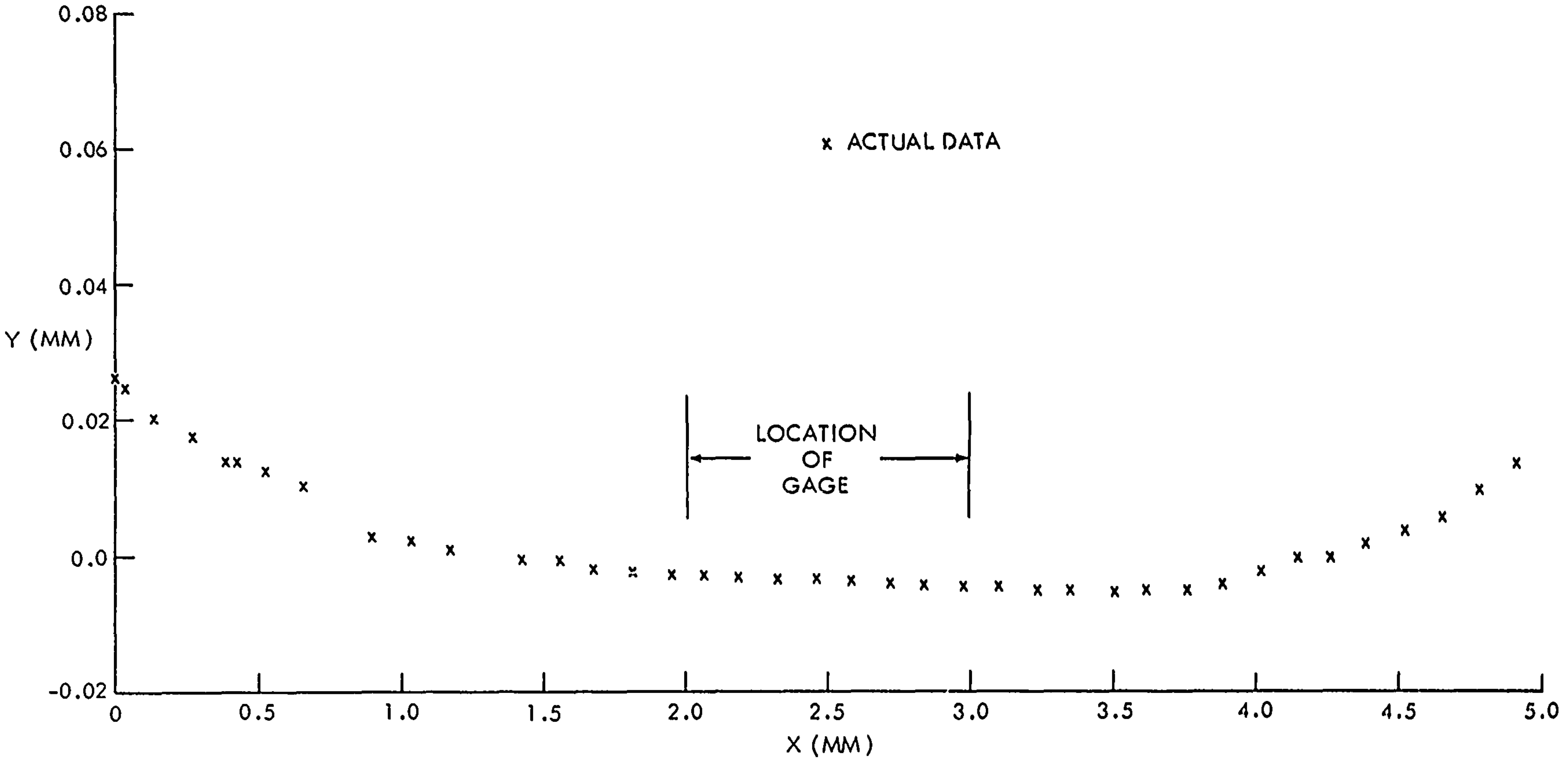


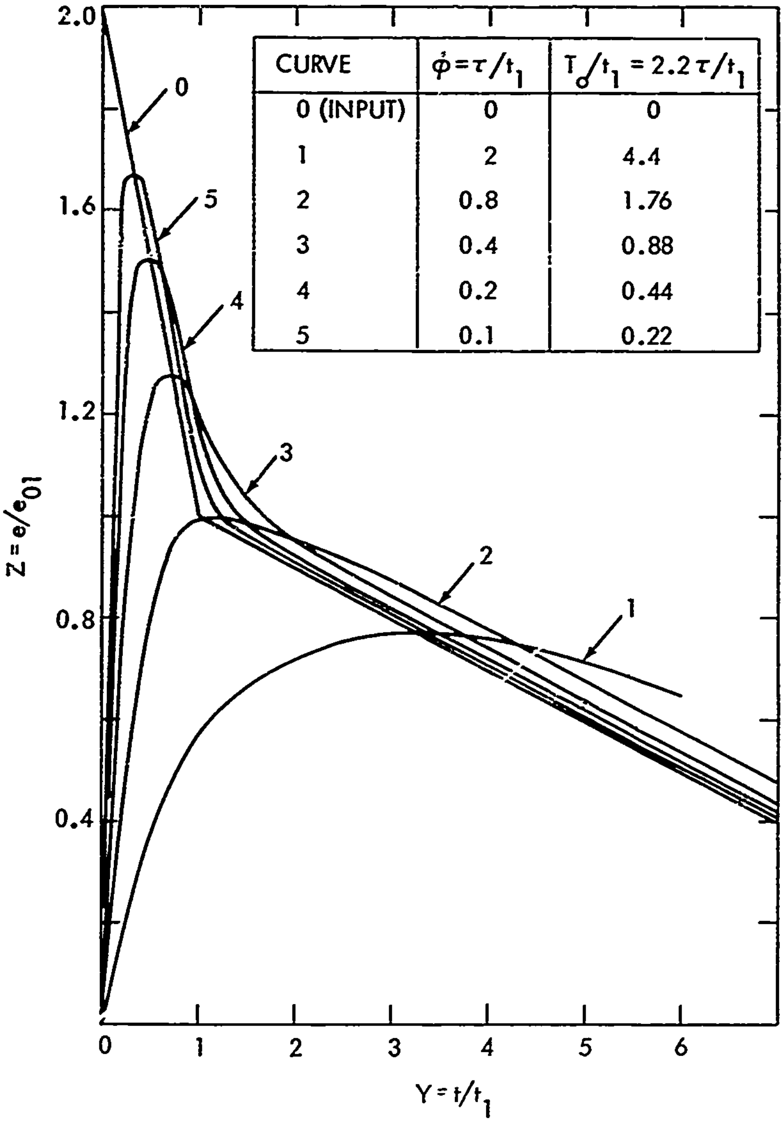
FIG. 4 DETONATION WAVE SHAPE IN CAST TNT

This would result in a rise time of 29 ns for factor 3, T_3. The total rise time, T_o, can be calculated using the equation

$$T_o = \sqrt{\sum_i T_i^2} \tag{2}$$

where the T_i's are the individual contributions listed above.[2,3] If we let T_3 = 0 and 29 ns, T_o is 87 and 92 ns for T_2 = 87 ns (two double reflections in the pickup foil using an average shock velocity of 6 mm/µsec). If three double reflections are used, T becomes 130 and 134 ns respectively. Table 1 lists the time observed for the trace to reach the maximum point in the curve, T_{max}, for experiments in which a 5 mil foil was used. T_o was estimated by taking 90% of T_{max}. All but three of the experiments have an estimated rise time below 134 ns. The longer rise times are attributed to a tilt greater than that shown in Figure 4. Thus, wave front tilt can have an appreciable effect on T_o, and it can be larger than the specific example given.

The effect of rise time on the true signal was investigated theoretically[2,3]. A triangular pulse whose initial fall off was rapid and then abruptly became less steep (i.e., double sloped) was used as the input to an RC circuit. A double sloped pulse was chosen because it is an approximation to the von Neumann spike followed by a Taylor wave. This calculation showed that the observed trace will overshoot the applied pulse at some time after the driving pulse has started to decay and then eventually closely parallel the applied pulse. The problem was made dimensionless by introducing the variables $Y = t/t_1$, $\phi = \tau/t_1$, and $Z_i = e_i/e_{01}$ where t_1 is the time to the break in the input pulse, τ = RC is the time constant of the circuit, and e_{01} is the amplitude of the pulse at the break. It is shown in Ref. 2 that $T_o \sim 2.2\tau$. The results of this calculation are shown in Figure 5. The calculation also showed that a recording system with a rise time smaller than 0.44 of the time to the break is needed to locate the break. If the reaction time in cast TNT is 0.30 µsec as Dremin claims[4] then our recording system will generally be able to reproduce this break.



CURVE	$\phi=\tau/t_1$	$T_o/t_1 = 2.2\tau/t_1$
0 (INPUT)	0	0
1	2	4.4
2	0.8	1.76
3	0.4	0.88
4	0.2	0.44
5	0.1	0.22

FIG. 5 RESPONSE OF RC CIRCUIT TO A DOUBLE SLOPE INPUT PULSE

Conductivity

The effect of conduction is very pronounced in detonating cast TNT and is observable in two ways: (a) different output voltage-time curves obtained when the base is left off the gage and (b) different u,t curves obtained for different Al gage thicknesses. Three experiments were attempted in which the base of the gage was removed. Figure 6 is a comparison of the results obtained for a baseless and a regular gage in cast TNT. The pseudo particle velocity obtained from the baseless gage lies 0.5 mm/μsec (~33%) below the particle velocity obtained from the regular gage. In an attempt to gain more information, the cable of the system was changed from 50 ohms (with a 50 ohm resistor in series with the gage) to 93 ohms (with a 93 ohm resistor in series with the gage). The results of this experiment are ~0.9 mm/μsec (~60%) below the regular gage valve; it was anticipated that the curve would lie between the regular gage and the 50 ohm baseless results. The full meaning of these results are not understood at present and further work is planned in this area. In surprising contrast to the present results from the detonation of cast TNT, the absence of the gage base in detonating pressed tetryl did not greatly affect the shape of the output-time curves.[17]

Dremin[4] has used various thicknesses of gages made of several different metals. He reported that gage thickness did not affect the output, provided the thickness was less than 6 mils. In attempting a spot check of this statement we found that in cast TNT, gage thickness does affect the results. Several experiments were tried with Al and copper foils (resistivity, 2.83×10^{-6} and 1.73×10^{-6} ohm-cm respectively) of different thickness. Figure 7 shows the results for 1 and 5 mil Al gages where all other factors are the same. As is evident from the figure, the thinner and, therefore, higher resistance gage gives much lower values of u, and u_{CJ} much lower than any generally accepted values for TNT. Figure 8 shows the results of a 3 mil copper gage and a 5 mil Al gage in otherwise identical experiments. (There is some spurious signal on the copper curve; this shot, however, was fired without the grounded Al baffle.)

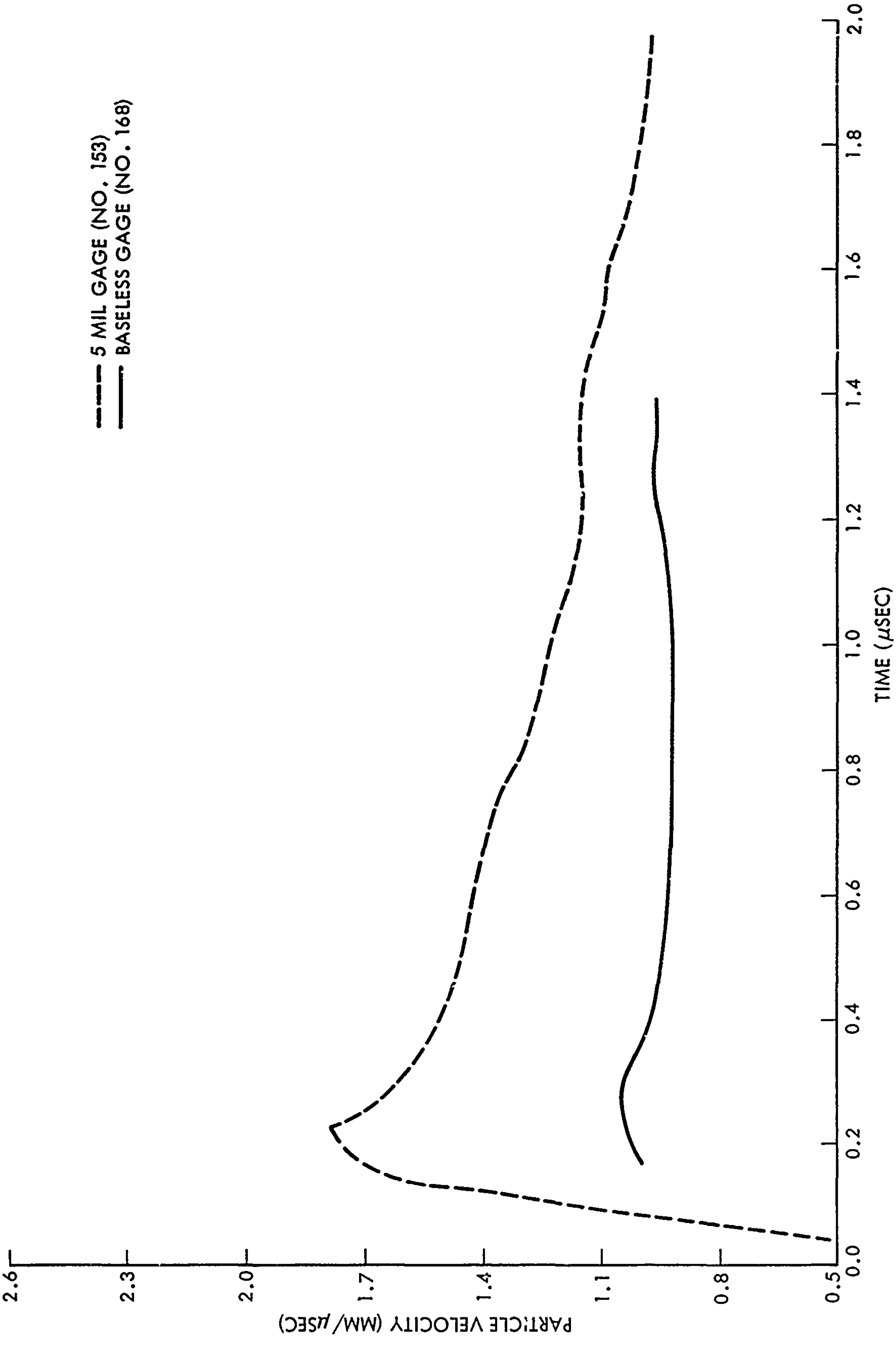


FIG. 6 RESULTS OF REGULAR AND BASELESS GAGE

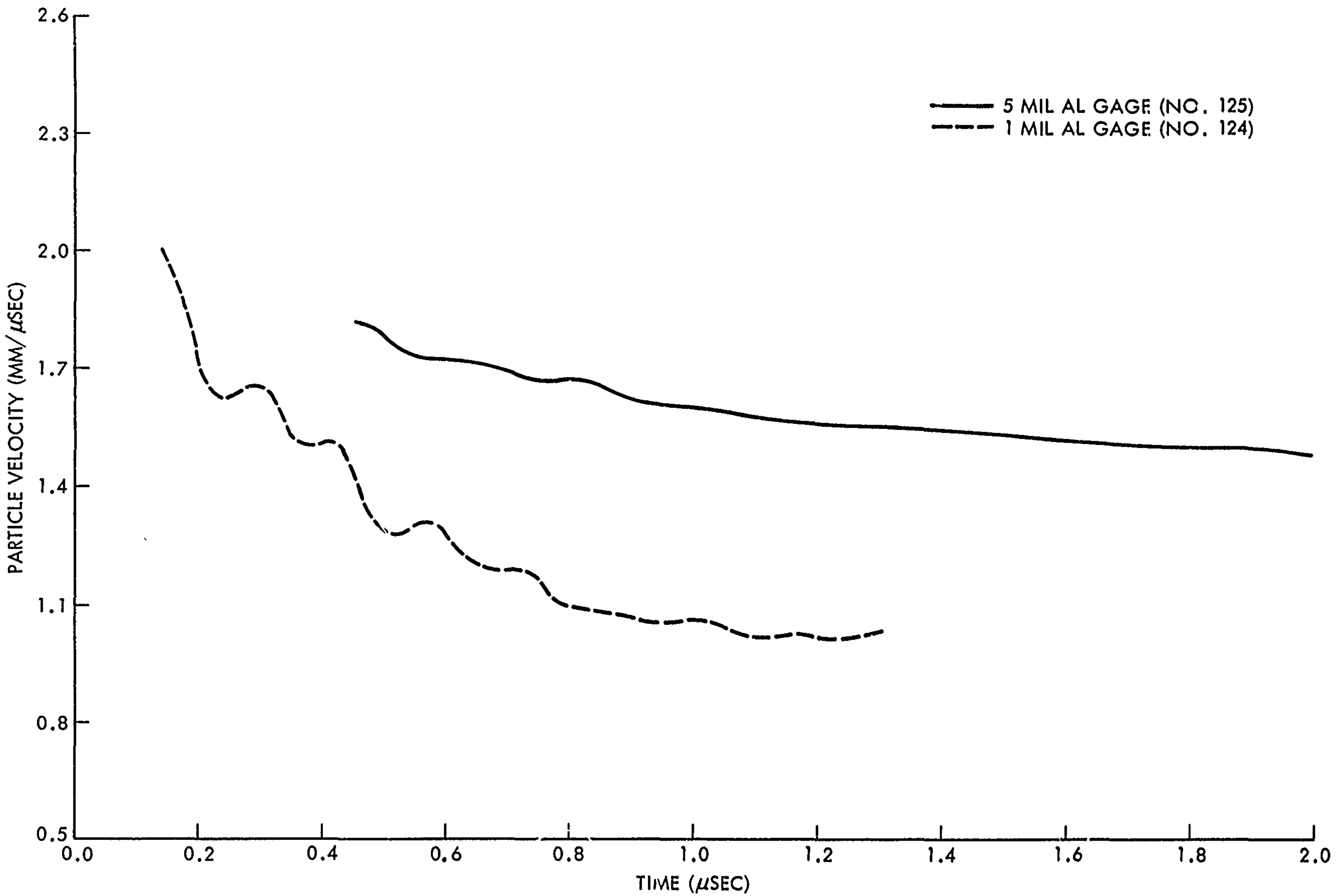


FIG. 7 RESULTS USING DIFFERENT THICKNESS AL FOILS

Figure 8 also shows the results for a 5 mil copper gage. The curves of the 3 mil Cu and 5 mil Al in Figure 8 are coincident to 3%. On the basis of these results, the 5 mil Al gage was selected for the present work.

APPLICATION OF THE EMV METHOD AND REPRODUCIBILITY

A total of 24 experiments have been carried out in cast TNT. Of these only one experiment resulted in no record being obtained. Four of the remaining 23 had a spurious signal superimposed on the trace but still produced some useful information. These experiments are listed in Table 2.

Reproduciblity

There are two types of reproduciblity involved in this work: (a) that of the u,t curves obtained from the two oscilloscopes for the same experiment; and (b) that of the u,t curves obtained for replicate experiments. Figure 9 shows the u,t curves obtained from the two oscilloscopes for shot 138; the curves are coincident to within reading error (±1%) for the time covered by the oscilloscope using the faster sweep. The oscilloscope with the faster sweep was able to record the rise of the signal whereas the other oscilloscope did not because of the slower sweep speed. The assumption is made that the records would be coincident for the entire range; the fact that the u,t curves also agree for replicate shots (see below) adds weight to this assumption. Figure 10 shows the u,t curves obtained from replicate shots ($x + L = 38.1$ mm, shots 138 and 144); the two curves, obtained from the HP 175 oscilloscope, agree to within ±1.5% for the region $100 < t < 500$ ns and to within ±4% over the remainder of the curves. The difference in the first 100 ns is due to differences in the rise time from shot to shot. Thus, reproduciblity is quite good.

Evaluation of Single Record Results

As mentioned in the Instrumentation Section, the oscilloscopes were triggered internally; the signal from the EMV gage is transmitted directly to the trigger circuits of the oscilloscopes but is delayed in transmission to the oscilloscopes deflection plates. Figure 11 is

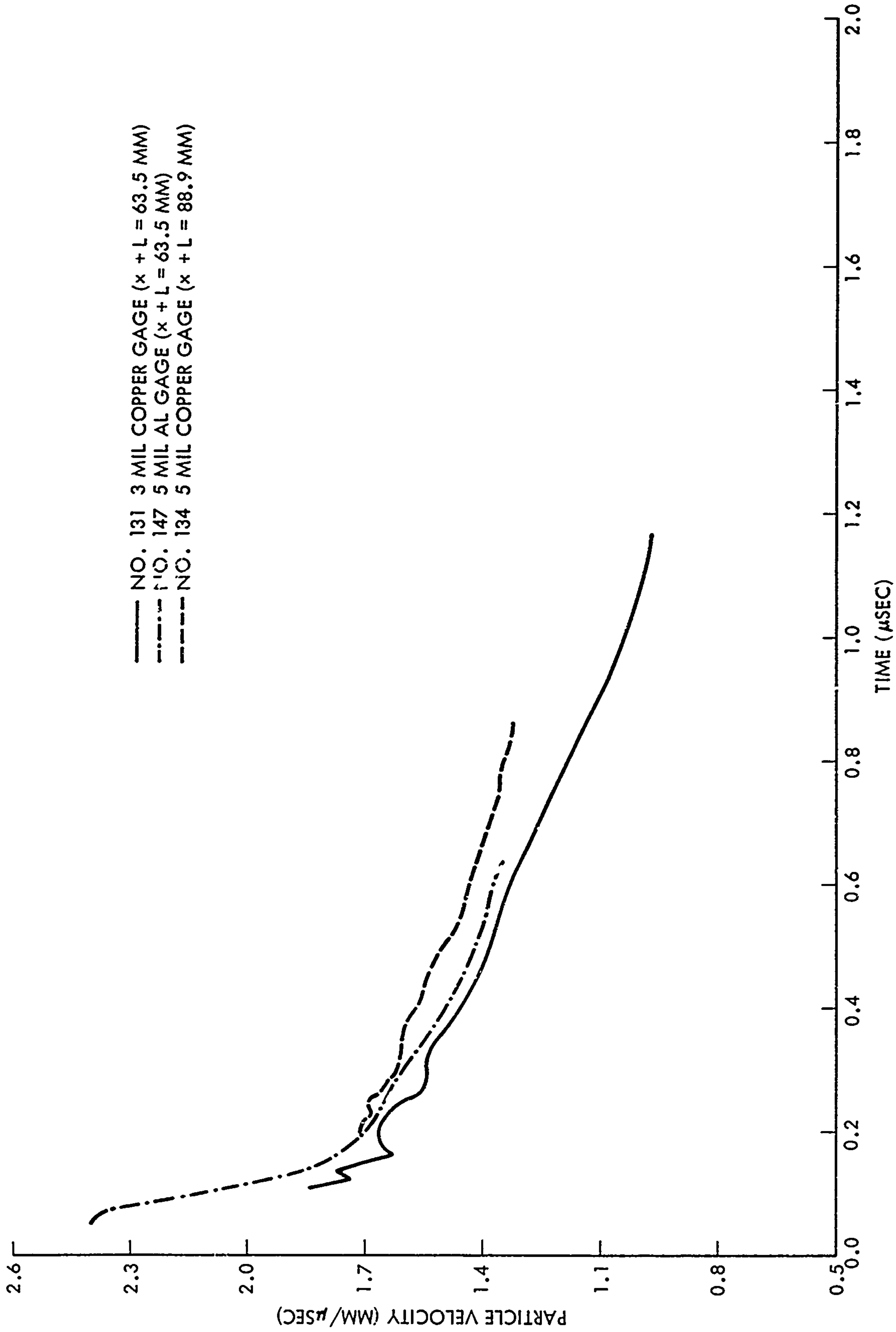


FIG. 8 COMPARISON OF COPPER AND ALUMINUM GAGES

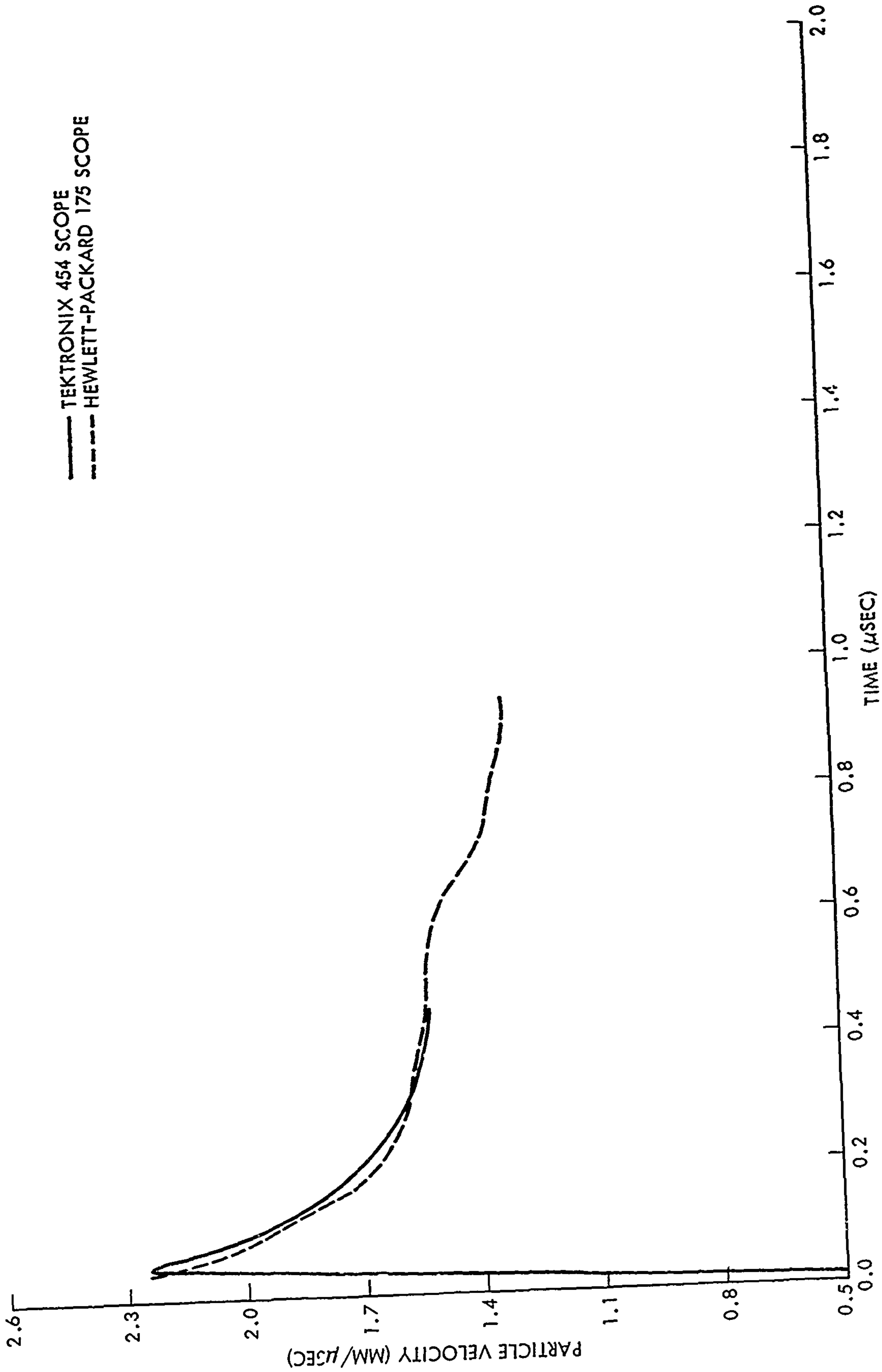


FIG. 9 COMPARISON OF OSCILLOSCOPE RECORDS FOR SAME SHOT (NO. 138, x + L = 38.1 MM)

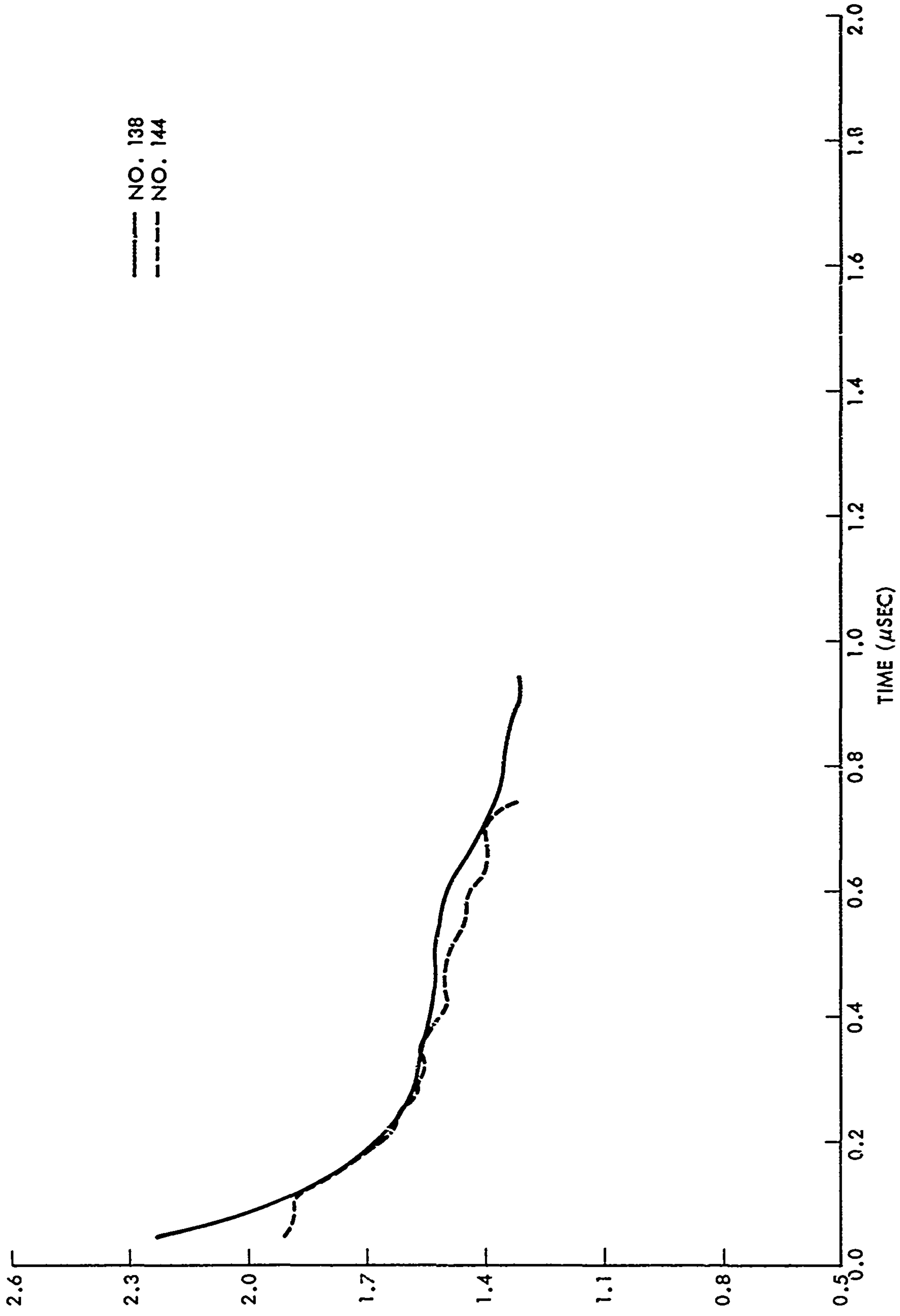


FIG. 10 COMPARISON OF RESULTS FOR REPLICATE SHOTS (x + L = 38.1 MM)

a set of typical records obtained from a single experiment; these records correspond to the u,t curves plotted in Figure 9. As can be seen from Figures 9, 10, and 11, no sharp break or sharp change of slope is evident on the records. This is true for all but two records for cast TNT. Figure 12 shows an example of a record with a break (shot 174). The undulations in the trace over the last half of the record are probably due to motion of the leads (which are connected to the cable) because the undulations occur after the detonation has reached the end of the charge. The infrequent appearance of a sharp break leads to the conclusion that the CJ condition cannot be obtained from a single experiment. The implication of similar work in the Russian literature[4] was that the CJ point could be determined from a single experiment if the rise time of the system was shorter than the reaction time. Dremin's records of cast TNT (Figs. 2a and 2b of Ref. 4) do indeed show a sharp break. When these records are plotted to the time scale used in this work, the sharp break disappears; Dremin's curves also agree in shape with ours (see Fig. 13). Because the break in the curve can be enhanced or reduced by using different time scales for the u,t plot, other approaches are desirable to insure that the break is meaningful. One such approach is described in the next section.

Comparison of Observed and Predicted u,t Curves

The discussion in Evaluation of Single Record Results section pointed out the fact that distinct breaks in a single record were infrequently observed and, therefore, u_{CJ} and the reaction time could not be determined with the EMV gage method using a single record with any degree of certainity. Another approach, which, in principle, can be used to determine u_{CJ}, is to place EMV gages at various distances from the boostering system and compare the u,t curves obtained for different lengths of run. This approach has been used by the Russians[5] in a situation where they could not observe a break which could be associated with the end of the reaction zone. The u,t curves should coincide in the reaction zone region regardless of the length of the charge, because the reaction zone is assumed to be independent of the charge length if the detonation has reached steady state. The falloff

NOT REPRODUCIBLE

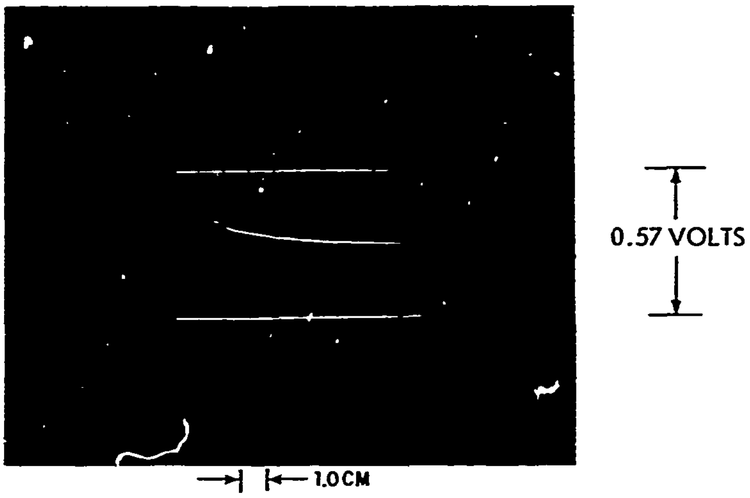


FIG. 11A TEK 454 OSCILLOSCOPE

SWEEP SPEED 0.05 μSEC/CM

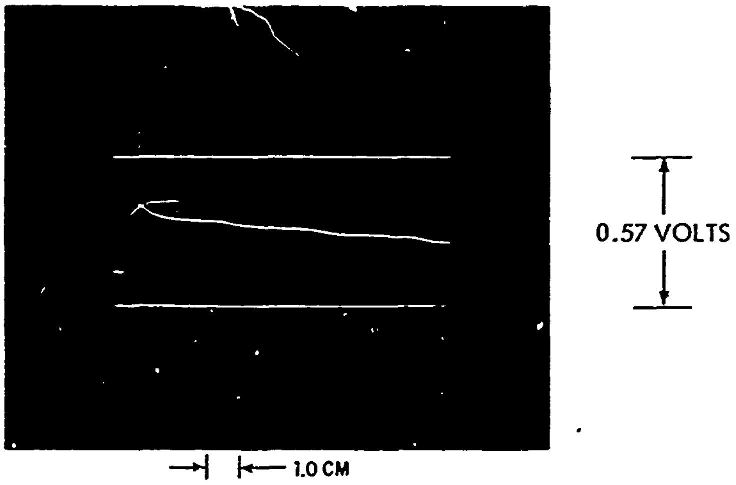


FIG. 11B HP 175 OSCILLOSCOPE

SWEEP SPEED 0.20 μSEC/CM

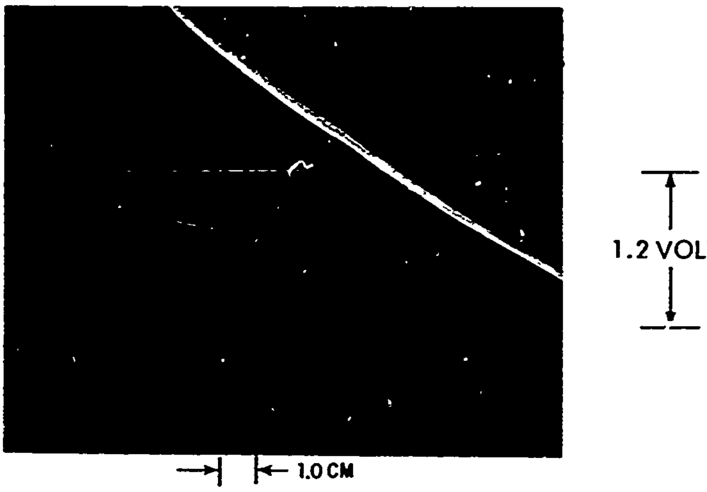
SHOT 138

GAGE LOCATED 25.4 MM FROM PENTOLITE BOOSTER

MAGNETIC FIELD 255 GAUSS

FIG. 11 TYPICAL RECORDS

NOT REPRODUCIBLE



SHOT 174

GAGE LOCATED 25.4 MM FROM PENTOLITE BOOSTER.
MAGNETIC FIELD 868 GAUSS
SWEEP SPEED 0.5 μSEC/CM

FIG. 12 RECORD SHOWING DISTINCT BREAK

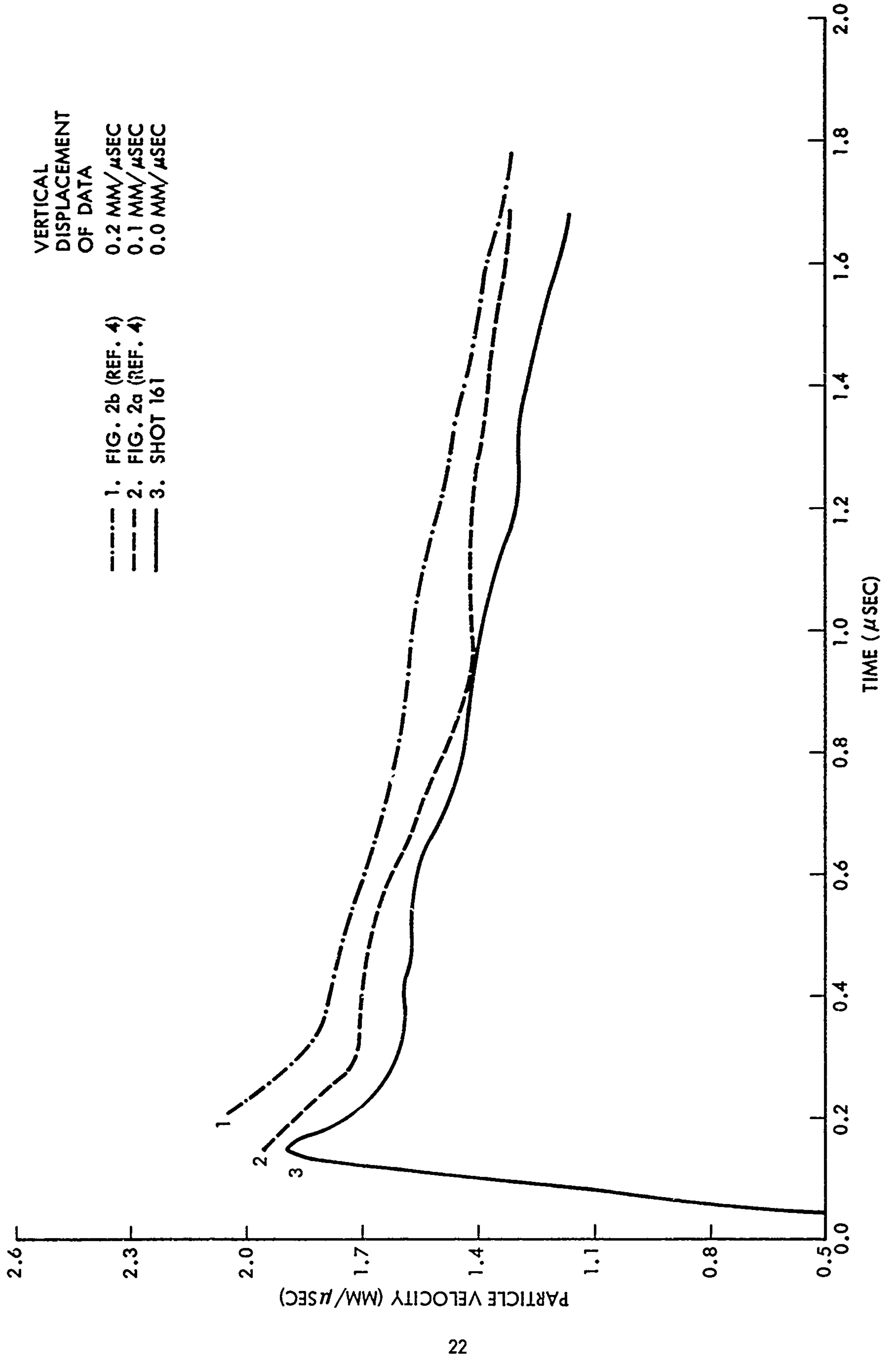


FIG. 13 COMPARISON OF PRESENT RESULTS WITH DREMIN'S RESULTS

in the u,t curves from the CJ value is called the Taylor wave, in which flow variables depend on the run length, x + L, of the charge. That is, as x + L is increased the slope of the u,t curve will decrease if the flow is one-dimensional. Thus, by plotting the u,t curves with the origin of the plot coinciding with the zero time of the individual records, one should observe a region where the curves coincide and then a region in which they diverge.

Qualitatively, the u,t curves behave as mentioned above. Figure 14 is a plot of the u,t curves obtained for charges having $(x + L)/d < 1$. For such charges, the flow should still be one-dimensional and the slope of the u,t curves should decrease with increasing x + L. This is the situation shown in Figure 14. The curves coincide for $t \lesssim 300$ ns and diverge from $t \sim 300$ ns. Figure 15 is a plot of the u,t curves obtained for $(x + L)/d \geq 1$. In this region, the flow probably is no longer one-dimensional because lateral rarefactions have had time to reach the center of the charge. The one-dimensional behavior of the u,t curves in the region following the reaction zone will no longer be present. Figure 15 shows that the region of coincidence for $t < 300$ ns is still the same, but the slopes of the u,t curves for $t > 300$ ns are not as reproducible and do not exhibit a trend with increase in (x + L). Thus, by qualitatively comparing the u,t curves for charges of different length, one arrives at a CJ velocity of ~1.60 mm/μsec and a reaction time of ~ 300 ns which are in excellent agreement with Dremin's results[4].

The experimental curves discussed above can be compared with computed curves for plane one-dimensional flow in a polytropic gas. The flow is described by

$$u = \frac{2(D-u_{CJ})}{\gamma-1}\left[\left(\frac{t}{t_R+\tau}\right)^{-\mu} -1\right] + u_{CJ} \qquad (3)$$

where

u = particle velocity

u_{CJ} = particle velocity at the CJ point

γ = adiabatic exponent of the gas

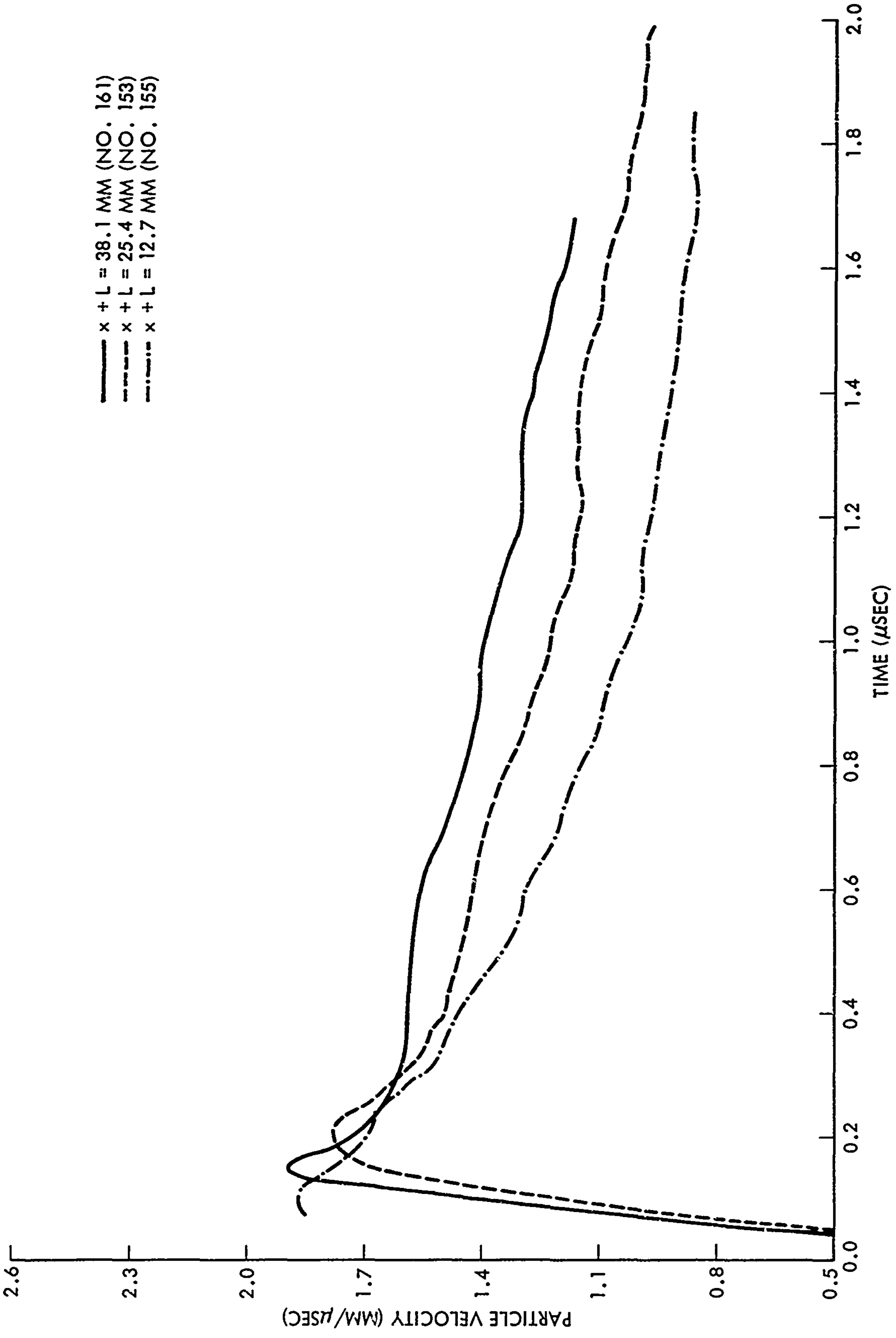


FIG. 14 u, t CURVES FOR (x+L)/d <1

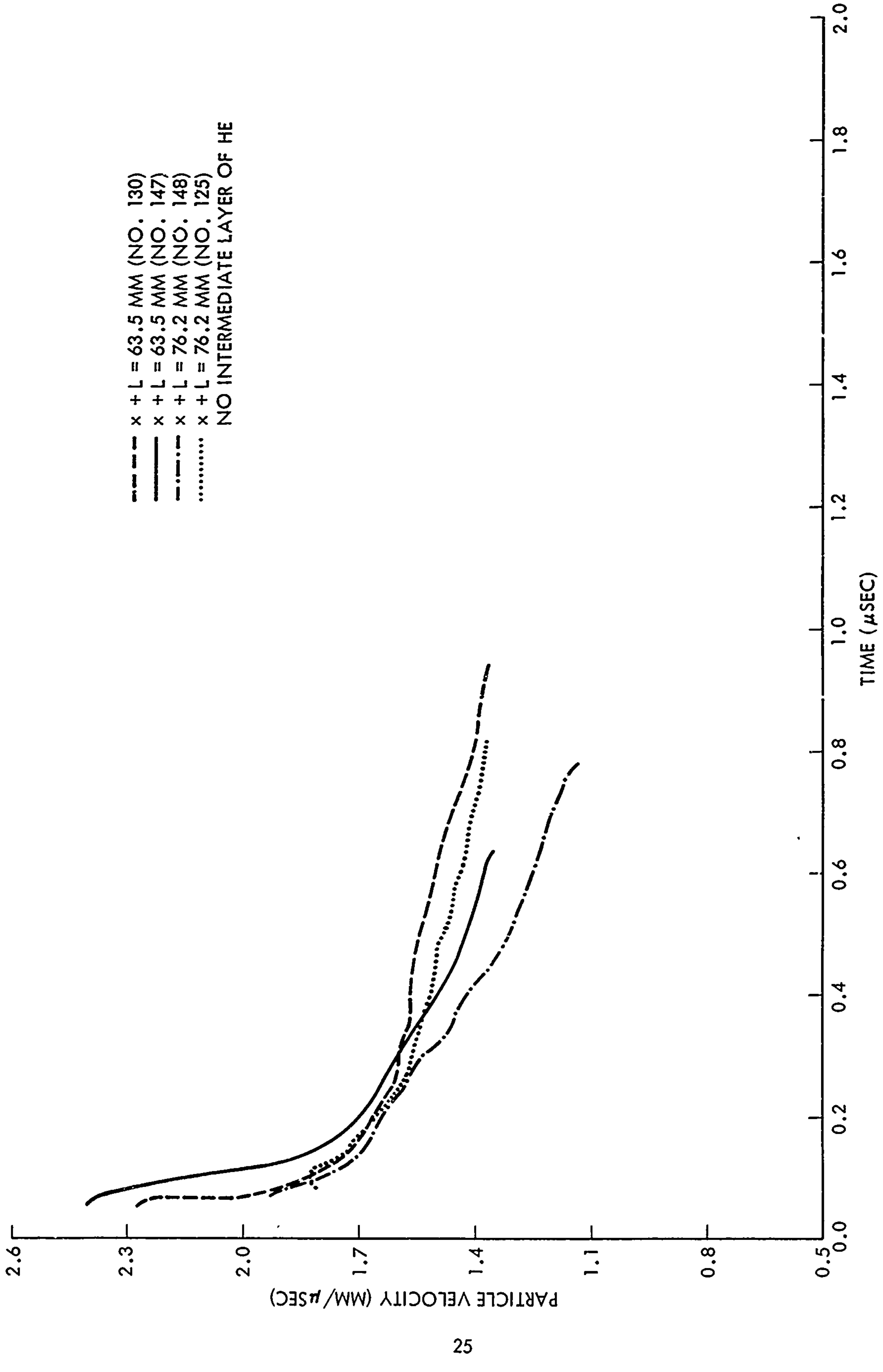


FIG. 15 u, t CURVES FOR (x + L)/d ≥1

t_R = $(x + L)/D$, the time required for the detonation to move from the PWB to the gage

τ = reaction time, t_{CJ}

D = detonation velocity, 6.85 mm/μsec

μ = $(\gamma - 1) / (\gamma + 1)$

x = length of the cast TNT specimen

L = length of the pressed TNT booster

Equation 3 is the relation between u and t in the Taylor wave which follows the reaction zone in the simple model of the detonation process. Some comments on the derivation of the relation are given in Appendix A. We force the computed curve to fit the experimental curve at the break by using the value of u at the break as the value of u_{CJ}. We also use the reaction time, τ, and the total length of the charge, $x + L$, to evaluate t_R. This latter assumption cannot be correct; the detonation starts in the PWB. Because the flow in the PWB is two-dimensional, there really is no point (or plane) in the PWB at which both the detonation and the following rarefaction wave originate. Hence, we can use this model for only limited guidance.

Figure 16 is a plot of the results from Shot 161 for which $x + L = 38.1$ mm. Computed Curve 1 is based on $u_{CJ} = 1.55$ μsec and $\tau = 0.60$ μsec. It coincides with the gage record in the time interval $0.60 \leq t \leq 1.2$ μsec and parallels it for $1.3 \leq t \leq 1.7$ μsec. Curve 2 is based on $u_{CJ} = 1.6$ mm/μsec and $\tau = 0.30$ μsec. This curve lies below the experimental curve and parallels it for $t > 0.6$ μsec. If we relied on these comparisons to pick the values of u_{CJ} and τ for Shot 161, we would take the values used for Curve 1, 1.55 mm/μsec and 0.60 μsec. This would be risky because of the uncertainty in the value we have used for the run length, $x + L$, as mentioned above.

It has been suggested[3] that the longer reaction time is more appropriate. This is justified by assuming that the TNT is not totally reacted after 0.3 μsec. Perhaps it is 99% reacted after this time, the other 1% reacting during the next 0.3 μsec, giving the level portion of the experimental curve.

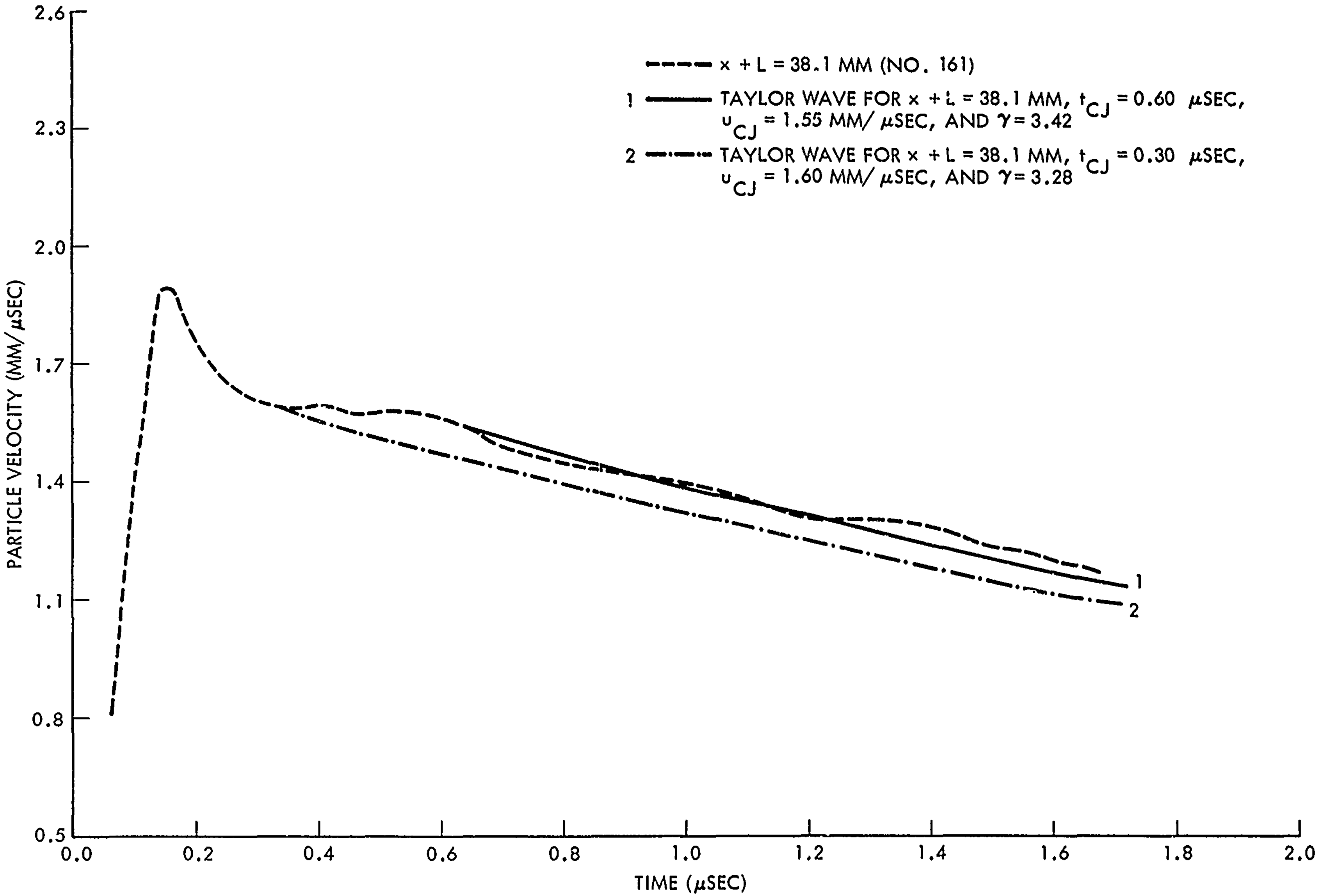


FIG. 16 COMPARISON OF OBSERVED AND PREDICTED RESULTS

COMPARISON OF PRESENT RESULTS WITH PREVIOUS WORK

The EMV gage method was used by Dremin and Shvedov[4] to obtain CJ values for cast TNT. Their two records (Fig. 2a and 2b, Ref. 4) are plotted in Figure 13 along with shot 161. Their curves have been displaced 0.1 and 0.2 mm/μsec for comparison of detail; the gaps in Dremin's curves are due to the superposition of time marks which obscure the record. Curve 2 (Dremin's Fig. 2a) and curve 3 (shot 161)) both have a level region for $300 < t < 600$ ns. Both of Dremin's curves roughly parallel shot 161. The fact that the curves are parallel even though run lengths are different (Dremin's records are for $(x + L) \geq 2.5$ d) is accidental; the fact that level regions are present and ignored by Dremin is significant. Craig[12] has investigated pressed TNT at a density very close to that of cast TNT. He used the free surface method with Dural as the inert and observed two breaks in his $u_{f.s.}$ vs x curve. He chose the first break as being associated with the CJ point while the region between the two breaks was described as being a "decay" zone. Veretennikov, Dremin, et al,[12] have shown that the double break observed by Craig can be eliminated by using a spall plane; this results in the elimination of the first break. Table 3 lists our results along with Dremin's and Craig's. As can be seen from this table, we are in good agreement with Dremin and with Craig's value of pressure at the second break point. Craig's first break point results in a CJ pressure which is 15% higher than Dremin's and ours. The accumulation of evidence (including the computation by Petrone[14]) makes it probable that Craig's interpretation of his data was incorrect.

CONCLUSIONS FOR CAST TNT

Reproduciblity of records for cast TNT from charge to charge is within ±3% for times of a few multiples of the reaction time, t_{CJ}. An aluminum gage having a thickness of 5 mils (0.13 mm) seems satisfactory for work in cast TNT. Thicker gages might extinguish the detonation and would lengthen the rise time as explained in <u>System Rise Time</u> section. Gages 1 mil (0.03 mm) thick give results which are too low.

The CJ parameters of cast TNT determined in this study are:

$$u_{CJ} = 1.60 \text{ mm/}\mu\text{sec}$$

and

$$t_{CJ} = 0.30\ \mu\text{sec}$$

These values are in agreement with Russian work[4] and with the second break in Craig's data[13].

Phenomena not yet completely understood are the records obtained with the baseless probes and the effect of gage thickness on the output. These have been tentatively attributed to the effect of conductivity of the detonation products in the first case and of the relative conductivity of the products as compared to the gage in the second case.

GENERAL CONCLUSIONS

A single record cannot be relied on to give u_{CJ} and t_{CJ}. Comparison of records for which the detonation front has traveled different distances removes most of the ambiguity in determining u_{CJ} and t_{CJ}.

When applying this method to other explosives, exploratory work should be carried out at two or more gage thicknesses.

ACKNOWLEDGMENTS

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Table 1

Estimated Rise Times

Shot #	Observed T_{max}(ns)	EST. T_o(ns)
125	108	97
126	72	65
129	75	68
130	55	50
134	171	154*
138	45	41
144	50	45
145	69	62
147	52	47
148	70	63
153	218	175
155	84	76
161	133	120
163	168	151
164	98	88
166	146	131
174	88	79
175	108	97

*Copper 5 mil foil; all others are Al 5 mil foil.

Table 2

Individual Experiments

x+L (mm)	x (mm)	L (mm)	Shot No.	Inter-mediate HE*	Foil Material	Magnetic Field (gauss)	PWB Dia. (mm)
Baseless Gage							
31.8	25.4	6.4	168	-	Al	760	63.5
31.8	25.4	6.4	170	PT	Al	895	63.5
76.2	76.2	0.0	128	PT	Al	845	50.8
1.0 mil Gage							
50.8	50.8	0.0	123	-	Al	835	50.8
76.2	76.2	0.0	124	-	Al	788	50.8
3.0 mil Gage							
63.5	50.8	12.7	131	P	Cu	790	50.8
5 mil Gage							
12.7	6.4	6.4	155	PT	Al	890	63.5
19.1	12.7	6.4	164	PT	Al	435	63.5
25.4	12.7	12.7	153	PT	Al	870	63.5
25.4	12.7	12.7	163	PT	Al	642	63.5
38.1	25.4	12.7	138	P	Al	255	50.8
38.1	25.4	12.7	144	P	Al	258	50.8
38.1	25.4	12.7	161	PT	Al	840	63.5
38.1	25.4	12.7	174	P	Al	868	63.5
38.1	25.4	12.7	166	PT	Al	847	63.5
50.8	50.8	0.0	126	-	Al	775	50.8
63.5	50.8	12.7	147	P	Al	800	50.8
63.5	50.8	12.7	130	P	Al	750	50.8
76.2	50.8	25.4	148	PT	Al	750	50.8
76.2	76.2	0.0	125	-	Al	800	50.8
76.2	76.2	0.0	145	-	Al	256	50.8
76.2	76.2	0.0	175	-	Al	839	63.5
88.9	76.2	12.7	134	P	Cu	792	50.8

*P = Pentolite
PT = Pressed TNT

Table 3

Comparison of Results for TNT

	Cast TNT		Pressed TNT					
	Present Results	Dremin's[4] Results	Craig's Results[a]		Russian Results			
			1st Break	2nd Break	Ref(4)	Ref(12)	Ref(7)	b
Density, gm/cc	1.62	1.62	1.63	1.63	1.59	1.59	1.59	1.59
u_{CJ}, mm/μsec	1.60	1.61	(1.83)	(1.64)	1.6	1.61-1.63	1.61-1.63	1.59
P, Kbar	(177.5)	(177)	(206.3)	(184.5)	(176.5)	(177-179)	(177-179)	(177)
t_{CJ}, μsec	0.30	0.30	-	-	<0.1	(0.147[c])	~0.1	0.22
D, mm/μsec	(6.85)	(6.85)	(6.92)	(6.92)	6.94	6.91-6.93	6.91-6.94	7.00

a. The results listed are the average of the values reported in Ref. 13. We have assumed Craig was using pressed TNT.

b. A. N. Dremin, K. K. Shvedov and V. A. Veretennikov, "Research into the Detonation of Ammonite PZh V-20 and Certain Other Explosives", Vzryvnoye Delo, 52 (9),10 (1963), UCRL-Translation 10405.

c. Derived from value of a 0.7 mm.

APPENDIX A

Derivation of One-Dimensional Plane Flow Equation

Equation (3) can be derived by starting with equation (46.06) from Courant and Friedrichs*. This equation is

$$x = -(\mu^{-2}-1)c_o t + \mu^{-2} c_o t_o\left(\frac{t}{t_o}\right)^{1-\mu^2} \qquad \text{(A1)}$$

which relates distance and time along the path of a particle in an adiabatic expansion process and where

x = distance,
t = time,
t_o = time for detonation to reach particle,
c_o = sound speed ahead of wave.

We also have the following relations:

$$\mu^2 = \frac{\gamma-1}{\gamma+1} \qquad \text{(A2)}$$

or

$$\mu^{-2} = \frac{\gamma+1}{\gamma-1} \qquad \text{(A3)}$$

and

$$\mu^{-2}-1 = \frac{2}{\gamma-1}\ . \qquad \text{(A4)}$$

We now substitute equation (A3) and (A4) into equation (A1) to obtain:

$$x = -\frac{2}{\gamma-1} c_o t + \frac{\gamma+1}{\gamma-1} c_o t_o\left(\frac{t}{t_o}\right)^{\frac{2}{\gamma+1}}\ . \qquad \text{(A5)}$$

To obtain the equation for u(t) we differentiate equation (A5) with respect to t. This yields

$$u = -\frac{2}{\gamma-1} c_o + \frac{2}{\gamma-1} c_o\left(\frac{t}{t_o}\right)^{-\frac{\gamma-1}{\gamma+1}}\ . \qquad \text{(A6)}$$

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*R. Courant and K. O. Freidrichs, "Supersonic Flow and Shock Waves", Interscience Publishers, Inc., New York, 1948, p. 104.

In order for this expression to represent the flow in the Taylor wave, boundary conditions must be imposed at $t=t_0=t_R + \tau_{CJ}$, at which time $u = u_{CJ}$. t_R is the time required for the detonation to reach the particle while t_{CJ} is the reaction time. The final equation is

$$u = \frac{2c_0}{\gamma-1}\left(-1 + \left(\frac{t}{t_R + \tau}\right)^{-\frac{\gamma-1}{\gamma+1}}\right) + u_{CJ} \qquad \text{(A7)}$$

In the computations u_{CJ} and D are the input parameters while c_0 and γ are calculated from

$$c_0 = D - u_{CJ}$$

and

$$\gamma = \frac{D}{u_{CJ}} - 1 \quad .$$

Equation A7 is evaluated for $t \geq t_R + \tau$.