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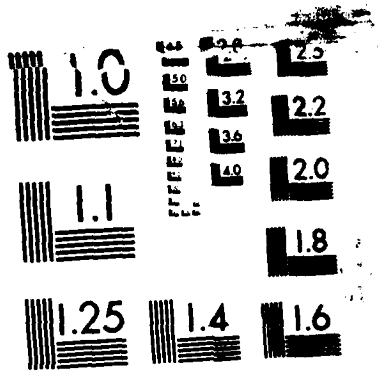

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MEMORANDUM REPORT BRL–MR–3516

DEPENDENCE OF FREE–FIELD IMPULSE ON THE DECAY TIME OF ENERGY EFFLUX FOR A JET FLOW

Kevin S. Fansler

May 1986

US ARMY BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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Until now, the peak energy efflux at the jet exit was considered the significant parameter in a scaling approach to estimate the peak overpressure, time-of-arrival, and positive phase duration from guns and shock tubes. The resulting predictions for the peak overpressure and time-of-arrival were satisfactory but the positive phase duration prediction was poor. This predicted value of the positive phase duration is used with the peak overpressure prediction to obtain an estimate of an important quantity: the impulse. Here we investigate the

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characteristic exhaust decay time for the energy efflux at the jet exit as a possible additional significant parameter that might be used to improve predictions for the impulse. Numerical simulation was used to establish that the impulse value depends upon this parameter. Comparison between simulation and experiment is satisfactory. This additional parameter was used to correlate the available impulse data. It was determined that the additional parameter significantly improves the prediction capability of the scaling method for predicting the impulse. An idealized wave form together with the predicted peak overpressure can be used to obtain an estimate of the positive phase duration. This approach yields less satisfactory agreement with the duration data but this fact is relatively unimportant since the impulse is the quantity of importance.

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I. INTRODUCTION

Guns and shock tubes under operation generate large pressure waves that can be harmful to nearby personnel and equipment. Industry and the Army employ these devices extensively and need to be acquainted with the salient characteristics of these blast waves. For these devices, the magnitude of the energy efflux from the tube exit and its history determine the characteristics of the blast wave and the associated gas-plume structure. Two principal characteristics of blast waves are the peak overpressure and the impulse. The impulse is the time integral of the pressure at a field point of interest. The positive phase duration is another often-used characteristic; it is the time duration for the positive pulse of a blast wave to pass over the field point. If we know the peak pressure and the positive phase duration value, the impulse for the wave can be estimated easily by assuming a simple expression for the pressure as a function of time.

Scaling theory is used extensively to predict blast wave characteristics; this approach yields simple but powerful methods. The scaling theory for instantaneous-energy blast waves[1] is well known and accepted. Reynolds[2] used a point blast scaling theory developed by Hopkinson[3] to treat gun-generated blast waves. Later, Westine[4] developed a scaling law from point blast theory but, in addition, introduced the length of the barrel as an important parameter. This modification permits his method to be applied successfully over a variety of weapons.

Smith,[5] and more recently, Fansler and Schmidt,[6] have predicted the blast wave characteristices from gun weapons by applying scaling theory to blasts generated by constant energy efflux conditions. Schmidt and Duffy[7] utilized the preceding reference[6] to predict the blast characteristics from shock tubes. Smith[5] and Fansler and Schmidt[6] selected the peak energy deposition

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1. Baker, W.E., Explosions in Air, U. Texas Press, Austin, 1973.

2. Reynolds, G.T., "Muzzle Blast Pressure Measurements," Report No. PMR-21, Princeton University, Princeton, NJ, April 15, 1944.

3. Hopkinson, B., British Ordnance Minutes, 13565, Royal Army Research Defence Establishment, Fort Halstead, England, 1915.

4. Westine, P., "The Blast Field About the Muzzle of Guns," The Shock and Vibration Bulletin, Vol. 39, Pt. 6, pp. 139-149, March 1969.

5. Smith, F., "A Theoretical Model of the Blast from Stationary and Moving Guns," ADPA 1st International Symposium on Ballistics, Orlando, FL, 13-15 November 1974.

6. Fansler, K.S., and Schmidt, E.M., "The Relationship Between Interior Ballistics, Gun Exhaust Parameters, and the Muzzle Blast Overpressure," AIAA/ASME 3rd Joint Thermophysics, Fluids, Plasma and Heat Transfer Conference, St. Louis, Missouri, 7-11 Jone 1982.

7. Schmidt, E.M., and Duffy, S.J., "Noise from Shock Tube Facilities," AIAA Paper 85-0049, January 1985.

rate as the significant parameter. With a steady energy deposition rate assumed in the dimensional analysis, the nondimensionalized quantities of peak pressure, time-of-arrival and impulse depend only upon the distance divided by the scaling length. For a given polar angle as measured from the axis, this scaling length for the blast wave varies as the square root of the peak energy deposition rate. However, the blast waves are highly directional, with their strengths decreasing with increasing polar angle from the forward axis direction. The form for the variation of peak overpressure with angle from the axis is obtained from moving charge theory;[5] it possesses one free parameter that determines how rapidly the overpressure falls off with the increase of polar angle. The assumed formulation for the peak overpressure generates two other free parameters. One parameter is the exponent of the distance from the gun muzzle; it determines how fast the peak pressure falls off with distance. The other parameter is the constant coefficient of the scaling expression. The available data are then used with the given scaling relation to perform a least squares fit that establishes values for the three free parameters. Smith[5] applied the scaling approach to a particular weapon. However, Fansler and Schmidt[6] assumed the resulting scaling expressions were universally applicable when using the initial energy-deposition rate as the characteristic value. The Fansler and Schmidt[6] model successfully predicts the peak overpressure and times-of-arrival for a variety of gun weapon systems. On the other hand, the method predicts that the positive phase duration increases with distance in a completely different fashion than for the well-studied instantaneous energy deposition explosions. However, the original generating method for the blast wave should have less relevance to the behavior of the blast wave as it travels away from its origin. Thus, for the larger distances, the behavior of the positive phase duration for the two cases should be quite similar.

It is the objective of this work to provide an improved prediction scheme for the impulse by modifying the scaling approach of Fansler and Schmidt.[6] From the data already accumulated, it appears that the energy-deposition rate decay affects the impulse. However, the waveforms obtained by experiment have significant amounts of noise generated by possible gage vibrations and turbulence; perhaps, the amount of turbulence can affect the impulse magnitude. The turbulence magnitude may in turn depend upon some other significant parameter such as the velocity of the projectile, etc. Thus, it is difficult to determine from the data whether the positive phase duration depends predominantly upon the energy efflux decay rate. To study this relationship, we use the Euler finite difference code, DAWNA, that calculates the blast wave field along the boreline of a gun.[8] It uses shock fitting, takes into account the decay rate of the energy efflux quantity, and executes much faster than a numerical axisymmetric scheme.

II. BACKGROUND AND SCALING DEVELOPMENT

As mentioned before, Fansler and Schmidt[6] assumed that the blast wave depended on the energy efflux. The functional dependence of the peak over-

8 Erdos, J., and del Guidice, F., "Calculation of Muzzle Blast Flowfields," AIAA Journal, Vol. 13, No. 8, August 1975, pp. 1048-1056.

pressure is expressed as

$$P = P(r,\rho_\infty,a_\infty,dE/dt) \ . \qquad (1)$$

Here r is the distance from the center of the explosion, ρ_∞ is the ambient density, a_∞ is the ambient sound speed, and dE/dt is the characteristic value for the rate of energy deposition. For a spherical blast, we assume the ideal equation of state; dimensional analysis yields a scaling length:

$$\ell \sim \sqrt{(dE/dt)/(p_\infty a_\infty)} \qquad (2)$$

and a nondimensionalized peak overpressure:

$$\begin{aligned}\overline{P} &= P/p_\infty \qquad (3)\\ &= \overline{P}\ (r/\ell) \ .\end{aligned}$$

In this report the overbarred quantity is defined as the quantity nondimensionalized by the significant quantities for the scaling analysis. The momentum of the propellant gas results in the strength of the blast wave decreasing markedly with polar angle. Smith[5] noted the similarity between moving-charge blast waves and gun blast waves. From moving charge theory, he obtained a scaling length, ℓ', for muzzle blast,

$$\ell'/\ell = \mu \cos\theta + (1 - \mu^2 \sin^2\theta)^{1/2}. \qquad (4)$$

Here, μ is the momentum index and is a measure of the directionality of the blast. It is a free parameter that is found by a least squares fit to experiment. With Equation (4), the resultant form of the overpressure relationship is assumed as,

$$\overline{P} = K\ (r/\ell')^n \ , \qquad (5)$$

with the values of K=2.4, n=-1.1, and μ=0.78 giving the best fit to the peak overpressure data. These data were collected from a variety of guns.[6] The resulting expression, when cast in the interior ballistic formulation and when some simplifying assumptions are made, resembles the form obtained by Westine.[4]

A further consequence of the dimensional analysis is that the positive phase duration should have the following functional dependence:

$$\begin{aligned}\overline{\tau} &= \tau\ a_\infty/\ell' \qquad (6)\\ &= \overline{\tau}\ (r/\ell') \ .\end{aligned}$$

Because of the general appearance of the 30mm data,[6] we used a linear fit to obtain the predictive curve for $\overline{\tau}$.[6] Figure 1 shows the fitted curve with the corresponding data. There is considerable scatter of the data around the fitted curve. The data also do not show any tendency to go toward the far-field asymptotic relation; i.e., the positive phase duration increases asymptotically as the square root of the log of the distance divided by some constant. Figure 2 shows the 30mm data more clearly delineated with the parameters being the angular position and firing conditions. The impulse could only be obtained directly from the set of experiments that was used to produce the results of Figure 2. Only data from these experiments were used to obtain the results of the present report. It is noted that some data subgroups are clustered so that there is not much overlap between the subgroups. These subgroups correspond to different polar angles or different values of ℓ'/ℓ. It is desirable to have substantial overlap of the subgroups to improve the reliability of the data and thus the derived results. This could have been accomplished by collecting data for larger distances. However, the facilities and instrumentation did not allow data acquisition at these larger distances.

Because the linear behavior of the data at the larger distances is clearly incorrect and the data are not well correlated by the curve fit, we decided to search for an additional significant parameter. A possible significant parameter is the characteristic emptying time of the propellant from the gun barrel. As noted before, the peak overpressure for a given distance and polar angle increases slowly, but insignificantly for most practical purposes, with increasing emptying time. However, the impulse may have a stronger dependence on the emptying time of the barrel.

A dimensional analysis performed with a characteristic emptying time, α, as a significant variable yields the π group,

$$\beta \sim (\alpha\, a_\infty)/\ell' \quad . \tag{7}$$

Corner[9] discusses the barrel emptying time and its relationship with easily observed parameters. To a first approximation,

$$\alpha \sim L/V_p \quad . \tag{8}$$

With the proportionality substituted into Equation (7), the new working π group can be defined as

$$\beta = (a_\infty L)/(\ell' V_p) \quad . \tag{9}$$

9. Corner, J., Theory of the Interior Ballistics of Guns, John Wiley, NY 150.

This new parameter can be interpreted as the ratio of the emptying time of the tube to the characteristic time for the development of the blast wave. We shall call the new parameter the nondimensional emptying time. Figure 3 shows the normalized energy efflux versus the nondimensional time divided by the nondimensional emptying time constant for a 30mm cannon, or equivalently, the time nondimensionalized by L/V_p. If the first part of the emptying process is deemed more important than the latter parts, we can assume an exponential function to fit the first part of the data. This approximation to the curve shows that the efflux data values are high compared with the fitted function for the longer times. The approximation shows that the exponential emptying time constant is $\alpha = (L/V_p)/1.68$. Thus, the exponential emptying time constant divided by L/V_p is $O(1)$, which agrees with intuition. With the nondimensional emptying time now assumed as a significant π grouping, the functional forms for the impulse and positive phase duration are

$$\bar{\tau} = \bar{\tau}(r/\ell', \beta), \tag{10}$$

$$\bar{I} = I\, a_\infty/(\ell' p_\infty) \tag{11}$$

$$= \bar{I}\,(r/\ell', \beta)\,.$$

In the present paper, we have treated the impulse as the primary parameter since it is used directly to assess vulnerability of actual or contemplated structures. Previously, an assumed form for the positive phase duration was correlated with available positive phase duration data and the impulse was then obtained using the most primitive form of the Friedlander waveform,[1] which is,

$$(p-p_\infty)/p_\infty = \bar{P}\,[1-(t-t_a)/\tau]\,\exp-[(t-t_a)/\tau]\,. \tag{12}$$

Here, t_a is the time of arrival of the blast wave front. However, the prior approach introduces a source of inaccuracy in the predictive method because the assumption of a specific waveform is an approximation.

As mentioned in the introduction, noise from turbulence and other sources were superimposed upon the waveforms. Such factors introduced difficulty in ascertaining that the emptying time was a major significant variable. Moreover, the limited range of distances over which the data were taken also makes it difficult to assert what the significant variables are with confidence. To isolate the effect of the emptying time from other possible significant parameters, we use numerical simulation. We chose the DAWNA code,[8] which computes the flow properties of the blast wave along the gun boreline. Although the method calculates the flow properties along the centerline, by the assumptions of the scaling approach, the results are applicable to the gun blast for arbitrary polar angle. In the jet plume portion, the property distribution of a steady jet is assumed along the centerline and the shock layer between the Mach disc and the blast wave front is computed with a finite difference method. The discontinuities are obtained using a shock fitting technique.

The method executes rapidly compared to an axisymmetric code and the position of the discontinuities are determined exactly whereas shock capturing schemes portray discontinuities as more or less steep rises or falls in the calculated gasdynamic quantities.

III. RESULTS AND DISCUSSION

The simulation performed was for the 30mm cannon firing the projectile at 572 m/s with a peak pressure of 8600 kPa. These conditions are for one of the firing conditions used in an earlier study.[10] To investigate the relationship between the dimensionless emptying time and the impulse, the value of β was varied from 1.37 to infinity, or equivalently, the barrel length was varied from 10 calibers to infinity. For a 40 caliber length barrel, the energy efflux history is shown in Figure 3. As discussed before, the time is proportional to the barrel length. Figure 4 shows overpressure versus time at different distances from the muzzle for the above conditions. The value of β is 5.47 or equivalently, the barrel length is 40 calibers. The wave generally resembles waves generated by instantaneous energy explosions. Figure 5 shows calculated waveforms with various barrel emptying times for a dimensionless distance of 4.54 calibers from the muzzle. The waveforms for larger emptying times result in larger values for the positive phase durations. Furthermore, the shape of the wave does not maintain geometric or affine similarity as the emptying time is increased. Thus, the similarity between the waves generated by instantaneous energy explosions and waves for finite energy explosions should become weaker as the dimensionless emptying time increases. In fact, for this position, the positive phase duration for the barrel of infinite length is longer than for the times calculated. In effect, the jet appears to be sustaining a positive pressure at some field positions, as one might intuitively expect.

The positive phase duration versus the distance from the muzzle for different values of the dimensionless emptying time is shown in Figure 6. For finite values of the emptying time, the positive phase duration at first increases rapidly and then starts to level off. This behavior occurs since at early times the blast wave strength is large and the front of the wave then travels at speeds appreciably greater than the speed of sound while the part of the wave where the overpressure is zero is traveling near the speed of sound. As the wave travels from the muzzle, the peak overpressure decreases and the wave front speed approaches the ambient sound speed. In the asymptotic limit, the positive phase duration involves a logarithmic term. For constant energy efflux, the positive phase duration increases rapidly with distance to very large values, as was noted from Figure 5.

Figure 7 gives the simulated impulse as a function of the distance from the muzzle for various values of the dimensionless emptying time. The impulse appears to decrease rapidly which we should expect since the overpressure is

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10. Fansler, K.S., and Keller, G.E., "Variation of Free-Field Muzzle Blast with Propellant Type," ADPA 6th International Symposium on Ballistics, Orlando, FL, October 1981.

decreasing more rapidly than the inverse power of the distance and the positive phase duration is increasing relatively slowly. Figure 8 shows that the impulse increases slowly but significantly with the barrel exhaust time. Figure 9 shows a comparison between the simulated values of the impulse and some experimental values for comparable values of the dimensionless emptying time. These data were obtained from the primitive waveform data for an earlier study.[10] The utilization of this additional parameter produces a marked improvement over the original predictive model of Fansler and Schmidt.[6] Although the comparable emptying times are smaller for the simulation, they predict higher values for the impulse. The simulated curves also show a steeper decline of the impulse with distance but this would be expected since simulations predict a steeper decline in peak overpressure than actually occurs. The reason for the steeper decline is not known. Considering that the simulation is based on a model that is a gross simplification of the muzzle blast flow, the agreement is quite good.

The complete data set[10] that was used in seeking a correlating relationship with the nondimensional emptying time is shown in Figure 10. The data cover a range over the nondimensional time from 3.23 to 32.3 which does not completely encompass the ranges occupied by gun weapons. Nevertheless, a correlation was sought with extrapolation to these ranges that would hopefully not result in large predictive errors. Further available data can later be added to yield an improved prediction. It was decided to employ a simple form devoid of any logarithmic expressions that the impulse might be tending to asymptotically. We have no data for performing a least squares fit in the far field. The nondimensional impulse was assumed to have a form such that when the data were fitted and the free parameters determined,

$$I = 0.50\ \beta^{0.2}\ (r/\ell')^{-0.6} \tag{13}$$

This form can easily be understood and used and shows that the impulse varies as a weak power law function of the barrel exhaust time and is consistent with how the simulated values of the impulse vary with the efflux decay time. A least squares fit was also attempted with the addition of the polar angle as an explicit variable but very little improvement in the correlation was obtained.

To display all the results on a plot, the function $\bar{I}$ must be transformed to a function depending on only one variable. Dividing $\bar{I}$ by the last factor in Equation (13), one obtains the reduced value of the impulse, I_r, that is no longer dependent on the nondimensional emptying time. Figure 11 shows the reduced impulse data together with the prediction. The scatter of the reduced data is significantly diminished by utilizing the barrel exhaust time in the correlation. Of course, some of the scatter can be attributed to random variations. Nevertheless, we have need of a larger data set with measurements performed for longer distances from the muzzle.

Now that we have developed a predictive expression for the more important quantity, the impulse, we can return to the positive phase duration and investigate whether an adequate predictive expression can be easily obtained. Of course, from Figure 5 we should expect that the impulse would not vary linearly with the positive phase duration. If we assume the Friedlander relationship as given in Equation (12), a very simple relationship exists between the nondimensional impulse and the nondimensional positive phase duration,

$$\bar{I} = \bar{P}\,\bar{\tau}/e \; . \tag{14}$$

Utilizing the expression for $\bar{I}$ in Equation (13) and the expression for $\bar{P}$ as given in Equation (5), we find by substituting into Equation (14),

$$\bar{\tau} \;=\; .57\,\beta^{\,0.2}\,(r/\ell')^{0.5} \tag{15}$$

As before with the impulse, the dimensionless positive phase duration is transformed to a function of the nondimensional distance. The positive phase duration data are likewise divided by $\beta^{0.2}$ to obtain a reduced form. The comparison between the predictive curve and the reduced data is shown in Figure 12. The data trend and the predictive curve have different slopes. It appears that a more complicated wave shape than is possible from Equation (12) would be needed to generate excellent predictions of the positive phase duration. However, attempts to obtain better agreement would seem to be wasted effort since with data being digitized and processed with computers, the impulse can easily be directly determined for a wave.

Although the data used here were obtained from gun weapons, the results should be applicable to any device that produces a jet flow with decaying energy efflux. Schmidt and Duffy[7] obtained pressure data in the field external to the exit of the shock tube. They did not obtain the impulse but they did measure the positive phase duration. They found that for r held constant:

$$\tau \sim \exp(0.25\,\cos\theta)\,. \tag{16}$$

Using Equation (15) and Equation (9),

$$\tau \sim (\ell'/\ell)^{\,0.3}\; . \tag{17}$$

A comparison of the two expressions is shown in Figure 13 and yields fair agreement even though the simple Friedlander waveform is used.

IV. SUMMARY AND CONCLUSIONS

An older predictive scheme for blast waves generated from gun weapons that is based on a scaling approach has not produced entirely satisfactory results. For example, this older model, which utilizes the peak energy deposition rate as the significant parameter, predicts that the positive phase duration increases linearly with the distance from the jet exit. However, for the well-studied explosions that are generated by instantaneous energy deposition, this sort of behavior does not exist. For these explosions, the positive phase duration at first increases steeply with the distance but the rate of increase with distance falls off rapidly as the wave travels away from its origin. It would seem that much the same behavior should exist for blast waves generated by jet flows that exit from gun tubes or shock tubes. The puzzling linear relationship between the positive phase duration and the scaled distance from the jet exit could be caused by neglect of a significant parameter. A possible significant parameter could be barrel exhaust time for the energy efflux passing the exit plane. To test this possibility, we employed a numerical simulation scheme that calculates the fluid dynamic quantities along the boreline. Although the simulation scheme is limited to the boreline direction, this is not a major impediment since the current scaling approach allows application of the results to all polar angles. The numerical scheme also executes very quickly and allows for isolation from turbulence and other phenomena occurring in the actual gun blast flow.

The simulation results show that the impulse increases with the decay time of the energy efflux. Moreover, comparisons of experiment data with simulation results show a similar dependence of the impulse upon the decay time of the energy efflux. Thus, it is felt that the barrel exhaust time is a significant parameter for improving the correlation of the impulse data. We correlated the data utilizing the new variable and obtained a power law dependence of the impulse upon the nondimensional energy efflux exhaust time. The predicted impulse increases at a slower rate for the larger distances, as it should. We can obtain corresponding positive phase duration values by using the most primitive Friedlander relation together with the predicted peak overpressures to construct idealized waveforms. This approach generates a simple expression for the positive phase duration. Comparison with the phase duration data yields different slopes and fair agreement. It is concluded that the positive phase duration prediction should only be used when there are no impulse data to compare with. A case in point is the shock tube results obtained by Schmidt and Duffy,[7] that had only the positive phase duration data readily available. The results of the present prediction agree reasonably well with the shock tube results even though we have used the simple Friedlander relationship.

In conclusion, the impulse given to nearby structures by guns or shock tubes can now be more accurately predicted in a range of distances where possible injury can result to personnel and equipment. This relationship is not applicable to very large distances from the gun or shock tube. Data have not yet been collected for correlation to these distances and the present function does not contain a logarithmic expression that is essential for the asymptotic form.

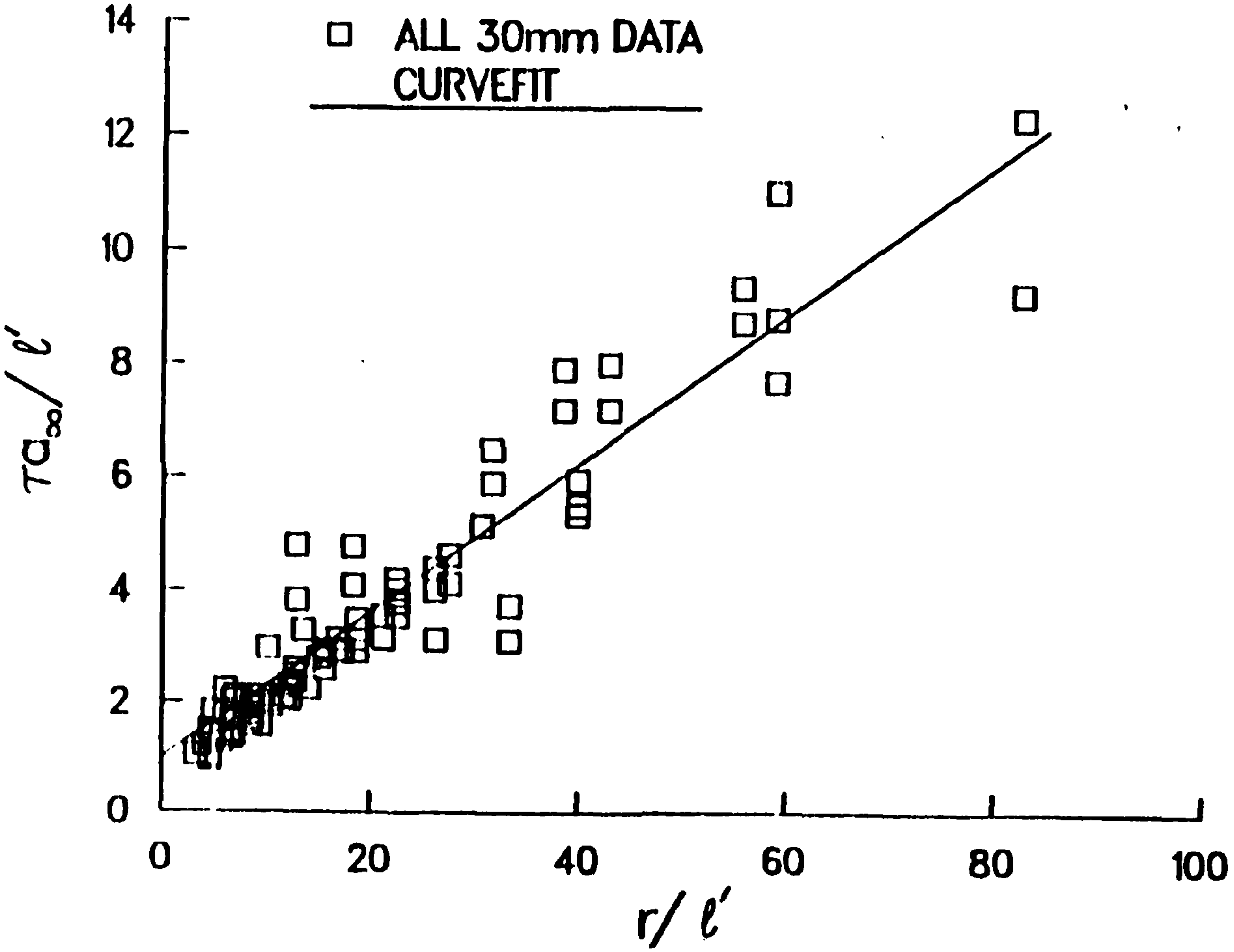

Figure 1. Positive Phase Duration Data from 30mm Firings and Accompanying Curve Fit of Reference 6

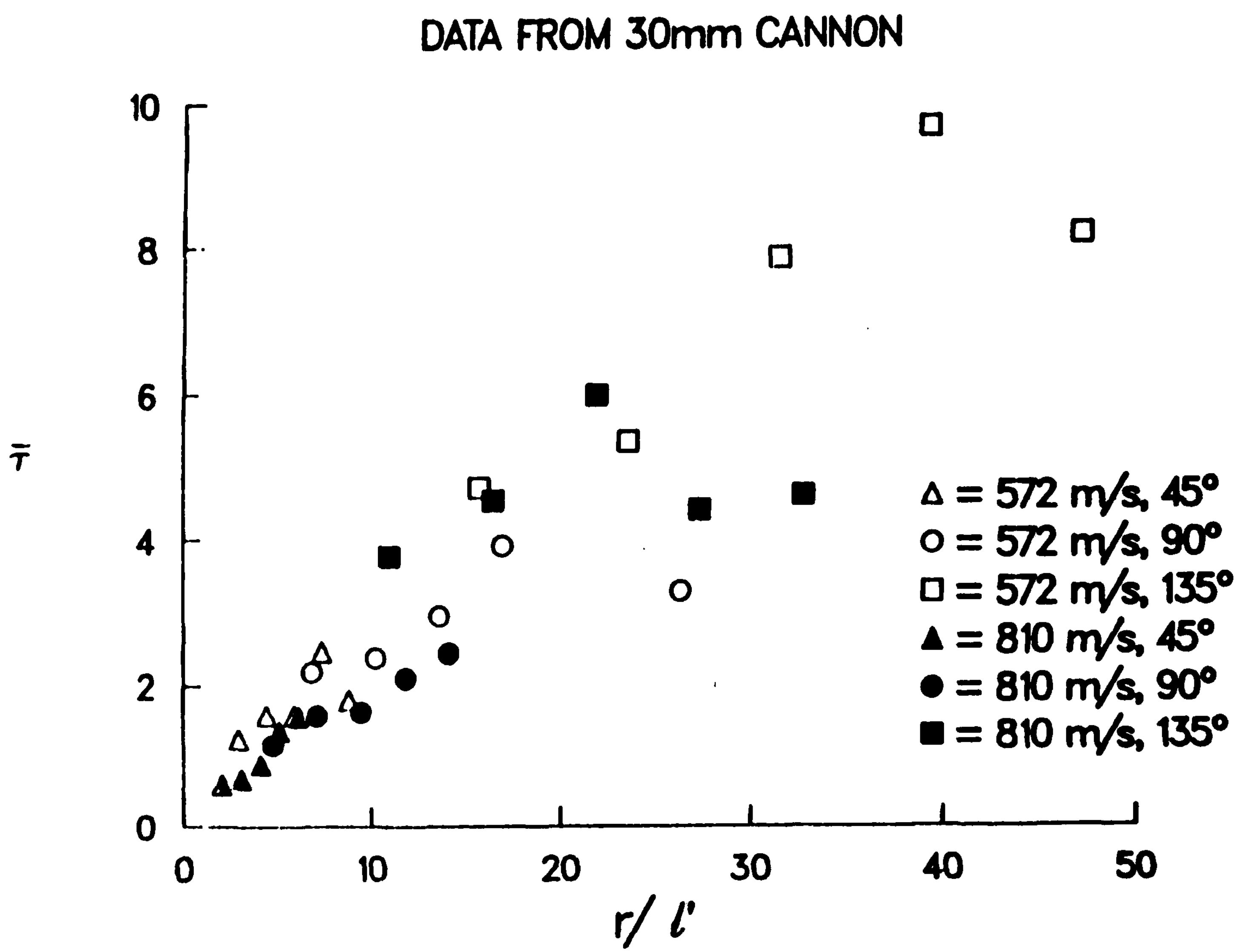

Figure 2. Positive Phase Duration Data Delineated into Subgroupings

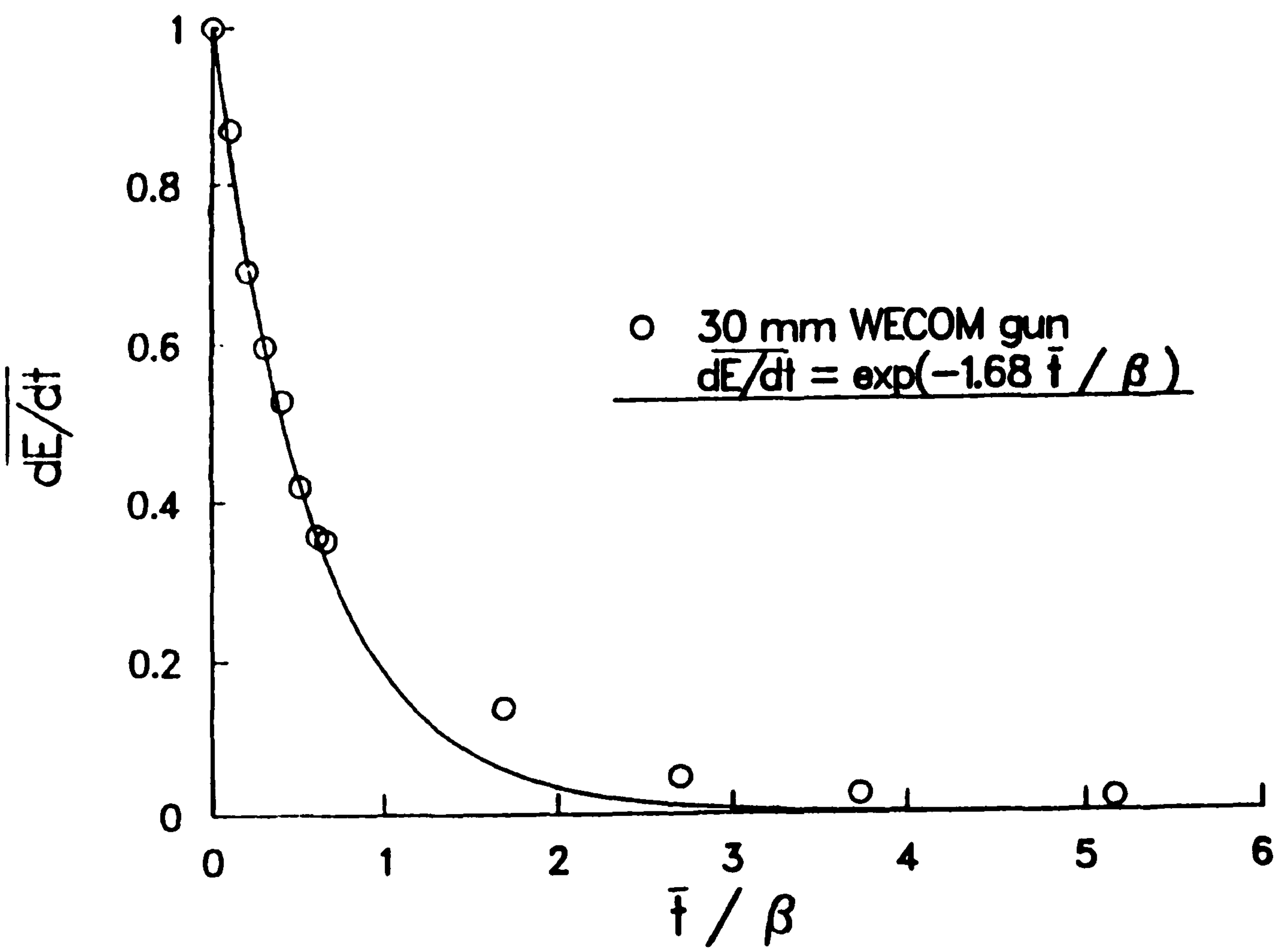

Figure 3. Energy Efflux versus Nondimensionalized Time for 30mm WECOM Cannon with Exponential Approximation

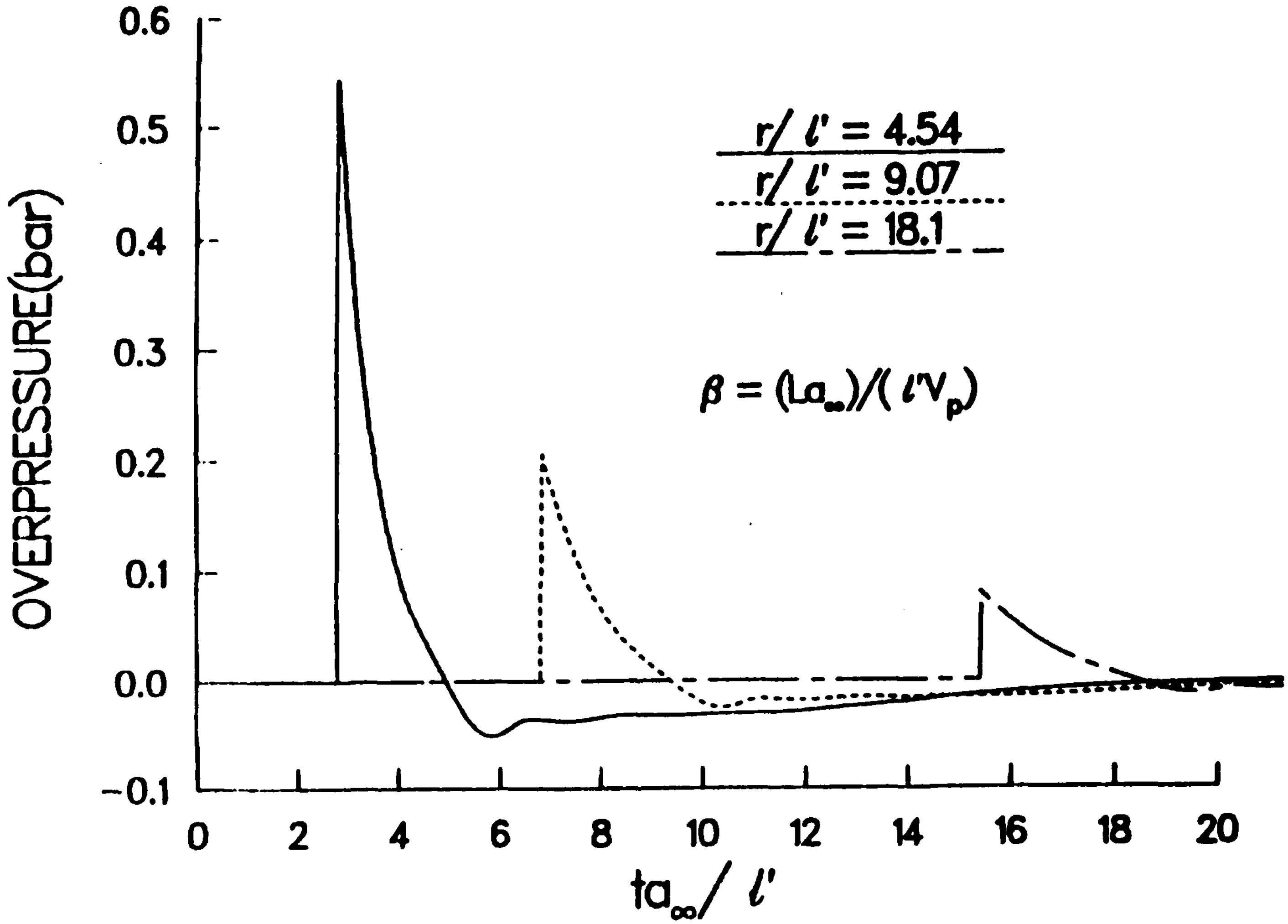

Figure 4. Blast Wave Overpressure versus Time for Different Distances from the Muzzle. Simulation of 30mm Cannon with 40 Caliber Barrel Length

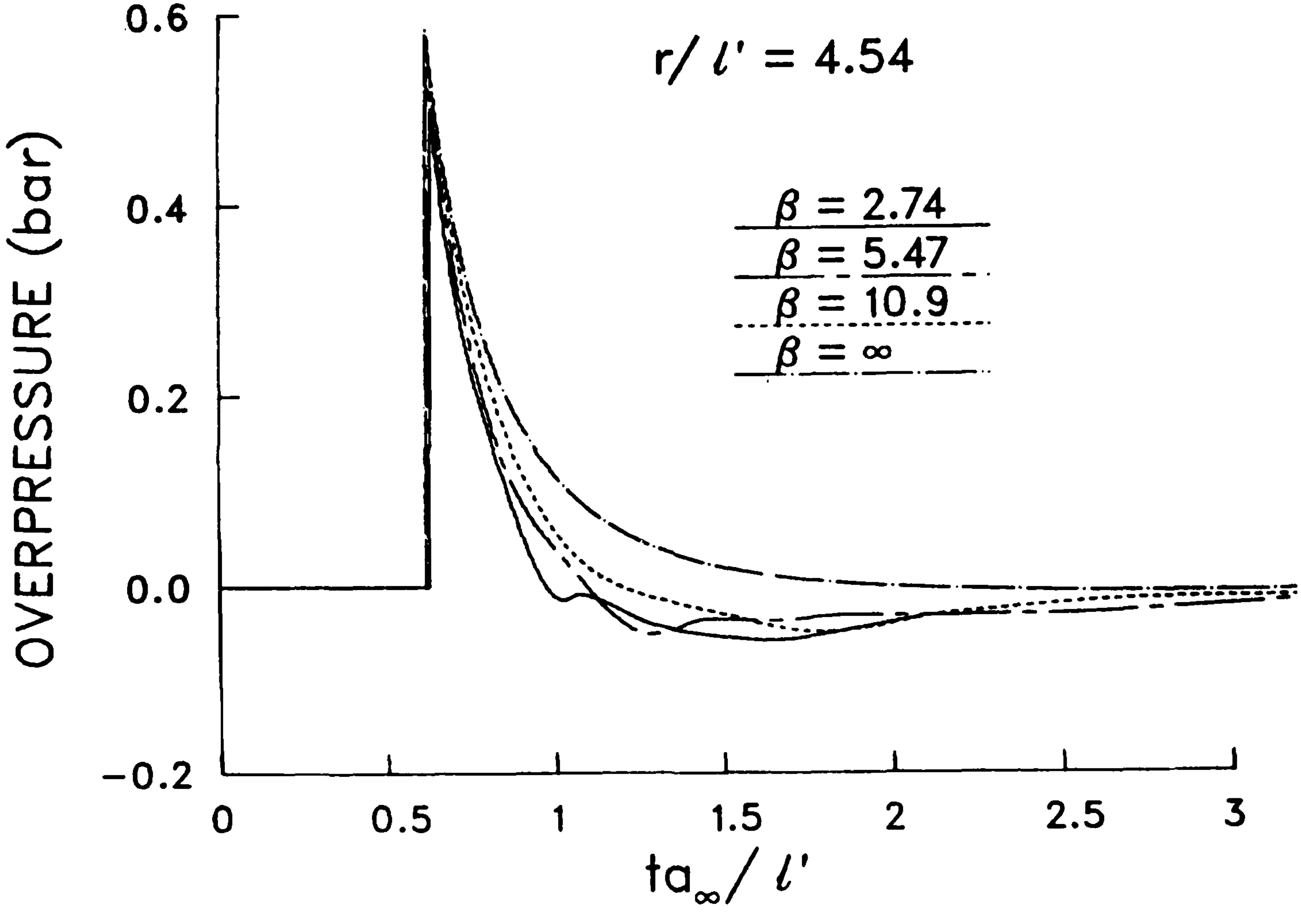

Figure 5. Waveform Comparison for Different Energy Efflux Decay Times

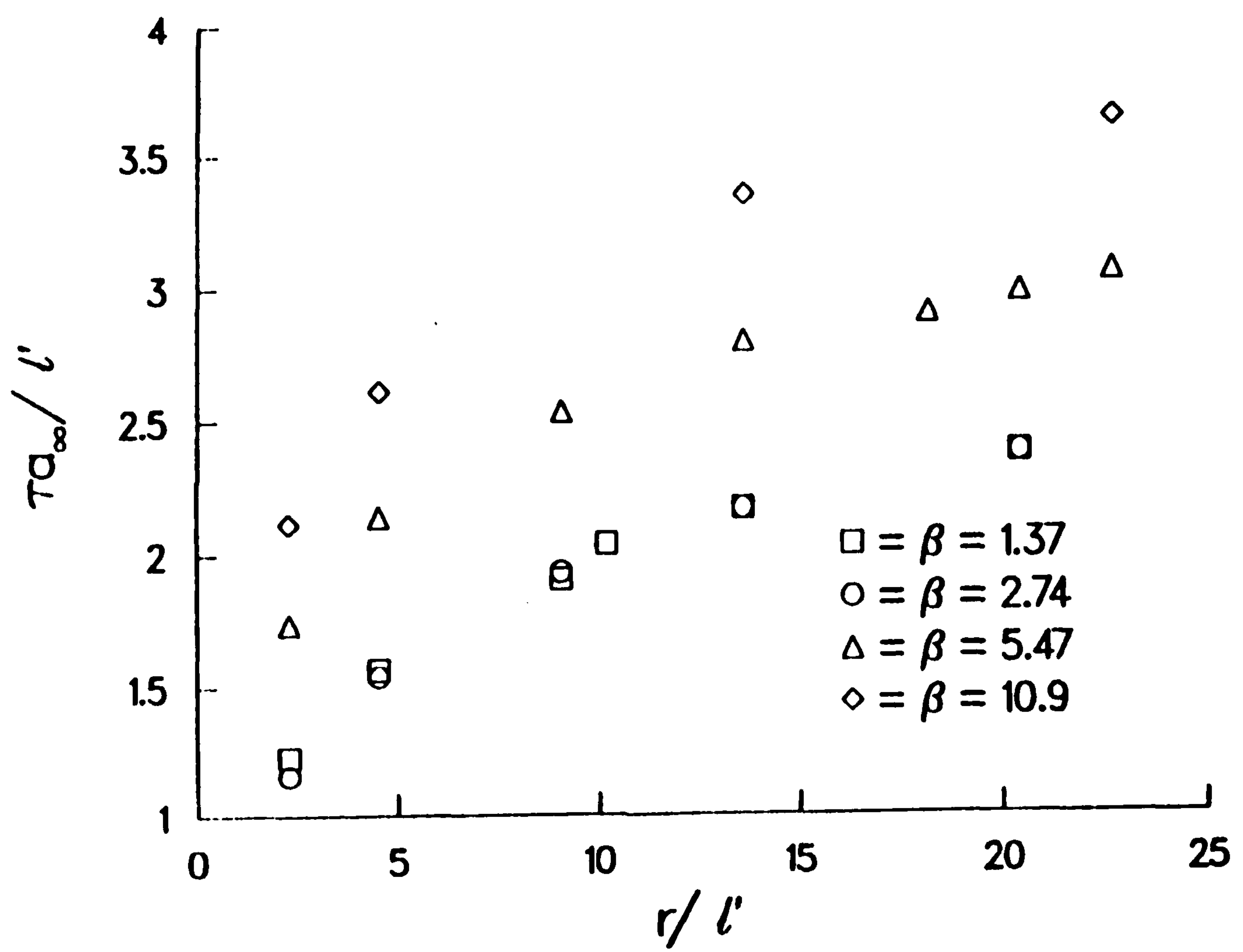

Figure 6. Positive Phase Duration versus Distance from Muzzle for Different Energy Efflux Decay Times

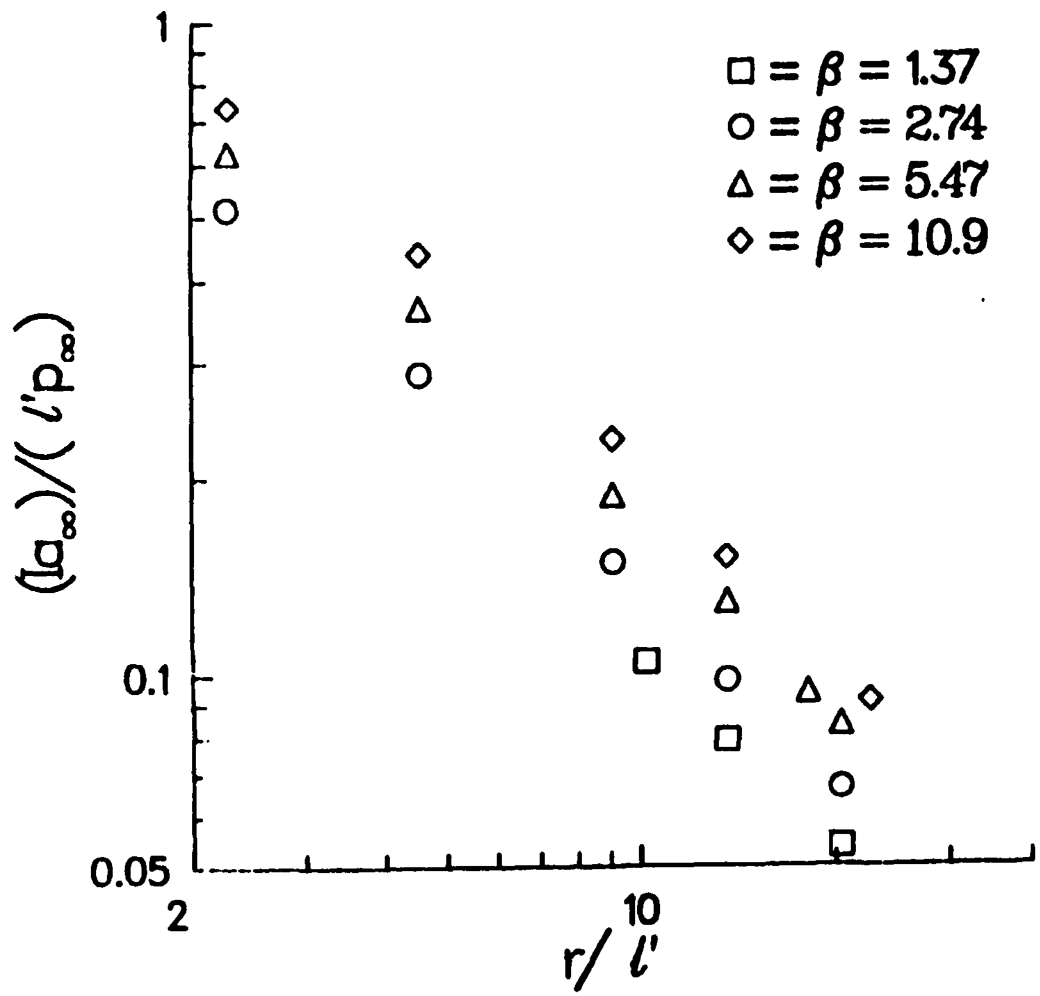

Figure 7. Dimensionless Impulse versus Distance from Muzzle for Different Energy Efflux Decay Times

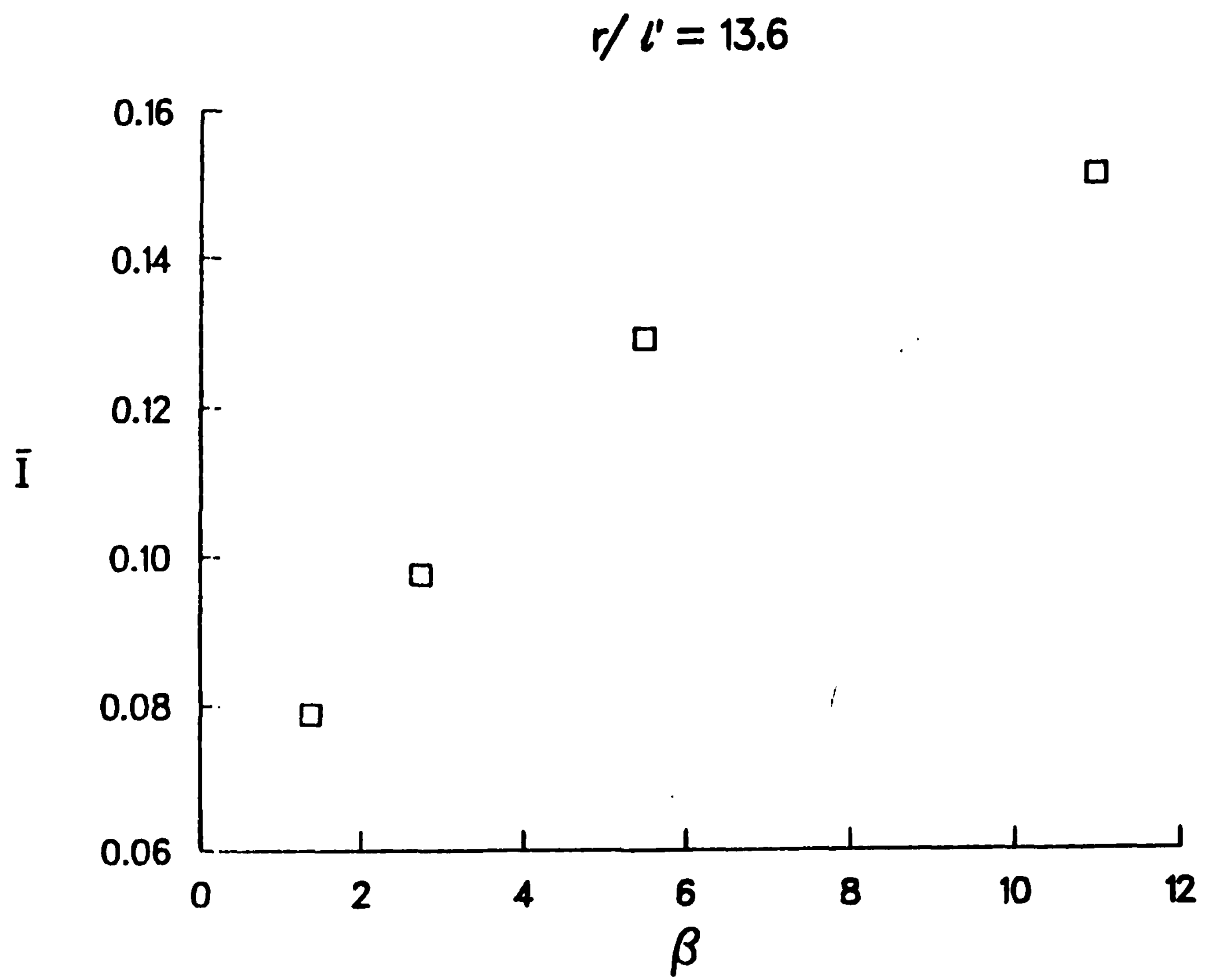

Figure 8. Imuplse versus the Energy Efflux Decay Time

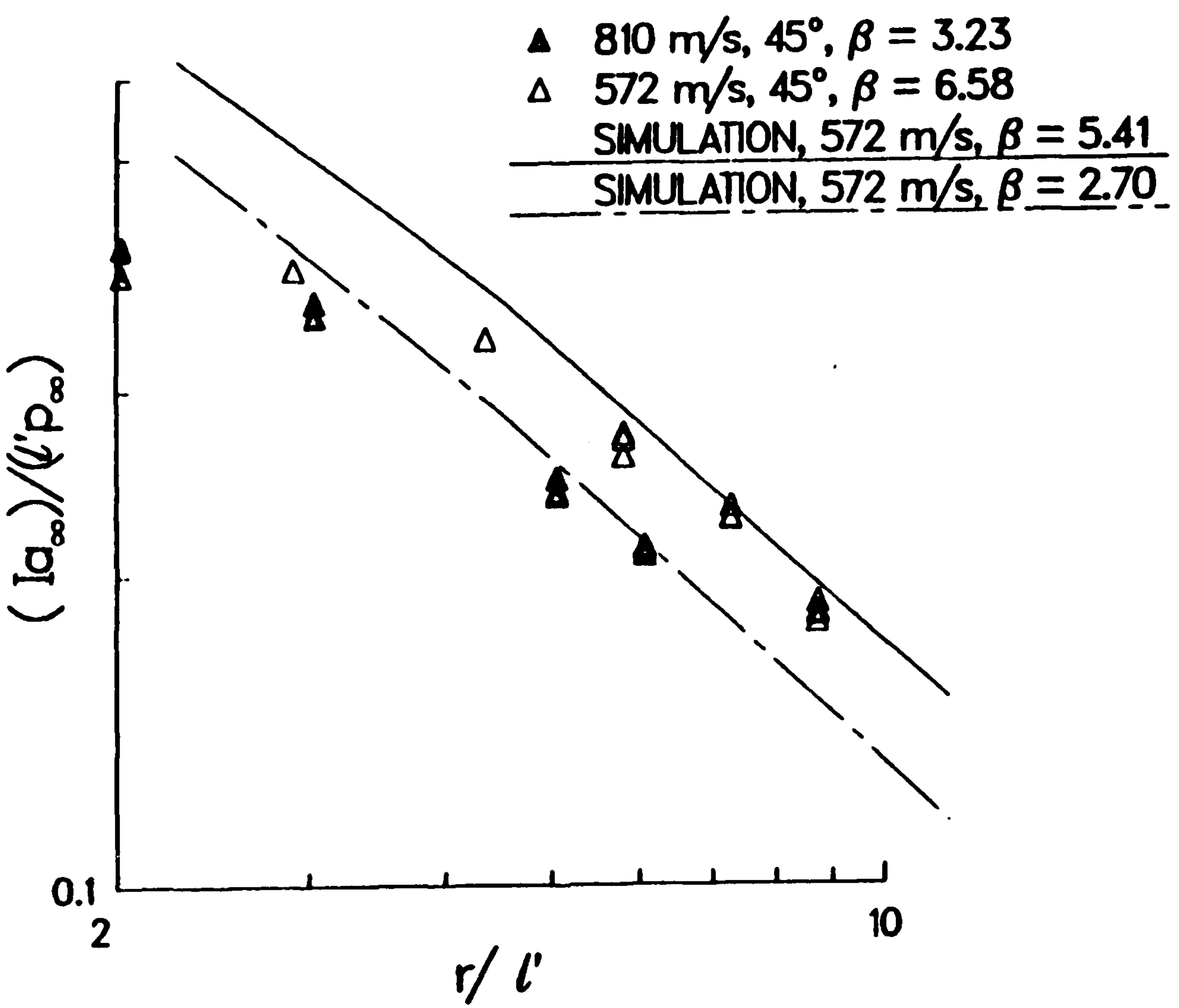

Figure 9. Comparison of Simulated and Experimental Values for the Impulse

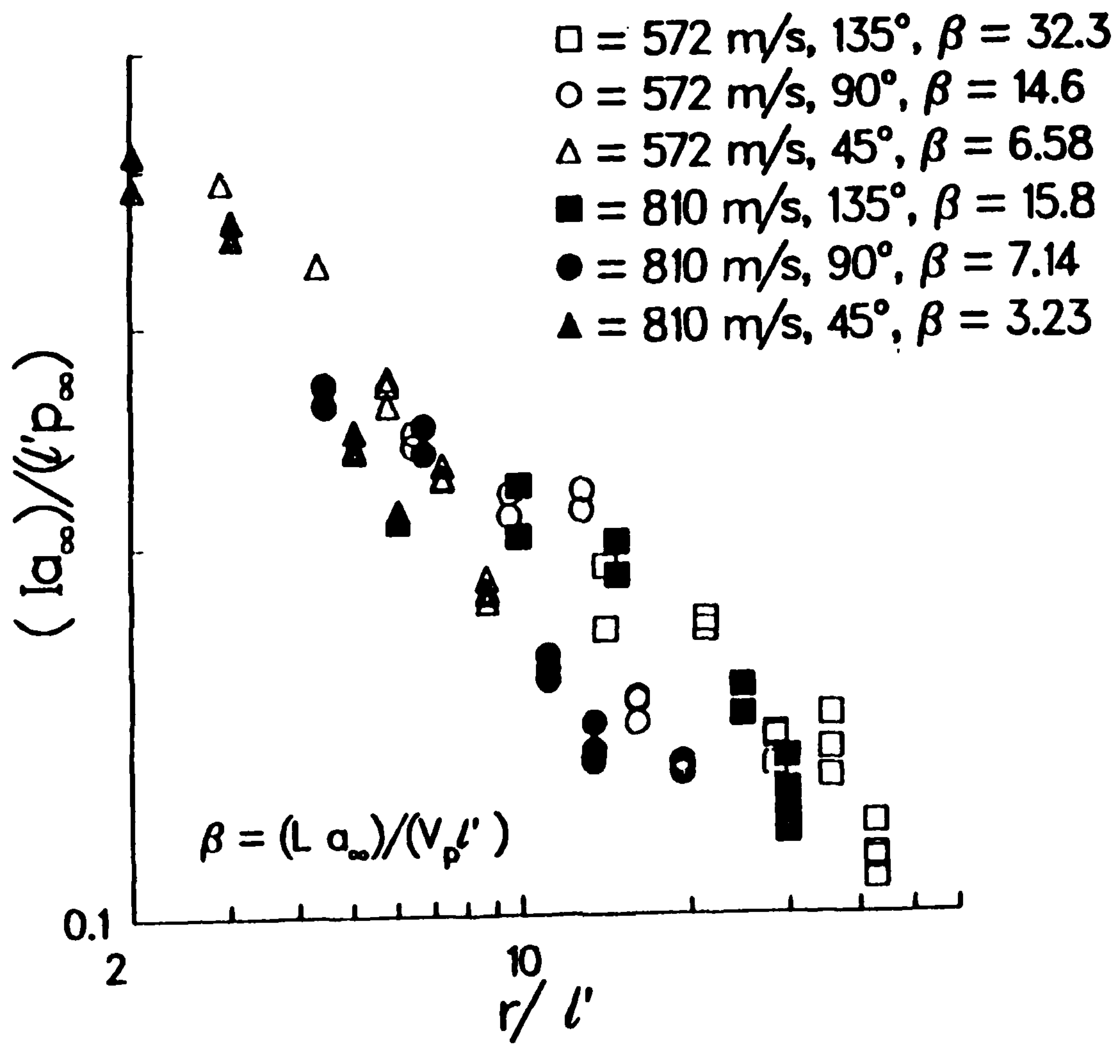

Figure 10. Scaled Impulse Data versus Scaled Distance for 30mm Cannon

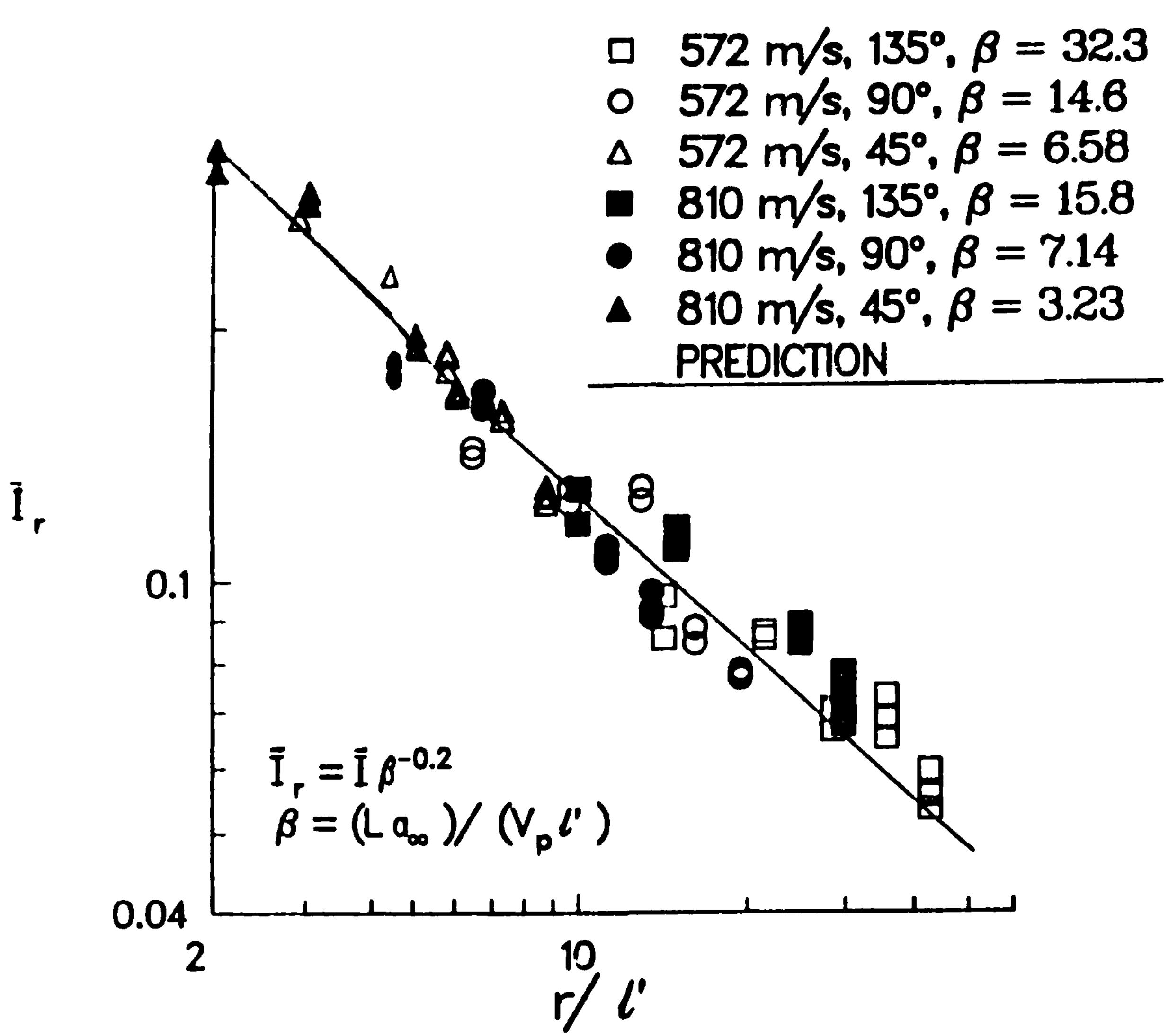

Figure 11. Reduced 30mm Impulse Data Compared with Present Prediction

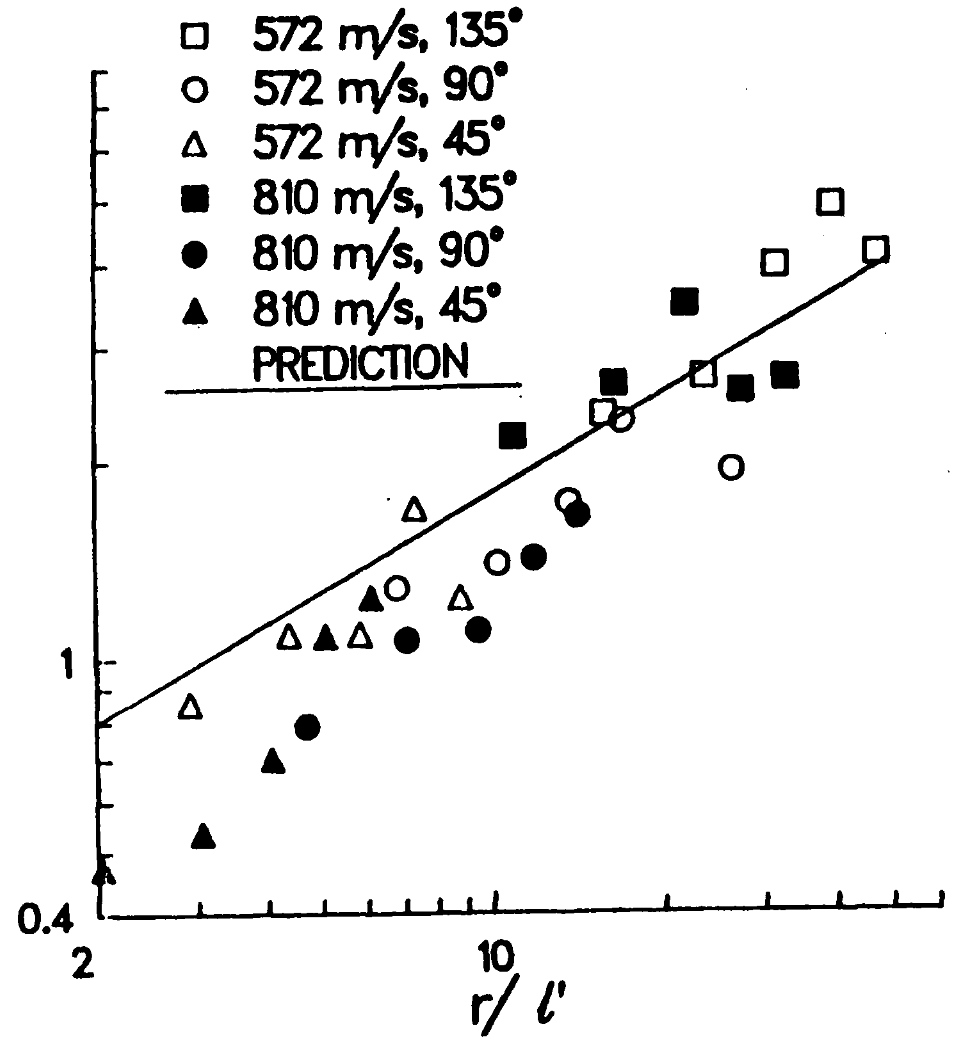

Figure 12. Reduced Positive Phase Duration Data Compared with Corresponding Prediction. The Prediction Utilizes Predicted Peak Overpressure and the Friedlander Waveform.

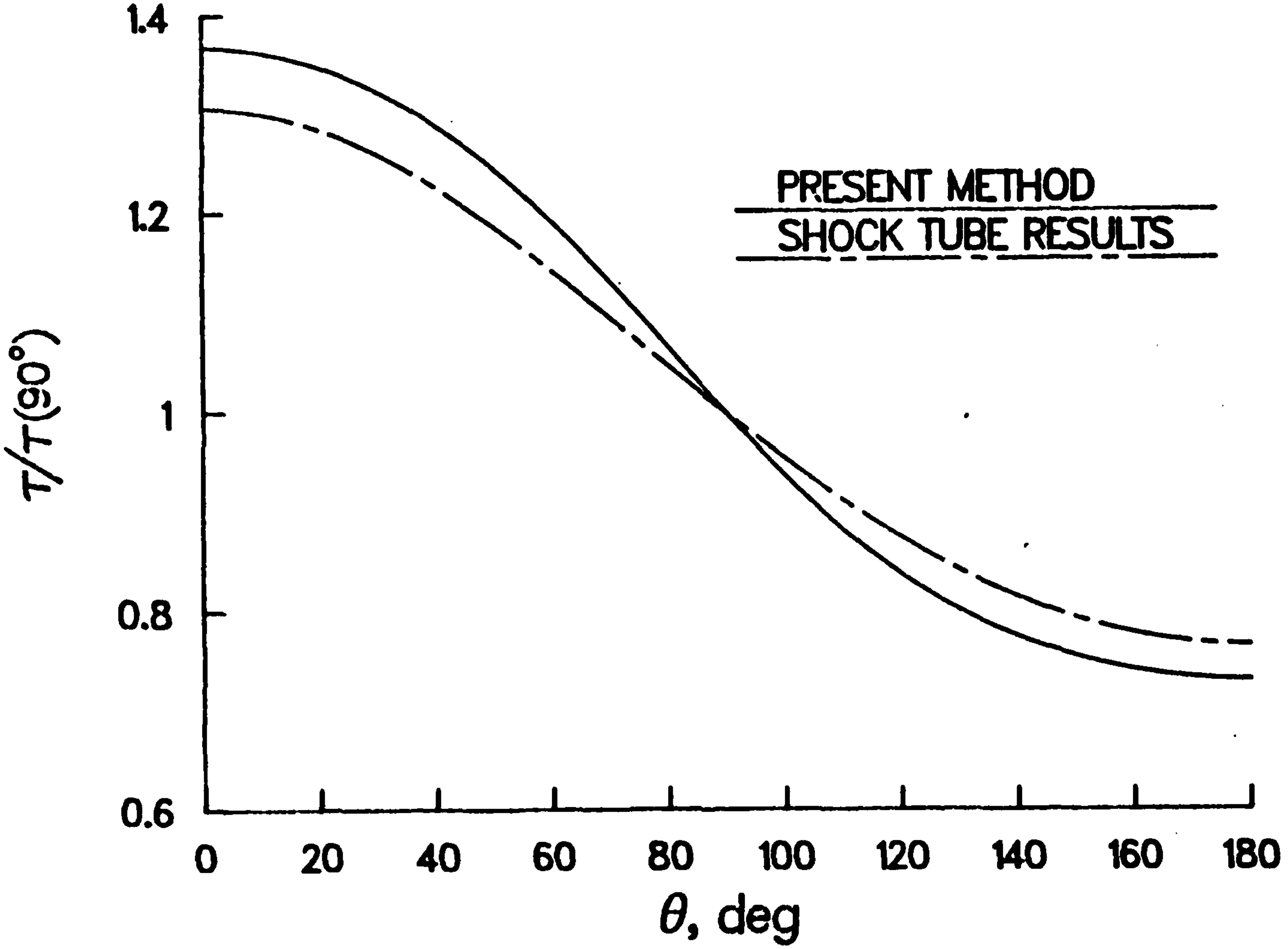

Figure 13. Comparison of Two Predictions for the Positive Phase Duration versus the Polar Angle. Reference 7 Prediction was Derived from Shock Tube Data.

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