INTERIOR BALLISTICS OF FIREWORKS MORTARS

DAVID E.G. JONES

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by

David E.G. Jones

ABSTRACT

This report describes the use of a ballistics model and computer code originally designed to model the performance of large guns, in order to predict the effect of various parameters on the behaviour of a firework shell in a mortar. The effect of such parameters as mass of the lift charge, mass of the shell and mortar length have been explored and compared with experimental results. The effects of parameters such as friction, leakage area, size and shape of the grains of black powder, which are not easily accessible by experiment, have also been studied.

INTRODUCTION

Interest in the behaviour of fireworks in mortars at the Canadian Explosives Research Laboratory (CERL) is a result of increasing concern by both industry and regulators about safety in the use of fireworks. Additionally, it is part of CERL'S mandate in the realm of investigation of the properties of fireworks under the Canada Explosives Act.

Consequently, a significant number of tests have been performed at CERL on fireworks with the aim of ensuring their safe use. Of importance to these studies are the effects of various parameters on the ejection of fireworks shells from mortars. Among these parameters are the mortar length, the "fit" of the shell in the mortar and the masses of the lift charge and of the shell. Contestabile and his co-workers at CERL have conducted such tests and the results have been described (1). These results are summarized below under the various parameters studied.

Effect of Mortar Length

In these tests, the effect of varying the mortar length from 56 to 134 cm was investigated. It was observed that the peak pressures were invariant with mortar length whereas both peak-pressure to exit time and exit speed of the shell increased.

Effect of Fit

This effect was studied by varying the ratio $(d/D)^2$ where d and D are the diameters of the shell and mortar, respectively. As $(d/D)^2$ increased, both the peak pressure and exit speed increased while the time from peak-pressure to exit decreased, as expected.

Effect of Mass of Lift Charge

It was observed that both the peak pressure and speed of the shell increased with an increase in mass of the lift charge and the time from peak-pressure to exit decreased accordingly.

Effect of the Mass of the Shell

As the shell mass increased, both the peak pressure and time from peak-pressure to exit appeared to reach minima, whereas the shell speed decreased.

Purpose of this Investigation

This report will describe the use of a simple ballistics model to treat the interior ballistics of fireworks shells. Shimizu has already developed such a model from first principles (2) and has compared the result of his model using defined propellant grains, with experimental results.

It is believed to be important to determine parameter predictions from ballistic models both for the purpose of comparing with experimental results and for investigating the effect of a number of parameters on the performance of the fireworks shells as well as factors affecting their safe performance in the mortar. The parameters studied here include some of those previously investigated experimentally as well as others. Some of the latter parameters are not easily accessible by experiments. These include the effect of friction between the shell and the mortar, leakage of gas around the shell, the volume available to the gas produced, etc.

BALLISTICS MODEL

The ballistic model has been used by Defence Research Establishment at Valcartier (DREV) to determine the interior ballistics of large guns (3)(4). DREV supplied a copy of the computer code, BALINT, based on this model. The code was written in FORTRAN and designed to run on a Honeywell mainframe computer. It was adapted to run on a PC. In the course of doing so, it was necessary to make some corrections to the code as well as making it interactive. A number of modifications are still required but the results presented here are believed to be as reliable as possible given the variation in some of the parameters, particularly the geometry of the black powder grains.

The model is based on four conditions which yield the following basic equations:

(i) Equation of state of gas from lift charge

$$(P(t)/m)(V(t) - mV) = \text{constant}$$

where $P(t)$ is the pressure of the gas, m is the mass of the lift charge, V is the covolume of the gas and $V(t)$ is the volume available to the gas given by

$$V(t) = V_{ch} + A(s(t)) - m\{1/d + Z(t)[V - 1/d]\}$$

where V_{ch} is the chamber volume (volume under the shell), A is the cross sectional area of the mortar, $s(t)$ is the distance that the shell has travelled in the mortar at time t and the last term expresses the volume occupied by the solid lift charge of density, d, corrected for the amount burned.

(ii) Equation of motion of the fireworks shell

$$dv/dt = (C_f P(t) A \Delta t)/M$$

where, v is the speed of the shell, C_f is the friction coefficient and M is the mass of the fireworks shell. Clearly, the speed, v is directly related to the "friction" between the shell and the mortar.

(iii) Burning rate equation

$$dx/dt = aP(t)^b$$

where, x is the distance that the grains have recessed at time, t and a and b are constants for a given composition of lift charge.

(iv) Form function, $\phi = \phi(Z(t))$

$$Z(t) = 1 - (V_{gr}(t))/V_o$$

where Z(t) is the fraction of the lift charge burned at time t, $V_{gr}(t)$ is the volume of the grains at time t and V_o is the initial volume of the grains. ϕ is a specific function of size parameters for each type of grain geometry. Therefore, it is necessary to make an assumption about the size and shape of the grains in the lift charge.

Table 1 lists the output that can be obtained from BALINT and Table 2 is a typical output chart.

To carry out these calculations it is necessary to input information about the properties of the lift charge, the shell and the mortar. In particular, the size and shape of the lift charge grains are essential data for the code. In all the calculations presented here, we have used for black powder the properties described by Sassé (5) which are similar to those of 2FA black powder.

To reduce the number of variables in determining the effect of various parameters on the output from the code, we have used the standard set of data listed in Table 3. Imperial units have been used in the calculations since there are some problems in the code with metric units.

RESULTS AND DISCUSSION

The effect of various parameters in the model on the time profiles of pressure, speed and lift charge consumption will be described. The standard set of data listed in Table 3 was used as each parameter was varied. In a few cases, data had to be altered in order to obtain meaningful results from the output. These cases will be noted in their particular section. Where appropriate, the results of the calculations will be compared with experimental results, but it should be borne in mind that initial adjustment to experimental results was achieved by altering the friction coefficient and leakage area.

Effect of Friction Coefficient, C_f

The effect of C_f is illustrated in Figure 1, from which it can be seen that the speed of the shell increases as C_f increases. Higher values of C_f indicate lower values of "friction" and conversely. Thus, increased peak pressure, exit times and lift charge consumption are observed at low values of C_f.

Effect of Leakage Area (used $C_f=5$)

Figure 2 shows the effect of leakage area on pressure, speed and lift charge consumption. As the leakage area increases, speed decreases and lift charge consumption increases, as expected. However, it is also noted that peak pressure increases and it is difficult to explain this observation. The opposite effect is observed from the ratio $(d/D)^2$ as reported experimentally. A direct comparison with experimental results will be discussed later.

Effect of Chamber Volume (Volume under shell) V_{ch}

The effect of the chamber volume on the pressure and speed profile is shown in Figure 3. Increasing the chamber volume decreases the peak pressure. Both the exit speed and lift charge consumption are essentially independent of the chamber volume, although higher speeds result earlier at lower chamber volumes. Thus, it is possible to obtain the same height for the shell with a larger chamber volume and increase the life of the mortar since lower peak pressures are experienced.

Stationary Shell

These results are linked to the previous study of the effect of chamber volume. Figure 4 shows the peak pressure reached in the mortar as a function of mass of lift charge for three different chamber volumes. The friction coefficient was set to zero, so that there was no movement of the shell in the mortar. The leakage area was also set to zero so that the maximum pressure consistent with the mass of the lift charge and the chamber volume used, resulted.

It is noted that lower peak pressures are achieved with larger chamber volumes, as previously observed and, as the chamber volume increases the peak pressure becomes independent of the mass of the lift charge. Finally, as the mass of the lift charge increases the peak pressure increases and the time to reach this pressure decreases.

Effect of Shot Travel (Mortar Length)

As expected, the speed, time to exit and lift charge consumption increase with mortar length. This is indicated in Figure 5. The peak pressure remains constant. Thus, the code predicts the same effect for the speed and peak pressure as observed in the experiments.

Effect of Mass of Lift Charge

Figure 6 depicts the effect of the mass of the lift charge on the calculated parameters. As the mass increases the peak pressure, speed and lift charge consumption increase and the peak to exit time decreases. Again, these results agree with experimental results.

Effect of the Mass of the Shell

From Figure 7, it can be seen that increasing the mass of the shell increases the peak pressure and lift charge consumption but decreases the speed, as expected. No minima in peak pressure and speed were detected, as reported from the experiments.

Effect of "Fit"

The results shown in Figure 8 represent an attempt to directly compare the predictions from the model with experimental results. The $(d/D)^2$ values quoted by Contestabile et al (1) were used to estimate the leakage areas given in Figure 8. As $(d/D)^2$ increases, the leakage areas decrease. In these calculations, C_f was set to 5 since higher values caused the code to generate floating point errors. The results indicate that the small differences in leakage areas resulted in very little difference in the pressure and speed profiles. This is definitely a limitation of the present code.

BLACK POWDER GRAIN PARAMETERS

Effect of the Diameter of the Spherical Grains

Figure 9 shows that the diameter of the grains of black powder has a dramatic effect on the peak pressure and, correspondingly, on the speed of the shell both in the mortar and at exit from the mortar. The latter affects the height that the shell attains. Smaller grains yield higher peak pressures, speeds and increased consumption of black powder. This is believed to be a result of the increased burning rate with grains having larger surface area to volume ratios.

Effect of the Shape of the Grains

The effect of the shape of the black powder grains on pressure and speed profiles is indicated in Figure 10. These calculations were done for cord, cylindrical and strip grains having the same volume as the spherical grains (diameter 0.12 in.) used in the standard set of data in Table 3. The peak pressures and speeds increase in the order spherical to cylinder to strip to cord, the order of increasing surface area and expected increase in burning rate. There is flexibility in adjusting the size parameters, particularly for the strip and cord and yet retaining the same volume. In general, the peak pressure and speeds are reduced as the strip approaches a cube and the cord approaches a cylinder.

Effect of Mixture of Sizes of Grains

Figure 11 compares the results of the standard set of data with a mixture of spherical grains containing equal mass of grains of diameter 0.08, 0.10, 0.12, 0.14 and 0.16 in., respectively (C_f = 5.0 and leakage area nil). This graph shows little difference between the results for the two sets of data, although peak pressures and speeds are slightly larger for the single grain case. This implies that the slower burning rate of the larger grains has a large influence on the result. It is probably more realistic to expect an unequal mass distribution of grain sizes (2)(5) and these results are merely intended to illustrate the limits to which the code can be extended.

Effect of Mixture of Grain Shapes

Calculations have been done for a mixture of spherical and cubic (strip) grains of equal mass and size (0.12 in.). These results are shown in Figure 12, along with the results for spherical grains under the same conditions (C_f = 5.0 and leakage area nil). Clearly, pressures and speeds for the mixture of grains are lower than those for the spherical grains. This result is believed to be caused by the slower burning rate of the cubic grains.

Effect of the Lift Charge Consumption (Mortar Length)

Figure 13 shows the time profile for black powder in the form of grains which are strips. This information illustrates the trend in pressure and speed for the case where all the lift charge is consumed prior to the shell reaching the end of the mortar. Inflection points in both the pressure and speed profiles are observed particularly for the "thinnest" grains. Additionally, Figure 13 demonstrates the effect of the size parameters on the magnitude of the peak pressure and exit speed. As the grains become more cubic, the peak pressure, exit speed and lift charge consumption decrease.

CONCLUSIONS

The ballistics model provides useful information about the performance of fireworks in a mortar. For the most part, there are good correlations with the trends observed in experiments. Additionally, the code provides information about effects for which limited experimental results are available. Despite a few shortcomings and obvious errors needing correction, it appears that additional calculations using BALINT are warranted.

ACKNOWLEDGMENT

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4. J. Maillette and D.H. Gladstone; 12th TTCP WTP-4 Meeting, Joint Tropical Trials and Research Establishment, Innistart Weapons and Research Laboratory, Adelaide, 1986.

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Table 1 - Output from BALINT

1. Time profiles of pressure, speed distance and amount of lift charge consumed

2. The above information for a mixture of up to 5 lift charges differing in size and/or shape eg. spherical, cylindrical, cord, strip (cube)

3. A summary including the time to peak pressure and the time to exit from the mortar, the exit speed and the value of the peak pressure

4. A summary of the energy distribution including that released by the lift charge and that consumed by various means such as internal gas, kinetic energy of the shell, heat loss, kinetic energy of the gas, friction, leakage, etc.

Table 2 - Output information from BALINT

TIME (MS)	PRESSURE (PSI) CHAMBER	BREECH	BASE	VELOCITY (FT/S)	TRAVEL (IN)	BURNT PROPELLANT (Bpwd)
.2	34	34	34	4	0.00	0.01
.4	63	63	63	17	0.02	0.02
.6	90	90	90	37	0.09	0.03
.8	109	109	109	64	0.21	0.04
1.0	117	117	117	94	0.40	0.04
1.2	116	116	116	125	0.66	0.05
1.4	108	109	108	155	1.00	0.06
1.6	98	98	98	183	1.40	0.07
1.8	87	87	87	207	1.87	0.08
2.0	77	78	77	229	2.40	0.09
2.2	69	69	68	248	2.97	0.10
2.4	62	62	61	266	3.59	0.10
2.6	56	56	55	281	4.24	0.11
2.8	51	51	51	295	4.93	0.12
3.0	47	47	47	308	5.66	0.13
3.2	44	44	43	320	6.41	0.14
3.4	41	41	40	331	7.20	0.14
3.6	38	39	38	342	8.00	0.15
3.8	36	36	36	351	8.84	0.16
4.0	34	35	34	361	9.69	0.16
4.2	33	33	32	370	10.57	0.17
4.4	31	32	31	378	11.46	0.18
4.6	30	30	30	386	12.38	0.18
4.8	29	29	28	394	13.32	0.19
5.0	28	28	27	401	14.27	0.20
5.2	27	27	26	408	15.24	0.20
5.4	26	26	26	415	16.23	0.21
5.6	25	26	25	422	17.23	0.22
5.8	25	25	24	428	18.25	0.22
6.0	24	24	23	435	19.29	0.23
6.2	23	24	23	441	20.34	0.24
6.4	23	23	22	447	21.41	0.24

MUZZLE VELOCITY : 450. FT/S
BASE PRESSURE MAXIMUM : 118. PSI
CHAMBER PRESSURE MAXIMUM: 118. PSI
BREECH PRESSURE MAXIMUM : 118. PSI
TIME TO MAXIMUM PRESSURE: 1.06 MS
TIME TO EXIT : 6.51 MS

Table 3 - Cylindrical Shell

Mass of lift charge, m = 3.5 oz⁺

Mass of shell, M = 3.0 lb

Black powder - spherical grains - diameter 0.12 in⁺

Shot Start Pressure 20 p.s.i.⁺
(chamber pressure required to initiate movement of the shell in the mortar)

Chamber Volume, V_{ch} = 70 in^3
(volume under shell)

Shot Travel 23 in
(assumed to be equal to mortar length, ie. neglect effect of shell size)

*Leakage Area 20 in^2
} assumed constant
*Friction Coefficient, C_f 15

* These parameters have been adjusted to give reasonable agreement with experimental values of peak pressure and exit speed (1). Leakage area option is not as yet available in code when using a mixture of grains of black powder of different sizes and/or shape.

\+ 1 in = 2.54 cm
1 p.s.i. = 6.89 kPa
1 ft s^{-1} = 30.5 cm s^{-1}
1 oz = 28.3 g

Figure 1

Effect of Friction Coefficient

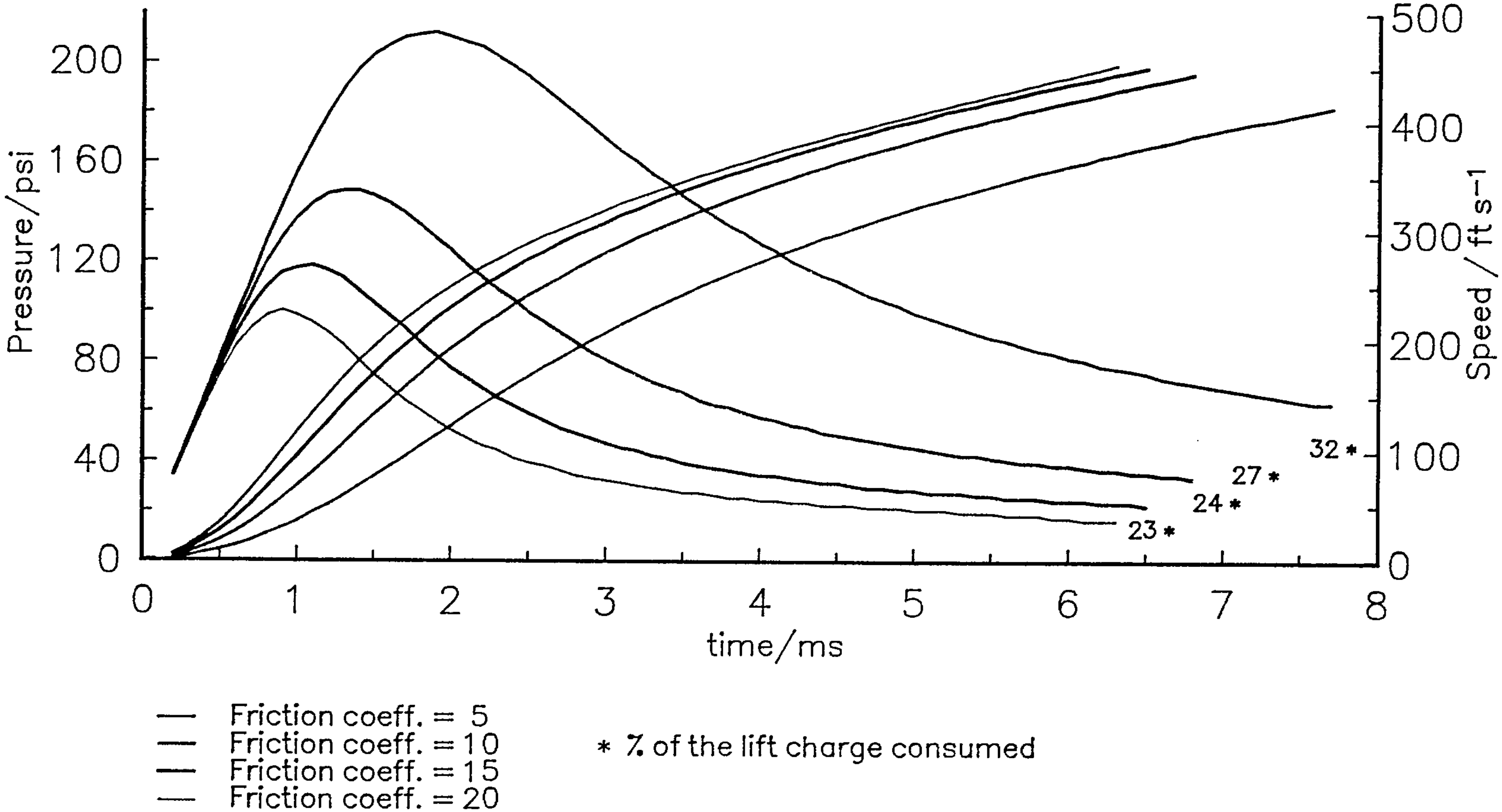


Figure 2

Effect of Leakage Area

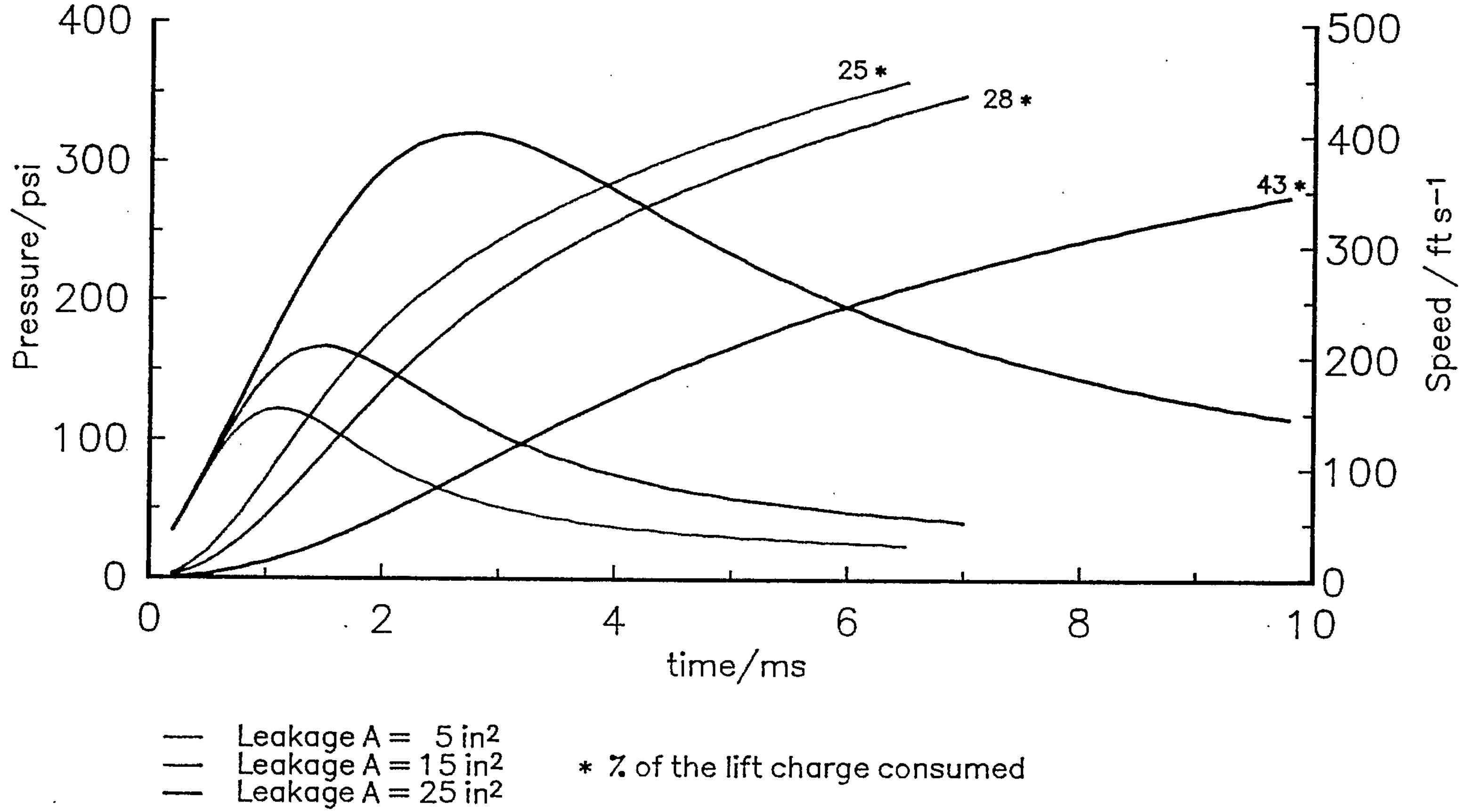
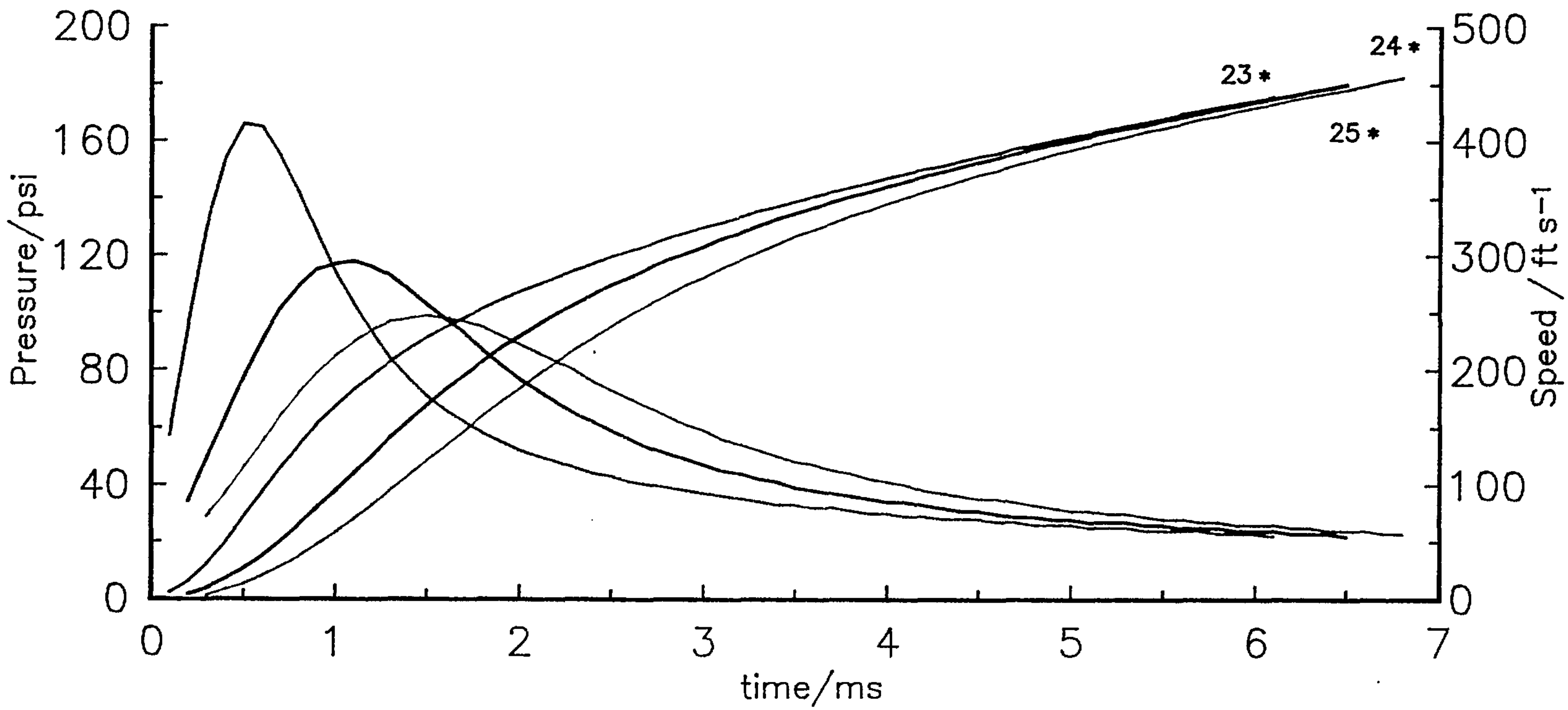


Figure 3

Effect of Chamber Volume



— Chamber Volume = 30 in³
— Chamber Volume = 70 in³
— Chamber Volume = 110 in³

* % of the lift charge consumed

Figure 4

Stationary Fireworks Shell

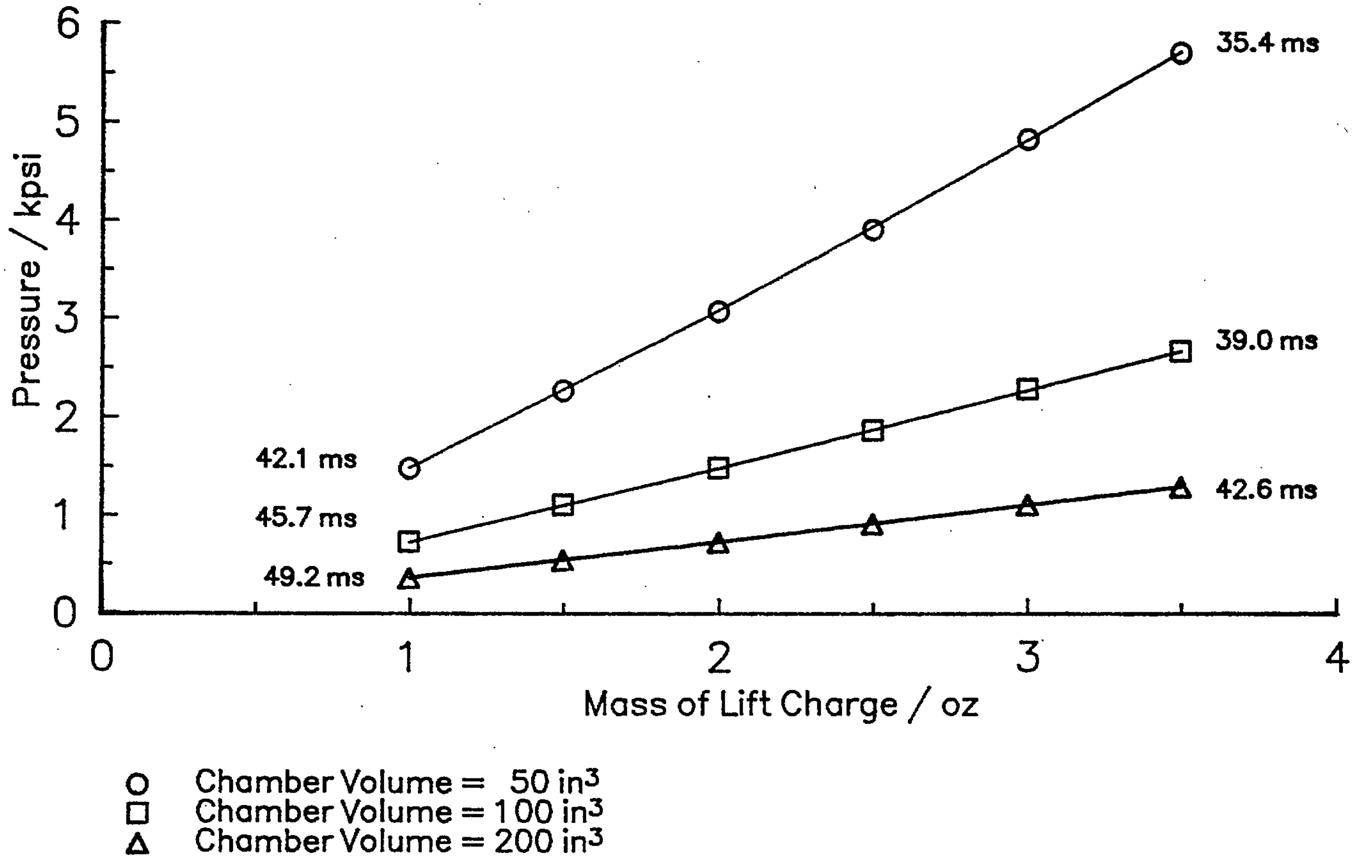


Figure 5

Effect of Mortar Length

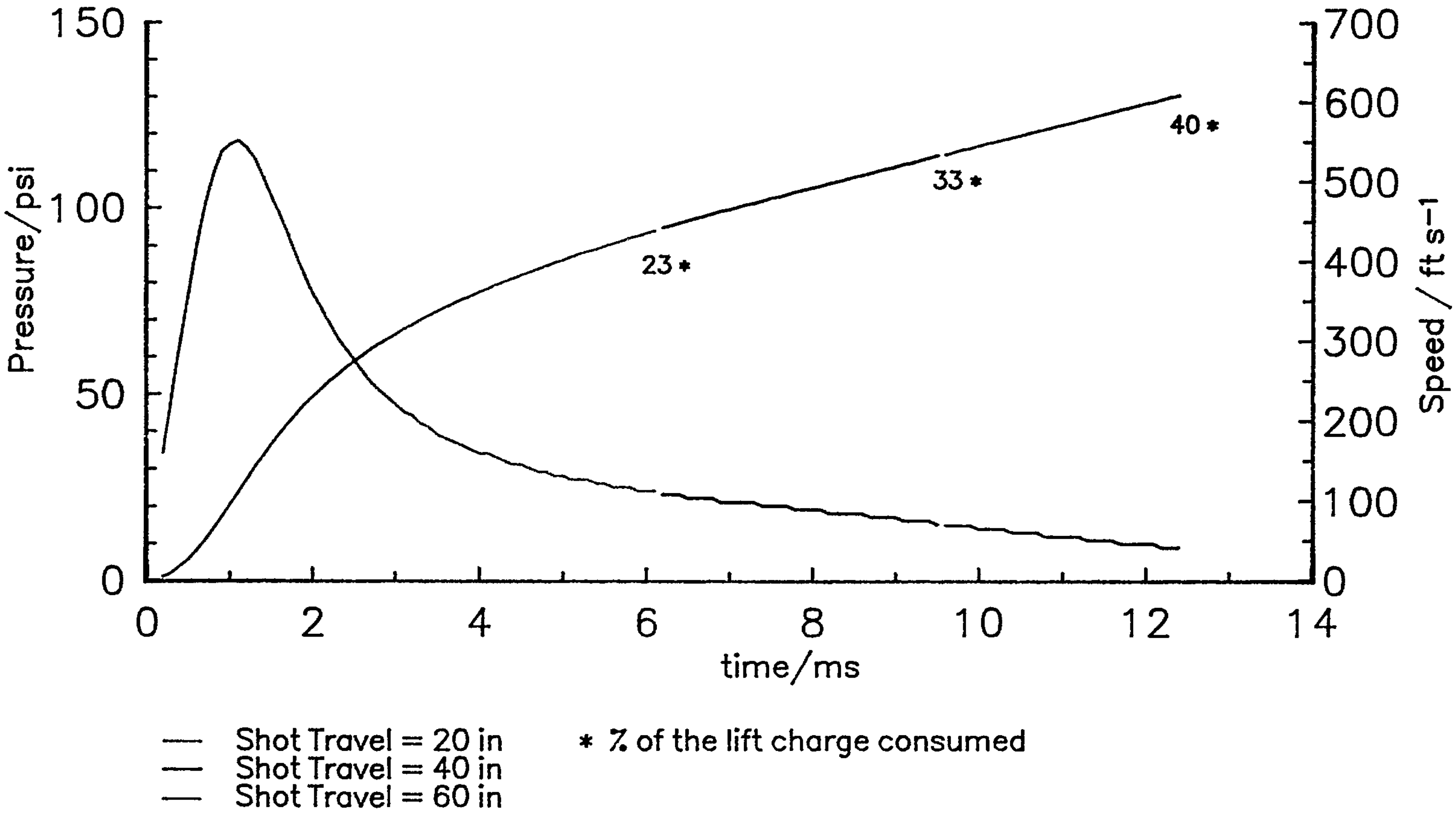


Figure 6

Effect of Mass of Lift Charge

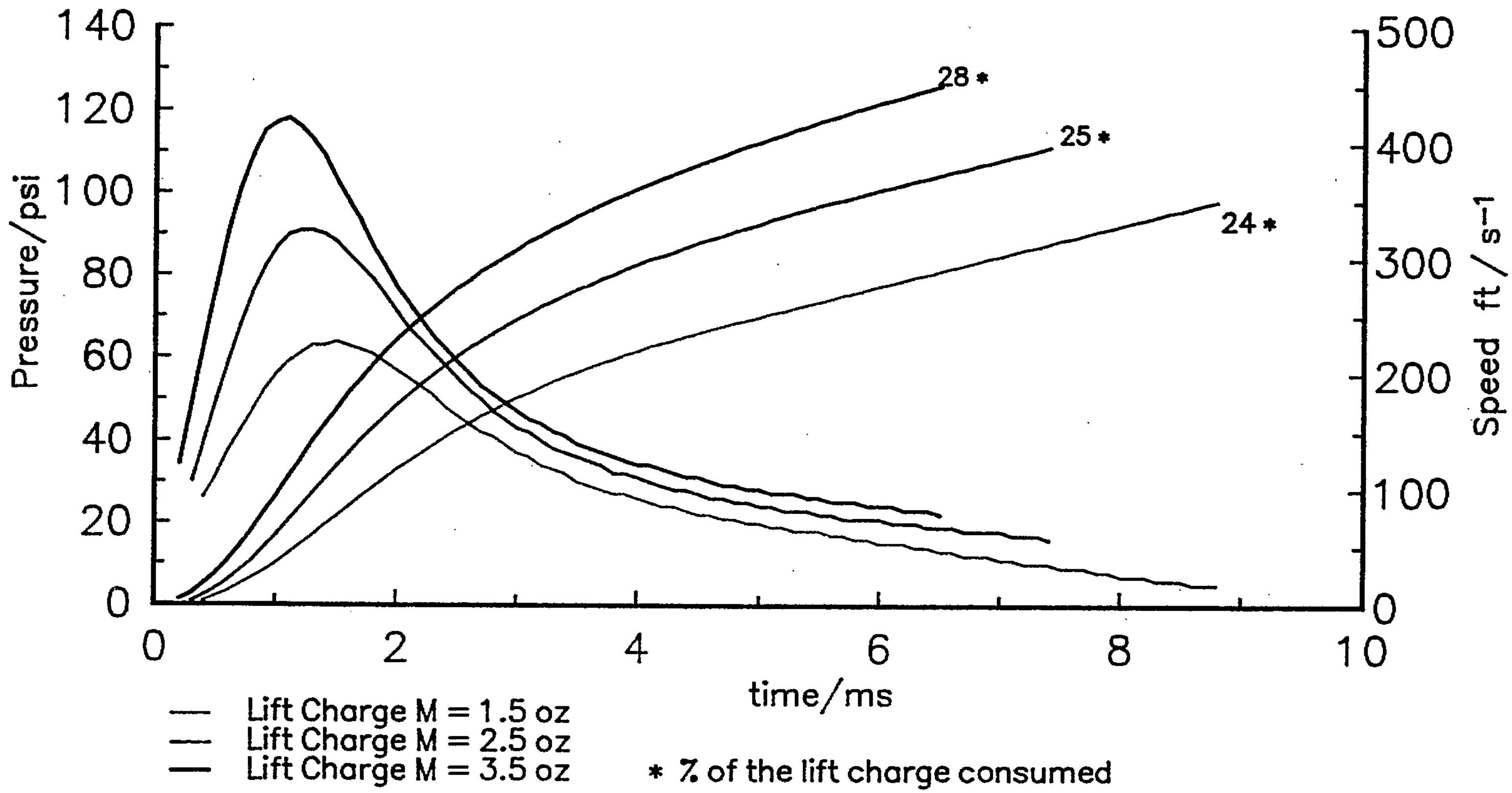


Figure 7

Effect of Mass of Shell

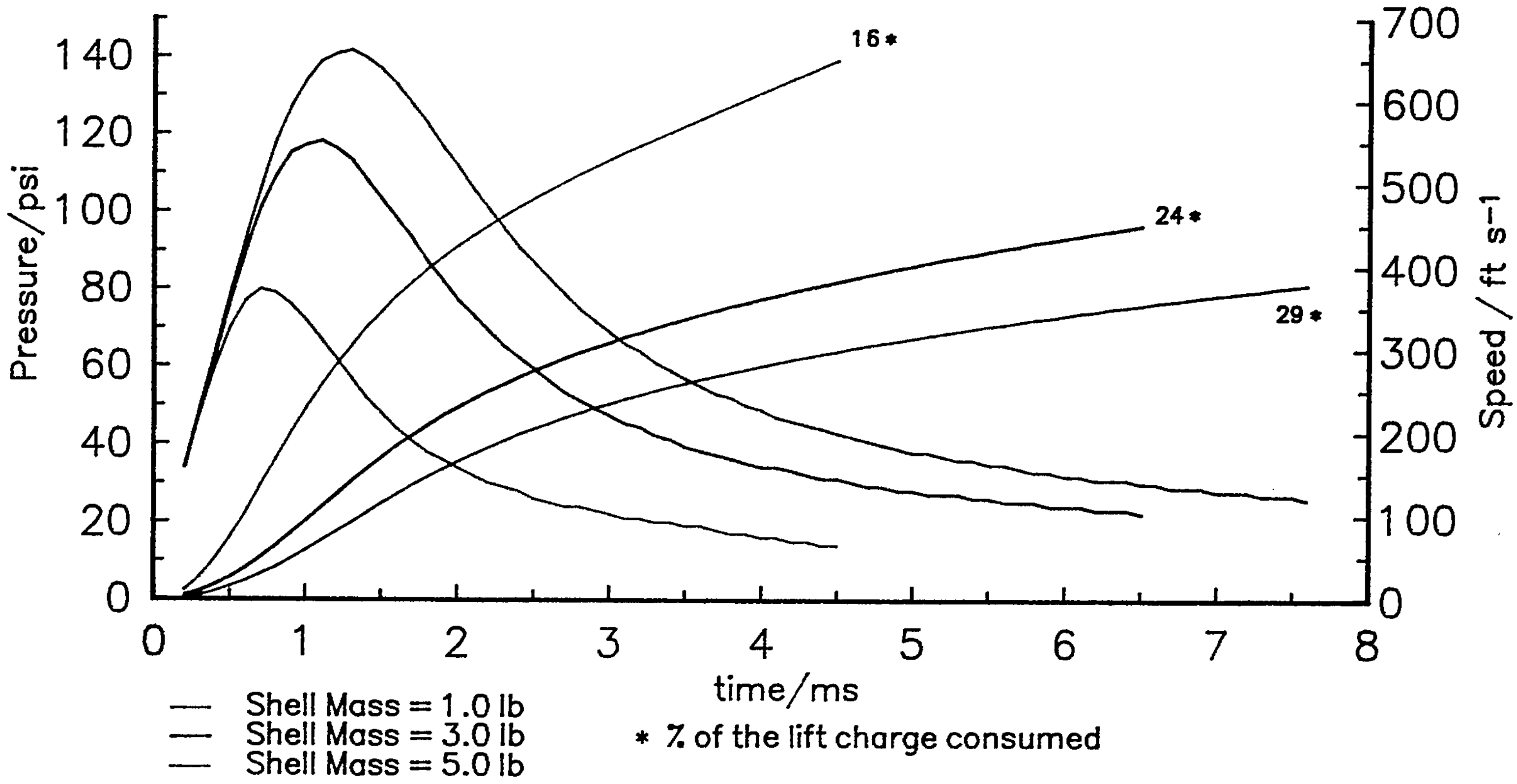


Figure 8

Effect of "Fit"

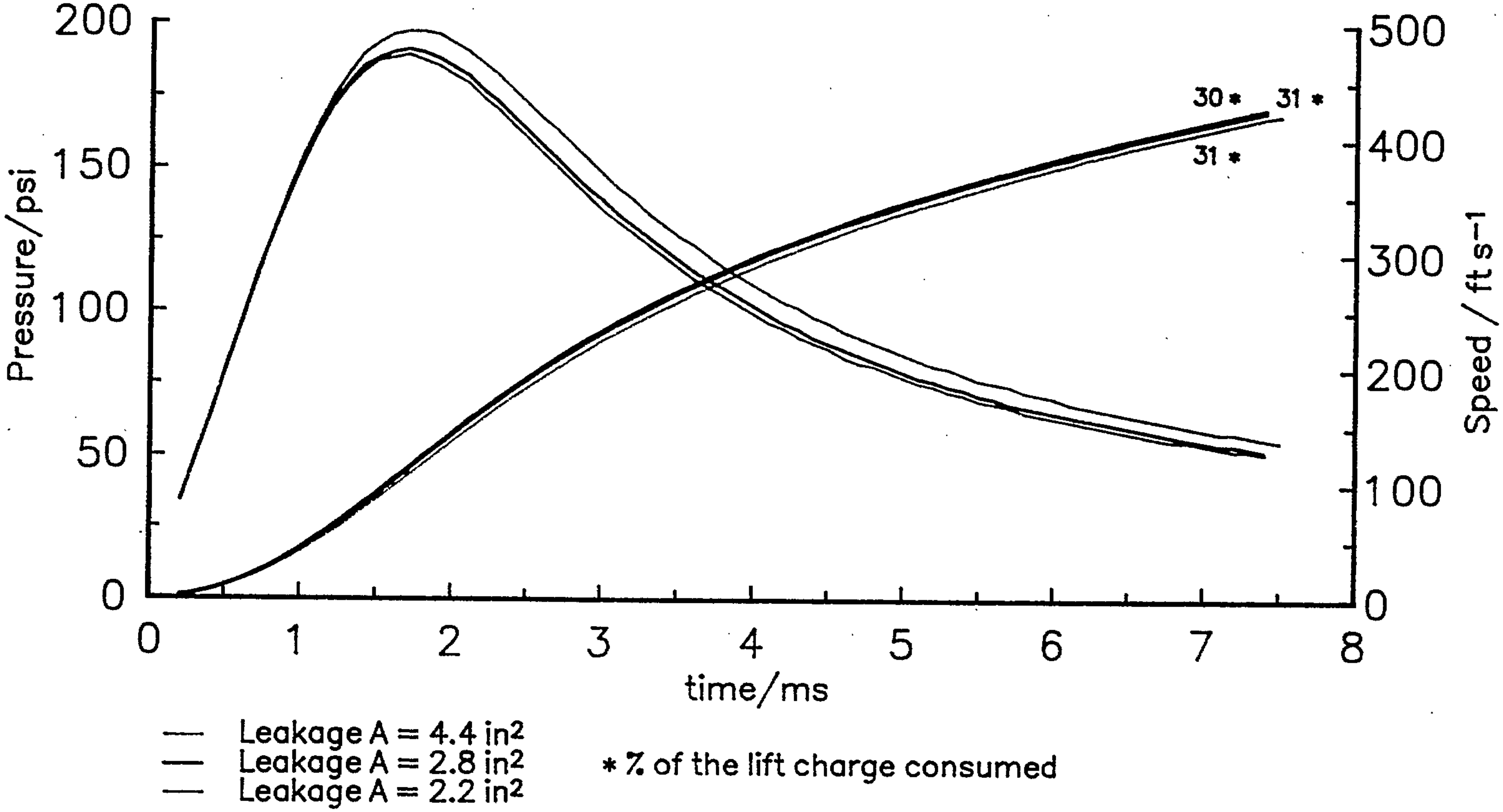
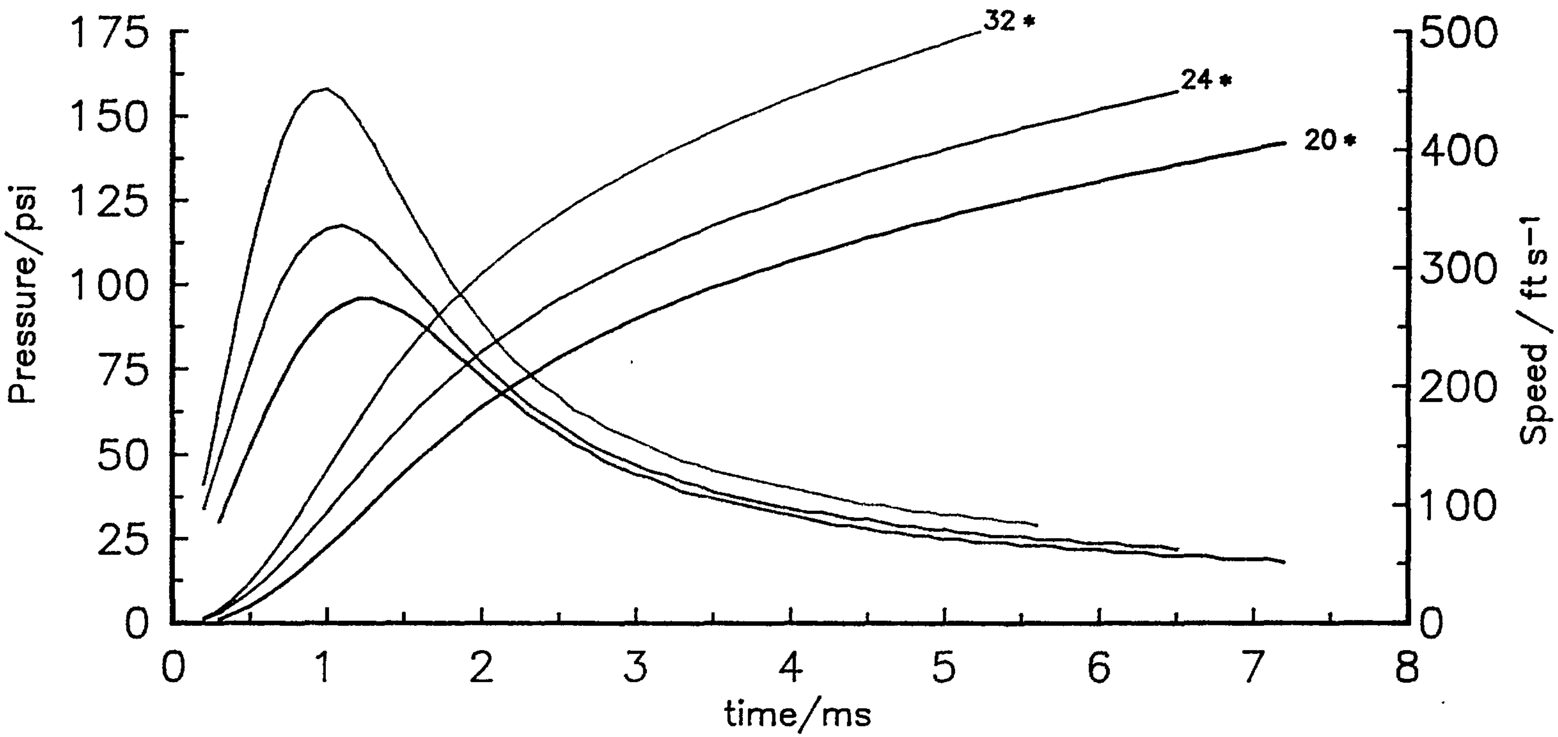


Figure 9

Effect of Size of Lift Charge Grains



— D = 0.08 in
— D = 0.12 in
— D = 0.16 in

* % of the lift charge consumed

Figure 10

Effect of Shape of Lift Charge Grains

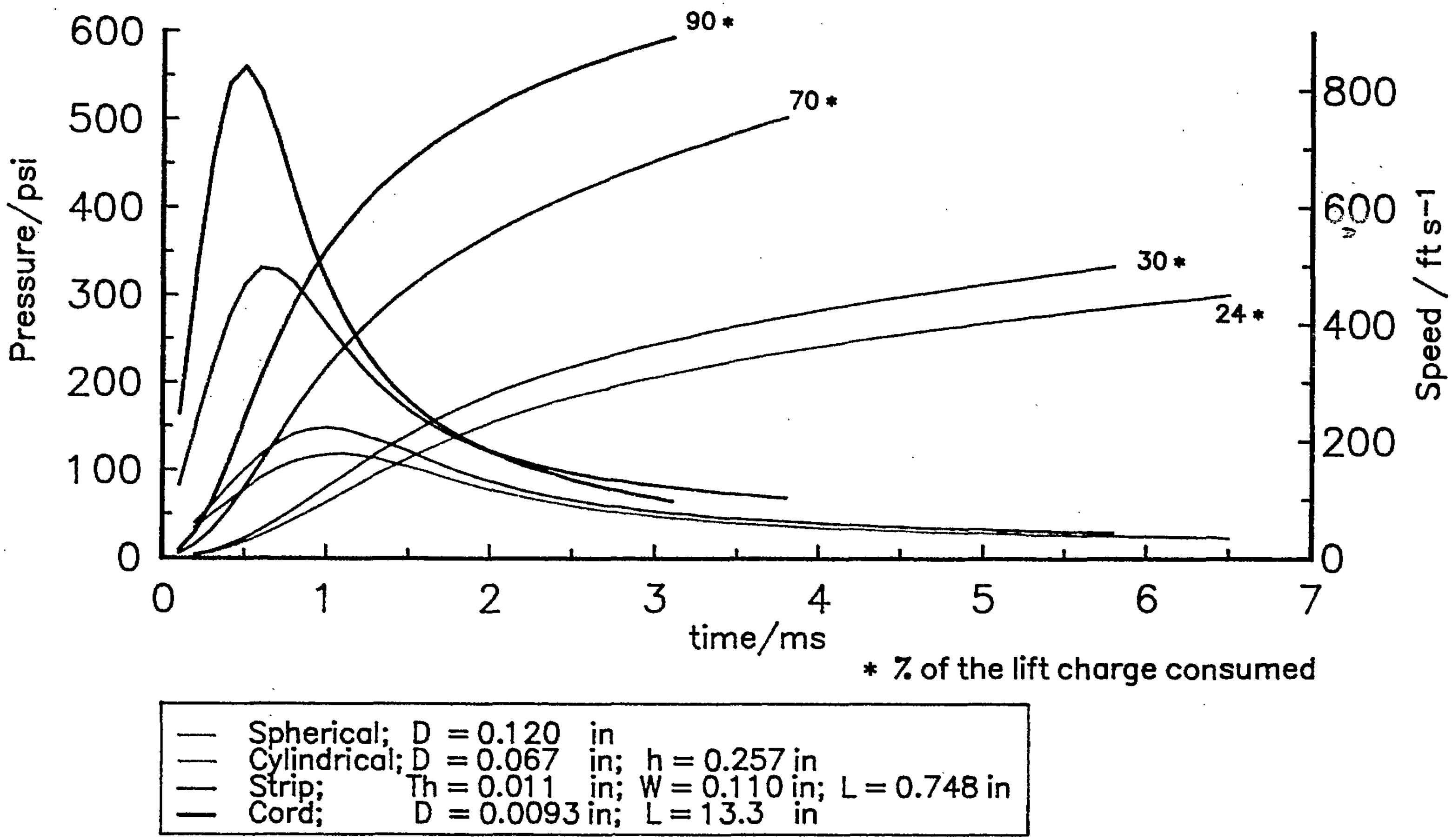


Figure 11

Effect of Mixtures of Sizes of Lift Charge Grains

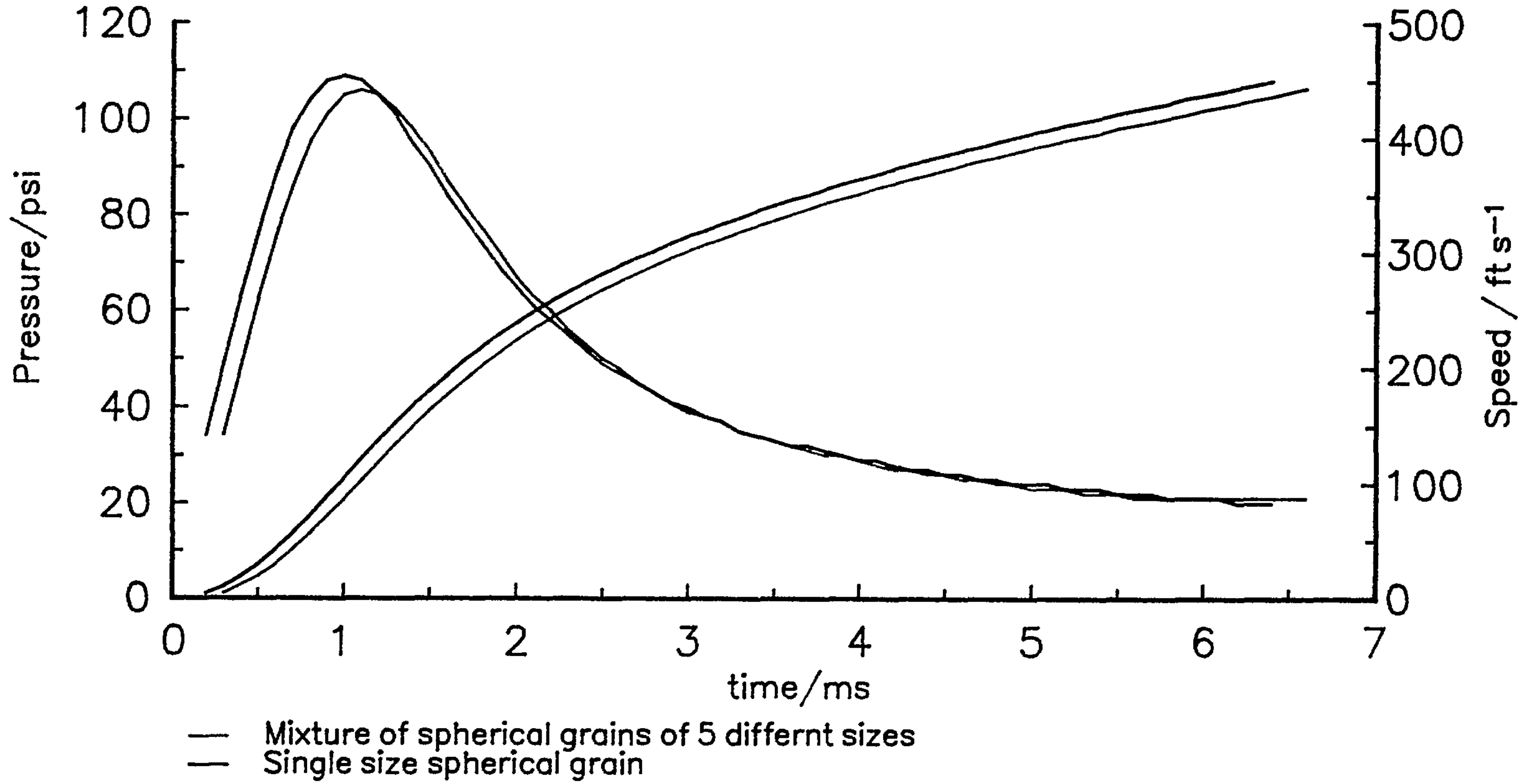


Figure 12

Effect of Mixtures of Lift Charge Grain Shapes

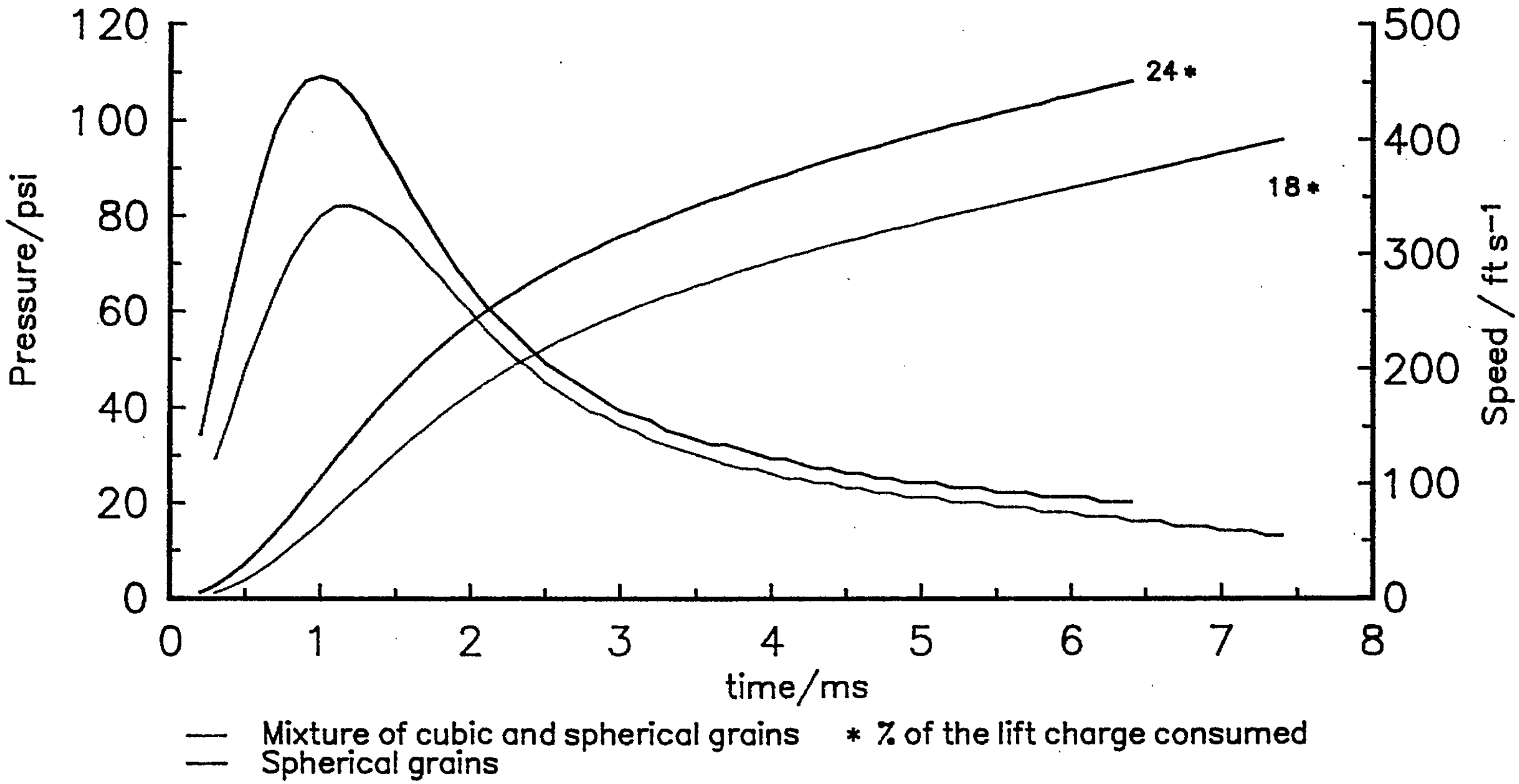


Figure 13

Effect of Strip Grains in 50 inch Mortar