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EVALUATION OF LARGE DIAMETER FIREWORKS SHELLS AND MORTARS

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EVALUATION OF LARGE DIAMETER FIREWORKS SHELLS AND MORTARS

by

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ABSTRACT

At the request from the fireworks industry, the Canadian Explosives Research Laboratory (CERL) undertook a project to measure various parameters to help evaluate large diameter firework mortars and shells. One of the aims of this study was to generate data that would be useful in determining if other materials besides steel could be safely used to manufacture large diameter mortars.

Such data as pressure, shell speed, burst height, time to burst, time to ground, and fall of shell are reported for 205, 255, and 305 mm diameter shells. The data were obtained for both imitation and live shells functioned from a 104 cm long steel mortar and for imitation shells only from a 244 cm long mortar. A comparison is made between the measured pressures and the specifications for the common mortar materials including fiber reinforced conduit pipe.

Some data will also be presented on functioning 180 mm (7 inch) shells from a steel 205 mm mortar.

INTRODUCTION

The Canadian Explosives Research Laboratory (CERL), has the mandate to test fireworks for the Chief Inspector of Explosives for the purpose of having such items authorized in Canada. During the past few years inquiries regarding fireworks mortars became more frequent and with the support of the American Pyrotechnic Association (APA), CERL undertook several projects to generate some basic scientific data. This particular study was aimed at answering some very specific questions regarding large diameter fireworks mortars. It seems that sufficient interest exists in manufacturing large mortars, that is 205, 255, and 305 mm diameter, with materials other than steel. Some of the drive to replace steel mortars stems solely from economic reasons, however, there is also the question of the associated hazards when shells accidentally function in them. With some serious recent accidents in

Britain, Canada, and the United States, some countries have already placed restrictions on the use of steel mortars.

EXPERIMENTAL SET-UP

A schematic of the specially-built mortars is shown in Fig 1. Except for the difference in diameter, the mortars were all designed in the same fashion and manufactured from steel pipe. The inside diameters of the pipes were 20.3, 25.4, and 30.5 cm with respective wall thicknesses of 0.82, 0.93, and 0.95 cm. The basic mortar of 104 cm length could be mated to a second 140 cm length of pipe for a total mortar length of 244 cm. As indicated in Fig 1, a transducer was mounted at the bottom of the mortar to monitor the pressure developed by the lift charge. Details of this arrangement have been reported previously [1].

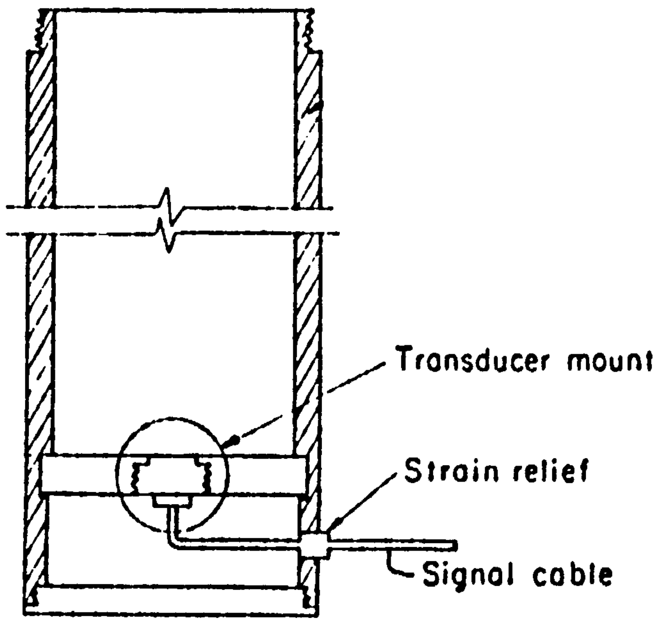

Fig. 1 - Instrumented mortar

The mortar was buried in the ground and oriented vertically with the use of a level. Figures 2 and 3 show the set-up used to measure the initial speed of the shell. A frame supporting the wire screens was aligned with the mortar. The frame held the two wire screens 1 m apart with the first screen being 0.5 m above the mouth of the mortar. The signals from the pressure transducer and the wire screens were recorded on a digital oscilloscope.

Tests were performed on three sizes of imitation shells and on both mortar lengths for a total of 36 shells.

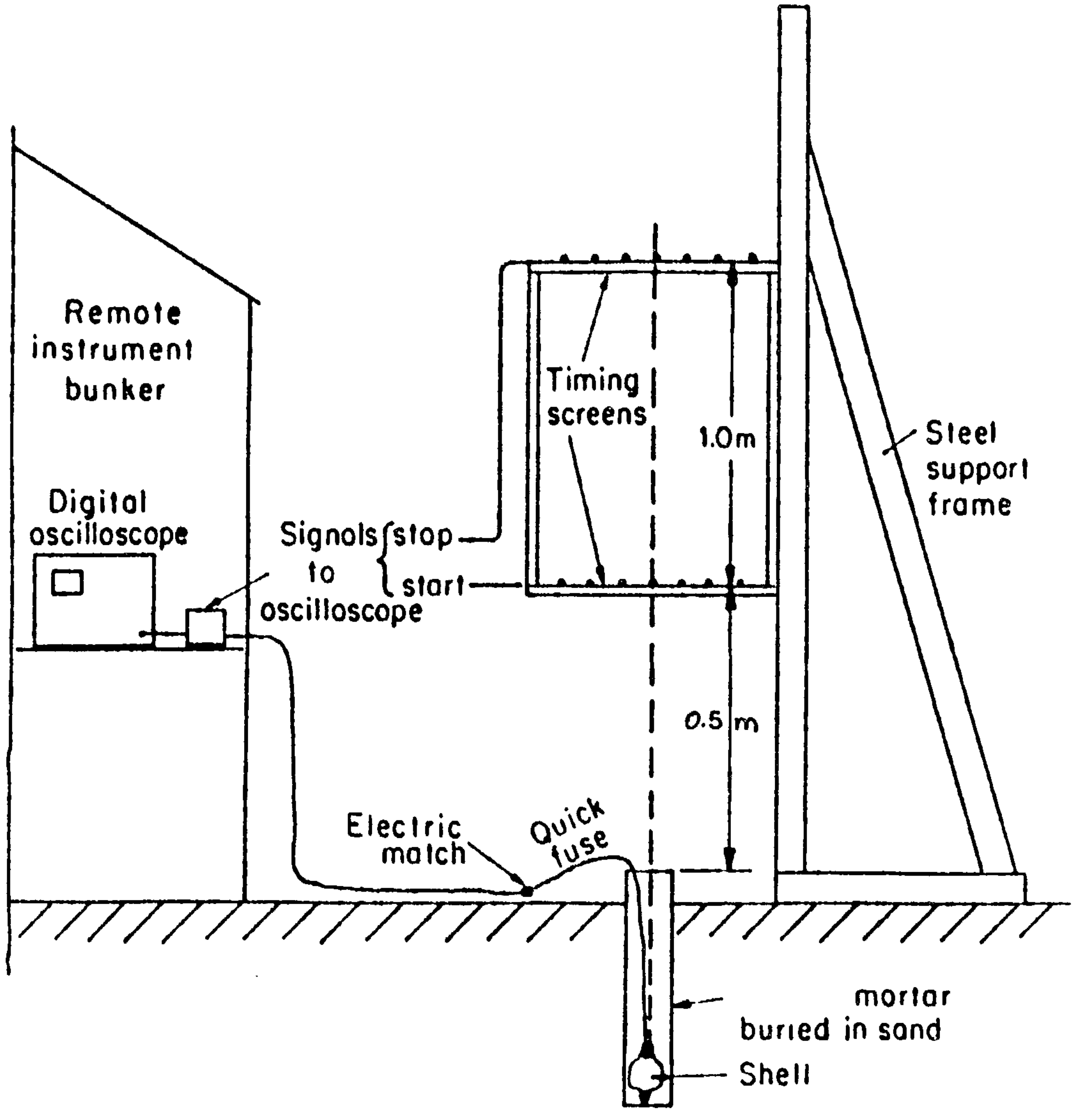

Fig. 2 - Schematic of experimental set-up

The imitation shells were specifically manufactured for this project, while the remaining live shells, of which only two were cylindrical, were remnants from a display competition.

Some tests were performed with two sizes of live shells fired from mortars that were one size larger to determine the associated hazards.

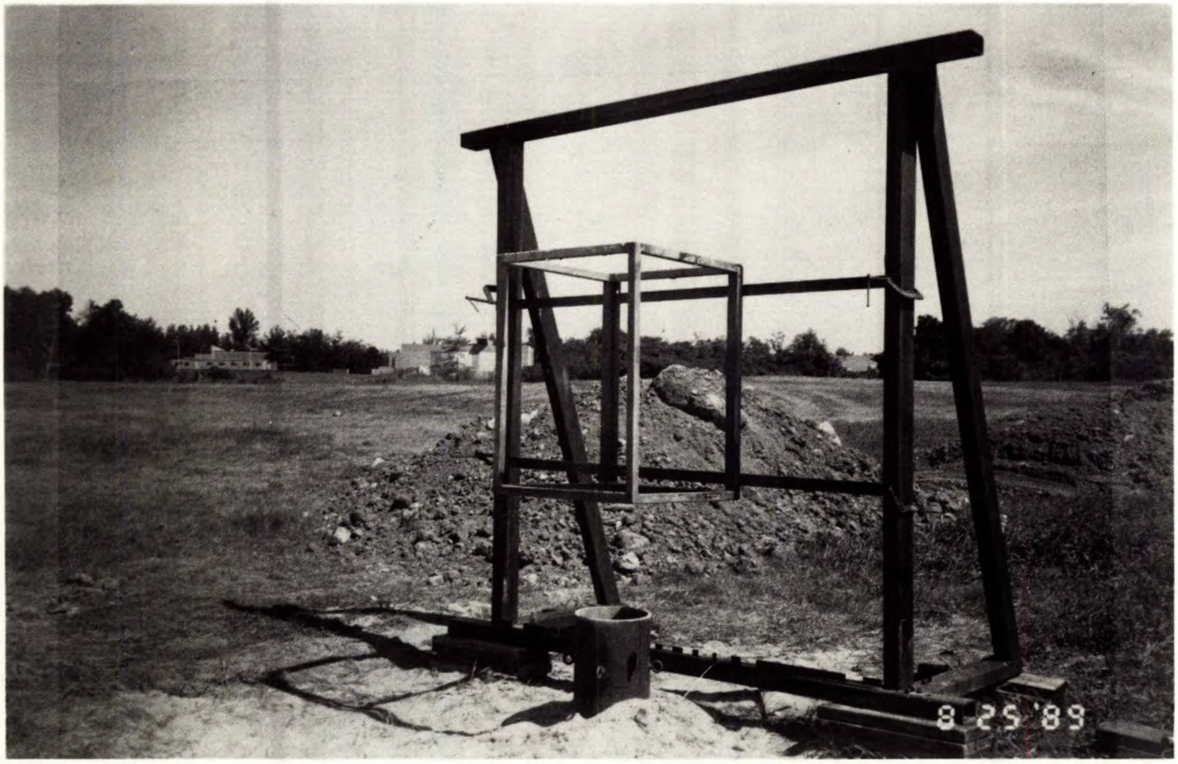

Fig. 3 - Short mortar set-up

DATA ANALYSIS

The data from functioning approximately one hundred shells were analyzed to generate values for such parameters as peak pressure, and impulse. Other data collected were the height at which the real shells functioned and the location of where the imitation shells fell.

A typical set of signals captured by the digital oscilloscope is shown in Fig 4. The lower trace represents the pressure profile while the upper trace shows the start and stop signals from the timing screens. The small peak to the left of the main pressure peak is the initial pressure disturbance due to the fuse burning just below the shell prior to the ignition of the lift charge.

The peak pressure was simply determined by measuring the voltage from the baseline (atmospheric pressure) to the peak of the main pressure pulse. Then, via the transducer's sensitivity value, the peak pressure is reported in kPa.

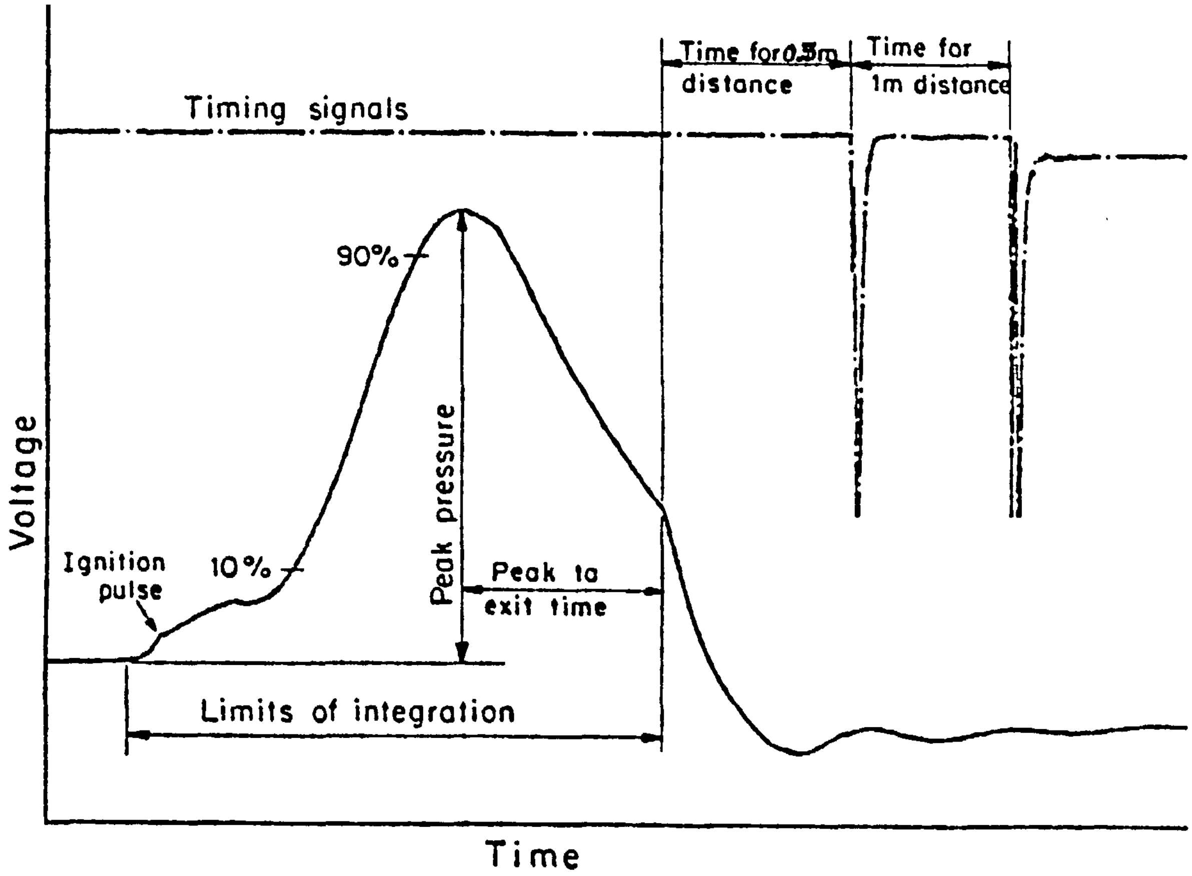

Fig. 4 - Normal timing signals in proper relation to pressure profile

To determine the impulse responsible for the shell's ejection, it was first necessary to identify the limits for the integration. The first point is the one where the pressure just begins to rise (the ignition pulse) with the second being that point on the pressure curve where the shell left the mouth of the mortar. This is easily identifiable since it is a point to the right of the pressure peak where the pressure abruptly decreases to the ambient value. The impulse is reported in kN ms.

A measurement that was found useful for correlation to other parameters, such as the shell's initial speed and the length of the mortar, was the time from the peak pressure value to the point identified as that at which the shell left the mouth of the mortar. This time, referred to as "peak-to-exit" is reported in ms and is expected to increase as the shell speed decreases and as the length of the mortar increases (all other parameters assumed to remain constant).

The speed of the shells was simply determined from the time measured between the start signal of the first screen to the stop signal of the second screen.

The height at which a shell burst was measured using equipment developed and manufactured at CERL. A full description of this apparatus will be the contents of a future report. Basically, a clock is first triggered by the firing signal to the electric match. When the shell bursts, the flash of light is detected, stops the clock and initiates a second counter. The clock displays the "time-to-burst". The counter stops when the sound of the burst is detected. Then, with the given speed of sound in air, the "height-to-burst" was determined. It is evident that there will be some inherent errors in these measurements that are dependent on the location of the equipment versus that of the bursting shells. This error was minimized by locating the equipment as best as possible under the area where the shells burst.

As indicated above, the time elapsed from a live shell leaving the mortar to its functioning, is reported as "time-to-burst. The time elapsed from a dummy shell leaving the mortar to it returning to the ground is reported as "time-to-ground". Both times are reported in seconds.

RESULTS

The results obtained from the measurements on imitation shells are listed in Table 1. Table 2 lists the results for the live shells and for those shells fired from larger mortars. In Appendix A, Table A1 lists some characteristics of the fall of shot survey for the imitation shells.

Table 1 - Test results for imitation shells.

Mortar Length /mm	Shell Size /mm	Avg* Mass /kg	Average Impulse /kN ms	Average Pressure /kPa	Avg Speed /m/s	Avg Time To Ground /s
104	205	2.71	213(5)	513(5)	83(3)	14.1
	255	4.49	498(5)	680(6)	88(3)	14.4
	305	8.85	776(5)	847(5)	75(3)	15.1
244	205	2.71	360(5)	654(6)	100(3)	15.9
	255	4.49	639(6)	731(6)	112(4)	16.2
	305	8.85	930(4)	996(4)	108(3)	17.0

* - Mass of shell only
( ) - Number of tests

Table 2 - Test results for live shells.
Mortar length 104 cm.

Shell Size /mm	Avg* Mass /kg	Average Impulse /kN ms	Average Pressure /kPa	Avg Speed /m/s	Avg Time To Burst /s	Avg Height /m
205	3.0	269(9)	460(9)	87(7)	3.5	205
	{2.3-4.0}				{3.1-3.8}	{134-302}
255	7.1	822(13)	1003(13)	98(11)	3.7	245
	{5.4-8.2}				{3.3-4.2}	{201-299}
255	14.1**	2430(2)	4098(2)	85(1)	5.8	322
	{14.0-14.2}				{5.7-5.9}	{307-337}
305	7.0	695(1)	505(2)	94(1)	5.7	196
	{6.9-7.0}				{5.7}	{132-259}
305	12.7	1404(6)	1290(6)	114(6)	4.2	274
	{12.5-13.1}				{3.7-5.1}	{242-339}
127***			(5)			1
180****	1.9	-------------	(5)	-------------	4.0	140
	{1.4-2.5}				{4.0}	{118-162}

() - Number of tests
{} - Value ranges
* - mass of complete shell
** - cylindrical shells
*** - fired from 155 mm mortar
**** - fired from 205 mm mortar

DISCUSSION

Shells functioned from larger diameter mortars

As indicated in Table 2, the two sizes of shells fired from correspondingly larger diameter mortars gave slightly different results. In reference (2), Shimizu indicates that the height attained by a shell depends on Q, the square of the ratio of the shell diameter to mortar diameter. He also states that when this ratio is approximately 0.5, the shell will not rise. The tests indicate that this is precisely what occurred. The 127 mm shells which had an actual diameter of about 114 mm and were fired from a 155 mm mortar had a Q = 0.54. These shells were propelled approximately 1 m above the mortar and as a result functioned on the ground. The 180 mm shells which had an actual diameter of about 167 mm and were fired from a 205 mm mortar had a Q = 0.68. These shells functioned at an average height of 140 m.

In the discussions that follow regarding the live shells, the following comments must be considered. Since there were only two cylindrical shells, the data obtained from them was not used in any of the graphs. The cylindrical shells had the lowest speed, the longest time-to-burst, the highest pressure, and the greatest burst height. Also, when comparing the live shells, the 7.0 kg, 305 mm shells did not seem to fit the scheme of increasing mass with increasing diameter and therefore, that data was also omitted from the graphs.

Variation of shell speed

Figure 5 indicates that the shell speed is almost constant for the imitation shells in either mortar length. The average speed measured on the 104 cm mortar was 82 m/s while that on the 244 cm long mortar was 107 m/s.

The speed of the live shells increased gradually and almost linearly with the mortar diameter. These values were all higher than those of the imitation shells functioned from the same mortar, however, direct comparisons cannot be made since the mass of the lift charge of the live shells was unknown.

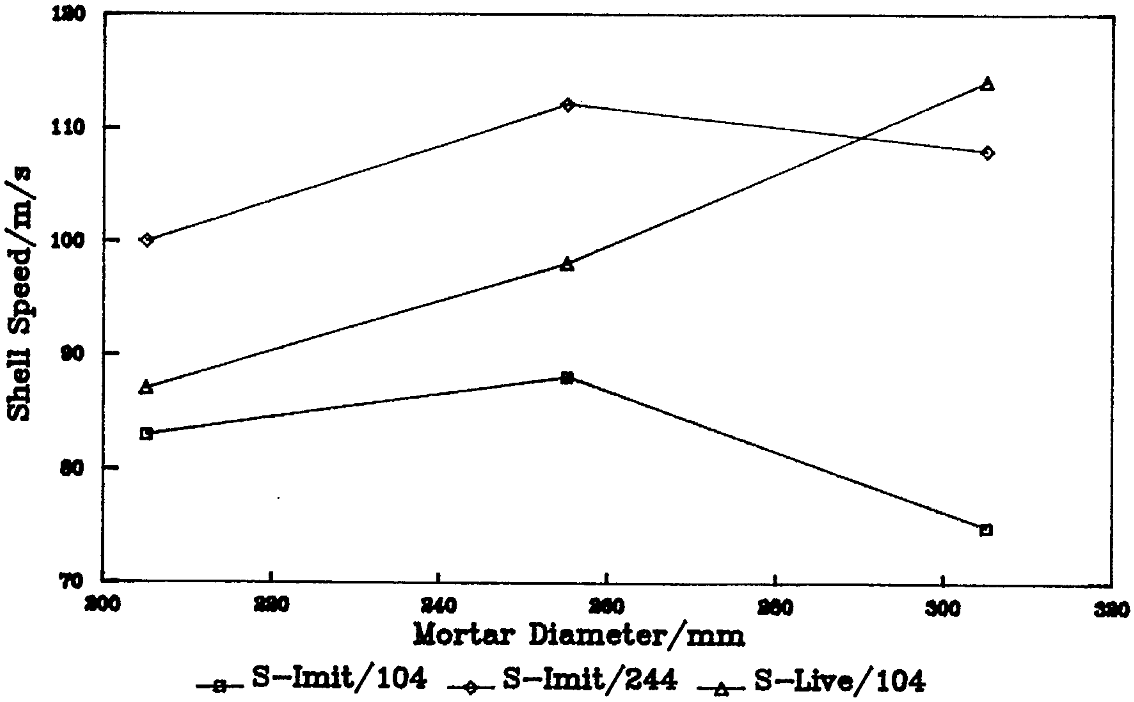

Fig. 5 - Shell speed as a function of mortar diameter

Figure 6 indicates that the shell speed and burst height of the live shells increase almost linearly with the peak pressure values for the corresponding mortar diameters.

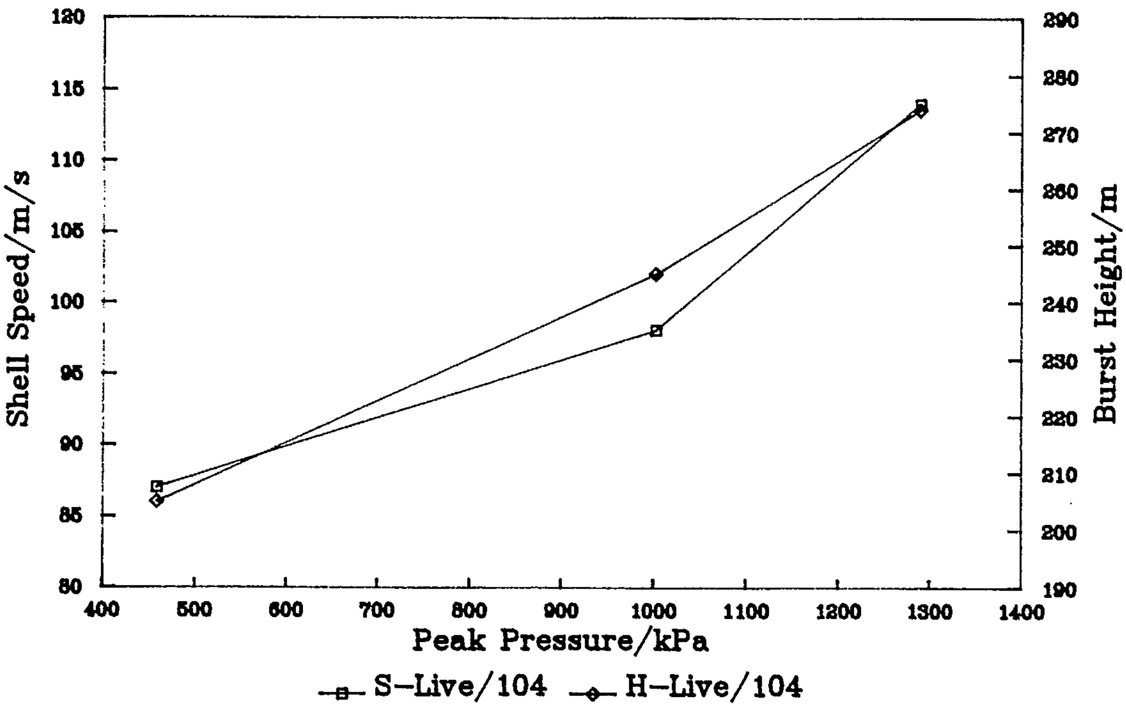

Fig. 6 - Shell speed and burst height versus peak pressure

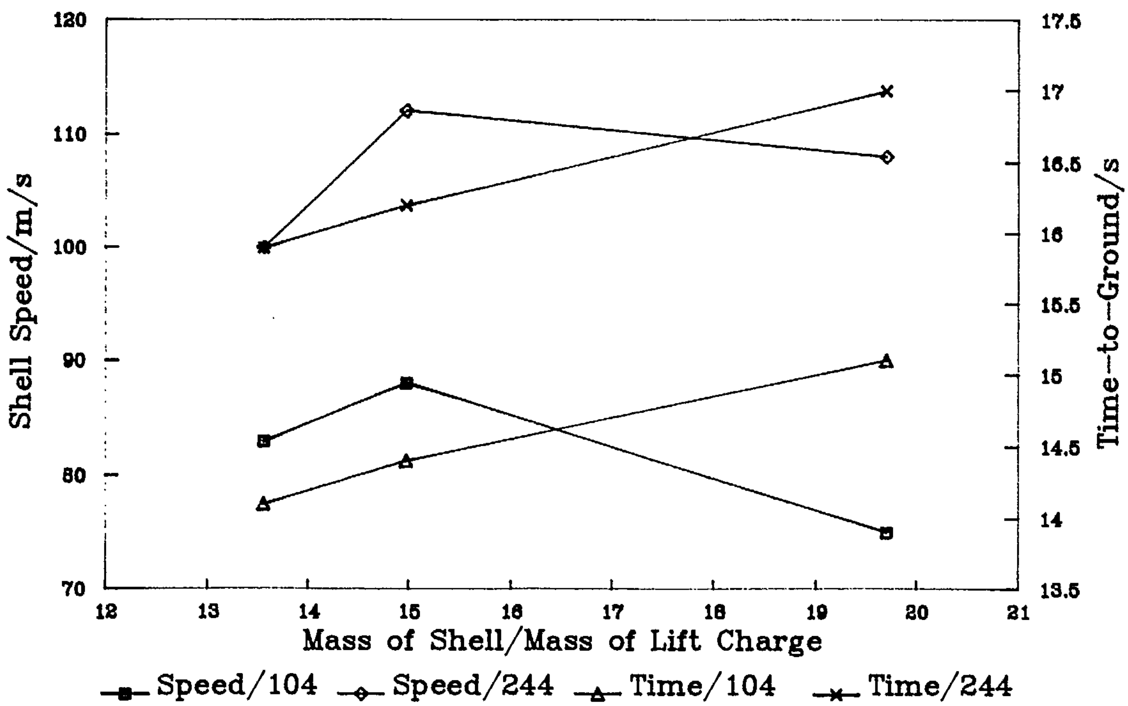

Fig. 7 - Shell speed and time to ground versus Q

When viewed as a function of the ratio of the mass of the charge to the mass of the shell, the shell speed first increases and then decreases, whereas, the time-to-ground behaves linearly. This is evident from Fig 7. The time-to-ground plots are almost parallel, indicating an almost constant difference of about 12.6% between the values for the two mortar lengths.

Pressure as a function of mortar diameter

A similar situation exists with the peak pressures as with the shell speeds. Figure 8 shows that the peak pressures of the imitation shells increase nearly linearly with the mortar diameter and are higher for the longer mortar. Again, since the masses of the lift charges for the live shells were not available, comparisons with the imitation shells are somewhat difficult. The graph, however, does indicate that pressures increase with increasing diameter but at a higher rate than those of the imitation shells.

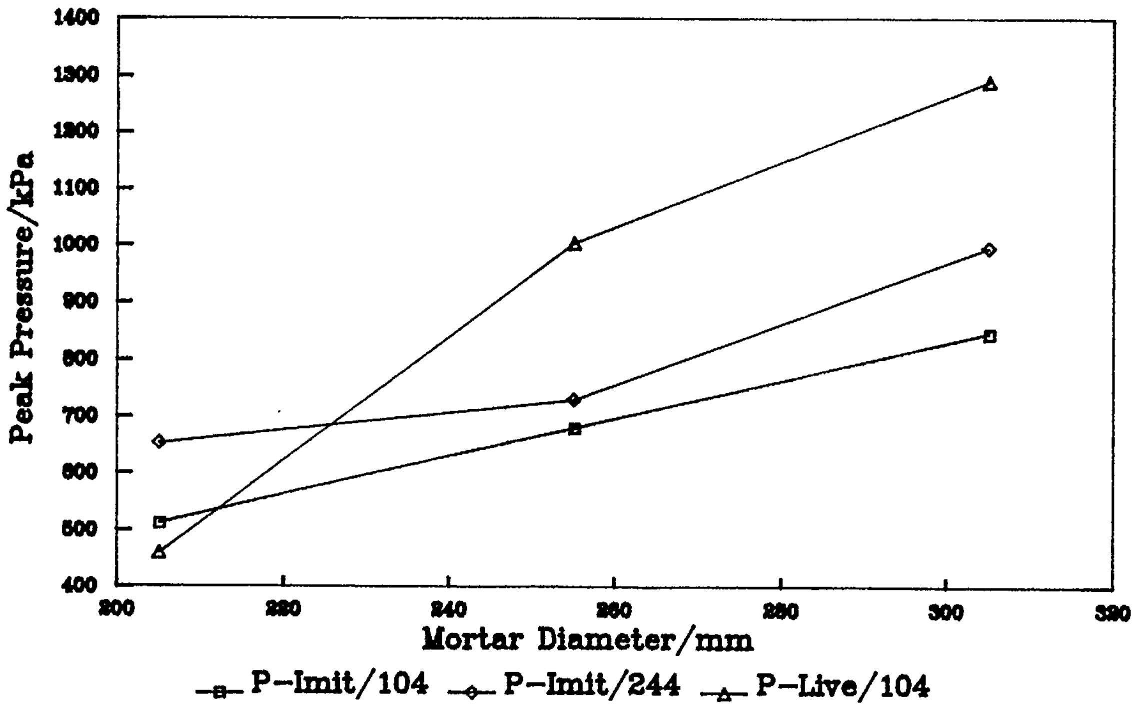

Fig. 8 - Peak pressure as a function of mortar diameter

Plotted as a function of the ratio of the mass of the shell and that of the lift charge (See Fig 9), the imitation shells again exhibit an almost linear response.

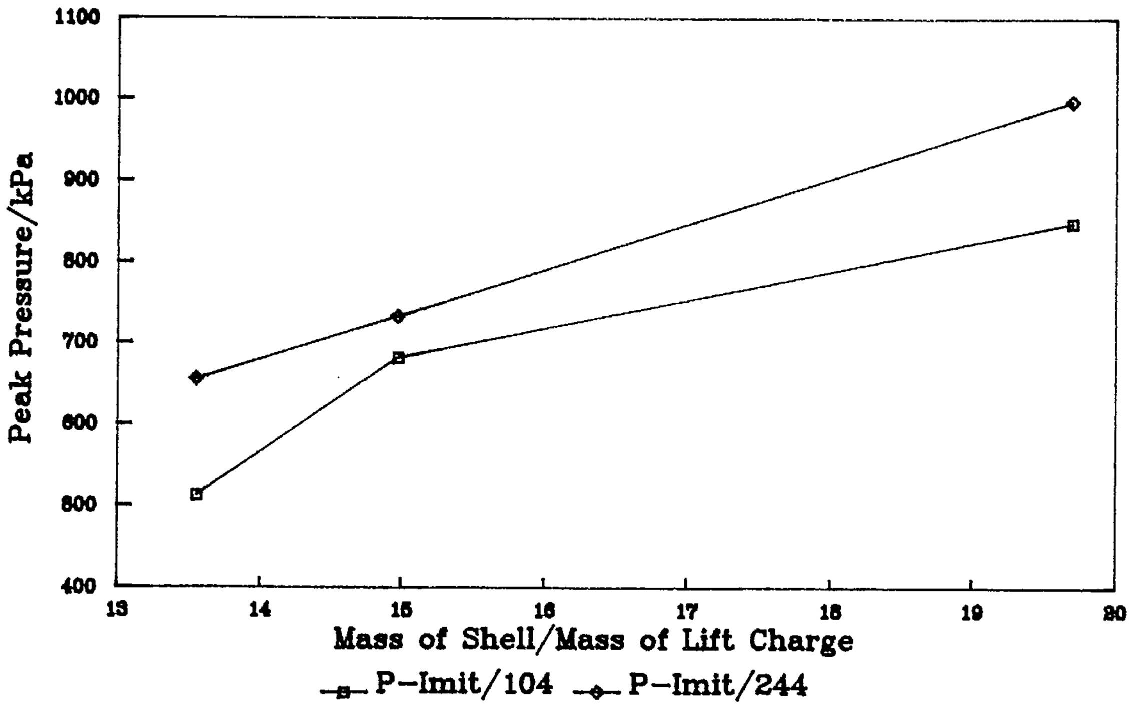

Fig. 9 - Peak pressure as a function of Q

Comments on mortar materials

Some of the physical properties of the various materials used in the manufacture of fireworks mortars are listed in Appendix B and summarized in Table 3. The tables in Appendix B list some odd pipe sizes. These were identified from a list of commonly available sizes and were chosen on the basis of their internal diameter which would qualify them as being suitable for mortars. The data shown in Table 3 must be used in conjunction with Appendix B where other pertinent data such as wall thickness is listed. At first glance, the high density polyethylene (HDPE) pressure ratings seem to be the lowest, however, if one considers that the bursting pressures may be six to ten times higher, then one should feel confortable with their use as mortars. HDPE mortars have been used in the United States, Britain, Canada (to 155 mm diameters) and elsewhere for several years.

Table 3 - Comparison of experimental data with available pressure data for various materials.

Shell Size /mm	Experimental Avg Pressure /kPa	Pressure Ratings /kPa PVC	HDPE	Fiber*	Paper^	Al	Steel
205	550 {460-654}	1000	441	2070	7600	2800	5600
255	800 {680-1003}	1100	345	2070	6200	2500	5000
305	1050 {847-1290}	710	552	2070	4800	2500	4700

{} - Value ranges
* - Estimated
^ - Burst pressure

It will be noted that some of the pressures quoted in Table 3 are lower than those measured experimentally. Since most fireworks mortars are manufactured from pipes or tubes designed for other applications, their specifications cannot be readly compared to data generated from functioning shells in mortars. This is further complicated by the values quoted under "pressure ratings" representing either working pressures or burst pressures. Generally speaking, the working pressure for a pipe is usually taken as 1/6, 1/8, or 1/10 of the bursting pressure (7).

To complicate matters, the yield and ultimate tensile strength of metals can easily double with the high strain rates normally encountered in the field of explosives or pyrotechnics. Then, ideally, the data obtained from functioning shells in mortars should be compared to the material data resulting from similar strain rates (Approximately 1000 s^{-1}). Lack of such data for the various materials used has led some (8) to evaluate mortars by functioning shells with double or triple the amount of lift charge. Such tests have resulted in the acceptance of paper and HDPE pipes for use as mortars in various countries.

CONCLUSIONS

The data presented in this report support the following conclusions.

a. A potential danger exists when undersize shells or proper size shells are fired from larger size mortars. The hazard increases when the ratio Q approaches 0.5 since the shell can then function in proximity to the operator.

b. The peak pressure for both live and imitation shells increased linearly with the mortar diameter. The longer mortars resulted in higher pressures.

c. The peak pressures developed by the cylindrical shells were approximately four times higher than the highest measured for the spherical shells.

d. The speed of the live shells increased with diameter whereas that for the imitation shells remained fairly constant. Also, the speed of the imitation shells increased approximately 30% when the length of the mortar was doubled.

e. The speed and burst height of the live shells increased linearly with the peak pressure.

f. The time-to-ground for the imitation shells increased linearly with the ratio of the mass of the shell to that of the lift charge.

Of the various materials mentioned in this report, the author is only aware of paper, HDPE, and steel being used in the construction of 205, 255, and 305 mm size mortars. Although, use of all of the materials could be substantiated on the basis of pressure ratings, taking into account the effect of strain rate, the mode of fragmentation in the case of an accidental functioning of a shell in a mortar, must be considered. The mode of fragmentation has in recent years led to discontinuing the use of PVC as mortar material. This phenomenon and that of the accompanying blast overpressure will be the focus of a report to be published in the near future.

Most display fireworks codes do not allow functioning cylindrical shells or any spherical shells with reports in anything but steel mortars in the 205, 255, and 305 mm mortars. Based on the limited number of test results from this study, this practice should continue.

ACKNOWLEDGEMENTS

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APPENDIX A

Table A1 - Fall of shot survey for imitation shells.

Mortar Length /mm	Shell Size /mm	Shell Mass /kg	Lift Charge /g	Fall Distance /m	Fall Direction (°)	Wind /knots	Time to Ground /g
104	205	2.71	200	91.4	37	< 1	----
				95.0	336		----
				26.5	120		----
				50.3	152		14.2
				59.7	149		14.0
				103.0	340		14.0
244				73.7	302		16.2
				38.4	81		15.8
				101.9	72		15.8
				70.4	69		16.0
				81.0	159		15.8
				82.9	113		----
104	255	4.49	300	96.2	99	< 1	14.5
				50.4	323		14.2
				71.0	359		14.0
				80.9	40		15.0
				51.7	67		14.5
				66.3	29		----
244				46.5	6		16.0
				75.6	249		16.5
				110.0	148		16.8
				175.0	164		15.8
				136.0	129		16.0
				79.0	144		15.8
104	305	8.85	450	50.0	250	3 SW	15.5
				32.0	76		15.0
				122.0	201		15.0
				78.2	202		15.0
				71.0	317		15.5
				45.2	167		14.5
244				64.5	14	5 SW	18.0
				70.4	279		17.0
				74.5	251		18.0
				92.3	45	< 1	16.0
				71.7	248	5 SW	16.2
				35.0	279		17.0

2FA lift charge
Fall direction in degrees from north

APPENDIX B

Properties of materials in the Manufacture of Fireworks Mortars

Table 1B - Polyvinyl Chloride (PVC)
Design Stress 5000 kPa

Mortar Size /mm	Nominal Size /in	Actual ID /mm	Wall /mm
Design Pressure 710 kPa			
50	2	52.5	3.89
76	3	77.4	5.74
102	4	99.6	7.37
Design Pressure 558 kPa			
127	5	126.4	7.44
155	6	150.6	8.86
Design Pressure 1000 kPa			
205	10	204.9	22.76
Design Pressure 1100 kPa			
255	12	252.4	31.29
Design Pressure 710 kPa			
305	14	308.0	23.55

Table 2B - High Density Polyethylene (HDPE)

Mortar Size /mm	Nominal ID /in	Actual ID /mm	Wall (t) /mm	SDR** Rating	Pressure* Rating /kPa
76	3	75.0	6.58	13.5	883
102	4	100.0	6.73	17.0	690
127	5	127.0	6.73	21.0	552
155	6	151.3	8.00	21.0	552
205	8	201.2	8.43	26.0	441
255	10	255.2	8.41	32.5	345
305	12	302.7	9.96	32.5	345
305	13	305.4	16.18	21.0	552

** SDR = OD/t
* P = 2s/(SDR-1)
t - is the wall thickness
s - hydrostatic design stress (Normally 5500 kPa)

Table 3B - Fiber Reinforced Conduit (3)
- Axial tensile strength 76 MPa
- Minimum rated pressure 2070 kPa to 305 mm diameter
- Burst pressure 10 MPa at pressure rate of 7 MPa/s (Certain sizes)

Mortar Size /mm	Nominal ID /in	Actual ID /mm	Wall /mm
50	2	50.8	1.68
76	3	76.2	1.68
102	4	101.6	1.68
127	5	127.0	2.44
155	6	152.4	2.44

Table 4B - Paper(4)

Mortar Size /mm	Mortar ID /in	Wall /mm	Burst Pressure* /MPa
76	3	12.7	31.0
102	4	12.7	9.3
127	5	12.7	8.6
155	6	12.7	7.6
205	8	19.0	7.6
255	10	19.0	6.2
305	12	19.0	4.8

* - Burst pressure is estimated by the manufacturer to be three times that measured to crush a 30 cm length of tube.
- The burst pressure of treated or impregnated tubes is estimated by the manufacturer to be 10% higher.

Table 5B - Aluminum - 6351-T6 (Schedule 40 pipe)
- Allowable stress 35 MPa
- Minimum tensile strength 300 MPa

Mortar Size /mm	Nominal ID /in	Actual ID /mm	Wall /mm	Pressure Rating /MPa	Burst Pressure* /MPa
50	2	52.5	3.91	7.5	40.2
76	3	77.9	5.49	4.9	38.3
102	4	102.3	6.02	4.1	32.7
127	5	128.2	6.55	3.5	28.8
155	6	154.1	7.11	3.2	26.2
205	8	202.7	8.19	2.8	23.2
255	10	254.5	9.27	2.5	21.1
305	12	303.2	10.82	2.5	20.7

* - Burst pressure determined from Barlow's formula.

Table 6B - Steel (Schedule 40 pipe)
- Allowable stress 70 MPa
- Minimum tensile strength 415 MPA

Mortar Size /mm	Nominal ID /in	Actual ID /mm	Wall /mm	Pressure Rating /MPa	Burst Pressure* /MPa
50	2	52.5	3.91	13.0	65.5
76	3	77.9	5.49	9.7	51.0
102	4	102.3	6.02	8.1	43.6
127	5	128.2	6.55	7.0	38.4
155	6	154.1	7.11	6.4	34.9
205	8	202.7	8.18	5.6	30.1
255	10	254.5	9.27	5.0	28.1
305	12	303.2	10.31	4.7	26.3

* - Burst pressure determined from Barlow's formula.