Model Studies of Fragmentation of Explosives

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SUMMARY.- Measurement of the size distribution of rock particles produced by explosive charges should indicate the relative effectiveness of any blasting design. Such data, although commonly used to optimise rock breakage in mineral processing, has not apparently been used to optimise the explosive rock breakage process. The paper describes the results of investigations into the size distribution of particles produced by blasting in small scale models. Crater testing techniques were used with the charge located at varying distances from the surface. A method of analysis has been developed to describe the particle size distribution in terms of the geometry and size of the explosive charge. The significance of these results to full scale blasting operations is discussed in relation to the modelling parameters used in the experiments.

I.-INTRODUCTION

The rock breaking process is an essential feature of most mineral extraction and processing operations. Fragmentation in primary and secondary breaking affects materials handling problems in mineral extraction, and crushing and grinding processes control the liberation of mineral particles in mineral processing. Although major technological advances have been made in the materials and power sources available to the mineral industry for rock breaking, the real efficiency of the rock breaking process remains very low. If the efficiency is to be increased, research is necessary to develop entirely new concepts.

Advanced research into the nature of rock breakage has not yet resulted in the development of a satisfactory theory to explain the observed phenomena in a rock mass subjected to impact loading. A rock breakage process cannot therefore be described using basic scientific principles. Initially an empirical approach must be made, followed by continuous improvements as the results of full scale applications become available until sufficient reliable data are obtained for a sound theory to be developed and tested. An example of this approach has been the development and application of rock breakage models in mineral processing. These models are based on size distribution analyses of the initial and final products. The application of this technique to rock breakage by explosives is restricted by a lack of knowledge of the size distribution of the material broken by blasting.

One major problem on the use of size distribution as a measure of blasting efficiency is the difficulty associated with the measurement of this parameter in full scale blasting operations. Attempts to overcome this problem by the use of photographic and sampling techniques have not yet been successful. However, further tests have been planned in which all material from a large-scale blast will be screened to obtain statistical information to improve sampling techniques. The main objective of the research programme on fragmentation in small scale blasting experiments, as described in this paper, was to develop a method of analysis which would indicate the nature of any relationship between size distribution and charge burden. This should reduce the amount of costly full-scale testing required to develop a practical mathematical model to optimise industrial rock breakage operations.

The current postgraduate research programme on rock fragmentation by explosives has been in progress since 1970. This paper describes the detailed results achieved during this period. A method of analysis to relate these results to full-scale operations is presented. Further large scale testing is planned to determine the significance of these model relationships. Because the available literature on this subject does not contain any reference to studies of this nature, detailed results have been presented in the Appendix to this paper.

II.- CRATER TESTING THEORY

The most commonly used method of evaluating the performance characteristics of a particular explosive in a given material is a series of crater tests. This allows the determination of critical depth, strain energy factor and optimum depth ratio as defined by Livingston in 1956 (Ref.1). Also inherent in the Livingston Crater theory is a method of scaling, which allows larger scale blasts to be designed from testing on a small scale.

The Livingston theory has been successfully applied to large scale production blasts by Bauer in 1961 (Ref. 2) and Grant in 1964 (Ref. 3).

For a concentrated charge buried below a free face, Livingston defined four ranges of behaviour of the blast, depending upon the burden or distance from the charge to the free face. These were:-

(a) Strain Energy Range

(b) Shock Range

(c) Fragmentation Range

(d) Air Blast Range

The above ranges occur in the above order as the burden is decreased from infinity, for charges of constant weight.

(a) Strain Energy Range

In this range no crater occurs. The energy of the explosion is completely absorbed by the molecular structure of the rock. The depth where surface breakage just becomes evident is called the critical depth and this point indicates the upper limit of the strain-energy range. Livingston describes a relationship between the critical depth and the weight of the charge, in the form

$$N = E_s(W_c)^{1/3}$$

where N = critical depth

W_c = weight of explosive charge

E_s = strain energy factor

The strain energy is constant for a particular combination of explosive type and rock type.

(b) Shock Range

With further decrease in depth, slabbing occurs at the surface due to reflection of shock waves. As the burden is reduced, the amplitude of the wave which is reflected at the free face increases. This increased slabbing results in a larger crater volume. Eventually the resultant burden between the charge and the final free face, after slabbing is complete, will be small enough to allow the radial cracking due to gas pressure effects to extend and cause complete loosening of material. This is the point of maximum utilisation of explosive energy and corresponds to the optimum depth defined by Livingston, in the equation below:-

$$D = \Delta_o E_s(W_c)^{1/3}$$

where D = optimum depth

Δ_o = optimum depth ratio = $(\frac{D}{N})$

(c) Fragmentation Range

With a decrease in depth below the optimum depth, a combination of shock energy and gas expansion energy causes the rock breakage. The upper limit of this range occurs when the quantity of energy transferred to the atmosphere exceeds that transferred to the rock.

(d) Air Blast Range

When the explosive charge is placed adjacent to the free face, surface breakthrough occurs and the remaining energy of the explosion is vented to the atmosphere. The effect of charge weight and depth of burial on crater volume is illustrated in Fig. 1, for one of the series of tests carried out at the University of Queensland Experimental Mine.

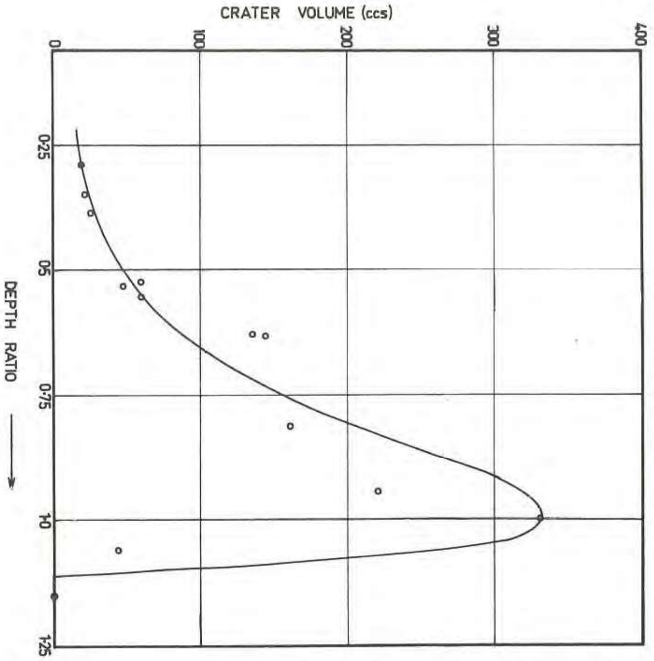

Fig. 1. Crater volumes (ccs) for various depth ratios (charge depth/optimum depth).

As the depth of a constant weight concentrated charge is increased from zero to the critical depth, the volume of the crater formed increases until the depth coincides with the optimum depth and then decreases in the shock range until it is zero at the critical depth.

The normal commercial production blast occurs in the fragmentation range defined by Livingston and design of large scale blasts involves investigation of this range of explosive behaviour. This research project involves determination of fragmentation for burdens varying from small values (corresponding to the air blast range) up to the optimum depth (the limit of the fragmentation range).

III.- EXPERIMENTAL TECHNIQUES

To obtain accurate relationships between fragmentation and burden, a large number of carefully controlled tests must be carried out. This is most easily accomplished by model testing. These cannot be relied upon to give results corresponding exactly to large scale applications, but they can give a good indication of the relationships involved. In order to determine the fragmentation characteristics for explosives in rock, it was decided to obtain these relationships for concentrated or point charges and for linear charges.

(a) Concentrated Charge Tests

The choice of explosive and rock type for this model was relatively simple. The rock had to be capable of being formed into required shapes with flat surfaces. It had to be homogeneous and isotropic with no fractures and planes of weakness. A cement mortar satisfied these conditions and concrete of proportions sand: cement: water of 2:1:0.5 was used. Tests were also carried out in sandstone.

The model explosive used had to be capable of complete detonation in very small quantities and small diameters. This necessitated the use of a high explosive such as P.E.T.N. For concentrated charges, detonators were used. Crater tests were carried out in concrete with No. 6 (0.24 gms. P.E.T.N.) and No. 8 star detonators (0.8 gms. P.E.T.N.) and in sandstone with No. 8 star detonators.

A block of concrete three feet square and 10 inches thick was large enough to carry out a series of 13 crater tests with No. 6 detonators. As each block was cast, cylindrical samples were taken so that strength and density tests could be carried out. The unconfined compressive strength and indirect tensile strength (Brazilian test) were calculated for each block before testing.

Holes were drilled from the bottom of the block using a masonary drill until the required burden remained at the top of the block. The detonator was placed in the hole and a cement slurry was used as a stemming agent. Electric instantaneous detonators were used because of their smaller size and minimum interference with the stemming material.

Each crater was fired upwards, using a plunger type exploder to initiate the detonator. The cratered particles were caught in a steel container lined with foam rubber and thick gasket rubber to minimise secondary particle breakage by collision.

After each test, the crater was completely cleaned of all broken material and the crater dimensions were measured. The rock broken by the blast was weighed and subjected to a screen size analysis to measure the degree of fragmentation.

(b) Linear Charge Tests

For linear charge testing the model materials used were concrete and sandstone. The model explosive was P.E.T.N. in the form of detonating fuse. As for crater testing, a block of concrete three feet square by ten inches thick was used. Holes were drilled in the small faces parallel to the large square faces of the block, which was the major free face. The burden was varied and accurately measured for each test. A constant length of hole was used for each series of tests.

The charge was initiated by a detonator attached to the end of the detonating fuse outside the hole. The concrete was shielded from the effects of the detonator by a steel plate with a central hole to permit passage of the detonating fuse. A large wooden box lined with rubber was used for collecting the fragmented particles after each test.

The broken material was collected for size analysis and the dimensions of the crater were measured.

IV.- EXPERIMENTAL RESULTS

The experimental results for concentrated charges are tabulated in Appendix I. For each series of tests, the following information is given:

(a) Explosive type

(b) Rock type and relevant physical properties

(c) Crater dimension

(d) Fragmentation parameters.

This experimental data allows the calculation of a relationship between the fragmentation produced and the charge burden. This set of equations is given at the end of each series of results in Appendix I. Preliminary results for linear charge tests indicate similar relationships. Further tests are currently in progress to determine more accurate relationships for linear charges.

The crater information sets out the burden or depth of burial of the charge for each hole and the corresponding crater volume. This allows the optimum depth to be calculated, as shown in Fig. 1. The fragmentation results tabulated consist of the size distribution for each test expressed as the cumulative percent passing a given screen size.

To determine the nature of any relationship between size distribution and burden, it was necessary first to establish Y as a function of (x/D) where Y = 100y = cumulative percent passing a screen of aperture x and D = optimum depth. To enable scaling of results, the size of particles and depth of burial of the explosives were expressed as dimensionless ratios in terms of the optimum depth. Analysis of results indicates a linear relationship between log ln Y and log (x/D).

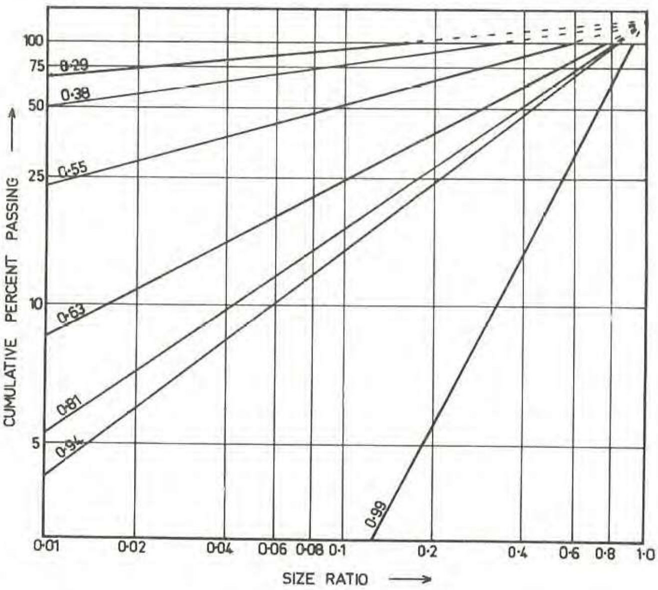

Fig. 2. Size distribution curves for different charge burden ratios.

$$(\text{Size ratio} = \frac{\text{particle size}}{\text{optimum charge depth}})$$

$$(\text{Burden ratio} = \frac{\text{charge burden}}{\text{optimum charge depth}})$$

Fig. 2 shows this relationship for a number of explosive burden ratios. This results in a relationship of the following form:

$$y = \frac{1}{100} e^{4.8(\frac{x}{D})^f}$$

where f is the gradient of fragmentation lines in Fig. 2. Since the gradient of these lines depends upon the burden ratio, a graph as illustrated in Fig. 3 was drawn to determine this relationship. In this graph log f is plotted against $\log (\frac{d}{D})$, where d is the burden and D is the optimum depth.

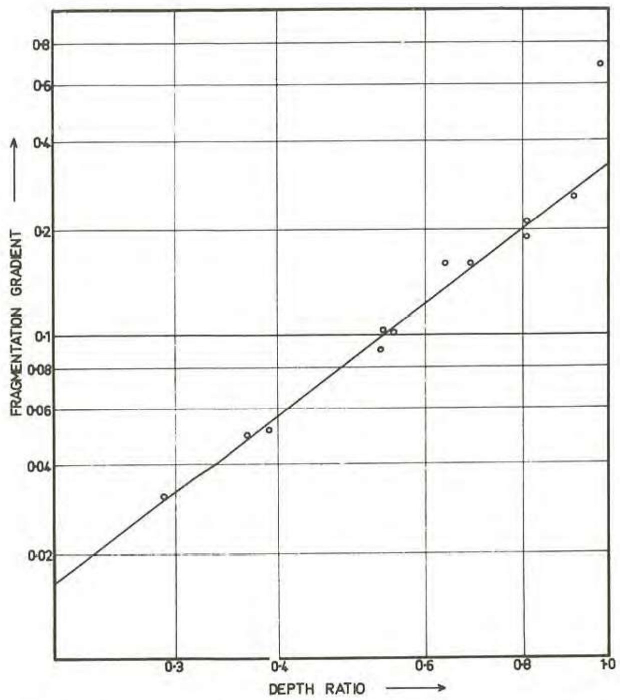

Fig. 3. Fragmentation gradient versus depth ratio $(\frac{\text{charge burden}}{\text{optimum depth}})$.

From Fig. 3, f is expressed as a function of $(\frac{d}{D})$ in the form

$$f = \frac{1}{E} (\frac{d}{D})^2$$

where E is a constant depending on the explosive type and material properties. Figs. 1, 2 and 3 show some of the results obtained from Block 2C, which resulted in a function of the form

$$y = \frac{1}{100} e^{4.8(\frac{x}{D})^f}$$

$$\text{where } f = \frac{1}{3.11} (\frac{d}{D})^2$$

Analysis of the results tabulated in Appendix I, and summarised in Table I shows that each set of a particular combination of rock and explosive type gives a similar relationship except for variations in the factor E. Thus a knowledge of this factor would immediately allow calculation of a certain size distribution for a certain burden ratio and would also allow estimation of the size of the largest particles.

V.- CONCLUSION

One of the main objectives of primary rock breaking operations is to fragment the rock mass into blocks which can be economically transported to the primary crushing stage. The degree of fragmentation is therefore one basic measure of the relative efficiency of different blasting designs. The problems associated with measuring this parameter in full scale operations has discouraged the use of this technique as a measure of blasting efficiency. Small scale model tests have been conducted in order to determine the relationship between size distribution and charge burden. Analysis of the results obtained has shown that it is possible to predict the size distribution for a particular charge burden, if these dimensions are expressed as dimensionless ratios in terms of the optimum charge depth. The application of this method of analysis on an industrial scale cannot be justified until large scale tests have been carried out. The model test results have provided sufficient justification for the expenditure of funds on large scale testing. These tests are currently in progress.

TABLE I

SUMMARY OF CRATER TEST RESULTS USING CONCENTRATED CHARGES

Block No.	Detonator Type (gms.P.E.T.N.)	Compressive Strength (p.s.i.)	Tensile Strength (p.s.i.)	Optimum Depth (cms.)	Critical Depth (cms)	Constant E Factor
2A	No.6-0.24 gms.	5730	425	3.32	4.00	5.63
2B	No.6-0.24 gms.	5500	410	2.70	3.45	5.63
2C	No.6-0.24 gms.	4300	210	3.45	3.65	3.11
1SS	No.8-0.8 gms.	4600	187	6.60	7.30	3.30
2F and 2G	No.8-0.8 gms.	3900	205	7.00	9.00	2.30

VI.- ACKNOWLEDGEMENTS

Thanks are expressed to the Companies who have made financial assistance available to support this work.

VII.- REFERENCES

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2. BAUER, A. - Application of the Livingston Theory. Quarterly, Colorado School of Mines, Vol. 56, Part 1, 1961.

3. GRANT, C.H. - Simplified Explanation of Crater Method. Engineering and Mining Journal, Vol. 165, Nov. 1964.

VII.- APPENDIX

RESULTS OF CRATER TESTS - CONCENTRATED CHARGES

Block 2A - No. 6 detonators in mortar

CONCRETE - Sand/Cement/Water = 2:1:0.5

SAND - Coarse river sand

Compressive strength = 5730 psi

Tensile strength = 425 psi (Brazilian Test)

Specific gravity = 2.15

CRATER INFORMATION (2A)

Hole No.	Burden Drilled (cms)	Burden to C/G of Charge (cms)	Crater Vol. (ccs)	Av. Crater Radius (cms)
2A1	0	0.32	8.5	2.2
2A2	0.5	0.82	17	3.0
2A3	1	1.32	19.5	3.2
2A4	1	1.32	24	4.4
2A5	2	2.32	56	5.4
2A6	2	2.32	60	5.7
2A7	2.5	2.82	102	6.7
2A8	3	3.32	148	7.5
2A9	3.5	3.32	148	7.3
2A10	3.5	3.82	95	6.0
2A11	3.5	3.82	Misfired	
2A12	4	4.32	Cracks occurred	
2A13	4	4.32	" "	
2A14	4.5	4.82	No effect	

From Crater results,

Optimum depth (D) = 3.32 cm

Critical depth (CD) = 4.00 cm

$\therefore$ $\Delta = 0.83$

FRAGMENTATION INFORMATION (2A)

Screen Size (x) (cms)	Cumulative % Passing (100Y)				
	2A1	2A2	2A3	2A4	2A5
2.69	100	100	100	100	100
1.885	100	100	100	83.52	95.4
1.33	100	100	100	63.26	84.26
.9423	100	100	100	46.78	73.27
.566	96.25	96.81	96.17	33.90	59.94
.3327	91.25	90.10	89.39	25.94	47.70
.1981	81.25	81.47	82.02	20.45	41.00
.085	48.78	50.48	52.81	11.36	25.41
0	0	0	0	0	0

Screen Size (x) (cms)	Cumulative % Passing (100Y)				
	2A6	2A7	2A8	2A9	2A10
2.69	100	100	100	93.46	4.84
1.885	90.55	86.35	83.48	80.91	4.84
1.33	72.41	70.78	63.22	58.58	4.84
.9423	66.23	55.25	43.93	40.91	3.94
.566	51.44	38.98	30.18	26.57	2.77
.3327	39.65	31.15	20.48	18.99	1.33
.1981	33.89	25.81	17.88	14.43	.93
.085	20.53	13.66	9.08	6.69	.37
0	0	0	0	0	0

These results plotted in the form

$$\log \ln (100Y) \text{ vs. } \log \frac{x}{D}$$

give the relationship $Y = \frac{1}{100} e^{4.8(\frac{x}{D})^f}$

where $f = \frac{1}{5.63} (\frac{d}{D})^2$ i.e. E = 5.63

d = burden

D = optimum depth

BLOCK 2B - No. 6 detonators in mortar

CONCRETE - Sand/Cement/Water = 2:1:0.5

SAND - Coarse river sand

Compressive strength = 5,500 psi

Tensile strength = 410 psi (Brazilian Test)

Specific Gravity = 2.15

CRATER INFORMATION (2B)

Hole No.	Burden Drilled (cms)	Burden to C/G of Charge (cms)	Crater Vol. (ccs)	Av. Crater Radius (cms)
2B1	3.49	3.81	Feint cracks on surface	
2B2	3.45	3.77	Larger cracks	
2B3	3.02	3.34	Very large cracks	
2B4	3.02	3.34	51	6.03
2B5	2.5	2.82	102	6.69
2B6	2.38	2.70	127	6.69
2B7	1.94	2.26	59	5.72
2B8	2.02	2.34	82	6.35
2B9	1.51	1.83	51	4.92
2B10	1.47	1.79	36	4.76
2B11	.87	1.19	16	3.02
2B12	.87	1.19	17	3.02
2B13	4.13	4.45	No visible effect	

From Crater results,

Optimum depth (D) = 2.7 cms

Critical depth (CD) = 3.45 cms

$\therefore\ \Delta = 0.78$

FRAGMENTATION INFORMATION (2B)

Screen Size (x) (cms)	Cumulative % Passing (100Y)			
	2B4	2B5	2B6	2B7
2.69	2.86	93.77	93.16	100
1.88	5.86	85.08	90.48	86.67
1.33	5.86	75.72	71.5	82.69
0.9423	3.25	60.34	53.5	72.64
0.566	2.14	42.33	38.17	58.84
0.3327	1.35	32.29	28.98	46.84
0.1981	1.03	25.68	22.21	39.20
0.085	.48	13.05	11.23	24.47
0	0	0	0	0

Screen Size (x) (cms)	Cumulative % Passing (100Y)			
	2B9	2B10	2B11	2B12
2.69	100	100	100	100
1.88	84.08	100	100	100
1.333	81.68	92.74	100	100
0.9423	76.50	79.96	100	96.19
0.566	64.52	73.69	97.86	93.65
0.3327	53.59	61.53	91.81	88.25
0.1981	45.25	52.13	84.34	81.27
0.085	27.8	32.83	55.16	53.97
0	0	0	0	0

From graphical representation of these results,

$$Y = \frac{1}{100} e^{4.8(\frac{x}{D})^f}$$

where $f = \frac{1}{5.63}(\frac{d}{D})^2$ i.e. E = 5.63

BLOCK 2C - No. 6 detonators in mortar

CONCRETE - Sand/Cement/Water = 2:1:0.5

SAND - Beach sand (fine)

Compressive strength = 4,300 psi

Tensile strength = 210 psi

Specific Gravity = 2.2

CRATER INFORMATION (2C)

Hole No.	Burden Drilled (cms)	Burden to C/G of Charge (cms)	Crater Vol. (ccs)	Av. Crater Radius (cms)
2C1	.67	.99	18	2.8
2C2	.87	1.19	20	3.0
2C3	1.00	1.32	25	3.3
2C4	2.46	2.78	121	7.5
2C5	2.46	2.78	160	8.5
2C6	3.33	3.65	43	5.1
2C7	2.92	3.23	225	9.6
2C8	3.12	3.43	330	11.5
2C9	1.85	2.17	145	8.5
2C10	1.82	2.14	137	8.5
2C11	1.47	1.79	62	5.5
2C12	1.5	1.82	46	5.2
2C13	1.59	1.90	63	6.0

From Crater results,

Optimum depth (D) = 3.45 cms.

Critical depth (CD) = 3.65 cms.

$\therefore\ \Delta = 0.94$

FRAGMENTATION INFORMATION (2C)

Screen Size (x) (cms)	Cumulative % Passing (100Y)					
	2C1	2C2	2C3	2C4	2C5	2C6
2.69	100	100	100	87.4	92.2	8.9
1.88	100	100	100	84.3	75.9	8.9
1.33	100	100	100	65.3	56.0	8.9
.9423	100	100	100	54.2	35.7	7.3
.566	98.2	92.2	94.7	34.8	26.8	5.7
.3327	92.9	85.0	83.7	22.4	17.5	3.3
.1981	86.3	74.4	74.4	15.9	12.3	2.7
.085	75.7	63.6	62.2	10.6	8.0	1.3
0	0	0	0	0	0	0

Screen Size (x) (cms)	Cumulative % Passing (100Y)						
	2C7	2C8	2C9	2C10	2C11	2C12	2C13
2.69	85.3	37.4	84.1	82	90.6	100	100
1.88	71.9	21.8	65	58.4	74	100	100
1.33	50.3	11.4	59.6	49.6	68.6	96	90.7
.9423	37.2	7.4	46.4	39.1	64.7	90.2	81.3
.566	22.4	4.5	32.9	28.2	52.1	77.8	67.4
.3327	14.2	2.5	23.8	20.4	43.3	62.6	50.2
.1981	9.9	1.6	18.8	16.6	36.3	50.2	40.2
.085	6.7	1.0	13.8	12.8	28.7	38.9	30.8
0	0	0	0	0	0	0	0

From graphical representation of these results,

$$Y = \frac{1}{100} e^{4.8(\frac{x}{D})^f}$$

where $f = \frac{1}{3.11}(\frac{d}{D})^2$ i.e. E = 3.11

BLOCK ISS - No. 8 detonators in sandstone

Compressive strength = 4600 psi

Tensile strength = 187 psi

Specific gravity = 2.3

CRATER INFORMATION (ISS)

Hole No.	Burden Drilled (cms)	Burden to C/G of Charge (cms)	Crater Vol. (ccs)	Av.Crater Radius (cms)
ISS1	1.27	1.90	38	3.5
ISS2	2.38	3.01	76	5.84
ISS3	3.81	4.44	254	8.87
ISS4	1.27	1.90	42	3.5
ISS5	1.75	2.38	64	5.08
ISS6	3.17	3.80	142	6.98
ISS7	4.44	5.07	351	9.65
ISS8	1.90	2.53	60	5.08
ISS9	5.40	6.03	790	12.7
ISS10	6.11	6.74	790	13.0
ISS11	6.50	7.13	340	10.6

From Crater results,

Optimum Depth (D) = 6.6 cm

Critical Depth (CD) = 7.3 cms

$\therefore \Delta = 0.9$

FRAGMENTATION INFORMATION (ISS)

Screen Size (x) (cms)	Cumulative % Passing (100 Y)					
	ISS1	ISS2	ISS3	ISS4	ISS5	ISS6
2.69	100	100	75.9	100	100	100
1.88	100	93.4	61.5	100	95.8	88.2
1.33	90.4	85.8	49.8	96.1	84.7	66.5
.9423	86.0	82.5	39.1	85.2	76.9	54.3
.566	80.9	71.9	26	75.5	66.8	36.8
.3327	73.4	59.4	19.4	67.5	60.2	28.0
.1981	67.3	53.3	15.9	61.3	54.8	22.9
.085	56.1	44.3	11.1	50.1	45.8	16.2
0	0	0	0	0	0	0

Screen Size (x) (cms)	Cumulative % Passing (100Y)				
	ISS7	ISS8	ISS9	ISS10	ISS11
2.69	66.7	100	30.1	30.9	17.0
1.88	52.3	90.4	19.4	19.4	1.5
1.33	38.9	85.2	12.3	13.5	1.5
.9423	30.2	80.2	8.0	9.0	1.5
.566	20.3	68.8	5.6	6.2	.9
.3327	15.1	61.8	3.4	4.0	.9
.1981	12.3	56	3.0	3.5	.9
.085	8.6	46.2	2.6	2.9	.7
0	0	0	0	0	0

From graphical representation of these results,

$$Y = \frac{1}{100} e^{4.8(\frac{x}{D})^f}$$

where $f = \frac{1}{3.3}(\frac{d}{D})^2$ i.e. E = 3.3

BLOCK 2F and 2G - No. 8 detonator in mortar

CONCRETE - Sand/Cement/Water = 2:1:0.5

SAND - Beach sand (fine)

Compressive strength = 3900 psi

Tensile strength = 205 psi

Specific gravity = 2.1

CRATER INFORMATION (2F & 2G)

Hole No.	Burden Drilled (cms)	Crater Vol. (ccs)	Burden to C/G of Charge (cms)	Av. Crater Radius (cms)
2F1	.6	54	1.25	4.5
2F2	.6	53	1.25	4.5
2F3		54	1.9	4.8
2F4	1.25	65	1.9	5.2
2F5	1.9	102	2.5	6.3
2F6	1.9	104	2.5	6.2
2F7	2.5	212	3.2	9.0
2F8	2.5	192	3.2	8.6
2F9	3.75	700	4.45	14.5
2F10	3.75	440	4.45	11.9
2F11	5.1	1150	5.7	15.5
2G12	5.1	Misfired	5.7	
2G13	6.3	1709	7.0	16.6
2G15	7.6	1200	8.3	14.4

$$Y = \frac{1}{100} e^{4.8(\frac{x}{D})^f}$$

$$f = \frac{1}{2.3} \times (\frac{d}{D})^2 \qquad \text{i.e. } E = 2.3$$

From Crater results,

Optimum Depth (D) = 7 cm

Critical Depth (CD) = 9 cm

$\therefore$ Δ = 0.78

FRAGMENTATION INFORMATION (2F & 2G)

Screen Size (x) (cms)	Cumulative % Passing (100Y)					
	2F1	2F2	2F3	2F4	2F5	2F6
2.69	100	100	100	100	100	75.9
1.88	100	100	100	100	91.1	75.9
1.33	100	100	100	97.5	80.6	73.8
.9423	97.1	98	100	96.2	76.6	67.8
.566	88.6	88.6	91.6	91.6	67.9	60.7
.3327	78.1	78.8	83.0	80.9	58.2	52.2
.1981	68.9	71.2	76.2	72.4	50.6	45.5
.085	58.9	62.1	67.3	62.1	42.7	38.2
0	0	0	0	0	0	0

Screen Size (x) (cms)	Cumulative % Passing (100Y)					
	2F7	2F8	2F9	2F10	2F11	2G13
2.69	100	93	83.6	97.1	51.1	
1.88	79.7	78.1	66.7	74.3	26.6	
1.33	66.2	69.7	51.5	58.4	15.5	
.9423	59.7	59.2	38	43.1	11.0	
.566	47.4	45.3	26.9	27.7	6.2	
.3327	38.3	36.5	14.2	19.0	3.9	
.1981	32.4	31.2	10.8	14.4	2.8	
.085	26.3	26.2	7.5	10.2	2.0	
0	0	0	0	0	0	

From graphical representation of these results,