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A STUDY ON FRAGMENTATION AND GROUND VIBRATION WITH AIR SPACE IN THE BLASTHOLE

BY

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A THESIS

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Charles J. Haas

ABSTRACT

The degree of fragmentation and the level of ground vibration from a bench blast employing standard full-column completely-coupled explosive charges are commonly controlled by varying one or more of the many dimensional variables of blast design. Blasting techniques such as decoupling and air-gapping, utilizing air space in the blasthole, have also been reported as having the potential to control rock fragmentation and ground vibration.

This investigation, using reduced-scale in situ bench blasts, examined the degree of fragmentation and the level of ground vibrations produced from the standard full-column completely-coupled, air-gapped, and decoupled methods of blasting to:

1. Compare the effectiveness of decoupled and air-gapped blasting for controlling fragmentation and ground vibrations;

2. Evaluate air-gapped blasting relative to the standard full-column completely-coupled method of blasting on the basis of fragmentation and ground vibration; and

3. Identify the more dominant of the two borehole phenomena that vary under decoupling conditions -- energy transfer and effective boremole pressure -- with respect to their influence on fragmentation.

It was found that air-gapping and decoupling had equal ability to control fragmentation and ground vibration at the same air-to-explosive volume ratio, and that the standard full-column completely-coupled method produced a higher degree of fragmentation and level of ground vibration than the air-gapped method of blasting. Furthermore, it was found that effective borehole pressure had a greater influence on fragmentation than energy transfer.

ACKNOWLEDGEMENTS

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I. INTRODUCTION

The unit costs of materials handling and processing play an important role in the overall economy of mining and construction operations (Langefors, 1963). These costs, in turn, are highly influenced by the efficiency of the blasting operation in its ability to control rock fragmentation. Furthermore, the blasting methods used to control rock fragmentation must include considerations for safety and environmental disturbances in order to aid in the success of the operation.

A. CONTROL OF ROCK FRAGMENTATION

Numerous investigations have shown that the degree of rock fragmentation resulting from a bench blast can be controlled by changing one or more of the many variables of blast design. For example, the influence of burden, spacing and other blast pattern dimensions on rock fragmentation is well recognized (Ash et. al., 1976). However, fragmentation may also be controlled from within the blasthole by less common techniques, such as the use of air-gapped, decoupled, or water-coupled charges (Konya, 1974; Melinkov, 1979; Warden, 1983). The association between these factors of blasthole design and the degree of fragmentation will be further addressed in this study.

B. GROUND VIBRATIONS

When an explosive detonates in a blasthole, the two types of seismic waves produced are the compressional wave, or body wave, and the surface wave. When compressional waves travel through a solid media and strike a free face, surface waves are generated. These surface waves are the cause of environmental disturbances in the form of ground vibrations which may damage structures in the vicinity of the blasting site (Taqieddin, 1982). Over the years, federal and local regulatory authorities have specified legal limits for ground vibrations in terms of the magnitude of their peak particle velocities.

C. EXPLOSIVE COUPLING AND DECOUPLING

Dick (1983) defines explosive coupling as being "the degree to which an explosive fills the borehole", and further states that "bulk loaded explosives are completely-coupled". He defines explosive decoupling as "the use of cartridged products significantly smaller in diameter than the borehole", and that "untamped cartridges are decoupled".

Explosive coupling, in the geometric sense, can be achieved by, first, using an explosive charge of the same diameter as the borehole, or second, by drilling the blasthole at a larger diameter than that of the charge and filling the annular opening with a solid or liquid. Explosive decoupling, however, is achieved when the annular opening around the charge remains air filled.

The extent of coupling or decoupling of an explosive charge has been shown to control the overall rock fragmentation and ground vibrations in bench blasting (Warden, 1983). As the size of the annulus or the type of enclosed medium is changed, there are two repercussions within the blasthole that affect fragmentation. First, there is a change in the efficiency of energy transfer from the explosive reaction to the wall of the blasthole. Second, there is a change in the effective borehole pressure of the explosion gasses.

D. EXPLOSIVE AIR-GAPPING

Air-gap blasting is a technique which was developed for fragmentation control by Soviet investigators in the 1930's (Melinkov, 1962). This method involves the introduction of one or more air-gaps into the powder column in a blasthole, replacing sections of the explosive charge. This is accomplished in the same manner as in deck loading, but uses interspaces of air rather than stemming material. The use of this technique has "resulted in increased efficiencies in both cratering and fragmenting" (Melinkov, 1962, p. 1). Fragmentation is stated to be controlled by the relationship between the volumes of air and explosive, frequency of air-gaps, dimensions of the air-gaps, and the location of the air-gaps.

E. THE PROBLEM

Two methods of utilizing air space in a blasthole to control fragmentation have been described above. While the effects of decoupling an explosive charge have been confirmed over a wide range of air-to-explosive volume ratios, the use of air-gapping between decks of explosives charges has resulted in conflicting reports.

It has also been indicated above that air space in a blasthole may influence fragmentation and ground vibrations through two mechanisms. First, under decoupling conditions it can cause significant impedance to the transfer of energy from the explosive reaction to the walls of the borehole. Second, under both decoupling and air-gap conditions, air space will reduce the borehole pressure of the gaseous explosion products.

F. THE PURPOSE

The purpose of this investigation is threefold. Primarily, it is designed to compare the effectiveness of decoupling and air-gapping as controls for rock fragmentation and ground vibrations on equal air-to-explosive volume bases. Secondly, it will examine the ability of air-gap blasting as a technique for improving fragmentation relative to the standard full-column completely-coupled explosive loading procedure. Lastly, it is to identify the more dominant of the two borehole phenomena that vary under decoupling conditions -- energy transfer and effective borehole pressure -- with respect to their influence on fragmentation.

II. REVIEW OF LITERATURE

A. ROCK FRAGMENTATION ASSESSMENT

"Overall costs in the mining, quarring and construction industries are affected appreciably by the degree of fragmentation" (Hagan, 1977, p. 329). In order to evaluate fragmentation, however, a physically suitable and economically acceptable method of measurement must be developed. The most meaningful results would be obtained from the analysis of fragment size distributions of completely screened full-scale production blasts. The associated effort and cost for this type of analysis would be impractical. These obstacles have led many investigators to assess fragmentation from production type blasts by other techniques. For example, Melinkov (1979) applied technioeconomic indices to evaluate the resulting rock fragmentation from full-scale completely-coupled and air-gapped production type blasts. This method primarily used four different technioeconomic indices: specific explosive consumption; excavator productivity; oversize fragment yield; and total drilling, blasting, and excavation costs.

Other methods of assessing the degree of fragmentation for full-scale production blasts include:

1. Still photographic evaluation of the muckpile (Noren and Porter, 1974);
2. High-speed photography of a blast in motion (Chiappetta and Borg, 1983, and Winzer et. al., 1979);
3. Random sampling and screening of the final muckpile (Just, 1979); and
4. Boulder count (Langefors, 1963).

Fragmentation studies using small-scale models have been performed in materials such as cement-mortar blocks by Bhandari and Vutukuri (1974), and in limestone and marble by Da Gama (1974). The results of such tests are somewhat difficult to extrapolate to those expected from full-scale production blasts through the use of empirical scaling laws, since the testing was performed in relatively homogeneous materials.

A compromise between full-scale and small-scale testing methods, commonly called reduced-scale blasting, has been shown to be an acceptable method of assessing rock fragmentation. Reduced-scale testing provides both the experimental control of modeling and the realism of insitu heterogeneous rock. This method of test blasting has been successfully used by Ash (1973), Dick et. al., (1973), Smith (1976), Brinkmann (1982), Warden (1983), and Wu (1984) for evaluating and comparing rock fragmentation produced during the variation of several blast design parameters.

To evaluate the overall fragmentation from a test blast, Smith, Brinkmann, Warden, and Wu screened all the blast fragments and used a series of bar charts to illustrate the percent, by weight, of eight size fractions. A single line was then established on the histograms, to indicate the 50-percent-passing size. Smith and Brinkmann further assessed the degree of fragmentation by using various fragmentation indices; the primary index F_c, is a dimensionless index associated with the centroid of the bar chart. Warden grouped all fractions into one of three ranges, coarse, medium, or fine. Wu extended his evaluation on fragmentation by the use of average fragment size. In most cases, all techniques provided the same relative results.

B. SIGNIFICANCE AND CONTROL OF GROUND VIBRATIONS

The detonation of a confined explosive within a borehole generates high pressures. This sudden application of pressure to the borehole wall generates high intensity stress waves in the rock, causing rock deformation in the vicinity of the shot point. These stress waves progressively decrease in intensity beyond the shot point and at free surfaces generate seismic waves which cause the ground vibrations responsible for environmental disturbances and structural damage (Dupont, 1977; Taquieddin, 1982).

Legal limits on the amount of ground vibrations produced from a blast have been set by various legal authorities in order to protect the environment. For instance, the Office of Surface Mining has imposed a limit only on peak particle velocity, the standard unit for ground vibrations, although they also recognize blast-vibration frequency as a factor for consideration. They also provide blast design standards for maintaining peak particle velocities below this limit. These standards are based on research done by the U. S. Bureau of Mines using the considerations that the weight of explosive detonated per delay, 8 milliseconds or greater, and the distance to the nearest dwelling or facility are prime factors affecting the magnitude of peak particle velocity experienced at the facility. This approach to defining a standard is commonly known as the scaled distance method, and can be expressed mathematically by the following equation (Dick et. al., 1983):

$$W = (D/DS)^2$$

where:

W = maximum charge weight per delay, lb;

D = distance from shot point to nearest structure of concern, ft; and

DS = scaled distance, $ft/lb^{\frac{1}{2}}$.

Scaled Distance is a factor of consideration when predicting the peak particle velocity of a seismic wave generated from a blast or the amount of explosive to be fired per delay to achieve a predicted value of peak particle velocity at some distance beyond the firing point. It is fundamentally defined for a single explosive charge as:

$$\text{Scaled distance} = D/w^{\frac{1}{2}};\ ft./lb^{\frac{1}{2}}$$

where:

D = distance from the given point to the blast, ft; and

W = the charge weight, lb.

Furthermore, by plotting the measured peak particle velocities for a given number of shots, similar in design, as a function of scaled distance on a log-log grid, an equation for the best fit line can be derived by linear regression. This equation can then be used to predict the peak particle velocity expected from a given blast at any scaled distance, providing the blast is similar to those used to develop the equation. Also, at a given scaled distance, one can compare changes in ground vibration caused by variations in blast design.

Upon defining the value for the scaled distance reflects which acceptable magnitudes of peak particle velocity, blast design can proceed with reasonable legal responsibility. The Office of Surface Mining stipulates a scaled distance of 60 $ft/lb^{\frac{1}{2}}$, or greater, in order to maintain a peak particle velocity below 1 in/sec. at the structure.

The geometry of a blast pattern or blasting method will affect the magnitude of ground vibrations produced to some extent. This has been confirmed by the reduced-scale investigations of Smith (1980), concerning the effects of blasthole confinement on ground vibrations, and Brinkmann (1982), on the influence of primer location on ground vibrations. Smith defined confinement as a spacing-to-burden ratio. His findings demonstrated that as spacing-to-burden ratio increases, the magnitude of ground vibrations decreases. Brinkmann found that collar priming a charged borehole significantly increased the magnitude of ground vibrations as compared to those resulting from bottom priming. In general, most blast design conditions that are associated with a high degree of fragmentation will also provide minimal magnitudes of ground vibration (Smith, 1980).

C. MECHANICS OF EXPLOSIVE DECOUPLING

The use of decoupled explosive charges has been used advantageously in smoothwall and pre-split blasting (Konya, 1974). This specialized method of blasting reduces the amount of overcrushing and fracturing of the rock immediately surrounding a borehole, as well as performing its primary function of providing controlled splits between adjacent blastholes. Decoupling research has been conducted by many investigators, including: Haas (1965), Nicholls (1962), Fogelson et. al., (1965), Atchison (1961), and Warden (1983).

The effectiveness of decoupling in controlling fragmentation, in general, is attributed to two factors. First, there is a variance in the efficiency in the transfer of energy from the explosive to the rock through an air annulus surrounding the charge when changes are made in the size of the annulus (Nicholls, 1962). Second, there is also a variance in the effective borehole pressure when the size of the annulus is changed (Ash, 1973; Bergmann, 1973). For example, it has been found that through the combined effect of both factors, the fragmentation improves as the size of the annulus decreases for a given charge diameter (Warden, 1983).

The efficiency in the transfer of energy from the explosive to the rock, through a medium, is controlled by the matching or mismatching of the acoustical, or characteristic, impedance of the explosive, annular medium, and the rock. That is, as energy, in the form of shock, is emitted from the detonation of the explosive, some is reflected at the explosive-air interface and again at the air-rock interface. One can roughly assess the ratio of reflected energy to incident energy through the following mathematical equations which presume a plane wave and normal incidence (Worsey, 1983):

$$A_r = [(z_2-z_1)/(z_2+z_1)]^2$$

where:

A_r = the ratio of reflected energy to incident energy;

z_1 = the characteristic impedance of the material from which the energy is emanated, lb-sec/ft^3; and

z_2 = the characteristic impedance of the material into which the energy enters, lb-sec/ft^3.

The characteristic impedance, z, of any material including an explosive, is determined by:

$$z = p_o c$$

where:

z = characteristic impedance of the material or an explosive, lb-sec/ft^3;

c = the longitudinal propagation velocity in the material or the detonation velocity in the explosive, ft/sec; and

p_o = mass density of the material or explosive, $\text{lb-sec}^2/\text{ft}^4$.

Haas (1965) found that air, as a coupling medium, was the most inefficient method of coupling a charge when compared to several dissimilar media. Also, greater energy transmittal is obtained when the characteristic impedances of the explosive, coupling medium, and the material being blasted are similar (Cook, 1965); maximum energy transfer occurs under completely-coupled conditions, and when the characteristic impedances of the explosive and the rock are identical (Nicholls, 1962).

Under completely-coupled conditions, the effective borehole pressure is usually referred to as the magnitude of the quasi-static pressure produced from the thermal chemical reaction of the explosive, and is generally considered to approximate one-half the ideal detonation pressure of the explosive. Decoupled conditions, however, provide a volume for the gas expansion, thereby causing a reduction in the borehole pressure from that produced under completely-coupled conditions (Ash, 1973). Ash suggests that the magnitude of effective borehole pressure resulting from decoupling is a relationship of the explosion pressure for a completely-coupled charge and the ratio of geometric coupling:

$$P_b = P_e(D)^2$$

where:

P_b = effective borehole pressure, psi;

P_e = borehole pressure for completely-coupled charge, psi; and

D = ratio of geometric coupling, (charge dia./hole dia.).

Bergmann (1973), Ucar (1975), and Cook (1958) made suggestions regarding the reduction of borehole pressure due to decoupling. Bergmann found through a complete screen analysis of his test blasts on decoupling in homogeneous granite blocks that a lower degree of fragmentation occurs as the size of the air annulus increases. These findings compare to those found by Warden (1983) for in situ dolomite.

However, in contrast to the above, studies involving the use of decoupled explosive charges have been cited by Hagan (1974) as indicating that "there is some evidence [Hagan, 1973); Persson et. al., (1969); Melinkov, (1962)] that prevention of crushing, by decoupling, may improve performance". This implies that fragmentation may become more uniform with a certain degree of decoupling. Persson noted through his work on decoupling that optimum results (greater mass of rock broken and greater distance of throw) were obtained when the ratio of the charge-to-hole diameter was about 0.50. This, however, is not evident from the complete screen analyses performed in Warden's and Bergmann's research.

D. ASPECTS OF EXPLOSIVE AIR-GAPPING

It has been suggested by Hagan (1974, 1977, 1979) that air-gapped explosive charges, where air space occurs in one or more decks, result in a reduction in the amount of overcrushing around a borehole, which results in a more uniform fragmentation with less explosive than used in standard full-column charges. Tests performed by Melinkov (1979) and Akaev (1971), using air-gapped explosive charges in actual production blasts, showed that this method of blasting reduces the yield of oversize fragments, increases the output of broken material, and considerably reduces the specific consumption of explosives. Melinkov (1962) reports the measurements of the fragments of blasted material from production type blasts employing air-gaps indicate that "the sectioned charges with air-pockets served markedly to increase the degree of fragmentation of the rock, to reduce the specific consumption of explosive by 10%, and appreciably to shorten the time required for setting the charge in the drill hole, as against the time required for solid (nonsectioned) charges".

The principles of the mechanism involved in air-gap blasting have been described by a pressure-time profile (Hagan, 1979; Melinkov, 1962, 1979; Akaev, 1971). Melinkov (1962) verbally explains this profile in that, "the air-pockets between sections of scattered charges serve to prolong the time in the build-up of the pressure, as in cratering explosions, while reducing the pressure to a certain limit and expanding the effect of the explosion to a larger volume of rock". He adds (Melinkov, 1979) that the compression of the air-pocket(s) cause a second shock wave to be produced that will propagate behind the main shock wave causing the original radial fractures to extend somewhat further, as depicted in Figure 1; thus, there is an extension in the time for the borehole pressure to fully penetrate all void spaces and openings.

The Russian technique of employing air-gaps has been to introduce them between the middle and upper portions of the blasthole. Konya (1974) reports from unpublished research results that, in basalt boulders, the use of the air-gap technique involving a single air-gap split the

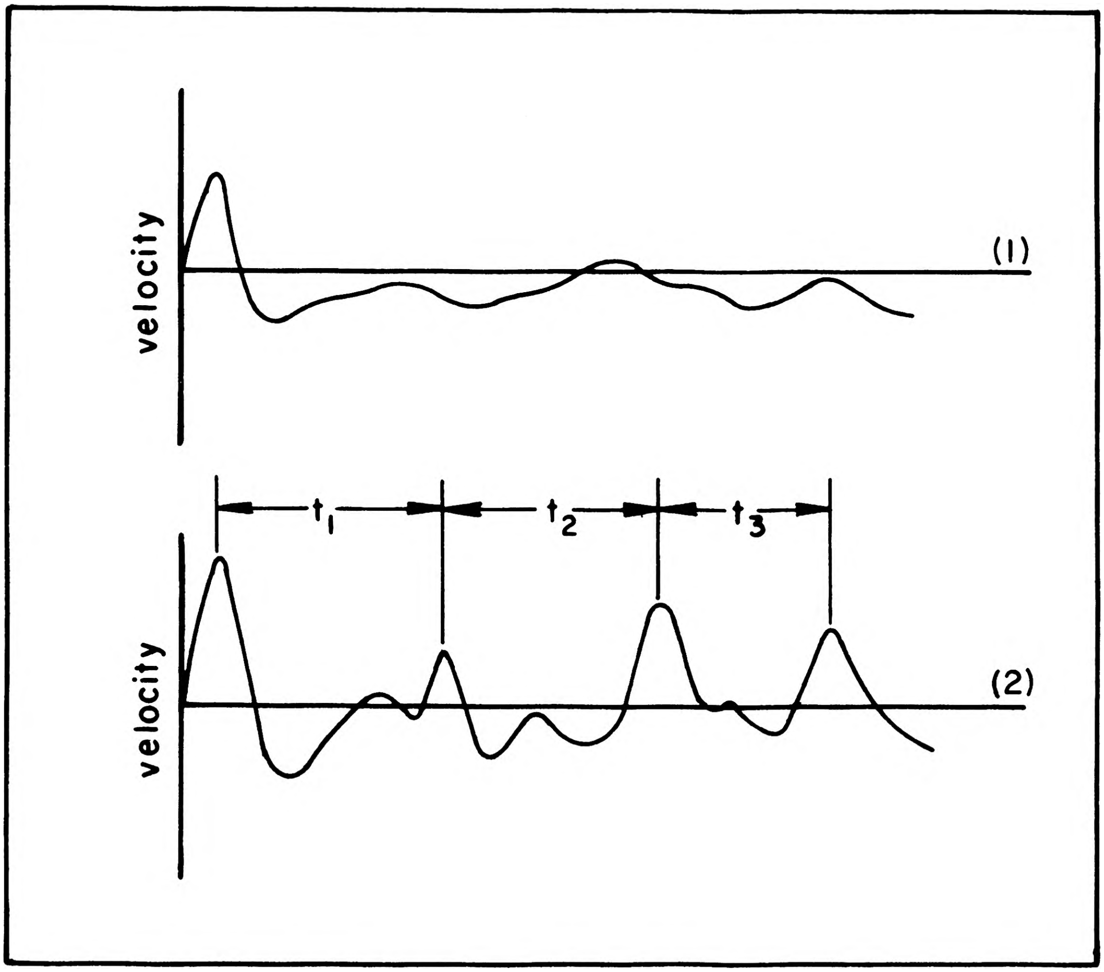


Figure 1. Oscillograph Traces of Velocity of Medium, Melinkov (1979)

(1) From explosion of long solid charge

(2) From explosion of air-gap charge

Note: This illustration is a complete reproduction of the original. The term "velocity" refers to "the motion of the solid medium".

boulders into 2 or 3 large fragments. He further reports the full-column charges broke into many fragments. Furthermore, Ash et. al., (1978) investigated the changes in the degree of fragmentation when the subgrade portion of a borehole was filled with either air, gravel, or explosive, and found that the degree of fragmentation was poorest when the subgrade contained air.

III. EXPERIMENTAL PROCEDURE

Under controlled experimental conditions, eight reduced-scale blasts were conducted in the Jefferson City Formation Dolomitic Rock outcropping on the property of the Experimental Mine of the University of Missouri-Rolla. The mine is located at the southwestern edge of the Rolla city limits in Phelps County, Missouri. These in situ bench blasts were conducted for the purpose of comparing rock fragmentation and ground vibration levels resulting from the use of air-gapped, completely-coupled, decoupled, and water-coupled charges.

The physical and elastic porperties of the Jefferson City Formation Dolomitic Rock are given in Appendix-A, Table A-I.

These three-hole single-row bench blasts were of design similar to those previously used for rock fragmentation and ground vibration experiments conducted at this site by Ash et. al., (1978), Smith (1976), Brinkmann (1982), and Warden (1983). Bench faces were oriented perpendicular to the major joint system as shown in the test pit layout in Figure 2. The three vertical blastholes used in each test blast were drilled perpendicular to the major bedding planes of the rock formation to depths of 50, 56, or 62 inches, depending on the bench height used. An illustration of the idealized blast design used in this experiment is shown in Figure 3.

The variables of bench geometry and blasthole design which were held constant throughout the entire project were the burden (B), spacing (S), charge diameter (D_c), stemming (T), sub-drilling (J), and the specific gravity of the explosive (SG_e). Other significant variables not always

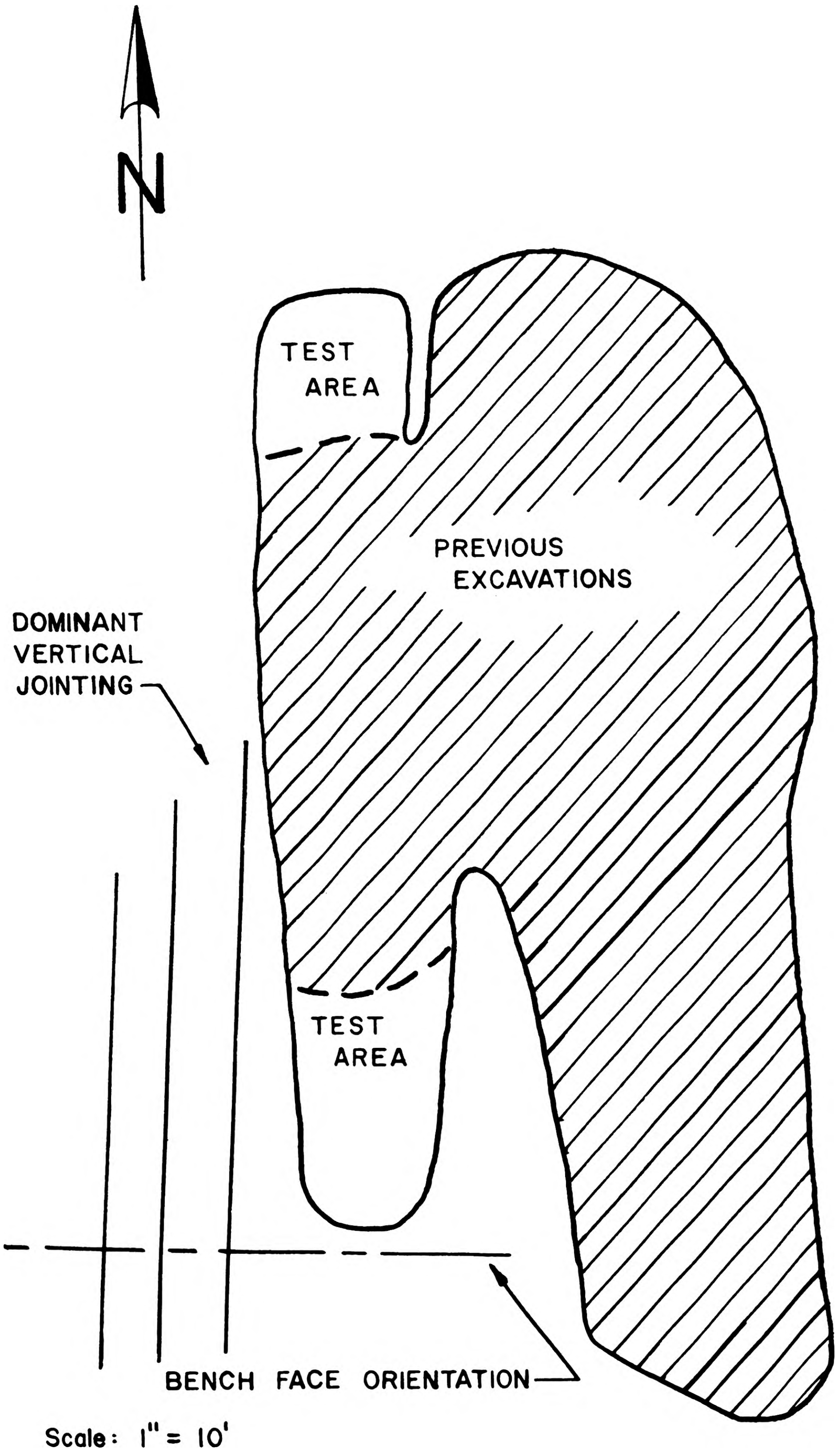


Figure 2. Test Blast Area, Quarry - UMR Experimental Mine

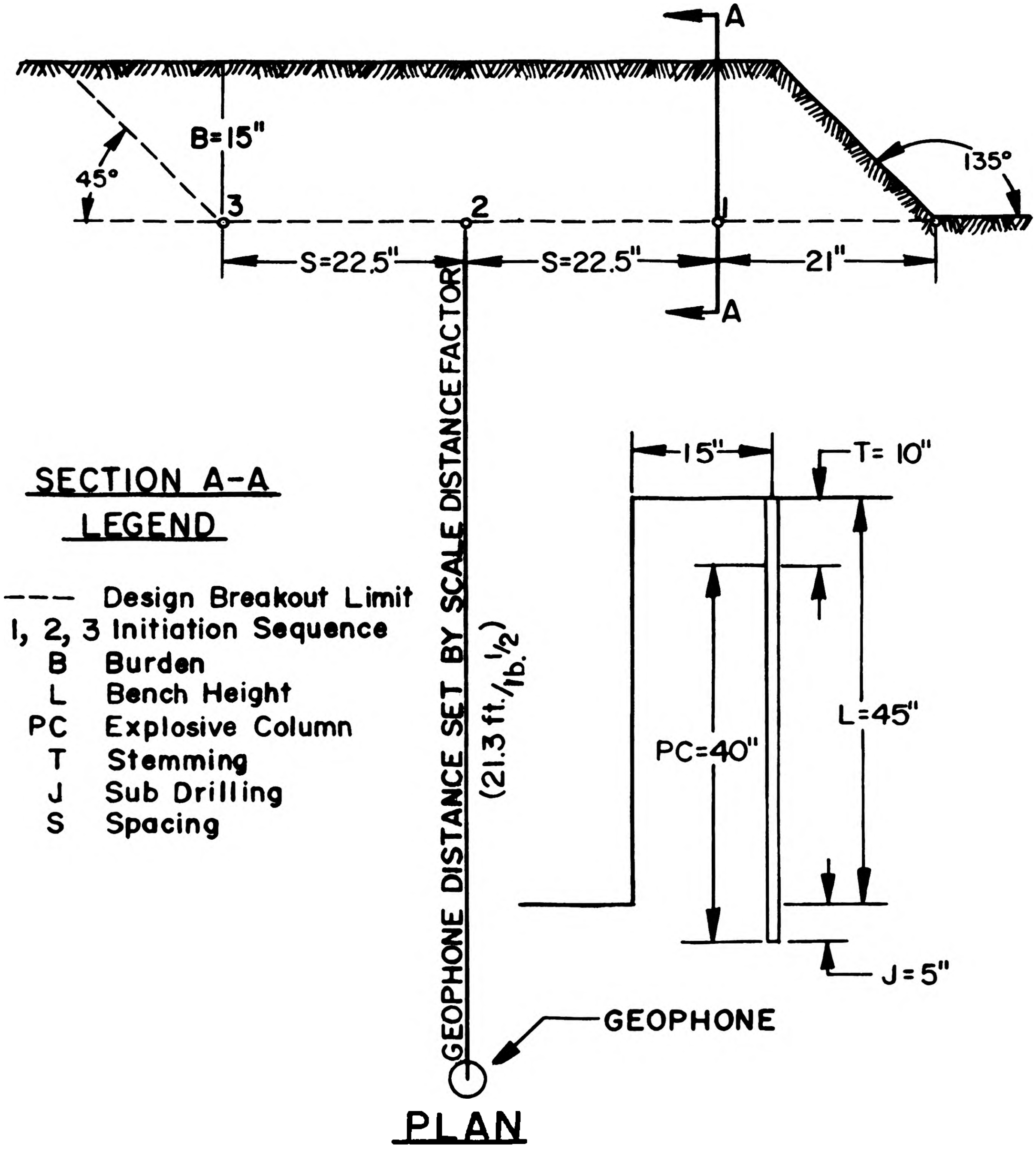


Figure 3. Idealized Bench Blast Design for 45 inch Bench Height

held constant were the blasthole diameter (D_h), bench height (L), and the powder column length (PC). The type of explosive used for each test was of an ammonia dynamite of approximately 60 percent weight strength; the properties of which are outlined in Appendix-A, Table A-II.

Table I gives a brief description of the design for each blast.

A. BENCH PREPARATION AND MAPPING

The objective of bench preparation was to obtain a straight vertical face. This was achieved by smoothwall blasting which amounted to the removal of approximately 3 tons of rock for every ton of rock produced from the test blasts used for fragmentation analyses. Preparation work was further complicated by weather conditions; Figure 4 shows the winter ice problems that were encountered during this study. However, the removal of inflowing water proved to be the most difficult of the weather-related problems. Normally a siphon was used to remove water when work was not in progress, while two gasoline-powered portable pumps were used to remove the water when there was activity in the pit, as shown in Figure 5.

After the bench was prepared to meet the design specifications, it was mapped to provide a pre-blast bench profile. The mapping technique was adopted from Warden (1983). This technique involved the setting up and leveling of a portable 5 feet by 6 feet wire mesh screen on a pre-referenced line. Distances were then measured from the screen to the vertical bench face on a 4 inch by 4 inch pattern. These distances were measured by inserting a 3/8 inch diameter, graduated steel rod through the 1/2 inch apertures in the screen mesh network, as shown in Figure 6. After the test blast was fired, the screen was repositioned again on the

TABLE I

DESIGN DATA FOR TEST BLASTS

BLAST NO.	TYPE	VOLUME OF AIR-TO-EXPLOSIVE RATIO	L/B RATIO	DESIGNED POWDER FACTOR (lb/ton)	CHARGE LENGTH (inches)	HOLE DIAMETER (inches)
A-67	decoupled	0.69	3.0	0.44	40.0	0.75
W-67	water-coupled	----	3.0	0.44	40.0	0.75
A-80	complete coupling	0.0	3.0	0.44	40.0	0.625
B-1	complete coupling	0.0	3.8	0.44	52.0	0.625
B-2	air-gapped (12")	0.30	3.8	0.34	2 @ 20.0 ea.	0.625
B-3	air-gapped (6")	0.15	3.4	0.39	2 @ 20.0 ea.	0.625
B-4	air-gapped (5.2")	0.15	3.0	0.39	2 @ 20.0 ea.	0.625
B-5	air-gapped (9.2")	0.30	3.0	0.34	2 @ 20.0 ea.	0.625

Note: The following variables were held constant for all tests --

Charge Diameter = 0.50 inches
Explosive Specific Gravity = 1.12
Spacing Dimension = 22.5 inches
Sub-drilling Dimension = 5 inches
Stemming Dimension = 10 inches
Burden Dimension = 15 inches

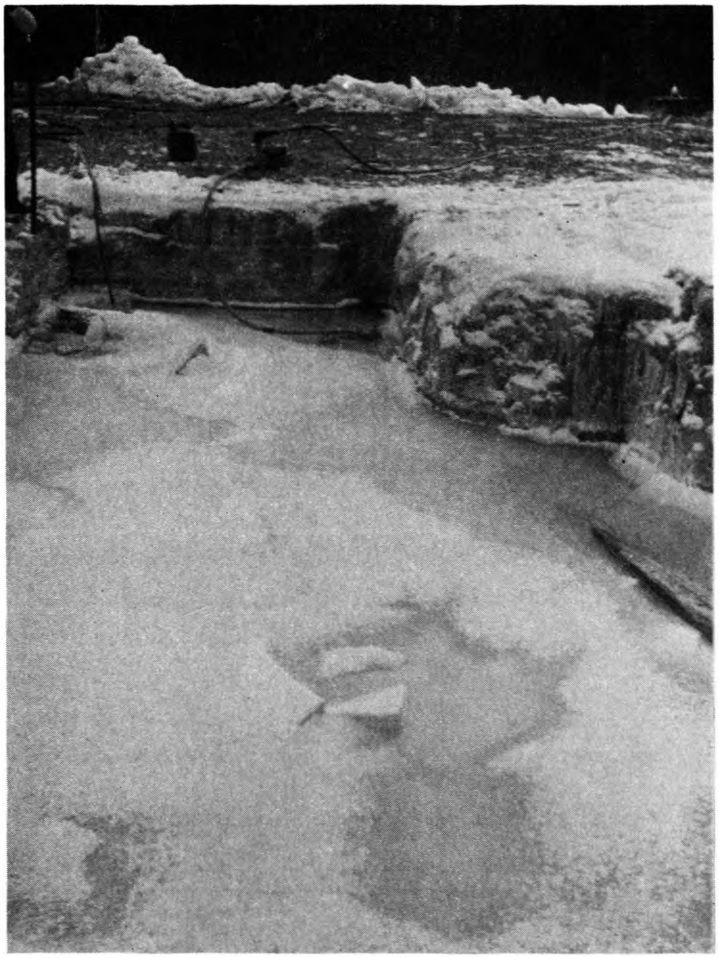


Figure 4. Winter Ice Problems

Figure 5. Gasoline-Powered Pumps Used For Water Removal

reference line to provide the post-blast bench profile. The pre-blast and post-blast bench profiles were then used to calculate the volume and weight of the total rock broken, the amount of backbreak and endbreak, and the amount of toe.

B. DRILLING AND EXPLOSIVE CHARGE PREPARATION

Drilling of the blasthole was done with a pneumatic percussion drill and integral drill rods. The blasthole diameter drilled was dependent upon the size of the required annulus surrounding the 1/2 inch diameter cylindrical explosive charge. Each test blasthole was sub-drilled 5 inches below the bench floor, loaded with explosive, and stemmed 10 inches at the hole collar as described in Figure 3. The blastholes were bottom primed with electric blasting caps and initiated on 25 millisecond intervals, using the initiation sequence illustrated in Figure 3. Charging of the blastholes was done with a prepacked 1/2 inch diameter explosive charge encased in a 1/2 inch inner diameter polyethylene tubing. This tubing had a wall thickness of 1/16 inch and an outer diameter of 5/8 inch.

Although the results of Warden (1983) were used as a starting point for this study, modifications of his experimental conditions had to be considered. Warden referred to the tubing as part of the coupling medium in his work on geometric coupling. The author, however, chose to refer to the tubing as a coupling medium displacer, since this work was to consider volumes of coupling medium in relation to explosive volume.

The following is a breakdown of the different types of blasts performed in this investigation.

1. Completely-Coupled Tests. A set of completely-coupled tests, consisting of two blasts, A-80 and B-1, were performed in this study to determine the effect of a completely-coupled explosive charge on rock fragmentation. Both test blasts, A-80, and B-1, used blastholes of 5/8 inch diameter, drilled to depths of 50 and 62 inches respectively. This hole diameter provided complete confinement of the explosive charge contained in the polyethylene tubing. The tubing's major function in this study was to provide confinement and charge shape with ease in loading. A drilling instrument capable of drilling this diameter and depth was not readily available. This problem was solved by machining down a readily available 5 foot 3 inch long, 3/4 inch hexagonal hollow-tubed integral drill steel to 1/2 inch in diameter. The cutting edge of the integral bit was reduced from 1-1/16 inch to 5/8 inch. These holes were loaded by sliding a prepacked explosive tube down each blasthole. The tubing provided a tight fit between the borehole and the explosive charge of 144 grams and 187 grams in weight for blasts A-80 and B-1, respectively.

2. Decoupled and Water-Coupled Tests. These tests were required to further the investigation of the decoupled and water-coupled work performed by Warden (1983). Warden's study used a range of geometric coupling between 0.15 and 0.57. These values defined the ratio of the explosive charge diameter to the hole diameter. The corresponding range for the ratios of the volume of coupling medium to the volume of explosive was from 40.69 to 1.50. For this study, however, it was necessary to obtain fragmentation data with a lower ratio of coupling medium to explosive volume for comparison with tests employing an air-gap. Therefore, a decoupled test, A-67, and a water-coupled test, W-67, were each performed

at a coupling medium-to-explosive volume ratio of 0.69. This ratio was the lowest practical ratio that could be obtained in a coupling type blast, and required that the blastholes be 3/4 inch in diameter and drilled 50 inches in depth. Once again, the drill rods used were especially machined down from hexagonal hollow-tubed integral drill steel. In each test blast, every borehole was loaded with 144 grams of explosive, prepacked in the polyethylene tubing. The annulus surrounding the prepacked charge was then filled with water in the water-coupled test, and left open in the decoupled test. In both tests, some waxed paper was placed at the top of the prepacked charge to prevent the stemming material, -3/16 inch gravel, from falling down and around the explosive charge.

3. Air-Gapped Tests. Four different air-gapped tests, B-2, B-3, B-4, and B-5, were performed. The blastholes of each air-gapped bench blast were drilled at 5/8 inch diameter to provide complete confinement of the explosive filled polyethylene tube to the borehole wall. Each prepacked charge contained an air-gap at the center of the powder column with equal amounts of the explosive distributed above and below the air-gap, as shown in Figure 7. The length of the air-gap and the amount of explosive were varied to provide the different air-to-explosive volume ratios used in these tests. These ratios and other design variables are given in Table I.

These air-gapped charges were made by cutting a desired length of polyethylene tubing and marking the location of the air-gap on the tubing. The blasting cap used to initiate the charge was then pushed through the tube with a strand of 5 grain per foot MDF (Mild Detonating Fuse) cord, PETN (Pentaerythrite Tetranitrate) explosive encased in lead, taped to the cap legwires. The MDF cord was cut 6 inches longer than the length of the

Figure 6. Procedure for Bench Mapping

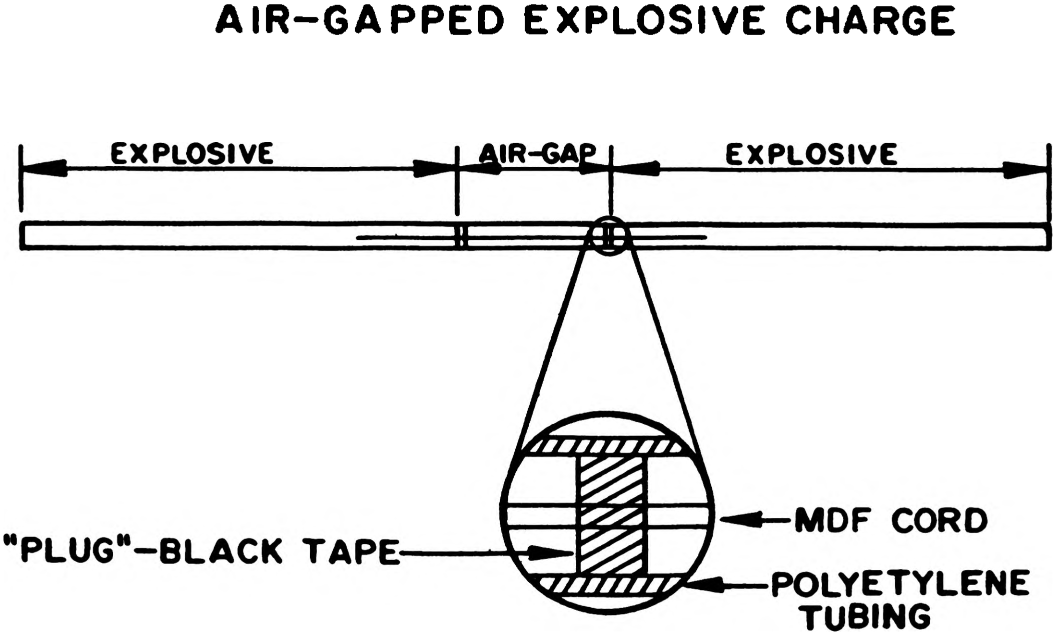


Figure 7. Idealized Air-Gap Charge

air-gap and taped to the cap legwires with 1/4 inch wide electrician's tape. The taping was built up around the legwires and the MDF cord to a diameter slightly under 1/2 an inch at each end of the air-gap. This taping provided a plug which prevented the explosive from entering the air-gap, as shown in Figure 7. The purpose of the MDF cord was to develop near simultaneous initiation of the top and bottom charges. The latter was initiated by the blasting cap.

C. FRAGMENTATION RECOVERY AND SIZING

Since the primary objective of this study was to evaluate the overall degree of rock fragmentation resulting from in situ reduced-scale bench blasts, standard methods for retaining, recovering and sizing the rock fragments had to be defined. The methods selected were the same as those used by previous investigators at this site. Prior to the test shot, the test pit floor was swept clean of any rock or loose debris and then blown clean with compressed air. After cleaning the pit floor, sheets of polyethylene plastic were laid over the immediate blasting area to catch any loose flyrock generated from the blast. A blasting mat was also placed over the test bench to retain the rock fragments produced from the blast. The blasting mat consisted of oak timbers placed at a slight angle over the bench. A typical blast site prior to and during shooting is shown in Figures 8 and 9; Figures 10 and 11 show a typical blast site after shooting.

After each test blast was fired, the rock fragments were recovered and sized for data evaluation. This was achieved, by first, hand-screening and weighing all the rock fragments above 3 inches in size. The rest of the rock fragments were then mechanically screened and weighed. This screening process provided 8 different fragment size ranges. These fragments sizes, in inches, were +12, +6, -12, +3 -6, +1½ -3, +3/4 -1½,

+3/8 -3/4, +3/16 -3/8, and -3/16. The mechanical shaker and portable scales are shown in Figure 12 and 13, respectively.

D. GROUND VIBRATIONS

Ground vibrations for the three orthogonal directions (vertical, longitudinal, and transverse) were recorded on a magnetic tape for each test blast, using a Vibra-Tech model S/N-2222 blasting seismograph, shown in Figure 14. To obtain the best possible readings, the geophone station was cleared of all loose material and placed in good contact with solid rock. The geophone was then weighted with a 50-pound sandbag. The location of the geophone station for each blast was directly behind the center hole of the pattern, at a distance which provided a scaled distance of 21.3 $ft/lb^{\frac{1}{2}}$.

Figure 8. Typical Test Area Before Blasting

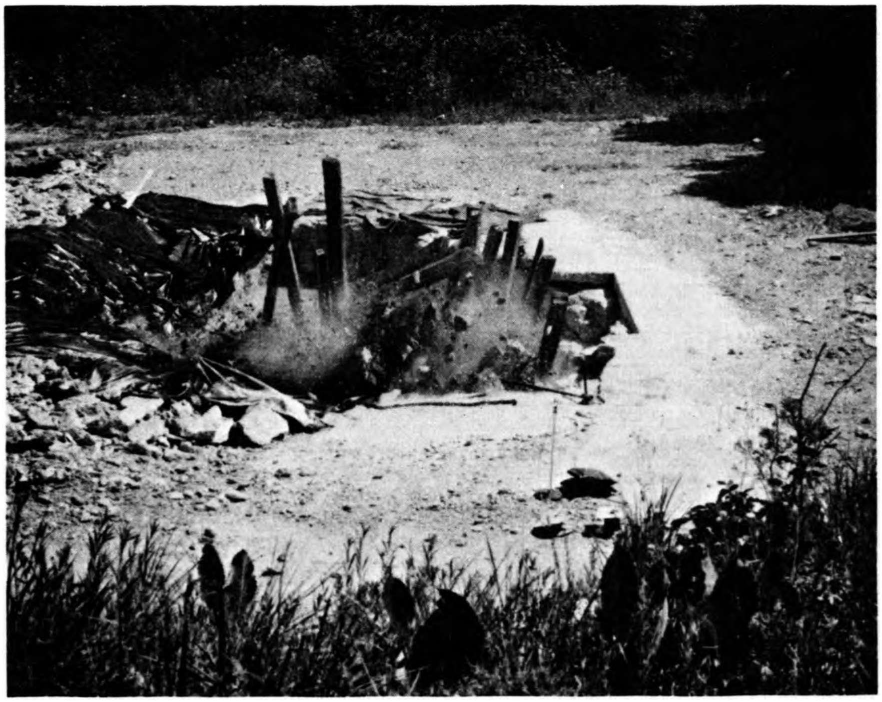


Figure 9. Typical Test Shot During Blasting

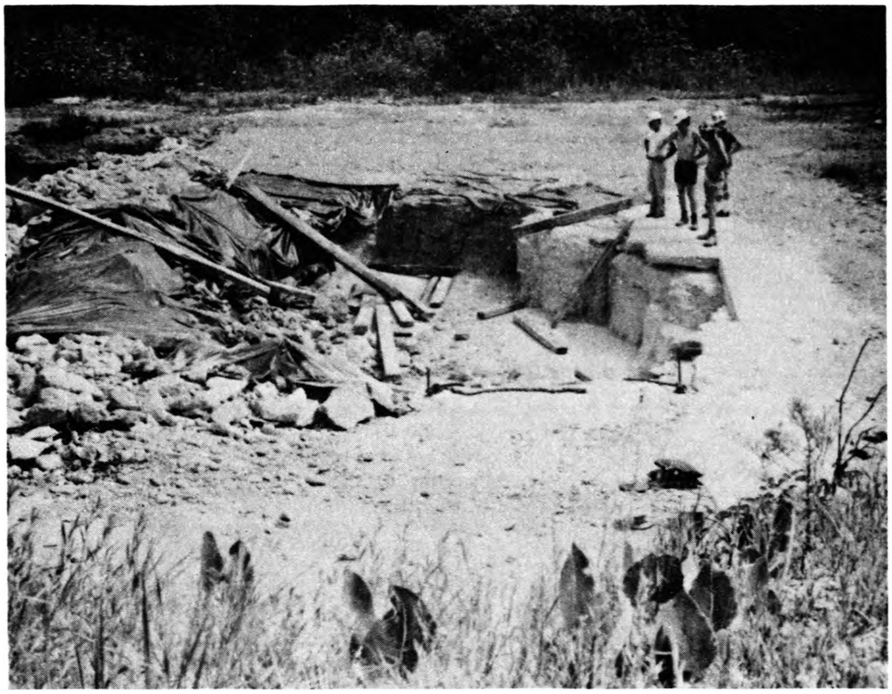


Figure 10. Typical Test Area After Blasting

Figure 11. Typical Test Site During Screening

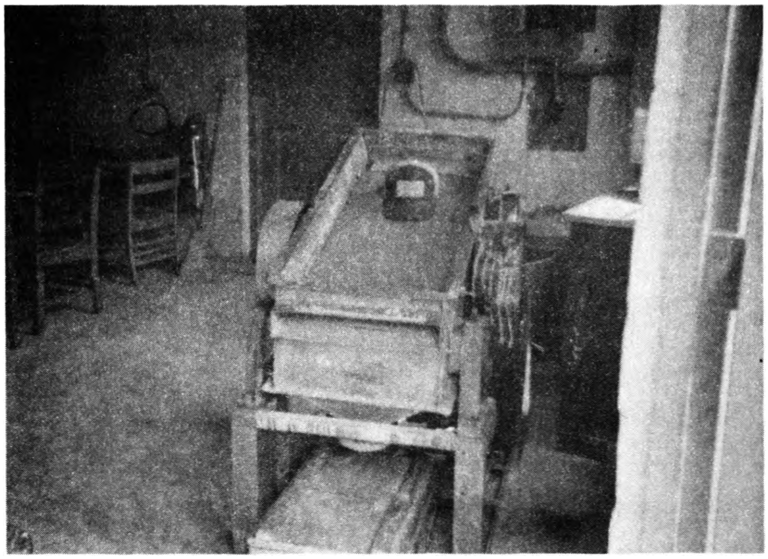


Figure 12. Mechanical Shaker For Sorting +1½ -3/16 inch Material

Figure 13. Portable Scale Used For Weighing The Rock Fragments

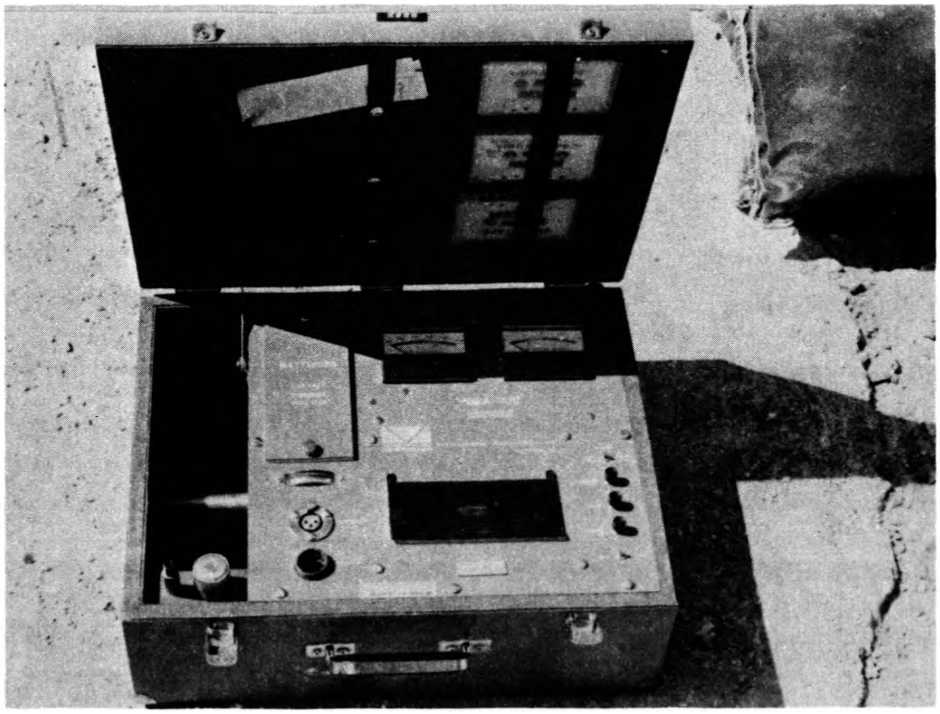


Figure 14. Vibra Tech Model S/N-2222 Seismograph

Used For Recording Ground Vibrations

IV. METHODS OF EVALUATING EXPERIMENTAL RESULTS

The basic data resulting from the test blasts performed in the study appear in the appendices and include:

1. Screen size analysis of the rock fragments by weight, as shown in Table C-I;
2. Peak particle velocity measurements in three orthogonal directions for each test blast, as shown in Table D-I; and
3. Burden-rock contour maps and pictures of each blast before and after firing, Figures E-I through E-24.

A. FRAGMENTATION INDICES

Bar charts, or histograms, are commonly used to graphically compare the particle size distributions, by weight percent, for any screened test blast. The results of those tests performed in this investigation are presented in this form in Figures 16 through 20. These histograms contain the position of the histogram centroid and a line indicating the 50-percent-passing-point which allows a better graphical interpretation of the degree of fragmentation.

Histograms are a good graphical method of evaluating the data. However, they do not provide a simple way of mathematically expressing a single numerical value which would describe the overall fragment-size distribution. Therefore, three, single-term numerical indices were used to evaluate the data obtained in this investigation. These indices, F_c, $F_{+}3$, and $F_{-3/4}$, were developed by Smith (1976) and later used by Brinkmann (1982).

The overall degree of fragmentation is expressed by the F_c index. This is a dimensionless numerical value associated with the centroid of the histogram, and is expressed as a relationship of the centroid of each fragment-size distribution and its moment-arm to the zero size particle. Thus, with a decrease in the F_c value, there is an increase in the proportion of the smaller fragments, indicating improved fragmentation.

The F_{+3} index, also dimensionless, represents the coarse-size-fragment distribution. This value is mathematically computed by dividing the weight of +3 inch screened material by the weight of -3 inch material. A decreasing F_{+3} value indicates a greater proportion of smaller-size fragments, -3 inch, and a lesser proportion of coarse-size-fragments, +3 inch, and therefore a greater degree of fragmentation.

The $F_{-3/4}$ index, also dimensionless, represents the fine-size-fragment distribution. This value is mathematically computed by dividing the weight of -3/4 inch screened material by the weight of +3/4 inch material. An increasing $F_{-3/4}$ value indicates a greater proportion of fine-size fragments, -3/4 inch, and a lesser proportion of larger-size-fragments, +3/4 inch, and therefore an increase in the degree of fragmentation. Table B-I lists the values of the fragmentation indices for each test blast performed in this study.

B. GROUND VIBRATIONS

The measured peak particle velocities of each of the three orthogonal directions are tabulated in Table D-I, and the greatest value of each set was used to construct a graph representing the peak particle velocity against the air-to-explosive volume ratio.

C. ROCK-YIELD, OVERBREAK AND TOE

The weights of the total rock-yield, overbreak (including endbreak and backbreak), and toe as calculated by planimetering the burden-rock contours are given in Table F-I.

V. DISCUSSION OF RESULTS

The purpose of this investigation was threefold, as follows:

1. Compare the effectiveness of decoupled and air-gapped blasting for controlling fragmentation and ground vibrations;

2. Evaluate air-gapped blasting relative to the standard full-column completely-coupled method of blasting on the basis of fragmentation and ground vibration; and

3. Identify the more dominant of the two borehole phenomena that vary under decoupling conditions -- energy transfer and effective borehole pressure -- with respect to their influence on fragmentation.

A. EFFECTIVENESS OF DECOUPLED AND AIR-GAPPED BLASTING FOR CONTROLLING FRAGMENTATION AND GROUND VIBRATIONS

1. Fragmentation. This phase of the investigation, in part, involved a continuation of the work performed by Warden (1983) on geometric coupling. Warden examined the effect of decoupled bench blasts on fragmentation for an air-to-explosive volume ratio range of 1.5 to 40.69 and found that decoupling had the potential to control fragmentation. The results of his work are illustrated in Figure 15 with details on the fragmentation indices given in Table B-III. An extension of his work, however, was needed to examine the fragmentation resulting from decoupled blasts with small air-to-explosive volume ratios, 0.0 to 1.5, since performing air-gapped tests with air-to-explosive volume ratios greater than 1.5 would be impractical. The impracticality of achieving higher air-to-explosive volume ratios would be due to the small amount of explosive required in an air-gapped blast.

To extend Warden's work, two different test blasts, A-80 and A-67,

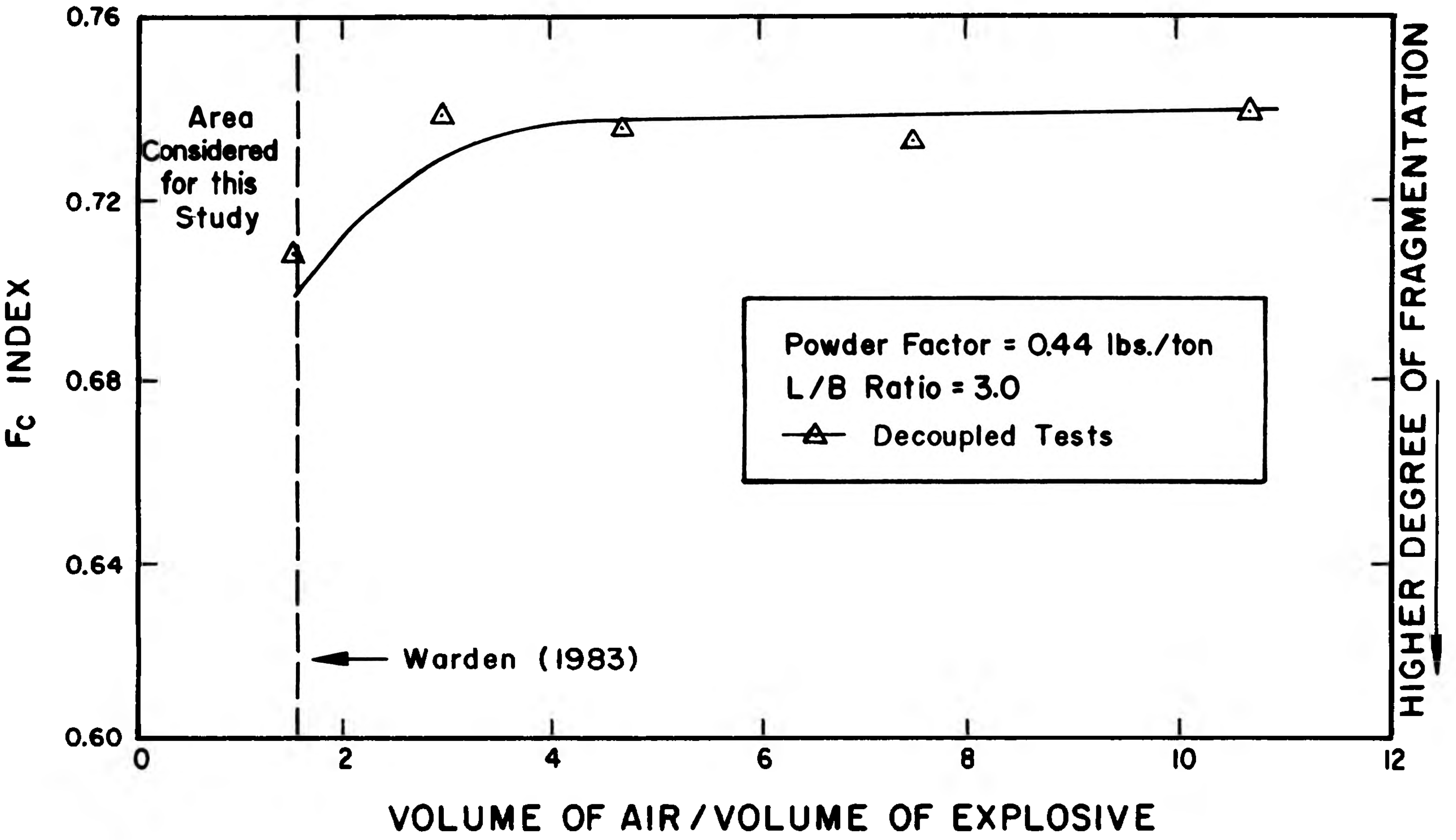
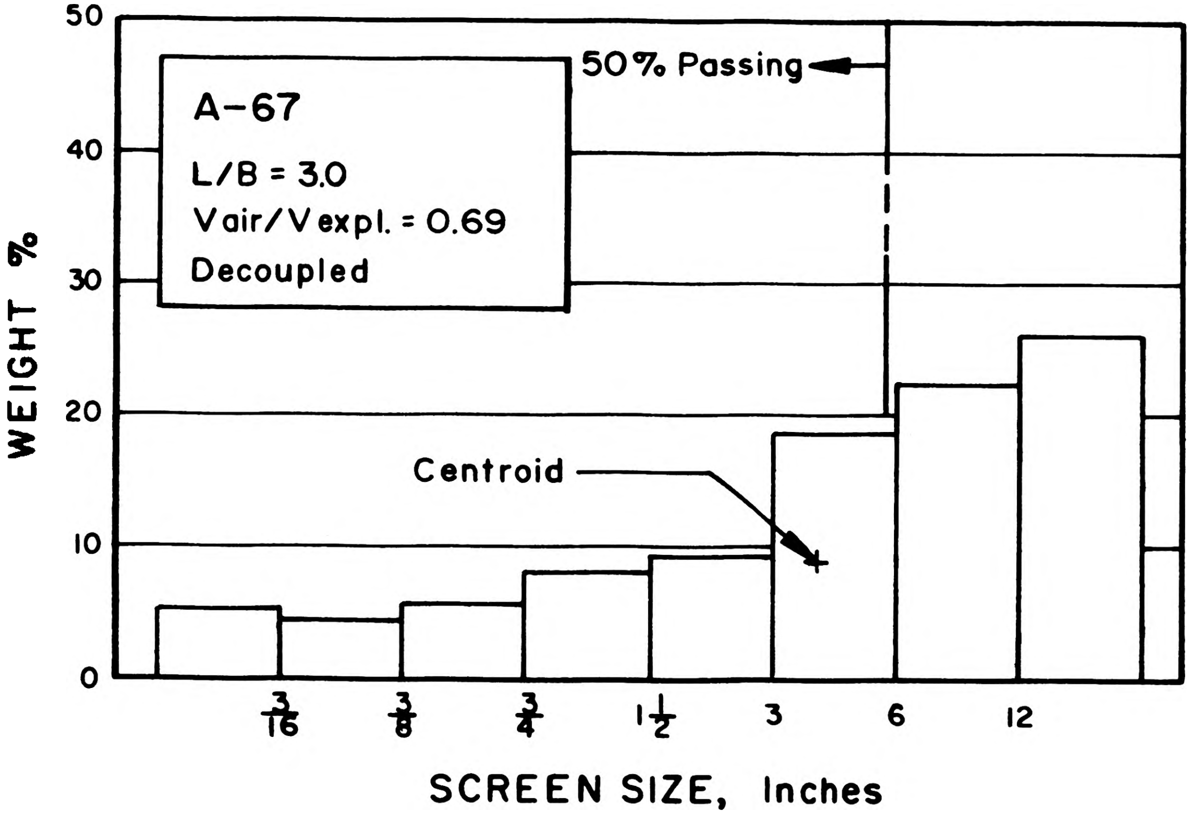


Figure 15. Fragmentation Index, F_c, Versus Volume of Air/Volume of Explosive for Warden's (1983) Decoupled Blasts

were performed. The screen analyses and calculated fragmentation indices for these blasts are given in Tables C-I and B-I, respectively. Histograms for each blast, showing the weight-percent of each size-fraction, are given in the upper portions of Figures 16 and 17. An inspection of these histograms and that of Warden's (1983) test blast, A-57, found in the lower portion of Figure 16, show the centroid and the 50-percent-passing-line shifts toward the coarser fractions as the air-to-explosive volume ratio increases, suggesting a poorer degree of fragmentation. This relationship is shown in Figure 21, and is further indicated through a comparison of the three fragmentation indices, which show in all cases that as the air-to-explosive volume ratio decreases in decoupling, the degree of fragmentation improves.

Utilizing four different air-gapped test blasts, B-2, B-3, B-4, and B-5, along with two different full-column completely-coupled test blasts, A-80 and B-1, the results of which are illustrated in Figure 21, it was obvious that as the air-to-explosive volume ratio increased, the degree of fragmentation decreased. This can also be seen in the histograms of each blast, Figures 17, 18, and 19. The three fragmentation indices calculated for each test blast are given in Table B-I.

Although, in both cases, decoupled and air-gapped, it was obvious that the degree of fragmentation decreased as the air-to-explosive volume ratio increased, it appears that at an equal air-to-explosive volume ratio, the decoupling method of blasting produces better fragmentation than the air-gapped method. However, all of the decoupled blasts were performed at a length-to-burden (L/B) ratio of 3.0, while the air-gapped tests were conducted at L/B ratios ranging from 3.0 to 3.8. Therefore, it was considered that the changes in the L/B ratio may have



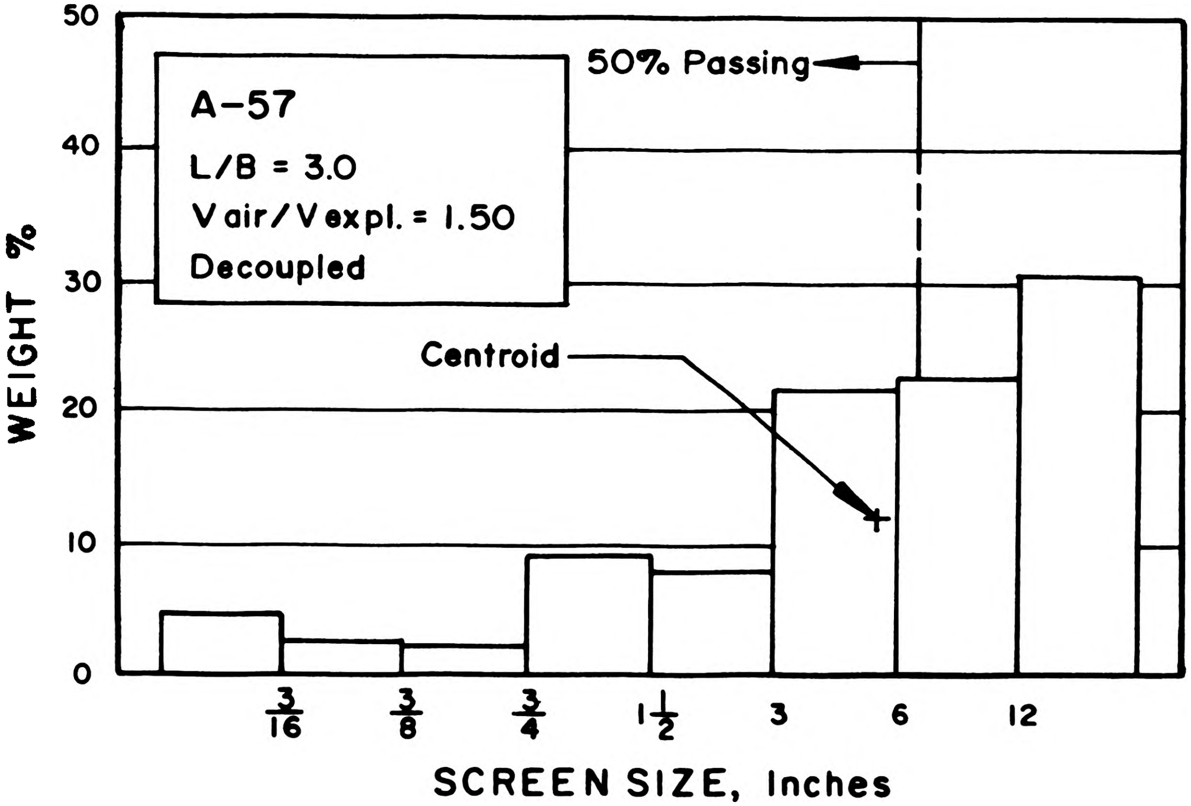
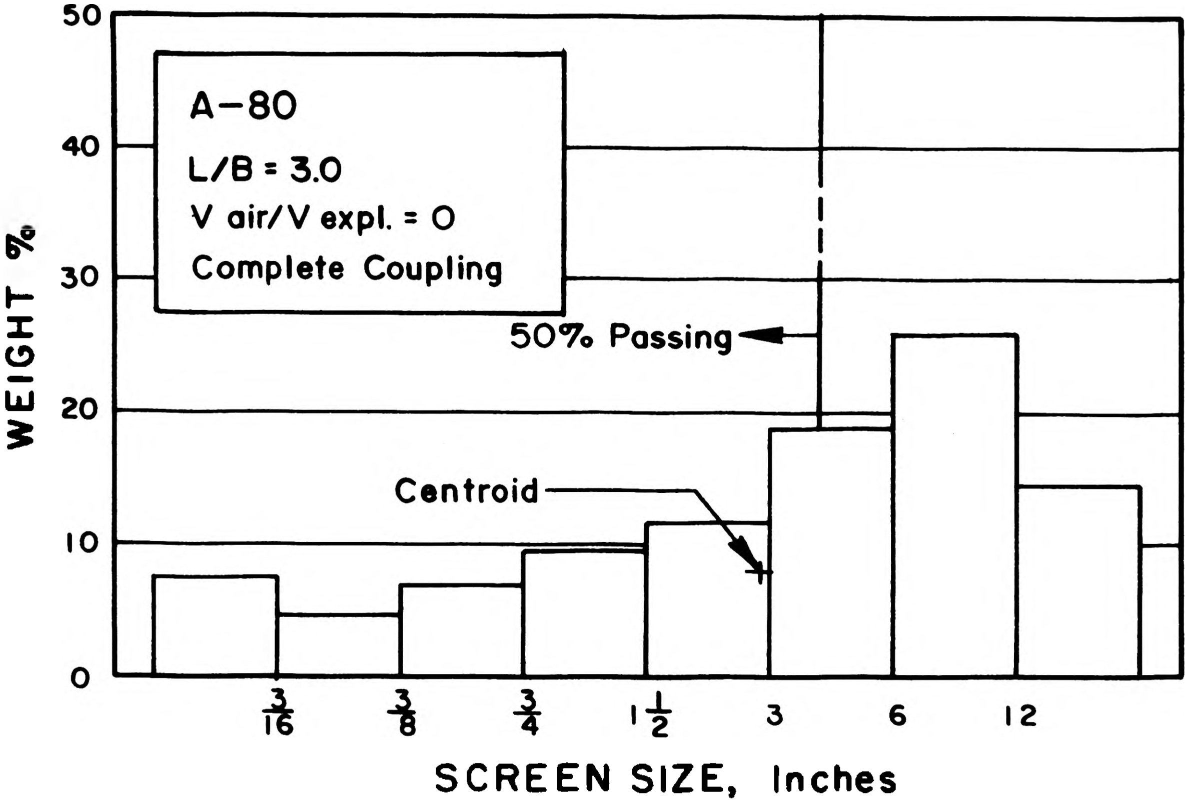


Figure 16. Histograms of Fragment-Size Distribution for Test Blast A-67 and Warden's (1983) Test A-57



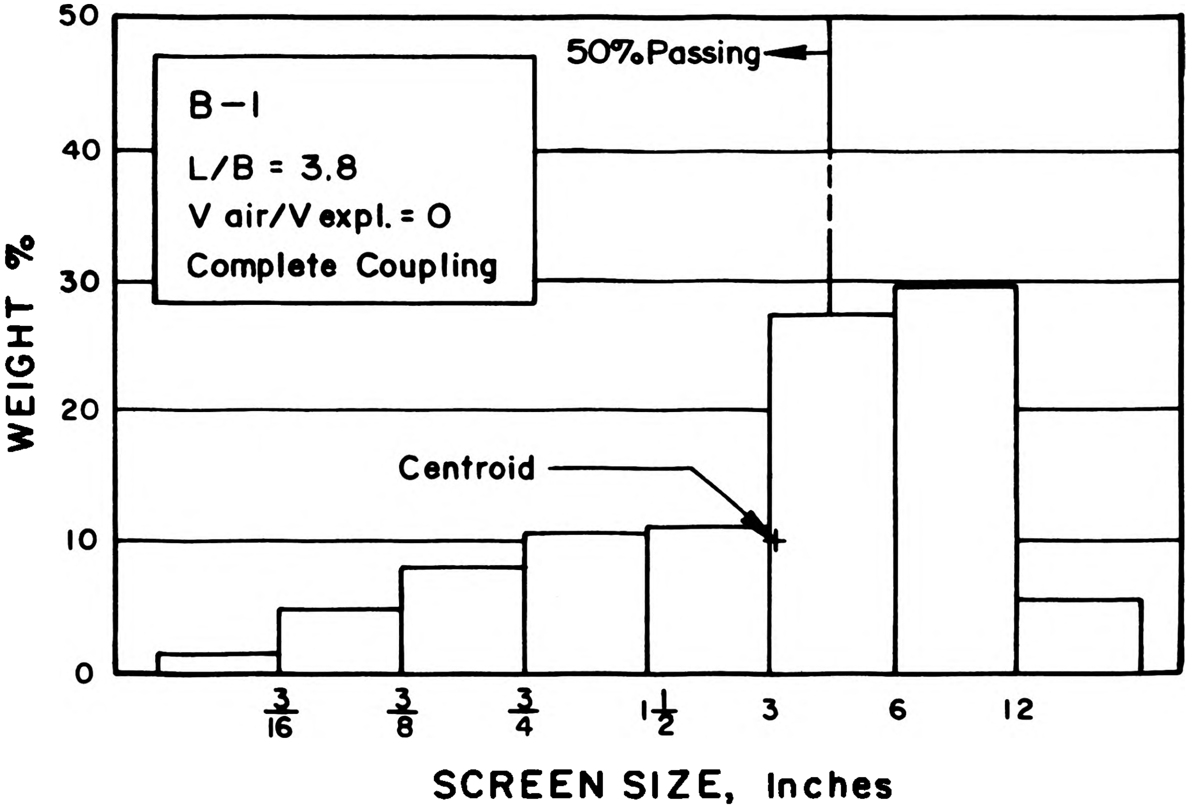
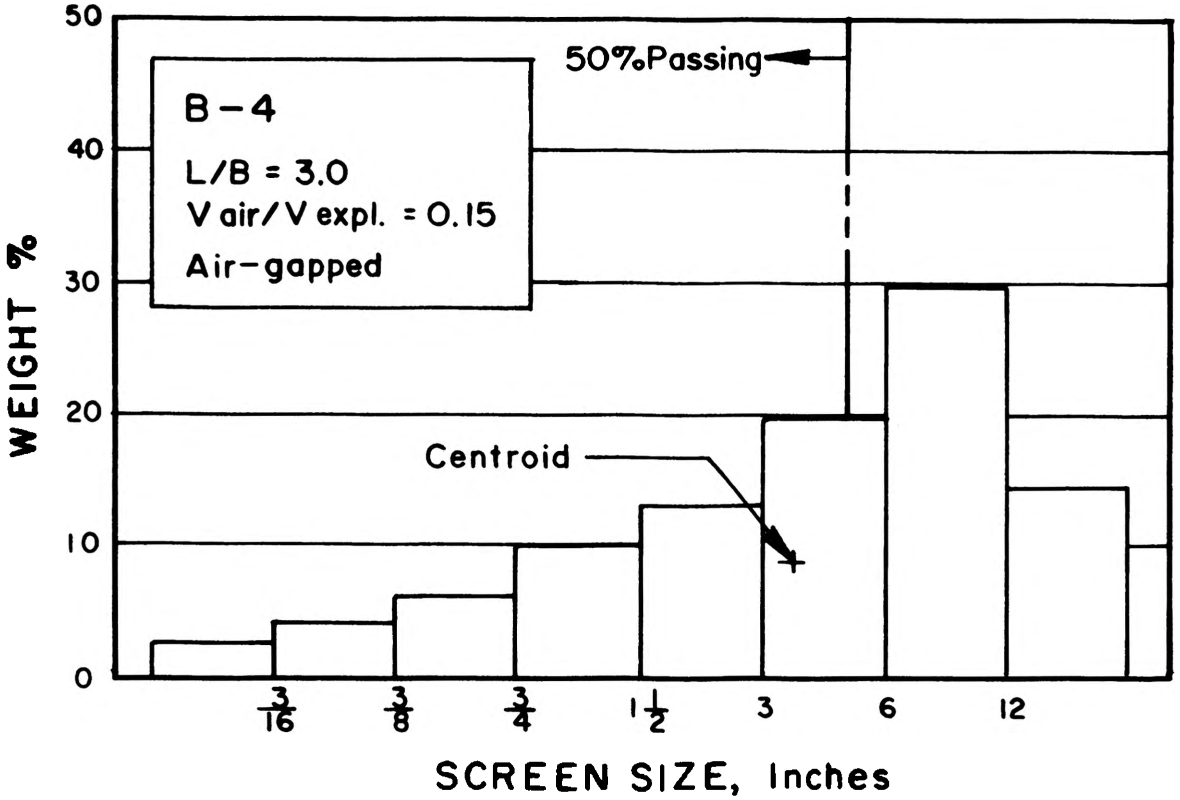


Figure 17. Histograms of Fragment-Size Distribution for Test Blasts A-80 and B-1



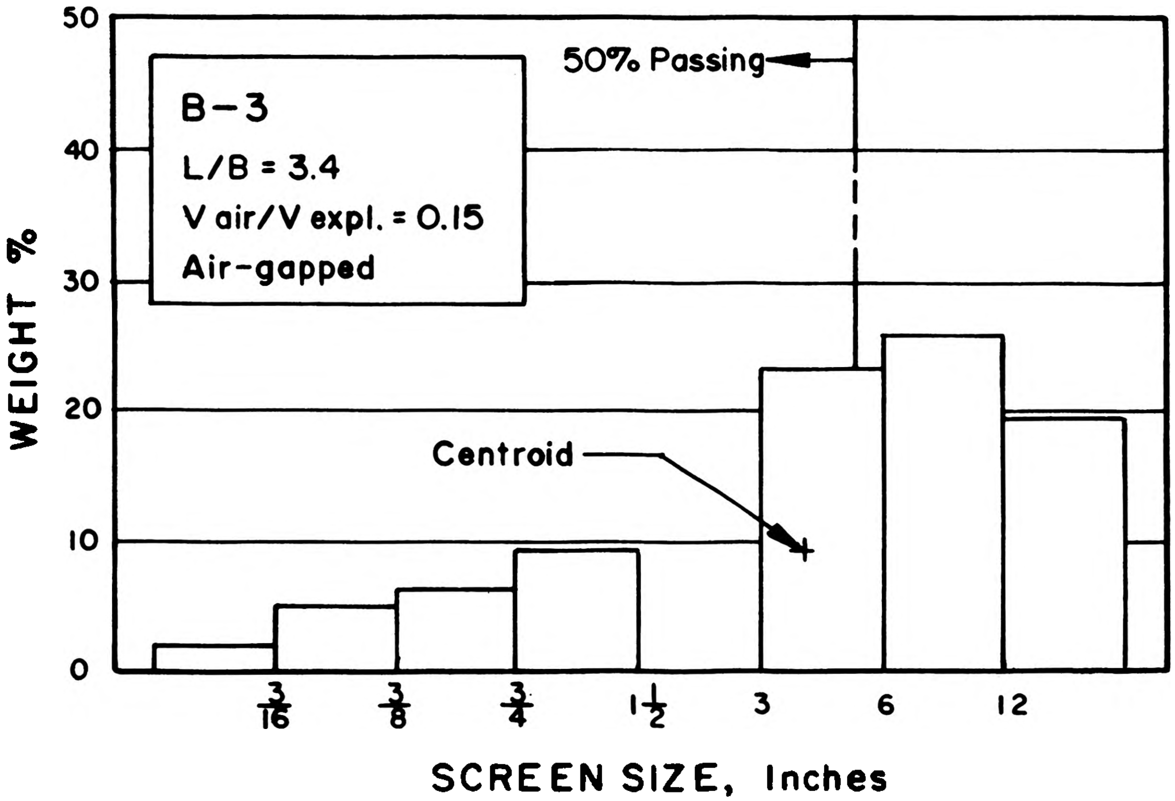
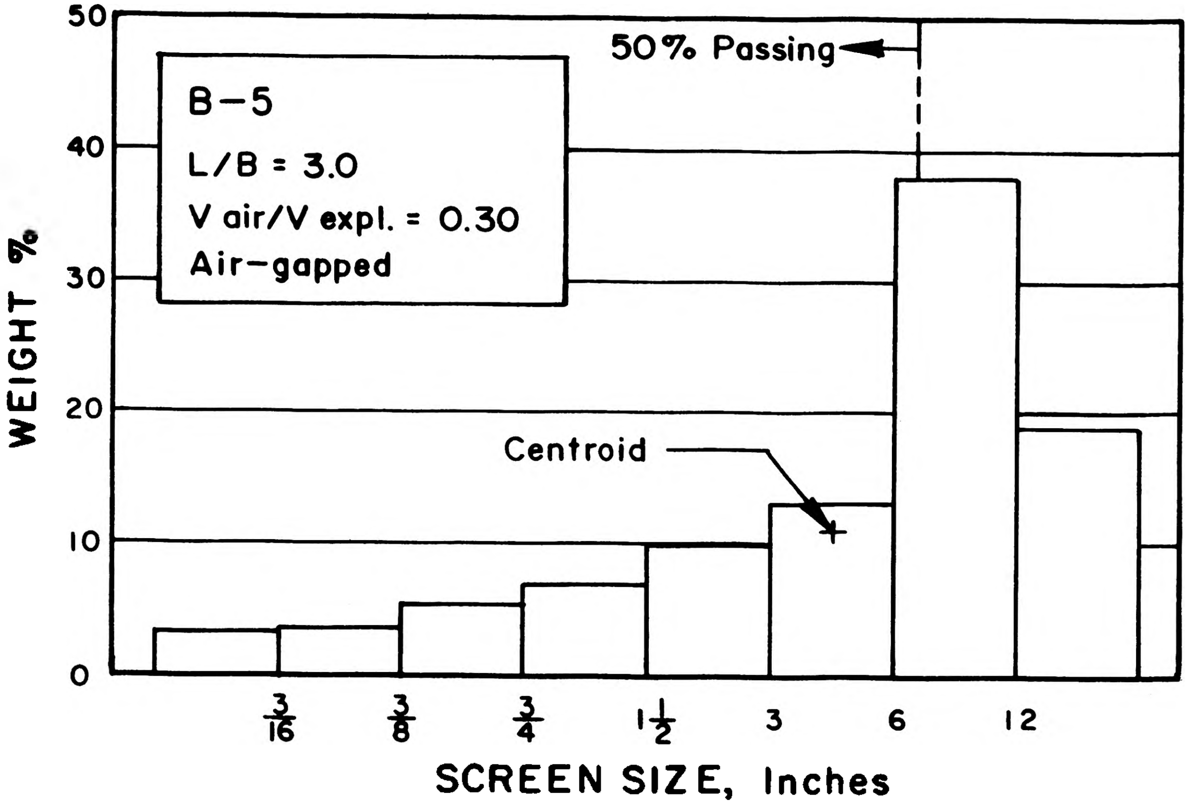


Figure 18. Histograms of Fragment-size Distributions for Test Blasts B-4 and B-3



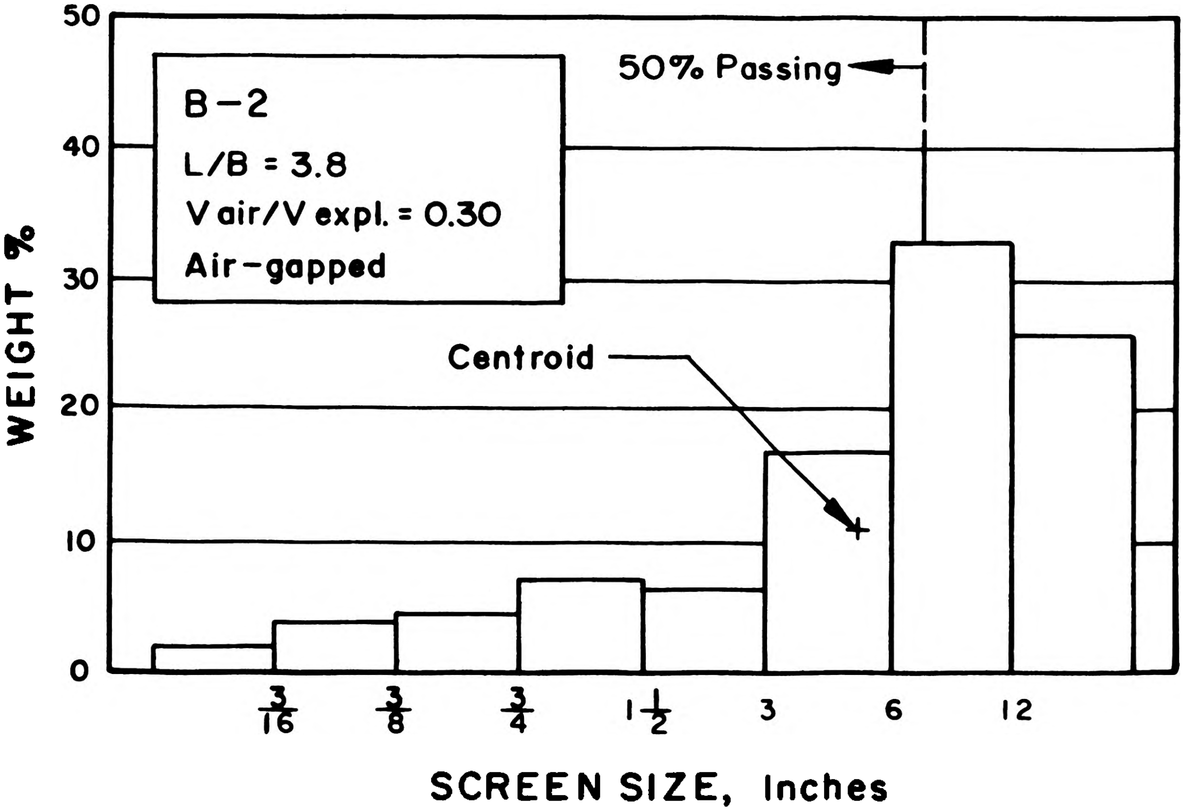


Figure 19. Histograms of Fragment-Size Distributions for Test Blasts B-5 and B-2

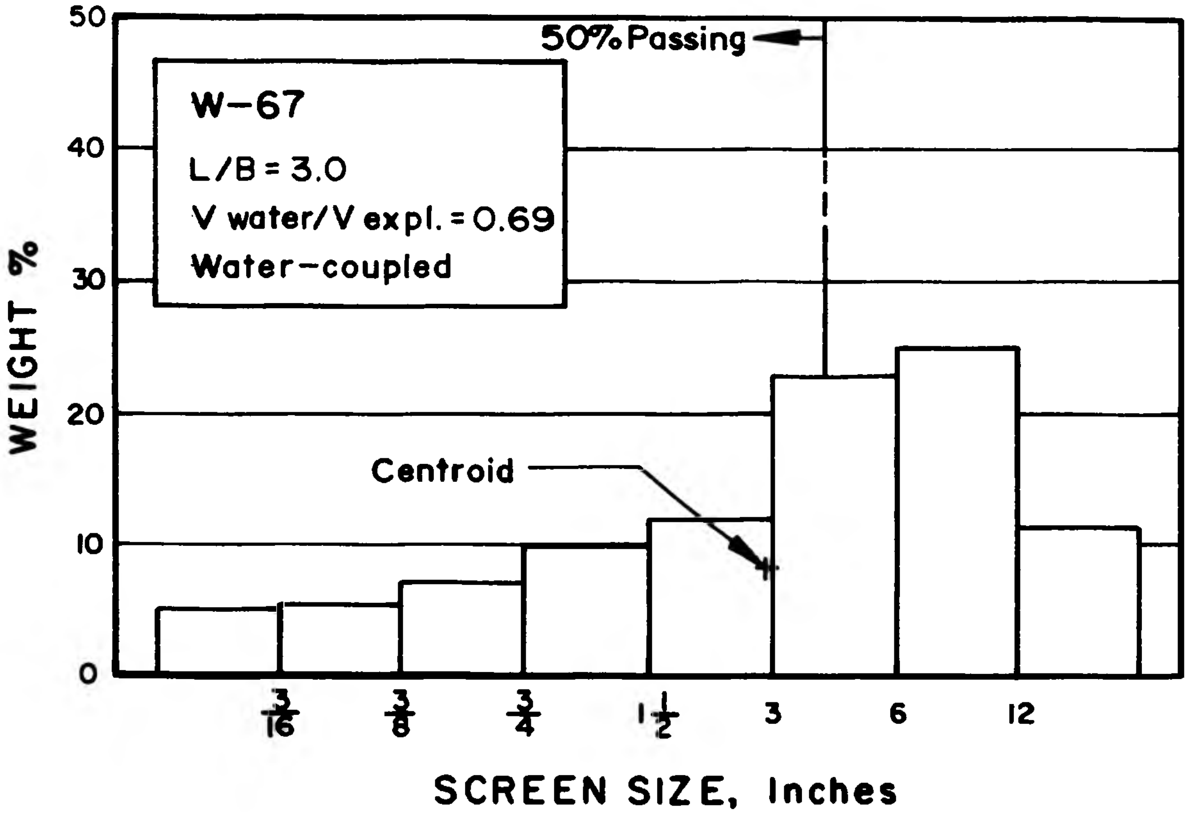


Figure 20. Histogram of Fragment-Size Distributions for Test Blast W-67

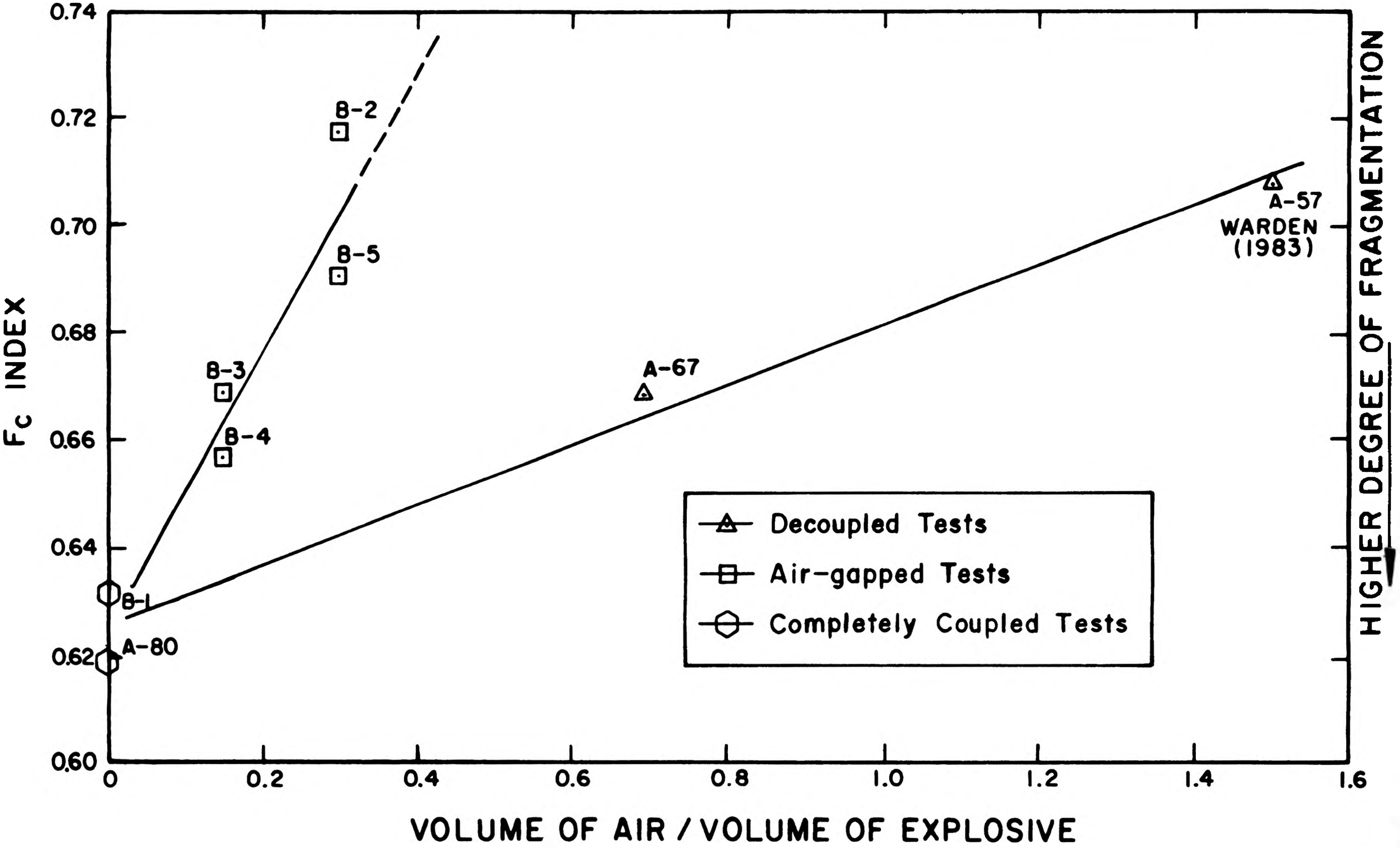


Figure 21. Fragmentation Index, F_c, Versus Volume of Air/Volume of Explosive, less than 1.60, for Air-gapped and Decoupled Tests

played a role in the resulting fragmentation from these air-gapped test blasts. Figures 22 and 23 were then constructed to evaluate the change in fragmentation due to the variation in the L/B ratio alone. As it can be seen, there is a slight decrease in the degree of fragmentation as the L/B ratio increased, at equal air-to-explosive volume ratios.

However, it was also necessary to consider the variation in the designed powder factor for each blast. The full-column completely-coupled and decoupled test blasts all had varying powder factors. Therefore, it was necessary to determine the effect that powder factor had on fragmentation. This was accomplished by plotting the fragmentation index, F_c, of 13 different water-coupled blasts versus their respective powder factors, as shown in Figure 24. These shots were performed by Smith (1976) at various times, each having different bench geometries. The fragmentation index, F_c, for each of these test shots is given in Table B-II. The result of this plot, Figure 24, definitely shows that powder factor, varied by bench geometry only, has an effect on fragmentation. The slope of this line, representing a unit change in fragmentation per unit change in powder factor, was then found and used to develop a family of lines representing decoupled type blasts having powder factors of 0.39 and 0.34 lb/ton. This can be achieved, since water-coupled type blasts act similarly to decoupled blasts; that is, the degree of fragmentation from each becomes uniformly poorer as the coupling media-to-explosive volume ratio increases,as will be discussed later and as is illustrated in Figure 27. These lines are equivalent to the powder factors of the air-gapped test shots performed in this study and are shown in Figure 25. This extrapolation showed that at equivalent L/B ratios, powder factors,

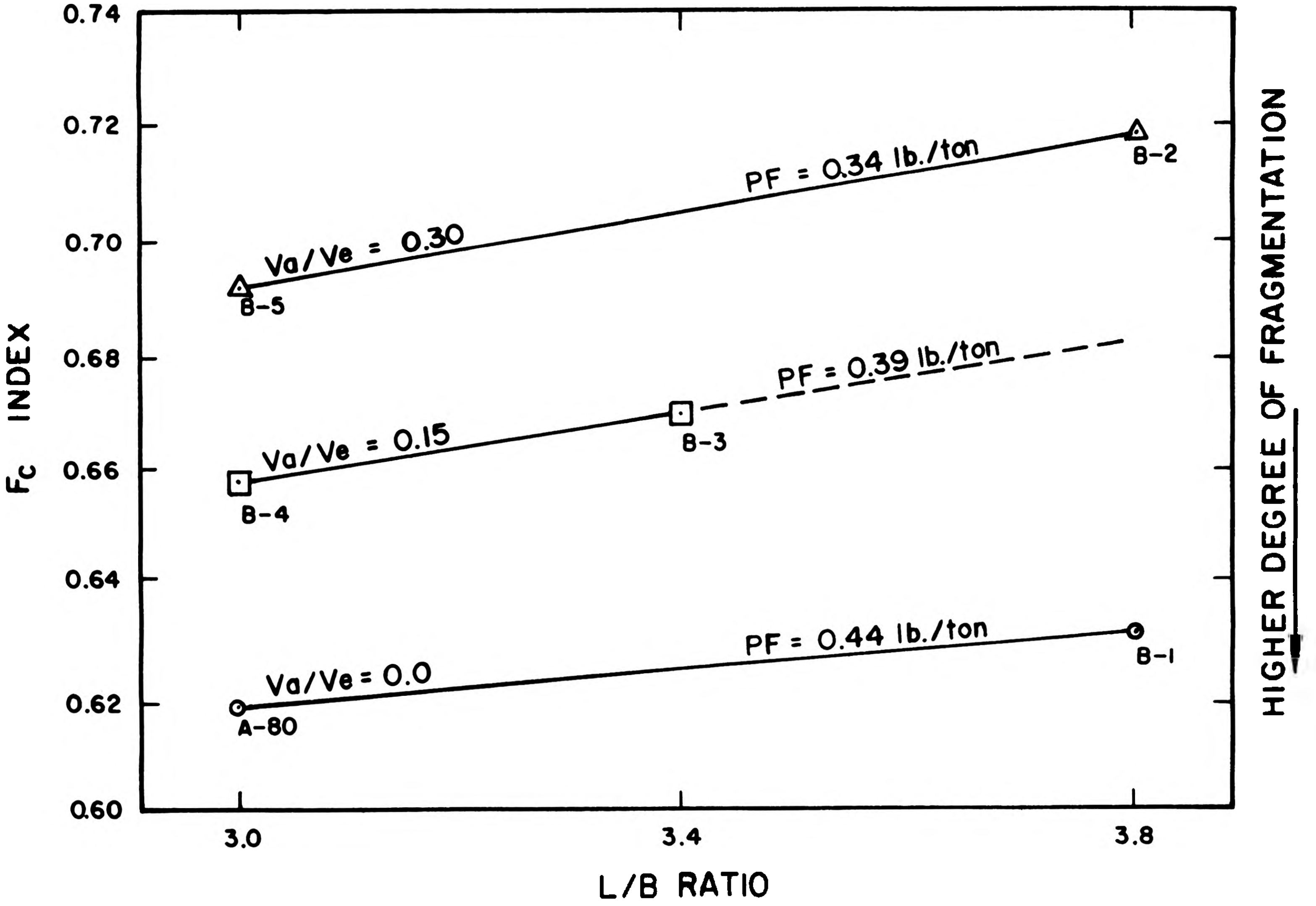


Figure 22. Fragmentation Index, F_c, Versus L/B Ratio

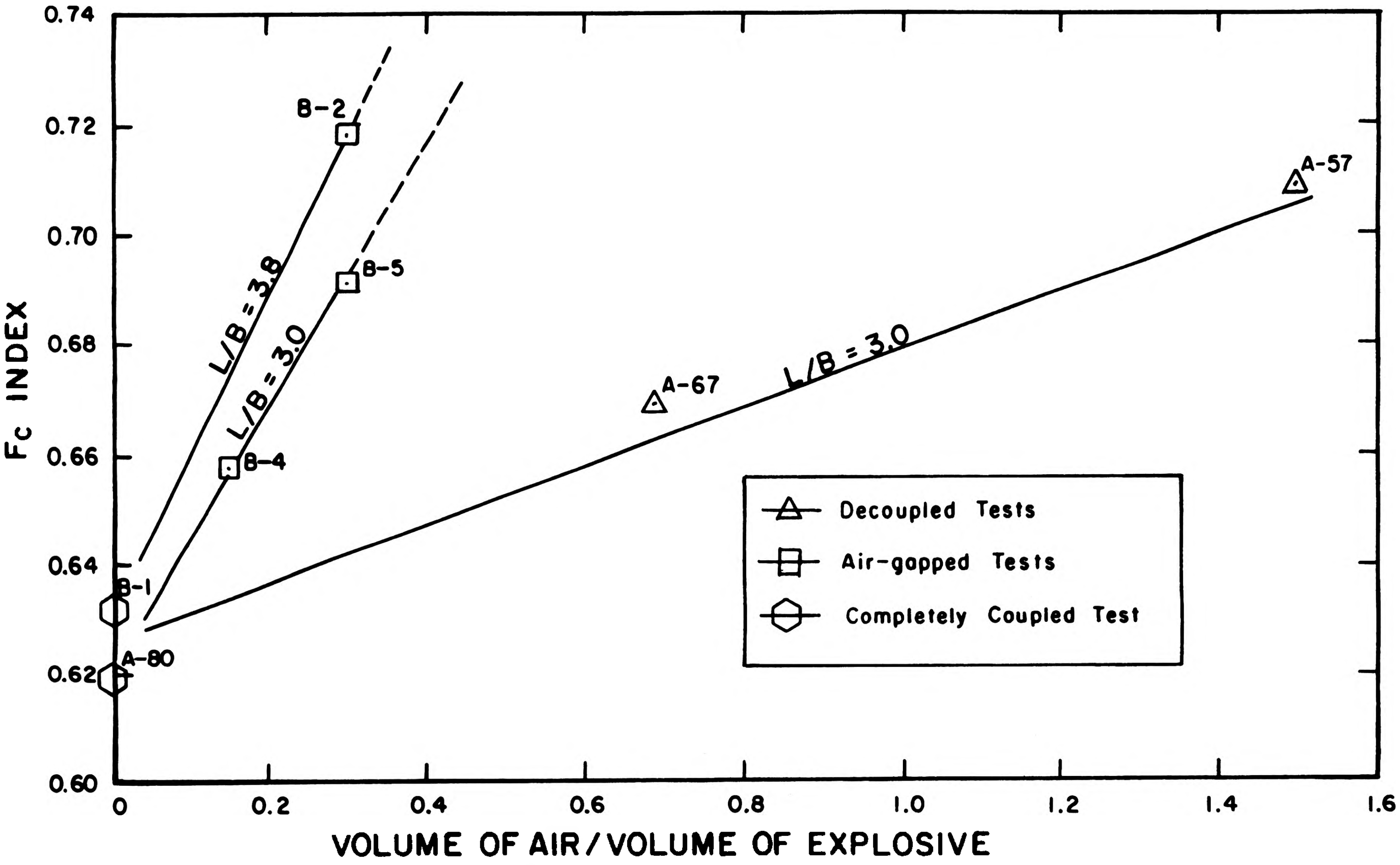


Figure 23. Fragmentation Index, F_c, Versus Volume of Air/Volume of Explosive, less than 1.60, for Air-gapped and Decoupled Tests with specified L/B Ratios

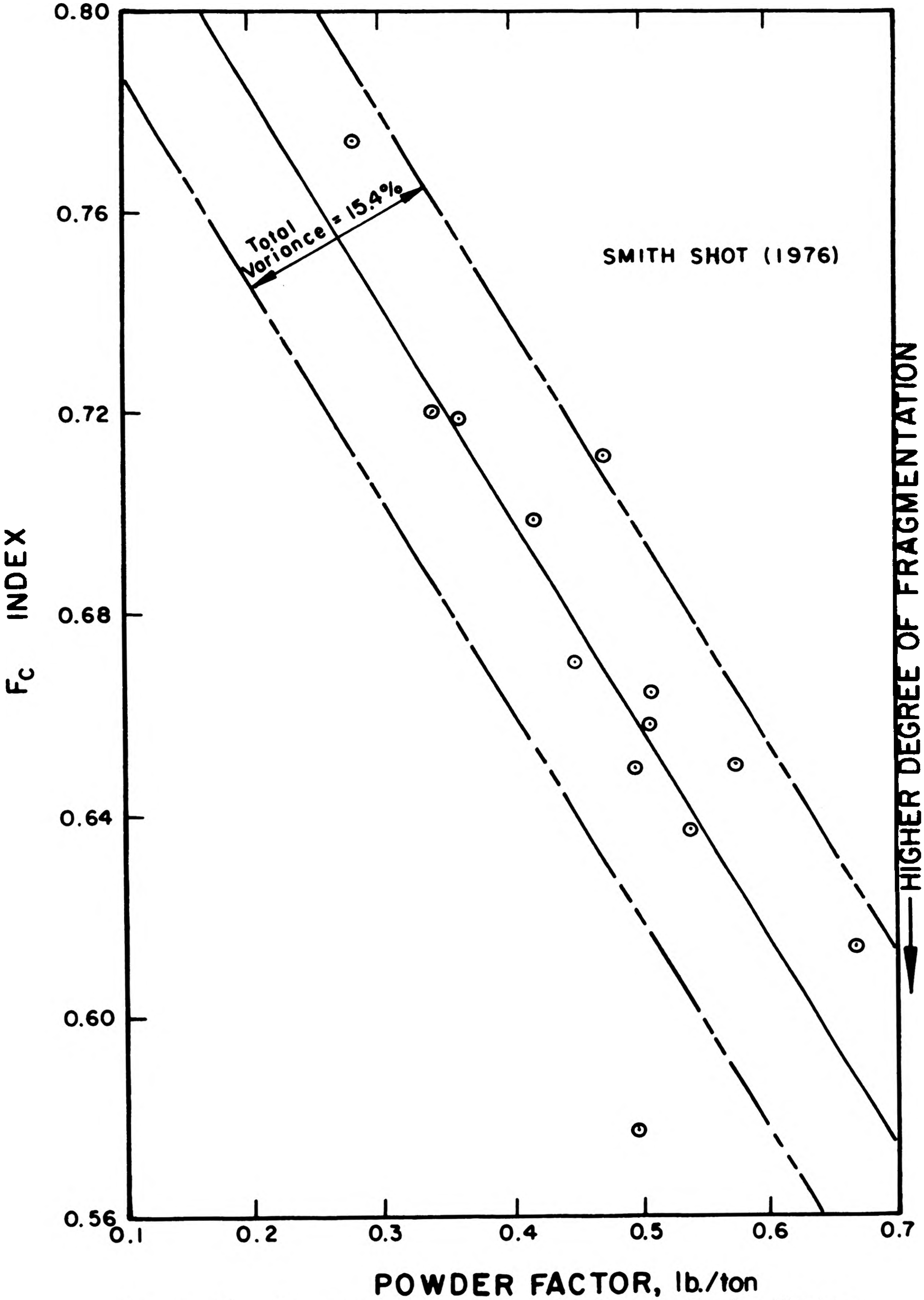


Figure 24. Fragmentation Index, F_c, Versus Powder Factor, lb/ton

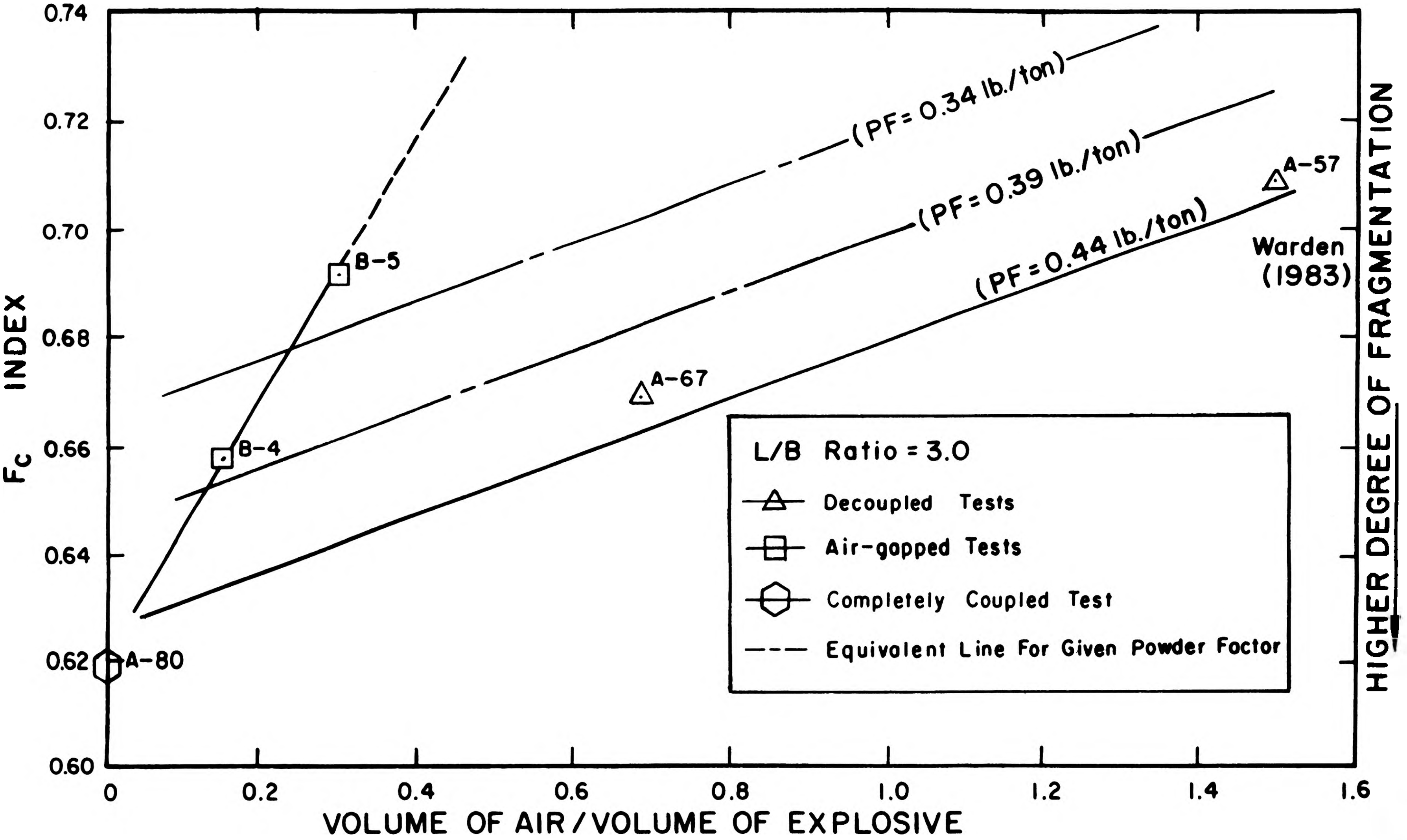


Figure 25. Fragmentation Index, F_c, Versus Volume of Air/Volume of Explosive, less than 1.60, for Air-gapped and Decoupled Tests with a L/B Ratio = 3.0 and Equivalent Decoupled Lines for a Given Powder Factor

and air-to-explosive volume ratios, there was very little difference in the degree of fragmentation resulting from either decoupled or air-gapped blasts at low air-to-explosive volume ratios, 0.0 to 1.5.

2. Ground Vibrations. The ground vibrations for all of the tests performed in this study were measured in three orthogonal directions in terms of their peak particle velocity, and are given in Table D-I. The level of ground vibration resulting from the decoupled blasts having a L/B ratio of 3.0 and a powder factor of 0.44 lb/ton, showed a uniform decrease in peak particle velocity when the air-to-explosive volume ratio increased, as illustrated in Figure 26. Therefore, the change in peak particle velocity can be attributed directly to the air-to-explosive volume ratio. The equation for the best-fit line for the decoupled blasts and the full-column completely-coupled blast, A-80, used in this study was found to be:

$$Y = -0.35(X) + 0.90$$

where:

Y = peak particle velocity, in/sec;

X = air-to-explosive volume ratio;

0.90 = y-intercept, peak particle velocity, in/sec; and

-0.35 = slope, peak particle velocity/air-to-explosive volume ratio, in/sec.

Similarly, the air-gapped blasts, at L/B ratios of 3.0 also showed a decrease in the peak particle velocity with an increase in the air-to-explosive volume ratio. In this case, however, one cannot immediately attribute the change in peak particle velocity solely to the change in the air-to-explosive volume ratio, because of the varied powder factors.

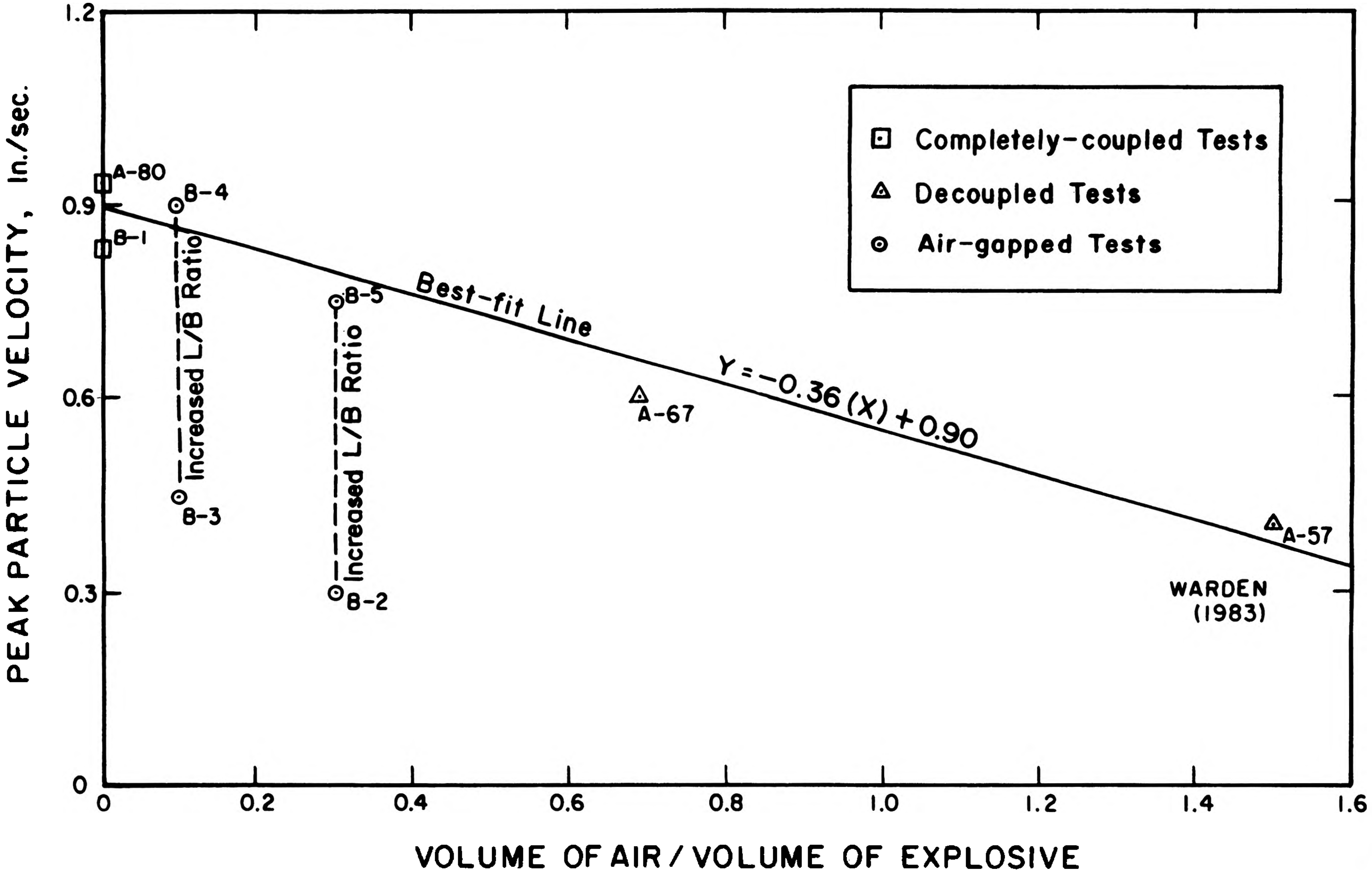


Figure 26. Peak Particle Velocity Versus Volume of Air/Volume of Explosive

However, the graphical combination of the results of these two air-gapped blasts, B-4 and B-5, having L/B ratios of 3.0, but varying powder factors, with those decoupled tests, A-67 and Warden's (1983) test A-57, and the full-column completely-coupled test, A-80, provided a line with the following equation:

$$Y = -0.36(X) + 0.90$$

where:

0.90 = y-intercept, peak particle velocity, in/sec; and

-0.36 = slope, peak particle velocity/air-to-explosive volume ratio, in/sec.

The difference between these two equations is insignificant on the basis of their y-intercepts and slopes, and it can be assumed that, first, powder factor plays no major role in the resulting peak particle velocity produced from either a decoupled or air-gapped blast, and second, at equal air-to-explosive volume ratios, for the decoupled or air-gapped method of blasting, the peak particle velocity is the same, as shown in Figure 26.

Further comparison of the peak particle velocities produced from the air-gapped test blasts also indicate that there was a decrease in the peak particle velocity with an increase in the L/B ratio, for air-gapped shots with equal air-to-explosive volume ratios, and this can be noted by the coordinates for shots B-2 and B-3 in Figure 26, compared to shots B-5 and B-4 respectively. Therefore, this study shows that the level of ground vibration is related to the air-to-explosive volume ratio in both the decoupled and air-gapped cases, and also the L/B ratio in the air-gapped case.

B. COMPARISON OF THE AIR-GAPPED BLASTING METHOD TO THE STANDARD FULL-COLUMN COMPLETELY-COUPLED METHOD ON THE BASES OF FRAGMENTATION AND GROUND VIBRATION

1. Fragmentation. Examination of the histogram, Figures 17, 18, and 19, for the shots performed in this study indicates that the centroids for the full-column completely-coupled blasts occur in a finer fraction than those of any air-gapped blast. This evaluation indicates that the standard full-column completely-coupled method of blasting provides a higher degree of fragmentation than the air-gapped method of blasting. Details of the calculated fragmentation indices are found in Table B-I.

2. Ground Vibrations. A higher level of ground vibration was produced from the standard full-column completely-coupled method of blasting than that of any air-gapped blast, at the same scale distance. It is therefore obvious that ground vibrations can be better controlled through the use of air-gapped explosive charges.

C. INVESTIGATION OF THE MORE DOMINANT OF THE TWO BOREHOLE PHENOMENA INFLUENCING ROCK FRAGMENTATION FROM DECOUPLED CHARGES

The resulting degree of fragmentation from a coupled-medium type blast has been attributed to two factors. First, the efficiency in the transfer of energy from the explosive charge, through a coupling medium, and second, a change in the effective borehole pressure. The investigation performed by Warden (1983) concluded that when comparing a water-coupled bench blast and a decoupled blast, the higher degree of fragmentation was always obtained from the water-coupled blasts, at equal coupling medium-to-explosive volume ratios. This was further confirmed with the addition of a decoupled blast, A-67, and a water-coupled blast, W-67, performed in this study. The relationship between the resulting fragmentation and the corresponding coupling medium-to-explosive volume ratio for each of these types of blasts are given in Figure 27. This situation can be explained through both phenomena, since it is apparent that the water-coupled case would obviously have a higher effective borehole pressure than the decoupled case, and also because the efficiency in the transfer of energy is higher in the water-coupled case than in the decoupled case. The overall efficiency of energy transfer can be seen through the calculated apparent ratios of reflected energy to incident energy using the formulas referenced on pages 10 and 11 of this thesis; the following explosive-medium-rock reflected energy ratios were calculated:

Completely-coupled type blast 0.616

Water-coupled type blast 0.856

Decoupled type blast 1.0

Therefore, with similar variables of blast design, the air-gapped blasting method should provide a higher degree of fragmentation than that of decoupling; the reason is that there is complete coupling in the case of an air-gapped charge and better transfer of energy expected than that from a decoupled charge. But, as stated previously, there is apparently no difference in the resulting degree of fragmentation between a decoupled or air-gapped bench blast, when using equivalent powder factors, L/B ratios and air-to-explosive ratios. Thus, it would appear that the significance of energy transfer as a controlling factor for fragmentation is questionable. Consequently, the effective borehole pressure would seem to be the predominant factor effecting fragmentation. Furthermore, it is the author's belief that the difference in fragmentation between coupled blasts having different coupling media, but equal coupling medium-to-explosive volume ratios can be explained by comparing the compressibilities of the coupling media. That is, a coupling medium that is less compressible than another, will be associated with a greater borehole pressure, resulting in a higher degree of fragmentation.

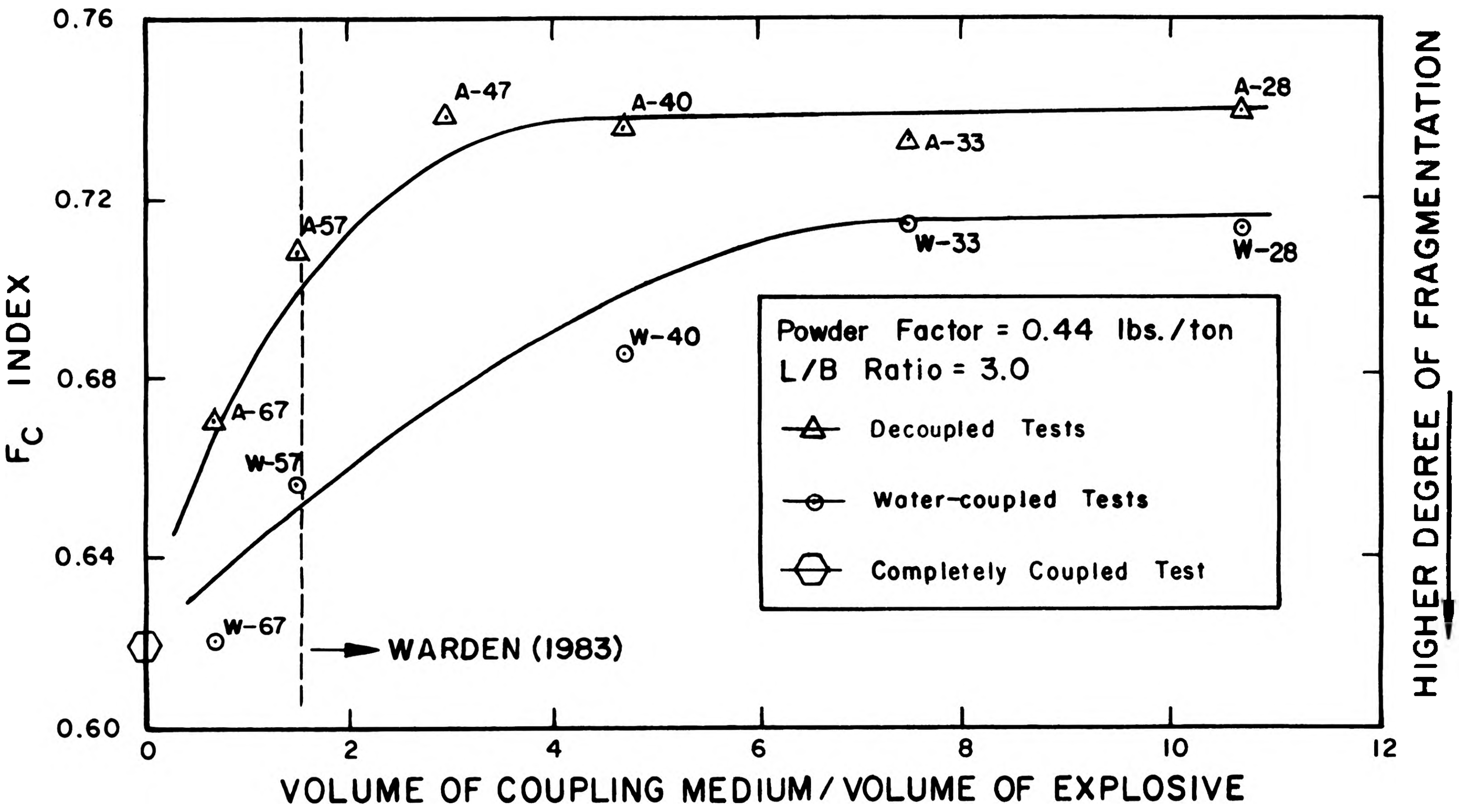


Figure 27. Fragmentation Index, F_c, Versus Volume of Coupling Medium/Volume of Explosive.

VI. CONCLUSIONS

1. The control of rock fragmentation and ground vibrations can be achieved by the lesser known blasting methods of decoupling and air-gapping.
2. The standard full-column completely-coupled method of blasting provides a higher degree of fragmentation and a higher level of ground vibration in comparison to the air-gapped or decoupled methods of blasting.
3. In this study, the degree of fragmentation and level of ground vibration decrease with an increase in the air-to-explosive volume ratio of either an air-gapped or decoupled blast when the air-to-explosive volume ratio is less than 1.5. This is also expected to hold true at higher air-to-explosive volume ratios.
4. It is expected that equivalent fragmentation can be achieved for air-gapped and decoupled blasts, when their powder factors, L/B ratios and air-to-explosive volume ratios are equivalent.
5. The more dominant of the two borehole phenomena that vary under decoupling conditions is the effective borehole pressure; efficiency of energy transfer from the explosive to the borehole wall apparently has little influence on fragmentation.

VII. RECOMMENDATIONS FOR FUTURE INVESTIGATIONS

1. Similar air-gapped tests should be performed with air-to-explosive volume ratios greater than 0.30 to determine the effect on fragmentation and ground vibrations.
2. A series of decoupled blasts having powder factors of 0.39 and 0.34 lb/ton should be performed, by altering bench geometry (spacing-to-burden ratio) to change the powder factor, to confirm the inference of the extrapolated lines in Figure 25.
3. A set of decoupled and air-gapped tests using identical air-to-explosive volume ratios should be conducted with measurements of the actual borehole pressure.
4. A series of coupled-medium type blasts using different media should be conducted to examine the relationship between the compressibility of a coupling medium and effective borehole pressure.

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VITA

Everett Ellsworth Bleakney III was born on June 5, 1960 in Ellwood City, Pennsylvania. He received his primary and secondary education in Ellwood City, Pennsylvania. In May of 1983, he was awarded a Bachelor of Science Degree in Mining Engineering from the University of Missouri - Rolla.

He has been enrolled in the Graduate School of the University of Missouri - Rolla since June, 1983 and was a Graduate Teaching Assistant in the Department of Mining Engineering for the period January, 1984 to June 1984.

His practical experience includes a combined total of 14 months of summer and other employment with Magnum Minerals, Inc., Branchton, Pennsylvania, and Buckeye and Industrial Mining Companies, Lisbon, Ohio.

APPENDIX A

PROPERTIES OF DOLOMITIC ROCK MEDIUM AND EXPLOSIVE USED IN TEST BLASTS

TABLE A-I

PROPERTIES OF JEFFERSON CITY FORMATION DOLOMITIC ROCK

(Deatherage, 1966 and Casquino, 1965)

PHYSICAL PROPERTIES:

90% Dolomite

10% Calcite

Tan to gray color

Massive bedding

Texture - crystalline; irregular and non-uniform shape and size of crystal; matrix is mainly dolomite

Specific Gravity 2.677

ELASTIC PROPERTIES:

Compressive Strength (dry)	9,000 psi
Tensile Strength (dry)	200 psi
Shear Strength (dry)	7,500 psi
Poisson's Ratio (dry)	0.27
Young's Modulus (static)	2.18 x 10^6 psi
(dynamic)	2.26 x 10^6 psi
Longitudinal Velocity (dry)	8,100 fps

TABLE A-II

CHARACTERISTICS OF EXPLOSIVE USED IN TEST BLASTS

(Ash, 1973)

Type: Ammonia Dynamite, 60 Percent Strength (Atlas Powder Co., Inc.)

Cartridge Count: 112 per 50-lb case, 1¼ x 8 inches

Ideal Performance Specifications:

Specific Gravity: 1.29

Heat of Formation: -1008 kcal/kg

Heat of Explosion: -702 kcal/kg

Detonation Temperature: 2930 Degree K

Detonation Pressure: 83.2 kbar

Detonation Velocity: 17,700 fps

Measured Field Performance Specifications:

Specific Gravity: 1.12

Detonation Velocity: 12,800 fps @ 1¼" dia.

11,300 fps @ 7/8" dia.

8,400 fps @ ½" dia.

Estimated Field Performance Pressures:

Maximum Detonation Pressure: 74 kbar

(adjusted to 1.12 Specific Gravity)

Borehole Pressure: 37 kbar

(0.5 Max. Detonation Pressure)

Detonation Pressure at a Detonation Velocity of 8,400 fps.

Cook's Approximation: 18.3 kbar
Brown's Approximation: 17.4 kbar
Dick's Approximation: 17.6 kbar

Note: Explosive used in tests was approximately 60% weight strength.

APPENDIX B

FRAGMENTATION INDICES FOR ALL TEST BLASTS

TABLE B-I

FRAGMENTATION INDICES FOR TEST BLASTS

BLAST NO.	TYPE	AIR-TO-EXPLOSIVE VOLUME RATIO	F_c INDEX	F_{+3} INDEX	$F_{-3/4}$ INDEX
A-67	decoupled	0.69	0.669	2.007	0.188
W-67	water-coupled	----	0.620	1.492	0.221
A-80	complete coupling	0.0	0.619	1.447	0.243
B-1	complete coupling	0.0	0.632	1.703	0.174
B-2	air-gapped (12")	0.30	0.718	3.110	0.116
B-3	air-gapped (6")	0.15	0.669	2.078	0.157
B-4	air-gapped (5.2")	0.15	0.657	1.729	0.153
B-5	air-gapped (9.2")	0.30	0.691	2.346	0.143
*A-57	decoupled	1.50	0.708	3.070	0.109

* Test Blast, A-57, performed by Warden (1983)

Note: Higher degree of fragmentation with:

1. decreasing F_c index
2. decreasing F_{+3} index
3. increasing $F_{-3/4}$ index

TABLE B-II

FRAGMENTATION INDEX, F_c, AND ASSOCIATED POWDER FACTORS FOR SMITH (1976) TEST BLASTS

SHOT	F_C INDEX	POWDER FACTOR, lb/ton
1	0.637	0.536
2	0.699	0.414
3	0.720	0.338
4	0.650	0.572
5	0.650	0.447
6	0.719	0.360
7	0.711	0.466
8	0.774	0.280
9	0.613	0.665
10	0.576	0.495
11	0.649	0.495
12	0.658	0.503
13	0.664	0.503

TABLE B-III

FRAGMENTATION INDEX, F_c, FOR TEST BLASTS PERFORMED BY WARDEN (1983)

BLAST NO.	AIR-TO-EXPLOSIVE VOLUME RATIO	F_c INDEX
A-57	1.50	0.708
A-47	2.95	0.738
A-40	4.69	0.735
A-33	7.44	0.732
A-28	10.69	0.738
W-57	1.50	0.655
W-40	4.69	0.684
W-33	7.44	0.713
W-28	10.69	0.712
W-15	40.69	0.734

Note: Blast Numbers beginning with A- are decoupled tests, while those beginning with W- are water-coupled.

APPENDIX C

SCREEN ANALYSES FOR ALL TEST BLASTS PERFORMED IN THIS STUDY

TABLE C-I

SCREEN ANALYSES OF TEST BLAST FRAGMENTATION

				Fragment Size Fraction (inches)					
Blast No.	Specification	-3/16	+3/16-3/8	+3/8-3/4	+3/4-1½	+1½-3	+3-6	+6-12	+12
A-67	Weight (lb)	240	207	257	366	409	822	996	1151
	Weight (%)	5.4	4.7	5.8	8.2	9.2	18.5	22.4	25.9
W-67	Weight (lb)	227	230	312	423	514	982	1073	491
	Weight (%)	5.3	5.4	7.3	10.0	12.1	23.1	25.2	11.6
A-80	Weight (lb)	271	171	245	335	415	657	914	509
	Weight (%)	7.7	4.9	7.0	9.5	11.8	18.7	26.0	14.5
B-1	Weight (lb)	82	262	433	578	586	1444	1562	299
	Weight (%)	1.6	5.0	8.3	11.0	11.2	27.5	29.8	5.7
B-2	Weight (lb)	128	252	299	474	435	1098	2155	1685
	Weight (%)	2.0	3.9	4.6	7.3	6.7	16.8	33.0	25.8
B-3	Weight (lb)	92	220	275	393	424	990	1106	821
	Weight (%)	2.1	5.1	6.4	9.1	9.8	22.9	25.6	19.0
B-4	Weight (lb)	99	156	226	368	477	695	1078	519
	Weight (%)	2.7	4.3	6.3	10.2	13.2	19.2	29.8	14.3

TABLE C-I (continued)

SCREEN ANALYSES OF TEST BLAST FRAGMENTATION

Blast No.	Specification	Fragment Size Fraction (inches)							
		-3/16	+3/16-3/8	+3/8-3/4	+3/4-1½	+1½-3	+3-6	+6-12	+12
B-5	Weight (lb)	151	155	234	310	438	574	1634	814
	Weight (%)	3.5	3.6	5.4	7.2	10.2	13.3	37.9	18.9

APPENDIX D

RECORDED PEAK PARTICLE VELOCITIES FOR EACH TEST BLAST, IN THREE ORTHOGONAL DIRECTIONS

TABLE D-I

RECORDED PEAK PARTICLE VELOCITIES FOR EACH TEST BLAST, IN THREE ORTHOGONAL DIRECTIONS*

		Peak Particle Velocity, in/sec		
Blast No.	Type	Longitudinal	Vertical	Transverse
A-67	decoupled	0.56	0.48	0.60
W-67	water-coupled	0.30	0.70	0.45
A-80	completely-coupled	0.23	0.93	0.55
B-1	air-gapped	0.70	0.83	0.50
B-2	air-gapped	0.23	0.23	0.30
B-3	air-gapped	0.35	0.45	0.33
B-4	air-gapped	0.40	0.90	0.28
B-5	air-gapped	0.45	0.50	0.75
**A-57	decoupled	0.20	0.40	0.30

*Scaled distance = 23.3 $ft/lb^{1/2}$ for all tests.

**Warden Shot (A-57), (1983).

APPENDIX E

PHOTOGRAPHS, BURDEN-ROCK CONTOURS, AND VERTICAL SECTIONS FOR TEST BLASTS

LEGEND

Symbol	Explanation
S	Spacing between blastholes.
L	Length of blasthole above grade.
B	Burden
B_{ave}	Mean burden of pattern determined by planimetering vertical sections.
B_1, B_2, B_3	Direction of burden measurement for indicated vertical section.
XXXXXXXX	Crest of bench, pre-blast.
___5____	Contour of free face, pre-blast, inches above grade level.
---10----	Contour of free face, post-blast, inches above grade level.
●	Blasthole.

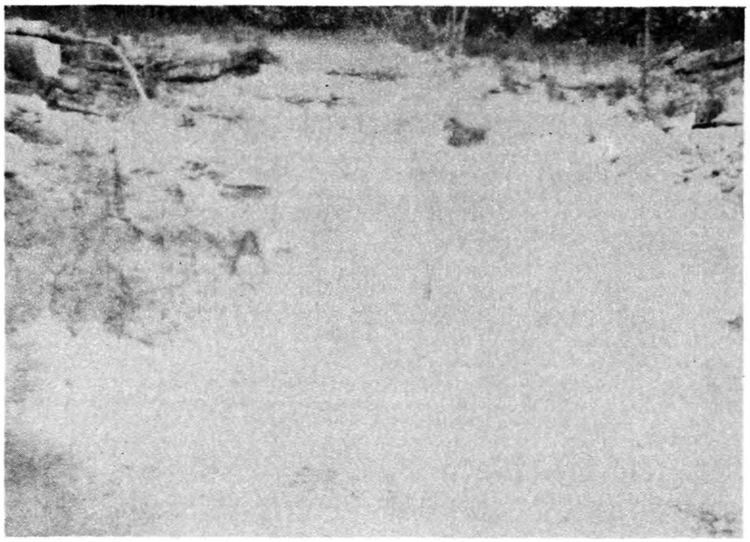

Figure E-1. Bench for Test A-67 Before Blasting

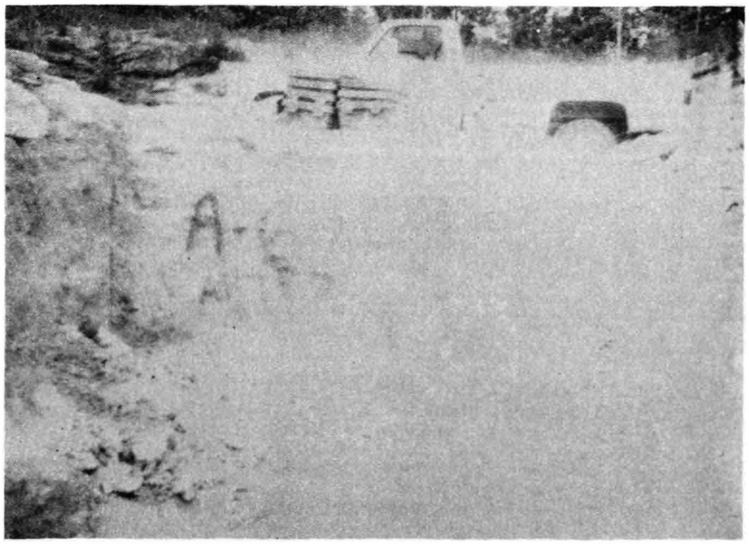

Figure E-2. Bench for Test A-67 After Blasting

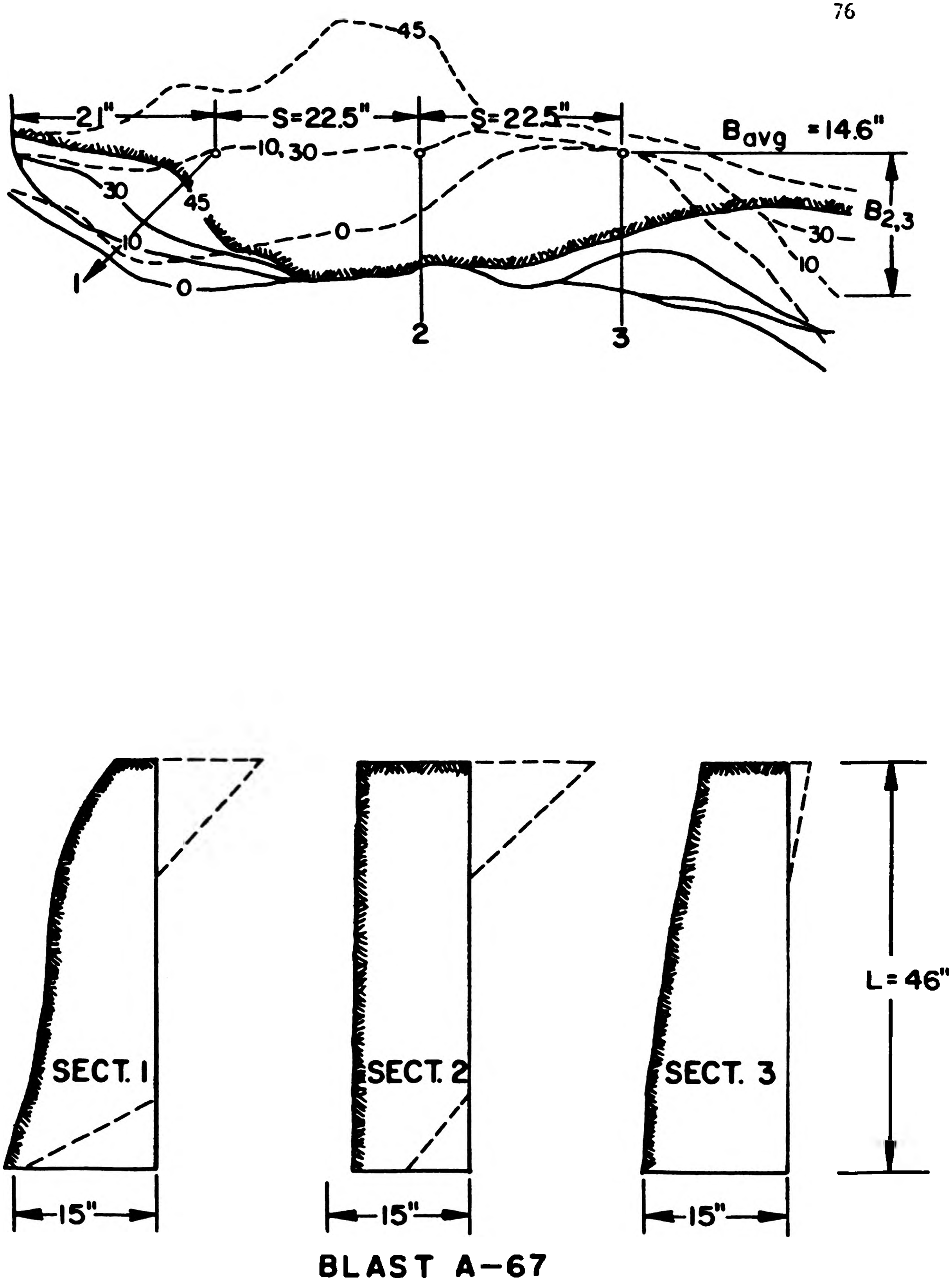

Figure E-3. Burden-Rock Contour and Vertical Sections for Test A-67

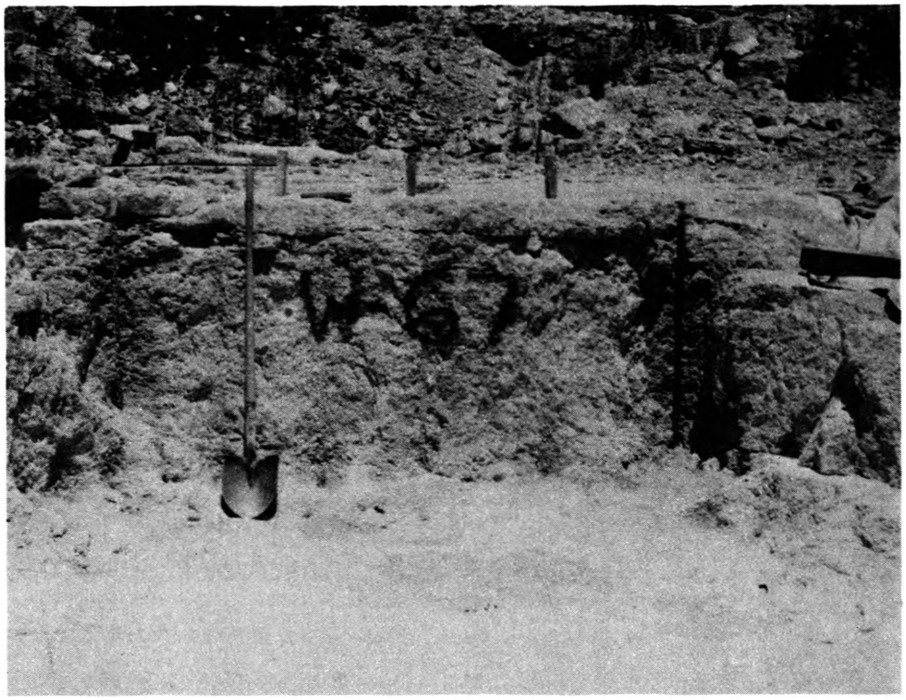

Figure E-4. Bench for Test W-67 Before Blasting

Figure E-5. Bench for Test W-67 After Blasting

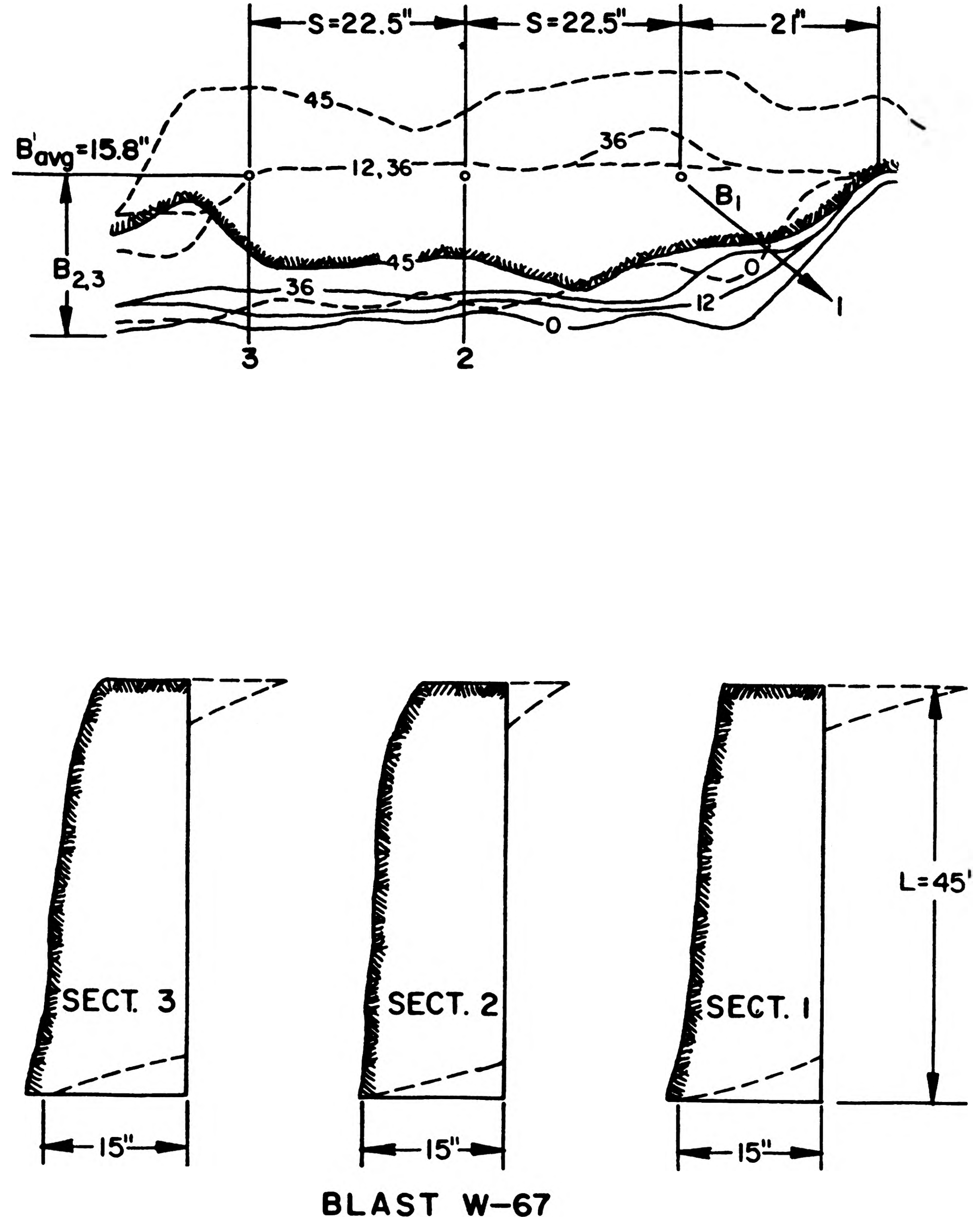

Figure E-6. Burden-Rock Contour and Vertical Sections for Test W-67

Figure E-7. Bench for Test A-80 Before Blasting

Figure E-8. Bench for Test A-80 After Blasting

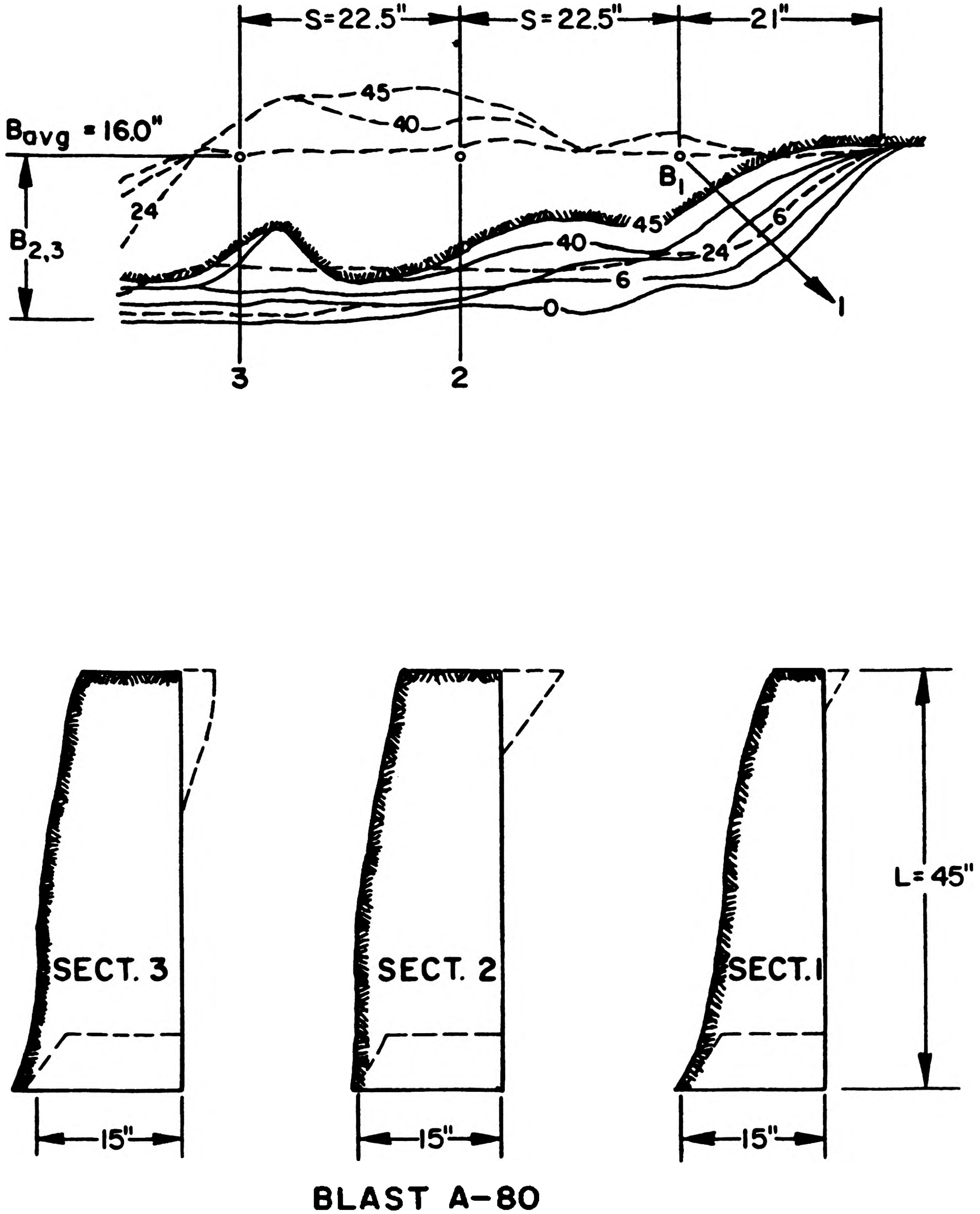

Figure E-9. Burden-Rock Contour and Vertical Sections for Test A-80

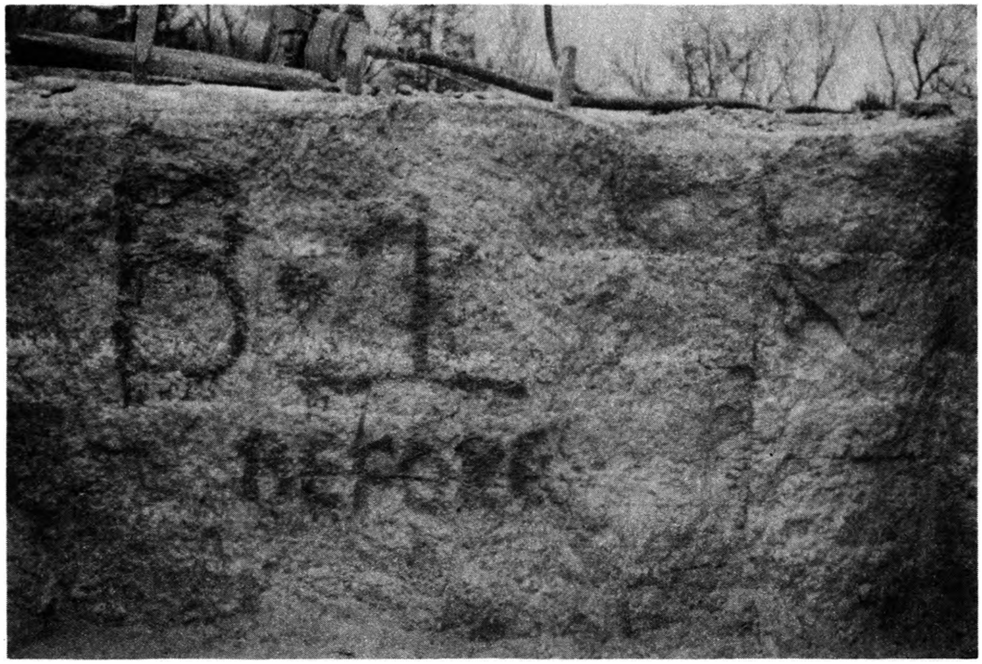

Figure E-10. Bench for Test B-1 Before Blasting

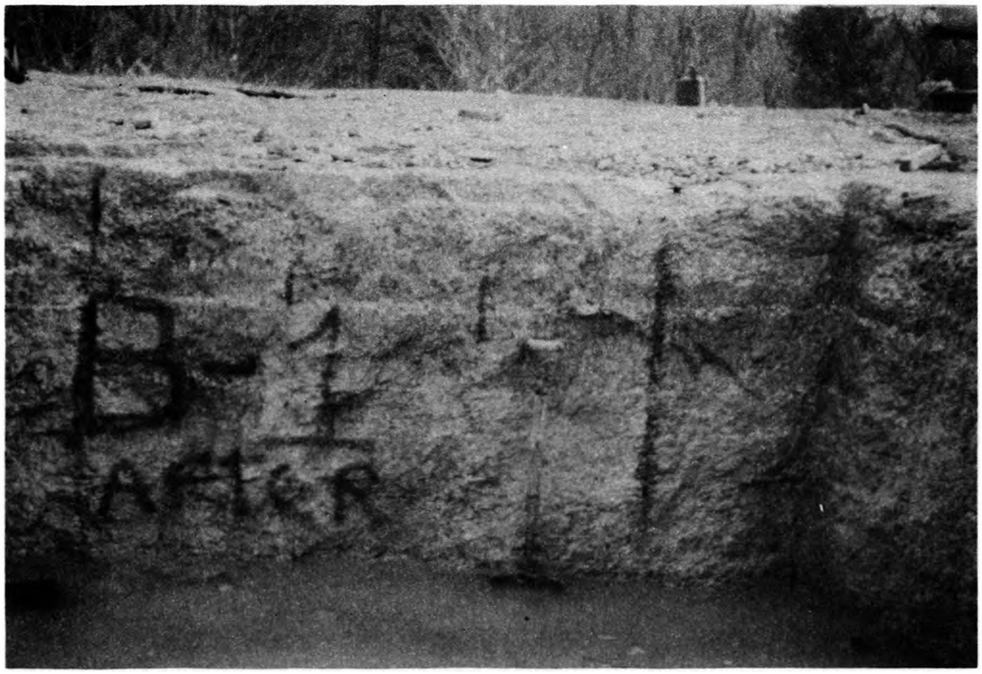

Figure E-11. Bench for Test B-1 After Blasting

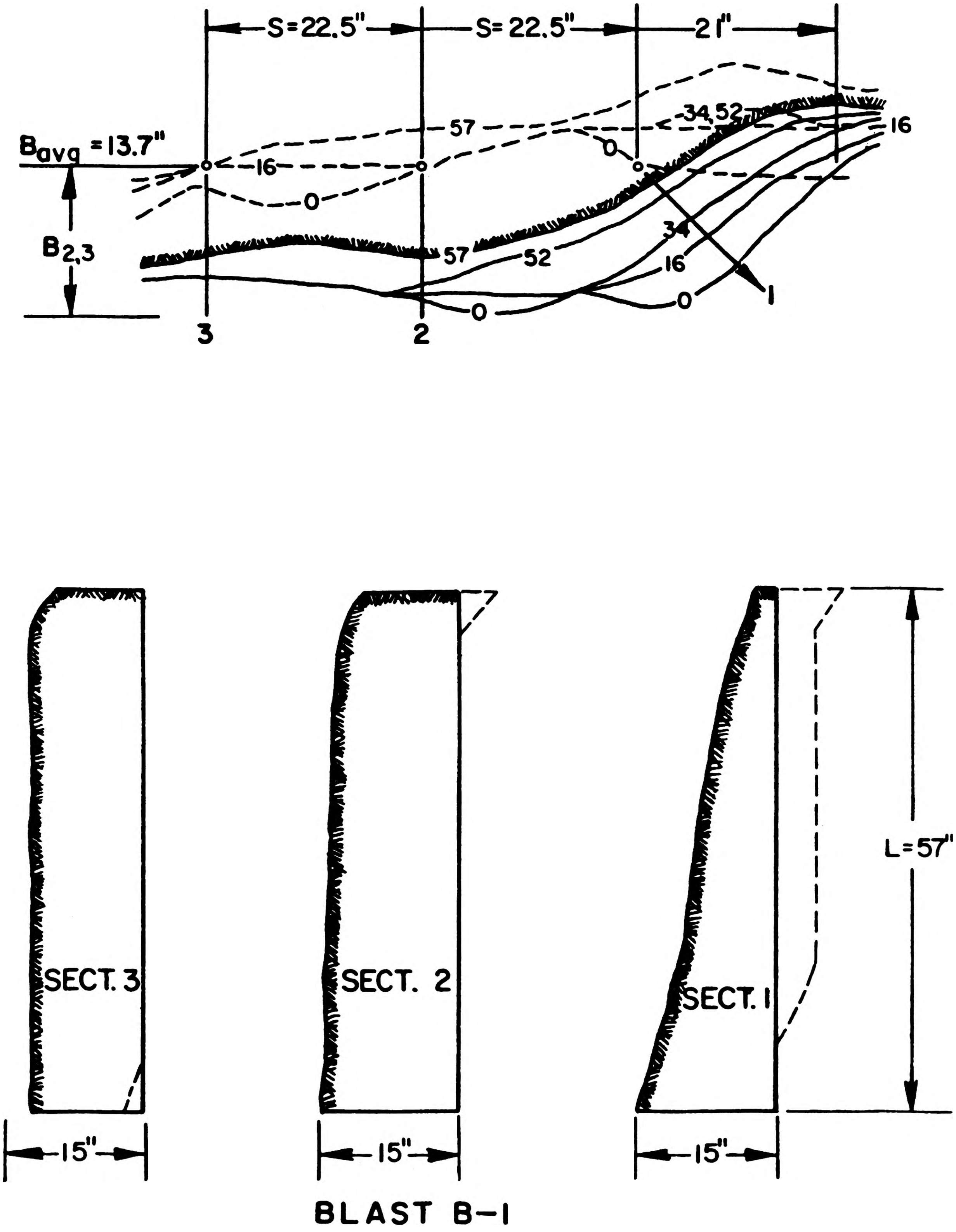

Figure E-12. Burden-Rock Contour and Vertical Sections for Test B-1

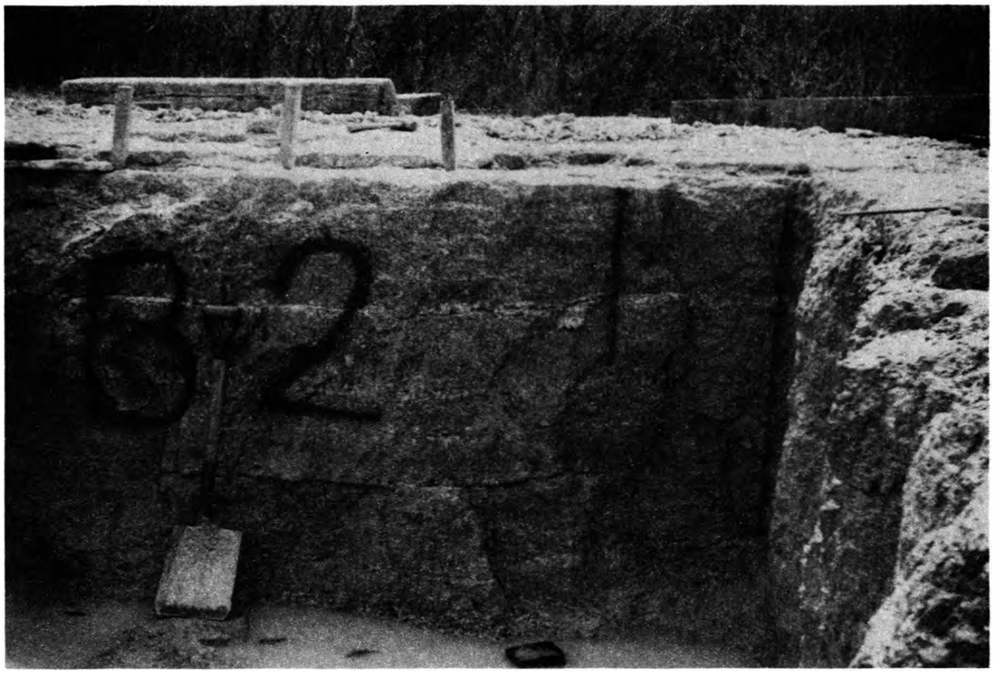

Figure E-13. Bench for Test B-2 Before Blasting

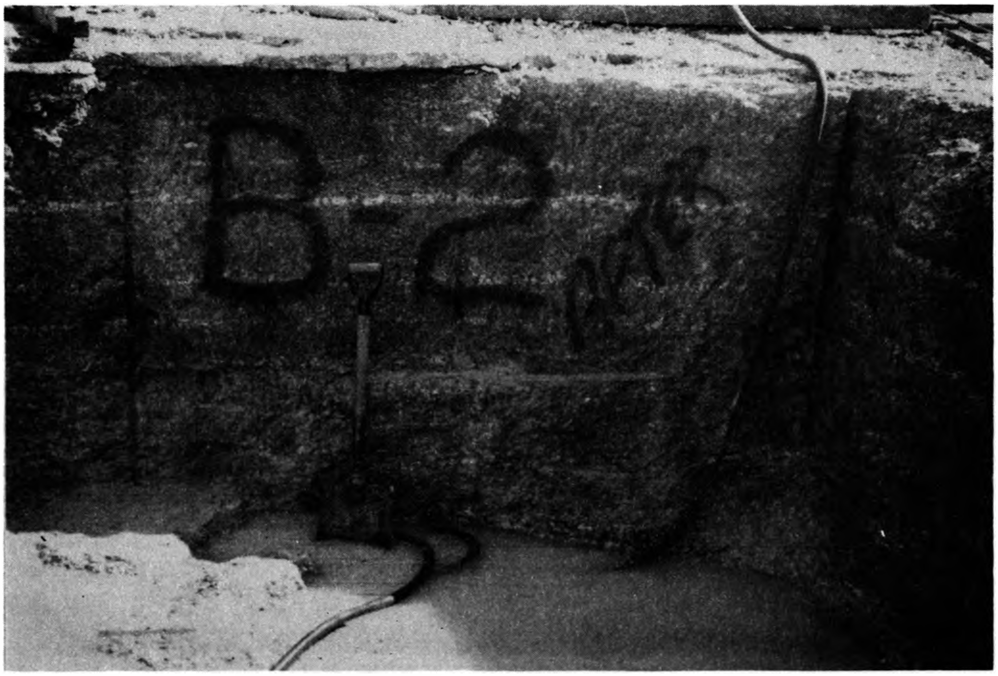

Figure E-14. Bench for Test B-2 After Blasting

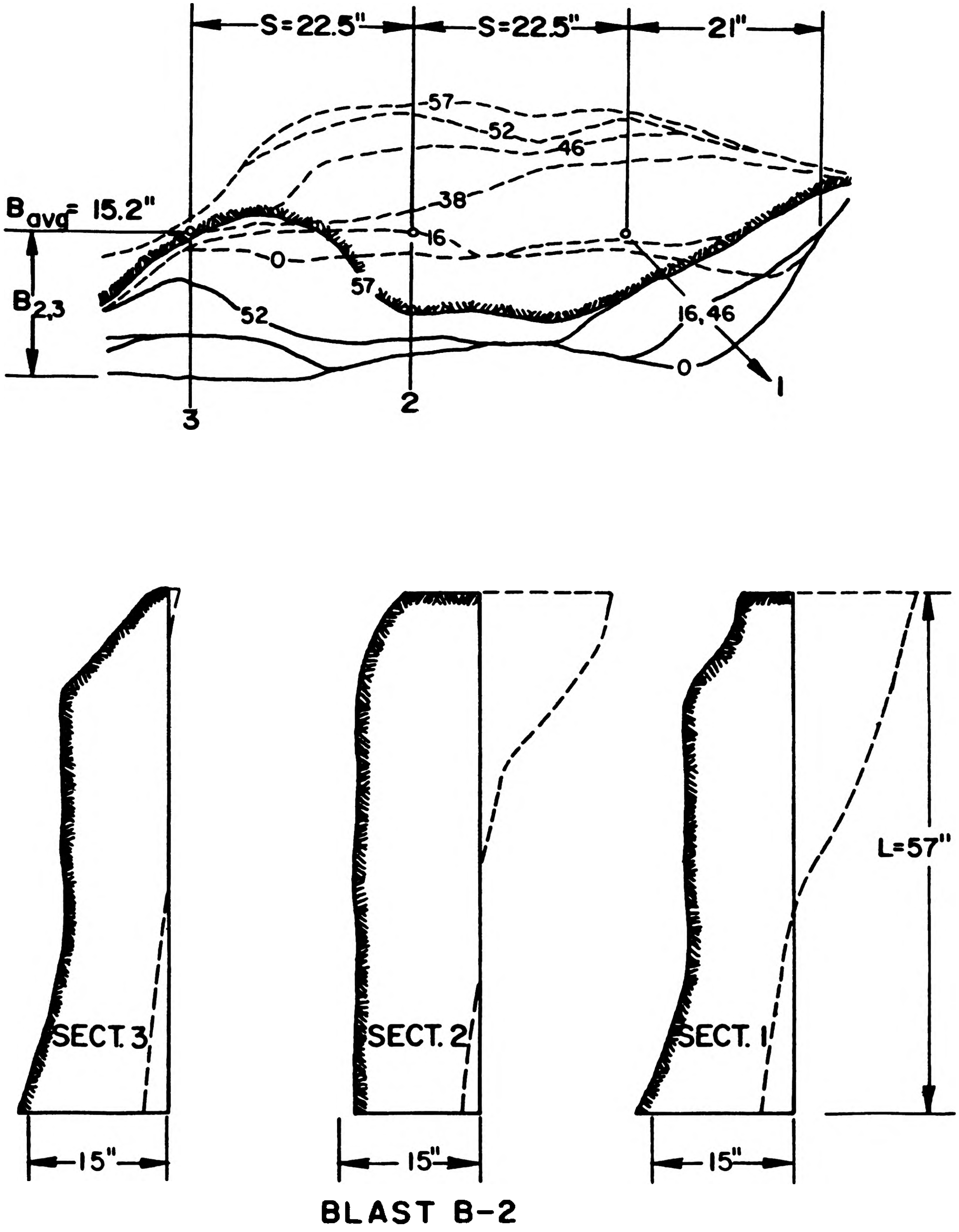

Figure E-15. Burden-Rock Contour and Vertical Sections for Test B-2

Figure E-16. Bench for Test B-3 Before Blasting

Figure E-17. Bench for Test B-3 After Blasting

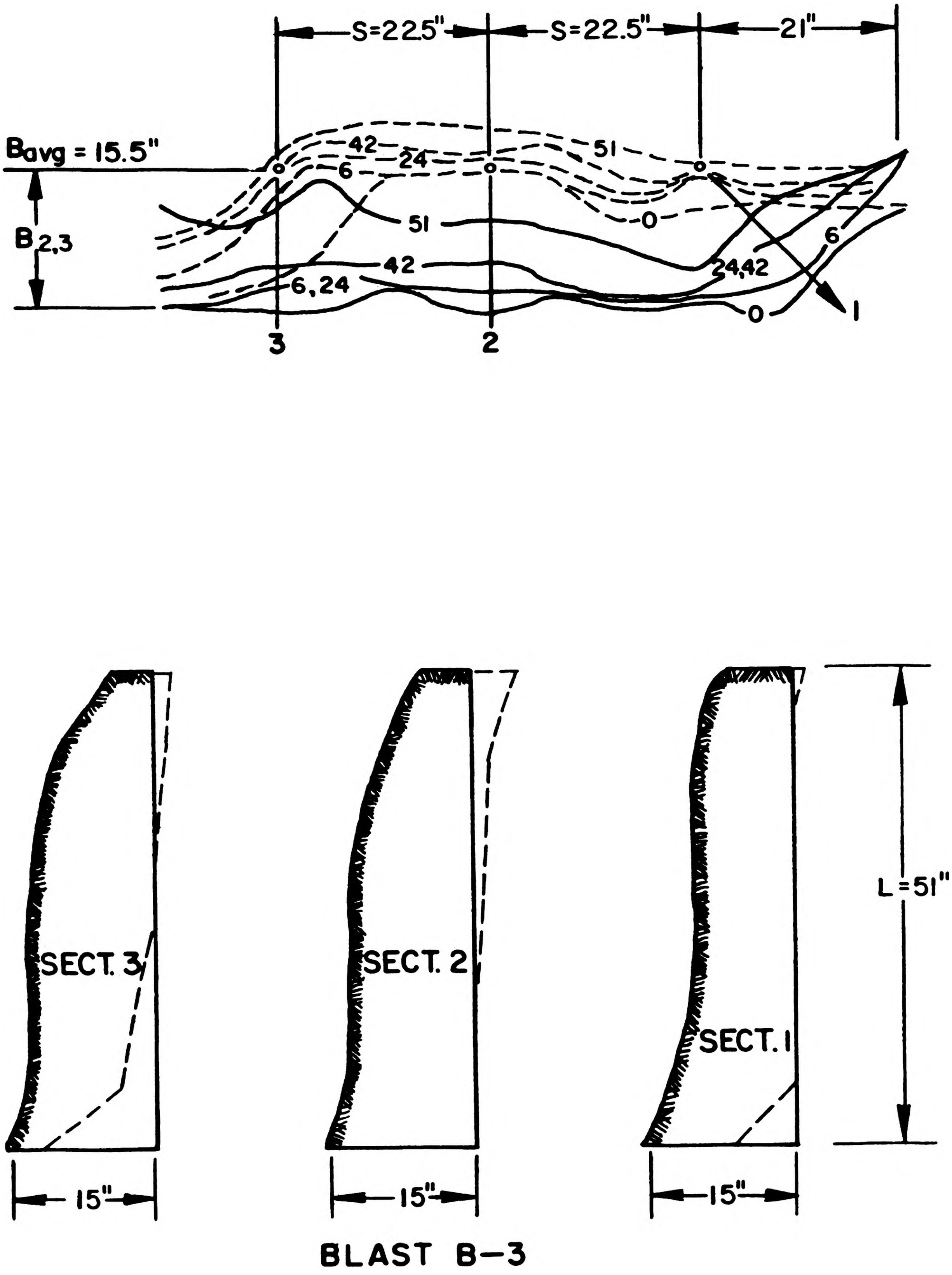

Figure E- 18 Burden-Rock Contour and Vertical Sections for Test B-3

Figure E-19. Bench for Test B-4 Before Blasting

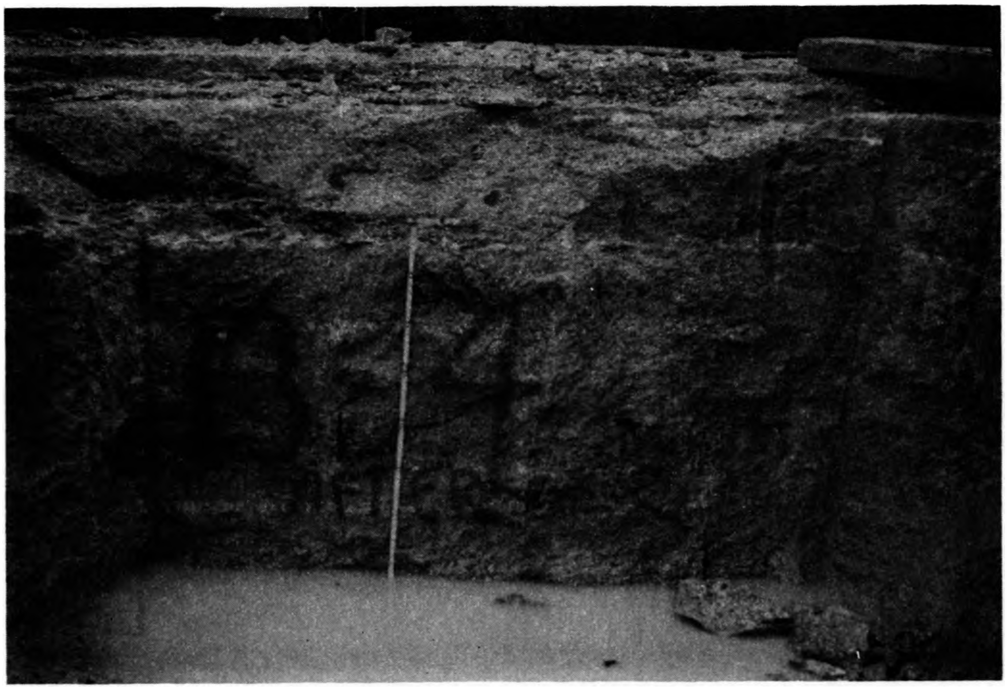

Figure E-20. Bench for Test B-4 After Blasting

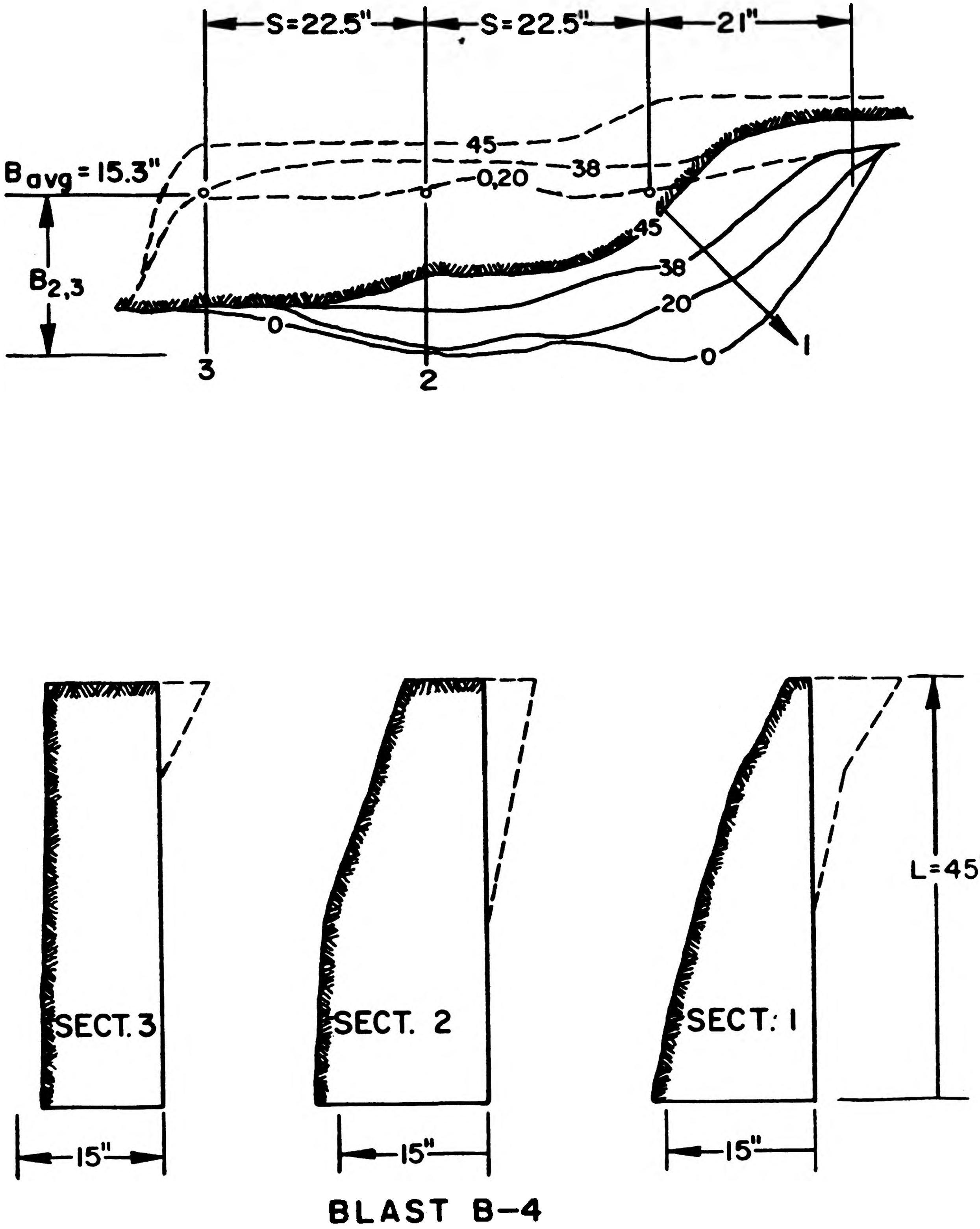

Figure E-21. Burden-Rock Contour and Vertical Sections for Test B-4

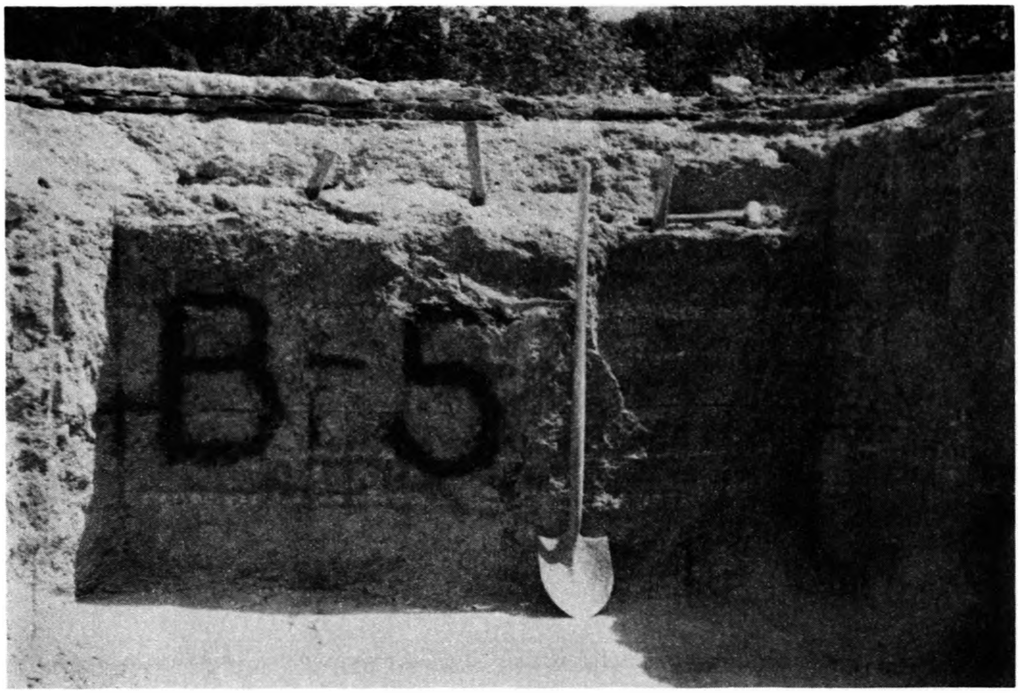

Figure E-22. Bench for Test B-5 Before Blasting

Figure E-23. Bench for Test B-5 After Blasting

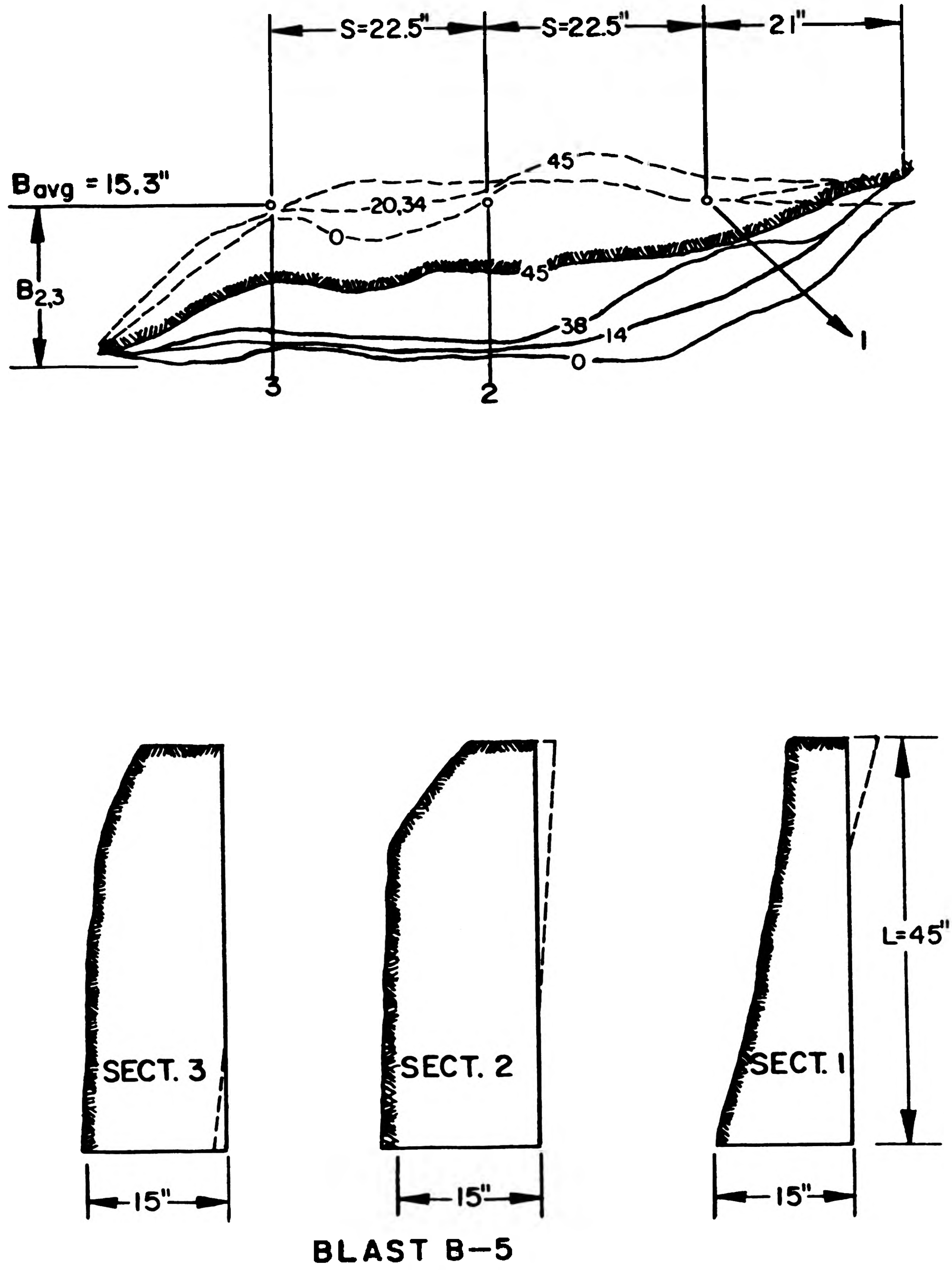

Figure E-24. Burden-Rock Contour and Vertical Sections for Test B-5

APPENDIX F

RESULTS FOR ROCK-YIELD, OVERBREAK, AND TOE FOR TEST BLASTS

TABLE F-I

RESULTS FOR ROCK-YIELD, OVERBREAK, AND TOE FOR TEST BLASTS

Blast No.	Design Weight (lb)	In Situ Weight (lb)	Broken Weight (lb)	Variance of Actual Weight From Design (percent)	Percent of Design Weight			
					Back-break	End-break	Total Over-break	Toe
A-67	4290	4268	4448	-3.7	+4.0	+14.2	+18.2	-2.2
W-67	4290	4077	4252	+0.9	+5.0	+6.5	+11.5	-7.1
A-80	4290	3233	3517	+18.0	+3.5	+4.7	+8.2	-11.7
B-1	5434	5218	5246	+3.5	+17.8	+2.9	+20.7	-0.2
B-2	5434	6377	6526	-20.1	+18.8	+0.4	+19.2	-3.6
B-3	4862	4027	4321	+11.1	+3.5	+1.1	+4.6	-5.1
B-4	4290	3867	3618	+15.7	+10.8	-0.5	+10.3	0.0
B-5	4290	4213	4310	-0.5	+5.0	+7.7	+12.7	-2.1