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FIELD EVALUATION OF FRACTURE CONTROL IN TUNNEL BLASTING

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16. Abstract

This report describes the procedures and results of field tests of fracture control, a procedure for achieving fracture plane control in tunnel blasting. Fracture control procedures modify conventional drill and blast techniques in three ways. First, side notches extending the length of the drill hole are employed to control the initiation site for the cracks which produce the fracture plane. Second, the pressure in the drill hole is maintained between specified limits by using cushioned charges of low explosive. Third, stemming length is increased to avoid venting which could cause premature arrest of the crack producing the controlled fracture plane.

The results of the test program indicate that, when compared with conventional smooth blasting techniques, fracture control techniques offer the advantages of (1) reduction of the number of perimeter holes and the amount of explosive used, (2) improved structural integrity of the remaining rock, (3) reduction in overbreak, and (4) reduction in vibration levels resulting from perimeter hole detonations.

When applied to opening cuts, it was found that fracture control techniques can reduce the number of holes and the amount of explosives as compared with conventional methods, while maintaining equivalent vibration levels and advance.

More field testing should be carried out to (1) test the fracture control procedures and document blasting design parameters in various rock types, and (2) develop and test a single pass combination drill bit and notching tool to reduce the cost of notching the drill holes and make fracture control techniques more economically desirable.

17. Key Words
Blasting, tunnel, smooth blasting, perimeter control, fracture control, blasting vibrations, opening cut, explosives, overbreak

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16. Abstract

The objective of this research was to implement fracture control procedures in a tunnel project and to assess the practicality, advantages, disadvantages, performance and cost effectiveness of fracture control methods against smooth blasting procedures. This report describes the procedures and results of field tests of fracture control--a procedure for achieving fracture plane control in tunnel blasting. It describes and discusses the project and site geology, the theory and applications of fracture control blasting, and the experimental procedures used. The report provides conclusions and recommendations for future research. The procedures and results of an experimental smooth blasting round utilizing milli-second delay detonating caps are described in Appendix A.

The results of the test program indicate that, when compared with conventional smooth blasting techniques, fracture control techniques offer the advantages of reduction of number of perimeter holes and amount of explosives used; improved structural integrity of remaining rock; reduction in overbreak; and reduction in vibration levels resulting from perimeter hole detonations. When applied to opening cuts, it was found that fracture control techniques can reduce the number of holes and the amount of explosives as compared with conventional methods, while maintaining equivalent vibration levels and advance. The authors recommend more field testing of these procedures and documentation of blasting design parameters in various rock types, and developing a single pass combination drill bit/notching tool to reduce cost of notching drill holes and make fracture control techniques economically desirable.

17. Key Words
Tunneling
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Explosives
Overbreak
Fracture Control
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Rail/Construction
Smooth Blasting
Perimeter Control

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PREFACE

This research was part of a program sponsored by the Office of Rail and Construction Technology, Office of Technology Development and Deployment, Urban Mass Transportation Administration (UMTA) of the U.S. Department of Transportation (DOT). The goal of the program is to find methods of reducing underground construction costs. The report presented herein was prepared by Haley & Aldrich, Inc. under contract No. DOT-TSC-1579, managed by the Transportation Systems Center (TSC), Cambridge, Massachusetts.

The Massachusetts Bay Transportation Authority (MBTA) is the owner of the tunnel. They provided the work site and compensated the contractor for special materials and delay time associated with the experiments. Station designers are Cambridge Seven Associates, Inc., Cambridge, Massachusetts. Perini Corporation of Framingham, Massachusetts, performed the work under contract to the MBTA.

The assistance and cooperation of Mr. Paul Witkiewicz, DOT/TSC Technical Monitor, and Mr. Edward Rickley, head of the DOT/TSC Noise Measurement and Assessment Laboratory, were greatly appreciated. Also deserving of recognition for their cooperation in carrying out the research are Mr. Ronald Tarallo, MBTA resident engineer at the site, and Messrs. Roger Borggaard, James Aceto, and Steve Moore of Perini Corporation.

Special thanks go to Professor James Dally, Dean of Engineering, University of Rhode Island and Professors Donald Barker and David Holloway of the University of Maryland, for their assistance in planning and executing the experiments.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol

LENGTH

in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km

AREA

in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha

MASS (weight)

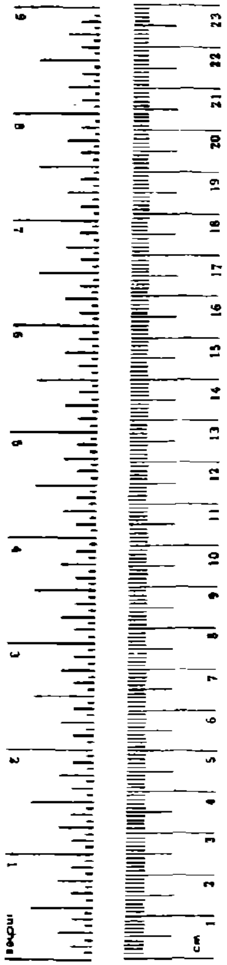
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t

VOLUME

tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3

TEMPERATURE (exact)

°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol

LENGTH

mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi

AREA

cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	

MASS (weight)

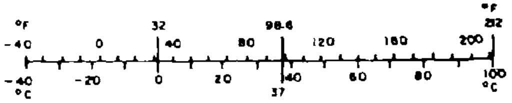
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	

VOLUME

ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3

TEMPERATURE (exact)

°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1. INTRODUCTION

1.1 BACKGROUND

Underground drill and blast excavation is usually accomplished with small diameter holes loaded with high energy explosives. The detonation pressures are extremely high and an extensive amount of energy is dissipated in the process; however, very little of this energy is used to create the desired fracture planes required for excavation. The available energy is expended in crushing the adjacent rock, in producing a dense, randomly oriented radial crack pattern about the holes, and in producing radially outgoing stress waves. This causes several undesirable effects:

a. Overbreak at the excavation perimeter, which results in more muck to remove and extra concrete or shotcrete to fill the voids.

b. Damage to or loosening of the remaining rock at the perimeter which may require additional support.

c. Ground vibrations and air blast, which could result in damage to nearby structures and complaints by people living or working in the area.

Several steps may be taken to minimize these effects. Where control of the perimeter is desired, smooth blasting techniques are generally employed, in which the spacing and burden of perimeter holes are reduced and lighter, decoupled charges are used. Where vibration damage to structures is feared, control is generally exercised by limiting the charge weight per delay period so that the ground vibrations at the nearest structure do not exceed a peak particle velocity of two inches per second. Where blasting complaints may be a problem, control may be a more complex task, since the human body can sense vibrations and noise levels that are significantly lower than those necessary to cause structural damage.

A modified drill and blast process, denoted herein as fracture control blasting, has been developed (1,2) to aid in controlling the undesirable blasting effects noted above. In this procedure, drill holes are grooved and loaded with very light, cushioned column charges and a concentrated bottom charge. By properly stemming the drill holes to confine the explosive gases, crack propagation will result between widely spaced drill holes. When utilized in perimeter holes, fracture control procedures offer the following advantages over smooth blasting:

a. Improved structural integrity of the remaining rock;

b. Improved ability to control the excavation dimensions; and

c. Reduction of the number of holes drilled and the amount of explosive used.

When utilized in the opening cut holes (which often produce the maximum vibrations within a given round), fracture control procedures can reduce the number of holes and the amount of explosive used, and thus may reduce the resulting maximum vibrations.

In addition to the undesirable effects noted above, the cost of drill and blast tunnel construction has increased rapidly in recent years. As a result, the Urban Mass Transit Administration (UMTA) is seeking methods to reduce underground construction costs. Fracture control in tunnel blasting has the potential to favorably affect the cost of hard rock tunnel construction. The procedure has been tested in the laboratory and has had limited field testing. It was felt by the investigators that the procedure warranted implementation on a test basis in an actual drill and blast tunnel project. In this program, fracture control procedures were tested in an actual pilot tunnel constructed in Porter Square, Cambridge, Massachusetts, as part of the Massachusetts Bay Transportation Authority (MBTA) Red Line Extension Northwest (see Section 2).

1.2 OBJECTIVES

The objective of this research was to implement fracture control procedures in a tunnel project and to assess the practicality, advantages, disadvantages, performance and cost effectiveness of fracture control methods as compared to smooth blasting procedures. To ensure a valid comparison of the two techniques, it was necessary to determine through experimentation the optimum smooth blasting technique for the site. Factors affecting the performance of the fracture control procedure, practical limitations, equipment and material requirements were defined.

During the experimental program, another area of investigation was added: utilizing millisecond delay detonating caps in conjunction with smooth blasting techniques to reduce the human response to blasting.

1.3 ORGANIZATION OF THE REPORT

In the next two sections, the project and the site geology are described. Following that is a discussion of the theory and applications of fracture control blasting. The experimental procedures used are described in Section 5. The experimentation was divided into two parts: perimeter control and opening cuts. The results of each of these are described in Sections 6 and 7, respectively. Conclusions are presented in Section 8, and finally, recommendations are made for future research. The procedures and results of an experimental smooth blasting round utilizing millisecond delay detonating caps are described in Appendix A.

2. PROJECT DESCRIPTION

The proposed Porter Square Station in Cambridge, Massachusetts will be constructed as a mined chamber in bedrock and is part of an underground rapid transit system extension being undertaken by the Massachusetts Bay Transportation Authority (MBTA). The pilot tunnel was excavated to expose geologic features at the crown of the proposed chamber and to evaluate the performance of the rock during drilling and blasting. The work was performed between November 1978 and February 1979 by Perini Corporation. The experimental work reported herein was directed and executed in accordance with the Blasting Test Program section of the MBTA contract specifications (MBTA Contract No. 091-301).

The project is located (Figure 2-1) in a densely populated, commercial-residential area in Cambridge, Massachusetts. The station lies beneath a major three-way street intersection, the parking lot of a medium-sized shopping center, and a Boston & Maine Railroad commuter rail line. Figure 2-2 shows two photographs of the site area.

The pilot tunnel has a 12 ft. (3.6 m) x 12 ft. (3.6 m) square cross section and is approximately 600 ft. (183 m) long (see Figure 2-3). Access to the tunnel is provided by a 23 ft. (7 m) diameter shaft, 87 ft. (27 m) deep (Figure 2-4). From the access shaft, there is an east-west access tunnel which leads to the main north-south pilot tunnel (Figure 2-3), where most of the experimental blasting was done. Rock cover over the pilot tunnel is approximately 30 ft. (9 m). The heading was drilled with two Gardner-Denver PR-123 drills on a Gardner Denver Mini-Bore jumbo (Figure 2-5). Mucking was done with an EIMCO model 912LHD loader with a 2.5 cu. yd. (1.9 cu. m) bucket (Figure 2-6). Figure 2-7 is a view of the north heading of the pilot tunnel.

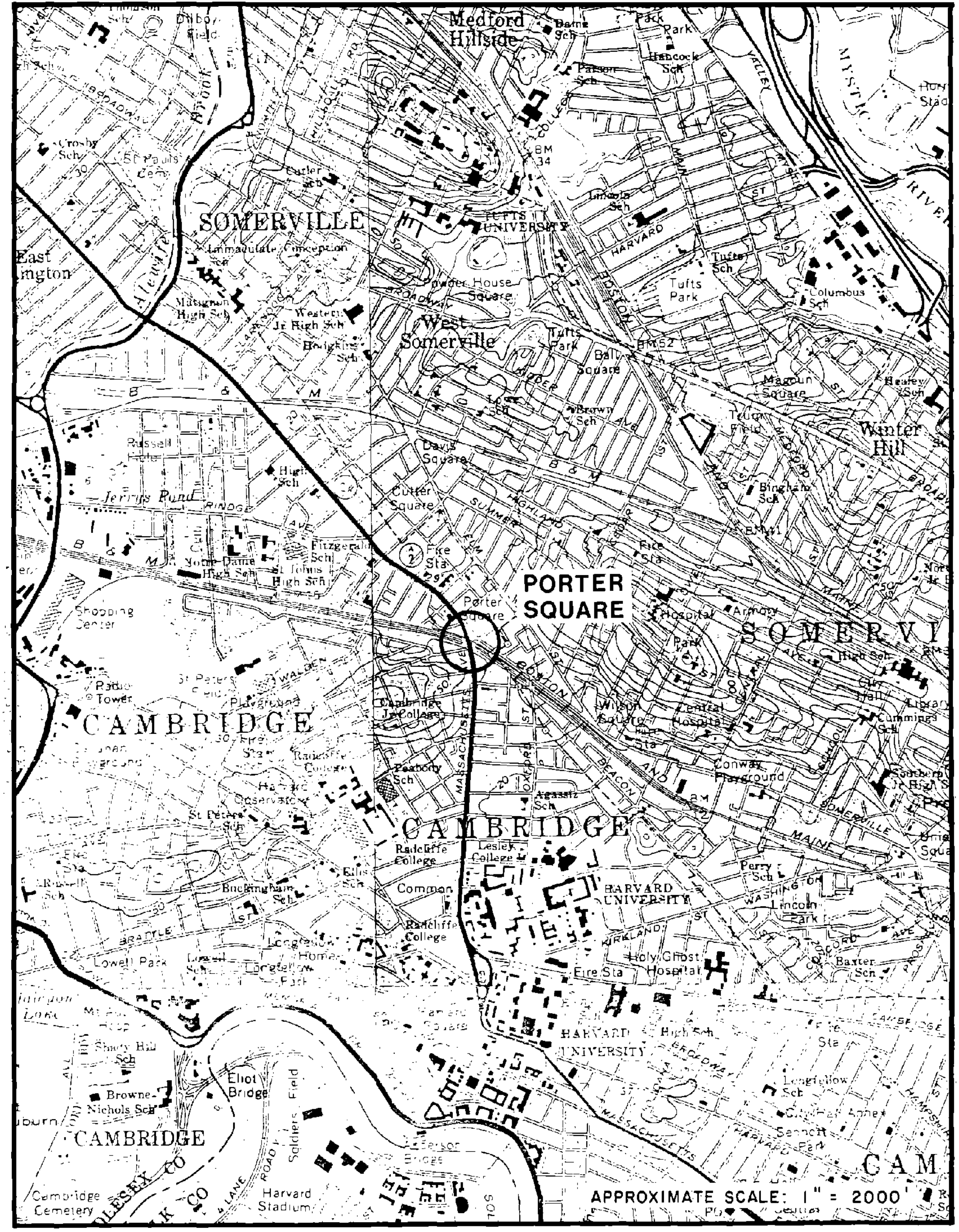
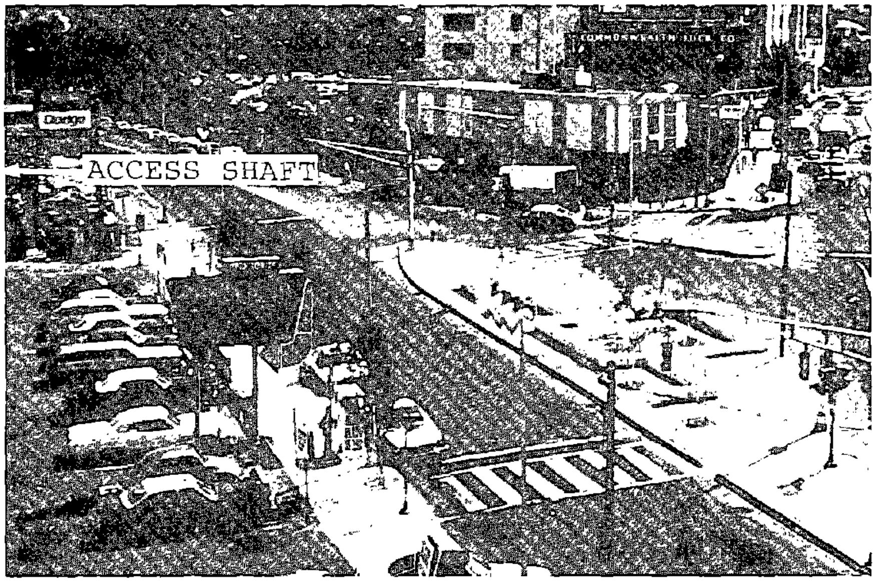


FIGURE 2-1. PROJECT LOCUS - PORTER SQUARE, CAMBRIDGE, MASSACHUSETTS

(a) Looking north towards Porter Square Shopping Center, pilot tunnel access shaft at right.



(b) Looking south, Massachusetts Avenue to right, Somerville Avenue to left.

FIGURE 2-2. VIEWS OF SITE AREA

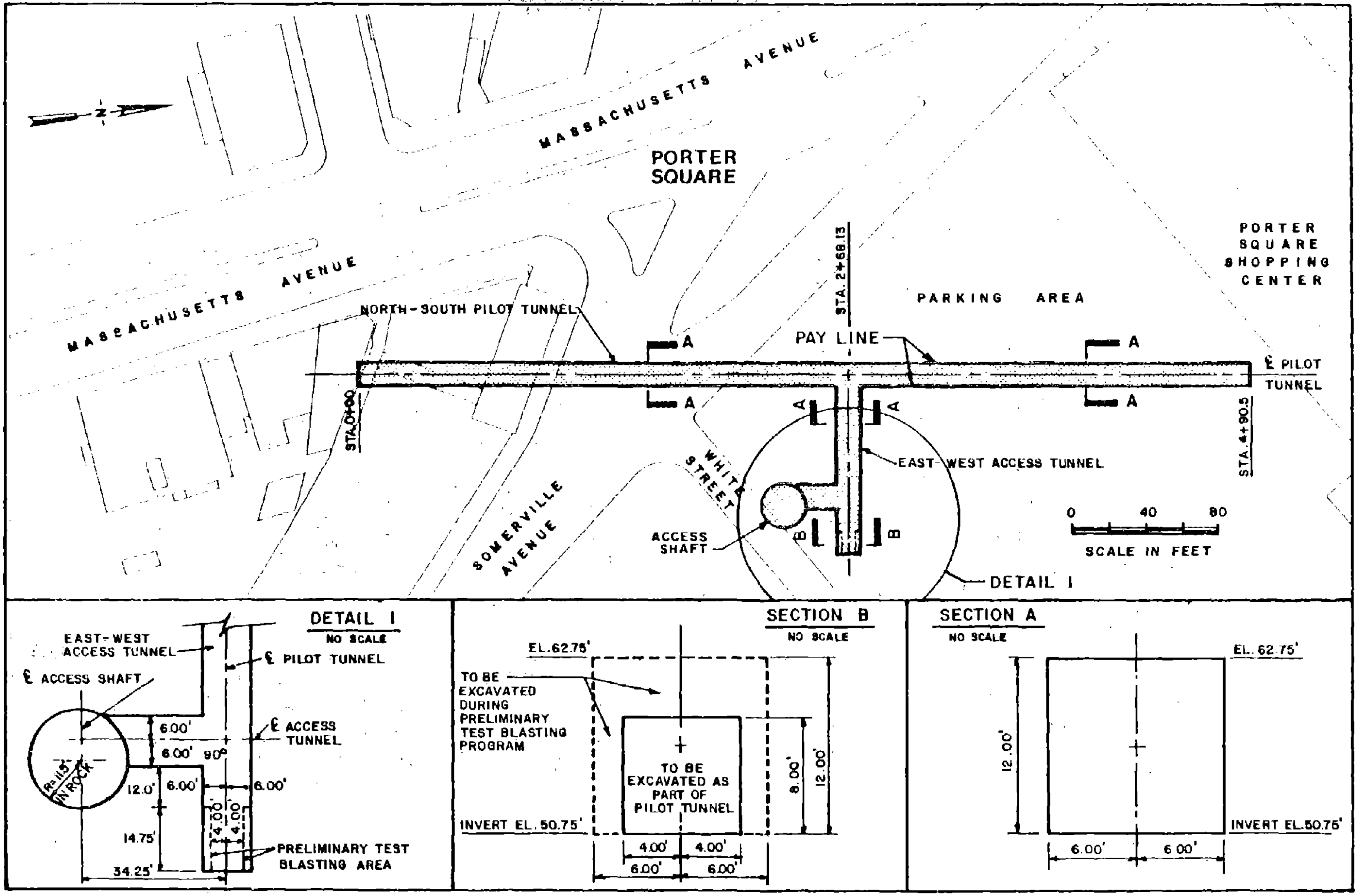


FIGURE 2-3. PILOT TUNNEL ALIGNMENT PLAN AND DETAILS

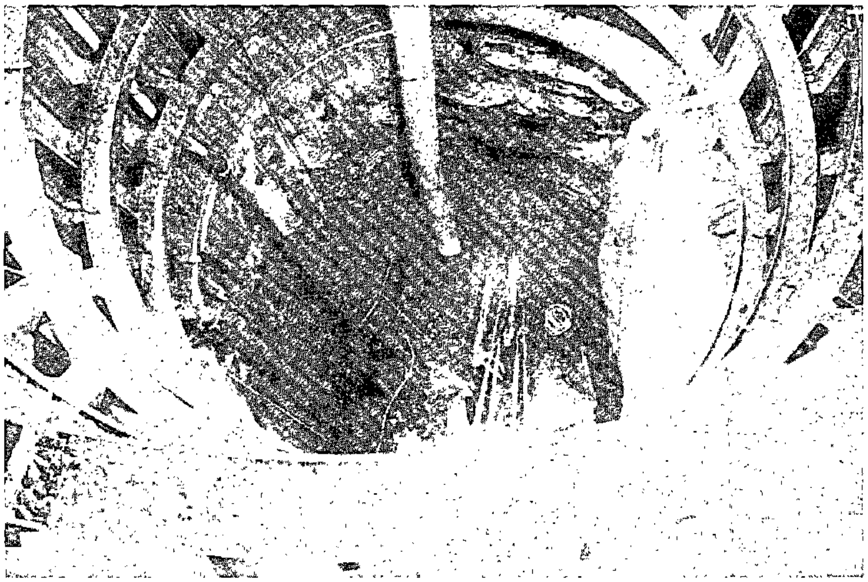


FIGURE 2-4. ACCESS SHAFT TO PILOT TUNNEL

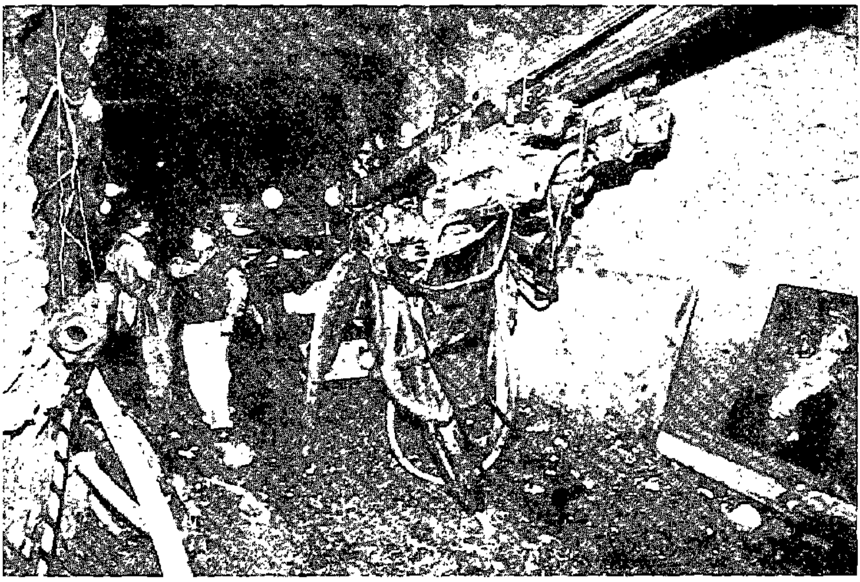


FIGURE 2-5. DRILLING JUMBO

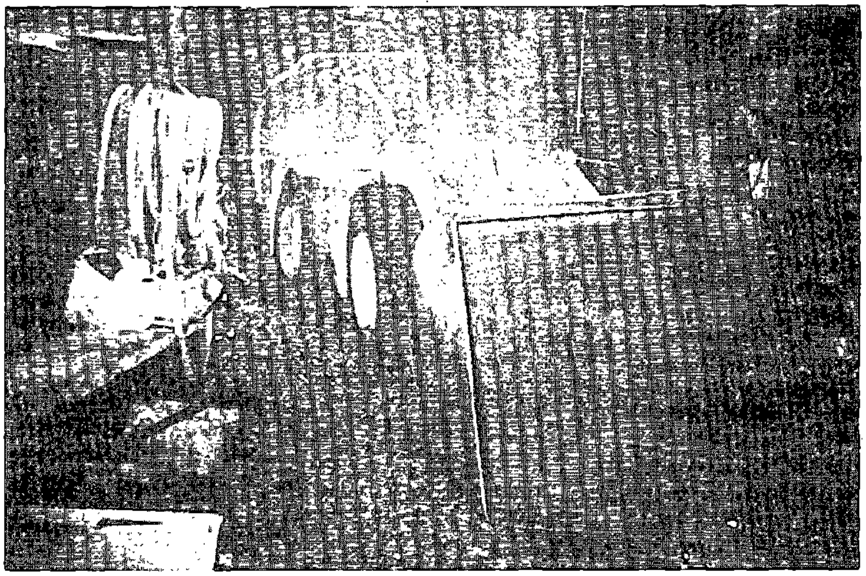


FIGURE 2-6. LOAD, HAUL, DUMP MACHINE USED FOR MUCKING TUNNEL

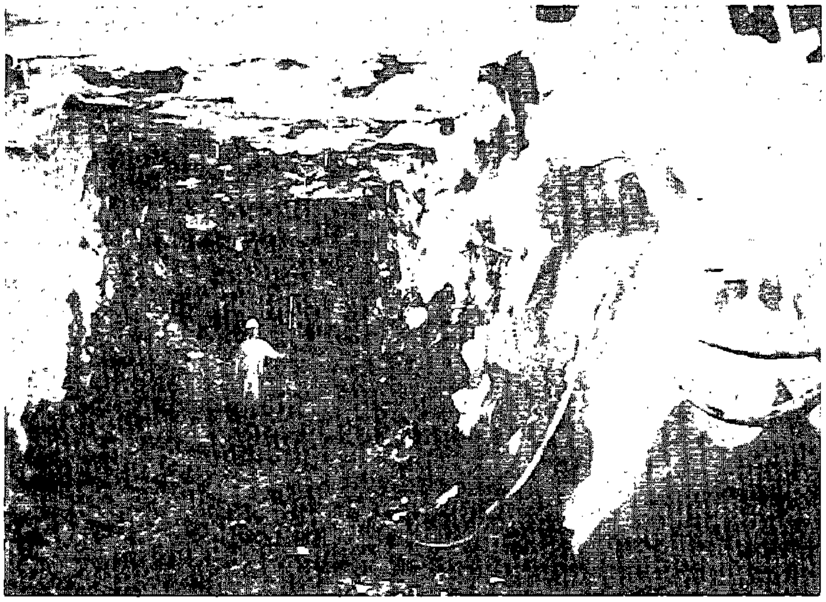


FIGURE 2-7. NORTH HEADING OF PILOT TUNNEL

3. SITE GEOLOGY

3.1 GENERAL

The pilot tunnel was constructed within a sedimentary rock formation known locally as the Cambridge Argillite. At the site, the rock is a slightly metamorphosed mudstone exhibiting rhythmic layering of alternating lighter and darker sediment layers. The rock is intruded frequently with dikes of igneous origin ranging from a few feet to several tens of feet in thickness.

Using the Terzaghi (3) classification, the rock mass may be described as moderately jointed to blocky and seamy. Typical index properties of the argillite are as follows:

Average Unit Weight = 172.6 lb/cu. ft. (2766. kg/cu. m)
Average RQD = 77%
Average Compressive Strength = 28,000 psi (193 MPa)
Average Schmidt Hardness = 54.4
Average Taber Abrasion Hardness = 1.32
Average Tangent Modulus ($E_{t_{50}} \times 10^6$) = 7.0

All but one fracture control round were conducted in the argillite. Fracture control round FC 7 was conducted in an igneous dike, petrographically described as an altered basalt, with the following typical index properties:

Average Unit Weight = 180.2 lb/cu. ft. (2888. kg/cu. m)
Average RQD = 91%
Average Compressive Strength = 20,000 psi (138 MPa)
Average Schmidt Hardness = 43.2
Average Taber Abrasion Hardness = 5.20
Average Tangent Modulus ($E_{t_{50}} \times 10^6$) = 9.4

Overlying bedrock is about 40 to 45 ft. (12 to 14 m) of overburden soil. The groundwater table is about 20 to 30 ft. (6 to 9 m) above the top of rock. Figure 3-1 shows a generalized geologic profile (Section A-A) through the main north-south pilot tunnel.

3.2 BEDROCK STRUCTURE

Bedding forms definite planes of weakness in the argillite and strikes approximately east-west and dips approximately 10° to the south. Joints in the argillite form three generalized groups:

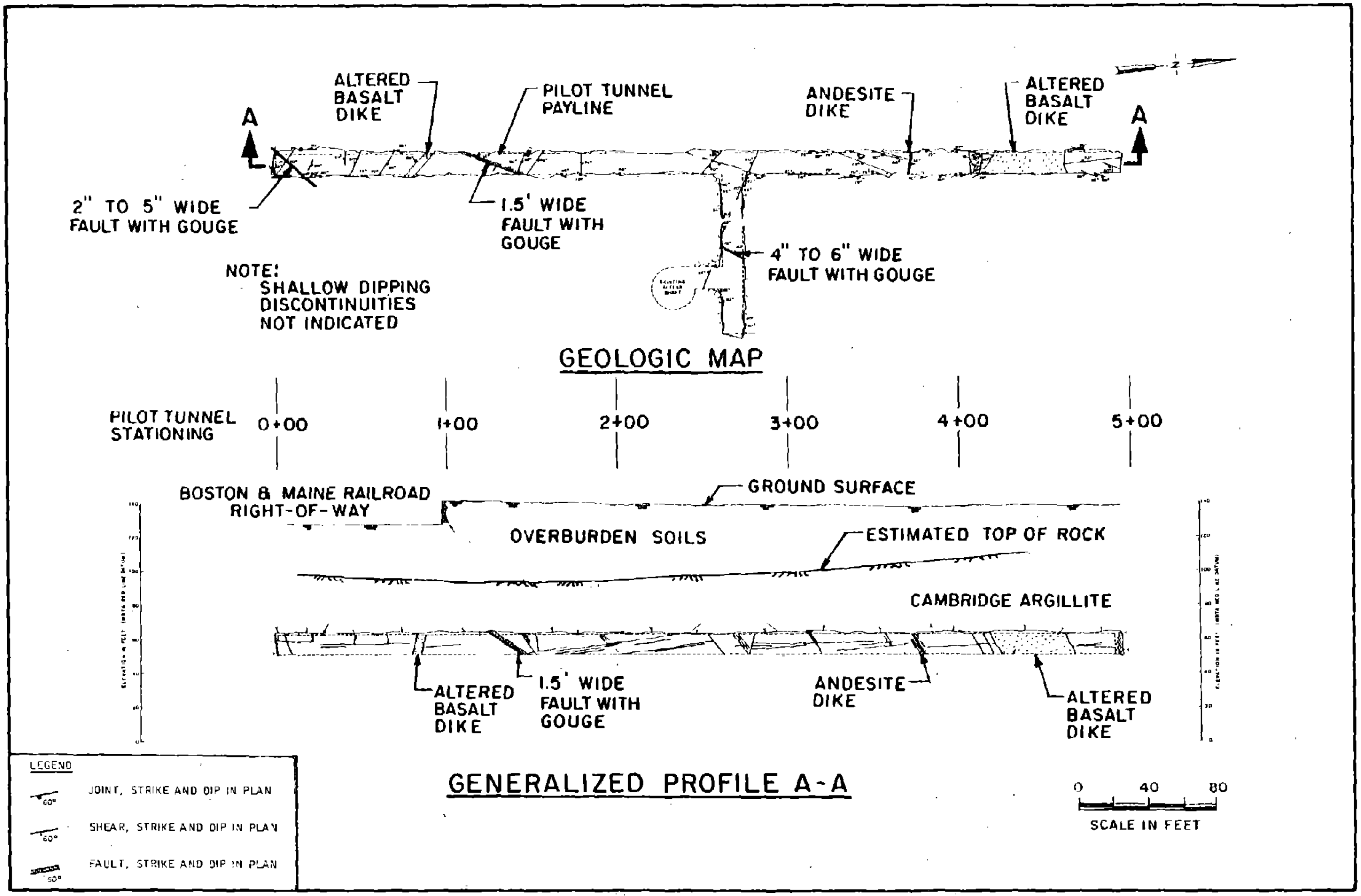


FIGURE 3-1. GEOLOGIC MAP AND GENERALIZED GEOLOGIC PROFILE, NORTH-SOUTH PILOT TUNNEL

Set No.	
1	Joints parallel to bedding, generally striking east-west and dipping south at 5° to 15°.
2	Joints generally striking east-west and dipping north at 40° to 60°.
3 and 4	Joints generally striking north-south and dipping very steeply east and west.

The joint surfaces are usually smooth, and many joints have secondary mineralization, usually calcite.

Joints parallel to bedding (Set No. 1) are spaced every 2 to 5 ft. (0.6 to 1.5 m) and are continuous over distances of 50 ft. (15 m) or more. However, the majority of the east-west joints (Set No. 2) are not continuous over the width or height of the pilot tunnel, the continuity of the joints being interrupted by shears parallel to bedding and other joints. Joint spacing varies from 0.5 to 15 ft. (0.15 to 4.5 m) apart.

The joints striking generally north-south (Set Nos. 3 and 4) form two conjugate sets. One set dips steeply to the east, and the second set dips steeply to the west. These sets form the most continuous joints observed in the pilot tunnel, being generally continuous over at least 20 to 40 ft. (6 to 12 m). Joints are spaced from 1 to 5 ft. (0.3 m to 1.5 m) apart.

Some of the principal geologic discontinuities encountered during excavation are shown on the generalized geologic map in Figure 3-1. Two faults were encountered in the south heading of the main north-south tunnel, both striking about N25°E and dipping about 60°NW. The faults were about 6 to 18 in. (0.15 to 0.45 m) in thickness, and had soil filling or gouge. Three igneous dikes were encountered at the locations shown on Figure 3-1. The largest dike, within which round FC 7 was shot, was located in the north heading and was about 43 ft. (13 m) wide along the axis of the tunnel.

3.3 EFFECTS OF GEOLOGIC FEATURES ON PERIMETER CONTROL RESULTS

Excavation of the pilot tunnel demonstrated how geologic features can affect overbreak in the blasted rock. In general, overbreak in the crown was controlled by joints and planes of weakness parallel to bedding (Set No. 1), forming large flat slabs (as shown in Figures 3-2 and 3-3). Sidewalls in the main north-south tunnel direction often broke to the steeply dipping north-south joints (Set Nos. 3 and 4), as can be seen in Figure

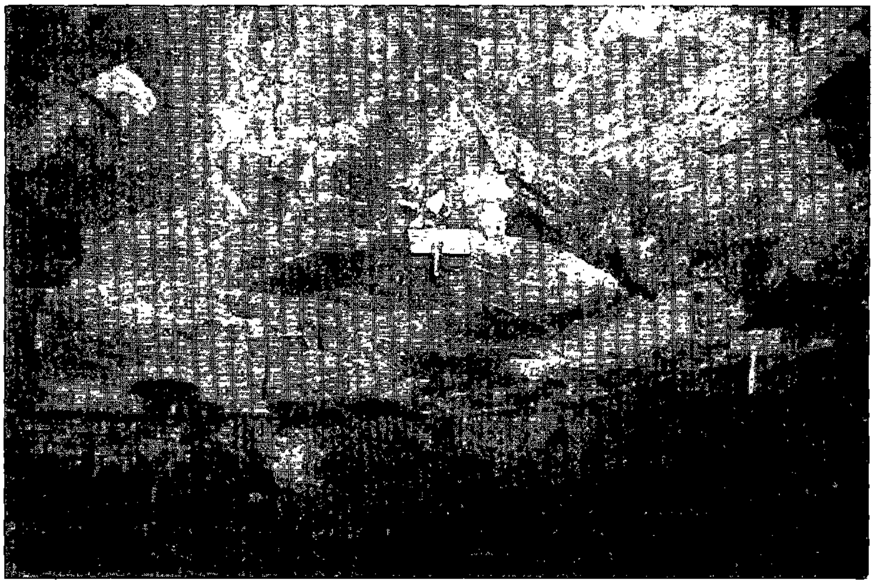


FIGURE 3-2. OVERBREAK IN CROWN PARALLEL TO BEDDING

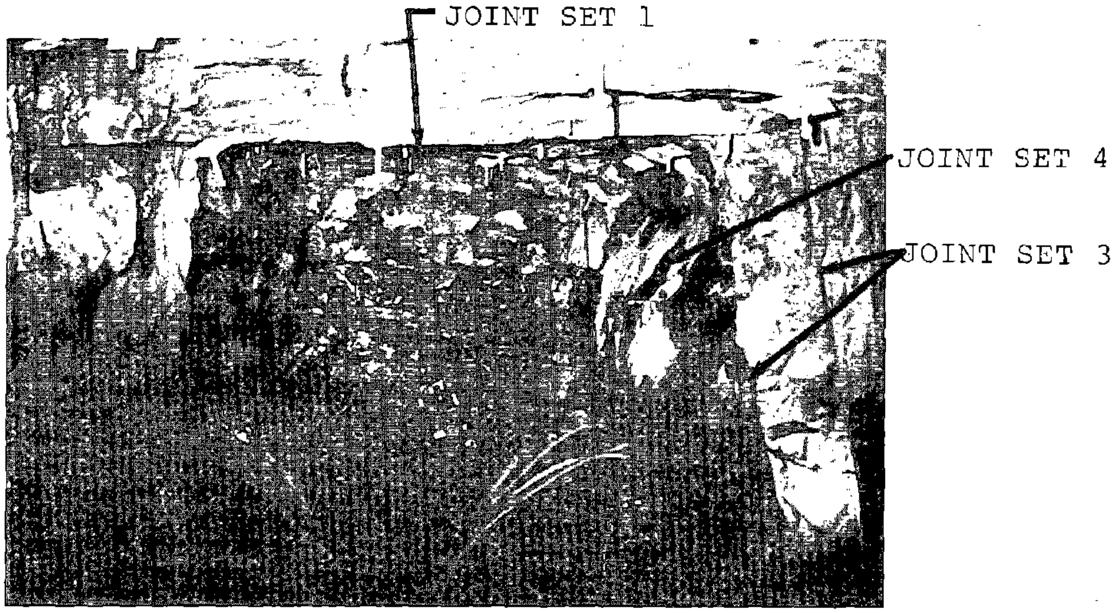


FIGURE 3-3. NORTH HEADING LOOKING NORTH, SHOWING SLABBING AT CROWN, OVERBREAK TO JOINT SETS 3 AND 4

3-3 and in Figure 2-7. Sidewalls in the east-west access tunnel sometimes broke to saw-toothed surfaces formed by the joints parallel to bedding (Set No. 1) and the east-west striking north dipping joint set (Set No. 2), as shown in Figure 3-4.

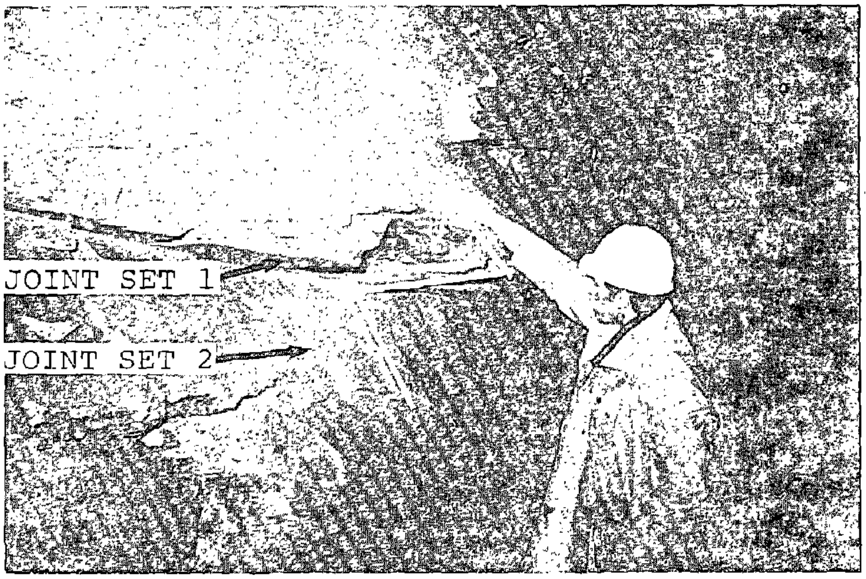


FIGURE 3-4. OVERBREAK IN SOUTH RIB OF EAST-WEST ACCESS TUNNEL CONTROLLED BY JOINT SETS 1 AND 2.

Intersecting joints at the corners of north-south and east-west tunnels resulted in substantial overbreak. Overbreak also occurred in the south heading where the two fault zones intersected the tunnel (see Section 6.4).

4. THEORY AND APPLICATION OF FRACTURE CONTROL

4.1 THEORY AND BACKGROUND

4.1.1 General

Fracture control blasting is based on controlling all phases of the fracture process: crack initiation, crack propagation, and crack arrest. Control of crack initiation involves specifying the number of cracks to be initiated and the location of the initiation sites on the wall of the drill hole. Control of the propagation phase requires orienting the cracks and providing a stress field which will produce the strain energy required to maintain the desired crack velocity. Finally, control of crack arrest necessitates maintenance of a stress state which is sufficiently large to avoid crack arrest until the crack has achieved its specified length. If all of these aspects of the fracture process can be controlled, then a blasting round can be designed to properly cut, fragment and move the rock.

4.1.2 Crack Initiation

Control of the location of crack initiation is achieved in fracture control blasting by notching the drill hole along most of its length. The notch in the wall of the drill hole is an effective means of concentrating stress at a specified location. The stress concentration ensures that the first crack to be initiated will be located at the notch. There is a pressure range which must be achieved in order to control initiation. If the pressure is too low, the crack will not initiate even at the notches; when the pressure is too high, cracks will form at the natural flaws on the side of the drill hole. The loading of the drill hole with a column charge which gives a satisfactory performance can usually be achieved with a few trials in the field.

In theory, the notch serves as a starter crack and should be very sharp and as deep as possible to facilitate initiation at the lowest possible pressure. One way of forming the notches would be to utilize high pressure water jets to cut narrow slots. When such equipment is fully developed and operational, such a method may be desirable. Until then, however, notches will be cut with a mechanical tool which will wear and the sharp point will become rounded. Also, the cutting forces and the time to notch the drill hole are both reduced if relatively shallow notches are employed. Based on experiences to date, it appears reasonable to suggest a notch depth of 1/4 in. (6 mm) for a 1-3/4 in. (44 mm) drill hole, as shown in Figure 4-1. The suggested

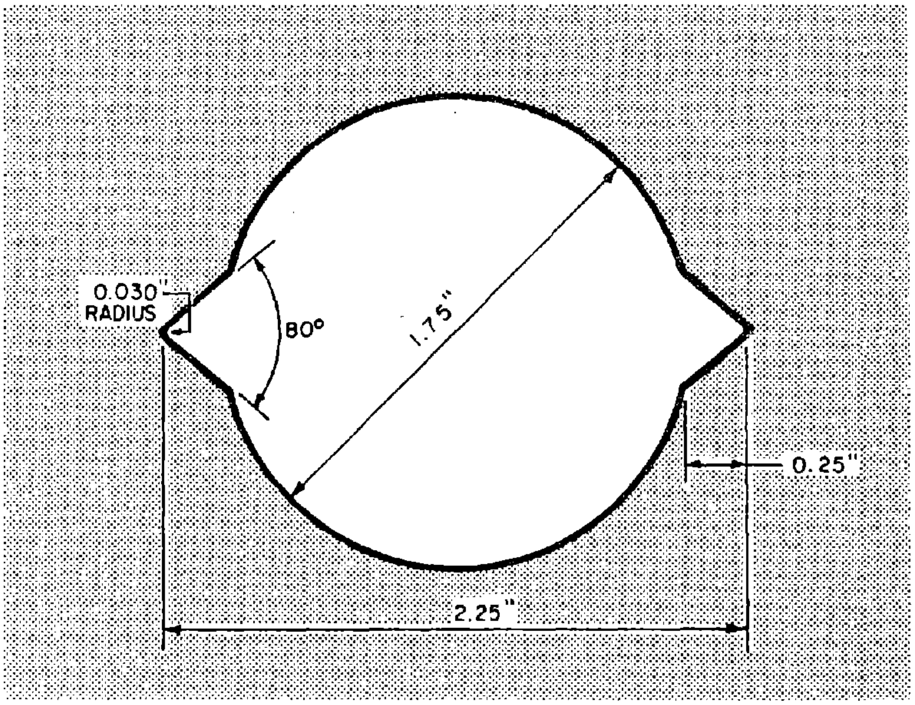


FIGURE 4-1. SUGGESTED DIMENSIONS FOR NOTCHES TO CONTROL CRACK INITIATION

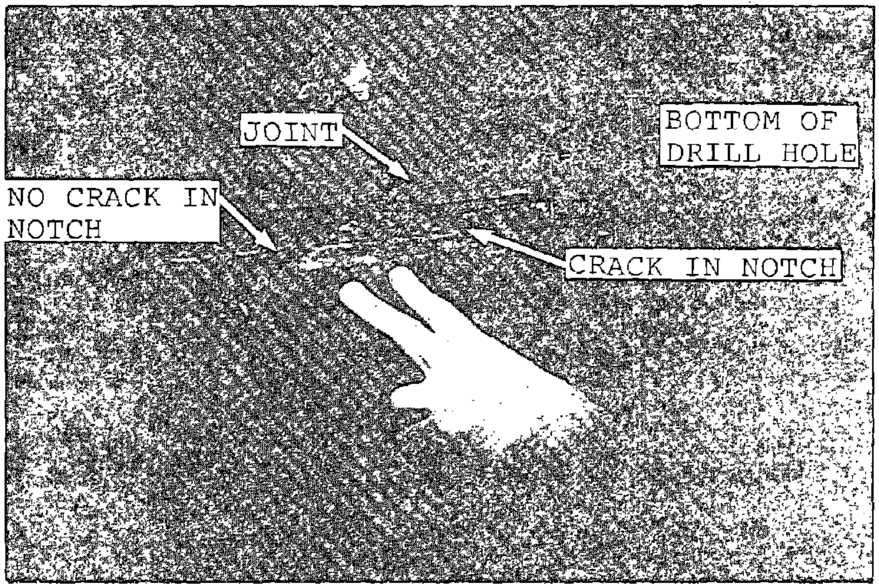


FIGURE 4-2. CRACK INITIATED IN NOTCH IN DRILL HOLE

radius of 0.030 in. (0.76 mm) should be sufficiently sharp for the notch to act as a crack yet large enough to resist rapid wear. The 80 degree included angle is to enhance gas flow into the crack and to provide for a sufficient shear area to minimize tool breakage.

Figure 4-2 shows a half cast, or half drill hole (see Section 5.3.5.2), left after a fracture control round. This perimeter hole had been notched longitudinally along a horizontal as well as a vertical plane, and one of the notches in the horizontal plane can be seen in the half cast. A joint strikes diagonally through the half cast. To the right of the joint, a crack was initiated, while to the left of the joint, near the collar of the drill hole, the borehole pressure was insufficient due to venting at the joint and a crack was not formed.

4.1.3 Crack Propagation

The next phase in the fracture control process involves controlling the orientation of the fracture plane. This orientation can be controlled quite easily if crack branching is inhibited. The cracks generated by the pressure in the drill hole will propagate along a straight radial line (assuming residual stresses are small as is almost always the case for near surface excavation) maintaining control of the fracture plane. Crack branching, which destroys control of the fracture plane, can occur for two reasons. First, if the crack intersects a large flaw in the rock structure, the flaw can arrest, divert or bifurcate the crack. The second reason for crack branching is the over-driven crack, which results when the strain energy available is much larger than the minimum strain energy required to propagate a crack. Branching due to over-driving can usually be controlled by limiting the pressure in the drill hole.

4.1.4 Crack Arrest

The final phase of fracture control involves the length of the crack which is driven from the drill hole. The crack length is controlled by maintaining the stress intensity factor at the crack tip above a critical arrest toughness K_{Im}(4). If the pressure in the drill hole is too high and particles plug the crack openings, the stress intensity factor K decreases with increasing crack length until $K < K_{Im}$ and the crack arrests. However, if the gas flows into the opening crack and pressurizes the fracture surface, the stress intensity at the crack tip increases with increasing crack length and there is no reason for cracks to arrest except for depletion of the gas supply due to the increase in the volume of the cavity or due to venting.

With proper stemming, where the stemming length is half the drill hole spacing, crack extensions 20 times the drill hole diameter can be achieved. It appears that in practice the crack length will be limited by flaws which arrest the crack or cause it to branch rather than the ability of the drill hole pressure to drive the crack.

4.1.5 Background of Fracture Control

The idea of fracture control through the use of notched drill holes is not a new one. In 1905, notching was described by Foster (5) as a method of promoting fracture. Haviland (6) described the practice of "reaming" drill holes in stone quarrying work in the late 1930's. Fracture control procedures have been more recently used in quarry work in Minnesota.* In their 1963 book, Langefors and Kihlström (7) discuss a way of guiding cracks by making a primary indication, or notch, in a hole.

Fracture control procedures were more fully developed and refined by Fourney and Dally (1,2,8,9) at the University of Maryland between 1975 and 1977. They conducted laboratory tests using small two-dimensional polymeric and rock models, together with high-speed photography for visualizing the dynamic fracture process. After establishing mechanisms of failure and parameters for groove geometry in the laboratory, they conducted field tests of fracture control methods on boulders of limestone and sandstone.

In late 1978 and early 1979, fracture control procedures were implemented at the Atlanta Research Chamber (10) during construction of the Peachtree Center Station of the Metropolitan Atlanta Rapid Transit Authority (MARTA) rapid transit system. This research, sponsored by the Urban Mass Transportation Administration, utilized a "scribing" tool to notch perimeter drill holes. Notched drill holes have also recently been used in excavation for a nuclear power plant and in demolition blasting of concrete structures.**

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* The use of notched drill holes in precision stone cutting was described in personal communication with Mr. Joe Peters of the Cold Springs Granite Quarry, in Minnesota.

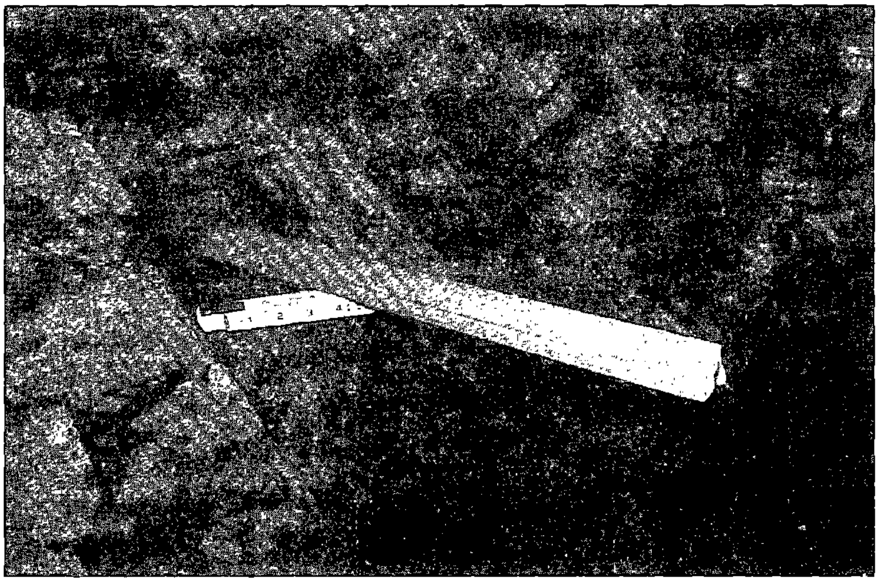
** Lewis J. Oriard, in personal communication, has described his use of notched drill holes in controlled blasting for construction of a Nuclear Power Station in Mississippi, and in concrete demolition at St. Paul, Minnesota. He cut 1/4 in. (6.4 mm) deep notches in drill holes with an oversize bit ground down on two sides, and used about 1/4 to 1/5 the charge concentration used in normal conditions.

4.2 APPLICATION TO PERIMETER CONTROL IN PORTER SQUARE STATION PILOT TUNNEL

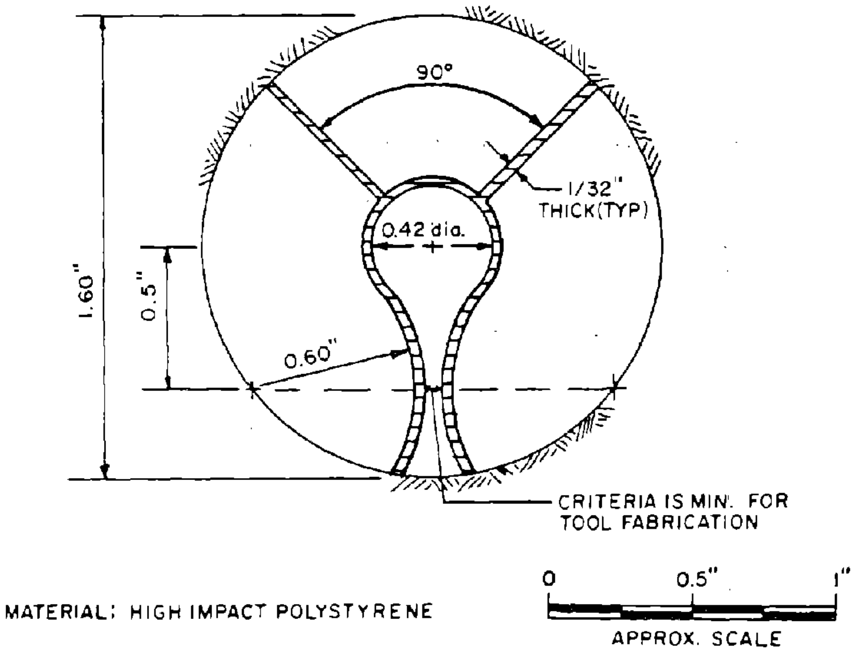
Fracture control perimeter control techniques were used in seven full heading rounds during the experimental program conducted in the Porter Square Station Pilot Tunnel. The perimeter holes were drilled using a 1-11/16 in. (43 mm) bit, and then notched using a specially designed notching tool. The notching tools, which will be described in detail in Section 4.4, were designed to cut 1/4 in. (6.4 mm) deep grooves in the drill holes. Figure 4-3 is a photograph of a notching tool entering a drill hole.

FIGURE 4-3. NOTCHING TOOL ENTERING DRILL HOLE

The perimeter holes in each experimental round were loaded with a specially designed string of explosives consisting of a concentrated bottom charge and a distributed column charge. The bottom charge consisted of one or two 1-1/4 x 8 in. (3.2 x 20 cm) sticks of 40 percent extra gelatin, at 0.53 lb. (0.24 kg.) per stick. The column charge generally consisted of a 4 to 5 ft. (1.2 to 1.5 m) length of 400 grain/ft. (0.09 kg/m) Primacord which was supported in the center of the drill hole by a specially designed spider tube. A photograph of the spider tube is shown in Figure 4-4a and a detail of the cross section is shown in Figure 4-4b. The Primacord perimeter loading, without the spider tube, is shown in Figure 4-5. The perimeter holes were stemmed with 24 in. (0.6 m)



(a) As Fabricated



(b) Cross Section Detail

FIGURE 4-4. SPIDER TUBE USED TO CENTER PRIMACORD CHARGE IN DRILL HOLE.

of either sand bags or water bags. Hercules Superdet Electric delay caps were used to detonate the round, with the perimeter holes being fired on the last four or five delays.

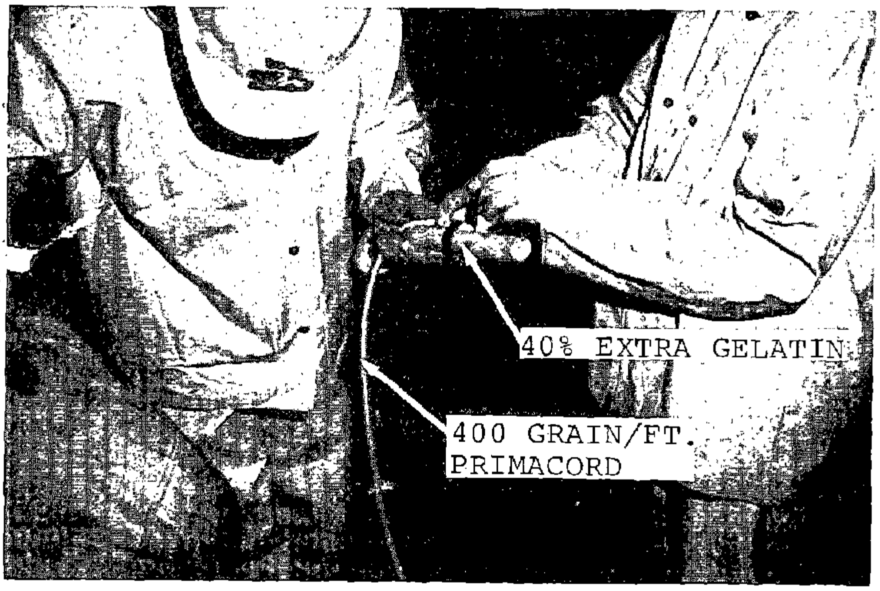


FIGURE 4-5. PRIMACORD PERIMETER HOLE LOADING (WITHOUT SPIDER TUBE)

4.3 APPLICATION TO OPENING CUTS

The most critical part of a tunnel round is the opening cut: this must provide a free face for the rest of the round to break toward. If the cut fails to pull to bottom, it is impossible for the remainder of the round to pull to bottom. The depth of a round is usually limited by the cut to a maximum of 60 to 70 percent of the smallest dimension of the tunnel. The cut is the most costly, time-consuming part of the round. Drill and powder factors are very high and holes must be drilled accurately. Because of the high confinement, the opening cut holes often produce the largest vibrations for a round.

In the application of fracture control (FC) blasting to the opening cut, it was hoped to significantly reduce the number and size of the holes which must be drilled, to relax the requirements for drill alignment and to reduce the amount of explosive used in forming the cut.

The opening cut developed using fracture control techniques is shown in Figure 4-6. Three 1-11/16 in. (43 mm) holes were drilled at the vertices of an equilateral triangle, and a 3 in. (77 mm) hole was drilled at the center of the triangle. The three outside holes were notched so that two cracks would propagate from each hole to form a hexagonal plug. The three holes were drilled with a slight look-in so the cross section of the plug would decrease with depth.

The three outside holes are loaded in a similar manner to that described previously for the perimeter holes - two sticks of 40 percent extra gelatin, a cushioned column charge of 400 grain/ft. (0.09 kg/m) Primacord, and stemming. When the holes are fired, the radial cracks cut a hexagonal cylinder free on all sides except the base.

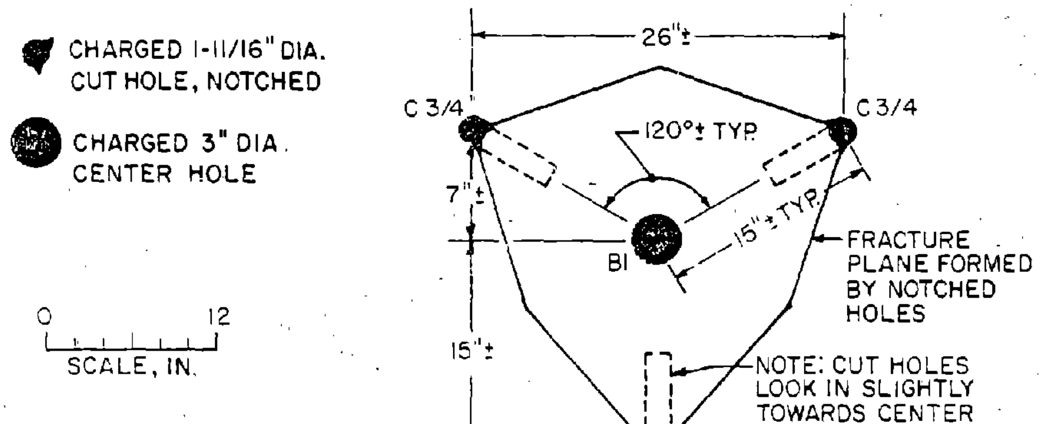
The hexagonal plug is removed by firing a decked charge in the center hole. The first charge is positioned at the bottom of the hole and the second charge is positioned 3 to 3-1/2 ft. (0.9 to 1.1 m) from the collar. The two charges are connected with 50 grain/ft. (0.01 kg/m) Primacord. Each charge contains four sticks, or 2.12 lb. (0.96 kg) of 40 percent extra gelatin. Firing the decked charges fragments the hexagonal plug and it is expelled from the tapered hole by the action of the trapped gasses.

4.4 TOOLS FOR NOTCHING DRILL HOLES

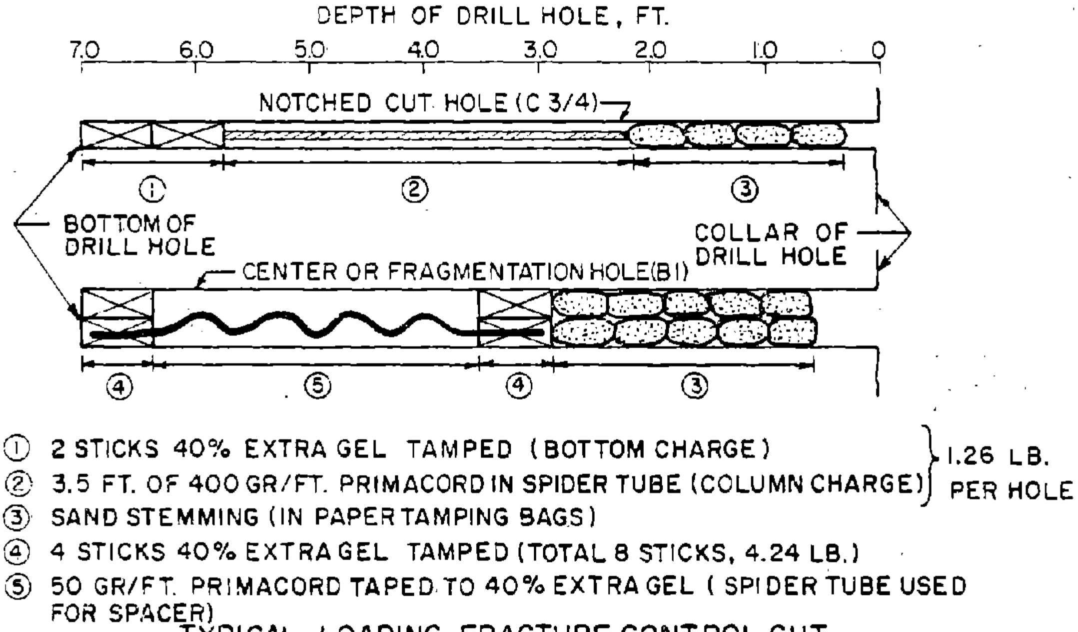
4.4.1 Notching Tools Used in the Experimental Program

In the Porter Square Station Pilot Tunnel experiments, drill holes were mechanically notched using specially designed tools. The notching operation was performed after the holes were drilled, utilizing the PR-123 drills used for drilling. The tools were attached to the drill steel with a rope thread and the only variations in normal drilling techniques were the prevention of rotation of the drill steel and reduction of intensity of the hammer action. Alignment of the notches was done by holding a wrench on the drill steel until the tool had entered the drill hole. This method of visual alignment was considered to be sufficiently accurate to produce the desired results. Alignment after the tool entered the hole was not required.

The test program provided an opportunity to evaluate a number of different notching tools. Photographs of the various tools evaluated are shown in Figure 4-7. One of the tools (see Figure 4-7b) was designed by the Mining Tool Group of Kennametal, Inc., Bedford, Pennsylvania, and two prototypes were provided. All other tools were designed and fabricated by the investigators.

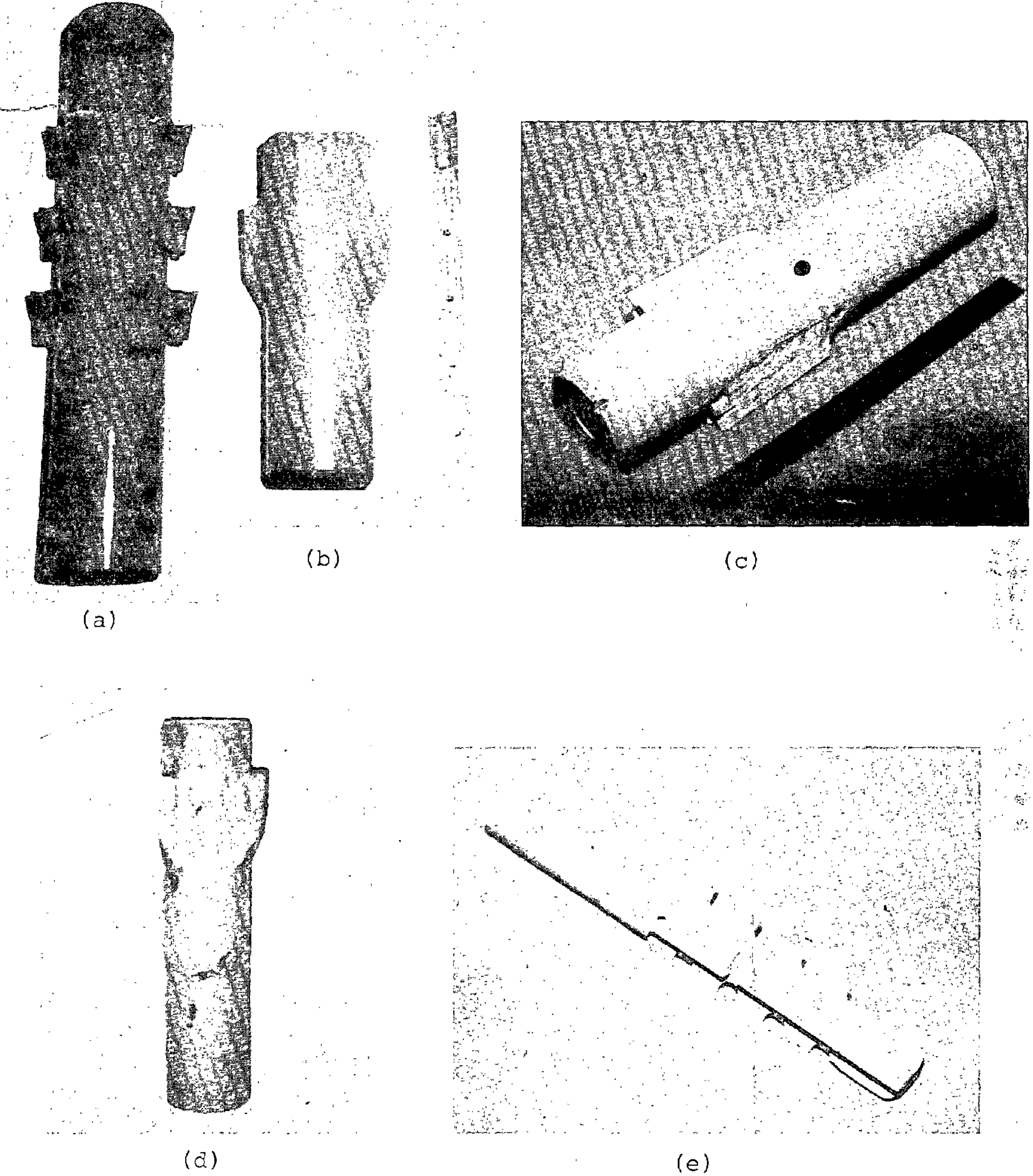


VIEW OF FACE



TYPICAL LOADING, FRACTURE CONTROL CUT

FIGURE 4-6. FRACTURE CONTROL OPENING CUT



(a) (b) (c) (d) (e)

FIGURE 4-7. TOOLS USED TO NOTCH DRILL HOLES

(a) Original Four Piece Straight Cut Broaching Tool
(b) Single Stage, Kennametal Design
(c) Single Stage, Investigators' Design
(d) Single Stage, Corner Cut - 110 Degree Included Angle
(e) Four Stage Broaching Tool, Hardened Tool Steel Cutters

All tools were designed with an alloy steel body (either 4140 or 4340 steel) fitted with a rope thread (2 threads/in.) (79 threads/m.) which was compatible with the standard drill steel. The tools were designed into a body diameter of 1-5/8 in. (41 mm) to fit into a 1-11/16 in. (43 mm) drill hole with a radial clearance. The cutting edges were designed to cut notches 1/4 inch (6.4 mm) deep. All but one of the designs had water holes to provide for a cooling fluid.

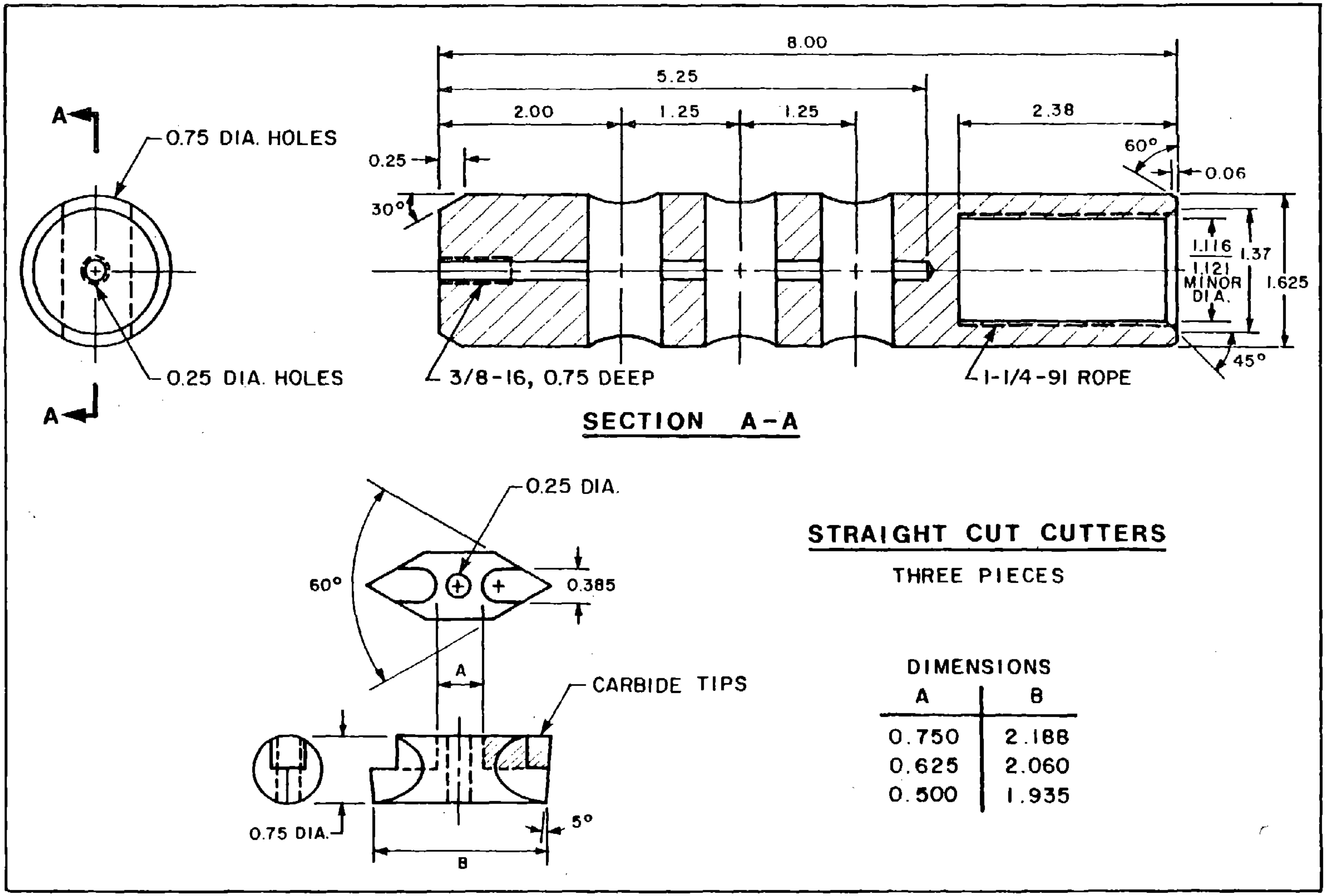
The original concept in tool design was to employ a broaching type tool which would notch to the required depth of 1/4 in. (6.4 mm) but not require the removal of large volumes of rock by a single cutter.

A four piece, three stage broach design is illustrated in Figure 4-7a. Details of this broach design are shown in Figure 4-8. The three cutters were progressively longer so that as the tool passed into the bore hole, the notch became deeper. The first cutter was 1.935 in. (49.1 mm) long, the second 2.06 in. (52.3 mm), and the third was 2.188 in. (55.6 mm) long. This tool was not water cooled and the cutters were made from 4140 steel rod, 3/4 in. (19 mm) in diameter. The carbide inserts used for cutting the rock were impact resistant, type 3055, manufactured by Kennametal. This tool was destroyed on the first pass. The removable cutters did not have sufficient bending resistance and/or shear strength and were broken off.

The tool provided by Kennametal (Figure 4-7b) performed well. The cutter was an integral part of the body, and the full 1/4 in. (6 mm) notch depth was achieved with the one-stage cutter. The carbide inserts (also type 3055) chipped after notching five to ten holes. When these inserts were replaced with more massive and more impact resistant carbide inserts (from a standard 1-3/4 in. (44 mm) four point drill bit) the tool held up much better. Photographs of the damaged Kennametal tool and the same tool after it was repaired are presented in Figure 4-9. Although the repair was rather crude, this modified tool was used to notch most of the holes in the experimental program.

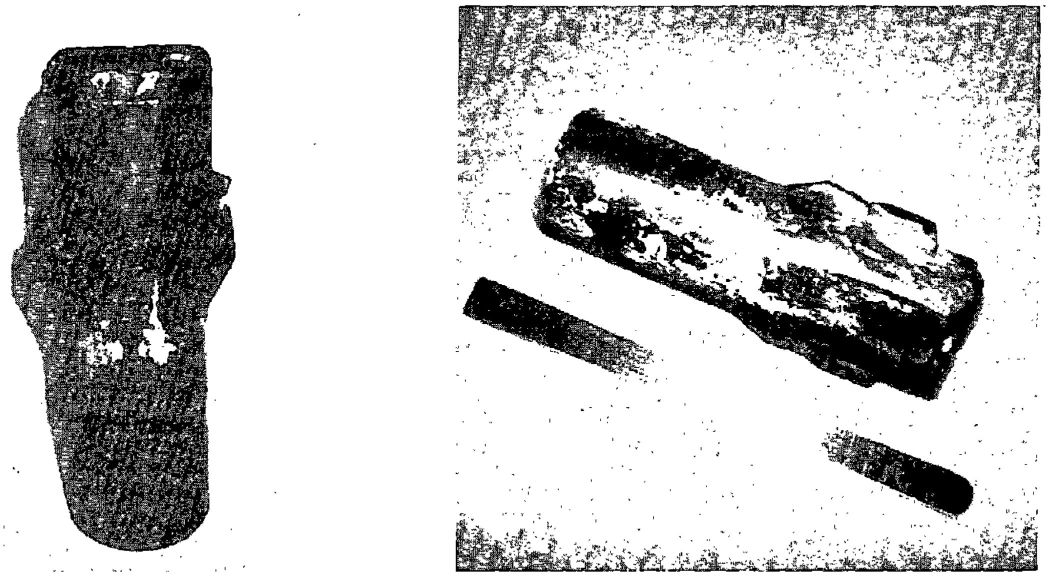
The tool shown in Figure 4-7c was similar to the Kennametal tool except for the very long cutter members which support the carbide inserts. The long supports were used to improve the notch alignment and to inhibit rotation of the tool in the drill hole. This tool failed after limited service when the carbide inserts broke off in a drill hole, either as a result of inadequate impact resistance or because they were not properly supported by the cutter.

The tool illustrated in Figure 4-7d was designed to cut a pair of notches with an included angle of 110 degrees. This tool



A	B
0.750	2.188
0.625	2.060
0.500	1.935

FIGURE 4-8. DETAILS OF FOUR PIECE, THREE STAGE BROACHING TOOL



(a) Damaged (b) Repaired

FIGURE 4-9. KENNAMETAL NOTCHING TOOL

was intended for use in corner holes at the perimeter and in fracture control cut holes. The body of this tool failed after it was accidentally driven into a bootleg hole and hammered against the bottom of the hole.

A broach design with four hardened steel cutting edges is shown in Figure 4-7e. The tool steel used was H-11. This tool cut sharp clean notches in several holes before the teeth began to break off. It is believed that quenching cracks occurred in the heat treatment process which caused premature failure of the teeth. It was noted that wear of the hardened steel was not excessive.

Of the problems which developed with the tools, the malfunctions were primarily due to one of three causes:

a. Insufficient impact resistance of carbide inserts;

b. Quenching cracks near welded regions, which resulted in body and insert support failures; or

c. Driving the tool against the bottom of the drill hole, which resulted in thread and body failures.

In addition to excessive tool breakage, two operating problems developed. First, in aligning the tool with the perimeter line, the tool would sometimes tend to rotate as it entered the hole, particularly if the tool was loose on the drill steel. To avoid this rotation and to enable the tool to be more easily aligned, future tools should incorporate a shank which can be held with a wrench until the tool is collared in the proper orientation in the drill hole. The second operational problem involved the tool becoming wedged in the drill hole after the hole was notched. This tool "hang-up" problem may have been due to one or more of the following reasons:

a. The repaired Kennametal tool and all tools designed by the investigators used very small or non-existent relief angles on the cutter, which inhibited the angular movement of the cutter in the notch and thus reduced the possibility of the cutter wiggling free if slightly misaligned when being pulled out.

b. The longer cutter members (which were used in the latter stages of the experimental program to provide better notch alignment while cutting) would also limit the movement of the cutter in the notch during tool retrieval from the drill hole.

c. The larger, more massive carbides used to replace the original broken carbides resulted in larger notches, or more cutter steel in the notch, which also served to reduce movement of the cutter in the notch upon removal.

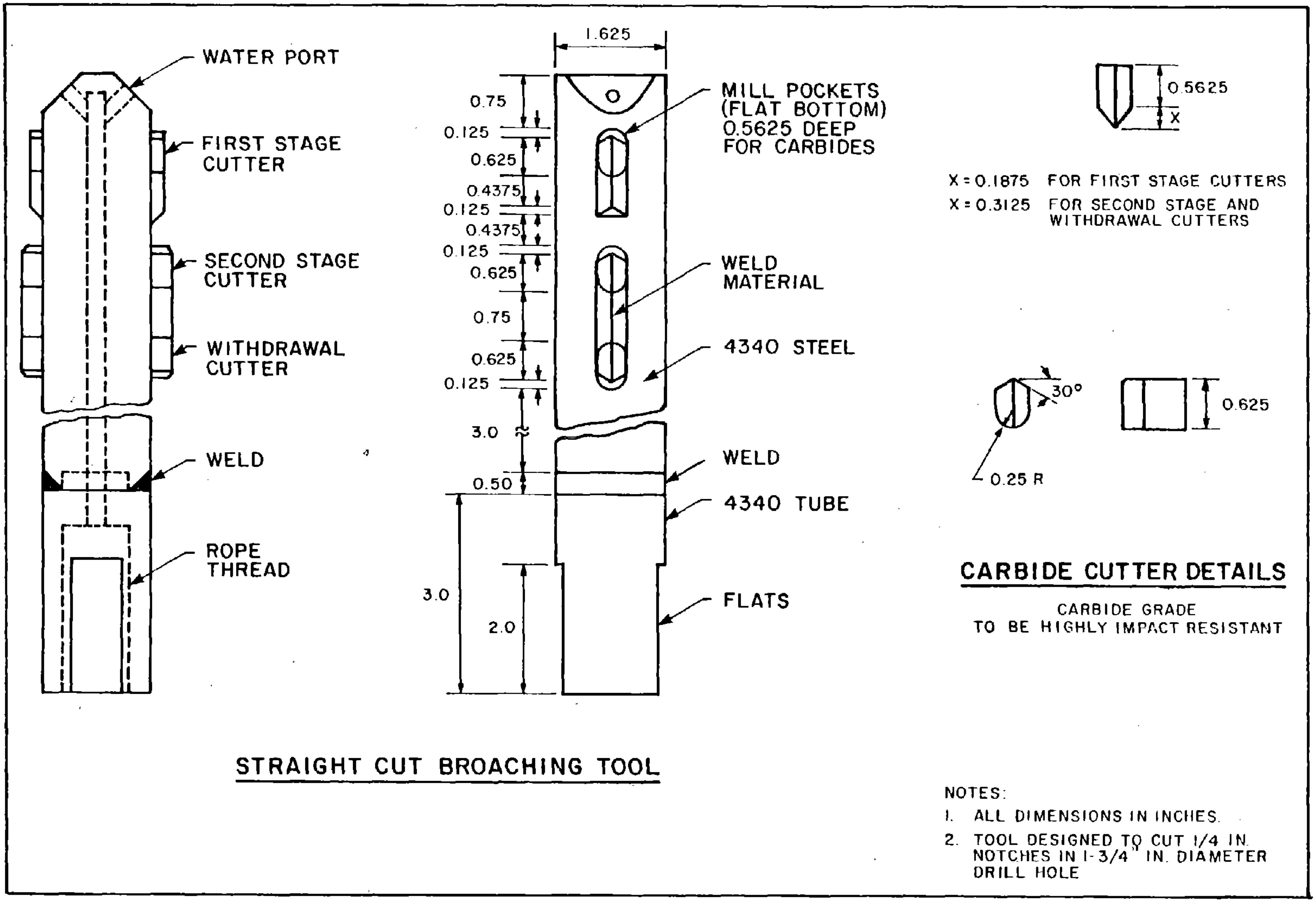
d. A different drilling/notching technique was employed in the north/south headings than in the preliminary test rounds fired in the blasting test chamber (see Section 5.2), which could have caused or aggravated the "hang-up" problem. Initially, each perimeter hole was drilled and notched prior to drilling the next hole. After drilling was completed in a hole, the drill bit was removed and replaced with the notching tool without moving the drill boom. As a result, the drill rod stayed aligned directly with the axis of the drill hole. This practice resulted in increased drill/notch times due to continually interchanging the bit and the notching tool. Because of increased drill/notch times, the perimeter holes in subsequent experimental rounds in the north-south pilot tunnel were drilled prior to the start of the notching operation. As a result, the drill steel was not accurately aligned with the drill hole axis when advancing the notching tool. This may have caused the tool to wedge in the hole when removal was attempted.

The notching tool "hang-up" problem can be avoided by providing proper relief in the cutters and providing cutting edges for both entrance and withdrawal.

4.4.2 Future Mechanical Notching Tool Design

Based on the experience with the various tool designs used in this research program, a recommended mechanical notching tool is shown in Figure 4-10. This broaching type tool incorporates carbide inserts for entrance and withdrawal, and provides adequate relief in the cutters.

In order to mechanically notch the bore holes in the fastest possible time, it would be best if the notching tool were made part of the drilling bit so that at the time the drilling was completed, the bore hole would also be notched. Figure 4-11 is a conceptual sketch of what such a tool might look like. Contract timing and the inertia of prototype tool manufacture prevented either of the designs shown in Figures 4-10 and 4-11 from being fabricated and field tested during this research program. However, both are worthy of future experimental programs.



NOTES:
1. ALL DIMENSIONS IN INCHES.
2. TOOL DESIGNED TO CUT 1/4 IN. NOTCHES IN 1-3/4" IN. DIAMETER DRILL HOLE

FIGURE 4-10. RECOMMENDED TWO STAGE MECHANICAL BROACHING TOOL

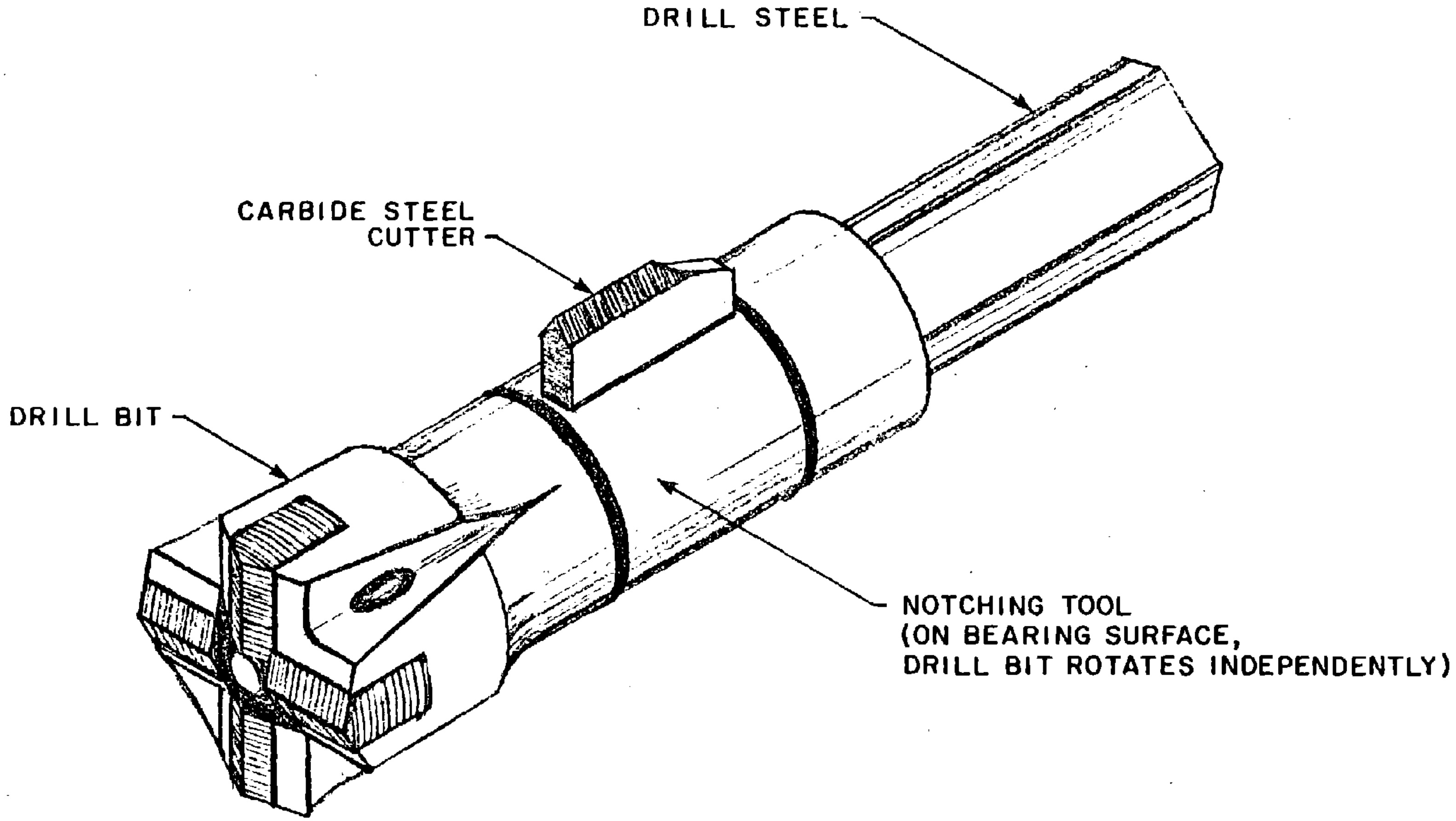


FIGURE 4-11. CONCEPTUAL SKETCH OF SINGLE PASS COMBINATION DRILL BIT/BROACHING TOOL

5. EXPERIMENTAL PROCEDURES

5.1 GENERAL

The sequence of performing the perimeter control experiments was as follows:

a. Test the various notching tools and other equipment and procedures to be used in the fracture control experiments. These tests were conducted in a preliminary test blasting chamber, located at the east end of the east-west access tunnel, so modifications in equipment and procedures could be made before starting the fracture control experiments in the main north-south pilot tunnel.

b. Allow time for the contractor to develop the specified smooth blasting round to both his and the owner's satisfaction; then document the procedures and results for several rounds.

c. Modify the contractor's smooth blasting round in order to determine the optimum perimeter control that could be achieved in the host rock using smooth blasting procedures.

d. Implement fracture control procedures in several tunnel rounds and compare the results with the optimum smooth blasting results.

The opening cut experiments were conducted in the following sequence:

a. Document the contractor's procedures and results for several rounds.

b. Test the fracture control opening cut, the contractor's opening cut and other types of opening cuts in the tunnel sidewall so that comparisons and refinements could be made before trying the fracture control opening cut in a full heading round.

c. Implement the fracture control opening cut in a full heading round, make necessary modifications, and compare the results to those of the contractor's round.

The experimental millisecond (ms) delay tunnel round (Appendix A) was detonated in the south heading as the last heading round of the project.

Figure 5-1 shows the location of the test chamber, and the various test rounds detonated in the pilot tunnel. Rounds labeled SSB were the contractor's specified smooth blasting rounds which

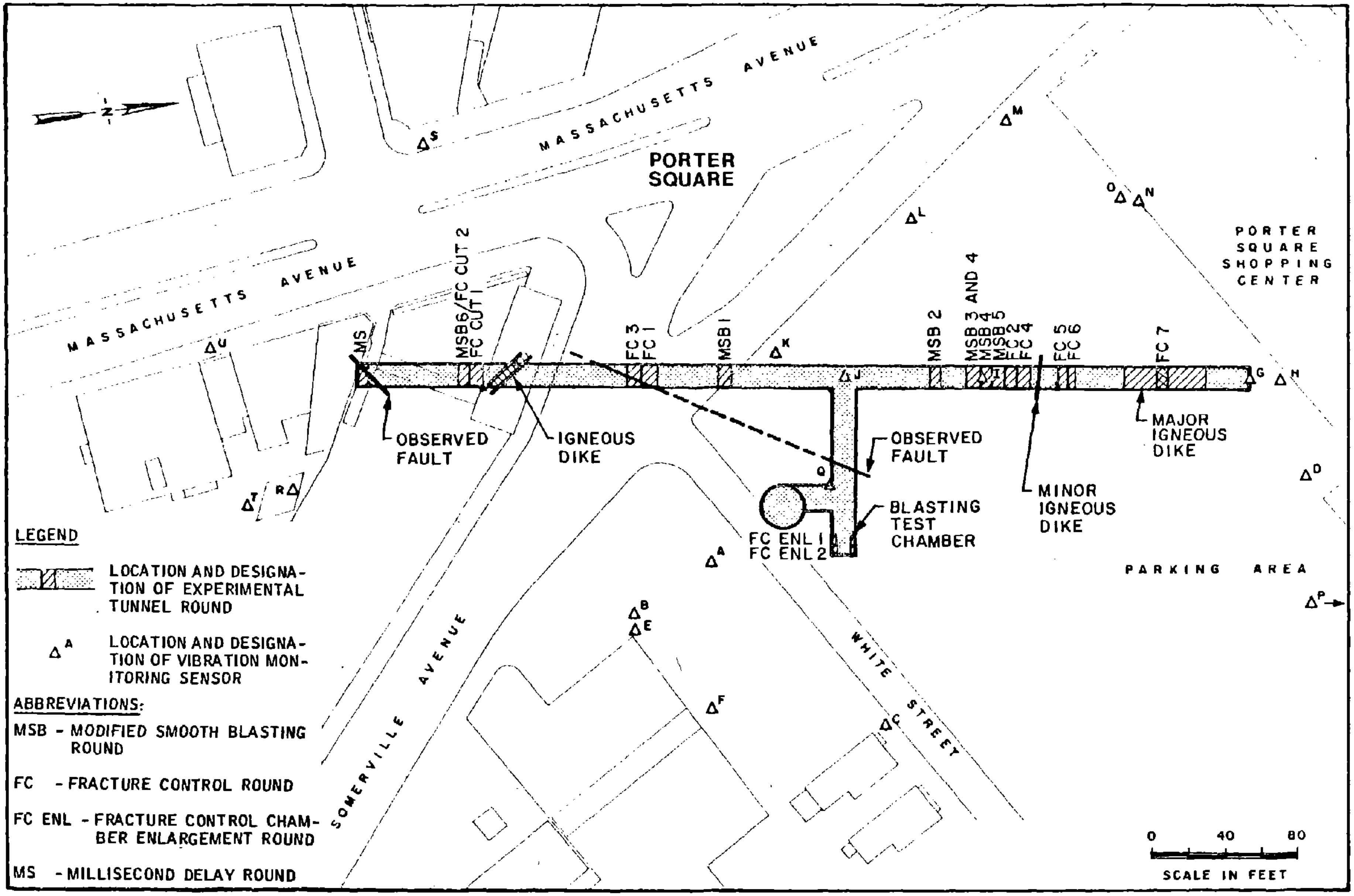


FIGURE 5-1. LOCATION PLAN SHOWING EXPERIMENTAL ROUNDS AND VIBRATION MONITORING SENSORS

were documented. Those labeled MSB were the modified smooth blasting rounds. Those rounds labeled FC used fracture control procedures.

The following Hercules explosives were used in the blasting experiments:

Type	Stick Size(in.)	Stick Wt.(lb.)	Use
40% Extra Gelatin	1-1/4 x 8 in. (3.2 x 20 cm)	0.53 lb. (0.24 kg)	Bottom charge
Gel Power A-2	1-1/4 x 16 in. (3.2 x 41 cm)	0.71 lb. (0.32 kg)	Column charge in reliever, lifter holes
Hercosplit WR	7/8 x 24 in. (2.2 x 61 cm)	0.60 lb. (0.27 kg)	Column charge in perimeter holes

Also used were 50 grain/ft. (0.01 kg/m) and 400 grain/ft. (0.09 kg/m) Primacord, manufactured by Ensign-Bickford Company, Simsbury, Connecticut. Stemming consisted of both sand filled paper tamping bags and plastic water bags. The water bags were manufactured by Central States Paper and Bag Company, Inc., St. Louis, Missouri. They were about 2 in. (51 mm) in diameter when full and were designed to be pressurized, then stretched longitudinally so they fit snugly into the drill holes. The bags frequently leaked, however, through the self sealing fill system, so their diameter was reduced in size and they often did not fit snugly in the drill holes.

Except for the millisecond (ms) delay round (Appendix A), all experimental rounds were detonated with Hercules Superdet electric delay caps manufactured by Hercules, Inc., Wilmington, Delaware. These standard delay caps had an average delay interval of about one second. The ms delay round used Atlas Rockmaster SF electric delay caps manufactured by the Atlas Powder Company, Dallas, Texas. Figure 5-2 shows some of the explosives products used in the experiments.

5.2 TEST CHAMBER EXPERIMENTS

During the early stages of excavation for the pilot tunnel, a 14.75 ft. (4.5 m) long, 8 ft. (2.4 m) x 8 ft. (2.4 m) preliminary test blasting chamber was required to be excavated. This test chamber, located in Figure 2-3, was enlarged to a 12 ft. (3.6 m) x 12 ft. (3.6 m) cross section area using fracture control perimeter control procedures. The test chamber allowed the notching tools and other fracture control equipment and procedures to be tested before the start of testing in full face rounds in the

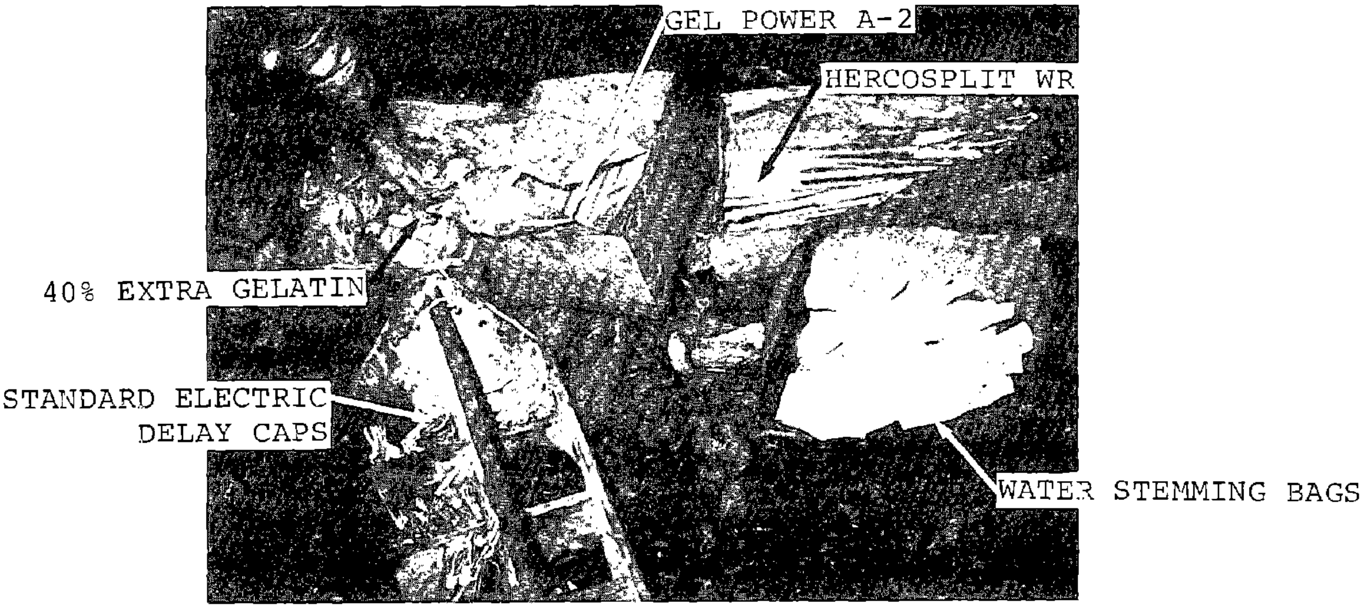


FIGURE 5-2. SOME EXPLOSIVES PRODUCTS USED IN EXPERIMENTS

main north-south pilot tunnel, so that there would be time to make modifications to the tools and the procedures if required.

Two rounds, called FC Enlargement 1 and FC Enlargement 2, were implemented to enlarge the test blasting chamber. The round designs are shown in Figures B-1 and B-2, respectively, in Appendix B. Several different perimeter hole loadings were used, and perimeter hole spacing was varied from about 24 to about 36 in. (0.61 to 0.91 m).

These preliminary tests pointed out the problems with the notching tools, which were described in Section 4.4, and aided in the design of the fracture control rounds which were later detonated in the main north-south pilot tunnel.

5.3 PERIMETER CONTROL EXPERIMENTS

5.3.1 Specified Smooth Blasting (SSB) Techniques

The project blasting specification included in the MBTA contract documents was based on current smooth blasting techniques used in the United States, which generally utilize the following:

a. Small diameter perimeter holes, 1-5/8 to 1-7/8 in. (40 to 48 mm);

b. Perimeter hole spacing of 18 to 24 in. (0.5 to 0.6 m) with burden of about 1.2 times the spacing; and

c. Perimeter hole bottom charge of about 0.5 lb. (0.22 kg) and column charge of about 0.25 to 0.30 lb/ft (0.37 to 0.45 kg/m) detonated last.

The specified smooth blasting (SSB) round finally adopted by the contractor is summarized in Figure 5-3, and consisted of the following:

a. Perimeter hole diameter of 1-11/16 in. (43 mm);

b. Average drill hole depth of 7 ft. (2.1 m);

c. Perimeter hole spacing of 24 in. (0.61 m) at the ribs and 21 in. (0.53 m) at the back (roof) for a total of 18 perimeter holes;

NOTE: The spacing was closer in the back because this was to be a final excavated surface in the proposed station chamber.

d. Perimeter hole burden of 29 in. (0.74 m) at the ribs and 24 in. (0.51 m) at the back;

e. Perimeter hole loading of 0.53 lb. (0.24 kg) bottom charge and 0.30 lb/ft (0.45 kg/m) column charge, stemmed with a quarter stick of tamped 40 percent extra gelatin;

f. Perimeter holes detonated with regular delays (average delay interval of about one second) on the last four delays of the round; and

g. Cut and reliever hole loading of 3.9 lb. (1.8 kg) per hole, well tamped, without stemming.

The hole factor* for the round was 1.28 holes/cu. yd. (1.67 holes/cu m) and the powder factor** was 3.77 lbs/cu. yd (2.24 kg/cu m). The complete round design for the final contractor specified smooth blasting round is shown in Figure B-3 in Appendix B.

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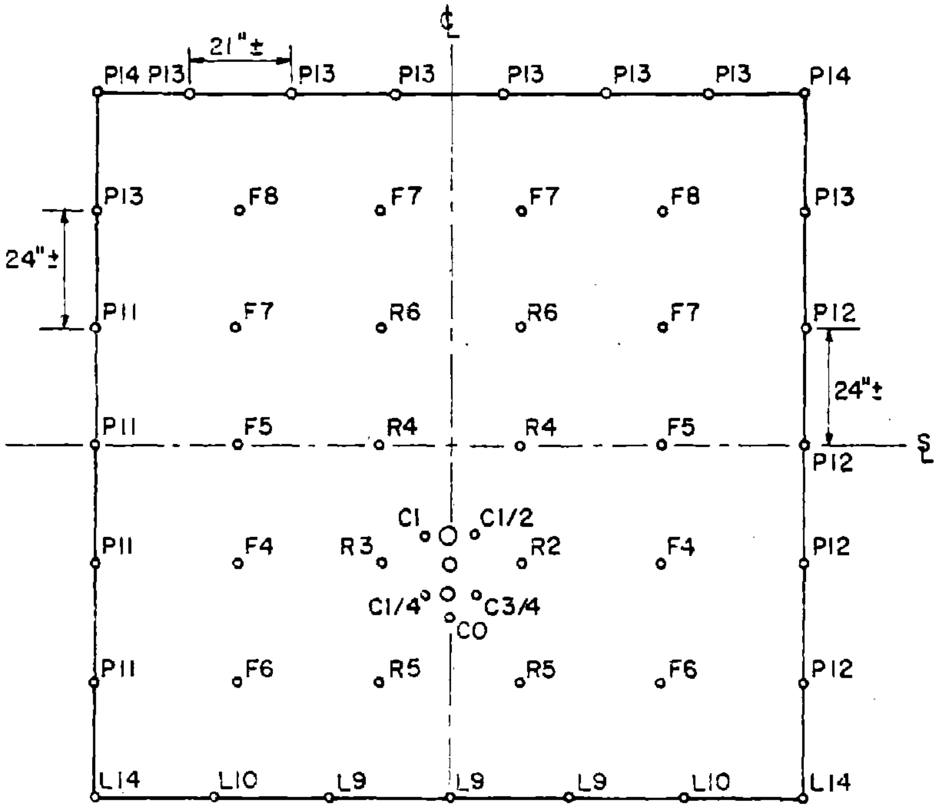
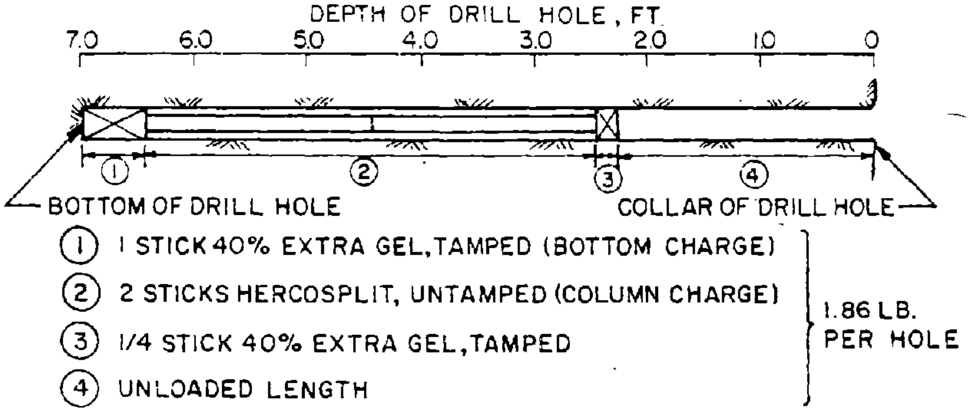
*The hole factor is the number of drill holes per cubic yard of rock broken, and is an indicator of the number of delay caps to be used and of drilling costs.

**The powder factor is the number of pounds of explosives used per cubic yard of rock broken, and is an indicator of the cost of explosives.



DRILLING PATTERN AND DELAY SEQUENCE



TYPICAL LOADING, PERIMETER HOLES

FIGURE 5-3. FINAL CONTRACTOR SPECIFIED SMOOTH BLASTING ROUND

5.3.2 Modified Smooth Blasting (MSB) Techniques

The specified smooth blasting round as adopted by the contractor was modified by the investigators during the test blasting program, one step at a time as summarized in Table 5-1.

The locations of the six modified smooth blasting (MSB) rounds are shown in Figure 5-1 and the complete round design for each is in Figure B-4 through B-9 in Appendix B. The changes described in Table 5-1 resulted in two final MSB rounds, MSB 5 and MSB 6. Round MSB 5 used a perimeter hole loading of 0.53 lb. (0.24 kg) bottom charge and a 0.19 lb/ft (0.28 kg/m) space loaded column charge, stemmed with sand. Figure 5-4 shows the perimeter hole loading, as well as the drilling pattern and delay sequence. The hole factor for the round was 1.26 holes/cu. yd. (1.65 holes/ cu m) and the powder factor was 3.17 lbs/cu. yd. (1.88 kg/cu m). The complete round design for MSB 5 is shown in Figure B-8 in Appendix B. In addition to round MSB 5, the space loaded MSB perimeter loading was also used in the west rib of round FC 1 and the east ribs of rounds FC 3, FC 4, and FC 5.

Round MSB 6 utilized a perimeter hole loading (Figure 5-5) of 0.53 lb. (0.24 kg) bottom charge and a 0.06 lb/ft (0.09 kg/m) column charge consisting of 400 grain/ft (0.09 kg/m) Primacord, stemmed with sand. The complete round design for MSB 6 is shown in Figure B-9 in Appendix B. This round also utilized the fracture control opening cut, which is described in Section 5.4. The hole factor for the round was 1.31 holes/cu.yd. (1.71 kg/cu. m) and the powder factor was 2.92 lbs/cu. yd. (1.73 kg/cu. m). In addition to round MSB 6, the Primacord MSB perimeter loading was also used in the east rib of round FC 2.

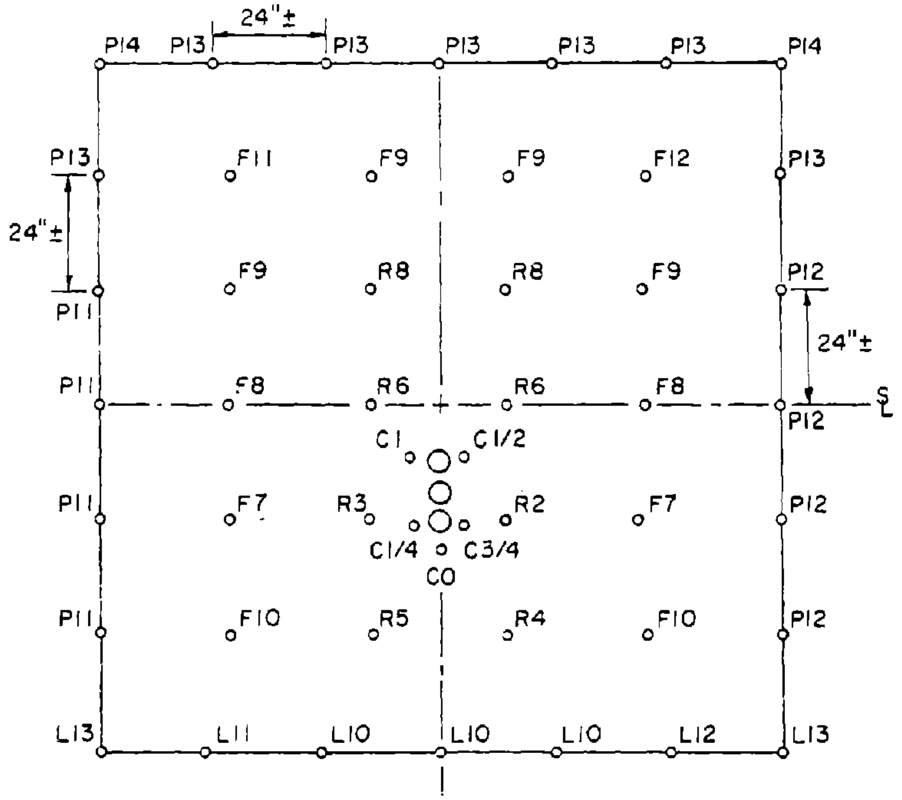
5.3.3 Fracture Control (FC) Techniques

Fracture control perimeter control techniques were used in seven full heading rounds. Figure 5-1 shows the locations of these rounds (FC 1 through FC 7). All rounds were in the argillite except FC 7. This round was in the large igneous dike in the north heading, and is described in Section 5.3.4.

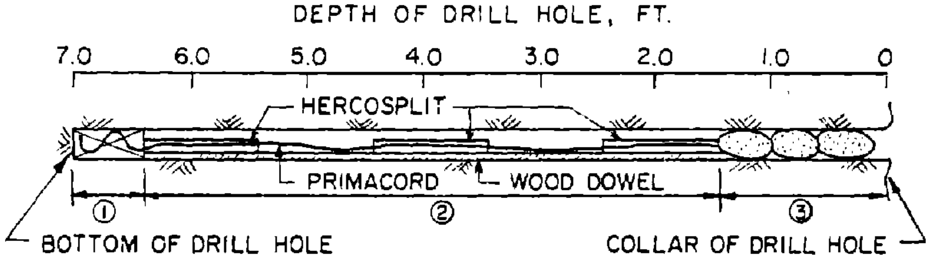
With the exception of round FC 4, fracture control rounds FC 1 to FC 6 utilized a delay sequence similar to the modified smooth blasting round, with the perimeter holes fired on the last four or five delays. The delay sequence and lifter hole loading in FC 4 was modified to that shown in Figure B-13, Appendix B, in an attempt to loosen the muck pile and make the mucking operation easier and quicker. Rounds FC 1 through FC 5 utilized the contractor's opening cut and used the same cut (C) and reliever (R,F) hole loading as round MSB 5 and MSB 6. The hole factors

TABLE 5-1. MODIFICATIONS TO CONTRACTOR'S SPECIFIED SMOOTH BLASTING ROUND

ROUND	CHANGES	COMMENTS
MSB 1	Modified delay sequence.	Provided better relief for first-row-in (F) holes.
	Increased perimeter (P) hole spacing at back to 24 in. (0.6 m).	Eliminated one hole at back.
	Stemmed all holes with inert stemming (sand or water bags).	Contained gasses in drill hole.
MSB 2	Reduced charge in cut (C) reliever (R,F) and lifter (L) holes to 3.37 lb. (1.53 kg).	Reduced powder factor, and fragmentation unaffected.
MSB 3 & 4	First-row-in (F) holes looked out parallel to (P) holes	Uniform burden allowed (P) holes to pull to bottom with less explosive
MSB 4	Reduced charge in (F) holes to about 3.26 lb. (1.48 kg).	Reduced back break into (P) hole burden.
MSB 5	Reduced column charge in (P) holes to 0.19 lb/ft. (0.28 kg/m).	Reduced overbreak and reduced damage to remaining rock.
MSB 6	Reduced (P) hole spacing to 18 in. (0.46 m). Reduced column charge in (P) holes to 0.06 lb/ft (0.09 kg/m).	Reduced overbreak and reduced damage to remaining rock.



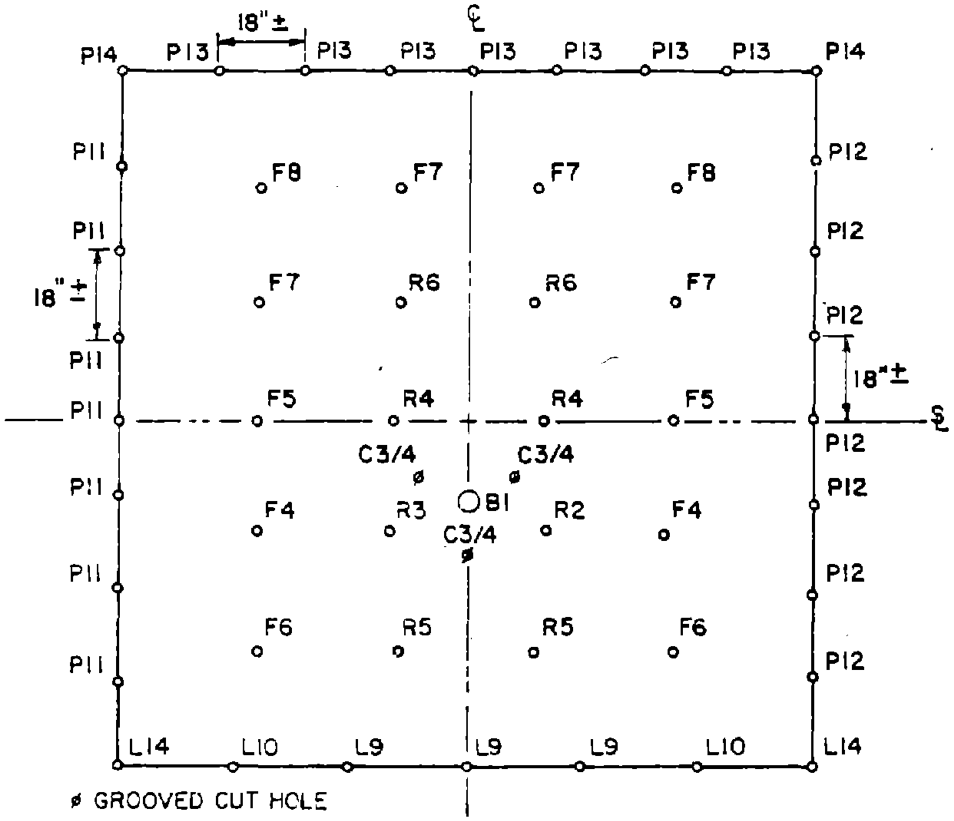
DRILLING PATTERN AND DELAY SEQUENCE



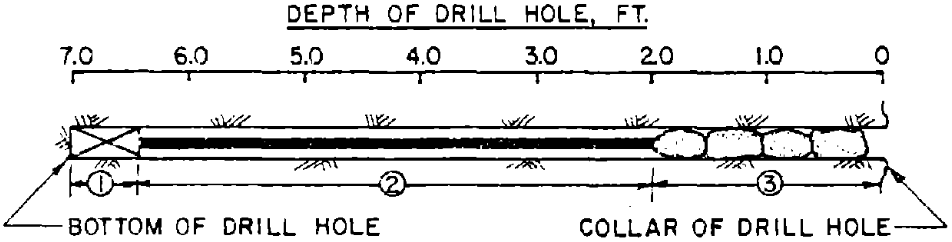
① 1 STICK 40% EXTRA GEL, TAMPED (BOTTOM CHARGE) ② 1 1/2 STICKS HERCOSPLIT, SPACE LOADED ON WOOD DOWEL, CONNECTED WITH 50 GRAIN/FT PRIMACORD ③ SAND STEMMING (IN PAPER TAMPING BAGS)	1.48 LB. PER HOLE

TYPICAL LOADING, PERIMETER HOLES

FIGURE 5-4. MODIFIED SMOOTH BLASTING ROUND MSB 5



DRILLING PATTERN AND IGNITION SEQUENCE



① I STICK 40% EXTRA GEL, TAMPED (BOTTOM CHARGE
② APPROX. 4.5 FT. OF 400 GRAIN/FT. PRIMACORD
} 0.80 LB. PER HOLE
③ SAND STEMMING (IN PAPER TAMPING BAGS)

TYPICAL LOADING PERIMETER HOLES

FIGURE 5-5. MODIFIED SMOOTH BLASTING ROUND MSB 6 for FC 1 through FC 5 ranged from 1.14 to 1.26 holes/cu. yd. (1.49 to 1.65 holes/cu. m) and the powder factors ranged from 2.97 to 3.13 lbs/cu. yd. (1.76 to 1.86 kg/cu. m). Round FC 6 utilized a fracture control opening cut. This round had a hole factor of 1.11 holes/cu. yd. (1.45 holes/cu. m) and a powder factor of 2.77 lbs/cu. yd. (1.64 kg/cu. m).

It was intended that all fracture control rounds have first-row-in (F) holes drilled with a look-out so they would be parallel to the perimeter holes, as was done in the smooth blasting modifications. Although most of the F holes were looked out, this was not consistently done in all rounds unless the drillers were continuously supervised.

All fracture control perimeter rounds, except FC 6 and FC 7, used notched perimeter holes at the back and at one rib. Perimeter (P) holes on the other rib were drilled and loaded using the modified smooth blasting techniques to allow a round by round comparison of results. In FC 6, all P holes were notched, while in round FC 7, all but four P holes were notched.

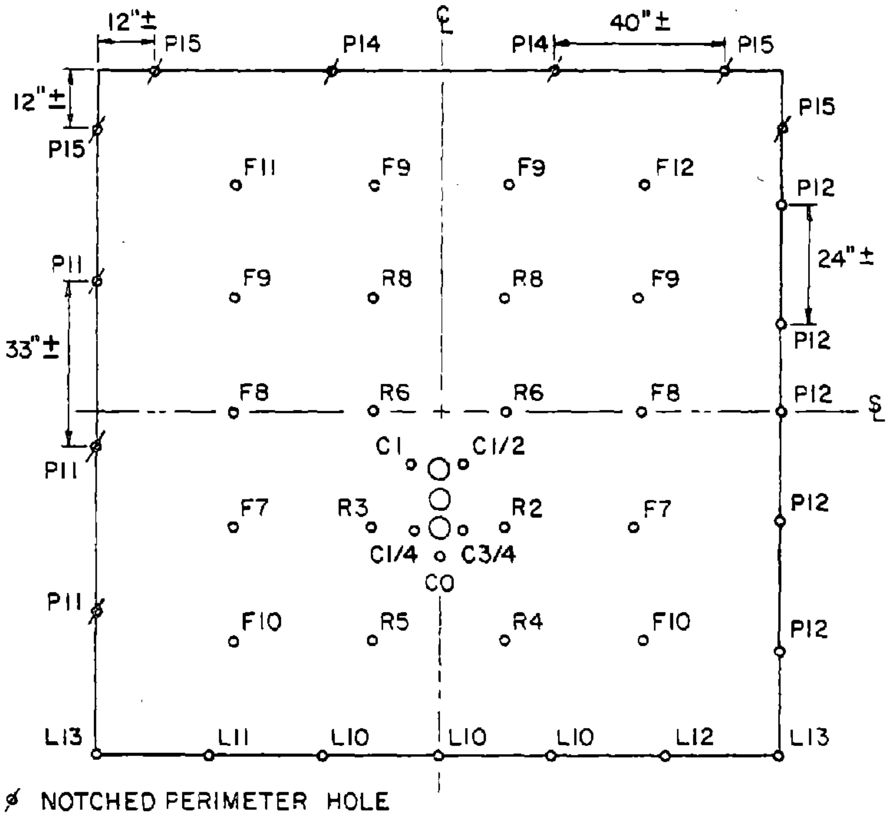
The fracture control bottom charge for the perimeter holes consisted of one or two sticks of 40 percent extra gelatin, 0.53 lb (0.24 kg) per stick. The perimeter hole column charge was generally similar to that of round MSB 6, consisting of 4 to 5 ft. (1.2 to 1.5 m) of 400 grain/ft (0.09 kg/m) Primacord. Perimeter holes were stemmed with about 24 in. (0.6 m) of either sand bags or water bags.

Spacing of notched perimeter holes was varied from 24 to 48 in. (0.6 to 1.2 m). The burden on the perimeter holes remained fairly constant (about 24 in. (0.61 m) at the back and 29 in. (0.74 m) at the ribs) although variations did occur due to inaccurate drilling.

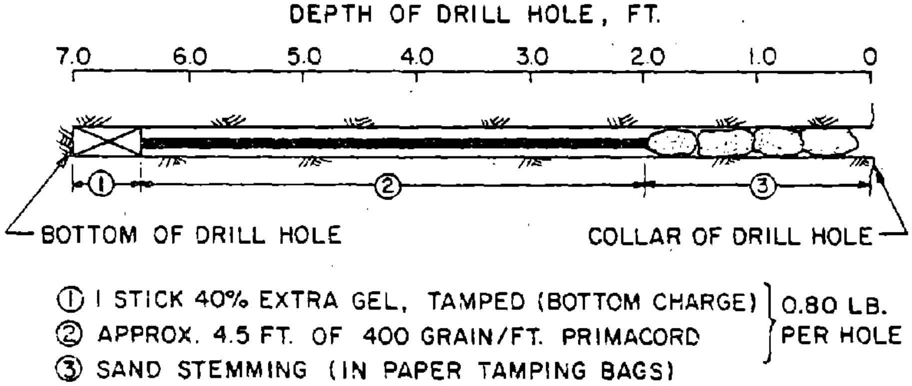
Figure 5-6 summarizes the drilling pattern, delay sequence, and perimeter hole loading for a typical fracture control round (FC 5). The complete round designs for FC 1 through FC 6 are shown in Figures B-10 through B-15, respectively, in Appendix B.

5.3.4 Techniques in Igneous Dike

In the large igneous dike in the north heading of the north-south pilot tunnel (see Figure 5-1), the contractor modified his specified smooth blasting round by adding a vertical row of four reliever holes. Figure 5-7 shows the perimeter hole loading, as well as the drilling pattern and delay sequence.

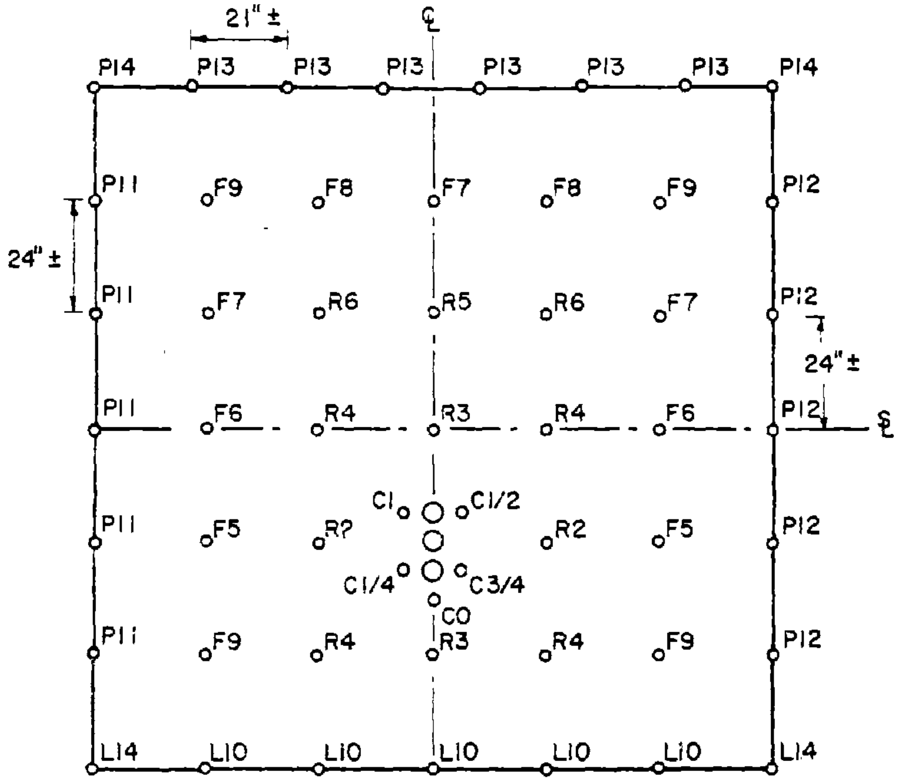


DRILLING PATTERN AND DELAY SEQUENCE



TYPICAL LOADING, NOTCHED PERIMETER HOLES

FIGURE 5-6. FRACTURE CONTROL ROUND FC 5



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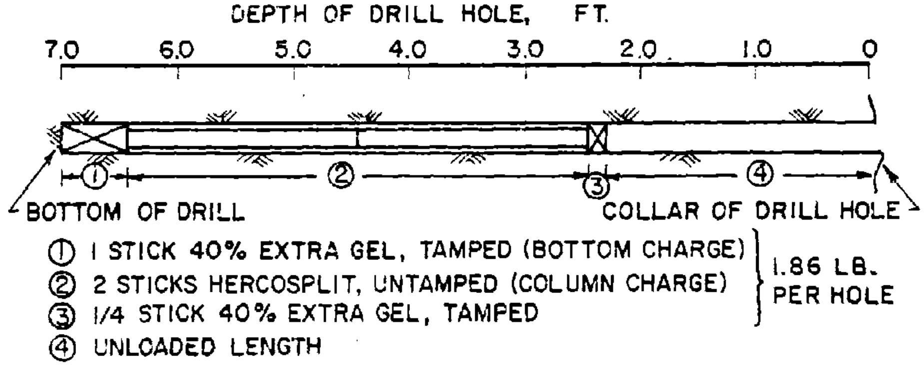


TYPICAL LOADING, PERIMETER HOLES

FIGURE 5-7. CONTRACTOR'S SPECIFIED SMOOTH BLASTING ROUND IN IGNEOUS DIKE

The round used 18 perimeter holes, with a charge weight of 1.86 lbs. (0.84 kg) per hole, at a spacing of 24 in. (0.6 m) at the ribs and 21 in. (0.5 m) at the back. The powder factor for the round was 4.20 lb/cu. yd. (2.48 kg/cu. m). The complete round design is shown in Figure B-16 in Appendix B. A total of six specified smooth blasting rounds were detonated in the igneous dike.

One fracture control round (FC 7) was implemented in the igneous dike. The location of the round is shown in Figure 5-1. Except for the perimeter holes, FC 7 used the same drilling pattern as the specified smooth blasting rounds. Figure 5-8 summarizes the drilling pattern, delay sequence, and perimeter hole loading for FC 7. The complete round design is shown in Figure B-17 in Appendix B.

Round FC 7 used 15 perimeter holes. At the left rib and back, spacing of 24 in. was used at the corners, with 32 in. (0.81 m) spacing for the interior holes. At the right rib, perimeter hole spacing of 24 in. (0.61 m) was used. All but four of the perimeter holes were grooved. Perimeter hole loading was generally 1.30 lb. (0.59 kg) per hole for notched holes, and 1.83 lb. (0.83 kg) per hole at the corners and in unnotched holes. The powder factor for the round was 3.55 lb/cu. yd. (2.10 kg/cu m).

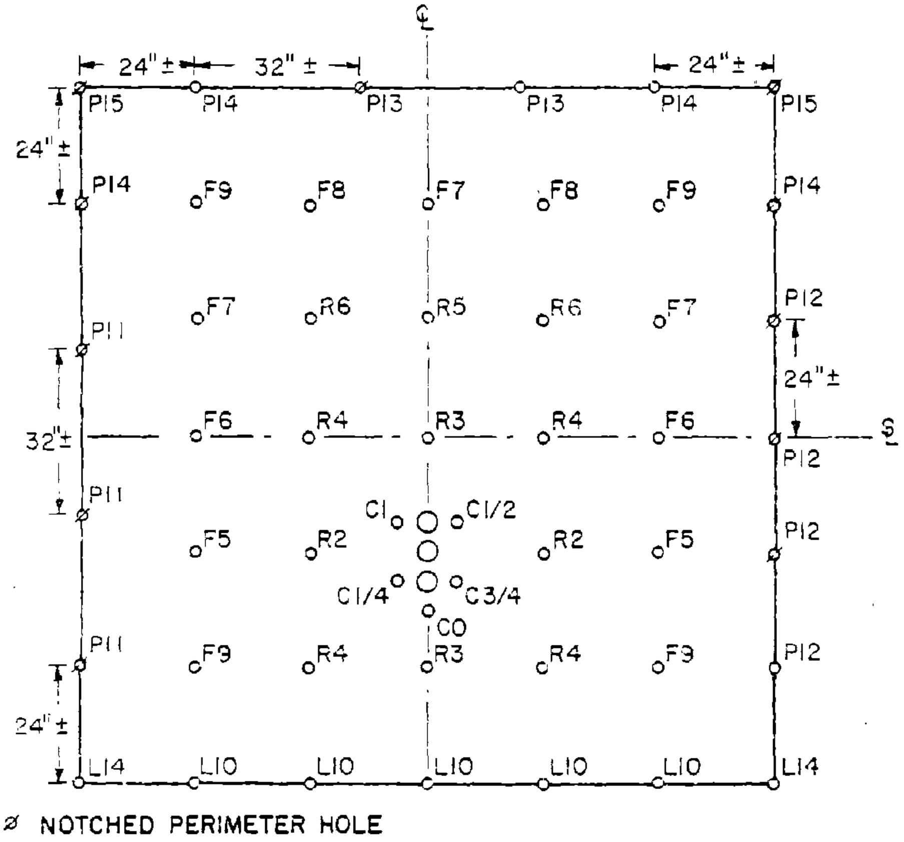
5.3.5 Evaluation Procedures

5.3.5.1 General - Most of the field evaluation was done using the three field data sheets shown in Figures 5-9, 5-10, and 5-11. A legend for the abbreviations and symbols used is shown in Figure 5-12.

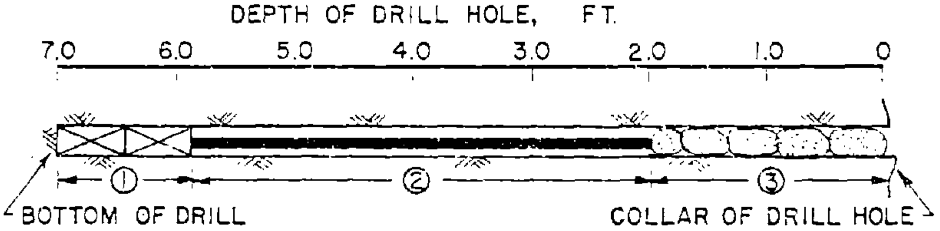
Figure 5-9 is a typical completed Drilling and Loading Report. It shows the as-drilled locations of the holes, the delay sequence, and typical loading of cut (C), reliever (R), first-row-in (F), and perimeter (P) holes.

Figure 5-10 is a typical completed Report of Advance. Advance measurements were made in two ways. First, a reference line was painted on the tunnel ribs and measurements were made from that. In addition, bootleg was measured (in brackets on the Report of Advance) and subtracted from the hole length.

Figure 5-11 is a Summary Report which lists the objectives of the round, summarizes the round geometry, and the results, and gives recommendations for changes to be made in subsequent rounds. Visual observations and measurements were made of flyrock throw, muck pile fragmentation, condition of perimeter hole half casts, and shear between perimeter holes. Maximum ground vibration and air blast noise measurements were noted, and the average advance



DRILLING PATTERN AND DELAY SEQUENCE



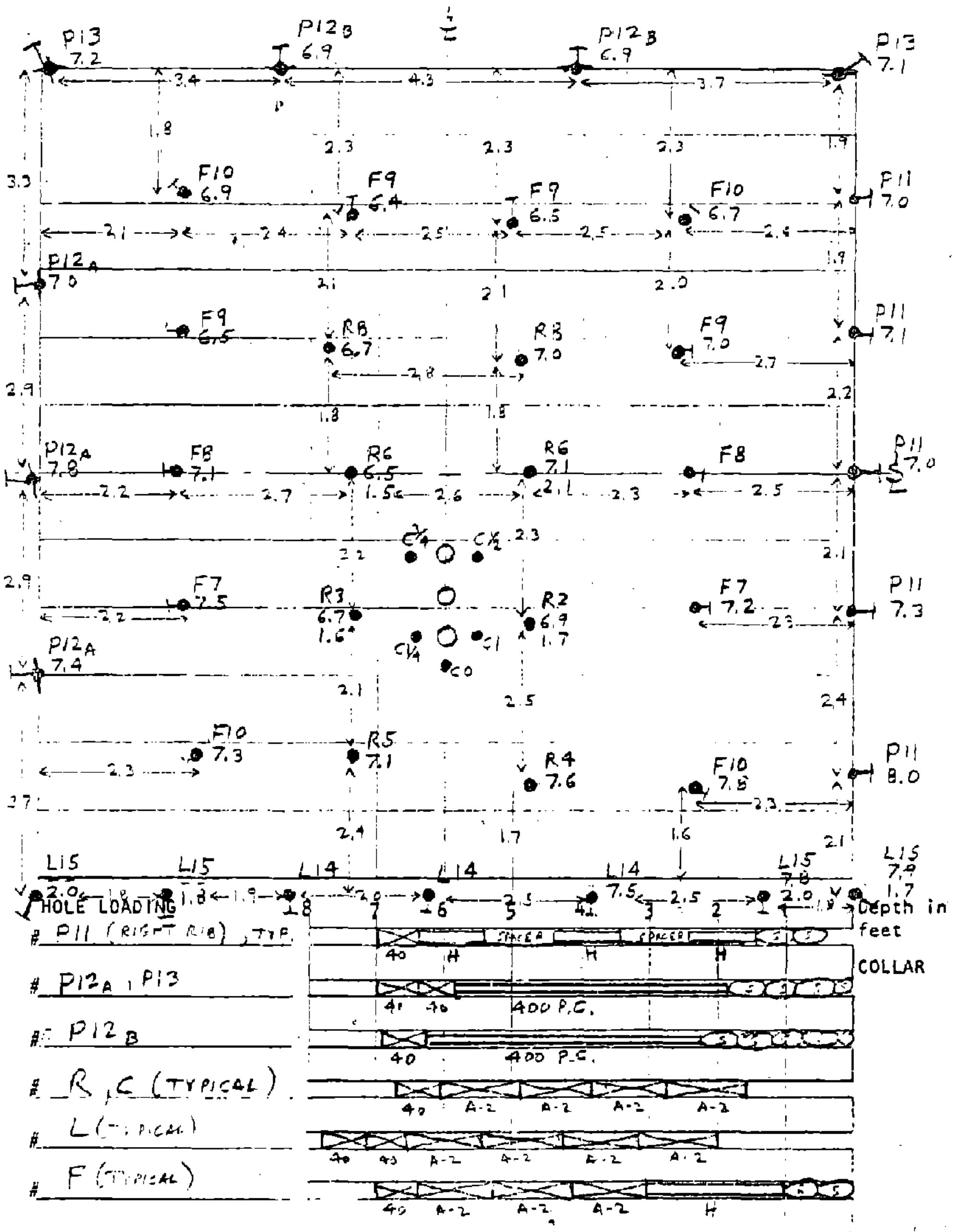
① 2 STICKS*40% EXTRA GEL, TAMPED (BOTTOM CHARGE)
② APPROX. 4.0 FT. OF 400 GRAIN/FT. PRIMACORD
1.30 LB. PER HOLE
③ SAND STEMMING (IN PAPER TAMPING BAGS)

TYPICAL LOADING, NOTCHED PERIMETER HOLES

* 3 STICKS USED IN CORNER HOLES (P15) AND UN NOTCHED HOLES

FIGURE 5-8. FRACTURE CONTROL ROUND FC 7 IN IGNEOUS DIKE

SCALE: ½" = 1'-0"



ACTUALLY MEASURE DEPTH, BURDEN AND SPACING OF EVERY HOLE. INDICATE LOOK OUT. PLOT TO SCALE.

SKETCH TYPICAL HOLE LOADINGS TO SCALE.

PORTER SQUARE PILOT TUNNEL BLASTING TEST PROGRAM

WEATHER & TEMP. Snowing

OBSERVER AFM/JWD/DBB

TIME OF DETONATION 1258

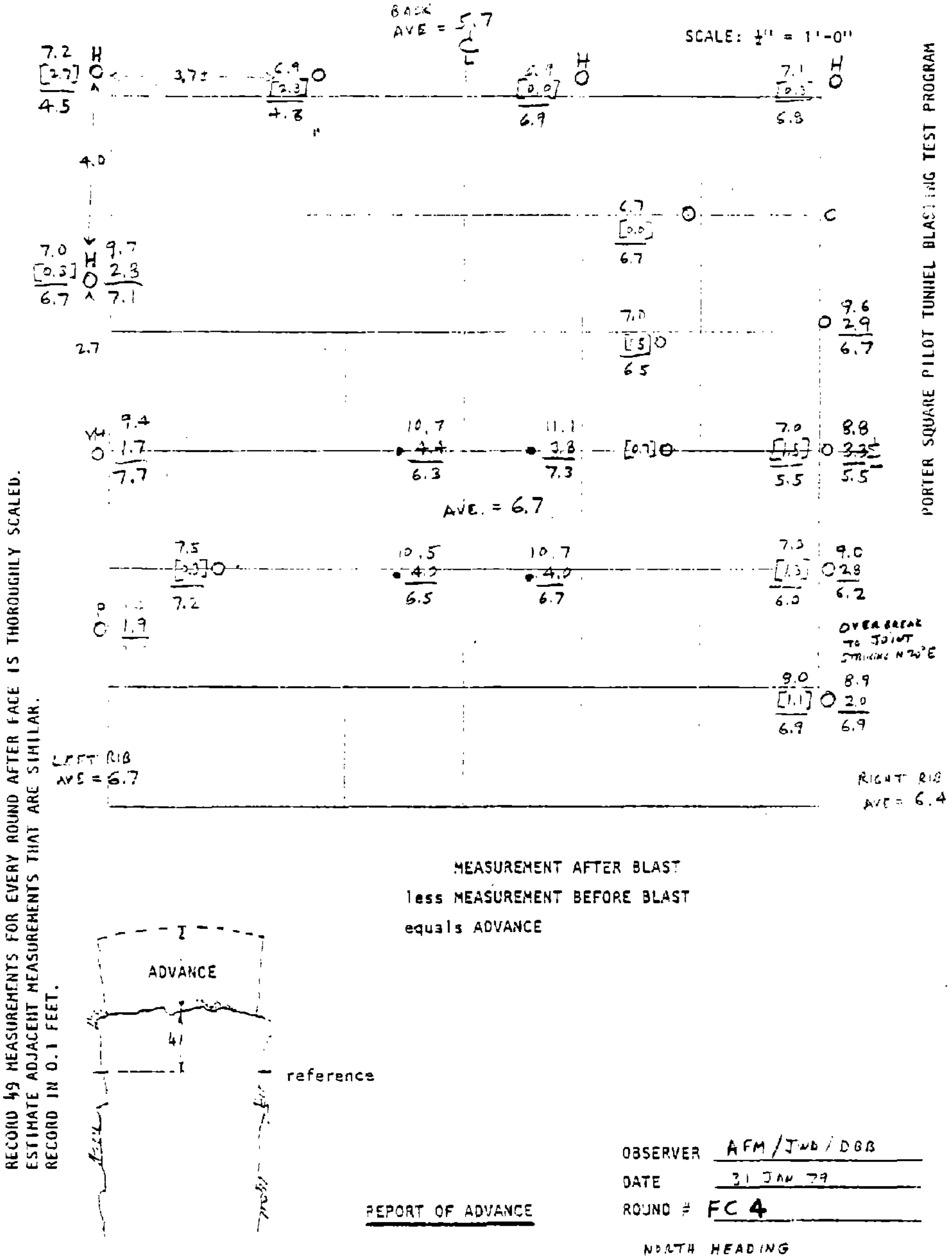
DATE 31 JAN 79

ROUND # F.C. 4

North Heading

DRILLING AND LOADING REPORT

FIGURE 5-9. TYPICAL DRILLING AND LOADING REPORT USED IN FIELD



MEASUREMENT AFTER BLAST
less MEASUREMENT BEFORE BLAST
equals ADVANCE

RECORD 49 MEASUREMENTS FOR EVERY ROUND AFTER FACE IS THOROUGHLY SCALED.
ESTIMATE ADJACENT MEASUREMENTS THAT ARE SIMILAR.
RECORD IN 0.1 FEET.

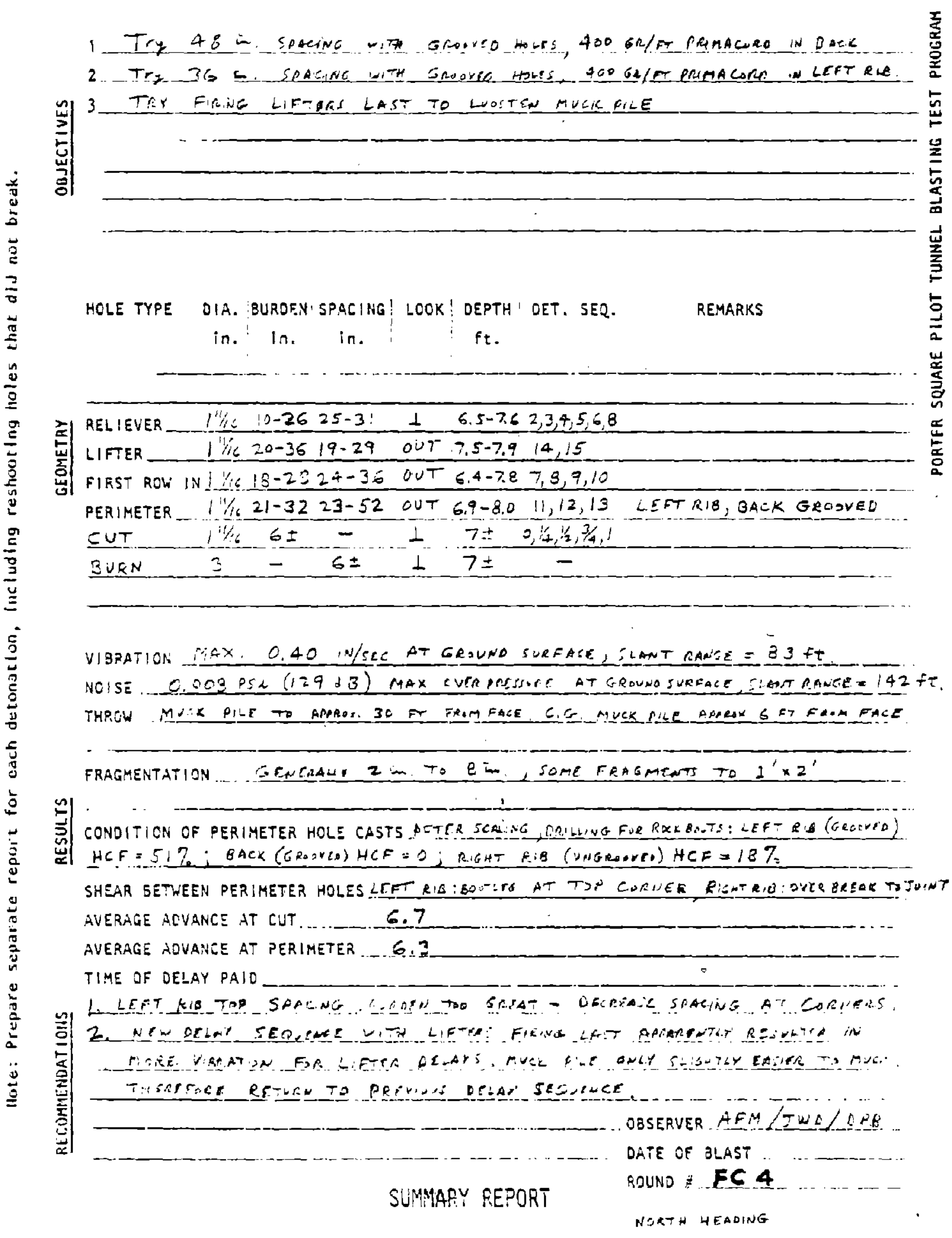
PORTER SQUARE PILOT TUNNEL BLASTING TEST PROGRAM

REPORT OF ADVANCE

OBSERVER AFM / JWB / DBB
DATE 31 JAN 79
ROUND # FC 4

NORTH HEADING

FIGURE 5-10. TYPICAL REPORT OF ADVANCE USED IN FIELD



PORTER SQUARE PILOT TUNNEL BLASTING TEST PROGRAM

Note: Prepare separate report for each detonation, including reshooting holes that did not break.

OBJECTIVES

1 TRY 48 in. SPACING WITH GROOVED HOLES, 400 GR/FT PRIMACORD IN BACK

2 TRY 36 in. SPACING WITH GROOVED HOLES, 400 GR/FT PRIMACORD IN LEFT RIB.

3 TRY FIRING LIFTERS LAST TO LOOSEN MUCK PILE

GEOMETRY

HOLE TYPE	DIA. in.	BURDEN in.	SPACING in.	LOOK	DEPTH ft.	DET. SEQ.	REMARKS
RELIEVER	1 11/16	10-26	25-31	⊥	6.5-7.6	2,3,4,5,6,8	
LIFTER	1 11/16	20-36	19-29	OUT	7.5-7.9	14,15	
FIRST ROW IN	1 11/16	18-23	24-36	OUT	6.4-7.8	7,8,9,10	
PERIMETER	1 11/16	21-32	23-52	OUT	6.9-8.0	11,12,13	LEFT RIB, BACK GROOVED
CUT	1 11/16	6±	–	⊥	7±	0,¼,½,¾,1	
BURN	3	–	6±	⊥	7±	–	

RESULTS

VIBRATION MAX. 0.40 IN/SEC AT GROUND SURFACE, SLANT RANGE = 83 FT

NOISE 0.009 PSI (129 dB) MAX OVERPRESSURE AT GROUND SURFACE, SLANT RANGE = 142 FT.

THROW MUCK PILE TO APPROX. 30 FT FROM FACE, C.G. MUCK PILE APPROX 6 FT FROM FACE

FRAGMENTATION GENERALLY 2 in. TO 8 in., SOME FRAGMENTS TO 1'×2'

CONDITION OF PERIMETER HOLE CASTS AFTER SCALING, DRILLING FOR ROCK BOLTS: LEFT RIB (GROOVED) HCF = 51%; BACK (GROOVED) HCF = 0; RIGHT RIB (UNGROOVED) HCF = 18%

SHEAR BETWEEN PERIMETER HOLES LEFT RIB: BOOTLEG AT TOP CORNER, RIGHT RIB: OVERBREAK TO JOINT

AVERAGE ADVANCE AT CUT 6.7

AVERAGE ADVANCE AT PERIMETER 6.3

TIME OF DELAY PAID

RECOMMENDATIONS

1. LEFT RIB TOP SPACING OFTEN TOO GREAT – DECREASE SPACING AT CORNERS.
2. NEW DELAY SEQUENCE WITH LIFTERS FIRING LAST APPARENTLY RESULTED IN MORE VIBRATION FOR LIFTER DELAYS, MUCK PILE ONLY SLIGHTLY EASIER TO MUCK. THEREFORE RETURN TO PREVIOUS DELAY SEQUENCE.

OBSERVER AFM/TWD/DPB

DATE OF BLAST

ROUND # FC 4

NORTH HEADING

SUMMARY REPORT

FIGURE 5-11. TYPICAL SUMMARY REPORT OF FIELD OBSERVATIONS AND MEASUREMENTS

PORTER SQUARE PILOT TUNNEL BLASTING TEST PROGRAM

SYMBOLS AND ABBREVIATIONS

DRILLING

P	Perimeter hole
C	Cut hole
R	Reliever hole
F	Hole in First row in from perimeter
L	Lifter hole

Figures on DRILLING AND LOADING REPORT (All measurements in feet)

P← 12 ——Perimeter hole
↖—Delay number. Hercules Superdet

7.9	Drilled depth of hole
2.0	Depth of unloaded hole at collar.

LOADING

▭	Untamped or stringloaded explosive	
⊠	Tamped explosive	
40	1-1/4" x 8" Hercules 40% Gelatin Extra 0.53#/stick	
A-2	1-1/4" x 16" Hercules Gel Power A-2	.71#/stick
H	7/8" Hercules Hercosplit	.30#/foot
400PC	400 grain/ft. Primacord	.06#/foot
WS	Water Stemming bag	
S	Sand Stemming in paper Tamping bags	

ADVANCE

Figures on REPORT OF ADVANCE (All measurements in feet)

8.2	Measurement before blast
$\underline{2.3}$	Measurement after blast
5.9	Subtraction equals advance
7.7	Drilled depth of hole
$\underline{[2.0]}$	Depth of bootleg after blast
5.7	Subtraction equals advance
$\overset{H}{o}$	Half cast remaining after blast (> 3 ft.±)
$\overset{P}{o}$	Partial half cast remaining after blast (1 ft. < H.C. < 3 ft.)

FIGURE 5-12. LEGEND FOR FIELD DATA SHEETS

at the cut holes and at the perimeter holes is estimated from the Report of Advance. In addition, the delay time, if any, associated with the special procedures and documentation was noted for use in compensating the contractor.

In an effort to make more meaningful and objective comparisons of the conditions of the ribs and back after the perimeter control experiment, other field measurements were made at the completion of the experimental program. Measurements were made of the total length of half casts visible at the perimeter of each round, and, from that a half cast factor was calculated. The half cast factor, which is described in more detail in the next section, gives a quantitative comparison of the condition of the ribs and back for each experimental round. In addition, silhouette photographs of tunnel cross sections, described in Section 5.3.5.3, were used to measure overbreak for each experimental round.

Also, vibration measurements, described in Section 5.3.5.4, were made so that vibrations from the experimental rounds could be evaluated and compared.

5.3.5.2 Half Cast Factors - The half casts left by perimeter drill holes (see Figure 5-13) after detonation of a tunnel round give an indication of perimeter control and the condition of the remaining rock. If all or a majority of perimeter hole half casts were present, it would indicate there was very little overbreak and that the remaining rock was not significantly damaged by the blast. If very few half casts were visible, it would indicate there was overbreak beyond the drill holes and the remaining rock may be damaged or loosened.

In order to make quantitative comparisons of the amount of perimeter control achieved using the three blasting techniques, a half cast factor (HCF) was devised. The HCF is defined as the total length of half casts visible, divided by the total length of perimeter holes. A HCF of 100 percent would indicate excellent perimeter control and no bootleg.

The HCF was determined from field measurements made after the pilot tunnel was completed. Because of scaling, roof bolt drilling and installation, shooting of subsequent rounds, and utility installation, some of the half casts were removed between the time the round was shot and the data was recorded. This is especially true in the back (roof) of the tunnel, where it is felt that this later activity caused breakage of rock slabs along the near horizontal bedding planes. As an example, field notes taken just after roof scaling was completed for round FC 5 indicate a HCF of almost 100 percent. The measurements taken after completion of the tunnel indicate a HCF of 55 percent. Thus, the HCF data from the back may be misleading, and in comparing the perimeter control techniques emphasis was placed on data from the ribs.

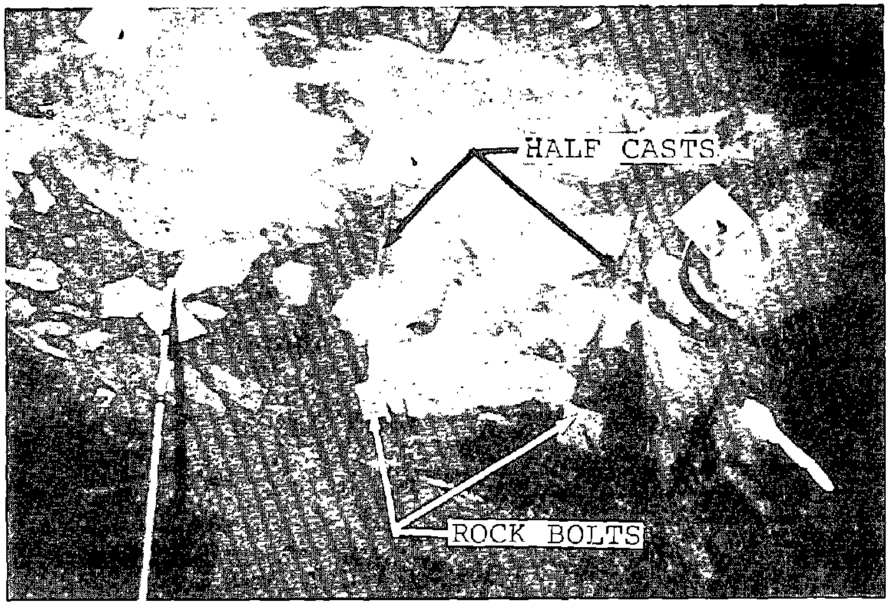


FIGURE 5-13. TYPICAL HALF CASTS LEFT BY PERIMETER DRILL HOLES AT BACK AFTER ROUND FC 5

Also, some half casts were removed in the west wall of the north heading by the opening cut experiments in that wall (Section 5.4.2). The west ribs of rounds MSB 4, MSB 5, FC 2, FC 4, and FC 6 were all partially damaged in that way. However, with the help of field notes, the HCF for these rounds were estimated and are considered to be reliable to within 5 to 10 percent.

The HCF does not reflect the wider spacing used in the fracture control rounds. To take into account this spacing, the specific half cast factor (SHCF) was introduced. This is simply the HCF divided by the number of holes per foot of perimeter. The SHCF gives an indication of the degree of perimeter contour control which also reflects the perimeter hole spacing. The larger the SHCF the better the control and/or the greater the spacing. (It should be noted that SHCF's greater than 100 can occur.)

5.3.5.3 Silhouette Photographs of Tunnel Cross Sections - In order to estimate and compare quantities of overbreak and underbreak, tunnel cross sections were recorded at the midpoint of each experimental round. The tunnel cross sections were recorded after the pilot tunnel was completed, using a silhouette photographic system. In this method, the tunnel lights were extinguished and

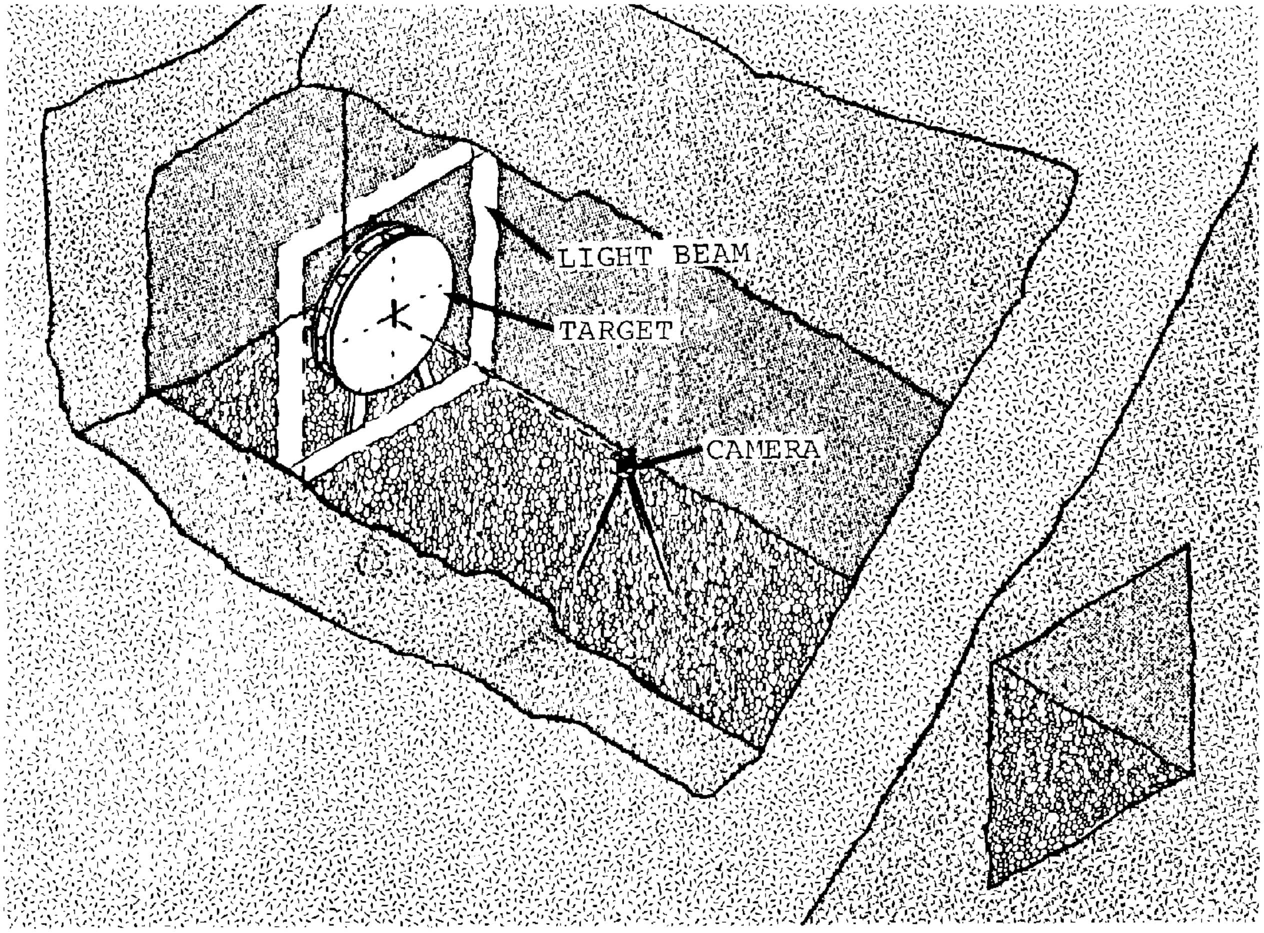


FIGURE 5-14. SCHEMATIC DRAWING OF TUNNEL SILHOUETTE PHOTOGRAPHIC TECHNIQUE

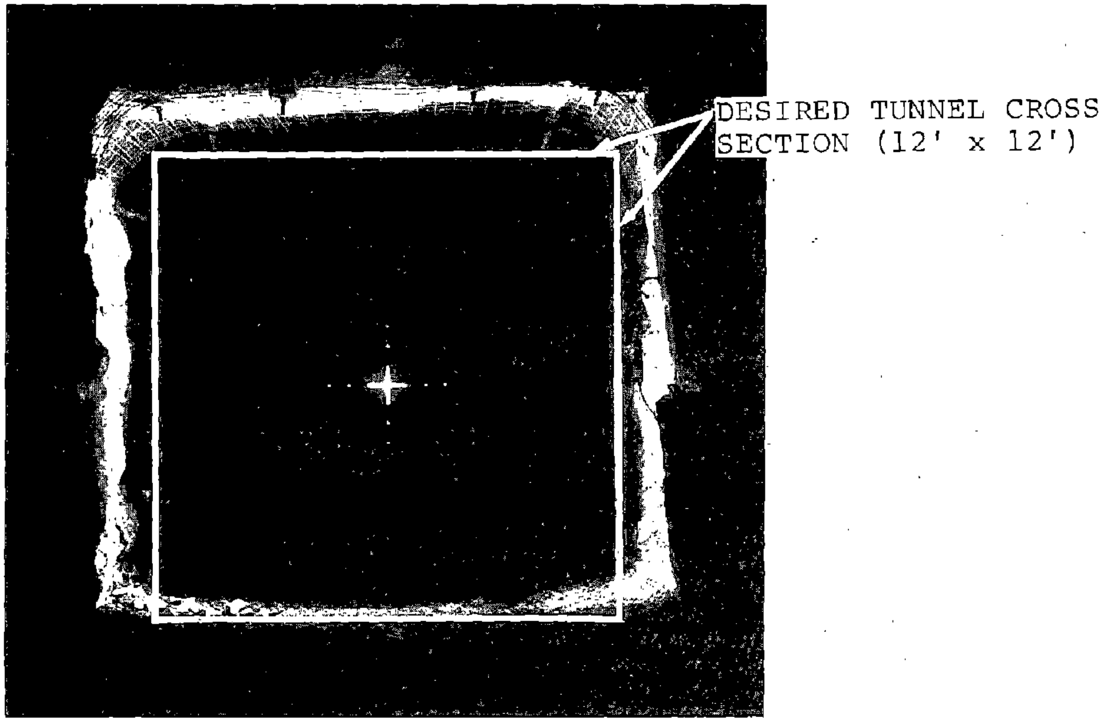


FIGURE 5-15. TYPICAL TUNNEL SILHOUETTE PHOTOGRAPH

a scaled photograph was taken of a narrow light beam which made visible the tunnel cross section. Figure 5-14 is a schematic, three dimensional drawing which illustrates the technique. Figure 5-15 shows a typical resulting tunnel silhouette photograph. By superimposing the design excavation limits onto the photograph, the cross sectional area of overbreak was measured with a planimeter at each rib and the back. This area was multiplied by the average tunnel round advance (about 6.6 ft.) (2.0 m) to get the estimated quantity of overbreak at each rib and the back.

As discussed in Section 5.3.5.2, the west ribs of several rounds in the north heading were damaged by the opening cut experiments in the sidewall. For rounds MSB 5 and FC 2, the damage was minor and overbreak data are considered reliable. For rounds MSB 4, FC 4, and FC 6, however, the damage precluded an accurate estimate of overbreak for the west rib.

5.3.5.4 Vibration Monitoring - The pilot tunnel contractor (Perini Corporation) measured ground vibrations and air blast overpressures adjacent to the nearest structures for almost every round fired. Measurements were made with a SINCO model S-5 Vibration Monitor with two independent remote sensors. Each sensor monitored three orthogonal components (vertical, longitudinal and transverse with respect to the source) of ground motion. Ground particle velocity, in in./sec., was recorded on direct write-dry photographic paper using a seven channel oscillographic recording system. The seventh channel recorded air blast overpressure, in psi, and was measured by a model 53108 remote air blast sensor.

The investigators monitored ground vibrations and air blast overpressures for several tunnel rounds. Ground vibrations were measured using a Sprengnether model VS-1100 engineering seismograph, equipped with a remote sensor (seismometer), which also measured ground particle velocity, in in./sec., in three orthogonal axes. Particle velocity was recorded on direct-write photographic paper using a four channel recording system. The fourth channel recorded air blast overpressure, in psi, and was measured by a model SM1 remote air wave detector.

Additional ground vibration measurements were made for several rounds by the Noise Measurement and Assessment Laboratory of the Department of Transportation/Transportation Systems Center (DOT/TSC). The DOT/TSC vibration monitoring equipment generally consisted of seven ENDEVCO model 2217E acceleration transducers fed into a Hewlett-Packard 3960A instrumentation recorder. Measured acceleration data were processed through a filter to a computer where the time history of ground accelerations was integrated to calculate particle velocity values. All transducers measured the vertical component of ground motion.

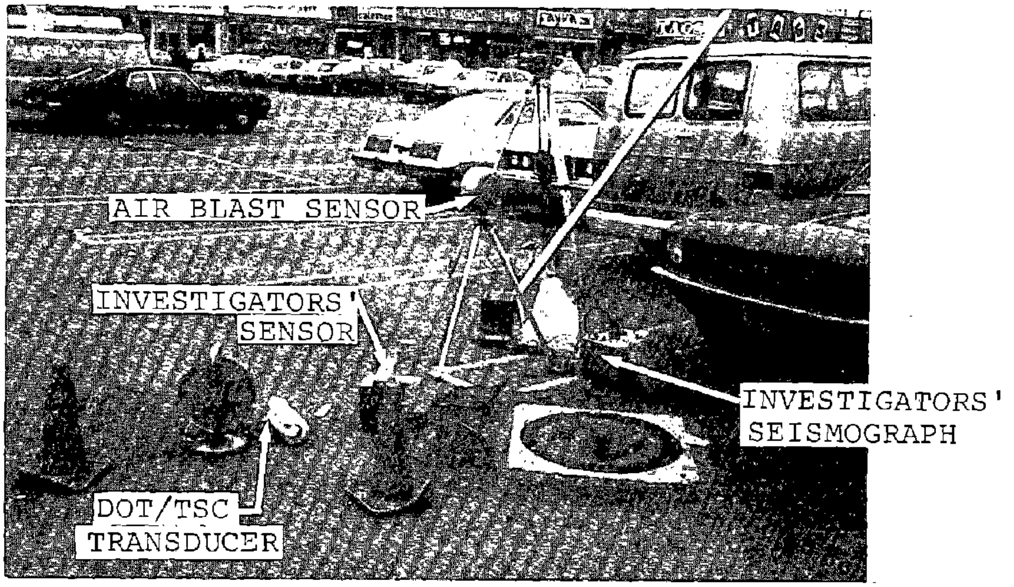


FIGURE 5-16. INVESTIGATORS' BLAST MONITORING EQUIPMENT AND DOT/TSC TRANSDUCER AT SENSOR LOCATION J

Figure 5-16 shows the locations near the site where sensors were deployed during the program. The investigators' sensor and those of the contractor were generally placed on a sidewalk or parking lot pavement and were anchored to prevent slippage of the sensor in the event that high ground accelerations were generated by blasting. Air wave detectors were mounted on tripods and located about four feet (1.2 m) above the ground surface. Figure 5-17 is a photograph of the investigators' blast monitoring equipment set up adjacent to a DOT/TSC transducer at sensor location J.

Except at sensor locations N, P, and Q, DOT/TSC transducers were mounted on 7/8 in. (22 mm) diameter by 1-ft. (0.3 m) long brass rods driven into the ground below the parking lot pavement. At sensor location N, the transducer was mounted on the exterior foundation wall of the CVS store within the Porter Square Shopping Center. At sensor location P, the transducer was located on the exterior foundation wall of Star Market within the Porter Square Shopping Center. At location Q, the DOT/TSC transducer was mounted on the tunnel wall.

Maximum vibrations at the various sensor locations were summarized for each round. In addition, data from perimeter delays were analyzed in an effort to compare maximum vibrations caused by the different perimeter control techniques. Data from all MSB and FC rounds, as well as from several SSB rounds were reduced and summarized. The SSB rounds chosen were generally adjacent to or in close proximity to the FC or MSB rounds so that the average slant range (radial distance from vibration source to sensor) would be about the same for each technique.

5.4 OPENING CUT EXPERIMENTS

5.4.1 Contractor's Techniques

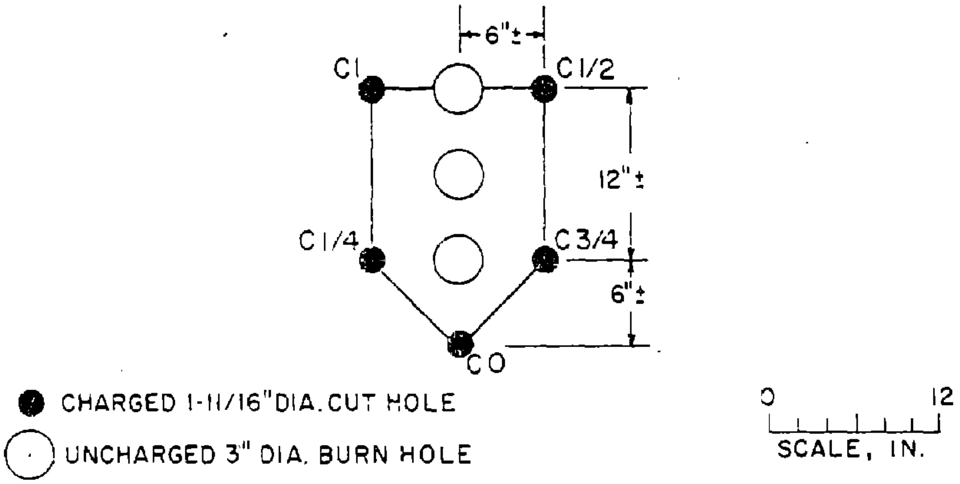
The opening cut used by the contractor is illustrated in Figure 5-17. This cut consisted of three 3-in. (75 mm) holes and five 1-11/16 in. (43 mm) holes, each drilled about 7 ft. (2.1 m) deep. The three large diameter holes provided relief for the cut. Each small diameter hole was loaded with about 3.9 lbs. (1.77 kg) of tamped explosive, and detonated with regular delay caps (Hercules Superdet Electric) in the sequence indicated on Figure 5-17.

5.4.2 Tests in Tunnel Sidewall

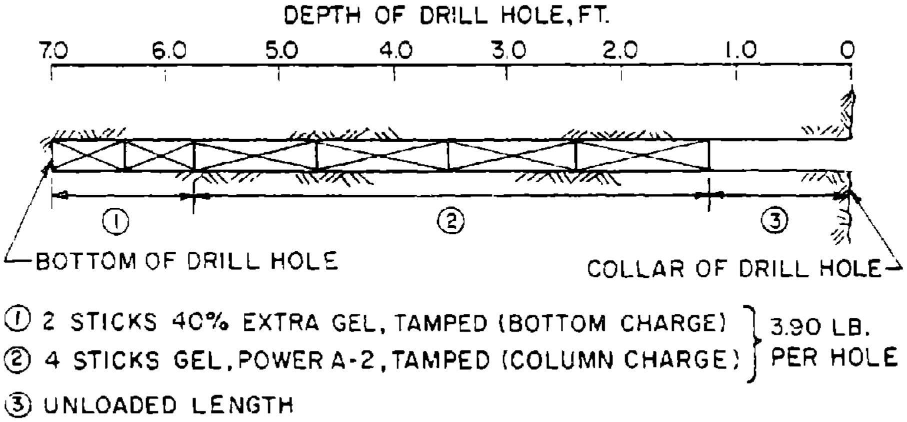
Both the contractor's cut and the fracture control cut were first evaluated by tests conducted separate from full heading rounds, in order to minimize disruption to the contractor and to allow for separate evaluation of the cuts.

The first opening cut experimentation was done at the same time as the test chamber experiments. The east-west access tunnel had been excavated and blasting was ready to start in the north heading of the main north-south pilot tunnel. At about Station 2+70, a fracture control cut, shown schematically in Figure 4-6, was drilled. It was planned to fire the cut in two stages. First, the three notched holes would be loaded and fired. The results would be observed, then the center hole would be loaded and fired, and the results again would be observed. However, when the three notched holes were fired, craters were formed from the drill holes which overlapped and destroyed the collar of the center hole. The damage prevented the center hole from being loaded and detonated.

Later in the program, several opening cut experiments were conducted in the west wall of the north heading of the main north-south pilot tunnel. In the first of these experiments, the fracture control cut (Figure 4-6) was drilled at Station 3+45. Just to the north, at Station 3+64, the contractor's cut (Figure 5-17) was also drilled in the tunnel wall. Both cuts were detonated at the same time as the next north heading round (FC 5).

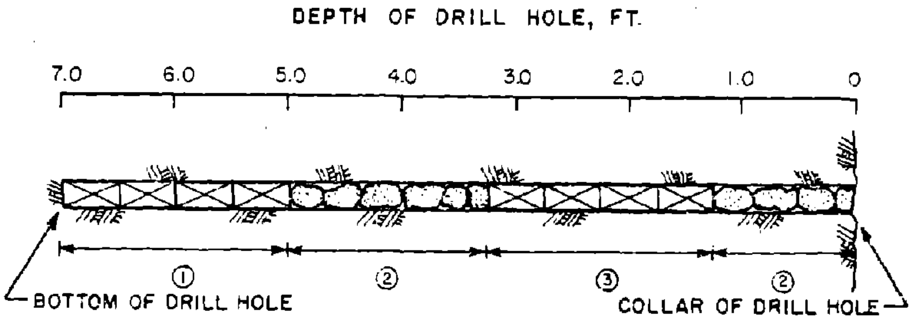


VIEW OF FACE



TYPICAL LOADING, CUT HOLES

FIGURE 5-17. CONTRACTOR'S OPENING CUT



① 4 STICKS 40% EXTRA GEL, TAMPED, ON DELAY CAP NO. 2
② SAND STEMMING (IN PAPER TAMPING BAGS)
③ 4 STICKS 40% EXTRA GEL, TAMPED, ON DELAY CAP NO. 3

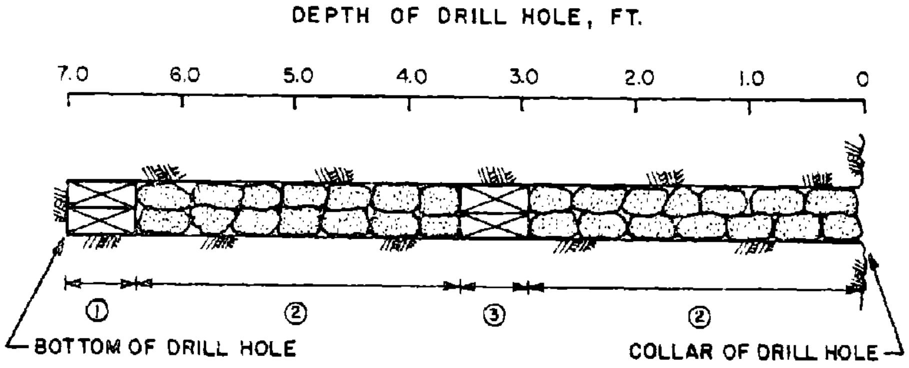
FIGURE 5-18. LOADING OF 1-11/16 IN. DIAMETER CRATER CUT HOLE IN TUNNEL SIDEWALL

Further north in the same west wall of the north heading, additional experiments were conducted to evaluate the fracture control cut. In these tests, a single hole was drilled and detonated, without the three notched holes around it, to see if the crater from a single loaded hole could form a sufficient opening cut. In the first of these tests, at Station 3+82, a 1-11/16 in. (43 mm) diameter hole was drilled to a depth of 7 ft. (2.1 m) and loaded as shown in Figure 5-18. The decked charges were fired on two separate delays, the charge nearest the collar on delay period 2 (1.5 sec.) and the bottom charge on delay period 3 (2.1 sec.).

In the second of these cratering experiments, at Station 3+95, the hole diameter was increased to 3 in. (76 mm) and a similar loading and delay sequence was used, as shown in Figure 5-19. In the 3 in. (76 mm) hole, the four sticks of 40 percent extra gelatin were taped together in a bundle.

5.4.3 Fracture Control Techniques in Full Heading Rounds

After the fracture control techniques had been evaluated in the tunnel sidewalls, three fracture control cuts were detonated as part of full heading rounds. The locations of these rounds, designated as FC 6, FC Cut 1, and MSB 6/FC Cut 2, are shown in Figure 5-1.



① 4 STICKS 40% EXTRA GEL, TAMPED, ON DELAY CAP NO. 2
② SAND STEMMING (IN PAPER TAMPING BAGS)
③ 4 STICKS 40% EXTRA GEL, TAMPED, ON DELAY CAP NO. 3

FIGURE 5-19. LOADING OF 3-IN. DIAMETER CRATER CUT HOLE IN TUNNEL SIDEWALL

Round FC 6 utilized a fracture control opening cut similar to that shown in Figure 4-6, except that:

a. The three notched cut holes did not look-in. It was intended that the holes be drilled perpendicular to the face, but in fact, measurements after the round indicated that two of the holes looked-out about 2 to 4 in. (50 to 100 mm).

b. The decked charges were detonated on separate delays, with the top charge detonated at 1.5 sec. and the bottom charge at 2.1 sec.

c. The diameter of the center fragmentation hole was 1-11/16 in. (43 mm).

Rounds FC Cut 1 and MSB 6/FC Cut 2 utilized the fracture control opening cut shown in Figure 4-6 and described in Section 4.3.

5.4.4 Evaluation Procedures

Field evaluation of the opening cut experiments utilized the field data sheets described in Section 5.3.5.1. Advance/bootleg measurements were considered the most important measurement in evaluating the opening cuts.

Vibration measurements were made using the equipment described in Section 5.3.5.4. Vibration records were analyzed so that maximum vibrations from both the contractor's opening cut and the FC opening cut could be tabulated and compared. Vibration data from the three FC cuts, as well as from several adjacent contractor opening cuts, were reduced and summarized.

6. PERIMETER CONTROL RESULTS

6.1 GENERAL

As described in Section 5.3, the perimeter control techniques were grouped into three classifications: specified smooth blasting (SSB) techniques as employed by the contractor, modified smooth blasting (MSB) techniques developed by the investigators, and fracture control (FC) techniques developed by the investigators. For comparison purposes, 11 SSB rounds were documented, along with the six MSB rounds and seven FC rounds. The procedures and results of these rounds, together with their locations, are summarized in Figure 6-1. For each round, the perimeter hole spacing and column load, as well as the half cast factor, the specific half cast factor, the amount of overbreak, and the advance, are noted. Those ribs or backs where the perimeter holes were notched are noted with an N after the perimeter hole spacing.

The tunnel silhouette photos (see Section 5.3.5.3) for the rounds noted in Figure 6-1 are shown in Appendix C.

6.2 SPECIFIED SMOOTH BLASTING (SSB) RESULTS

In general, the contractor's specified smooth blasting round pulled well and mucked easily but caused the most damage to the final rock surfaces of the three techniques used. The average half cast factor for the SSB rounds noted in Figure 6-1 was only 9.4 percent. The high column charge (0.30 lb/ft) (0.45 kg/m) was felt to contribute most to this condition, along with the geologic factors noted in Section 3.3.

The average overbreak was 11.5 cu. yd. (8.8 cu. m) per round. This large amount of overbreak was attributed mainly to relaxed drilling control, which will be discussed in subsequent sections, as well as to the high column charge utilized and to the geologic factors noted in Section 3.3.

The average advance for the SSB rounds was generally about 90 to 95 percent of the average drilled depth. However, the perimeter (P) holes often left bootleg, especially at the corners. The average advance at the P holes for the four SSB rounds in Figure 6-1, where advance measurements were made, was 86 percent of the average P hole depth. The bootleg was attributed to relaxed drilling control and to the increased burden at the bottoms of the holes due to "looking out" the P holes. Figure 6-2 shows the ribs and back of a typical SSB round.

SECTION A-A

SOUTH HEADING

ROUND NO.	M.S. DELAY	SSB 92	SSB 81	MSB 6/ FC CUT 2	FC CUT 1	SSB 53	FC 3	FC 1	SSB 47	MSB 1	SSB 35	SSB 33
WEST RIGHT RIB	24 .30 2% (1) 10 5.04 (1) 94%	24 .32 7% 14 6.99 -	24 .32 10% 20 4.74 -	18 .06 50% 75 4.20 80%	24 .30 7% 14 4.50 91%	24 .32 5% 10 2.20 -	29 N 0 (3) 32% 77 2.74 90%	24 .19 25% 50 4.16 91%	24 .32 19% 38 4.79 -	24 .30 31% 62 4.40 88%	24 .32 32% 64 2.84 68%	24 .32 - - 1.56 75%
BACK	21 .30 11% 19 2.35 -	21 .32 13% 23 3.33 -	21 .32 1% 2 3.33 -	18 .06 27% 41 2.35 96%	21 .30 0% 0 3.42 -	21 .32 0% (1) 0% (1) - (1) -	36 N 0 (2) 0% (1) 0% (1) - (1) -	24 (4) .06N/.19 6% 12 3.27 -	21 .32 10% 18 4.35 -	24 .30 19% 38 3.52 76%	21 .32 0% 0 3.96 -	21 .32 - - 2.69 -
LEFT RIB EAST	24 .30 32% 64 1.22 95%	24 .32 5% 10 3.17 -	24 .32 17% 34 2.30 -	18 .06 35% 53 1.22 95%	24 .30 16% 32 1.66 84%	24 .32 4% 8 2.30 -	29 .19 21% (1) 51 (1) 4.25 (1) 86%	24 N .06 13% (1) 26 (1) 6.89 (1) 90%	24 .32 0% 0 5.13 -	24 .30 21% 42 6.06 80%	24 .32 11% 22 4.01 81%	24 .32 - - 3.72 94%

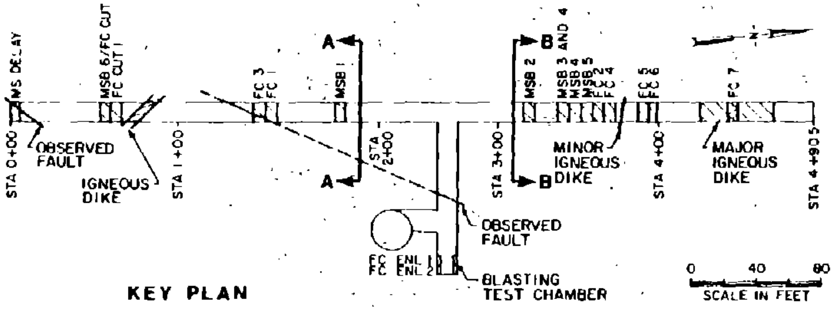
0+0 0+20 0+40 0+60 1+40 1+60 1+80 2+10 2+20

SECTION B-B

NORTH HEADING

ROUND NO.	SSB 34	SSB 36	MSB 2	SSB 42	MSB 3 & 4	MSB 4	MSB 5	FC 2	FC 4	SSB 54	FC 5	FC 6	SSB 64	SSB 74	FC 7
WEST LEFT RIB	24 .32 13% 26 4.20 89%	24 .32 11% 22 3.52 90%	24 .30 18% 36 3.76 96%	24 .32 14% 28 3.13 -	24 .30 16% 32 3.62 98%	24 .30 - (5) - (5) - (5) 88%	24 .19 - (5) - (5) 2.69 (5) 92%	29 N .06 56% (5) 135 (5) 1.32 (5) 89%	36 N .06 (6) 51% (5) 153 (5) - (5) 89%	24 .32 12% 24 2.64 -	33 N .06 70% 193 3.33 78%	36 N .06 - (5) - (5) - (5) 56%	24 .32 35% 70 3.18 -	24 .32 10% 20 1.56 -	29 N .06 (8) 50% 121 1.96 85%
BACK	21 .32 0% 0 6.40 -	21 .32 0% 0 5.04 -	24 .30 10% 20 5.33 -	21 .32 0% 0 4.20 -	24 .30 7% 14 2.74 -	24 .30 3% 6 3.13 -	24 .19 12% 24 2.84 91%	36 N .06 0% 0 3.71 -	48 N .06 0% 0 3.62 83%	21 .32 2% 4 2.10 -	40 N .06 (7) 55% 183 5.82 97%	36 N .06/0 (3) 10% 30 5.57 77%	21 .32 0% 0 4.55 -	21 .32 0% 0 4.20 -	29 (9) .06 (8) 13% 31 3.62 94%
RIGHT RIB EAST	24 .32 16% 32 4.89 92%	24 .32 8% 16 4.89 99%	24 .30 11% 22 5.87 98%	24 .32 10% 20 4.74 -	24 .30 3% 6 4.20 93%	24 .30 13% 26 3.96 89%	24 .19 42% 84 4.50 86%	24 .06 48% 96 3.13 97%	24 .19 18% 36 4.64 85%	24 .32 7% 14 3.03 -	24 .19 9% 18 1.17 92%	36 N 0 (3) 37% 111 3.18 34%	24 .32 18% 36 3.18 -	24 .32 7% 14 4.11 -	24 N .06 (8) 32% 64 1.96 90%

3+0 3+20 3+40 3+60 3+80 4+00 4+40



KEY PLAN

NOTES:

(1) FAULT ZONE PASSED THROUGH RIB OR BACK. HCF, SHCF, AND OVERBREAK DATA REFLECT OVERBREAK INTO FAULT ZONE.

(2) BOTTOM CHARGE OF 0.53 LB. USED WITHOUT COLUMN CHARGE.

(3) BOTTOM CHARGE OF 1.06 LB. USED WITHOUT COLUMN CHARGE.

(4) TWO OF FIVE HOLES AT BACK WERE NOTCHED, HCF AND SHCF CALCULATED FOR NOTCHED HOLES. HCF = 0 FOR UNNOTCHED HOLES.

(5) RIB DAMAGED BY EXPERIMENTAL OPENING CUT BLAST BEFORE HCF MEASURED. IF HCF, SHCF AND OVERBREAK DATA ARE SHOWN, THEY ARE ESTIMATES BASED ON FIELD OBSERVATIONS AND MEASUREMENTS PRIOR TO THE OPENING CUT EXPERIMENTS.

(6) BOTTOM CHARGE OF 1.06 USED.

(7) CORNER HOLES AT BACK HAD 1.06 LB. BOTTOM CHARGE.

(8) BOTTOM CHARGE OF 1.06 LB. USED EXCEPT AT CORNERS, WHERE 1.59 LB. USED.

(9) ONLY ONE OF FOUR HOLES NOTCHED.

LEGEND:

33N	PERIMETER HOLE SPACING, IN., N INDICATES DRILL HOLE NOTCHED
.06	PERIMETER HOLE COLUMN CHARGE, LB./FT.
70%	HALF CAST FACTOR (HCF)
193	SPECIFIC HALF CAST FACTOR (SHCF)
3.33	VOLUME OF OVERBREAK, CU. FT.
78%	ADVANCE, % OF AVE. PERIMETER HOLE DEPTH

$$\text{HFC} = \frac{\text{TOTAL LENGTH OF HALF CASTS VISIBLE}}{\text{TOTAL AS DRILLED LENGTH OF ALL PERIMETER HOLES IN RIB (OR BACK)}}$$

$$\text{SHCF} = \frac{\text{HCF}}{\text{NO. OF DRILL HOLES PER FT. OF PERIMETER}}$$

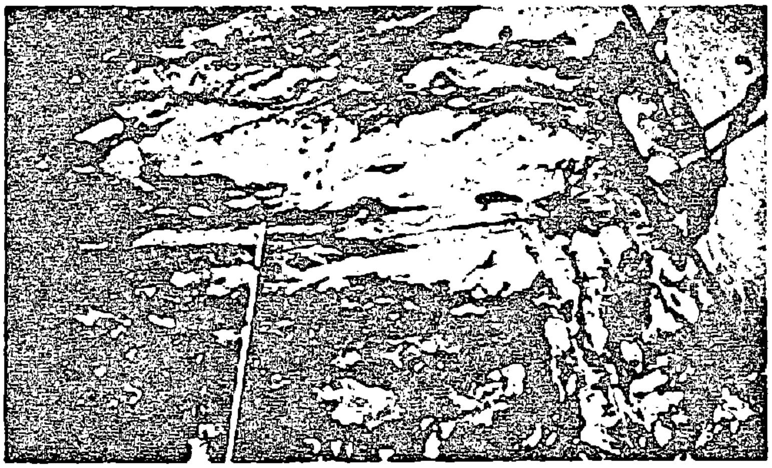
GENERAL NOTES:

1 IF PERIMETER HOLES ARE NOTCHED, IT IS NOTED. OTHERWISE, HOLES WERE NOT NOTCHED.

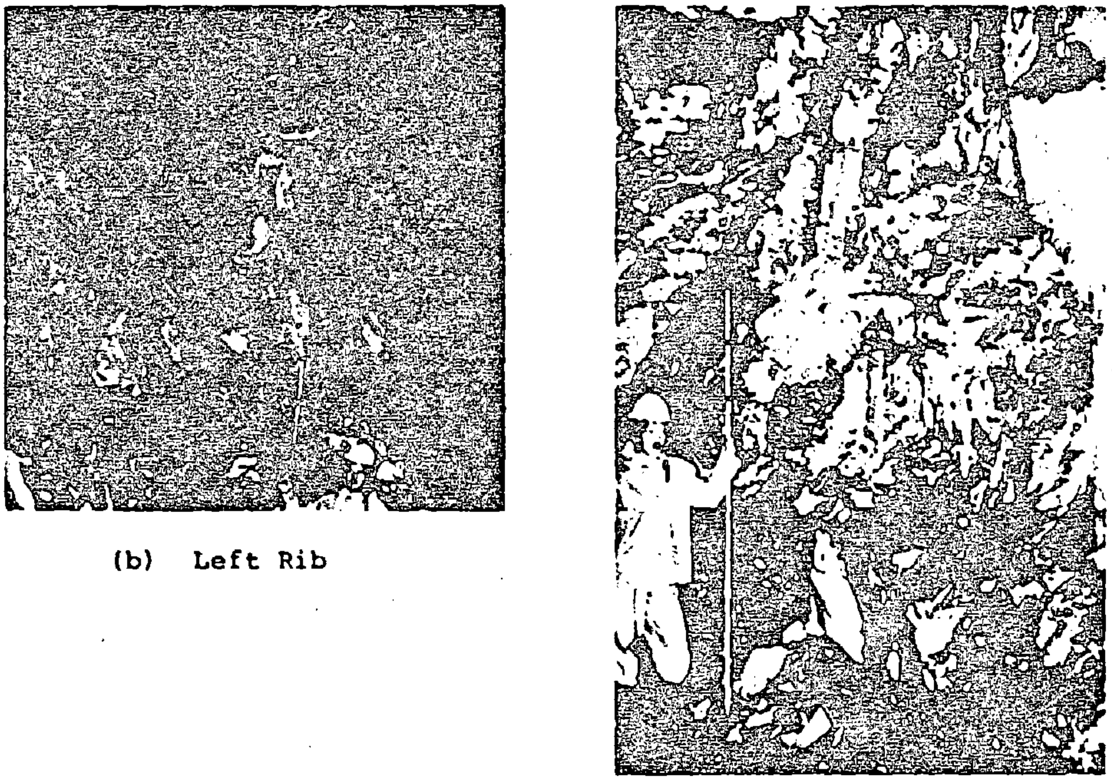
2 BOTTOM CHARGE OF 0.53 LBS. WAS USED IN PERIMETER HOLES UNLESS OTHERWISE NOTED.

3 HALF-CASTS WERE MEASURED AT COMPLETION OF EXCAVATION. SCALING OF LOOSE ROCK, INSTALLATION OF ROCK BOLTS, AND SUBSEQUENT BLASTING MAY HAVE REMOVED SOME HALF-CASTS.

FIGURE 6-1. SUMMARY OF PERIMETER CONTROL PROCEDURES AND RESULTS



(a) Back



(b) Left Rib

(c) Right Rib

FIGURE 6-2. BACK AND RIBS OF TYPICAL SSB ROUND (SSB 54)

The average drilling time for the SSB rounds was 2.2 hours. An average of 1.3 hours was used to load and shoot the round, and mucking generally took about 2.3 hours. The muck pile was generally about 6 ft. (1.8 m) high at the face and extended about 40 ft. (12 m) from the exposed tunnel face. The muck size was generally 2 to 6 in. (5 to 15 mm), with occasional slabs to about 2 ft. x 1 ft. (0.3 m x 0.6 m). Figure 6-3 shows the muck pile after a typical SSB round.

FIGURE 6-3. MUCK PILE AFTER TYPICAL SSB ROUND (SSB 36)

6.3 MODIFIED SMOOTH BLASTING (MSB) RESULTS

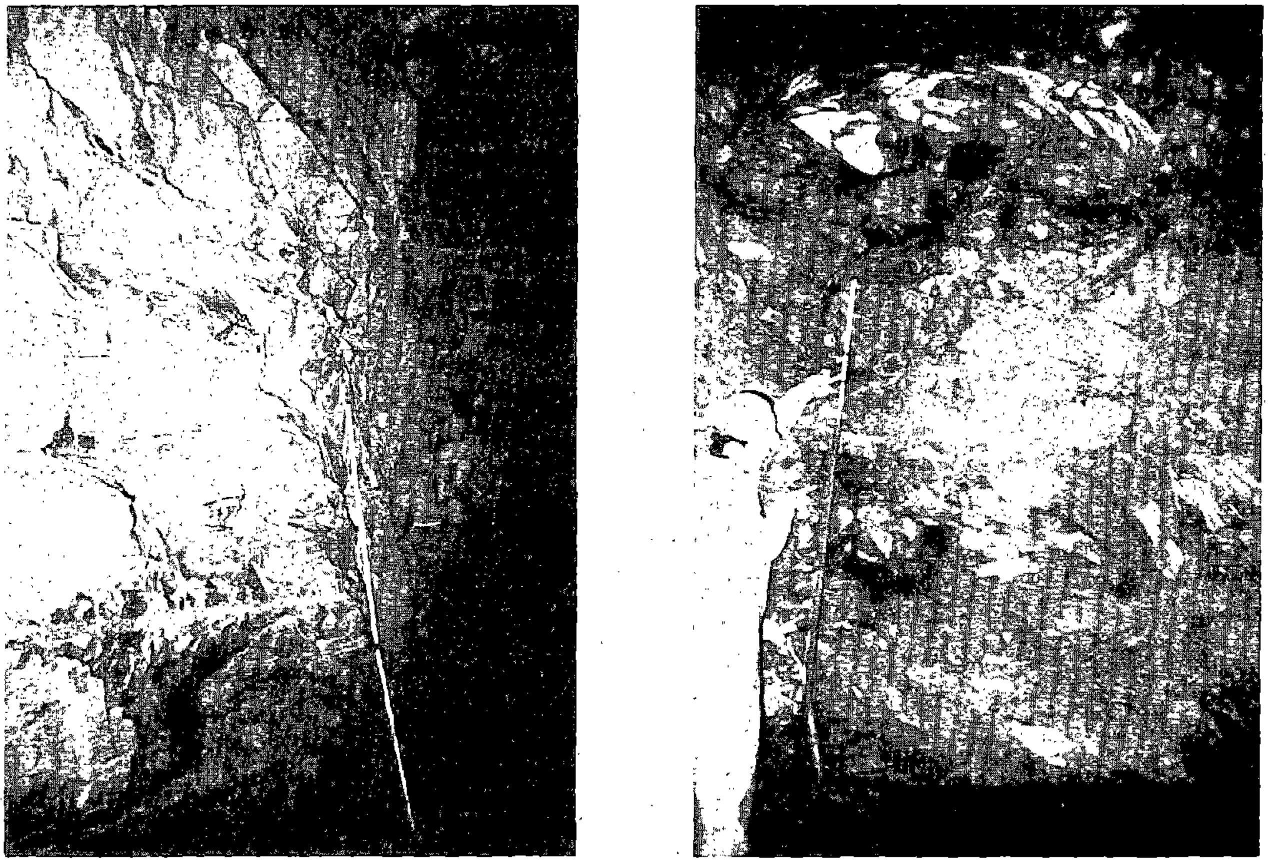
As noted in Table 5-1, the major changes made in modifying the contractor's specified smooth blasting round were to:

a. Change the delay pattern to provide better relief for first-row-in holes;

b. Reduce the charge in cut, reliever and lifter holes;

c. Look the first-row-in holes out to put a uniform burden on the perimeter holes; and

d. Reduce charge in and stem perimeter holes with inert stemming.



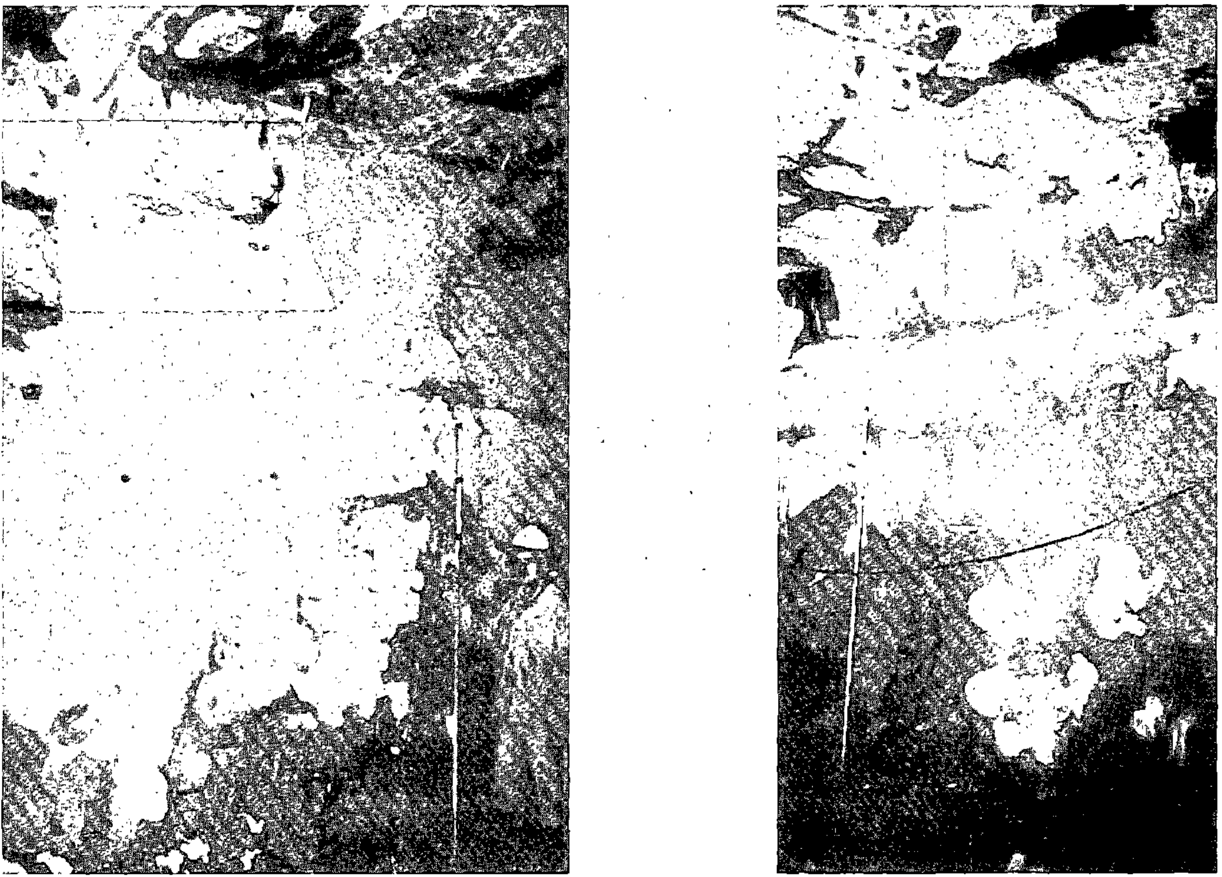
(a) Left Rib (b) Right Rib

FIGURE 6-4. RIBS OF ROUND MSB 6

The modified smooth blasting (MSB) techniques produced noticeably sounder excavated surfaces, especially when perimeter holes were shot on 18-in. (0.46 m) centers with 400 grain/ft. (0.09 kg/m) Primacord , as in round MSB 6 (see Figure 5-5). Figure 6-4 shows the ribs after MSB 6. The average half cast factor using the MSB Primacord loading was 37.8 percent. The average overbreak was 8.7 cu. yd. (6.7 cu. m) per round. The average advance at the perimeter was 92 percent of the average perimeter hole depth. It should be noted that the MSB Primacord loading was only used in round MSB 6 and in one rib of round FC 2.

The other MSB technique used space loaded perimeter holes, shot on 24-in. centers with a column charge of 0.19 lb/ft (0.28 kg/m), as in round MSB 5 (see Figure 5-4). Figure 6-5 shows the ribs and back after MSB 5. This technique was also used in the west rib of round FC 1 and in the east ribs of rounds FC 3, FC 4,

(a) Back



(b) Left Rib

(c) Right Rib

FIGURE 6-5. BACK AND RIBS OF ROUND MSB 5 and FC 5. The average half cast factor using the MSB space loaded perimeter loading was 19.7 percent. The average overbreak was 9.7 cu. yd (7.4 cu. m) per round. The average advance at the perimeter was 89 percent of the average perimeter hole depth.

The cycle times for the MSB rounds were about the same as those for the contractor's SSB rounds. The muck piles from the MSB rounds were somewhat tighter than the SSB rounds. However, there was no significant increase in mucking time. The muck pile after round MSB 6, shown in Figure 6-6, was about 7 ft. (2.1 m) high and extended about 30 ft. (9 m) from the exposed tunnel face. The MSB 5 muck pile was about 7.5 ft. (2.3 m) high and extended about 25 ft. (8 m) from the exposed tunnel face. For both rounds, the muck size was slightly larger than that produced from the SSB rounds. The fragments were generally 3 to 9 in. (7.5 to 22.5 mm), with occasional slabs to about 2 ft. x 1 ft. (0.6 m x 0.3 m).

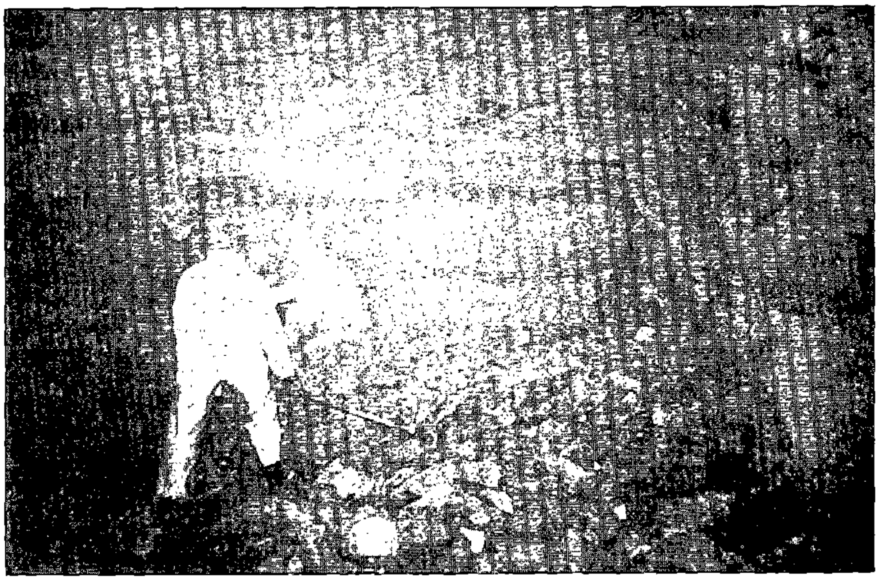


FIGURE 6-6. MUCK PILE AFTER ROUND MSB 6

6.4 FRACTURE CONTROL (FC) RESULTS

Figure 6-1 shows the locations in the tunnel of the seven full face rounds (FC 1 through FC 7) where fracture control perimeter control techniques were utilized. Two of the rounds, FC 1 and FC 3, were in the south heading, and a fault zone was encoun-

FIGURE 6-7. LEFT RIB OF ROUND FC 1, NOTCHED PERIMETER HOLES

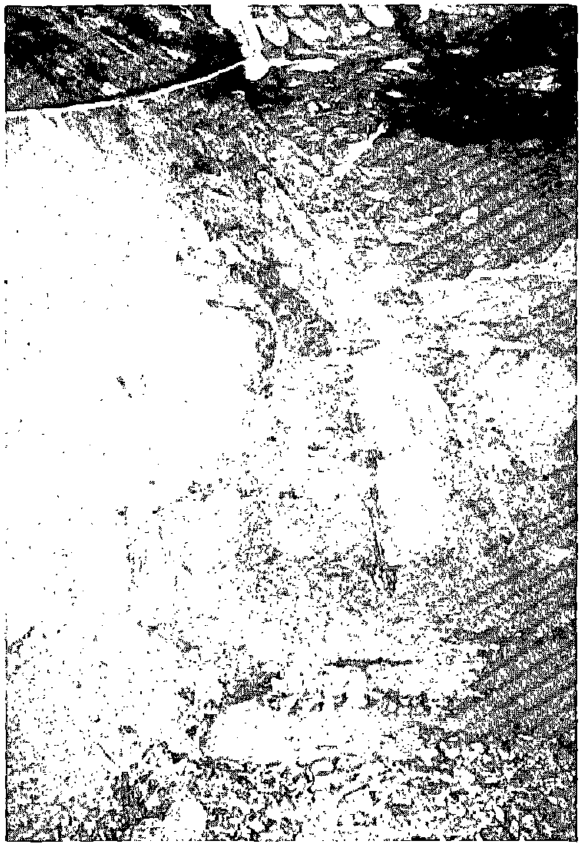


FIGURE 6-8. LEFT RIB OF ROUND FC 3, MSB SPACE LOADING

tered in the left (east) rib of these adjoining rounds (see Figure 3-1). In round FC 1, the perimeter holes in the left rib were notched and shot on 24-in. centers (0.61 m) using 4.5 ft. (1.4 m) of 400 grain/ft. Primacord (0.06 lb/ft). In round FC 3, the left rib was shot using the space loaded MSB loading (0.19 lb/ft), with notched perimeter holes on 29 in. (0.74 m) centers. In spite of these perimeter control techniques, there was considerable overbreak into the fault zone in both rounds. At the left rib of FC 1, there was about 9.6 cu. yd. (5.3 cu. m) of overbreak, and the HCF was 13 percent. That quantity of overbreak would be equivalent to the left rib being an average of 2.3 ft. (0.7 m) outside the desired dimension. The average advance at the rib was about 90 percent of the average perimeter hole depth. At the left rib of FC 3, there was 4.3 cu. yd. (3.3 cu. m) of overbreak, the HCF was 21 percent, and the average advance was 86 percent of the average perimeter hole depth. Figures 6-7 and 6-8 show the left (east) ribs of FC 1 and FC 3, respectively.

The right (west) rib of FC 1 was shot with the space loaded MSB loading (0.19 lb/ft) (0.28 kg/m) in unnotched perimeter holes on 24-in. centers. Figure 6-9 shows this rib, which had a HCF of 25 percent and 4.2 cu. yd. (3.2 cu. m) of overbreak. The average advance at the rib was 89 percent of the average perimeter hole depth. The right rib of FC 3 utilized notched perimeter holes spaced at about 29 in. (0.74 m). These perimeter holes were loaded with a bottom charge consisting of two tamped sticks of 40 percent extra gelatin (1.06 lbs.) (0.48 kg) and no column charge. The collar was stemmed with two feet (0.6 m) of sand, tamped against a spider tube used as a spacer. Figure 6-10 shows the results of this loading. The rib had a HCF of 32 percent and 2.7 cu. yd. (2.1 cu. m) of overbreak. The average advance at the rib was 90 percent of the varege perimeter hole depth.

The results of rounds FC 1 and FC 3 indicate that in a large open discontinuity, such as a fault, no advantage is gained by using fracture control procedures. In the right (west) ribs, however, the fracture control procedures used a wider perimeter hole spacing and resulted in a higher half cast factor and less overbreak, with the same advance, as the space loaded MSB techniques.

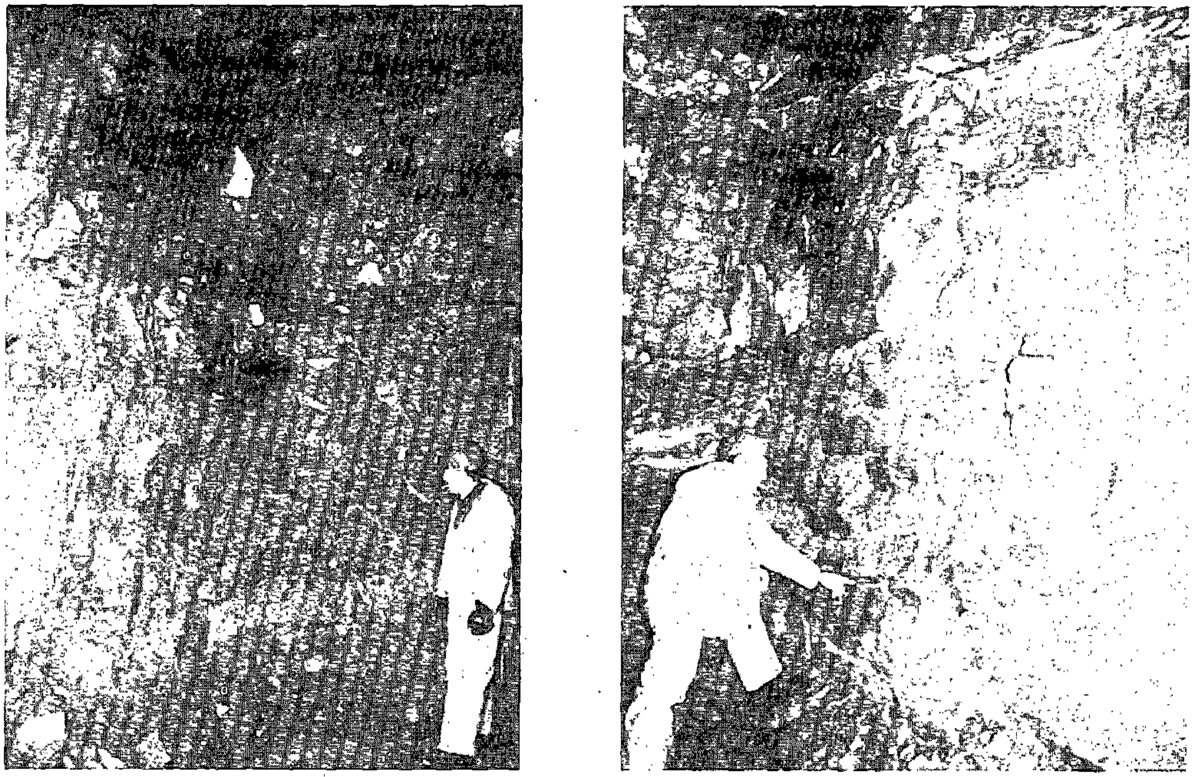
The remainder of the fracture control rounds were shot in the north heading. The rock quality in the north heading was generally better than in the south heading, and it was expected that better results would be obtained. Rounds FC 2 and FC 4 were adjoining rounds which utilized fracture control techniques in the left (west) ribs and back and modified smooth blasting techniques in the right (east) ribs. The left rib and back perimeter holes in round FC 2 were notched and loaded with a 0.53 lb. (0.24 kg) bottom charge and a column charge of about 3.5 to 4 ft.

FIGURE 6-9. RIGHT RIB OF ROUND FC 1, MSB SPACE LOADING

FIGURE 6-10. RIGHT RIB OF ROUND FC 3, NOTCHED PERIMETER HOLES, NO COLUMN CHARGE

(1.1 to 1.2 m) of 400 grain/ft. Primacord (0.06 lb/ft). Spacing was 29 in. (0.74 m) in the left rib and 36 in. (0.91 m) in the back. In the right rib, the perimeter holes were not notched. The same loading was used, with 24 in. (0.61 m) spacing.

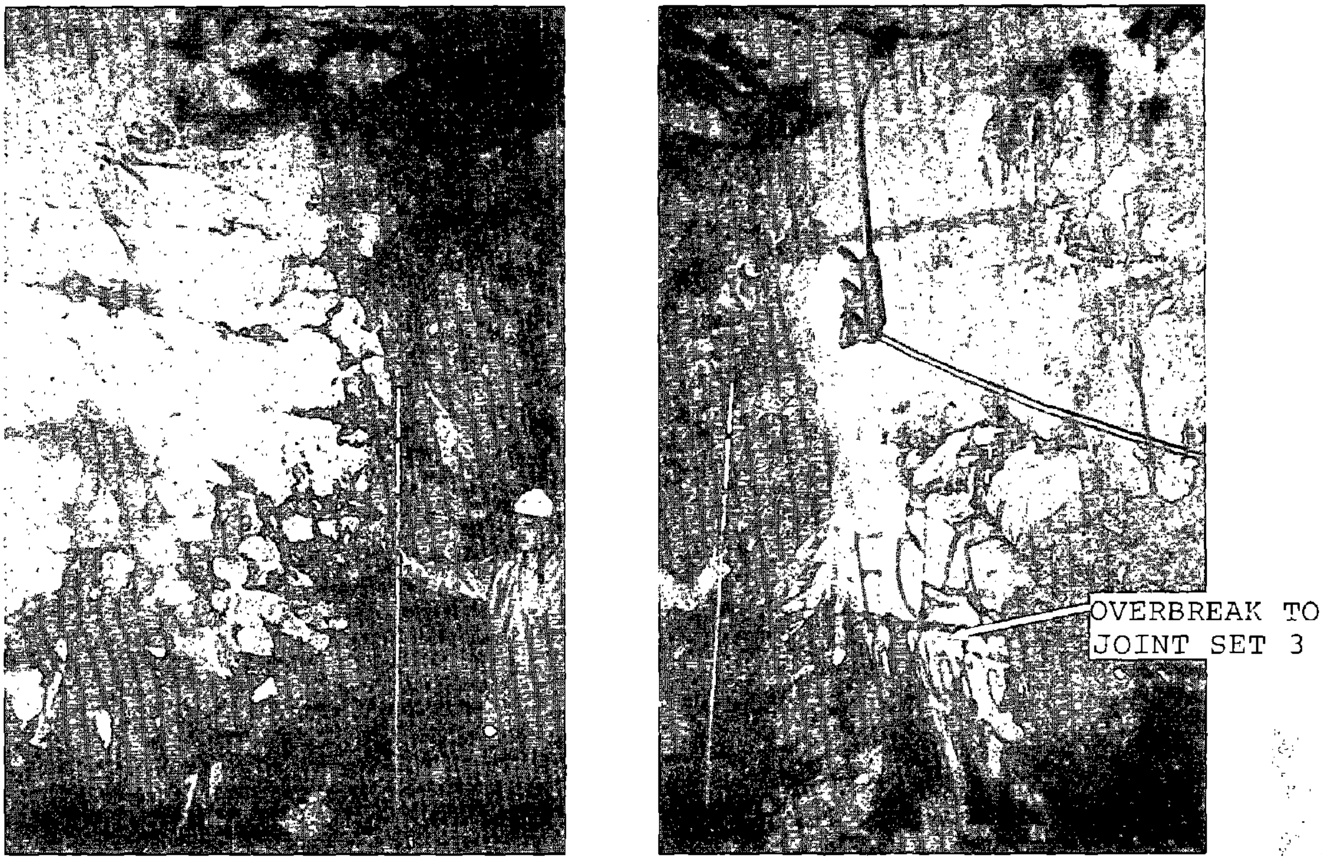
At the left (west) rib of FC 2, there was 1.3 cu. yd. (1.0 cu. m) of overbreak and the half cast factor was 56 percent. As discussed in Sections 5.3.5.2 and 5.3.5.3, field notes were used to estimate these values since the opening cut experiments in the sidewall had damaged the rib. The average advance at the left rib perimeter holes was 89 percent of the average perimeter hole depth. Figure 6-11a shows the left rib of FC 2 prior to the damage caused by the opening cut experiments. At the right rib, there was 3.1 cu. yd. (2.4 cu. m) of overbreak, the HCF was 48 percent, and the average perimeter advance was 97 percent of the perimeter hole depth. Figure 6-11b shows the right rib of FC 2.



(a) Left Rib, Notched Perimeter Holes

(b) Right Rib, MSB Primacord Loading

FIGURE 6-11. RIBS OF ROUND FC 2



(a) Left Rib, Notched Perimeter Holes

(b) Right Rib, MSB Space Loading

FIGURE 6-12. RIBS OF ROUND FC 4

The left (west) rib perimeter holes in round FC 4 were notched and loaded with a 1.06 lb. (0.48 kg) bottom charge and a column charge of 4 ft. (1.2 m) of 400 grain/ft. Primacord (0.06 lb/ft). Spacing was 36 in. (0.91 m). In the unnotched right (east) rib, the space loaded MSB loading (0.19 lb/ft) was used. The notched left rib had an HCF of 51 percent and an average advance of 89 percent of the average perimeter hole depth. The HCF was estimated from measurements and field notes, and overbreak could not be measured due to the damage caused by the opening cut experiments in the tunnel wall.

Figure 6-12a shows the left rib of FC 4. The unnotched right rib is shown in Figure 6-12b. This rib had a half cast factor of 18 percent, overbreak of 4.5 cu. yd. (3.5 cu. m) and an average advance of 85 percent of the average perimeter hole depth. The relatively large amount of overbreak in the right (east) rib was due, for the most part, to a joint (from Joint Set No. 3) striking about N20°E and dipping about 75°SE.

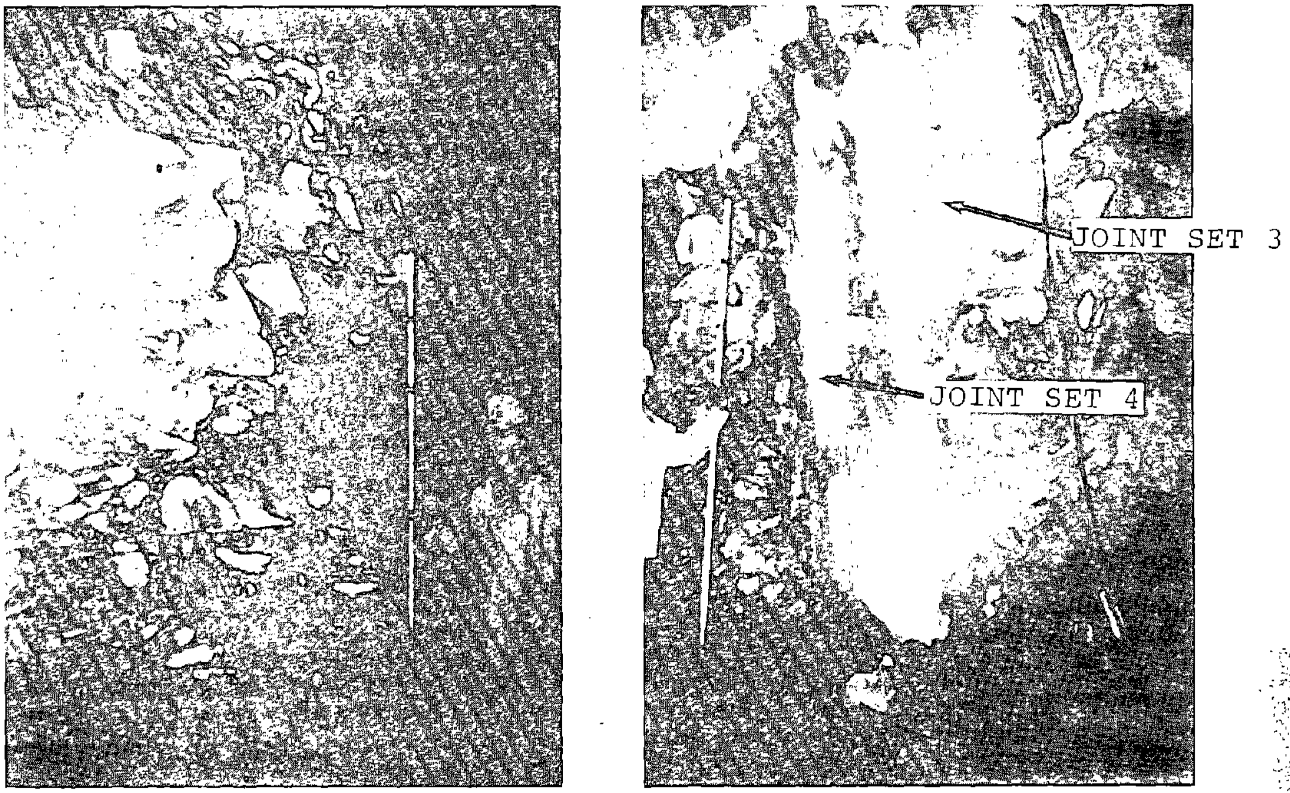
Round FC 5 utilized notched perimeter holes at the left (west) rib and back. In this round, an attempt was made to break the corners at the back using two notched holes, spaced one foot away from the corner, as shown in Figure 5-6. These corner perimeter holes were loaded with a 1.06 lb. (0.48 kg) bottom charge and a column charge of about 4 ft. (1.2 m) of 400 grain/ft. (0.09 kg/m) Primacord (0.06 lb/ft). The other left rib perimeter holes were notched and loaded with a 0.53 lb (0.24 kg) bottom charge and a column charge of about 4.5 ft. (1.4 m) of 400 grain/ft. (0.09 kg/m) Primacord. Spacing at the left rib was 33 in. (0.84 m). The right rib perimeter holes were not notched. Spacing was 22 in. (0.56 m) and loading consisted of the space loaded MSB loading (0.19 lb/ft.).

The notched left rib of FC 5, shown in Figure 6-13a, had a HCF of 70 percent, overbreak of 3.3 cu. yd. (2.5 cu. m), and an average advance of 78 percent of the average perimeter hole depth. The left corner perimeter holes pulled well but there was some rock left at the corner between them. The other three perimeter holes left about 2 ft. (0.6 m) of bootleg each. This bootleg was attributed to an insufficient bottom charge for the spacing used.

The unnotched right rib of FC 5 had a HCF of 9 percent, overbreak of 1.2 cu. yd. (0.9 cu. m), and an average advance of 94 percent of the average perimeter hole depth. The right corner perimeter holes left about a foot of bootleg and considerable rock betwen them at the corner, while the other perimeter holes pulled well. Figure 6-13b shows that the right rib perimeter holes broke to a joint (from Joint Set No. 3) striking about N20°E and dipping about 80°SE.

The relatively low overbreak and low HCF of the right (east) rib, together with the high overbreak and HCF of the opposite rib, indicate that the round was located and drilled about 9 in. (0.23 m) to the east of the correct alignment. In addition, despite a high HCF at the back (see Section 5.3.5.2), there was almost 6 cu. yd (4.6 cu. m) of overbreak recorded at the back. Measurements at the face prior to loading the drill holes indicated an average distance of 12.6 ft. (3.8 m) from the left to the right rib perimeter holes (and 13.3 ft. (4.1 m) from the lifter holes to the perimeter holes at the back. These and other measurements suggest that relaxed alignment and drilling control, and not perimeter control technique or geology, was the most important factor in the large quantities of overbreak recorded.

In round FC 6, all perimeter holes were notched and 36 in. (0.91 m) spacing was used. The perimeter hole loading was varied as shown in Figure B-15 in Appendix B. At the left rib, 400 grain/ft.

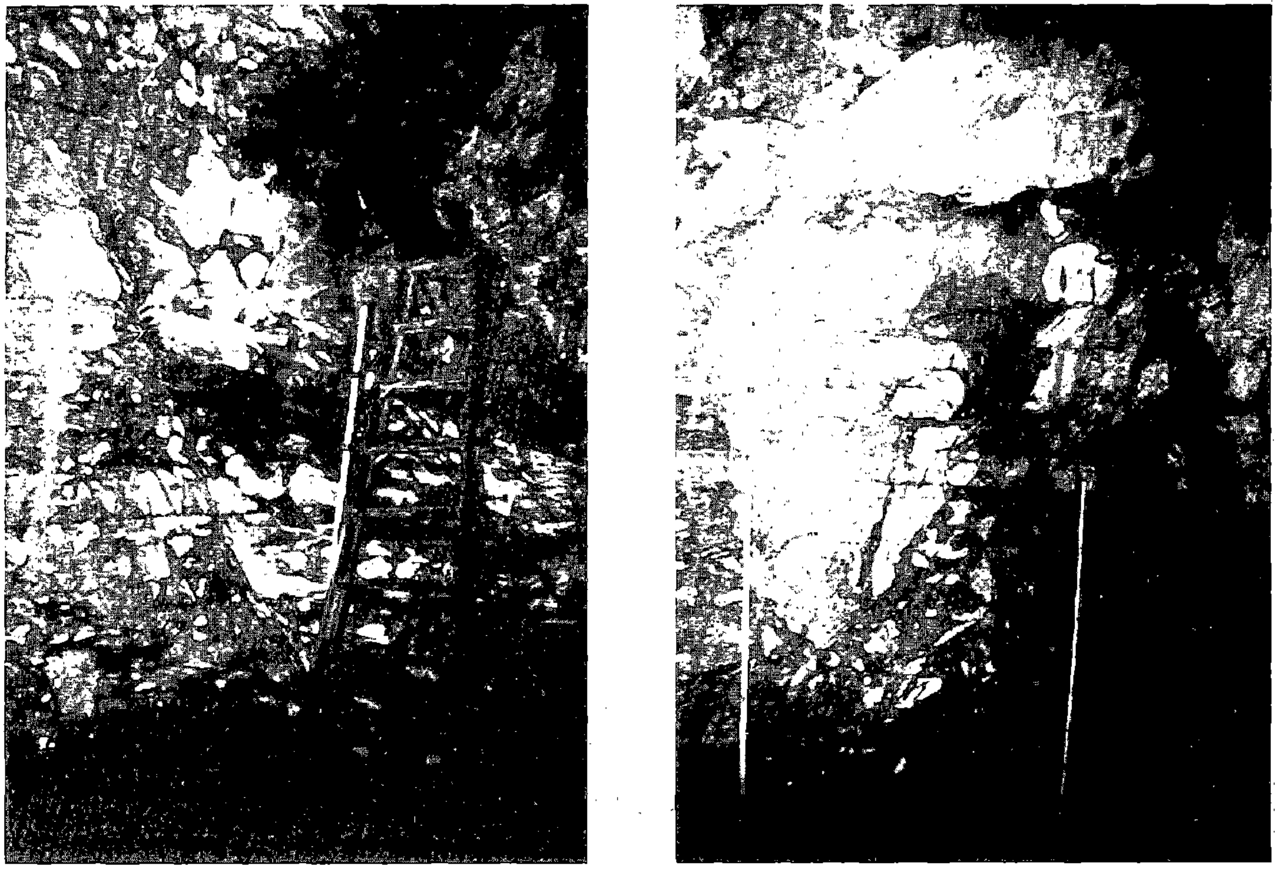


(a) Left Rib, Notched Perimeter Holes (b) Right Rib, MSB Space Loading

FIGURE 6-13. RIBS OF ROUND FC 5

Primacord (0.06 lb/ft) was used as a column charge. The lower two holes used a 0.80 lb. (0.36 kg) bottom charge while the 3 corner holes used a 1.06 lb. (0.48 kg) bottom charge. At the right rib, no column charge was used, instead a piece of spider tube was used as a spacer to place the water bag stemming against. The bottom charge used was the same as the corresponding holes at the left rib. This round also used a fracture control opening cut, the results of which will be described in more detail in Section 7.

Round FC 6 did not break well, and considerable bootleg was left at the perimeter holes, especially at the top corner holes and the right rib. This can partially be attributed to the fracture control opening cut used (see Section 7) which had an advance of only 68 percent of the average cut hole length. Excluding the top corner hole, which had 5.5 ft. (1.7 m) of boot-



(a) Left Rib, Notched Perimeter Holes

(b) Right Rib, Notched Perimeter Holes, No Column Charge

FIGURE 6-14. RIBS OF ROUND FC 6

leg, the average advance at the left rib was 72 percent of the average perimeter hole depth, and the HCF was estimated from field notes to be about 40 percent. The overbreak could not be determined due to damage to the rib by an opening cut experiment in the tunnel sidewall. At the right rib, excluding the top corner hole, the average advance was only 29 percent of the average perimeter hole depth, and the HCF was 36 percent. Figures 6-14a and 6-14b show the left and right ribs, respectively, of round FC 6.

Despite the low advance of the cut, the first-row-in (F) holes in FC 6 had an average advance of 90 percent of the average F hole depth. Thus, the bootleg at the perimeter was mainly a result of the spacing and burden being too great for the amount of powder in the holes, especially in the right rib, where no column charge was used.

The tunnel silhouette photograph measurements indicate an overbreak at the right rib of round FC 6 of 3.2 cu. yd. (2.4 cu. m). This would be equivalent to the right rib being an average of 1.1 ft. (0.34 m) outside the desired dimension. A field measurement was made from the tunnel centerline (as marked by the contractor) to a bootleg hole at the right rib. The measured distance was 7.0 ft. (2.1 m), which indicates the overbreak was mainly the result of improper hole location and excessive lookout.

The average cycle time for the fracture control rounds was about 6.5 hours, broken down as follows:

Average Drilling time:	2.05 hrs.
Average Notching time:	1.05 hrs.
Average Loading time:	1.30 hrs.
Average Mucking time:	2.20 hrs.

This was about 0.9 hours more than the SSB and MSB cycle times, and is attributable to the time required to notch the holes. The notching times ranged from about three minutes per hole in the test chamber to as much as 15 minutes per hole in the later full face rounds. The average notching time for the full face rounds was about six minutes per hole. The longer grooving times were the result of changes in the tool design which caused the tools to "hang up" on removal (see Section 4.4).

The muck piles from the FC rounds were similar to the MSB rounds in that they were generally 6 to 8 ft. (1.8 to 2.4 m) high and extended about 25 to 30 ft. (7.6 to 9.1 m) from the exposed face. The muck size was generally 3 to 12 in. (7.6 to 30.5 mm), with occasional slabs to about 2 ft. x 1 ft. (0.6 m x 0.3 m).

As with the MSB rounds, the muck piles from the FC rounds were somewhat tighter than the SSB rounds. Although this did not lead to an increase in mucking time, complaints were received from the load haul dump operator that this muck pile was very tight near the face. In round FC 4, the delay pattern was changed and the lifter holes were fired last in an effort to loosen the muck pile. The resulting muck pile, shown in Figure 6-15, was about 6 ft. (1.8 m) high, extended about 30 ft. (9 m) from the exposed face, and had muck size of about 2 to 8 in. (5 to 20 mm) with occasional larger slabs. The muck pile was more loose near the face and mucking time for that round was less than two hours. However, the lifter hole delays caused significantly higher ground vibrations than had been previously recorded, so the FC 4 delay pattern was not used again.

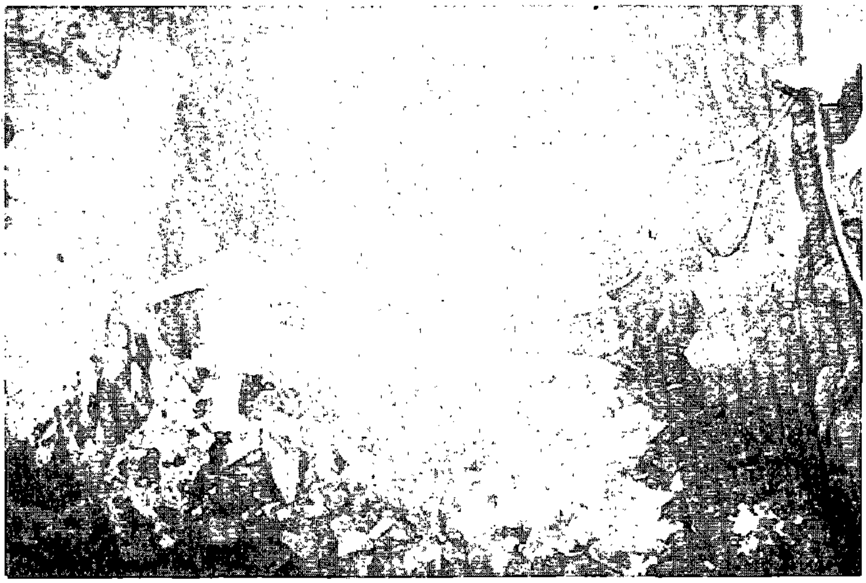
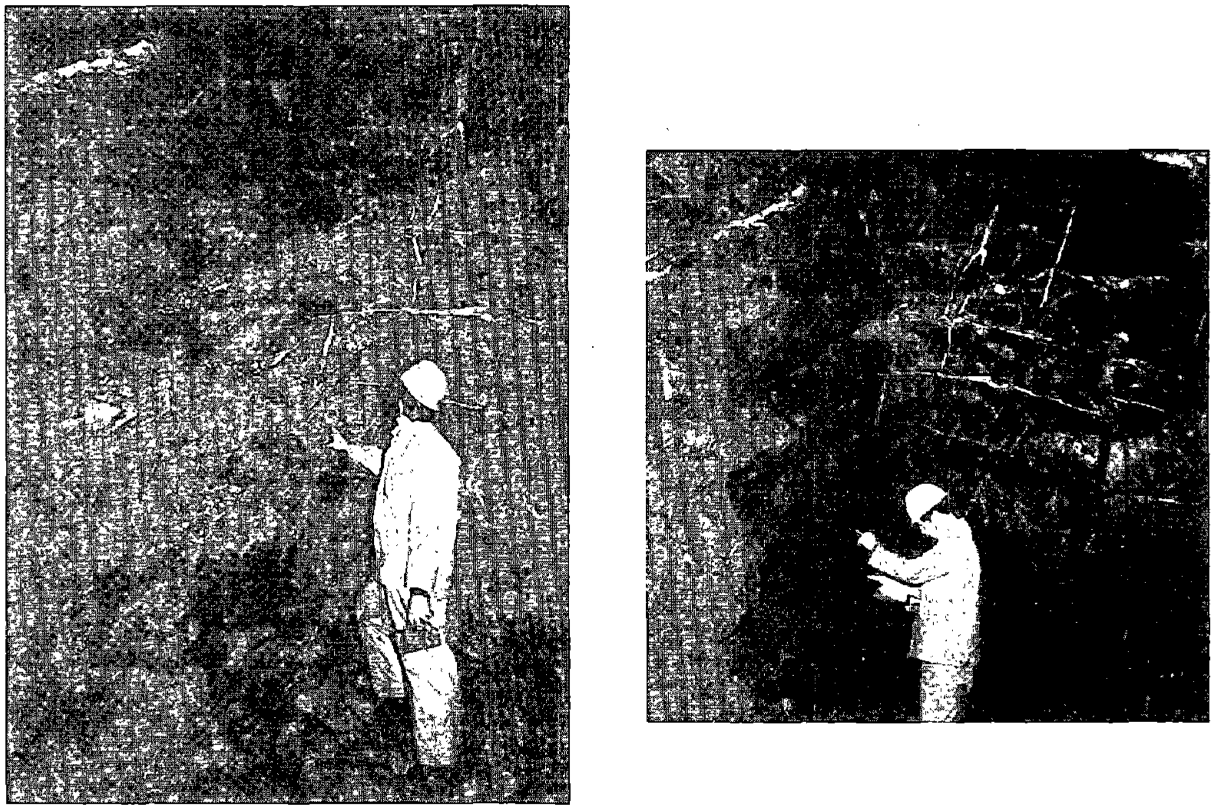


FIGURE 6-15. MUCK PILE AFTER ROUND FC 4

6.5 TECHNIQUES IN IGNEOUS DIKE

Round FC 7 was shot in the igneous dike in the north heading of the pilot tunnel. The location, procedures and results of this round and the specified smooth blasting round which preceded it (SSB 74) are summarized in Figure 6-1. Round SSB 74 used perimeter hole spacing of 24 in. (0.61 m) at the ribs and 21 in. (0.53 m) at the back. The perimeter hole loading, shown in Figure 5-7, was the same as that used in the argillite. Round FC 7 used perimeter hole spacing of 24 to 32 in. (0.61 to 0.81 m) at the left rib and back, and 24 in. (0.61 m) at the right rib. The perimeter hole loading and spacing is shown in Figure 5-8.

Except at FC 7, very few half casts are visible in the igneous dike. The left (west) rib of round SSB 74 had a HCF of 10 percent and overbreak was 1.6 cu. yd. (1.2 cu. m). At the right (east) rib, the HCF was 7 percent and overbreak was 4.1 cu. yd. (3.1 cu. m). No advance measurements were made for this round but the perimeter holes generally pulled well. It should be noted that the SSB round subsequent to FC 7, which was not documented, did not break well, leaving an average of 2 to 3 ft. (0.6 to 0.9 m) of bootleg throughout.



(a) Left Rib, Notched, 24-32 in. Spacing

(b) Right Rib, Notched, 24-in. Spacing

FIGURE 6-16. RIBS OF ROUND FC 7

At the left rib of round FC 7, the HCF was 50 percent, overbreak was 1.9 cu. yd. (1.5 cu. m) and the average advance was 85 percent. At the right rib, the HCF was 32 percent, overbreak was 1.9 cu. yd. (1.5 cu. m) and the average advance was 90 percent. Figures 6-16a and 6-16b show the left and right ribs, respectively, of round FC 7.

The cycle times for SSB 74 and FC 7 were similar except that it took 1.1 hours to notch the 11 perimeter holes in FC 7. The muck piles from both rounds were also similar. They were about 6 ft. (1.8 m) high and extended about 30 ft. (9.1 m) from the exposed tunnel face. The muck size in the igneous dike was somewhat larger than in the argillite. The fragments were generally between 2 and 18 in. (0.05 and 0.46 m) and well graded.

6.6 VIBRATION MEASUREMENTS

A summary of all vibration measurements made is presented in Appendix D. This summary table gives explosives data submitted by the contractor, peak particle velocities for the round at the various sensor locations, and peak air overpressures for the round at the various sensor locations. The sensor locations are shown on Figure 5-1.

A portion of a typical vibration record from the contractor's seismograph is shown in Figure 6-17. The recorder tape speed used was about 4 in/sec. (0.10 m/sec.) so that individual hole detonations could be identified. Because of scatter in the detonators used, it was found that most of the holes in the round detonated independently. The scatter in the perimeter detonators was often as much as one to two seconds. Thus, identifying the correct delay number for an individual detonation was sometimes difficult.

For most rounds, the maximum vibrations summarized in Appendix D occurred during cut or reliever hole detonations. In order

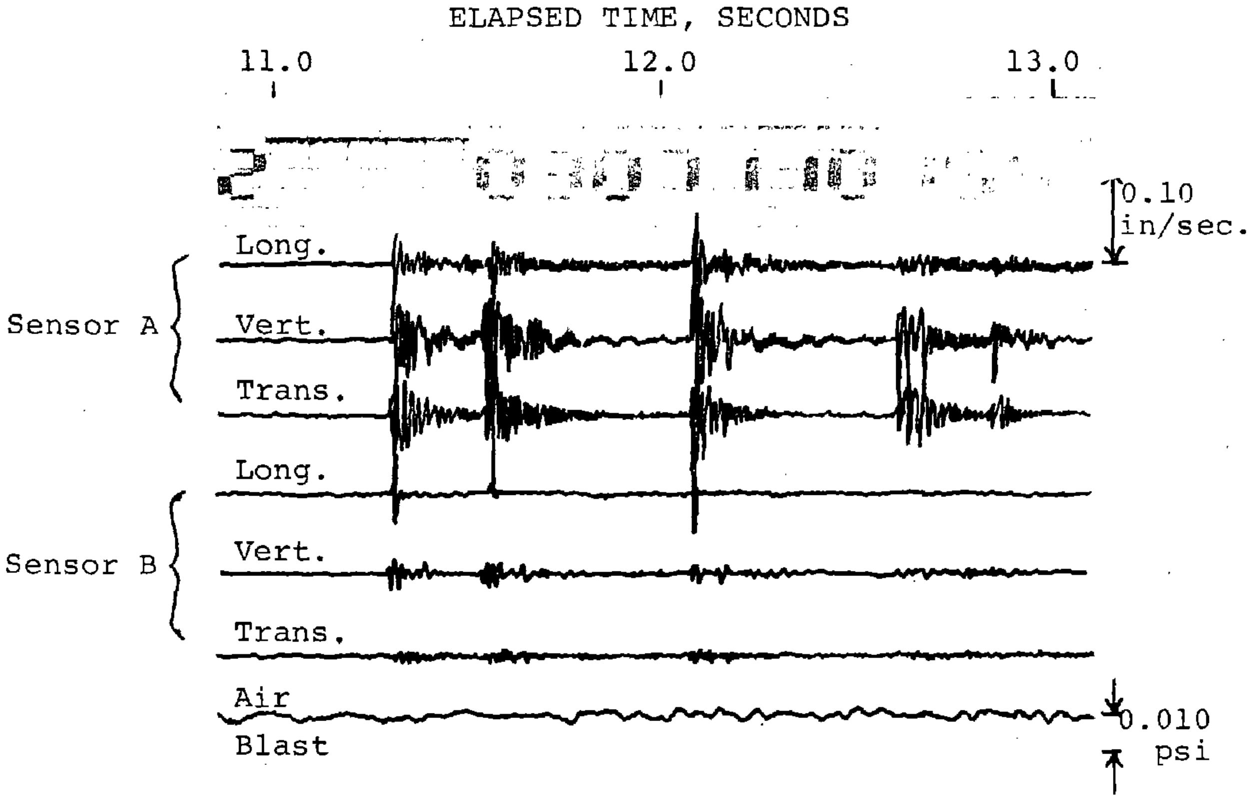


FIGURE 6-17. TYPICAL VIBRATION RECORD FROM CONTRACTOR'S SEISMOGRAPH

to compare vibrations from the various perimeter control techniques, data from the perimeter delays of the MSB, FC, and several SSB rounds are summarized in Table 6-1. For each round, the table gives the sensor location (see Figure 5-1) and the slant range from the blast to the sensor. For each perimeter delay in the round, the loading technique is noted, as well as the nominal firing time of that delay, the maximum ground vibration velocity recorded for that delay, and the actual time of the maximum recorded velocity. Also noted is the maximum air blast overpressure associated with the perimeter delays, if that measurement was made.

The results summarized in Table 6-1 indicate an average maximum particle velocity for the SSB perimeter delays noted of 0.099 in/sec. (0.25 cm/sec.) at an average slant range of 146 ft. (45 m). For the MSB space loaded perimeter delays, the average maximum particle velocity was 0.068 in/sec. (0.17 cm/sec.) at an average slant range of 154 ft. (47 m). The MSB Primacord loaded perimeter delays had an average maximum particle velocity of 0.063 in/sec. (0.16 cm/sec.) at an average slant range of 167 ft. (51 m), and the FC perimeter delays had an average maximum particle velocity of 0.051 in/sec. (0.13 cm/sec.) at an average slant range of 148 ft. (45 m). Thus the decrease in charge weight in the perimeter holes had the expected result of reducing the ground vibrations associated with the perimeter hole delays.

It was also expected that stemming the perimeter holes with inert stemming for MSB and FC rounds, as against the 1/4 stock of 40 percent extra gelatin used by the contractor in the SSB rounds, would reduce the air blast noise associated with the perimeter delays. The results in Table 6-1 indicate an average maximum air blast overpressure of 0.0051 psi (0.035 kPa) for the SSB perimeter delays, 0.0038 psi (0.026 kPa) for the MSB space loaded perimeter delays, 0.0030 psi (0.021 kPa) for the MSB Primacord loaded perimeter delays, and 0.0031 psi (0.021 kPa) for the FC delays. The slant ranges were all similar to those noted for the perimeter delays.

As noted previously, the maximum vibrations within each round generally did not result from perimeter delay detonations. Therefore, although the perimeter delay vibrations were significantly lower using fracture control procedures, this did not affect the maximum vibration levels within each round. However, because the MSB and FC rounds used less charge weight per hole in cut and reliever holes, there was a slight reduction in maximum vibration levels in comparison with the SSB rounds. For those rounds noted in Table 6-1, the average peak particle velocity (from data in Appendix D) at the sensors noted was 0.17 in/sec. (0.43 cm/sec.) for the SSB rounds, and 0.12 in/sec. (0.30 cm/sec.) for the MSB and FC rounds. The average maximum air blast overpressure was 0.007 psi (0.048 kPa) for the SSB rounds and 0.006 psi (0.041 kPa) for the MSB and FC rounds. The contract documents specified a maximum allowable peak particle velocity of ground vibrations (measured adjacent to any structure in the vicinity of blasting operations) of 1.9 in./sec. (4.8 cm/sec.). Air blast noise adjacent to nearby structures was required to be kept below an equivalent peak air overpressure of about 0.15 psi (1.03 kPa).

TABLE 6-1. SUMMARY OF VIBRATION DATA FOR PERIMETER HOLE DELAYS

ROUND NO.(1)	SENSOR LOCATION	SLANT RANGE (ft.)	PERIMETER DELAY NO.(2)	LOADING TECHNIQUE(3)	NOMINAL FIRING TIME (sec.)	MAXIMUM PARTICLE VELOCITY(4) (in./sec.)	ACTUAL FIRING TIME (sec.)	MAXIMUM AIR BLAST OVERPRESSURE(4) (psi)
SOUTH HEADING								
SSB 33	B	166	13	SSB	12.5	0.09	12.7	0.009
SSB 35	B	164	11	SSB	10.0	0.08	10.0	0.008
SSB 45	B	156	11	SSB	10.0	0.08	10.2	0.006
SSB 47	B	155	13	SSB	12.5	0.18	13.3	0.005
FC 1	B	154	12	SL	11.2	0.08	11.1	0.005
			14	FC	14.0	0.05	15.7	0.002
FC 3	B	154	11	SL	10.0	0.12	10.3	0.003
			13	FC	12.5	0.08	12.5	0.004
SSB 53	B	155	11	SSB	10.0	0.16	10.7	0.004
SSB 55	B	157	13	SSB	12.5	0.18	13.2	0.002
SSB 75	B	176	14	SSB	14.0	0.06	15.4	0.006
MSB 6	B	183	11	PC	10.0	0.08	10.3	0.003
SSB 81	B	136	12	SSB	11.2	0.14	12.0	0.005
NORTH HEADING								
MSB 5	H	179	11	SL	10.0	0.13	10.1	0.002
	O	148	12	SL	11.2	0.04	11.4	-
FC 2	H	173	12	PC	11.2	0.02	11.9	0.003
			13	FC	12.5	0.06	13.4	0.003
	O	145	12	PC	11.2	0.03	11.9	-
			13	FC	12.5	0.05	13.4	-
FC 4	H	166	11	SL	10.0	0.04	10.0	0.002
			13	FC	12.5	0.02	12.5	0.002
	O	142	11	SL	10.0	0.05	10.0	-
			13	FC	12.5	0.02	12.5	-
54	NO RECORD							
56	H	156	12	SSB	11.2	0.07	11.7	0.002
	O	137	13	SSB	12.5	0.07	13.0	-
FC 5	H	150	11	FC	10.0	0.04	10.4	0.003
			12	SL	11.2	0.04	11.5	0.004
	O	135	11	FC	10.0	0.03	10.4	-
			12	SL	11.2	0.03	11.5	-
FC 6	H	145	12	FC	11.2	0.08	11.8	0.004
	O	130	12	FC	11.2	0.06	11.8	-
62	H	140	14	SSB	14.0	0.09	13.3	0.004
	O	132	14	SSB	14.0	0.05	13.3	-
74	H	110	14	SSB	14.0	0.14	15.0	0.004
	O	130	14	SSB	14.0	0.07	15.0	-
FC 7	H	106	15	FC	15.5	0.12	15.5	0.004
	O	130	15	FC	15.5	0.07	15.5	-

NOTES:
(1) THE SSB ROUNDS NOTED WERE SELECTED SO THAT THE AVERAGE SLANT RANGE (RADIAL DISTANCE FROM VIBRATION SOURCE TO SENSOR) WOULD BE ABOUT THE SAME AS FOR THE MSB AND FC ROUNDS NOTED.
(2) BECAUSE OF SCATTER IN THE PERIMETER DETONATIONS, IT WAS SOMETIMES DIFFICULT TO IDENTIFY THE CORRECT DELAY NUMBER.
(3) SSB = CONTRACTOR'S SPECIFIED SMOOTH BLASTING TECHNIQUE.
SL = SPACE LOADED MODIFIED SMOOTH BLASTING TECHNIQUE.
PC = PRIMACORD LOADED MODIFIED SMOOTH BLASTING TECHNIQUE.
FC = FRACTURE CONTROL TECHNIQUE.
(4) ALL MEASUREMENTS NOTED WERE MADE WITH THE CONTRACTOR'S VIBRATION MONITORING EQUIPMENT.

6.7 COMPARISON OF OPTIMUM PERIMETER CONTROL TECHNIQUES

Table 6-2 summarizes the optimum parameters for the perimeter control techniques used in the experiments. Table 6-3 summarizes the results obtained with each of the techniques. It can be seen from these tables that the fracture control procedures had the following advantages over the smooth blasting techniques:

a. Maintained remaining rock condition equal to or better than the smooth blasting techniques and reduced overbreak (in the ribs) by 10 to 30 percent;

b. Reduced the number of perimeter holes by 23 to 43 percent;

c. Reduced the total explosive weight in the perimeter holes by 43 to 69 percent; and

d. Reduced maximum ground vibration velocities resulting from perimeter delay detonations by 19 to 48 percent, and reduced maximum air blast overpressures resulting from perimeter delay detonations by up to 39 percent.

The only drawback for the fracture control techniques, as compared with smooth blasting, was the average cycle time, which was about 0.9 hours longer for the fracture control rounds than the smooth blasting rounds, due to the extra time required to notch the perimeter holes.

6.8 ECONOMIC COMPARISON OF PERIMETER CONTROL METHODS

Table 6-4 is an economic comparison of the perimeter control techniques described herein for a hypothetical tunnel excavated in argillite. For each technique, the perimeter hole costs are estimated for excavating an assumed horseshoe shaped (cross section) tunnel with a 10 ft. (3.0 m) radius and a 50 ft. (15.2 m) perimeter above invert. It is assumed that the optimum spacing and loading given in Table 6-2 are applicable and that the drill holes are 12 ft. (3.6 m) deep. Cost data presented in Table 6-4 are direct costs per round at the tunnel heading, and do not take into account any additional overhead costs associated with increased construction time.

If drilling and loading costs are compared, it can be seen that, although fracture control (FC) procedures substantially reduce the number of perimeter holes drilled and the total weight of explosives used, the estimated total drilling and loading costs are slightly higher than the contractor's specified smooth blast-

TABLE 6-2. SUMMARY OF OPTIMUM PERIMETER CONTROL PROCEDURES

		CONTRACTOR'S SPECIFIED SMOOTH BLASTING	MODIFIED SMOOTH BLASTING		FRACTURE CONTROL
			SPACE LOADED	PRIMACORD	
PERIMETER HOLES					
AVERAGE SPACING	in.	21(1)	24	18	33
BURDEN	in.	24 to 38 NON-UNIFORM	24 to 29 UNIFORM	24 to 29 UNIFORM	24 to 29 UNIFORM
BOTTOM CHARGE	lb	0.53	0.53	0.53	0.53
COLUMN CHARGE					
TYPE		CONTINUOUS	SPACED	CONTINUOUS	CONTINUOUS
WEIGHT	lb/ft	.30	.19	.06	.06
LENGTH(1)	in.	48	60	54	54
TOTAL CHARGE/HOLE	lb	1.86	1.48	.80	.80
NUMBER OF HOLES		18	17	23	13
TOTAL PERIMETER CHARGE WEIGHT	lb	33.5	25.2	18.4	10.4
COLLAR LENGTH(2)	in.	28	18	24	24
STEMMING MATERIAL		1/4 STICK POWDER	-------SAND OR WATER BAGS----------------		
DETONATION SEQUENCE		------------------LAST 4 DELAYS----------------			LAST 4 OR 5 DELAYS
FIRST-ROW-IN HOLES					
SPACING	in.	--------------------------24 to 36 ----------------------------			
BURDEN	in.	--------------------------18 to 29 ----------------------------			
ORIENTATION		PERPENDICULAR TO FACE	---------- PARALLEL TO PERIMETER HOLES------		
CHARGE	lb	3.90	3.37	3.37	3.37

NOTES: (1) 21 IN. SPACING USED AT BACK, WHICH WAS TO BE FINAL EXCAVATED SURFACE.
24 IN. SPACING USED AT RIBS.
(2) ASSUMING HOLE DEPTH OF 7.0 FT. (2.13 M)

TABLE 6-3. SUMMARY OF PERIMETER CONTROL RESULTS

		CONTRACTOR'S SPECIFIED SMOOTH BLASTING	MODIFIED SMOOTH BLASTING SPACE LOADED	MODIFIED SMOOTH BLASTING PRIMACORD	FRACTURE CONTROL
CONDITION OF BACK: (1)					
AVE. OVERBREAK	cu. yd.	3.9	2.8 (2)	2.4 (2)	4.0
AVE. HCF	%	3.4	12.0 (2)	27.0 (2)	14.8
AVE. SHCF		6.0	24.0 (2)	40.5 (2)	45.2
CONDITION OF RIBS: (1)					
AVE. OVERBREAK	cu. yd.	3.7	3.4	2.9	2.3
AVE. HCF	%	13.3	23.5	44.3	48.5
AVE. SHCF		26.6	47.0	74.5	123.9
AVERAGE OVERBREAK PER ROUND (1)	cu. yd.	11.3	9.6	8.2	8.6
AVERAGE ADVANCE AT PERIMETER	% of ave. P hole depth	85	89	92	88
FRAGMENTATION (PREDOMINANT MUCK SIZE)	in.	2 to 6	3 to 9	3 to 9	3 to 12
MUCK PILE					
AVE. HEIGHT	ft.	6	7.5	7	7
AVE. DISTANCE FROM FACE	ft.	40	25	30	25
POWDER FACTOR	lb./cu. yd.	3.77	3.17	2.92	2.77
HOLE FACTOR	ea./cu. yd.	1.28	1.26	1.31	1.11
VIBRATIONS FROM PERIMETER HOLE DELAYS					
AVE. MAX. PARTICLE VELOCITY	in./sec.	0.099	0.068	0.063	0.051
AVE. MAX. AIR BLAST OVER-PRESSURE	psi	0.0051	0.0038	0.0030	0.0031
AT AVE. SLANT RANGE	ft.	146	154	167	148
AVERAGE CYCLE TIMES					
DRILL	HRS.	----------	---------- 2.2	----------	2.05
NOTCH	HRS.	----------	---------- N.A.	----------	1.05
LOAD & SHOOT	HRS.	----------	---------- 1.2	----------	1.3
MUCK	HRS.	----------	---------- 2.3	----------	2.2
TOTAL CYCLE TIME	HRS.		5.7		6.6

NOTES: (1) NOT INCLUDING DATA FROM ROUND FC 6, WHICH DIDN'T BREAK WELL DUE IN PART TO FC CUT, AND SOME RIBS AND BACKS WHERE RESULTS WERE SIGNIFICANTLY AFFECTED BY FAULT ZONES OR WHERE EXTENSIVE DAMAGE TO RIBS WAS CAUSED BY OPENING CUT EXPERIMENTS IN TUNNEL SIDE WALL.

(2) DATA FROM ONLY ONE ROUND

TABLE 6-4. ECONOMIC COMPARISON OF PERIMETER CONTROL METHODS (1)

	CONTRACTOR'S SPECIFIED SMOOTH BLASTING	MODIFIED SMOOTH BLASTING SPACE LOADED	MODIFIED SMOOTH BLASTING PRIMACORD	FRACTURE CONTROL
DRILLING COST				
LABOR 2 MEN @ $.25/min x 6 min	$3.00	$3.00	$3.00	$3.00
GROOVE 2 MEN @ $.25/min x 6 min	-	-	-	3.00
BITS & STEEL 12 ft @ $.20	2.40	2.40	2.40	2.40
BROACHING TOOL 12 ft @ $.30	-	-	-	3.60
EQUIPMENT 12 ft @ $.40	4.80	4.80	4.80	7.20
TOTAL DRILL COST	$10.20	$10.20	$10.20	19.20
LOADING COST				
LABOR 1 MAN @ $.25/min	$1.25	$1.75	$1.25	$1.25
BLASTING CAP	.75	.75	.75	.75
PRIMER STICK (0.53 lb)	.25	.25	.25	.25
SMOOTH BLASTING POWDER (10 ft)	2.25	1.20	-	-
PRIMACORD (10 ft)	-	.60	3.75	3.75
SPACER/SPIDER TUBE	-	1.20	1.00	1.00
STEMMING	.20	.20	.20	.20
MISCELLANEOUS SUPPLIES	.30	.30	.30	.30
TOTAL LOAD COST	$5.00	$6.25	$7.50	$7.50
TOTAL COST PER HOLE	$15.20	$16.45	$17.70	$26.70
HOLE SPACING (in)	21	24	18	33
NUMBER OF HOLES	28	24	32	17
TOTAL COST OF DRILLING AND LOADING PERIMETER HOLES	**$426.**	**$395.**	**$566.**	**$454.**
OVERBREAK COST				
ESTIMATED VOLUME OF OVERBREAK (yd^3)	26.0	22.1	18.9	19.8
FOR UNLINED TUNNEL:				
MARGINAL COST OF EXTRA MUCKING (3) ($5./$yd^3$)	$ 35.50	$ 16.00	$ 0	$ 4.50
TOTAL COST FOR UNLINED TUNNEL	**$462.**	**$411.**	**$566.**	**$459.**
FOR LINED TUNNEL:				
MARGINAL COST OF EXTRA SHOTCRETE (3) ($75./$yd^3$)	$532.50	$240.00	$ 0	$ 67.50
TOTAL COST FOR LINED TUNNEL	**$994.**	**$651.**	**$566.**	**$525.**

NOTES: (1) COMPARISON BASED ON EXCAVATING A 20 FT. TUNNEL WITH 50 FT. PERIMETER ABOVE INVERT AND DRILL HOLES 12 FT. DEEP. IT IS ASSUMED THAT THE SPACING AND LOADING GIVEN IN TABLE 6-2 IS USED. ESTIMATED COSTS ARE DIRECT COSTS AT THE HEADING, AND DO NOT TAKE INTO ACCOUNT ANY ADDITIONAL OVERHEAD COSTS DUE TO INCREASED TOTAL CONSTRUCTION TIME.

(2) ESTIMATED VOLUME OF OVERBREAK CALCULATED BASED ON OVERBREAK DATA IN TABLE 6-3. TOTAL AVERAGE OVERBREAK PER ROUND FOR THE EXPERIMENTAL ROUNDS (36 FT. PERIMETER AND 6.6 FT. ADVANCE) IS MULTIPLIED BY A FACTOR = $\frac{50 \text{ FT.}}{36 \text{ FT.}} \times \frac{11 \text{ FT.}}{6.6 \text{ FT.}} = 2.3$ TO GET ESTIMATED AVERAGE OVERBREAK PER ROUND FOR 50 FT. PERIMETER AND 11 FT. ADVANCE.

(3) MARGINAL COSTS BASED ON VOLUME OF OVERBREAK ABOVE THAT ESTIMATED FOR MSB PRIMACORD PROCEDURES.

ing (SSB) techniques and the space loaded modified smooth blasting (MSB) techniques. The reasons for the higher FC costs are:

a. The additional time and equipment costs associated with notching the FC perimeter holes, and

b. The relative high cost of the 400 grain/ft. (0.09 Kg/m) Primacord needed to achieve the required low column charge distribution in the FC perimeter holes.

It should be noted that the total drilling and loading costs are highly dependent on the assumed optimum perimeter hole spacing. This factor and others (such as drilling/notching times and charge weight per hole) may vary in different rock types.

The drilling and loading costs do not reflect the fact that the less costly smooth blasting techniques will result in more overbreak and will not produce as sound an excavated surface as the FC techniques. This economic analysis does not include the possible cost reductions in rock support measures which may result from a sounder excavated rock surface. However, the effect of the additional overbreak is seen in Table 6-4 when the estimated cost of overbreak is included for each technique.

First, an unlined tunnel is considered. An estimate is made of the quantity of overbreak per round for each technique, based on the results in Table 6-3. The marginal cost of extra mucking was then calculated and added to the drilling and loading costs for each technique. For the unlined tunnel, the MSB space loaded round is still the most economical, but the FC costs become comparable to the costs for the SSB procedures.

Finally, a lined tunnel is considered, and the marginal cost of extra shotcrete required to backfill the overbreak is estimated for each technique. If this marginal cost of shotcrete is added to the total costs for the unlined tunnel, it can be seen that the FC and MSB Primacord techniques become most economical.

It should be noted that, since it was felt that relaxed alignment and drilling control were significant factors in the total amount of overbreak (see Section 6.4), part of the reduction in overbreak in the MSB and FC rounds may have been due to increased drilling control when the investigators were present. A study of the overbreak data in Figure 6-1 shows that for the four SSB rounds prior to the start of the MSB rounds, the average overbreak was about 11.9 cu. yd. (9.1 cu. m) per round, while the average overbreak for rounds using SSB techniques after the start of the MSB rounds (including MSB 1 and FC Cut 1) was about 11.1 cu. yd. (8.5 cu. m). This may indicate a slight increase in drilling control, however, the results of round FC 5 (Section 6.4), where a large amount of overbreak was attributed to drilling inaccuracy, do not indicate such an improvement.

In order to realize the economic advantage of the increased spacing allowable with FC procedures, additional research should be devoted to developing a single pass drilling and notching tool, such as that described in Section 4.4.2. With such a tool, perimeter holes could be notched as they are being drilled. If such a tool were available, the grooving time in Table 6-4 could be eliminated and the cost of drilling and loading for the fracture control round would be reduced from $454.00 to $403.00. This would make the FC drilling and loading cost comparable to the cost of the MSB space loaded round and less than the contractor's SSB round drilling and loading cost.

7. OPENING CUT RESULTS

7.1 TESTS IN TUNNEL SIDEWALL

The opening cuts shot in the west wall of the north heading, at Stations 3+45 and 3+64, gave a good indication of the effectiveness of the fracture control opening cut as compared to the contractor's opening cut. The crater formed by the contractor's opening cut is shown in Figure 7-1. It should be noted that one hole, designated C1 in Figure 5-17, did not detonate with the rest of the cut holes. This hole was reloaded and fired at the same time as the subsequent north heading round. The photograph of the crater (Figure 7-1) was taken after all holes had been detonated. The crater formed by the fracture control cut at Station 3+45 is shown in Figure 7-2. It can be seen that the fracture control cut pulled deeper and removed more rock than did the contractor's cut.

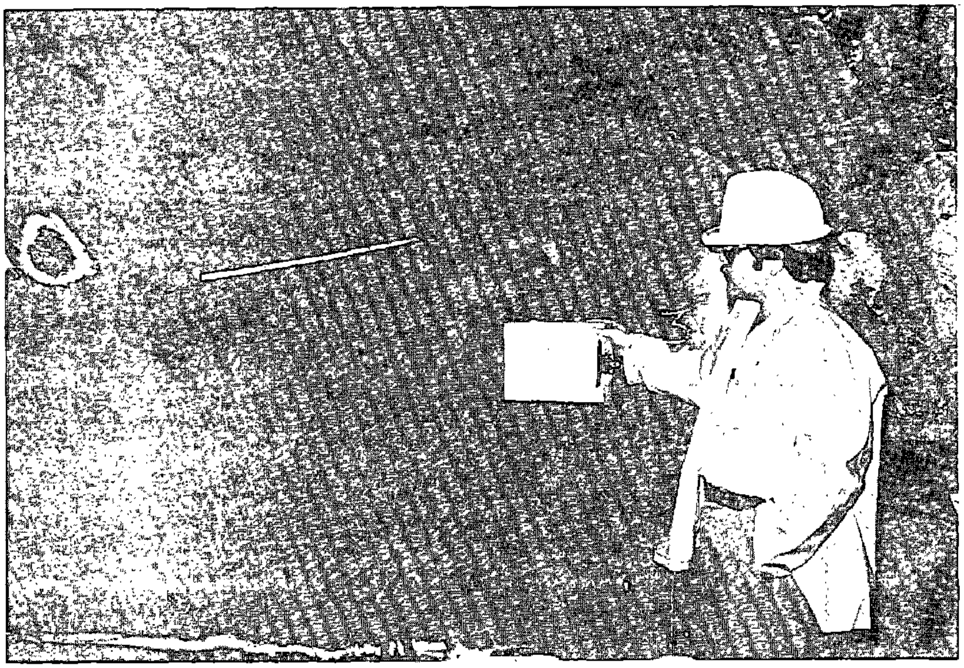


FIGURE 7-1. RESULTS OF CONTRACTOR'S OPENING CUT IN SIDEWALL AT STATION 3+64.

The single hole crater cut experiments at Stations 3+82 and 3+95 indicated that the center fragmentation hole in the fracture control cut will not create a sufficient opening cut without the three

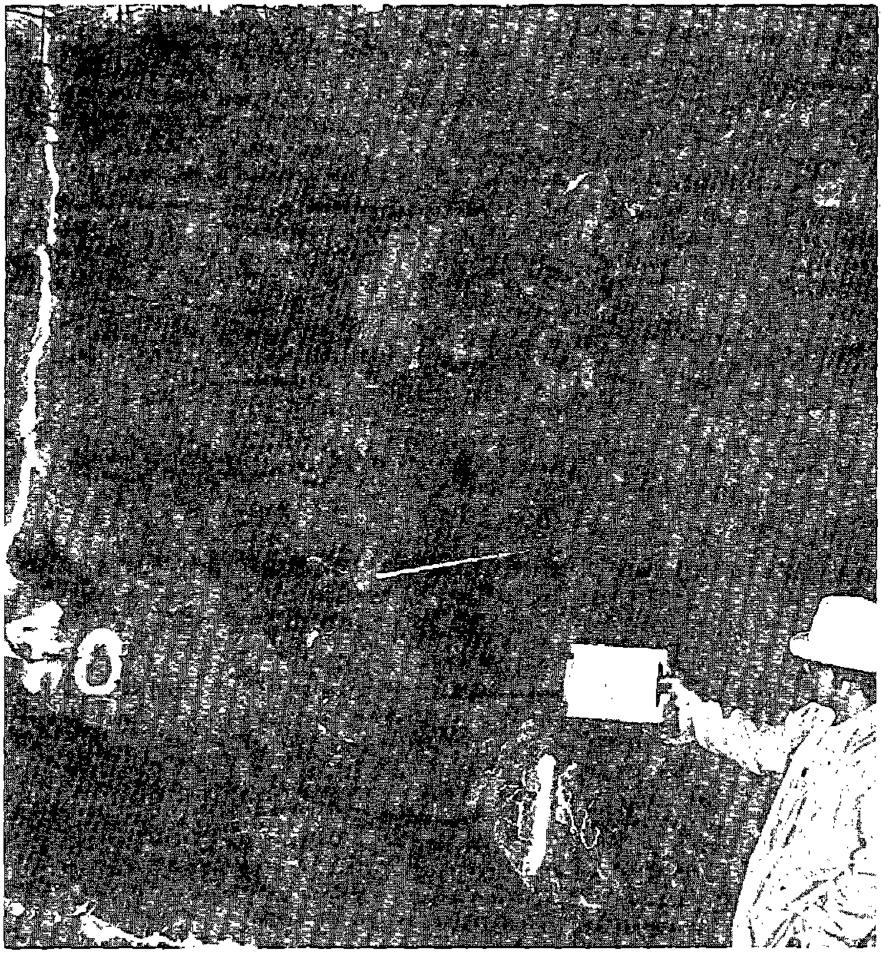


FIGURE 7-2. RESULTS OF FRACTURE CONTROL OPENING CUT IN SIDEWALL AT STATION 3+45.

cut holes around it. In both cases the collar of the drill hole was blown off but the hole remained intact below a depth of about 2 to 3 ft. (0.6 to 0.9 m) from the collar.

7.2 RESULTS IN FULL HEADING ROUNDS

7.2.1 Advance

The average advance of the contractor's opening cut was generally about 90 to 95 percent of the average cut hole length. The first full heading fracture control cut, used in round FC 6, had an average advance only about 68 percent of the average cut hole depth. This opening cut was thought to be unsuccessful for one or more of the following reasons:

a. The cut holes were not looked in towards the center fragmentation hole, so it was difficult for the center hole to eject the plug formed by the cut holes.

b. The decked charges were on separate delays, with the top charge detonated first. The top charge may have ejected the sand stemming and bottom charge.

c. The diameter of the center fragmentation hole was only 1-11/16 in. (43 mm).

FC Cut 1 had an average advance of about 95 percent of the average cut hole depth, while the average advance of FC Cut 2 was about 89 percent of the average cut hole depth. Both these rounds used the drilling pattern and loading shown schematically on Figure 4-6. In this design the cut holes were looked in, the decked charges were connected by 50 grain/ft.(0.01 Kg/m) Primacord so they detonated simultaneously, and the center fragmentation hole had a 3 in. (76 mm) diameter.

7.2.2 Vibrations

In order to compare vibrations from the fracture control opening cuts with those from the contractor's opening cuts, data from cut delays of FC Cut 1 and FC Cut 2/MSB 6 are summarized in Table 7-1 along with data from several adjacent SSB rounds which utilized the contractor's opening cut. The maximum particle velocity from the cut holes of FC Cut 1 was 0.055 in./sec. (0.14 cm/sec.) while the maximum particle velocity for the cut holes of FC Cut 2 was 0.020 in/sec. (0.05 cm/sec.). Since the opening cut holes were loaded the same in both rounds, and the slant ranges were about the same, the large variance in cut hole vibration velocity cannot be explained. The average maximum particle velocity for the SSB cut holes was about 0.11 in/sec. (0.28 cm/sec.).

The average maximum air blast overpressure for the fracture control opening cut holes was about 0.004 psi (0.028 kPa) while for the SSB rounds the average maximum air blast overpressure for the cut holes was about 0.005 psi (0.034 kPa).

It can also be seen in Table 7-1 that the maximum vibration for the round occurred on the cut hole delays only twice out of the six rounds fully documented.

7.3 COMPARISON OF OPENING CUTS

Table 7-2 summarizes the techniques and average results for the contractor's opening cut and the fracture control opening cut shown in Figure 4-6.

7-1. SUMMARY OF VIBRATION DATA FOR OPENING CUTS

ROUND NO. (1)	OPENING CUT HOLE VIBRATIONS (2)				MAXIMUM VIBRATIONS FOR ROUND (2)			
	GROUND VIBRATION VELOCITY (3)		AIR BLAST OVERPRESSURE (4)		GROUND VIBRATION VELOCITY (3)		AIR BLAST OVERPRESSURE (4)	
	MAXIMUM (in./sec.)	SLANT RANGE (ft.)	MAXIMUM (psi)	DISTANCE OF SENSOR FROM ACCESS SHAFT (ft.)	MAXIMUM (in./sec.)	AT ELAPSED TIME (sec.)	MAXIMUM (psi)	AT ELAPSED TIME (sec.)
SSB 71	0.080	169	0.005	135	0.12	9.9	0.007	1.5
SSB 75	0.070	176	0.004	135	SAME AS	CUT HOLES	0.006	7.7
FC CUT 1	0.055	179	0.003	135	0.10	5.7	0.007	5.9
FC CUT 2/ MSB 6	0.200	183	0.005	135	SAME AS	CUT HOLES	0.008	5.7
SSB 81	0.065	186	0.005	135	0.16	6.2	0.006	5.6
SSB 83	0.140	189	- (5)	-	- (6)	-	-	-
SSB 86	0.170	197	0.005	135	0.22	6.0	0.006	6.0

NOTES:
(1) THE SSB ROUNDS NOTED WERE ADJACENT TO THE FC CUT ROUNDS SO THAT THE AVERAGE SLANT RANGE (RADIAL DISTANCE FROM VIBRATION SOURCE TO SENSOR) WOULD BE ABOUT THE SAME AS THE FC CUT ROUNDS.
(2) ALL VIBRATION MEASUREMENTS NOTED WERE MADE WITH THE CONTRACTOR'S VIBRATION MONITORING EQUIPMENT.
(3) GROUND VIBRATION MEASUREMENTS MADE AT SENSOR LOCATION B (SEE FIGURE 5-1).
(4) AIR BLAST OVERPRESSURE MEASUREMENTS MADE AT SENSOR LOCATION C (SEE FIGURE 5-1).
(5) AIR BLAST OVERPRESSURE NOT RECORDED.
(6) VIBRATION MEASUREMENTS ONLY RECORDED FOR INITIAL 2 SECONDS OF ROUND DETONATION BEFORE MONITORING EQUIPMENT RAN OUT OF PAPER.

TABLE 7-2. SUMMARY OF OPENING CUT RESULTS

	CONTRACTOR'S OPENING CUT	FRACTURE CONTROL (1) OPENING CUT
DRILLING		
NUMBER OF 3" DIAMETER HOLES	3	1
NUMBER OF 1-11/16" DIAMETER HOLES	5	3
TOTAL NUMBER OF HOLES DRILLED FOR CUT HOLES	8	4
EXPLOSIVES		
NUMBER OF DELAYS	5	2
TOTAL CHARGE WEIGHT FOR CUT HOLES	19.5 lbs.	8.0 lbs.
ADVANCE	90 to 95%	92%
GROUND VIBRATIONS (2)		
AVE. MAXIMUM PARTICLE VELOCITY FOR CUT HOLES	0.11 in./sec.	0.13 in./sec.
AT SLANT RANGE OF:	183 ft.	181 ft.
AIR BLAST OVERPRESSURE (2)		
AVE. MAXIMUM AIR BLAST OVERPRESSURE	0.005 psi	0.004 psi
AT SLANT RANGE OF:	135 ft.	135 ft.

NOTES: (1) DATA SUMMARIZED FOR ROUNDS FC CUT 1 AND FC CUT 2, WHICH USED FINAL FC CUT DESIGN SHOWN IN FIGURE 4-6.

(2) VIBRATION DATA TAKEN FROM TABLE 7-1.

Using fracture control techniques, the number of opening cut holes was reduced by 50 percent and the total charge weight was reduced by 70 percent, while average advance, ground vibrations and air blast overpressures were about the same for both techniques.

More field tests are necessary, but it appears that the fracture control opening cut can significantly reduce the number and size of the holes and the amount of explosive used in forming the cut.

8. CONCLUSIONS

8.1 GENERAL

The following conclusions can be drawn from the controlled blasting experiments at the Porter Square Station Pilot Tunnel. It should be noted that these conclusions are based on limited testing at one site and in one rock formation. Additional field testing of the methods is required, particularly in different rock types. Nevertheless, it is felt that these conclusions will be generally applicable to other rock types.

8.2 DRILLING ACCURACY

In drill and blast excavation, four factors control the overbreak and soundness of the remaining rock:

a. Intact rock properties (strength, hardness, modulus, etc.),

b. Site geology (joints, faults, in-situ stress, lithology, etc.),

c. Blasting technique, and

d. Drilling accuracy.

The intact rock properties and site geology cannot be changed once the structure is located. However, the other two factors can be controlled. If either is neglected, the quality of the rock surface is compromised.

Too much emphasis is often placed on blasting techniques and not enough on drilling accuracy. In this study, it was concluded that the major cause of overbreak was not improper blasting techniques or poor rock properties, but relaxed drilling control. In some cases, drill holes were found to be collared as much as 12 to 15 inches outside the correct locations. In addition, perimeter hole look-out was often excessive. This conclusion was emphasized by the fact that overbreak for the Porter Square Station Pilot Tunnel was calculated from silhouette photographs to be about 30 percent of the total design volume of the tunnel.

In arriving at the conclusions contained herein, it was difficult to differentiate between reduced overbreak resulting from the blasting techniques and those resulting from increased drilling control resulting from the investigators' presence in the tunnel. It is the investigators' opinion that blasting technique contributed more significantly to the beneficial performance of the test rounds.

8.3 PERIMETER CONTROL

a. Fracture control procedures can reduce the number of perimeter holes as compared with smooth blasting while maintaining equivalent or better control of overbreak and improved preservation of the structural integrity of the remaining rock. In this study, the optimum fracture control techniques increased the perimeter spacing by 38 to 83 percent over the various smooth blasting techniques. The average half cast factor at the tunnel ribs was increased by 15 to 270 percent over the various smooth blasting techniques, while overbreak at the ribs was reduced by 10 to 30 percent.

b. Fracture control procedures can reduce the amount of explosives required in perimeter holes as compared to smooth blasting. In this study, the optimum fracture control techniques reduced the total explosive weight in the perimeter holes by 43 to 69 percent. However, it should be noted that the type of explosives required in fracture control perimeter holes is currently relatively expensive and until a more economical light column charge is commercially available, the benefit of reduced explosive quantity may be offset by increased explosive costs.

c. Fracture control procedures can reduce the vibration levels resulting from perimeter hole delays as compared with smooth blasting techniques. In this study, the fracture control perimeter delays had an average maximum particle velocity which was about 20 to 50 percent less than the average maximum vibrations produced by the various smooth blasting perimeter delays. Average maximum air blast overpressure from the fracture control perimeter delays was equivalent to or less (by up to 40 percent) than the average maximum air blast overpressure produced by the various smooth blasting perimeter delays.

However, it should be noted that the maximum vibration and air blast overpressure did not generally occur as a result of the perimeter hole delays. Therefore, although vibrations from the perimeter holes may be reduced, maximum vibrations from the round may remain unchanged.

d. Geologic features such as joints, faults, or bedding planes can influence the perimeter control achieved with fracture control by arresting, diverting, or bifurcating the driven crack or by venting the explosive gasses (See sections 3.3, 4.1.2, 4.1.3, 4.1.4, and 6.4). The results in granite quarries and in concrete demolition described in section 4.1.5, as well as the fracture control round in the igneous dike (FC 7) indicate that the fracture control procedures may result in better perimeter control in rock formations that are more massive, homogeneous, and less jointed than the argillite at the Porter Square site. It should be noted, however, that the perimeter hole spacing and burden in more massive and homogeneous rock formations may be limited not by the ability to drive a crack between the perimeter holes but by the ability of the perimeter hole charges to achieve the desired advance (pull to the bottom of the round).

e. To make fracture control techniques more economically desirable, a less expensive method of notching the drill holes, such as a single pass combination drill bit and notching tool, should be developed.

f. At the present time, the space loaded, modified smooth blasting technique appears to be the most economical perimeter control method for unlined tunnels, and produces better results than the method usually specified in the United States. For lined tunnels, where shotcrete is used to backfill areas of overbreak, fracture control procedures and Primacord loaded modified smooth blasting procedures may result in substantial cost savings over conventional smooth blasting techniques.

8.4 OPENING CUTS

Opening cuts using fracture control techniques can reduce the number of holes and the amount of explosives as compared with other methods, while maintaining equivalent vibration levels and advance.

9. RECOMMENDATIONS FOR ADDITIONAL RESEARCH

9.1 GENERAL

Based on the results of experiments conducted during this research project on a full scale tunnel project, the investigators have concluded that fracture control procedures can be successful in: reducing the number of perimeter drill holes, reducing explosives quantity, reducing overbreak and increasing the quality of the rock left in place as compared to standard practice. The practical advantages of the procedure are limited by as yet undeveloped efficient tooling and the availability of economical commercially available explosives in the proper charge distribution.

9.2 RECOMMENDATIONS

To make the procedure more economically attractive to the industry, the following additional research and development is suggested:

a. Design, develop and test a single pass drill and broaching tool to be used in drilling and broaching perimeter drill holes. An artist's conceptual drawing of such a tool is shown on Figure 4-11. Such a tool would permit drilling the perimeter holes and notching them without the additional time currently required to change bits, realign the drills, and notch the holes with a separate tool.

b. Test the tool and fracture control procedures in different rock formations to evaluate performance, limitations, and blasting design parameters in differing rock types. Currently, testing in a quarry environment and ongoing rock tunnel projects is envisioned as the most economical means.

c. Develop and document blasting design parameters for use in various rock formations with fracture control procedures. Parameters would include drill hole size, notch configuration, perimeter hole spacing, burden, charge distribution and type, all related to rock formation.

APPENDIX A
USE OF MS DELAY ROUND TO REDUCE HUMAN RESPONSE TO BLASTING

A.1 BACKGROUND

To minimize the possibility of damage to nearby structures, a maximum peak particle velocity of ground vibrations (measured adjacent to any structure in the vicinity of blasting operations) of 1.9 in/sec. (4.8 cm/sec.) was specified in contract documents. To prevent air blast damage and reduce disturbance to the public, air blast noise adjacent to nearby structures was required to be kept below an equivalent peak air overpressure of about 0.15 psi (1.03 kPa). In addition, the contractor was prohibited from blasting between 10 PM and 7 AM and on weekends and holidays.

The contractor measured ground vibrations and air blast overpressures adjacent to the nearest structures for every round fired. Additional ground vibration measurements were made by the investigators and by the Noise Measurement and Assessment Laboratory of the Department of Transportation/Transportation Systems Center (DOT/TSC). The measured ground vibrations and air blast noise were well within the specified limits. As shown in Appendix D, peak particle velocities were maintained below 0.6 in/sec. (0.015 m/sec.) at the nearest structures, about 100 ft. (30 m) away. Air blast noise at similar distances was maintained below 0.020 psi (0.14 kPa) peak air overpressure.

In spite of these relatively low vibration and noise levels, complaints were made by residents in the area. As a result of these complaints, the Cambridge City Council passed a resolution reducing the hours of blasting to between 7 AM and 8 PM.

It was felt that the complaints were a result of the following factors, listed in order of importance:

a. Duration of vibration. The contractor was using 19 delay periods of standard delay caps (Hercules Superdet Electric) which resulted in a duration of vibration and noise of over 16 seconds.

b. Timing of blast detonations. The complaints began after the contractor started working two shifts and blasts were detonated on two successive evenings at about 7 PM, a time of very low ambient noise level in the area. Previously, all blasts had been between the hours of 7 AM and 3 PM. Ambient noise levels are relatively high during the 7 AM and 3 PM period, mainly due to heavy traffic in the square.

c. A heightened awareness of the blasting, brought about by organized opposition to the construction.

A.2 PROCEDURE

The Blasting Test provision of the contract was used to have the contractor detonate a heading round with millisecond (ms) delay caps (Atlas Rockmaster SF Electric) in order to minimize the duration of the blast and thus minimize human response to the vibrations. There was concern that the ms delays might result in the following undesirable effects:

a. Possible increased vibration levels. With the regular delays used by the contractor, the scatter in detonation time from the nominal firing time for any given delay number was often as much as one second, especially in the larger delay numbers. This resulted in most of the holes in a given delay firing independently. With millisecond delays, the scatter would be far less and some of the holes in a delay would be expected to fire simultaneously. In addition, with the shorter intervals, there is more likelihood of overlap of one delay with another.

b. Possible failure of the cut holes to detonate, due to a tendency of the water gel explosives to "dead-press" in closely spaced holes detonated with ms delays.

c. Possible damage to utilities in the tunnel from excessive flyrock.

After assessing these possible disadvantages, it was agreed to try one ms round, the last full round of the project. To reduce the possibility of the undesirable effects described, the round design was modified to meet the following criteria:

a. Cut holes were loaded with extra gelatin dynamite in place of the water gel explosive. Each cut hole was loaded with seven sticks, or 3.7 lb. (1.7 kg), of 40 percent extra gelatin.

b. Reliever and lifter holes:

    1. Maximum of two holes or 7.8 lb. (3.5 kg) per delay (50 percent of usual charge with regular delays).

    2. The detonation sequence was modified to prevent excessive vibrations due to overlap.

c. Perimeter holes:

    1. Maximum of four holes, or 6.9 lb. (3.1 kg) per delay (67 percent of perimeter charge with regular delays).

2. The contractor's SSB perimeter hole spacing and loading was used except that perimeter holes were stemmed with sand.

The complete ms round design is shown in Figure A-1. A total of twenty-five delays were used in the round.

A.3 RESULTS

Some of the results from the ms delay round, as well as the previous SSB round (SSB 92), are summarized in Figure 6-1. The following results are of particular significance:

a. The duration of vibrations was reduced from over 16 seconds for the regular delay round to about 2.2 seconds for the ms delay round. Figure A-2, which shows a vibration record from a typical tunnel round, together with a record of the ms round, illustrates this reduction in duration of vibrations.

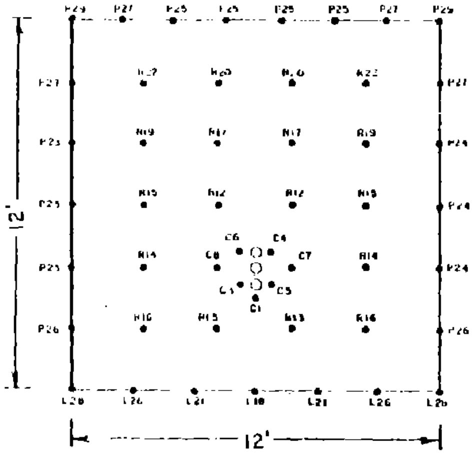
b. The maximum measured ground vibration, at a distance of about 120 ft. (37 m) from the blast, had a peak particle velocity of about 0.4 in/sec. (1.0 cm/sec.), which was about the same as for the preceding regular delay round.

c. Although the muck was thrown further down the tunnel (about 50 ft. (15 m) compared to about 25 ft. (8 m) for the contractor's round), there was no flyrock damage to utilities. In addition, because fragmentation was better and the muck pile was less compact, mucking operations were improved.

d. The round generally pulled beyond the bottom of the drill holes. The advance was greater than 100 percent at the cut holes, was about 95 percent at the left rib, and about 94 percent at the right rib.

e. Figure A-3 shows the left rib, back, and right rib of the ms delay round. A fault passes through the right rib of the round. As a result, there was about 5.0 cu. yd. (3.8 cu. m) of overbreak at that rib and the half cast factor was only 2 percent. However, at the left rib and back, the overbreak was only 1.2 cu. yd. (0.9 cu. m) and 2.4 cu. yd. (1.8 cu. m), respectively. The HCF for the left rib was 32 percent, while for the back the HCF was 11 percent. Thus, the perimeter contour performance of the ms round was significantly better than the average contractor SSB round.

SKETCH OF BLAST PATTERN



HOLE FACTOR 1.28 HOLES/YD^3

DRILL FACTOR 8.98 LF/YD^3

TUNNEL ROUND CHARGE DISTRIBUTION

TYPE OF HOLE	NUMBER OF HOLES	BOTTOM CHARGE LOAD (# STICKS)	COLUMN CHARGE LOAD (# STICKS)	UNLOADED LENGTH (STEMMING)	CHARGE WT PER HOLE (LBS.)
BURN	3	NONE	NONE	7'-9"	0
CUT	7	40% (1) -LT-	40% (6) -T-	3'-4"	3.71
RELIEVER	18	SAME AS CUT	A-2 (4) -T-	2'-4"	3.37
LIFTER	7	SAME AS CUT	A-2 (4) -T-	2'-4"	3.37
PERIMETER	18	SAME AS CUT	H (2) -NT-	2'-4" (SAND)	1.73

DESIGN HOLE DIA 1-11/16 (3 BURN) IN.

DESIGN HOLE LENGTH 7 FT.

TUNNEL ROUND SUMMARY

TYPE OF HOLE(S)	DELAY NO	NO. OF HOLES PER DELAY	CHARGE WT PER HOLE (LBS)	CHARGE WT PER DELAY (LBS.)	DESIGN SPACING (INCHES)	DESIGN BURDEN (INCHES)
CUT	1	1	3.71	3.71	3	3
	3	1	3.71	3.71	3	3
	4	1	3.71	3.71	3	3
	5	1	3.71	3.71	3	3
	6	1	3.71	3.71	3	3
	7	1	3.71	3.71	24	9
	8	1	3.71	3.71	24	9
RELIEVER	12	2	3.37	6.74	29	18
	13	2	3.37	6.74	24 - 29	15 - 18
	14	2	3.37	6.74	36	29
	15	2	3.37	6.74	24 - 29	17
	16	2	3.37	6.74	24 - 29	17
	17	2	3.37	6.74	29 - 36	24
LIFTER	18	1	3.37	3.37	24	24
RELIEVER	19	2	3.37	6.74	24 - 29	17
	20	2	3.37	6.74	29 - 36	24
LIFTER	21	2	3.37	6.74	24	20
RELIEVER	22	2	3.37	6.74	24 - 29	17
PERIMETER	23	3	1.73	5.19	24	29
	24	3	1.73	5.19	24	29
	25	4	1.73	6.92	20.5	24
	26	2	1.73	10.20	24 - 34	17
LIFTER	26	2	3.37		24 - 34	18
PERIMETER	27	4	1.73	6.92	20.5- 32	18
LIFTER	28	2	3.37	6.74	24	17
PERIMETER	29	2	1.73	3.46	20.5- 24	14

MAX. CHARGE WT. PER DELAY 10.20 LBS., ON DELAY NO. 26

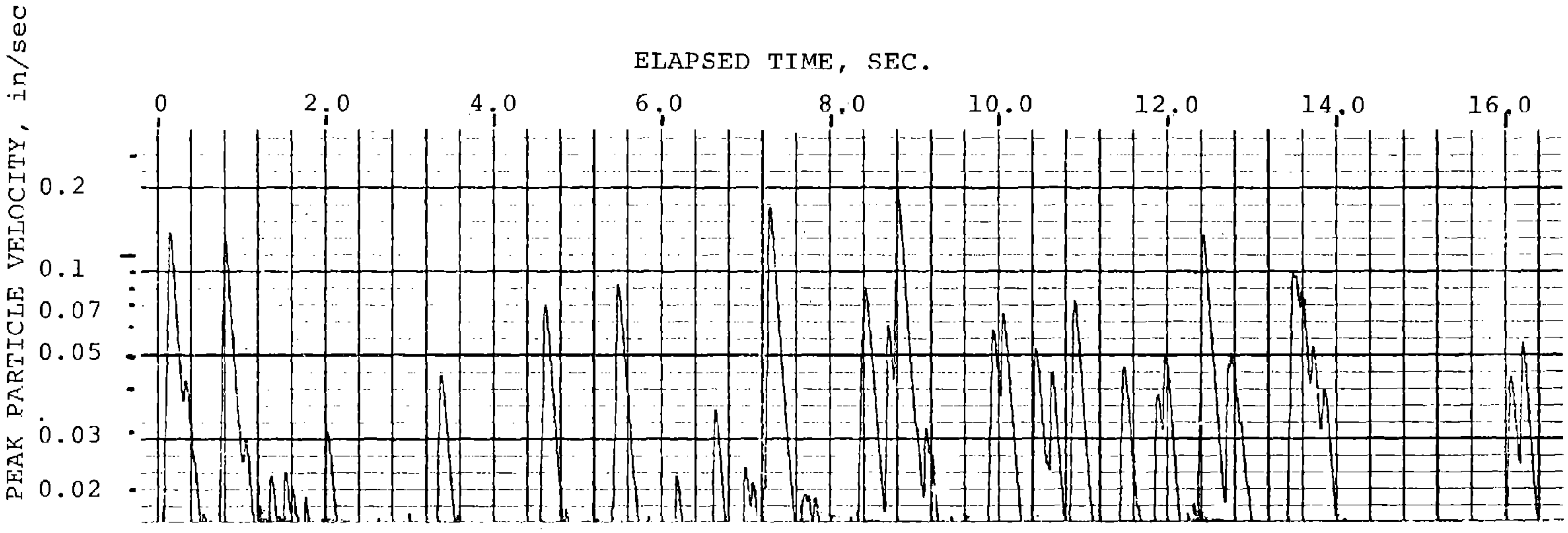
TOTAL CHARGE WT. OF ROUND 141.4 LBS.

POWDER FACTOR 3.42 LBS. PER CUBIC YARD

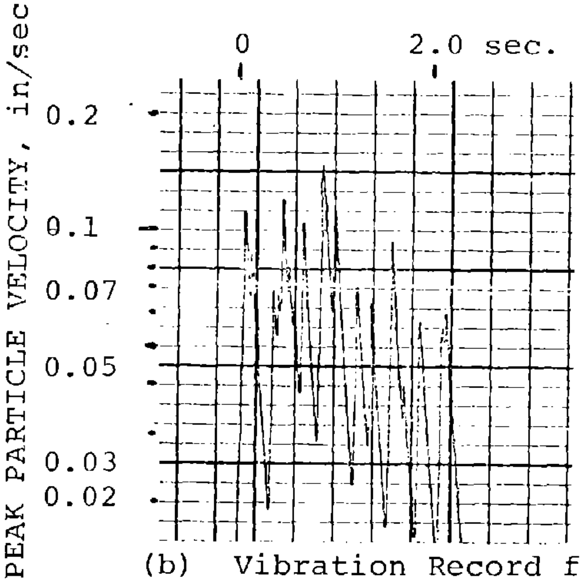
TYPE OF DETONATORS ATLAS ROCKMASTER SF ELECTRIC

BLAST LOCATION:
STATION: 0+6.5, E TO 0+0-, E

FIGURE A-1. TUNNEL ROUND DESIGN - MS DELAY ROUND

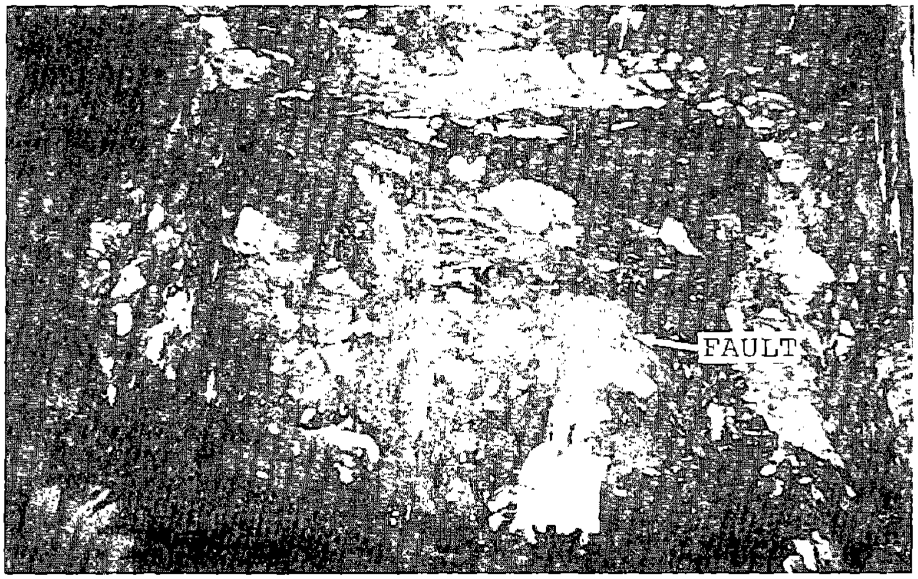


(a) Vibration Record for Typical Contractor SSB Round Using Regular Delays

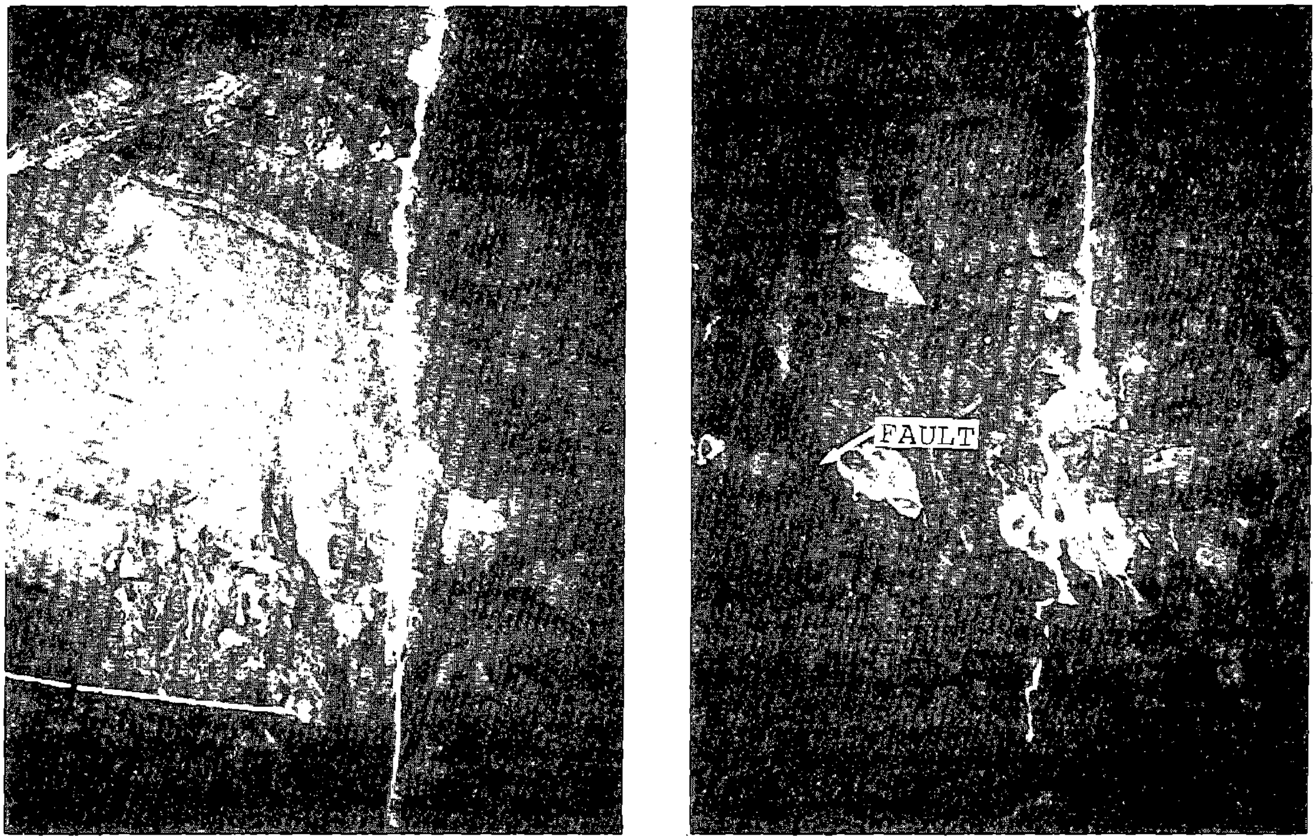


(b) Vibration Record for Millisecond (MS) Delay Round

FIGURE A-2. COMPARISON OF VIBRATION RECORDS FROM TYPICAL CONTRACTOR SSB ROUND AND MS DELAY ROUND



(a) Ribs and Back



(b) Left Rib

(c) Right Rib

FIGURE A-3. RIBS AND BACK OF MS DELAY ROUND

A.4 CONCLUSIONS

Although such a conclusion is subjective, it was agreed by personnel at the site that the disturbance to the public was greatly reduced with the millisecond delay round due to the reduction in duration of the noise and vibrations.

A.5 RECOMMENDATIONS

Additional experimentation should be done with the use of millisecond delays in tunnel rounds, using both conventional and fracture control procedures. Testing should be aimed at assessing:

a. Vibration levels and human response as compared with standard tunnel delays.

b. The use of water gel explosives in cut holes and the probability of the explosives "dead pressing" in the holes when detonated with ms delays.

c. Fragmentation and mucking operations as compared with standard tunnel delays.

d. Perimeter control performance as compared with standard tunnel delays.

e. Advance per round as compared with standard tunnel delays.

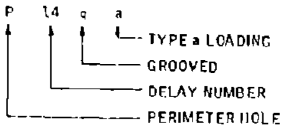
APPENDIX B
TUNNEL ROUND DESIGN DETAILS

SYMBOLS AND ABBREVIATIONS

DRILLING

○	UNLOADED 3" DIAMETER BURN HOLE
●	LOADED 3" DIAMETER HOLE
•	LOADED 1-5/8" TO 1-3/4" DIAMETER (APPROX.) CUT, RELIEVER, LIFTER OR PERIMETER HOLE
┍	LOADED 1-5/8" TO 1-3/4" DIAMETER (APPROX.) GROOVED PERIMETER OR CUT HOLE USED IN EXPERIMENTAL FRACTURE CONTROL ROUNDS AND CUTS
B	DESIGNATION USED FOR LOADED CENTER HOLE IN FRACTURE CONTROL OPENING CUT
C	CUT HOLE
R	RELIEVER HOLE
R+	FIRST ROW IN OF RELIEVER HOLES (DESIGNATED ONLY WHEN LOADED DIFFERENTLY FROM INTERIOR RELIEVER HOLES)
L	LIFTER HOLE
P	PERIMETER HOLE

LEGEND:



LOADING

EXPLOSIVES:

40%	40% GELATIN EXTRA DYNAMITE MANUFACTURED BY HERCULES INCORPORATED STICK SIZE: 1-1/4" x 8" STICK WEIGHT: 0.53 LB./STK. = 0.80 LB./FT
A-2	GEL-POWER A-2 PACKAGED SLURRY EXPLOSIVE MANUFACTURED BY HERCULES INCORPORATED STICK SIZE: 1-1/4" x 16" STICK WEIGHT: 0.71 LB./STK. = 0.53 LB./FT.
H	HERCOSPLIT WR SEMIGELATIN DYNAMITE MANUFACTURED BY HERCULES INCORPORATED STICK SIZE: 7/8" x 24" STICK WEIGHT: 0.60 LB./STK. = 0.30 LB./FT.
PC	PRIMACORD MANUFACTURED BY THE ENSIGN BICKFORD COMPANY 400 PC: 400 GRAINS/FT. = 0.06 LB./FT. 50 PC: 50 GRAINS/FT. = 0.01 LB./FT.

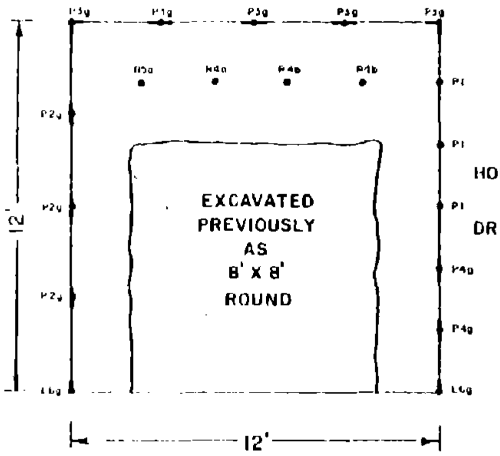
TAMPING:

-NT-	NOT TAMPED
-LT-	LIGHTLY TAMPED
-T-	TAMPED

NOTES

1. POWDER, HOLE AND DRILL FACTORS COMPUTED BASED ON THE FOLLOWING ASSUMED VOLUMES EXCAVATED:
   SHAFT ROUNDS: 98.86 CUBIC YARDS (24' DIA. x 5.9')
   12' BY 12' TUNNEL ROUNDS: 41.31 CUBIC YARDS (13' x 13' x 6.6')
   8' BY 8' TUNNEL ROUNDS: 16.50 CUBIC YARDS (9' x 9' x 5.5').
2. UNLOADED LENGTHS COMPUTED ASSUMING A TAMPING FACTOR OF 0.75 FOR TAMPED EXPLOSIVES AND 0.85 FOR LIGHTLY TAMPED EXPLOSIVES.
3. SHAFT AND TUNNEL ROUNDS TYPICALLY DETONATED BY SUPERDET ELECTRIC DELAY CAPS MANUFACTURED BY HERCULES INCORPORATED.
4. PERINI REVISION 4 ROUND AT STATION 4 + 02, ℄ TO STATION 4 + 08, ℄ DETONATED BY NONEL PRIMADET NON-ELECTRIC DELAY CAPS MANUFACTURED BY THE ENSIGN BICKFORD COMPANY.
5. MILLISECOND DELAY ROUND DETONATED BY ROCKMASTER SF ELECTRIC MILLISECOND DELAY CAPS MANUFACTURED BY THE ATLAS POWDER COMPANY.
6. DATA PRESENTED ON ROUND SUMMARIES INCLUDED HEREIN ARE AS DESIGNED AND MAY NOT REPRESENT AS DRILLED AND SHOT CONDITIONS.

SKETCH OF BLAST PATTERN



HOLE FACTOR N.A. HOLES/YD³

DRILL FACTOR N.A. LF/YD³

TUNNEL ROUND CHARGE DISTRIBUTION

TYPE OF HOLE	NUMBER OF HOLES	BOTTOM CHARGE LOAD (# STICKS)	COLUMN CHARGE LOAD (# STICKS)	UNLOADED LENGTH (STEMMING)	CHARGE WT PER HOLE (LBS)
BURN	0	NONE	NONE	---	0
CUT	0	NONE	NONE	---	0
RELIEVER	2 a	40% (1) -T-	A-2 (4) -T- 40% (1) -T-	1'-7"	3.90
	2 b		A-2 (5) -T- 40% (1) -T-	7"	4.61
LIFTER	2	40% (2) -T-	A-2 (4) 40% (1) -T-	1'-1"	4.43
PERIMETER	13	40% (2) -T-	400 PC (4') -NT-	1'-7" (WATER BAGS)	1.30

DESIGN HOLE DIA. 1-11/16 IN.

DESIGN HOLE LENGTH 6.6 (AVE.) FT.

TUNNEL ROUND SUMMARY

TYPE OF HOLE(S)	DELAY NO.	NO. OF HOLES PER DELAY	CHARGE WT PER HOLE (LBS.)	CHARGE WT PER DELAY (LBS.)	DESIGN SPACING (INCHES)	DESIGN BURDEN (INCHES)
PERIMETER	1	3	1.30	3.90	24	24
	2 g	3	1.30	3.90	36	24
	3 g	5	1.30	6.50	36	23 - 24
	4 g	2	1.30	11.11	24	24
RELIEVER	4 a	1	3.90		29	24
	4 b	1	4.61		29	24
	5 a	1	3.90	8.51	29	24
	5 b	1	4.61		29	24
LIFTER	6 g	2	4.43	8.86	24 - 36	24

MAX. CHARGE WT. PER DELAY 11.11 LBS., ON DELAY NO. 4

TOTAL CHARGE WT. OF ROUND 42.78 LBS.

POWDER FACTOR N.A. LBS. PER CUBIC YARD

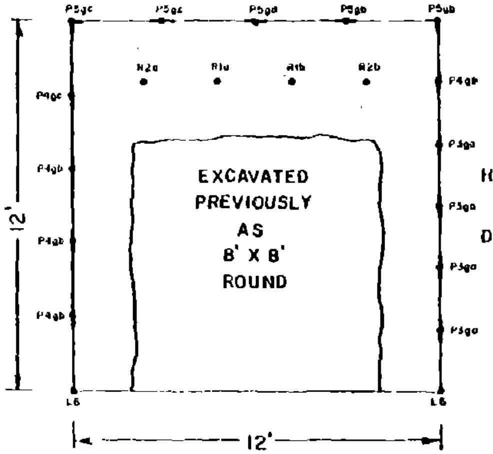
TYPE OF DETONATORS HERCULES SUPERDET ELECTRIC

BLAST LOCATION:

STATION: 2 + 68.13, 89' RIGHT TO 95' RIGHT

FIGURE B-1. TUNNEL ROUND DESIGN - FC ENL. 1

SKETCH OF BLAST PATTERN



HOLE FACTOR N.A. HOLES/YD^3

DRILL FACTOR N.A. LF/YD^3

TUNNEL ROUND CHARGE DISTRIBUTION

TYPE OF HOLE	NUMBER OF HOLES	BOTTOM CHARGE LOAD (# STICKS)	COLUMN CHARGE LOAD. (# STICKS)	UNLOADED LENGTH (STEMMING)	CHARGE WT. PER HOLE (LBS)
BURN	0	NONE	NONE	---	0
CUT	0	NONE	NONE	---	0
RELIEVER	2 a	40% (1)	A-2 (3) -T-	2'-3" (SAND BAGS)	2.66
	2 b		A-2 (4) -T-	1'-3" (SAND BAGS)	3.37
LIFTER	2	40% (2) -T-	A-2 (3) -T-	1'-9" (SAND BAGS)	3.19
PERIMETER	4 ga	40% (1) -T-	400 PC (4.5") -NT-	9" (SAND BAGS)	0.80
	6 gb	40% (2) -T-	NONE, SPACER	4'-9" (SAND BAGS)	1.06
	3 gc	40% (2) -T-	400 PC (1") -NT-	1'-9" (SAND BAGS)	1.24
	1 gd	40% (1) -T-	NONE, SPACER	5'-3" (SAND BAGS)	0.53

DESIGN HOLE DIA 1-11/16 IN.

DESIGN HOLE LENGTH 5.75' (AVE.) FT.

TUNNEL ROUND SUMMARY

TYPE OF HOLE(S)	DELAY NO.	NO. OF HOLES PER DELAY	CHARGE WT PER HOLE (LBS.)	CHARGE WT PER DELAY (LBS.)	DESIGN SPACING (INCHES)	DESIGN BURDEN (INCHES)
RELIEVER	1 a	1	2.66	6.03	29	24
	1 b	1	3.37		29	24
	2 a	1	2.66	6.03	29	24
	2 b	1	3.37		29	24
PERIMETER	3 ga	4	0.80	3.20	24	24
	4 gb	4	1.06	5.48	24 - 29	17 - 24
	4 gc	1	1.24		29	17
	5 gb	2	1.06	5.13	36	18 - 24
	5 gc	2	1.24		36	22 - 24
	5 gd	1	0.53		36	24
LIFTER	6	2	3.19	6.38	24 - 29	24

MAX. CHARGE WT. PER DELAY 6.38 LBS., ON DELAY NO. 6

TOTAL CHARGE WT. OF ROUND 32.25 LBS.

POWDER FACTOR N.A. LBS. PER CUBIC YARD

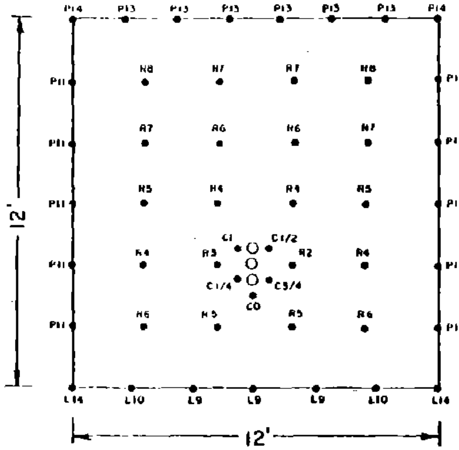
TYPE OF DETONATORS HERCULES SUPERDET ELECTRIC

BLAST LOCATION:

STATION: 2 + 68.13, 95' RIGHT TO 100' RIGHT

FIGURE B-2. TUNNEL ROUND DESIGN - FC ENL. 2

SKETCH OF BLAST PATTERN



HOLE FACTOR 1.28 HOLES/YD^3

DRILL FACTOR 8.98 LF/YD^3

TUNNEL ROUND CHARGE DISTRIBUTION

TYPE OF HOLE	NUMBER OF HOLES	BOTTOM CHARGE LOAD (# STICKS)	COLUMN CHARGE LOAD (# STICKS)	UNLOADED LENGTH (STEMMING)	CHARGE WT. PER HOLE (LBS.)
BURN	3	NONE	NONE	7'-9"	0
CUT	5	40% (1) -NT-	A-2 (4) 40% (1) -T-	1'-10"	3.90
RELIEVER	20	SAME AS CUT	SAME AS CUT	1'-10"	3.90
LIFTER	7	SAME AS CUT	SAME AS CUT	1'-10"	3.90
PERIMETER	10	SAME AS CUT	H (2) -NT-	2'-4" (SAND)	1.73

DESIGN HOLE DIA. 1-11/16 (3 BURN) IN.

DESIGN HOLE LENGTH 7 FT.

TUNNEL ROUND SUMMARY

TYPE OF HOLE(S)	DELAY NO.	NO. OF HOLES PER DELAY	CHARGE WT. PER HOLE (LBS.)	CHARGE WT. PER DELAY (LBS.)	DESIGN SPACING (INCHES)	DESIGN BURDEN (INCHES)
CUT	0	1	3.92	3.90	3.90	3
	1/4	1	3.92	3.90	3.90	3
	1/2	1	3.92	3.90	3.90	3
	3/4	1	3.92	3.90	3.90	3
	1	1	3.92	3.90	3.90	3
RELIEVER	2	1	3.91	3.90	3.90	9
	3	1	3.92	3.90	3.90	9
	4	4	3.92	3.90	15.C0	10 - 29
	5	4	3.92	3.90	15.60	15 - 18
	6	4	3.92	3.90	15.60	18 - 24
	7	4	3.92	3.90	15.60	18 - 24
	8	2	3.92	3.90	7.80	18
LIFTER	9	3	3.92	3.90	11.70	24
	10	2	3.92	3.90	7.80	19
PERIMETER	11	5	1.73	1.73	8.65	29
	12	5	1.73	1.73	8.65	29
	13	6	1.73	1.73	10.38	24
	14	2	1.73	1.73	11.26	16
LIFTER	14	2	3.92	3.90		18

MAX. CHARGE WT. PER DELAY 15.60 LBS., ON DELAY NO. 4, 5, 6 AND 7

TOTAL CHARGE WT. OF ROUND 155.9 LBS.

POWDER FACTOR 1.77 LBS. PER CUBIC YARD

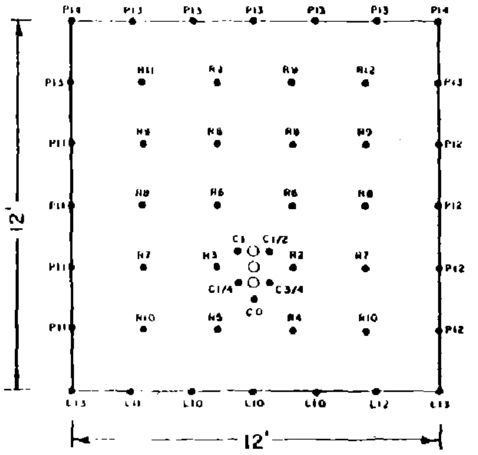
TYPE OF DETONATORS HERCULES SUPERDET ELECTRIC

BLAST LOCATION:

STATION: 0 + 00, ℄ TO 4 + 26, ℄

FIGURE B-3. TUNNEL ROUND DESIGN - CONTRACTOR'S FINAL SSB ROUND

SKETCH OF BLAST PATTERN



HOLE FACTOR 1.26 HOLES/YD³

DRILL FACTOR 8.81 LF/YD³

TUNNEL ROUND CHARGE DISTRIBUTION

TYPE OF HOLE	NUMBER OF HOLES	BOTTOM CHARGE LOAD (# STICKS)	COLUMN CHARGE LOAD (# STICKS)	UNLOADED LENGTH (STEMMING)	CHARGE WT. PER HOLE (LBS.)
BURN	3	NONE	NONE	7'-9"	0
CUT	5	40% (1) -LT-	40% (1) A-2 (4) -T-	1'-11"	3.90
RELIEVER	20	SAME AS CUT	SAME AS CUT	1'-11"	3.90
LIFTER	7	SAME AS CUT	SAME AS CUT	1'-11"	3.90
PERIMETER	17	SAME AS CUT	II (2) -NT-	2-5" (SAND)	1.73

DESIGN HOLE DIA. 1-11/16 (3 BURN) IN.

DESIGN HOLE LENGTH 7 FT.

TUNNEL ROUND SUMMARY

TYPE OF HOLE(S)	DELAY NO.	NO. OF HOLES PER DELAY	CHARGE WT. PER HOLE (LBS.)	CHARGE WT. PER DELAY (LBS.)	DESIGN SPACING (INCHES)	DESIGN BURDEN (INCHES)
CUT	0	1	3.90	3.90	3	3
	1/4	1	3.90	3.90	3	3
	1/2	1	3.90	3.90	3	3
	3/4	1	3.90	3.90	3	3
	1	1	3.90	3.90	3	3
RELIEVER	2	1	3.90	3.90	24	9
	3	1	3.90	3.90	24	9
	4	1	3.90	3.90	24	20
	5	1	3.90	3.90	24 - 29	20
	6	2	3.90	7.80	29	20
	7	2	3.90	7.80	36	29
	8	4	3.90	15.60	24 - 36	18 - 24
	9	4	3.90	15.60	24 - 36	18 - 24
	10	2	3.90	19.50	24 - 30	18
LIFTER	10	3	3.90		24 - 30	24 - 26
RELIEVER	11	1	3.90	14.72	29 - 37	18
LIFTER	11	1	3.90		24 - 34	18
PERIMETER	11	4	1.73		24	29
RELIEVER	12	1	3.90	14.72	29 - 37	18
LIFTER	12	1	3.90		24 - 34	18
PERIMETER	12	4	1.73		24	29
LIFTER	13	2	3.90	19.91	24	17
PERIMETER	13	7	1.73		24	24
	14	2	1.73	3.46	24	17

MAX. CHARGE WT. PER DELAY 19.91 LBS., ON DELAY NO. 13

TOTAL CHARGE WT. OF ROUND 154.2 LBS.

POWDER FACTOR 3.73 LBS. PER CUBIC YARD

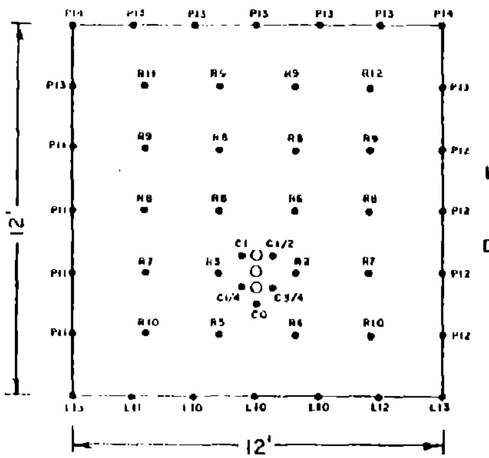
TYPE OF DETONATORS HERCULES SUPERDET ELECTRIC

BLAST LOCATION:

STATION: 2+05, ℄ TO 1+99 ℄

FIGURE B-4. TUNNEL ROUND DESIGN - MSB 1

SKETCH OF BLAST PATTERN



HOLE FACTOR 1.26 HOLES/YD^3

DRILL FACTOR 8.81 LF/YD^3

TUNNEL ROUND CHARGE DISTRIBUTION

TYPE OF HOLE	NUMBER OF HOLES	BOTTOM CHARGE LOAD (# STICKS)	COLUMN CHARGE LOAD (# STICKS)	UNLOADED LENGTH (STEMMING)	CHARGE WT. PER HOLE (LBS.)
BURN	3	NONE	NONE	7'-9"	0
CUT	5	40% (1) -LT-	A-2 (4) -T-	2'-5"	3.37
RELIEVER	20	SAME AS CUT	SAME AS CUT	2'-5"	3.37
LIFTER	7	SAME AS CUT	SAME AS CUT	2'-5"	3.37
PERIMETER	17	SAME AS CUT	B (2) -NT-	2'-5" (SAND)	1.73

DESIGN HOLE DIA 1-11/16" (3 BURN) IN.

DESIGN HOLE LENGTH 7 FT.

TUNNEL ROUND SUMMARY

TYPE OF HOLE(S)	DELAY NO.	NO. OF HOLES PER DELAY	CHARGE WT PER HOLE (LBS.)	CHARGE WT PER DELAY (LBS.)	DESIGN SPACING (INCHES)	DESIGN BURDEN (INCHES)
CUT	0	1	3.37	3.37	3	3
	1/4	1	3.37	3.37	3	3
	1/2	1	3.37	3.37	3	3
	3/4	1	3.37	3.37	3	3
	1	1	3.37	3.37	3	3
RELIEVER	2	1	3.37	3.37	24	9
	3	1	3.37	3.37	24	9
	4	1	3.37	3.37	24	20
	5	1	3.37	3.37	24 - 29	20
	6	2	3.37	6.74	29	20
	7	2	3.37	6.74	36	29
	8	4	3.37	13.48	24 - 36	18 - 24
	9	4	3.37	13.48	24 - 36	18 - 24
	10	2	3.37	16.85	24 - 30	18
LIFTER	10	3	3.37		24 - 30	24 - 26
RELIEVER	11	1	3.37	13.66	29 - 37	18
LIFTER	11	1	3.37		24 - 34	18
PERIMETER	11	4	1.73		24	29
RELIEVER	12	1	3.37	13.66	29 - 37	18
LIFTER	12	1	3.37		24 - 34	18
PERIMETER	12	4	1.73		24	29
LIFTER	13	2	3.37	18.85	24	17
PERIMETER	13	7	1.73		24	24
	14	2	1.73	3.46	24	17

MAX. CHARGE WT. PER DELAY 18.85 LBS., ON DELAY NO. 13

TOTAL CHARGE WT. OF ROUND 137.3 LBS.

POWDER FACTOR 3.32 LBS. PER CUBIC YARD

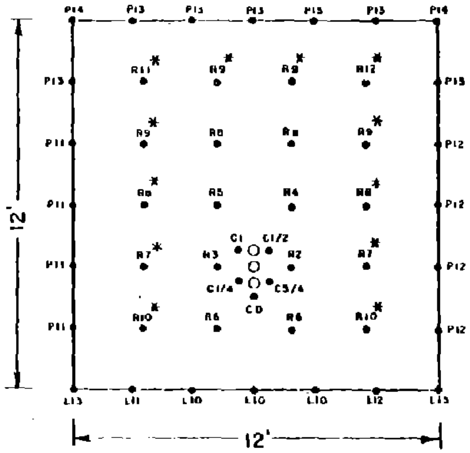
TYPE OF DETONATORS HERCULES SUPERDET ELECTRIC

BLAST LOCATION:

STATION: 3+14, ℄ TO 3+21, ℄

FIGURE B-5. TUNNEL ROUND DESIGN - MSB 2

SKETCH OF BLAST PATTERN



HOLE FACTOR 1.26 HOLES/YD^3

DRILL FACTOR 8.81 LF/YD^3

TUNNEL ROUND CHARGE DISTRIBUTION

TYPE OF HOLE	NUMBER OF HOLES	BOTTOM CHARGE LOAD (# STICKS)	COLUMN CHARGE LOAD (# STICKS)	UNLOADED LENGTH (STEMMING)	CHARGE WT PER HOLE (LBS.)
BURN	3	NONE	NONE	7'-9"	0
CUT	5	40% (1) -LT-	A-2 (4) -T-	2'-5"	3.37
RELIEVER	12*	SAME AS CUT	A-2 (3) -T- H (1) -NT-	1'-5" (SAND BAG)	3.26
	8	SAME AS CUT	SAME AS CUT	2'-5"	3.37
LIFTER	7	SAME AS CUT	SAME AS CUT	2'-5"	3.37
PERIMETER	17	SAME AS CUT	H (2) -NT-	2'-5" (SAND)	1.73

DESIGN HOLE DIA. 1-11/16 (3 BURN) IN.

DESIGN HOLE LENGTH 7 FT.

TUNNEL ROUND SUMMARY

TYPE OF HOLE(S)	DELAY NO.	NO. OF HOLES PER DELAY	CHARGE WT PER HOLE (LBS.)	CHARGE WT PER DELAY (LBS.)	DESIGN SPACING (INCHES)	DESIGN BURDEN (INCHES)
CUT	0	1	3.37	3.37	3	3
	1/4	1	3.37	3.37	3	3
	1/2	1	3.37	3.37	3	3
	3/4	1	3.37	3.37	3	3
	1	1	3.37	3.37	3	3
RELIEVER	2	1	3.37	3.37	24	9
	3	1	3.37	3.37	24	9
	4	1	3.37	3.37	24	20
	5	1	3.37	3.37	24 - 29	20
	6	2	3.37	6.74	29	20
	7*	2	3.26	6.52	36	29
	8*	2	3.26	13.26	24 - 36	18
	8	2	3.37		29 - 36	24
	9*	4	3.26	13.04	24 - 36	18 - 24
	10*	2	3.26	16.63	24 - 30	18
LIFTER	10	3	3.37		24 - 30	24 - 26
RELIEVER	11*	1	3.26	13.55	29 - 37	18
LIFTER	11	1	3.37		24 - 34	18
PERIMETER	11	4	1.73		24	29
RELIEVER	12*	1	3.26	13.55	29 - 37	18
LIFTER	12	1	3.37		24 - 34	18
PERIMETER	12	4	1.73		24	29
LIFTER	13	2	3.37	18.85	24	17
PERIMETER	13	7	1.73		24	24
	14	2	1.73	3.46	24	17

MAX. CHARGE WT. PER DELAY 18.85 LBS., ON DELAY NO. 13

TOTAL CHARGE WT. OF ROUND 135.9 LBS.

POWDER FACTOR 3.29 LBS. PER CUBIC YARD

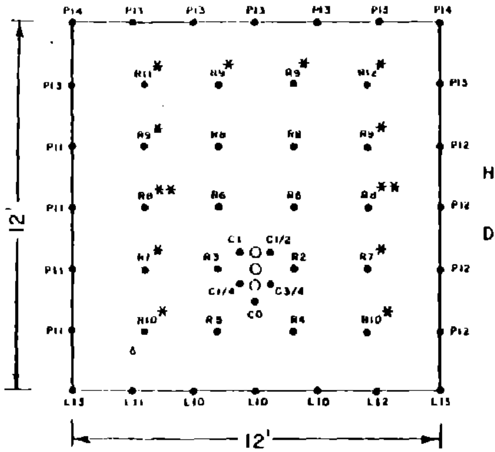
TYPE OF DETONATORS HERCULES SUPERDET ELECTRIC

BLAST LOCATION:

STATION: 3+35, ℄ TO 3+42, ℄

FIGURE B-6. TUNNEL ROUND DESIGN - MSB 3 & 4

SKETCH OF BLAST PATTERN



HOLE FACTOR 1.26 HOLES/YD³

DRILL FACTOR 8.81 LF/YD³

TUNNEL ROUND CHARGE DISTRIBUTION

TYPE OF HOLE	NUMBER OF HOLES	BOTTOM CHARGE LOAD (# STICKS)	COLUMN CHARGE LOAD (# STICKS)	UNLOADED LENGTH (STEMMING)	CHARGE WT. PER HOLE (LBS)
BURN	3	NONE	NONE	7'-9"	0
CUT	5	40% (1) -LT-	A-2 (4) -T-	2'-5"	3.37
RELIEVER	2**	SAME AS CUT	A-2 (3.5) -T-	2'-11"	3.02
	10*	SAME AS CUT	A-2 H (1) (3) -T- -NT-	1'-5" (SAND)	3.26
	8	SAME AS CUT	SAME AS CUT	2'-5"	3.37
LIFTER	7	SAME AS CUT	SAME AS CUT	2'-5"	3.37
PERIMETER	17	SAME AS CUT	H (2) -NT-	2'-5" (SAND)	1.73

DESIGN HOLE DIA. 1-11/16 (3 BURN) IN.

DESIGN HOLE LENGTH 7 FT.

TUNNEL ROUND SUMMARY

TYPE OF HOLE(S)	DELAY NO.	NO. OF HOLES PER DELAY	CHARGE WT PER HOLE (LBS.)	CHARGE WT PER DELAY (LBS.)	DESIGN SPACING (INCHES)	DESIGN BURDEN (INCHES)
CUT	0	1	3.37	3.37	3	3
	1/4	1	3.37	3.37	3	3
	1/2	1	3.37	3.37	3	3
	3/4	1	3.37	3.37	3	3
	1	1	3.37	3.37	3	3
RELIEVER	2	1	3.37	3.37	24	9
	3	1	3.37	3.37	24	9
	4	1	3.37	3.37	24	20
	5	1	3.37	3.37	24 - 29	20
	6	2	3.37	6.74	29	20
	7*	2	3.26	6.52	36	29
	8**	2	3.02	12.78	24 - 36	18
	8	2	3.37		29 - 36	24
	9*	4	3.26	13.04	24 - 36	18 - 24
	10*	2	3.26	16.63	24 - 30	18
LIFTER	10	3	3.37		24 - 30	24 - 26
RELIEVER	11*	1	3.26	13.55	29 - 37	18
LIFTER	11	1	3.37		24 - 34	18
PERIMETER	11	4	1.73		24	29
RELIEVER	12*	1	3.26	13.55	29 - 37	18
LIFTER	12	1	3.37		24 - 34	18
PERIMETER	12	4	1.73		24	29
LIFTER	13	2	3.37	18.85	24	17
PERIMETER	13	7	1.73		24	24
	14	2	1.73	3.46	24	17

MAX. CHARGE WT. PER DELAY 18.85 LBS., ON DELAY NO. 13

TOTAL CHARGE WT. OF ROUND 135.4 LBS.

POWDER FACTOR 3.28 LBS. PER CUBIC YARD

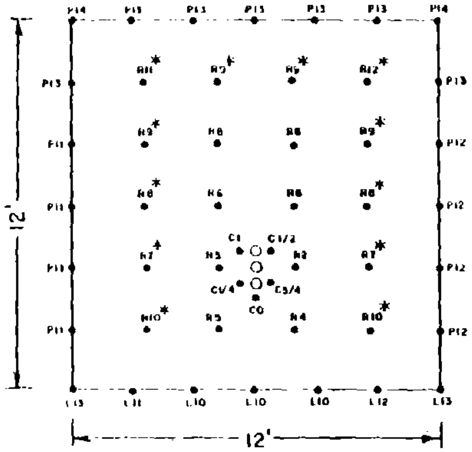
TYPE OF DETONATORS HERCULES SUPERDET ELECTRIC

BLAST LOCATION:

STATION: 3+42, E TO 3+49, E

FIGURE B-7. TUNNEL ROUND DESIGN - MSB 4

SKETCH OF BLAST PATTERN



HOLE FACTOR 1.26 HOLES/YD³

DRILL FACTOR 8.81 LF/YD³

TUNNEL ROUND CHARGE DISTRIBUTION

TYPE OF HOLE	NUMBER OF HOLES	BOTTOM CHARGE LOAD (# STICKS)	COLUMN CHARGE LOAD (# STICKS)	UNLOADED LENGTH (STEMMING)	CHARGE WT PER HOLE (LBS)
BURN	3	NONE	NONE	7'-9"	0
CUT	5	40% (1) -LT-	A-2 (4) -T-	2'-5"	3.37
RELIEVER	12*	SAME AS CUT	A-2 (3) -T- H (1) -NT-	1'-5" (Sand)	3.26
	8	SAME AS CUT	SAME AS CUT	2'-5"	3.37
LIFTER	7	SAME AS CUT	SAME AS CUT	2'-5"	3.37
PERIMETER	17	SAME AS CUT	H † (3 x 1/2) 12" Space Between Stks -NT-	1'5" (Sand)	1.43

† Half sticks taped to wood dowel.

DESIGN HOLE DIA. 1-11/16 (3 Burn) IN.

DESIGN HOLE LENGTH 7 FT.

TUNNEL ROUND SUMMARY

TYPE OF HOLE(S)	DELAY NO.	NO. OF HOLES PER DELAY	CHARGE WT PER HOLE (LBS.)	CHARGE WT PER DELAY (LBS.)	DESIGN SPACING (INCHES)	DESIGN BURDEN (INCHES)
CUT	0	1	3.37	3.37	3	3
	1/4	1	3.37	3.37	3	3
	1/2	1	3.37	3.37	3	3
	3/4	1	3.37	3.37	3	3
	1	1	3.37	3.37	3	3
RELIEVER	2	1	3.37	3.37	24	9
	3	1	3.37	3.37	24	9
	4	1	3.37	3.37	24	20
	5	1	3.37	3.37	24 - 29	20
	6	2	3.37	6.74	29	20
	7*	2	3.26	6.52	36	29
	8*	2	3.26	13.26	24 - 36	18
	8	2	3.37		29 - 36	24
	9*	4	3.26	13.04	24 - 36	18 - 24
	10*	2	3.26	16.63	24 - 30	18
LIFTER	10	3	3.37		24 - 30	24 - 26
RELIEVER	11*	1	3.26	12.35	29 - 37	18
LIFTER	11	1	3.37		24 - 34	18
PERIMETER	11	4	1.43		24	29
RELIEVER	12*	1	3.26	12.35	29 - 37	18
LIFTER	12	1	3.37		24 - 34	18
PERIMETER	12	4	1.43		24	29
LIFTER	13	2	3.37	16.75	24	17
PERIMETER	13	7	1.43		24	24
	14	2	1.43	2.86	24	17

MAX. CHARGE WT. PER DELAY 16.75 LBS., ON DELAY NO. 13

TOTAL CHARGE WT. OF ROUND 130.8 LBS.

POWDER FACTOR 3.17 LBS. PER CUBIC YARD

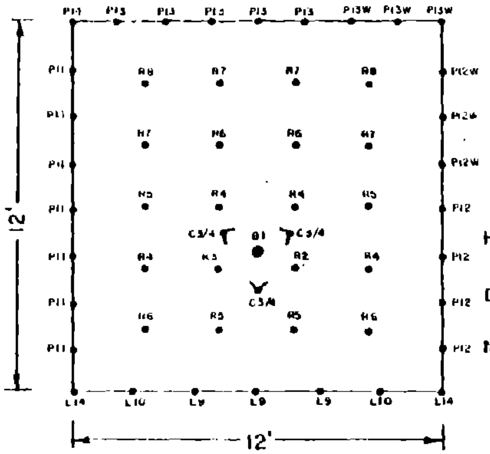
TYPE OF DETONATORS HERCULES SUPERDET ELECTRIC

BLAST LOCATION:

Station: 3+49, ℄ to 3+56, ℄

FIGURE B-8. TUNNEL ROUND DESIGN - MSB 5

SKETCH OF BLAST PATTERN



HOLE FACTOR 1.31 HOLES/YD^3

DRILL FACTOR 9.15 LF/YD^3

NOTE: ALL C3/4 HOLES GROOVED AND LOOKED IN SLIGHTLY TOWARD B1.

TUNNEL ROUND CHARGE DISTRIBUTION

TYPE OF HOLE	NUMBER OF HOLES	BOTTOM CHARGE LOAD (# STICKS)	COLUMN CHARGE LOAD (# STICKS)	UNLOADED LENGTH (STEMMING)	CHARGE WT. PER HOLE (LBS.)
BURN	1	40%† (4) -T-	40%† (4) -LT-	2'-10" (SAND)	4.32
CUT	3	40% (2) -LT-	400PC (4.0') -NT-	1'-10" (SAND)	1.30
RELIEVER	20	40% (1) -LT-	A-2 (4) -T-	2'-5"	3.37
LIFTER	7	40% (2) -LT-	A-2 (4) -T-	1'-10"	3.90
PERIMETER	6 12	40% (1) -LT-	400PC (4.0') -NT-	2'-5" (WATER BAGS) 2'-5" (SAND)	0.77

† NOTE: BURN HOLE LOADED WITH DECKED CHARGE, EACH CHARGE CONSISTING OF 4 STICKS OF 40% EXTRA GEL TAPED IN A BUNDLE. CHARGES SEPARATED BY 3 FT. OF PLASTIC SPIDER TUBE, CONNECTED BY 50 GRAIN PRIMACORD. DELAY CAP IN TOP DECK.

DESIGN HOLE DIA 1-11/16 (3 Burn) IN.

DESIGN HOLE LENGTH 7 FT.

TUNNEL ROUND SUMMARY

TYPE OF HOLE(S)	DELAY NO.	NO. OF HOLES PER DELAY	CHARGE WT PER HOLE (LBS.)	CHARGE WT. PER DELAY (LBS.)	DESIGN SPACING (INCHES)	DESIGN BURDEN (INCHES)
CUT	3/4	3	1.30	3.90	26	-
BURN	1	1	4.32	4.32	-	-
	2	1	3.37	3.37	18	9
	3	1	3.37	3.37	18	9
	4	4	3.37	13.48	29 - 36	12 - 18
RELIEVER	5	4	3.37	13.48	24 - 29	12 - 18
RELIEVER	6	4	3.37	13.48	29 - 36	18 - 24
	7	4	3.37	13.48	29 - 36	18 - 24
	8	2	3.37	6.74	24 - 29	19
LIFTER	9	3	3.90	11.70	24	24
	10	2	3.90	7.80	24	18
PERIMETER	11	7	0.77	5.39	18	29
	12	7	0.77	5.39	18	29
	13	7	0.77	5.39	18	24
	14	2	0.77	9.34	18	12
LIFTER	14	2	3.90		18 - 24	15

MAX. CHARGE WT. PER DELAY 13.48 LBS., ON DELAY NO. 4, 5, 6 and 7

TOTAL CHARGE WT. OF ROUND 120.6 LBS.

POWDER FACTOR 2.92 LBS. PER CUBIC YARD

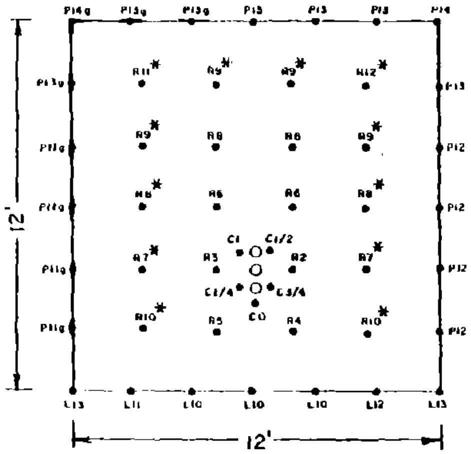
TYPE OF DETONATORS HERCULES SUPERDET ELECTRIC

BLAST LOCATION:

STATION: 0+61, ℄ to 0+55.5, ℄

FIGURE B-9. TUNNEL ROUND DESIGN - MSB6/FC CUT 2

SKETCH OF BLAST PATTERN



HOLE FACTOR 1.26 HOLES/YD^3

DRILL FACTOR 8.81 LF/YD^3

TUNNEL ROUND CHARGE DISTRIBUTION

TYPE OF HOLE	NUMBER OF HOLES	BOTTOM CHARGE LOAD (# STICKS)	COLUMN CHARGE LOAD (# STICKS)	UNLOADED LENGTH (STEMMING)	CHARGE WT. PER HOLE (LBS.)
BURN	3	NONE	NONE	7'-9"	0
CUT	5	40% (1) -LT-	A-2 (4) -T-	2'-5"	3.37
RELIEVER	12*	SAME AS CUT	(3) A-2 -T- (1) H -NT-	1'-5" (SAND)	3.26
	8		SAME AS CUT	2'-5"	3,37
LIFTER	7	SAME AS CUT	SAME AS CUT	2'-5"	3,37
PERIMETER	8 g	SAME AS CUT	400 PC (4.5") -NT-	1'-11" (SAND)	0.80
	9		(3x½ H STKS -NT-	1'-5" (SAND)	1.43

DESIGN HOLE DIA. 1-11/16 (3 BURN) IN.

DESIGN HOLE LENGTH 7 FT.

TUNNEL ROUND SUMMARY

TYPE OF HOLE(S)	DELAY NO.	NO. OF HOLES PER DELAY	CHARGE WT. PER HOLE (LBS.)	CHARGE WT PER DELAY (LBS.)	DESIGN SPACING (INCHES)	DESIGN BURDEN (INCHES)
CUT	0	1	3.37	3,37	3	3
	1/4	1	3.37	3.37	3	3
	1/2	1	3,37	3.37	3	3
	3/4	1	3.37	3.37	3	3
	1	1	3.37	3.37	3	3
RELIEVER	2	1	3.37	3,37	24	9
	3	1	3.37	3,37	24	9
	4	1	3,37	3.37	24	20
	5	1	3.37	3,37	24 - 29	20
	6	2	3.37	6.74	29	20
	7*	2	3.26	6.52	36	29
	8*	2	3.26	13.26	24 - 36	18
	8	2	3.37		29 - 36	24
	9*	4	3,26	13.04	24 - 36	18 - 24
	10*	2	3.26	16.63	24 - 30	18
LIFTER	10	3	3.37		24 - 30	24 - 26
RELIEVER	11*	1	3.26	9.83	29 - 37	18
LIFTER	11	1	3,37		24 - 34	18
PERIMETER	11 g	4	0.80		24	29
RELIEVER	12*	1	3.26	12.35	29 - 37	18
LIFTER	12	1	3.37		24 - 34	18
PERIMETER	12	4	1.43		24	29
LIFTER	13	2	3.37	14.86	24	17
PERIMETER	13 g	3	0.80		24	24
	13	4	1,43		24	24
	14 g	1	0.80	2,23	24	17
	14	1	1.43		24	17

MAX. CHARGE WT. PER DELAY 16.63 LBS., ON DELAY NO. 10

TOTAL CHARGE WT. OF ROUND 125.8 LBS.

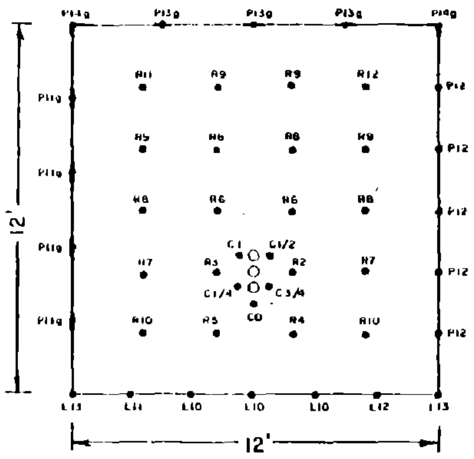
POWDER FACTOR 3.05 LBS. PER CUBIC YARD

TYPE OF DETONATORS HERCULES SUPERDET ELECTRIC

BLAST LOCATION:
STATION: 1 + 63, ℄ TO 1 + 56, ℄

FIGURE B-10. TUNNEL ROUND DESIGN - FC 1

SKETCH OF BLAST PATTERN



HOLE FACTOR 1.19 HOLES/YD³

DRILL FACTOR 8.30 LF/YD³

TUNNEL ROUND CHARGE DISTRIBUTION

TYPE OF HOLE	NUMBER OF HOLES	BOTTOM CHARGE LOAD (# STICKS)	COLUMN CHARGE LOAD (# STICKS)	UNLOADED LENGTH (STEMMING)	CHARGE WT. PER HOLE (LBS.)
BURN	3	NONE	NONE	7'-9"	0
CUT	5	40% (1) -LT-	A-2 (4) -T-	2'-5"	3.37
RELIEVER	20	SAME AS CUT	SAME AS CUT	2'-5"	3.37
LIFTER	7	40% (2) -LT-	SAME AS CUT	1'-10"	3.90
PERIMETER	14	SAME AS CUT	400 PC (4.4') -NT-	2'-0" (WATER BAGS)	0.80

DESIGN HOLE DIA. 1-11/16 (3 BURN) IN.

DESIGN HOLE LENGTH 7 FT.

TUNNEL ROUND SUMMARY

TYPE OF HOLE(S)	DELAY NO.	NO. OF HOLES PER DELAY	CHARGE WT PER HOLE (LBS.)	CHARGE WT PER DELAY (LBS.)	DESIGN SPACING (INCHES)	DESIGN BURDEN (INCHES)
CUT	0	1	3.37	3.37	3	3
	1/4	1	3.37	3.37	3	3
	1/2	1	3.37	3.37	3	3
	3/4	1	3.37	3.37	3	3
	1	1	3.37	3.37	3	3
RELIEVER	2	1	3.37	3.37	24	9
	3	1	3.37	3.37	24	9
	4	1	3.37	3.37	24	20
	5	1	3.37	3.37	24 - 29	20
	6	2	3.37	6.74	29	20
	7	2	3.37	6.74	36	29
	8	4	3.37	13.48	24 - 36	18 - 24
	9	4	3.37	13.48	24 - 36	18 - 24
	10	2	3.37	18.44	24 - 30	18
LIFTER	10	3	3.90		24 - 30	24 - 26
RELIEVER	11	1	3.37	10.47	29 - 37	18
LIFTER	11	1	3.90		24 - 34	18
PERIMETER	11 g	4	0.80		29	29
RELIEVER	12	1	3.37	11.27	29	18
LIFTER	12	1	3.90		24 - 34	18
PERIMETER	12	5	0.80		24	29
LIFTER	13	2	3.90	10.2	24 - 29	16 - 18
PERIMETER	13 g	3	0.80		36	24
PERIMETER	14	2	0.80	1.60	24 - 36	19

MAX. CHARGE WT. PER DELAY 18.44 LBS., ON DELAY NO. 10

TOTAL CHARGE WT. OF ROUND 122.8 LBS.

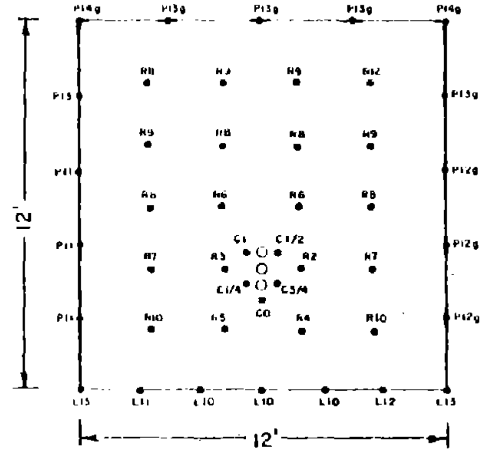
POWDER FACTOR 2.97 LBS. PER CUBIC YARD

TYPE OF DETONATORS HERCULES SUPERDET ELECTRIC

BLAST LOCATION:
STATION: 3 + 56, ℄ 3 + 63, ℄

FIGURE B-11. TUNNEL ROUND DESIGN - FC 2

SKETCH OF BLAST PATTERN



HOLE FACTOR 1.16 HOLES/YD^3

DRILL FACTOR 8.13 LF/YD^3

TUNNEL ROUND CHARGE DISTRIBUTION

TYPE OF HOLE	NUMBER OF HOLES	BOTTOM CHARGE LOAD (# STICKS)	COLUMN CHARGE LOAD (# STICKS)	UNLOADED LENGTH (STEMMING)	CHARGE WT PER HOLE (LBS.)
BURN	3	NONE	NONE	7'-9"	0
CUT	5	40% (1) -LT-	A-2 (4) -T-	2'-5"	3.37
RELIEVER	20	SAME AS CUT	SAME AS CUT	2'-5"	3.37
LIFTER	7	40% (2) -LT-	SAME AS CUT	1'-10"	3.90
PERIMETER	4	SAME AS CUT	" † (3x½) -NT-	1'-5" (SAND)	1.43
	3 g	SAME AS CUT	400 PC (4.4') -NT-	2'-0" (SAND)	0.80
	6 ga	SAME AS LIFTER	400 PC (3.8') -NT-	2'-0" (SAND)	1.29

† Half sticks taped to wood dowel, separated by 12".

DESIGN HOLE DIA 1-11/16 (3 BURN) IN.

DESIGN HOLE LENGTH 7 FT.

TUNNEL ROUND SUMMARY

TYPE OF HOLE(S)	DELAY NO.	NO. OF HOLES PER DELAY	CHARGE WT PER HOLE (LBS.)	CHARGE WT PER DELAY (LBS.)	DESIGN SPACING (INCHES)	DESIGN BURDEN (INCHES)
CUT	0	1	3.37	3.37	3	3
	1/4	1	3.37	3.37	3	3
	1/2	1	3.37	3.37	3	3
	3/4	1	3.37	3.37	3	3
	1	1	3.37	3.37	3	3
RELIEVER	2	1	3.37	3.37	24	9
	3	1	3.37	3.37	24	9
	4	1	3.37	3.37	24	20
	5	1	3.37	3.37	24 - 29	20
	6	2	3.37	6.74	29	20
	7	2	3.37	6.74	36	29
	8	4	3.37	13.48	24 - 36	18 - 24
	9	4	3.37	13.48	24 - 36	18 - 24
	10	2	3.37	18.44	24 - 30	18
LIFTER	10	3	3.90		24 - 30	24 - 26
RELIEVER	11	1	3.37	13.66	29 - 37	18
LIFTER	11	1	3.90		24 - 34	18
PERIMETER	11	3	1.43		29 - 30	29
RELIEVER	12	1	3.37	11.14	29 - 37	18
LIFTER	12	1	3.90		24 - 34	18
PERIMETER	12 ga	3	1.29		29 - 30	29
LIFTER	13	2	3.90	12.92	24 - 29	18
PERIMETER	13	1	1.43		29	29
	13 g	3	0.80		36	24
	13 ga	1	1.29		29	29
	14 ga	2	1.29	2.58	29 - 36	22

MAX. CHARGE WT. PER DELAY 18.44 LBS., ON DELAY NO. 10

TOTAL CHARGE WT. OF ROUND 129.5 LBS.

POWDER FACTOR 3.13 LBS. PER CUBIC YARD

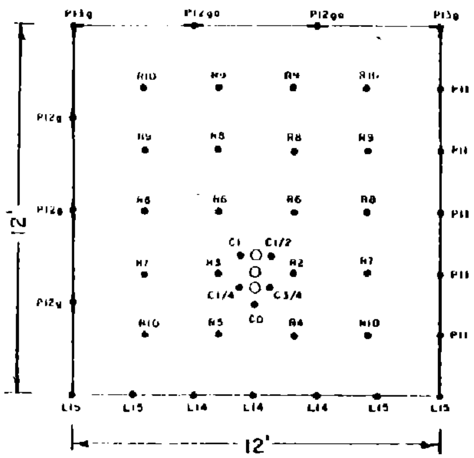
TYPE OF DETONATORS HERCULES SUPERDET ELECTRIC

BLAST LOCATION:

STATION: 1 + 56, ℄ TO 1 + 48.5, ℄

FIGURE B-12. TUNNEL ROUND DESIGN - FC 3

SKETCH OF BLAST PATTERN



HOLE FACTOR 1.14 HOLES/YD^3

DRILL FACTOR 7.96 LF/YD^3

TUNNEL ROUND CHARGE DISTRIBUTION

TYPE OF HOLE	NUMBER OF HOLES	BOTTOM CHARGE LOAD (# STICKS)	COLUMN CHARGE LOAD (# STICKS)	UNLOADED LENGTH (STEMMING)	CHARGE WT PER HOLE (LBS)
BURN	3	NONE	NONE	7'-9"	0
CUT	5	40% (1) -LT-	A-2 (4) -T-	2'-5"	3.37
RELIEVER	20	SAME AS CUT	SAME AS CUT	2'-5"	3.37
LIFTER	7	40% (2) -LT-	SAME AS CUT	1'-10"	3.90
PERIMETER	5	SAME AS CUT	H † (3x½) -NT-	1'-5" (SAND)	1.43
	5 g	SAME AS CUT	400 PC (4.4') -NT-	2'-0" (SAND)	0.80
	2 ga	SAME AS LIFTER	400 PC (3.8') -NT-	2'-0" (SAND)	1.29

† Half sticks taped to wood dowel, separated b- 12".

DESIGN HOLE DIA. 1-11/16 (3 BURN) IN.

DESIGN HOLE LENGTH 7 FT.

TUNNEL ROUND SUMMARY

TYPE OF HOLE(S)	DELAY NO.	NO. OF HOLES PER DELAY	CHARGE WT PER HOLE (LBS)	CHARGE WT PER DELAY (LBS.)	DESIGN SPACING (INCHES)	DESIGN BURDEN (INCHES)
CUT	0	1	3.37	3.37	3	3
	1/4	1	3.37	3.37	3	3
	1/2	1	3.37	3.37	3	3
	3/4	1	3.37	3.37	3	3
	1	1	3.37	3.37	3	3
RELIEVER	2	1	3.37	3.37	24	9
	3	1	3.37	3.37	24	9
	4	1	3.37	3.37	24	20
	5	1	3.37	3.37	24 - 29	20
	6	2	3.37	6.74	29	20
	7	2	3.37	6.74	36	29
	8	4	3.37	13.48	24 - 36	18 - 24
	9	4	3.37	13.48	24 - 36	18 - 24
	10		3.37	13.48	24 - 29	18
PERIMETER	11	5	1.43	7.15	24 - 29	29
	12 g	2	0.80	5.47	48	24
	12 ga	3	1.29		36	29
	13 ga	2	1.29	2.58	24 - 40	22 - 26
LIFTER	14	3	3.90	11.70	24 - 30	24
	15	4	3.90	15.60	24 - 36	18 - 32

MAX. CHARGE WT. PER DELAY 15.60 LBS., ON DELAY NO. 15

TOTAL CHARGE WT. OF ROUND 126.8 LBS.

POWDER FACTOR 3.07 LBS. PER CUBIC YARD

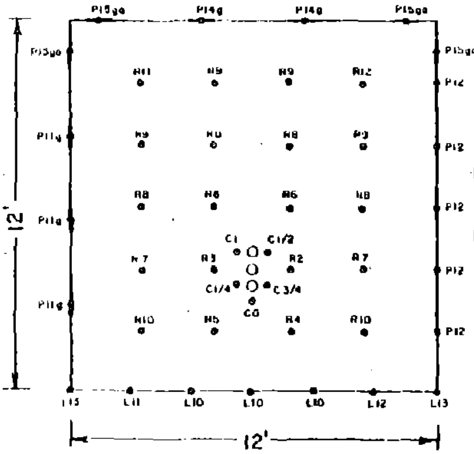
TYPE OF DETONATORS HERCULES SUPERDET ELECTRIC

BLAST LOCATION:

STATION: 3 + 63, ℄ TO 3 + 70, ℄

FIGURE B-13. TUNNEL ROUND DESIGN - FC 4

SKETCH OF BLAST PATTERN



HOLE FACTOR 1.19 HOLES/YD^3

DRILL FACTOR 8.30 LF/YD^3

TUNNEL ROUND CHARGE DISTRIBUTION

TYPE OF HOLE	NUMBER OF HOLES	BOTTOM CHARGE LOAD (# STICKS)	COLUMN CHARGE LOAD (# STICKS)	UNLOADED LENGTH (STEMMING)	CHARGE WT. PER HOLE (LBS.)
BURN	3	NONE	NONE	7'-9"	0
CUT	5	40% (1) -LT-	A-2 (4) -T-	2'-5"	3.37
RELIEVER	20	SAME AS CUT	SAME AS CUT	2'-5"	3.37
LIFTER	7	40% (2) -LT-	SAME AS CUT	1'-10"	3.90
PERIMETER	5	SAME AS CUT	H † (3x½) -NT-	1'-5" (WATER BAGS)	1.43
	5 g	SAME AS CUT	400 PC (4.4') -NT-	2'-0" (SAND)	0.80
	4 ga	SAME AS LIFTER	400 PC (3.8') -NT-	2'-0" (WATER BAGS)	1.29

† Half sticks taped to wood dowel, separated by 12".

DESIGN HOLE DIA. 1-11/16 (3 BURN) IN.

DESIGN HOLE LENGTH 7 FT.

TUNNEL ROUND SUMMARY

TYPE OF HOLE(S)	DELAY NO.	NO. OF HOLES PER DELAY	CHARGE WT. PER HOLE (LBS.)	CHARGE WT. PER DELAY (LBS.)	DESIGN SPACING (INCHES)	DESIGN BURDEN (INCHES)
CUT	0	1	3.37	3.37	3	3
	1/4	1	3.37	3.37	3	3
	1/2	1	3.37	3.37	3	3
	3/4	1	3.37	3.37	3	3
	1	1	3.37	3.37	3	3
RELIEVER	2	1	3.37	3.37	24	9
	3	1	3.37	3.37	24	9
	4	1	3.37	3.37	24	20
	5	1	3.37	3.37	24 - 29	20
	6	2	3.37	6.74	29	20
	7	2	3.37	6.74	36	29
	8	4	3.37	13.48	24 - 36	18 - 24
	9	4	3.37	13.48	24 - 36	18 - 24
	10	2	3.37	18.44	24 - 30	18
LIFTER	10	3	3.90		24 - 30	24 - 26
RELIEVER	11	1	3.37	9.67	29 - 37	18
LIFTER	11	1	3.90		24 - 34	18
PERIMETER	11 g	3	0.80		33 - 42	17 - 29
RELIEVER	12	1	3.37	14.42	29	18
LIFTER	12	1	3.90		24 - 34	18
PERIMETER	12	5	1.43		24	29
LIFTER	13	2	3.90	7.80	24 - 33	18 - 20
PERIMETER	14 g	2	0.80	1.60	40	24
	15 ga	4	1.29	5.16	12 - 40	30

MAX. CHARGE WT. PER DELAY 18.44 LBS., ON DELAY NO. 10

TOTAL CHARGE WT. OF ROUND 127.9 LBS.

POWDER FACTOR 3.10 LBS. PER CUBIC YARD

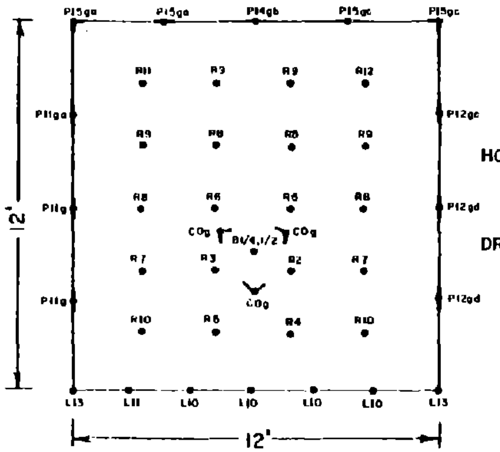
TYPE OF DETONATORS HERCULES SUPERDET ELECTRIC

BLAST LOCATION:

STATION: 3 + 84, ℄ TO 3 + 91, ℄

FIGURE B-14. TUNNEL ROUND DESIGN - FC 5

SKETCH OF BLAST PATTERN



HOLE FACTOR 1.11 HOLES/YD^3

DRILL FACTOR 7.79 LF/YD^3

TUNNEL ROUND CHARGE DISTRIBUTION

TYPE OF HOLE	NUMBER OF HOLES	BOTTOM CHARGE LOAD (# STICKS)	COLUMN CHARGE LOAD (# STICKS)	UNLOADED LENGTH (STEMMING)	CHARGE WT PER HOLE (LBS.)
BURN	1	40% † (4) -T-	40% † (4) -T-	1'-6" (SAND)	4.32 †
CUT	3 g	40% (2) -LT-	400 PC (4.0') -NT-	1'-10" (WATER BAGS)	1.30
RELIEVER	20	SAME AS CUT	SAME AS CUT	2'-5"	3.37
LIFTER	7	40% (2) -LT-	SAME AS CUT	1'-10"	3.90
PERIMETER	2 g	40% (1.5) -LT-	400 PC (4.1') -NT-	2'-0" (WATER BAGS)	1.04
	3 ga	40% (2) -LT-	400 PC (4.4') -NT-	2'-0" (WATER BAGS)	1.29
	1 gb	40% (1) -LT-	400 PC (3.8') -NT-	2'-0" (WATER BAGS)	0.80
	3 gc	40% (2) -LT-	NONE ††	6'-0" (WATER BAGS)	1.06
	2 gd	40% (1.5) -LT-	NONE ††	6'-3" (WATER BAGS)	0.80

† NOTE: BURN HOLE LOADED WITH DECKED CHARGE, EACH CHARGE CONSISTING OF 4 STICKS OF 40% EXTRA GEL STRING LOADED AND TAMPED. CHARGES SEPARATED BY 3 FT. OF SAND. ¼ DELAY CAP IN TOP DECK, ½ DELAY IN BOTTOM DECK.

†† Four ft. of Spider Tube used as Spac

DESIGN HOLE DIA. 1-11/16 IN.

DESIGN HOLE LENGTH 7 FT.

TUNNEL ROUND SUMMARY

TYPE OF HOLE(S)	DELAY NO.	NO. OF HOLES PER DELAY	CHARGE WT PER HOLE (LBS.)	CHARGE WT PER DELAY (LBS.)	DESIGN SPACING (INCHES)	DESIGN BURDEN (INCHES)
CUT	0 g	3	1.30	3.90	24	–
	1/4	1	4.32	2.16	—	—
	1/2			2.16		
RELIEVER	2	1	3.37	3.37	24	9
	3	1	3.37	3.37	24	9
	4	1	3.37	3.37	24	20
	5	1	3.37	3.37	24 - 29	20
	6	2	3.37	6.74	29	20
	7	2	3.37	6.74	36	29
	8	4	3.37	13.48	24 - 36	18 - 24
	9	4	3.37	13.48	24 - 36	18 - 24
	10	2	3.37	18.44	24 - 30	18
LIFTER	10	3	3.90		24 - 30	24 - 26
RELIEVER	11	1	3.37	10.64	29 - 37	18
LIFTER	11	1	3.90		24 - 34	18
PERIMETER	11 g	2	1.04		36	29
	11 ga	1	1.29		36	29
RELIEVER	12	1	3.37	9.93	29 - 30	18
LIFTER	12	1	3.90		24 - 34	18
PERIMETER	12 gc	1	1.06		36	29
	12 gd	2	0.80		36	29
LIFTER	13	2	3.90	7.80	24 - 36	19
PERIMETER	14 gb	1	0.80	0.80	36	24
	15 ga	2	1.29	4.70	36	24 - 36
	15 gc	2	1.06		36	24 - 36

MAX. CHARGE WT. PER DELAY 18.44 LBS., ON DELAY NO. 10

TOTAL CHARGE WT. OF ROUND 114.5 LBS.

POWDER FACTOR 2.77 LBS. PER CUBIC YARD

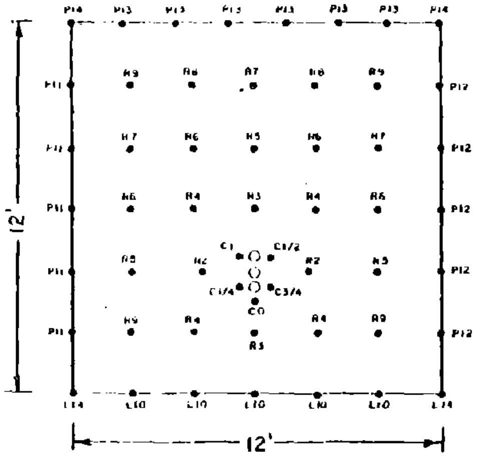
TYPE OF DETONATORS HERCULES SUPERDET ELECTRIC

BLAST LOCATION:

STATION: 3 + 91, ℄ TO 3 + 95, ℄

FIGURE B-15. TUNNEL ROUND DESIGN - FC 6

SKETCH OF BLAST PATTERN



HOLE FACTOR 1.30 HOLES/YD³

DRILL FACTOR 9.66 LF/YD³

TUNNEL ROUND CHARGE DISTRIBUTION

TYPE OF HOLE	NUMBER OF HOLES	BOTTOM CHARGE LOAD (# STICKS)	COLUMN CHARGE LOAD (# STICKS)	UNLOADED LENGTH (STEMMING)	CHARGE WT. PER HOLE (LBS.)
BURN	1	NONE	NONE	7'-9"	0
CUT	5	40% (1) -NT-	A-2 (4) 40% (1) -T-	1'-10"	3.90
RELIEVER	24	SAME AS CUT	SAME AS CUT	1'-10"	3.90
LIFTER	7	SAME AS CUT	SAME AS CUT	1'-10"	3.90
PERIMETER	18	SAME AS CUT	" (2) -NT-	2'-4" (SAND)	1.73

DESIGN HOLE DIA. 1-11/16 (1 BURN) IN.

DESIGN HOLE LENGTH 7 FT.

TUNNEL ROUND SUMMARY

TYPE OF HOLE(S)	DELAY NO.	NO OF HOLES PER DELAY	CHARGE WT PER HOLE (LBS.)	CHARGE WT PER DELAY (LBS.)	DESIGN SPACING (INCHES)	DESIGN BURDEN (INCHES)
CUT	0	1	3.92	3.92	3	3
	1/4	1	3.92	3.92	3	3
	1/2	1	3.92	3.92	3	3
	3/4	1	3.92	3.92	3	3
	1	1	3.92	3.92	3	3
RELIEVER	2	2	3.92	7.84	19	18
	3	2	3.92	7.84	19	18
	4	4	3.92	15.68	24	20
	5	3	3.92	11.76	34	24
	6	4	3.92	15.68	24 - 34	17
	7	3	3.92	11.76	24 - 34	17 - 24
	8	2	3.92	7.84	24 - 34	17
	9	4	3.92	15.68	24	17
LIFTER	10	5	3.92	19.60	24	24
PERIMETER	11	5	1.80	9.00	24 - 34	24
	12	5	1.80	9.00	24 - 34	24
	13	6	1.80	10.80	20.5 - 32	24
	14	2	1.80	11.44	24	17
LIFTER	14	2	3.92		24	17

MAX. CHARGE WT. PER DELAY 19.60 LBS., ON DELAY NO. 10

TOTAL CHARGE WT. OF ROUND 173.5 LBS.

POWDER FACTOR 4.20 LBS. PER CUBIC YARD

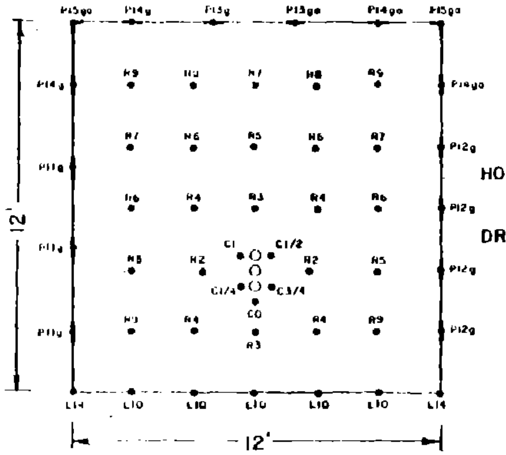
TYPE OF DETONATORS HERCULES SUPERDET ELECTRIC

BLAST LOCATION: USED TO EXCAVATE DIKE ROCK IN NORTH HEADING

STATION: 4+26, ₵ TO 4+91+, ₵

FIGURE B-16. TUNNEL ROUND DESIGN - CONTRACTOR'S SSB ROUND IN IGNEOUS DIKE

SKETCH OF BLAST PATTERN



HOLE FACTOR 1.31 HOLES/YD^3

DRILL FACTOR 9.15 LF/YD^3

TUNNEL ROUND CHARGE DISTRIBUTION

TYPE OF HOLE	NUMBER OF HOLES	BOTTOM CHARGE LOAD (# STICKS)	COLUMN CHARGE LOAD (# STICKS)	UNLOADED LENGTH (STEMMING)	CHARGE WT PER HOLE (LBS)
BURN	3	NONE	NONE	7'-9"	0
CUT	5	40% (1) -LT-	A-2 (4) -T-	2'-5"	3.37
RELIEVER	24	SAME AS CUT	SAME AS CUT	2'-5"	3.37
LIFTER	7	SAME AS CUT	40% (1) A-2 (4)	1'-10"	3.92
PERIMETER	8 g	40% (2) -LT-	400 PC (3.2') -NT	1'-10" (SAND)	1.25
	3 ga	40% (3) -LT-	400 PC (3.2') -NT	1'-3" (SAND)	1.78
	2	40% (2) -LT-	400 PC (3.2') -NT	1'-10" (SAND)	1.25
	2 a	40% (3) -LT-	400 PC (3.2') -NT	1'-3" (SAND)	1.78

DESIGN HOLE DIA. 1-11/16 IN.

DESIGN HOLE LENGTH 7.0 FT.

TUNNEL ROUND SUMMARY

TYPE OF HOLE(S)	DELAY NO.	NO. OF HOLES PER DELAY	CHARGE WT PER HOLE (LBS)	CHARGE WT PER DELAY (LBS.)	DESIGN SPACING (INCHES)	DESIGN BURDEN (INCHES)
CUT	0	1	3.37	3.37	3	3
	1/4	1	3.37	3.37	3	3
	1/2	1	3.37	3.37	3	3
	3/4	1	3.37	3.37	3	3
	1	1	3.37	3.37	3	3
RELIEVER	2	2	3.37	6.74	19	18
	3	2	3.37	6.74	19	18
	4	4	3.37	13.48	24	20
	5	3	3.37	10.11	34	24
	6	4	3.37	13.48	24 - 34	17
	7	3	3.37	10.11	24 - 34	17 - 24
	8	2	3.37	6.74	24 - 34	17
	9	4	3.37	13.48	24	17
LIFTER	10	5	3.92	19.60	24	24
PERIMETER	11 g	3	1.25	3.75	29	24
	12	1	1.25	5.00	24	24
	12 g	3	1.25		24	24
	13 a	1	1.78	3.03	29	24
	13 g	1	1.25		29	24
	14	1	1.25	13.90	29	24
	14 a	1	1.78		29	24
	14 g	1	1.25		29	24
	14 ga	1	1.78		24	24
LIFTER	14	2	3.92		24 - 29	18
PERIMETER	15 ga	2	1.78	3.56	24 - 29	24

MAX. CHARGE WT. PER DELAY 19.60 LBS., ON DELAY NO. 10

TOTAL CHARGE WT. OF ROUND 146.6 LBS.

POWDER FACTOR 3.55 LBS. PER CUBIC YARD

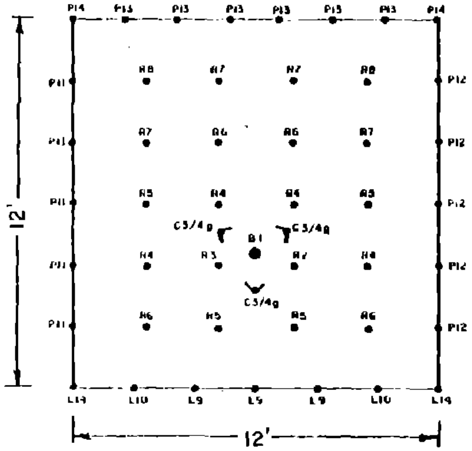
TYPE OF DETONATORS HERCULES SUPERDET ELECTRIC

BLAST LOCATION:

STATION: 4+39, ℄ TO 4+45, ℄

FIGURE B-17. TUNNEL ROUND DESIGN - FC 7, IN IGNEOUS DIKE

SKETCH OF BLAST PATTERN



HOLE FACTOR 1.19 HOLES/YD³

DRILL FACTOR 8.30 LF/YD³

NOTE: ALL C3/4g HOLES GROOVED AND LOOKED IN SLIGHTLY TOWARD B1.

TUNNEL ROUND SUMMARY

TYPE OF HOLE(S)	DELAY NO.	NO. OF HOLES PER DELAY	CHARGE WT. PER HOLE (LBS.)	CHARGE WT PER DELAY (LBS.)	DESIGN SPACING (INCHES)	DESIGN BURDEN (INCHES)
CUT	3/4 9	3	1.30	3.90	26	-
BURN	1	1	4.32	4.32	-	-
RELIEVER	2	1	3.90	3.90	18	9
	3	1	3.90	3.90	18	9
	4	4	3.90	15.60	29 - 36	12 - 18
	5	4	3.90	15.60	24 - 29	15 - 24
	6	4	3.90	15.60	24 - 36	18 - 24
	7	4	3.90	15.60	24 - 36	18 - 24
	8	2	3.90	7.80	24 - 29	18
LIFTER	9	3	3.90	11.70	24	24
	10	2	3.90	7.80	24	18
PERIMETER	11	5	1.73	8.65	24	29
	12	5	1.73	8.65	24	29
	13	6	1.73	10.38	21	24
	14	2	1.73	11.26	21 - 24	16
LIFTER	14	2	3.90		24	18

MAX. CHARGE WT. PER DELAY 15.60 LBS., ON DELAY NO. 4, 5, 6 and 7

TOTAL CHARGE WT. OF ROUND 144.7 LBS.

POWDER FACTOR 3.50 LBS. PER CUBIC YARD

TYPE OF DETONATORS HERCULES SUPERDET ELECTRIC

BLAST LOCATION:

STATION: 0+67.5, ℄ to 0+61, ℄

TUNNEL ROUND CHARGE DISTRIBUTION

TYPE OF HOLE	NUMBER OF HOLES	BOTTOM CHARGE LOAD (# STICKS)	COLUMN CHARGE LOAD (# STICKS)	UNLOADED LENGTH (STEMMING)	CHARGE WT. PER HOLE (LBS.)
BURN	1	40%† (4) -T-	40%† (4) -LT-	2'-10" (SAND)	4.32
CUT	3 g	40% (2) -LT-	400PC (4.0') -NT-	1'-10" (SAND)	1.30
RELIEVER	20	40% (1) -LT-	A-2 (4) 40% (1) T	1'-10"	3.90
LIFTER	7	SAME AS RELIEVER	SAME AS RELIEVER	1'-10"	3.90
PERIMETER	18	SAME AS RELIEVER	II (2) -NT-	2'-4" (SAND)	1.73

† NOTE: BURN HOLE LOADED WITH DECKED CHARGE, EACH CHARGE CONSISTING OF 4 STICKS OF 40% EXTRA GEL TAPED IN A BUNDLE. CHARGES SEPARATED BY 3 FT. OF PLASTIC SPIDER TUBE, CONNECTED BY 50 GRAIN PRIMACORD. DELAY CAP IN TOP DECK.

DESIGN HOLE DIA. 1-11/16 (1 Burn) IN.

DESIGN HOLE LENGTH 7 FT.

FIGURE B-18. TUNNEL ROUND DESIGN - FC CUT 1

APPENDIX C
SILHOUETTE PHOTOGRAPHS OF TUNNEL CROSS SECTIONS

The silhouette photographs which follow (Figures C-1 through C-26) were used to calculate overbreak for each experimental round. The calculated overbreak is noted in Figure 6-1. See Section 5.3.5.3 for details of the silhouette photographic technique.

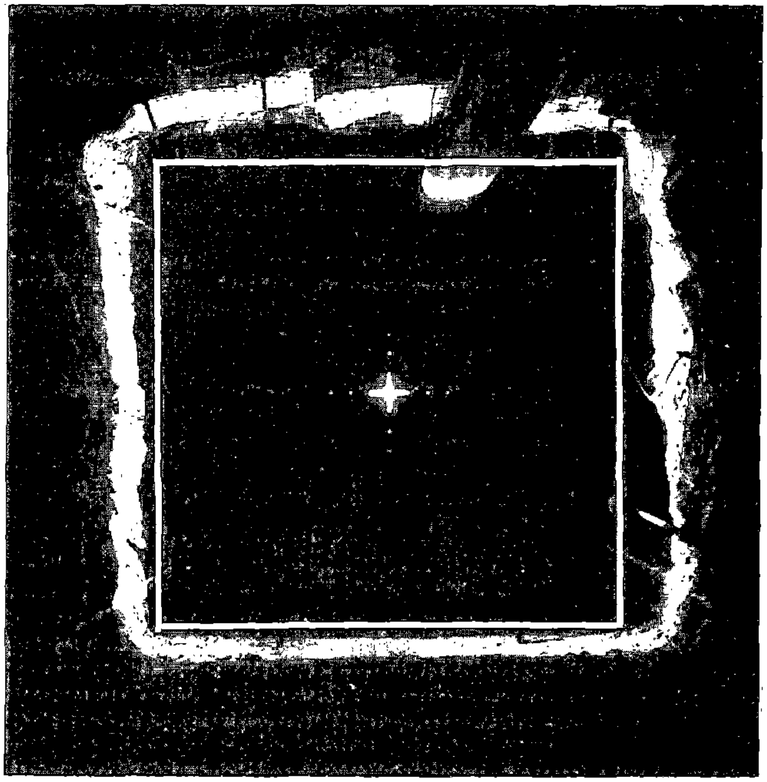


FIGURE C-1

TUNNEL SILHOUETTE

NORTH HEADING

Round No.:	SSB 34
Station:	3+03
Offset:	0.0
Scale:	1"=5'

Looking North

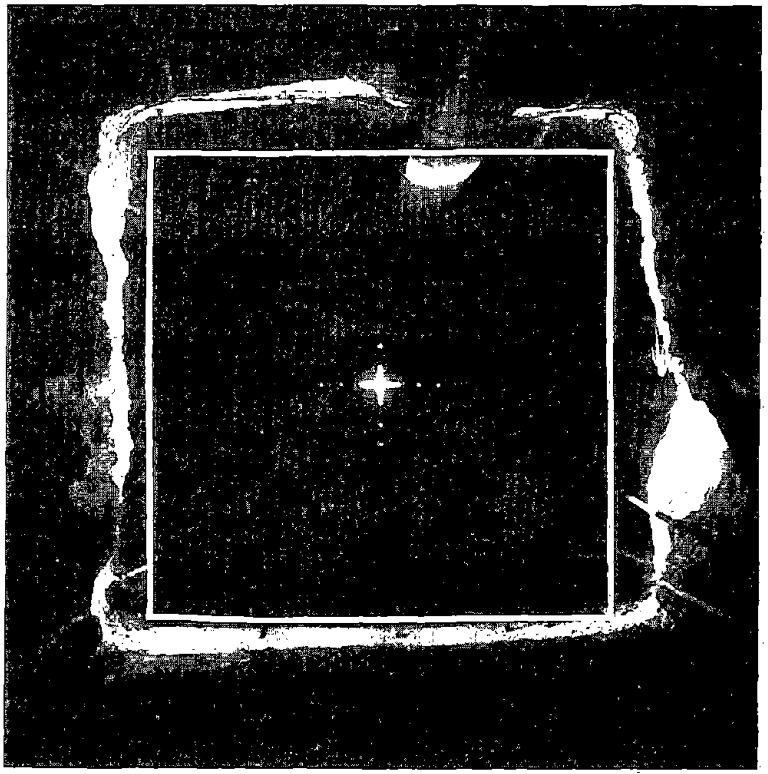


FIGURE C-2

TUNNEL SILHOUETTE

NORTH HEADING

Round No.:	SSB 36
Station:	3+11
Offset:	0.0
Scale:	1"=5'

Looking North

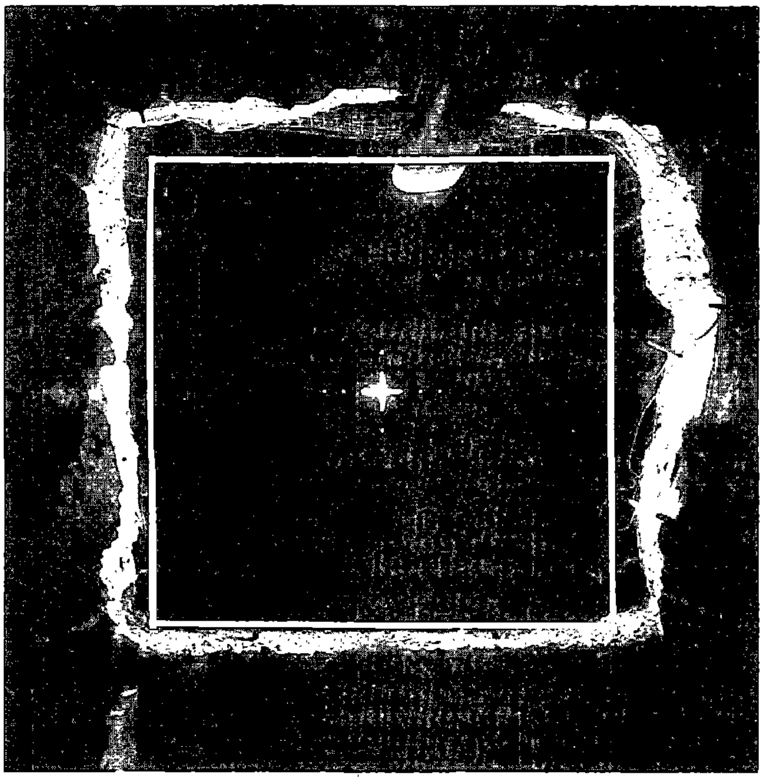


FIGURE C-3

TUNNEL SILHOUETTE

NORTH HEADING

Round No.: MSB 2
Station: 3+18
Offset: 0.0
Scale: 1"=5'
Looking North

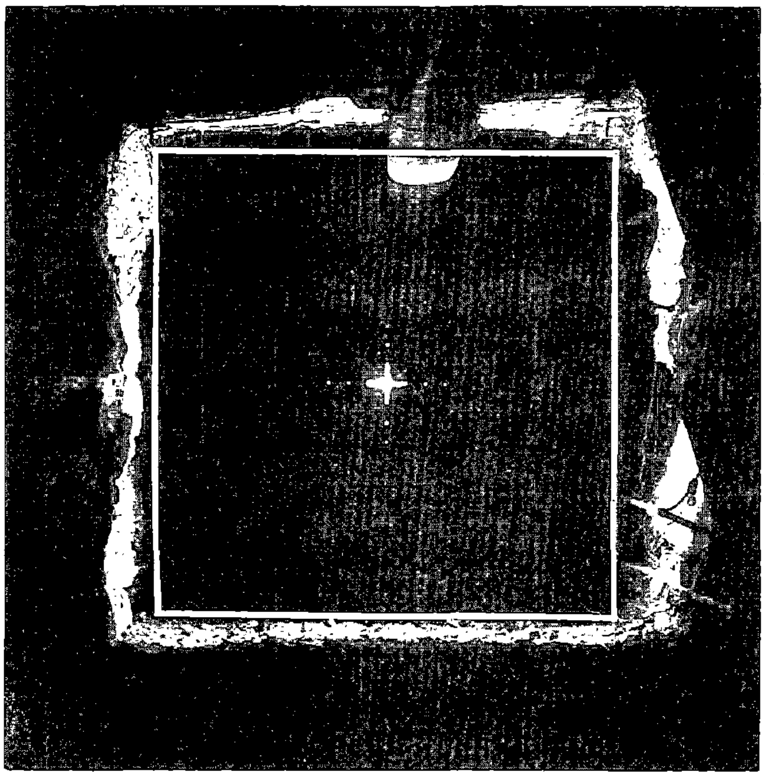


FIGURE C-4

TUNNEL SILHOUETTE

NORTH HEADING

Round No.: SSB 42
Station: 3+32
Offset: 0.0
Scale: 1"=5'
Looking South

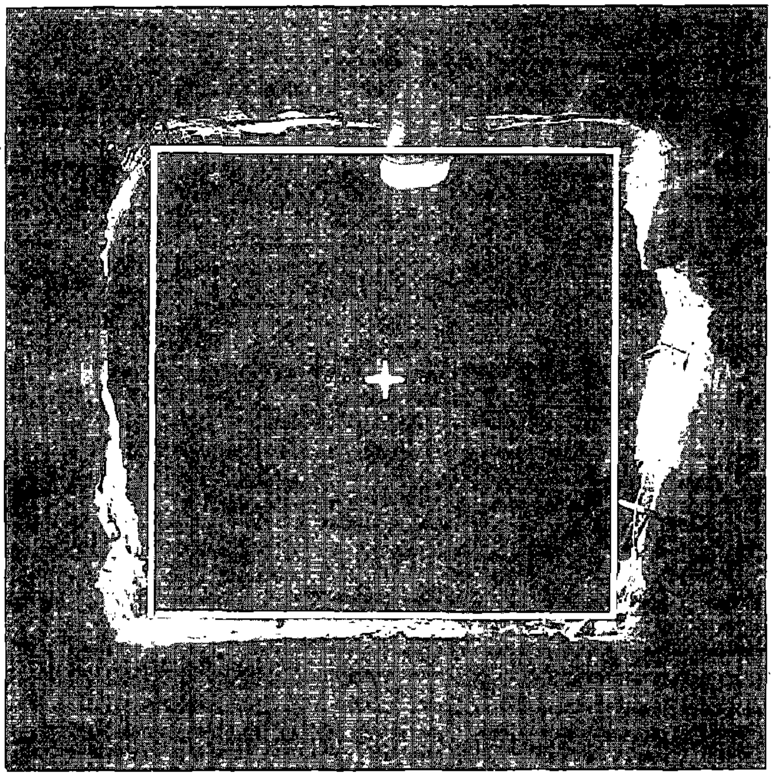


FIGURE C-5

TUNNEL SILHOUETTE

NORTH HEADING

Round No.:	MSB 3&4
Station:	3+38
Offset:	0.0
Scale:	1"=5'

Looking North

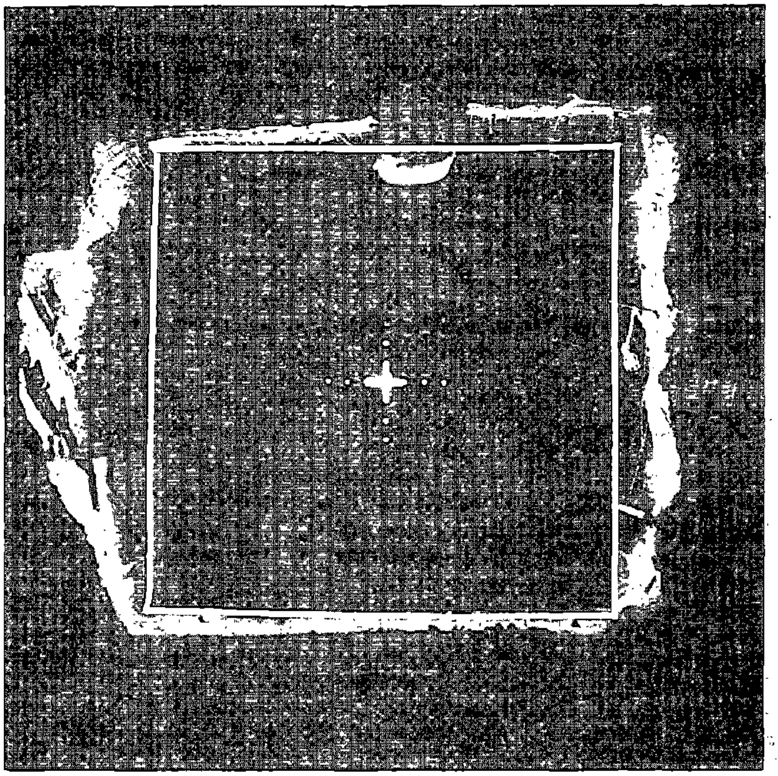


FIGURE C-6

TUNNEL SILHOUETTE

NORTH HEADING

Round No.:	MSB 4
Station:	3+46
Offset:	0.0
Scale:	1"=5'

Looking North

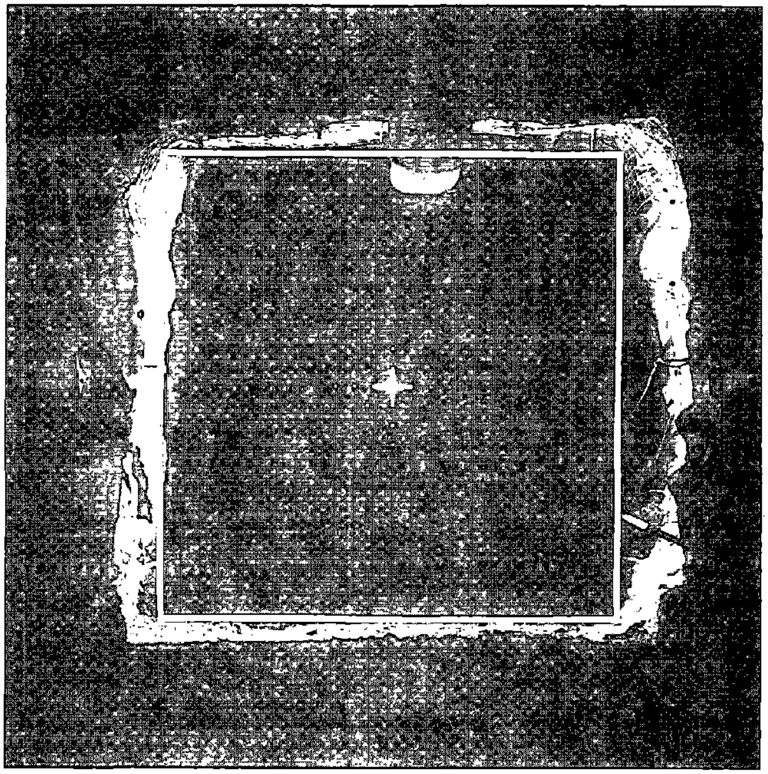


FIGURE C-7

TUNNEL SILHOUETTE

NORTH HEADING

Round No.: MSB 5
Station: 3+53
Offset: 0.0
Scale: 1"=5'
Looking North

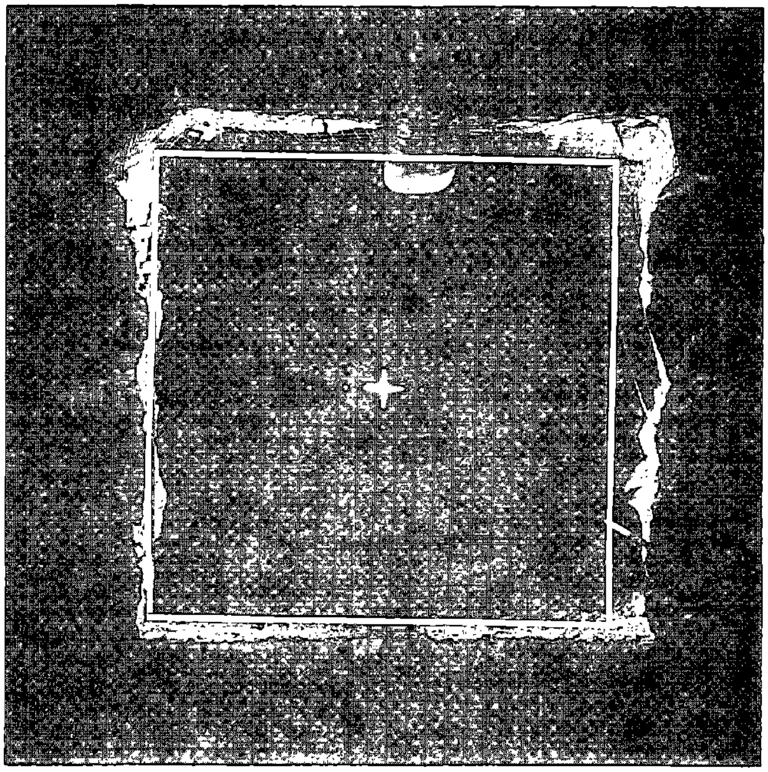


FIGURE C-8

TUNNEL SILHOUETTE

NORTH HEADING

Round No.: FC 2
Station: 3+60
Offset: 0.0
Scale: 1"=5'
Looking North

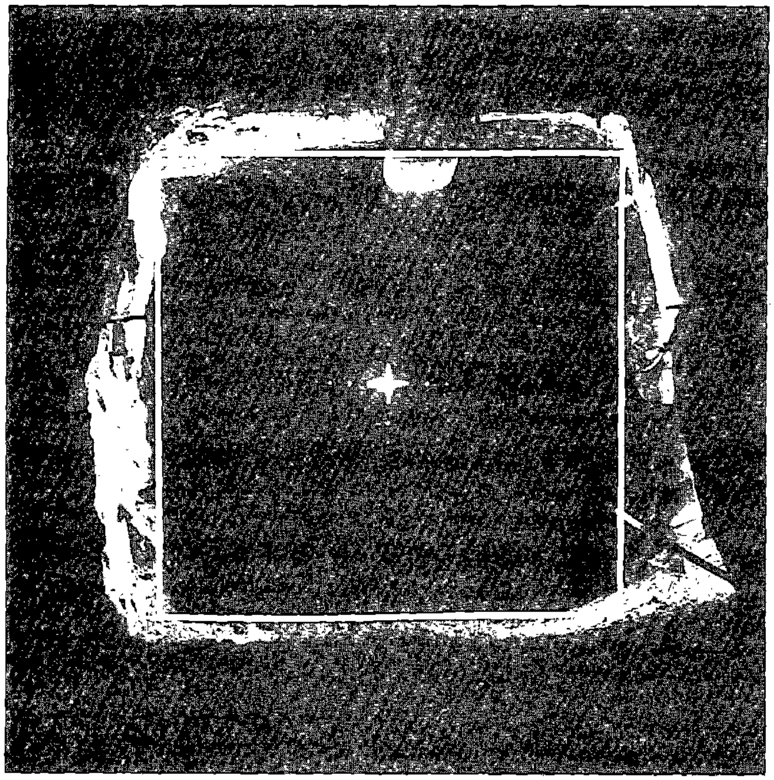


FIGURE C-9

TUNNEL SILHOUETTE

NORTH HEADING

Round No.: FC 4
Station: 3+67
Offset: 0.0
Scale: 1"=5'
Looking North

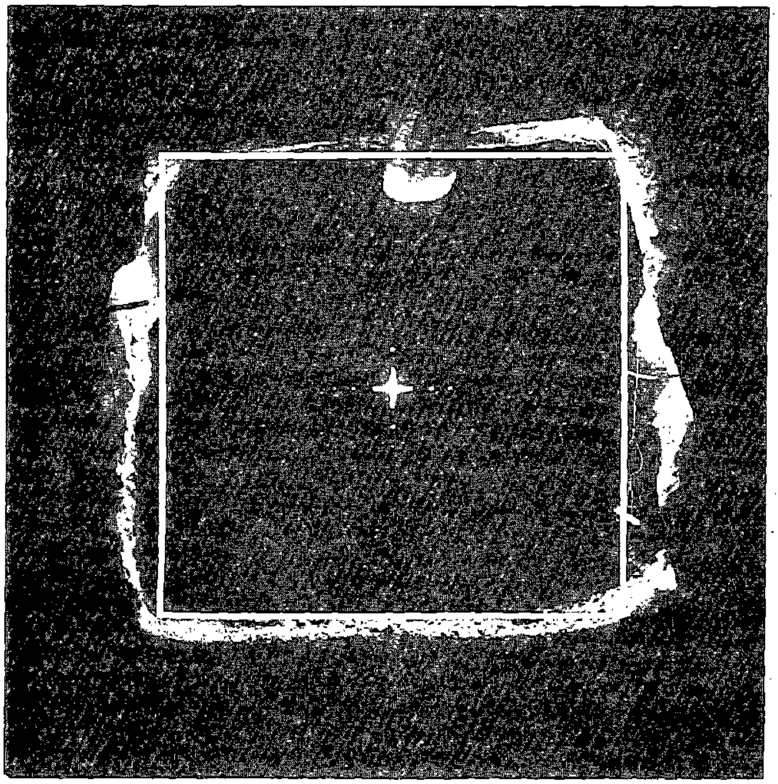


FIGURE C-10

TUNNEL SILHOUETTE

NORTH HEADING

Round No.: SSB 54
Station: 3+72
Offset: 0.0
Scale: 1"=5'
Looking North

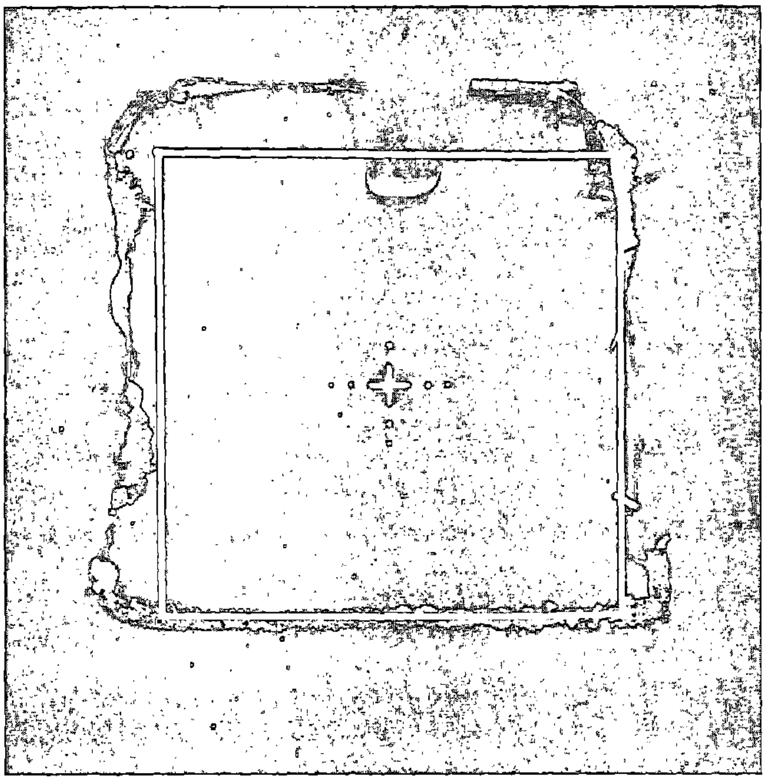


FIGURE C-11

TUNNEL SILHOUETTE

NORTH HEADING

Round No.:	FC 5
Station:	3+88
Offset:	0.0
Scale:	1"=5'

Looking North

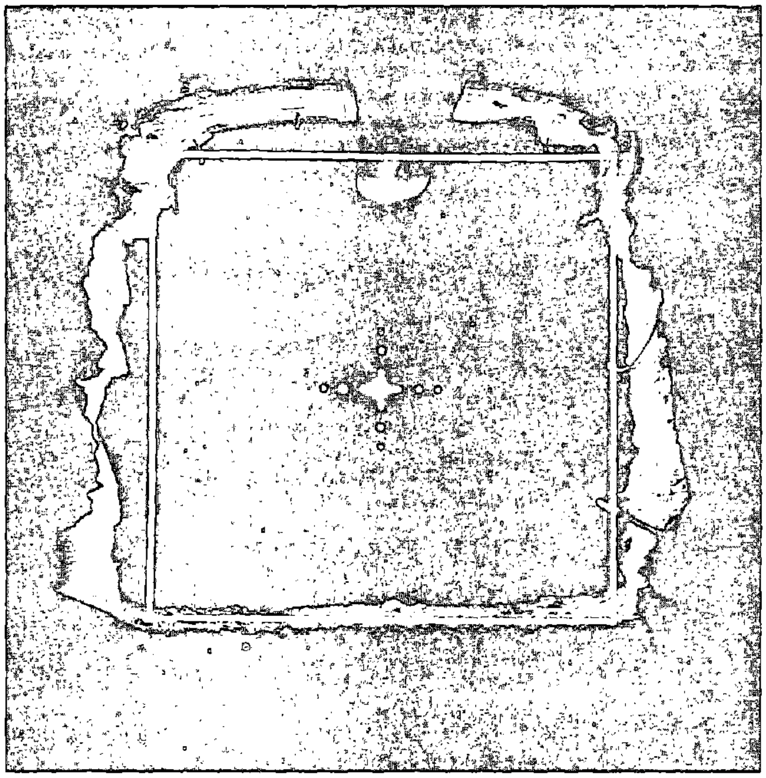


FIGURE C-12

TUNNEL SILHOUETTE

NORTH HEADING

Round No.:	FC 6
Station:	3+93
Offset:	0.0
Scale:	1"=5'

Looking North

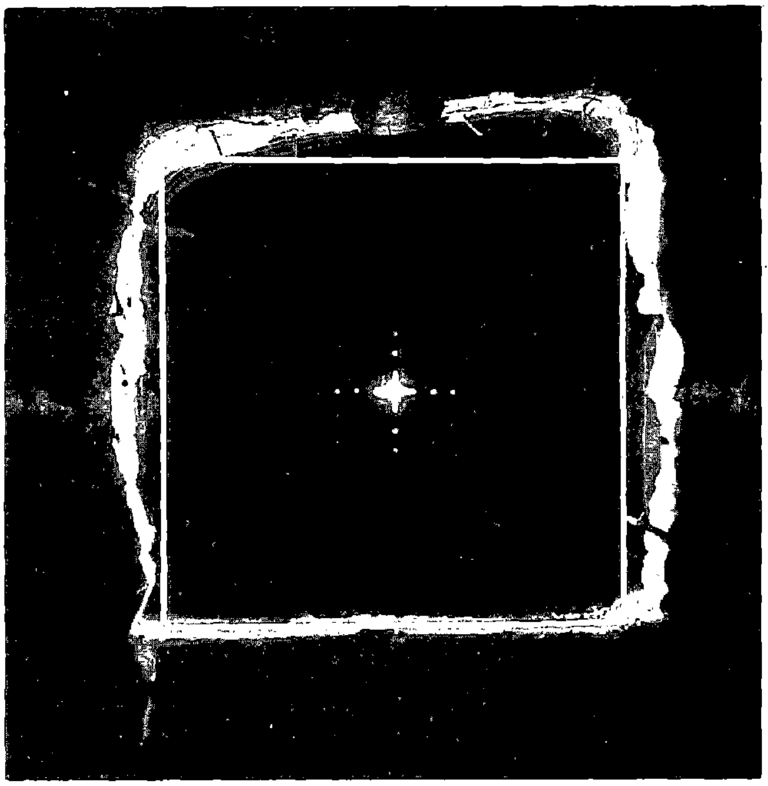


FIGURE C-13

TUNNEL SILHOUETTE

NORTH HEADING

Round No.: SSB 64
Station: 4+07
Offset: 0.0
Scale: 1"=5'
Looking North

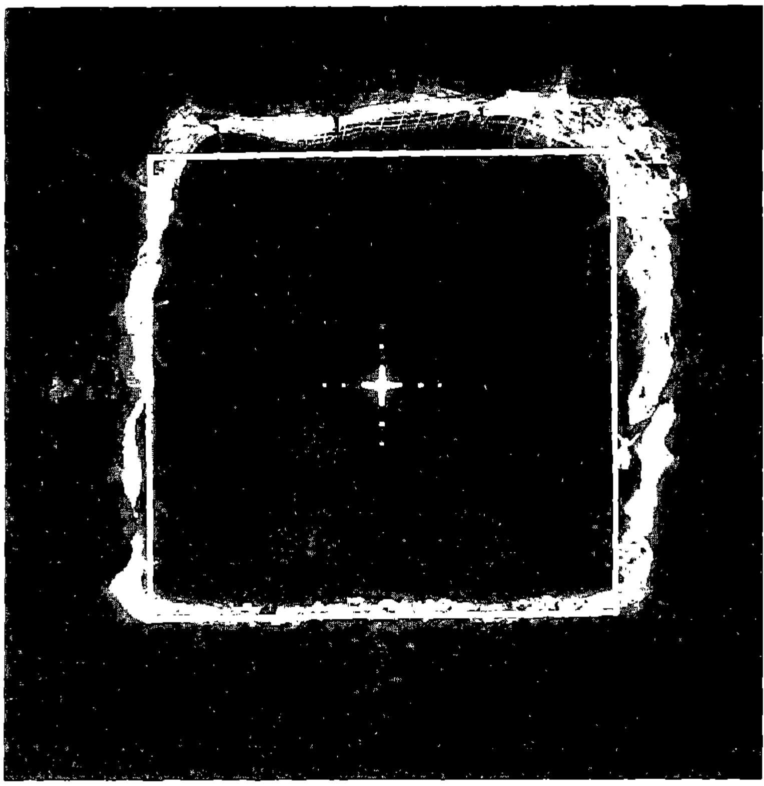


FIGURE C-14

TUNNEL SILHOUETTE

NORTH HEADING

Round No.: SSB 74
Station: 4+36
Offset: 0.0
Scale: 1"=5'
Looking North

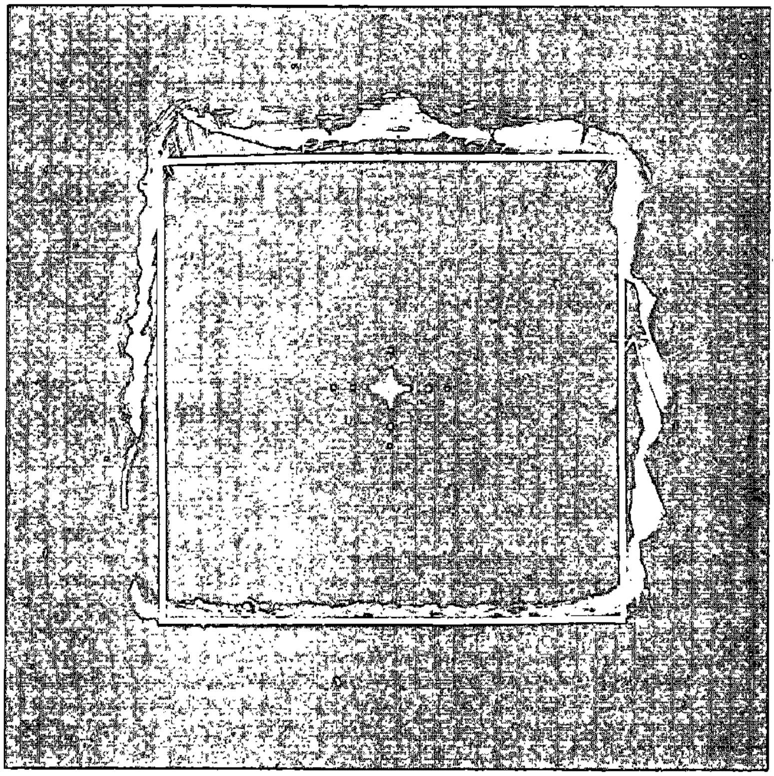


FIGURE C-15

TUNNEL SILHOUETTE

NORTH HEADING

Round No.: FC 7
Station: 4+42
Offset: 0.0
Scale: 1"=5'
Looking North

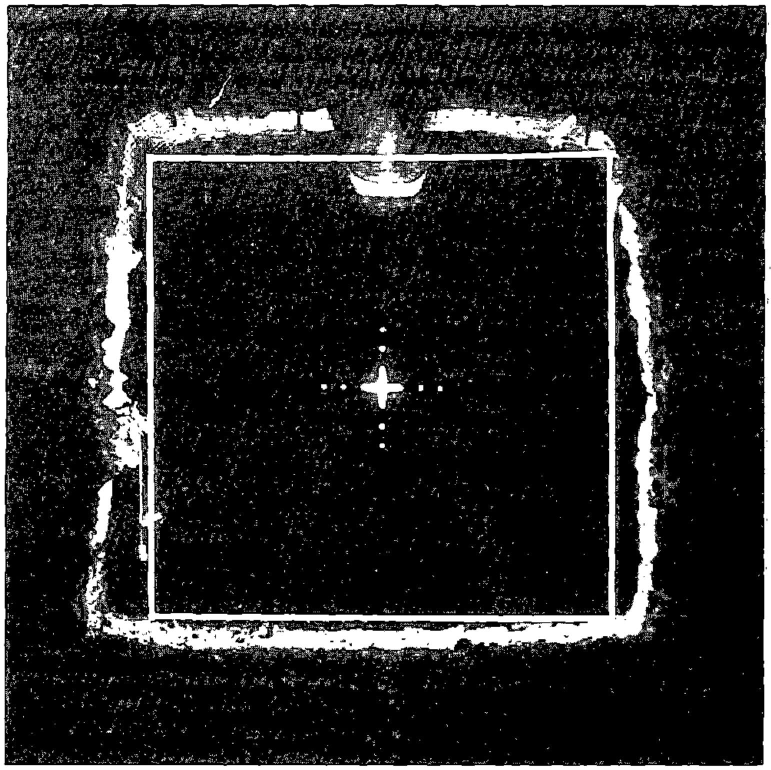


FIGURE C-16

TUNNEL SILHOUETTE

SOUTH HEADING

Round No.:	SSB 35
Station:	2+08
Offset:	0.0
Scale:	1"=5'

Looking South

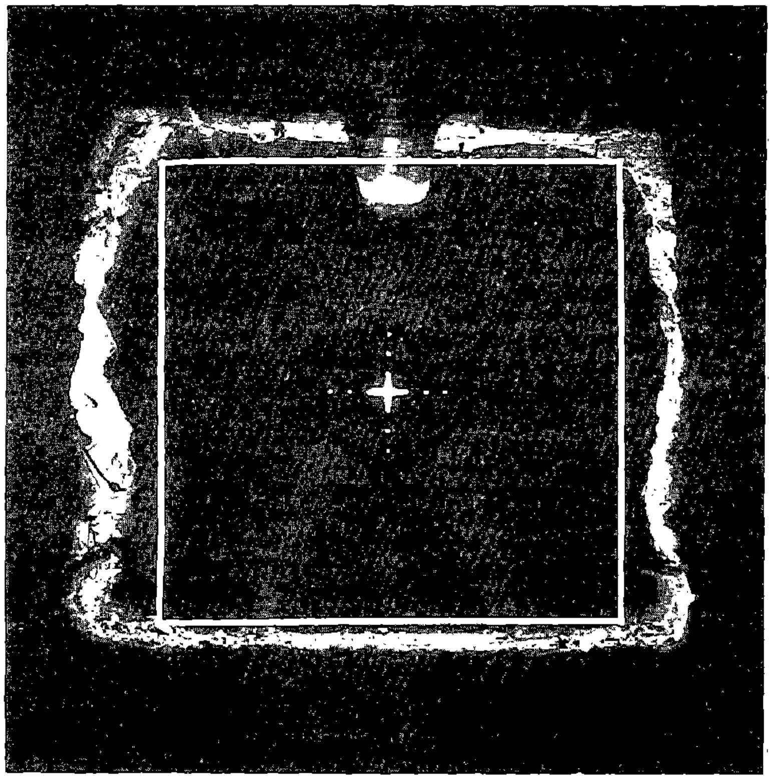


FIGURE C-17

TUNNEL SILHOUETTE

SOUTH HEADING

Round No.:	MSB 1
Station:	2+02
Offset:	0.0
Scale:	1"=5'

Looking South

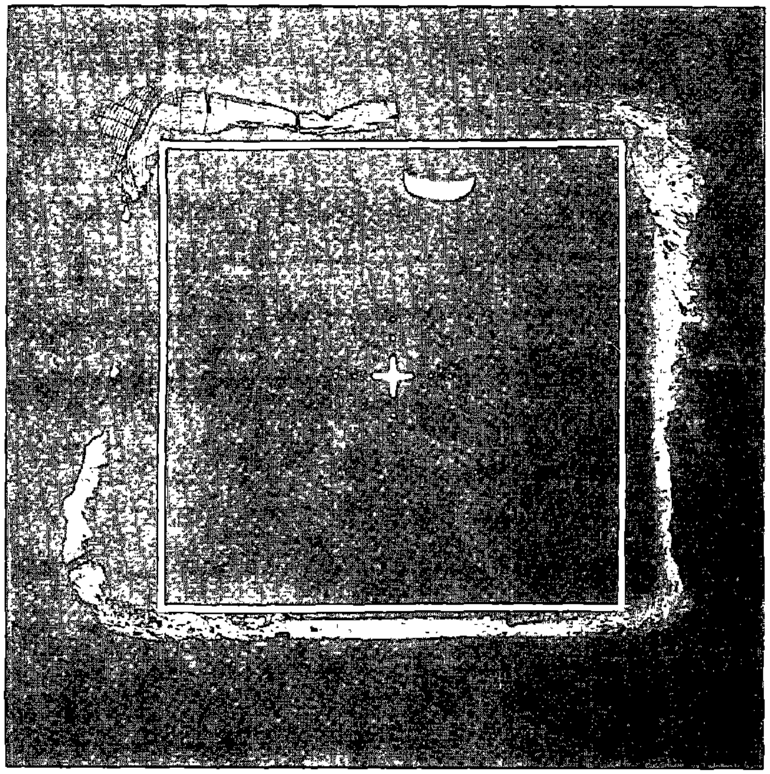


FIGURE C-18

TUNNEL SILHOUETTE

SOUTH HEADING

Round No.: SSB 47
Station: 1+67
Offset: 0.0
Scale: 1"=5'
Looking South

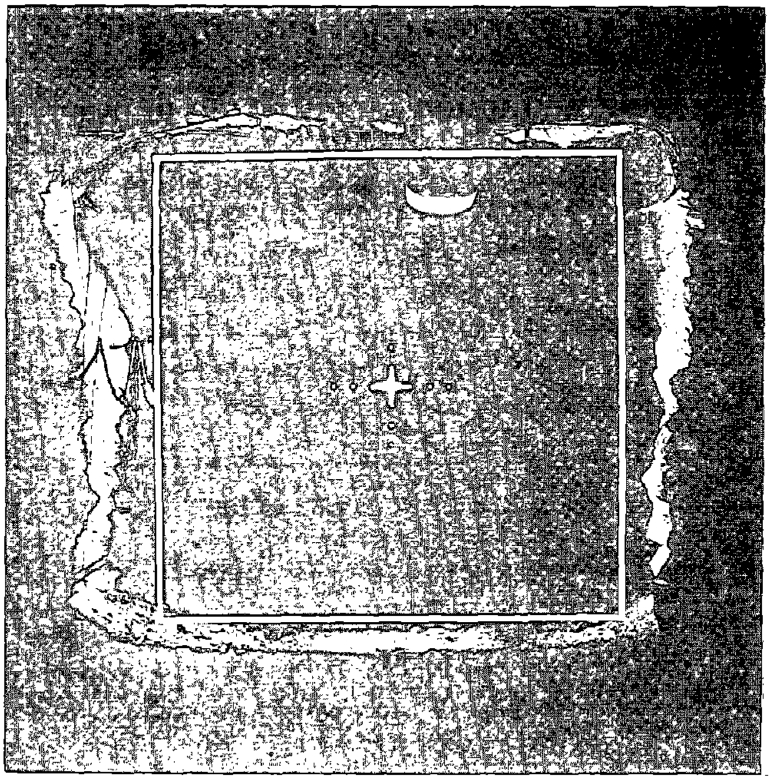


FIGURE C-19

TUNNEL SILHOUETTE

SOUTH HEADING

Round No.: FC 1
Station: 1+60
Offset: 0.0
Scale: 1"=5'
Looking South

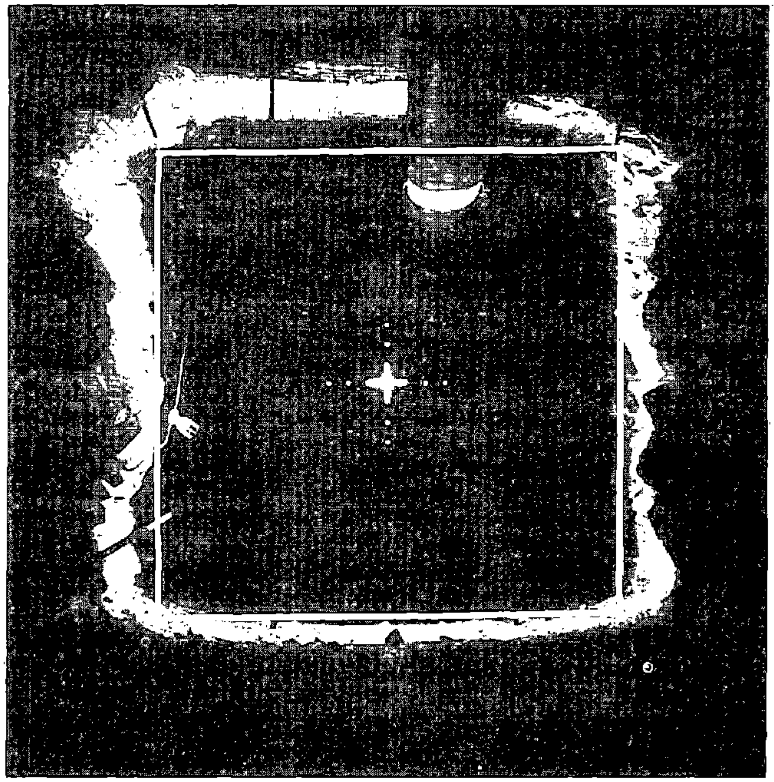


FIGURE C-20

TUNNEL SILHOUETTE

SOUTH HEADING

Round No.: FC 3
Station: 1+53
Offset: 0.0
Scale: 1"=5'
Looking South

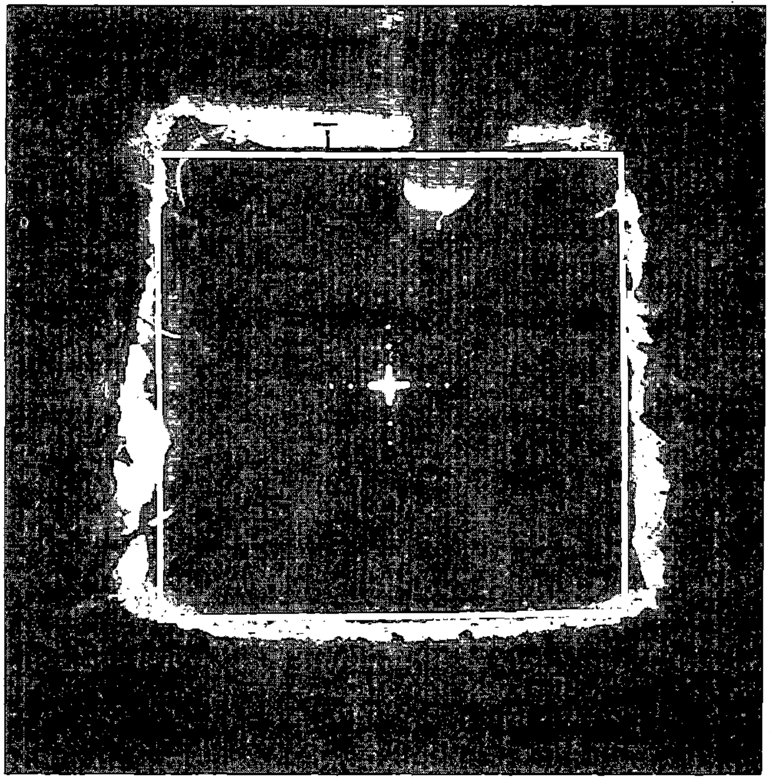


FIGURE C-21

TUNNEL SILHOUETTE

SOUTH HEADING

Round No.: SSB 53
Station: 1+46
Offset: 0.0
Scale: 1"=5'
Looking South

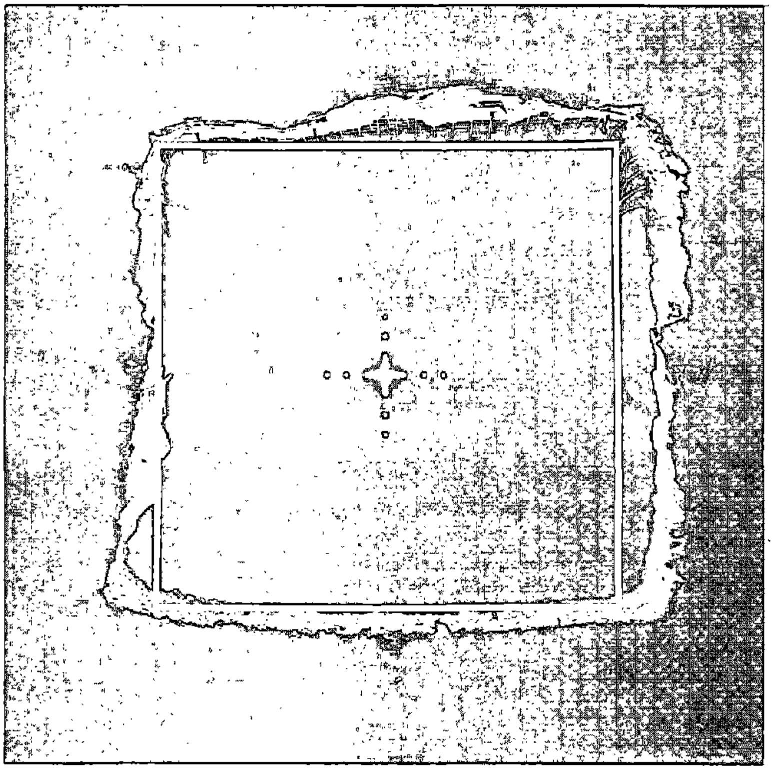


FIGURE C-22

TUNNEL SILHOUETTE

SOUTH HEADING

Round No.: FC Cut 1
Station: 0+65
Offset: 0.0
Scale: 1"=5'
Looking South

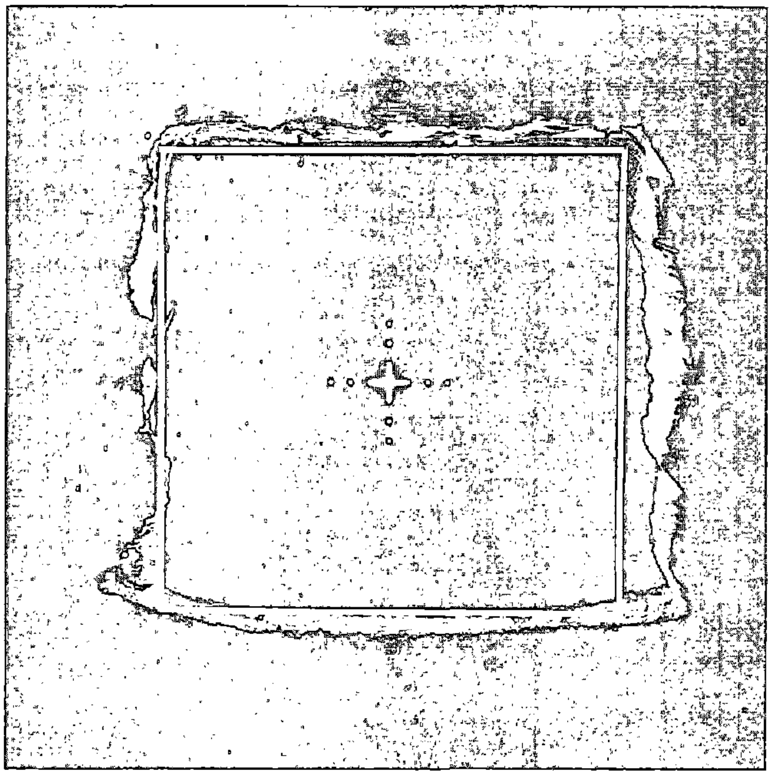


FIGURE C-23

TUNNEL SILHOUETTE

SOUTH HEADING

Round No. MSB 6/
FC Cut 2
Station: 0+59
Offset: 0.0
Scale: 1"=5'
Looking South

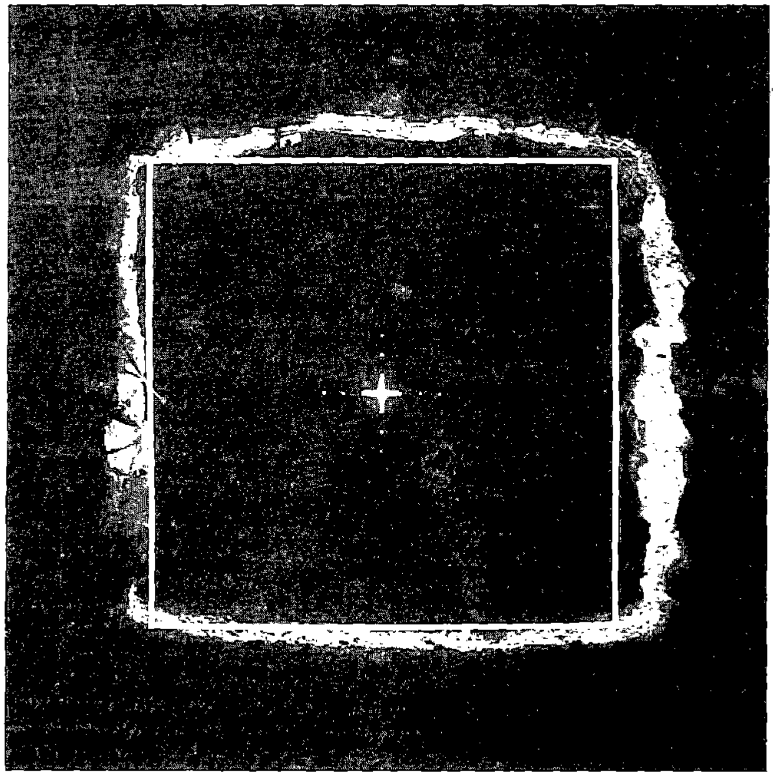


FIGURE C-24

TUNNEL SILHOUETTE

SOUTH HEADING

Round No.: SSB 81
Station: 0+52
Offset: 0.0
Scale: 1"=5'
Looking South

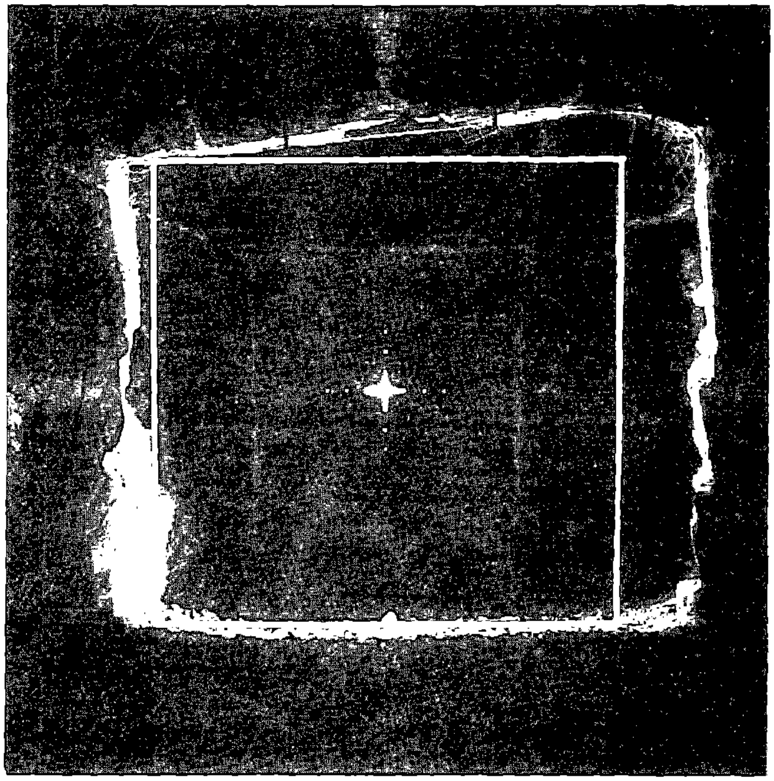


FIGURE C-25

TUNNEL SILHOUETTE

SOUTH HEADING

Round No.: SSB 92
Station: 0+10
Offset: 0.0
Scale: 1"=5'
Looking South

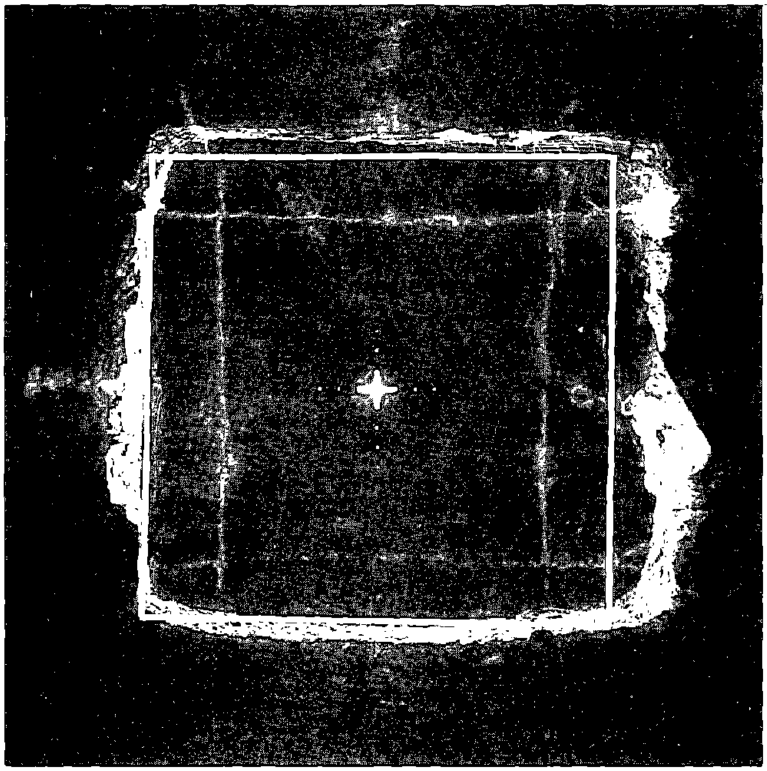


FIGURE C-26

TUNNEL SILHOUETTE

SOUTH HEADING

Round No.: M.S. Delay
Station: 0+03
Offset: 0.0
Scale: 1"=5'
Looking South

APPENDIX D

SUMMARY OF BLAST VIBRATION MONITORING

Porter Square Station Pilot Tunnel

SHEET 1 OF 12

ROUND NO.	DATE / TIME	LOCATION OF BLAST (1) STATION AND OFFSET (ft.)	EXPLOSIVE DATA (2)			GROUND VIBRATION DATA					AIR BLAST OVERPRESSURE DATA					
			Total Charge Wt. for Round (lbs.)	Total Number of Delays	Max. Charge Wt. per Delay (lbs.)	Sensor (1) Location Point	(3) Measured by:	Slant (4) Range (ft.)	Peak Particle Velocity (in./sec.)	Direction (5) Of Max. Component	Sensor (1) Location Point	(6) Measured by:	Slant (4) Range (ft.)	Peak PSI	Level dB	Approx. Equiv Noise Level on A-Scale (7) (dB)
SSB 1	27 Nov.78 1914	Sta: 2 + 47 Offset: 67 East	184	15	40.8	C	Perini	157	0.20	V	F	Perini	151	0.016	135	100
SSB 2	29 Nov.78 1933	Sta: 2 + 53 Offset: 67 East	215.5	14	43.0	B C	Perini Perini	141 155	0.23 0.23	V V	F	Perini	153	0.017	135	100
SSB 3	6 Dec.78 1536	Sta: 2 + 59 Offset: 67 East	173.5	12	33.3	B B C	H&A Perini Perini	145 145 153	0.17 0.12 0.11	V L V	B	H&A	145	0.007	127	92
SSB 4	7 Dec.78 1711	Sta: 2 + 65 Offset: 67 East	173	18	17.4	B B C	H&A Perini Perini	149 149 152	0.18 0.16 0.16	V L V	C B	Perini H&A	153 149	0.019 0.017	136 135	101 100
SSB 5	8 Dec.78 1844	Sta: 2 + 68 Offset: 67 East	109	18	10.4	B C	Perini Perini	150 151	0.09 0.06	V,L V	C	Perini	152	0.020	137	102
SSB 6	12 Dec.78 1217	Sta: 2 + 68 Offset: 60 East	177	18	22.7	G	Perini	246	0.06	V	C G	Perini Perini	151 246	0.012 0.007	132 127	97 92
SSB 7	14 Dec.78 1948	Sta: 2 + 68 Offset: 53 East	167	18	20.6	B C	Perini Perini	161 165	0.19 0.19	V V	C	Perini	165	0.012	132	97
SSB 8	15 Dec.78 1942	Sta: 2 + 68 Offset: 45 East	187	18	19.3	B C	Perini Perini	165 171	0.11 0.20	V,L V	C	Perini	171	0.012	132	97
SSB 9	18 Dec.78 1643	Sta: 2 + 68 Offset: 76 East	206	18	30.8	B B C	H&A Perini Perini	166 166 145	0.23 0.17 0.20	V V V	B C	H&A Perini	166 145	0.017 0.019	135 136	100 101
SSB 10	19 Dec.78 1814	Sta: 2 + 68 Offset: 83 East	145	19	13.9	B C	Perini Perini	149 140	0.11 0.12	V V	C	Perini	140	0.02	136	101
SSB 11	20 Dec.78 1750	Sta. 2 + 68 Offset: 38 East	153	19	15.1	B C	Perini Perini	168 177	0.19 0.20	V V	C	Perini	177	0.014	134	99

NOTES:
1) See Blast Monitoring Location Plan , Figure 5 - 1 .
2) Explosive data taken from Contractor's "as shot" tunnel round submittals.
3) Haley and Aldrich, Inc. measurements made with Sprengnether Model VS - 1100 Engineering Seismograph. Perini measurements made with SINCO Model S-5 Engineering Seismograph. Seismometers were bolted to asphalt or concrete surface.
4) Slant range is radial distance from blast to sensor.
5) Three components of motion measured as follows: T = Transverse (Horizontal), V = Vertical, L = Longitudinal (Horizontal)
6) Haley & Aldrich, Inc. measurements made with Sprengnether Model SM - 1 Air Wave Detector. Perini measurements made with SINCO Model Air Wave Detector. Detectors were mounted on Tripod about 4 ft. above the ground.
7) Sound level measured on the A weighting scale would be less than the peak sound level measured by the air wave detectors, due to the low frequency components of the airblast noise. Due to the impulsive nature of the airblast noise, frequency is difficult to determine, so the approximate A scale noise levels given assume a frequency of 50 HZ.

Porter Square Station Pilot Tunnel

ROUND NO.	DATE/ TIME	LOCATION OF BLAST (1) STATION AND OFFSET (ft.)	EXPLOSIVE DATA (2)			GROUND VIBRATION DATA					AIR BLAST OVERPRESSURE DATA					
			Total Charge Wt. for Round (lbs.)	Total Number of Delays	Max. Charge Wt. per Delay (lbs.)	Sensor (1) Location Point	(3) Measured by:	Slant (4) Range (ft.)	Peak Particle Velocity (in./sec.)	Direction (5) Of Max. Component	Sensor (1) Location Point	(6) Measured by:	Slant (4) Range (ft.)	Peak Level PSI	Peak Level dB	Approx. Equiv. Noise Level on A-Scale (7) (dB)
SSB 12	20 Dec.78 1939	Sta: 2 + 68 Offset: 90 East	88(8)	15(8)	10.1	B	Perini	147	0.15	L	C	Perini	135	0.014	134	99
						C	Perini	135	0.12	V						
SSB 13	21 Dec.78	Sta: 2 + 68 Offset. 32 East	156	18	22.0	B	Perini	172	0.11	V	C	Perini	183	0.015	134	99
						C	Perini	183	0.11	V						
SSB 14	21 Dec.78 1946	Sta: 2 + 68 Offset: 96 East	88(8)	15(8)	10.7	B	Perini	145	0.20	V	C	Perini	129	0.015	134	99
						C	Perini	129	0.20	V						
SSB 15	26 Dec.78 1221	Sta: 2 + 68 Offset: 25' East	139	18	16.9	B	Perini	174	0.115	V	C	Perini	189	0.015	134	99
						C	Perini	184	0.12	V						
SSB 16	27 Dec.78 2121	Sta: 2 + 68 Offset: 19' East	167	16	20.9	B	Perini	181	0.12	V	C	Perini	194	0.011	132	97
						C	Perini	194	0.145	V						
SSB 17	28 Dec.78 2120	Sta: 2 + 68 Offset: 13' East	161	16	24.2	B	Perini	184	0.085	V	C	Perini	201	0.014	134	99
						C	Perini	201	0.10	V						
SSB 18	29 Dec.78 1838	Sta: 2 + 68 Offset: 7' East	157	19	23.6	B	Perini	188	0.08	V	C	Perini	206	0.013	133	98
						C	Perini	206	0.08	V						
SSB 19	3 Jan.79 1438	Sta: 7 + 68 Offset: 0	139	19	21.8	B	Perini	193	0.12	V	C	Perini	212	0.012	132	97
						C	Perini	212	0.08	V						
SSB 22	4 Jan.79 1747	Sta· 2 + 59	151	17	18.9	B	Perini	186	0.07	V	C	Perini	213	0.014	134	99
						C	Perini	213	0.075	V						
SSB 23	5 Jan.79 1603	Sta: 2 + 52	152	18	22	B	Perini	182	0.105	V	C	Perini	216	0.012	132	97
						C	Perini	216	0.08	V						
SSB 24	8 Jan.79 1533	Sta: 2 + 45	149	18	17.8	B	Perini	178	0.20	V	C	Perini	216	0.014	134	99
						C	Perini	216	0.17	V						
SSB 25	10 Jan.79 1100	Sta: 2 + 39	146	16	13.9	B	Perini	176	0.105	V	C	Perini	219	0.015	134	99
						C	Perini	219	0.07	V						

NOTES·
1) See Blast Monitoring Location Plan, Figure 5 - 1.
2) Explosive data taken from Contractor's "as shot" tunnel round submittals,
3) Haley and Aldrich, Inc. measurements made with Sprengnether Model VS - 1100 Engineering Seismograph. Perini measurements made with SINCO Model S-5 Engineering Seismograph. Seismometers were bolted to asphalt or concrete surface.
4) Slant range is radial distance from blast to sensor.
5) Three components of motion measured as follows: T = Transverse (Horizontal), V = Vertical, L = Longitudinal (Horizontal)
6) Haley & Aldrich, Inc. measurements made with Sprengnether Model SM - 1 Air Wave Detecter. Perini measurements made with SINCO Model Air Wave Detector. Detectors were mounted on Tripod about 4 ft. above the ground.
7) Sound level measured on the A weighting scale would be less than the peak sound level measured by the air wave detectors, due to the low frequency components of the airblast noise. Due to the impulsive nature of the airblast noise, frequency is difficult to determine, so the approximate A scale noise levels given assume a frequency of 50 HZ.
8) This round was used to create 8' X 8' tunnel section to use in experimental test blasting program.

Porter Square Station Pilot Tunnel

SHEET 3 OF [illegible]

ROUND NO.	DATE	LOCATION OF BLAST (1) STATION AND OFFSET (ft.)	EXPLOSIVE DATA (2)			GROUND VIBRATION DATA					AIR BLAST OVERPRESSURE DATA					
			Total Charge Wt. for Round (lbs.)	Total Number of Delays	Max. Charge Wt. per Delay (lbs.)	Sensor (1) Location Point	(3) Measured by:	Slant (4) Range (ft.)	Peak Particle Velocity (in./sec.)	Direction (5) Of Max. Component	Sensor (1) Location Point	(6) Measured by:	Slant (4) Range (ft.)	Peak PSI	Level dB	Approx. Equiv. Noise Level on A-Scale (7) (dB)
SSB 26	10 Jan.79 1331	Sta: 2 + 79	128	18	12.1	B C	Perini Perini	190 211	0.10 0.105	V V	C	Perini	211	0.0125	133	98
SSB 27	11 Jan.79 1254	Sta: 2 + 33	147	17	14.0	C	Perini	220	0.05	V	-	----	---	-----	----	---
SSB 28	11 Jan.79 1725	Sta: 2 + 86	149	19	21.8	B C	Perini Perini	202 212	0.20 0.145	V V	C	Perini	212	0.014	134	99
SSB 29	12 Jan.79 1224	Sta: 2 + 27	155	18	14.9	B C	Perini Perini	170 222	0.175 0.075	V V	C	Perini	222	0.010	131	96
SSB 30	12 Jan.79 1431	Sta: 2 + 92	141	18	13.6	B C	Perini Perini	207 211	0.13 0.010	V V	C	Perini	211	0.0145	134	99
SSB 31	15 Jan.79 1041	Sta: 2 + 21	135	18	13.0	B C	Perini Perini	168 244	0.13 0.045	V V	C	Perini	244	0.008	129	94
SSB 32	15 Jan.79 1542	Sta: 2 + 98	136	18	16.3	B C	Perini Perini	212 209	0.09 0.055	V V	C	Perini	209	0.0065	127	92
SSB 33	16 Jan.79 1240	Sta: 2 + 14	148	18	14.3	B C	Perini Perini	166 228	0.155 0.065	V V	C	Perini	228	0.012	132	97
SSB 34	16 Jan.79 1701	Sta: 3 + 04	148	18	14.4	B C J	Perini Perini H&A	215 212 86	0.105 0.065 0.4	V V V	C	Perini	212	0.010	131	96
SSB 35	17 Jan.79 1136	Sta: 2 + 8	143	18	13.3	B C J	Perini Perini H&A	164 228 109	0.155 0.07 0.24	V V L	C	Perini H&A	228 109	0.014 0.010	134 131	99 96
SSB 36	17 Jan.79 1655	Sta: 3 + 11	153	18	19.1	B C J	Perini Perini H&A	219 212 89	0.11 0.055 0.30	V V V	C	Perini H&A	212 89	0.011 0.0095	132 130	97 95

NOTES:
1) See Blast Monitoring Location Plan, Figure 5 - 1.
2) Explosive data taken from Contractor's "as shot" tunnel round submittals.
3) Haley and Aldrich, Inc. measurements made with Sprengnether Model VS - 1100 Engineering Seismograph. Perini measurements made with Sinco Model S - 5 Engineering Seismograph. Seismometers were bolted to asphalt or concrete surface.
4) Slant range is radial distance from blast to sensor.
5) Three components of motion measured as follows: T = Transverse (Horizontal), V = Vertical, L = Longitudinal (Horizontal)
6) Haley & Aldrich, Inc. measurements made with Sprengnether Model SM - 1 Air Wave Detector. Perini measurements made with Sinco Model Air Wave Detector. Detectors were mounted on Tripod about 4 ft. above the ground.
7) Sound level measured on the A weighting scale would be less than the peak sound level measured by the air wave detectors, due to the low frequency components of the airblast noise. Due to the impulsive nature of the airblast noise, frequency is difficult to determine, so the approximate A scale noise levels given assume a frequency of 50 HZ.

Porter Square Station Pilot Tunnel

SHEET 4 OF 12

ROUND NO.	DATE	LOCATION OF BLAST (1) STATION AND OFFSET (ft.)	EXPLOSIVE DATA (2)			GROUND VIBRATION DATA					AIR BLAST OVERPRESSURE DATA					
			Total Charge Wt. for Round (lbs.)	Total Number of Delays	Max. Charge Wt. per Delay (lbs.)	Sensor (1) Location Point	(3) Measured by:	Slant (4) Range (ft.)	Peak Particle Velocity (in./sec.)	Direction (5) Of Max. Component	Sensor (1) Location Point	(6) Measured by:	Slant (4) Range (ft.)	Peak Level PSI	Peak Level dB	Approx. Equiv. Noise Level on A-Scale (7) (dB)
MSC 1	18 Jan.79 1255	Sta: 2 + 02	154	18	19.9	B	Perini	162	0.125	V	C	Perini	231	0.012	132	97
						C	Perini	231	0.045	V						
						J	HEA	106	0.17	L						
						J	DOT/TSC	106	0.11	V						
						I	DOT/TSC	165	0.04	V						
						G	DOT/TSC	307	0.032	V						
						K	DOT/TSC	86	0.22	V						
						L	DOT/TSC	161	0.055	V						
						M	DOT/TSC	229	0.032	V						
SSB 38	18 Jan.79 1716	Sta: 3 + 18	146	18	15.6	B	Perini	224	0.14	V	C	Perini	212	0.0075	128	93
						C	Perini	212	0.06	V						
SSB 39	19 Jan.79 1210	Sta: 1 + 95	150	18	22.1	B	Perini	160	0.17	V						
						C	Perini	234	0.075	V						
						J	DOT/TSC	109	0.13	V						
						I	DOT/TSC	170	0.045	V						
						G	DOT/TSC	313	0.039	V						
						K	DOT/TSC	89	0.31	V						
						L	DOT/TSC	166	0.074	V						
						M	DOT/TSC	234	0.041	V						
MSC 2	19 Jan.79 1706	Sta: 3 + 25	137.3	18	18.9	B	Perini	230	0.07	V	C	Perini	214	0.0085	129	94
						C	Perini	214	0.055	V						
SSB 41	22 Jan.79 1203	Sta: 1 + 88	161	18	24.4	B	Perini	157	0.105	V	C	Perini	237	0.007	128	93
						C	Perini	237	0.05	V						
						J	DOT/TSC	115	0.16	V						
						I	DOT/TSC	176	0.053	V						
						G	DOT/TSC	320	0.039	V						
						K	DOT/TSC	92	0.26	V						
						L	DOT/TSC	171	0.053	V						

NOTES:
1) See Blast Monitoring Location Plan , Figure 5 - 1.
2) Explosive data taken from Contractor's "as shot" tunnel round submittals.
3) Haley and Aldrich, Inc. measurements made with Sprengnether Model VS - 1100 Engineering Seismograph. Perini measurements made with Sinco Model S - 5 Engineering Seismograph. Seismometers were bolted to asphalt or concrete surface.
4) Slant range is radial distance from blast to sensor.
5) Three components of motion measured as follows: *T = Transverse (Horizontal), V = Vertical, L = Longitudinal (Horizontal)*
6) Haley & Aldrich, Inc. measurements made with Sprengnether Model SM - 1 Air Wave Detector. Perini measurements made with Sinco Model Air Wave Detector. Detectors were mounted on Tripod about 4 ft. above the ground.
7) Sound level measured on the A weighting scale would be less than the peak sound level measured by the air wave detectors, due to the low frequency components of the airblast noise. Due to the impulsive nature of the airblast noise, frequency is difficult to determine, so the approximate A scale noise levels given assume a frequency of 50 HZ.

Porter Square Station Pilot Tunnel

SHEET 5 OF 12

ROUND NO.	DATE	LOCATION OF BLAST (1) STATION AND OFFSET (ft.)	EXPLOSIVE DATA (2)			GROUND VIBRATION DATA					AIR BLAST OVERPRESSURE DATA					
			Total Charge Wt. for Round (lbs.)	Total Number of Delays	Max. Charge Wt. per Delay (lbs.)	Sensor (1) Location Point	(3) Measured by:	Slant (4) Range (ft.)	Peak Particle Velocity (in./sec.)	Direction (5) Of Max. Component	Sensor (1) Location Point	(6) Measured by:	Slant (4) Range (ft.)	Peak PSI	Level dB	Approx. Equiv. Noise Level on A-Scale (7) (dB)
SSC 41	22 Jan. 79 1203	Sta: 1 + 88	161	18	24.4	M	DOT/TSC	239	0.028	V						
						N	DOT/TSC	278	0.014	V						
SSB 42	23 Jan. 79 1404	Sta: 3 + 32	150	18	15.6	B	Perini	235	0.055	L	C	Perini	214	0.010	131	96
						C	Perini	214	0.05	V						
						J	DOT/TSC	101	0.23	V						
						I	DOT/TSC	.81	0.44	V						
						G	DOT/TSC	181	0.11	V						
						K	DOT/TSC	128	0.055	V						
						L	DOT/TSC	122	0.091	V						
						M	DOT/TSC	168	0.052	V						
						N	DOT/TSC	165	0.021	V						
SSB 43	24 Jan. 79 1029	Sta: 1 + 81	150	18	14.9	B	Perini	158	0.125	V	--	-----	--	-----	--	--
						C	Perini	241	0.06	V						
						J	DOT/TSC	120	0.11	V						
						I	DOT/TSC	181	0.052	V						
						K	DOT/TSC	95	0.2	V						
						L	DOT/TSC	176	0.051	V						
						M	DOT/TSC	245	0.031	V						
MSB 3 & 4	24 Jan. 79 1535	Sta: 3 + 39	136	18	18.9	H	Perini	192	0.055	V	O	Perini	155	0.005	125	90
						O	Perini	155	0.06	V						
						J	DOT/TSC	105	0.14	V						
						I	DOT/TSC	80	0.38	V						
						G	DOT/TSC	179	0.13	V						
						K	DOT/TSC	134	0.071	V						
						L	DOT/TSC	125	0.11	V						
						M	DOT/TSC	166	0.13	V						
						P	DOT/TSC	350	0.009	V						

NOTES:
1) See Blast Monitoring Location Plan, Figure 5 - 1.
2) Explosive data taken from Contractor's "as shot" tunnel round submittals.
3) Haley and Aldrich, Inc. measurements made with Sprengnether Model VS - 1100 Engineering Seismograph. *Perini measurements made* with Sinco Model S - 5 Engineering Seismograph. Seismometers were bolted to asphalt or concrete surface.
4) Slant range is radial distance from blast to sensor.
5) Three components of motion measured as follows: T = Transverse (Horizontal), V = Vertical, L = Longitudinal (Horizontal)
6) Haley & Aldrich, Inc. measurements made with Sprengnether Model SM - 1 Air Wave Detector. *Perini* measurements made with Sinco Model Air Wave Detector. Detectors were mounted on Tripod about 4 ft. above the ground.
7) Sound level measured on the A weighting scale would be less than the peak sound level measured by the air wave detectors, due to the low frequency components of the airblast noise. Due to the impulsive nature of the airblast noise, frequency is difficult to determine, so the approximate A scale noise levels given assume a frequency of 50 HZ.

Porter Square Station Pilot Tunnel

SHEET [illegible] OF 12

ROUND NO.	DATE	LOCATION OF BLAST (1) STATION AND OFFSET (ft.)	EXPLOSIVE DATA (2)			GROUND VIBRATION DATA					AIR BLAST OVERPRESSURE DATA					
			Total Charge Wt. for Round (lbs.)	Total Number of Delays	Max. Charge Wt. per Delay (lbs.)	Sensor (1) Location Point	(3) Measured by:	Slant (4) Range (ft.)	Peak Particle Velocity (in./sec.)	Direction (5) Of Max. Component	Sensor (1) Location Point	(6) Measured by:	Slant (4) Range (ft.)	Peak PSI	Level dB	Approx. Equiv. Noise Level on A-Scale (7) (dB)
SSB 45	25 Jan.79 1150	Sta: 1 + 74	147	18	14.5	B	Perini	156	0.13	V	C	Perini	244	0.007	128	93
						C	Perini	244	0.06	V						
MSB 4	25 Jan.79 1615	Sta: 3 + 46	135	18	18.9	H	Perini	185	0.055	V						
						O	Perini	152	0.06	V	O	Perini	152	0.004	123	88
						J	H&A	75	0.37	V	J	H&A	75	0.002	116	81
SSB 47	26 Jan.79 1208	Sta: 1 + 67	145	18	15.6	B	Perini	155	0.175	V	C	Perini	247	0.007	128	93
						C	Perini	247	0.055	V						
						J	H&A	131	0.18	V						
						J	DOT/TSC	131	0.12	V						
						I	DOT/TSC	195	0.061	V						
						G	DOT/TSC	341	0.059	V						
						K	DOT/TSC	104	0.14	V						
						L	DOT/TSC	187	0.062	V						
						M	DOT/TSC	255	0.042	V						
						Q	DOT/TSC	113	0.14	V						
MSB 5	26 Jan.79 1601	Sta: 3 + 53	131	18	16.8	H	Perini	179	0.14	T						
						O	Perini	148	0.055	V	O	Perini	148	0.004	123	88
						J	H&A	114	0.30	V	J	H&A	114	0.003	119	84
						J	DOT/TSC	114	0.14	V						
						I	DOT/TSC	80	0.36	V						
						G	DOT/TSC	166	0.087	V						
						K	DOT/TSC	139	0.053	V						
						L	DOT/TSC	128	0.096	V						
						M	DOT/TSC	165	0.05	V						
						Q	DOT/TSC	110	0.19	V						
FC 1	29 Jan.79 1547	Sta: 1 + 59	126	18	16.6	B	Perini	154	0.125	V	C	Perini	253	0.005	125	90
						C	Perini	253	0.055	V						
						J	H&A	138	0.14	V						

NOTES:
1) See Blast Monitoring Location Plan, Figure 5 - 1.
2) Explosive data taken from Contractor's "as shot" tunnel round submittals.
3) Haley and Aldrich, Inc. measurements made with Sprengnether Model VS - 1100 Engineering Seismograph. Perini measurements made with Sinco Model S - 5 Engineering Seismograph. Seismometers were bolted to asphalt or concrete surface.
4) Slant range is radial distance from blast to sensor.
5) Three components of motion measured as follows: T = Transverse (Horizontal), V = Vertical, L = Longitudinal (Horizontal)
6) Haley & Aldrich, Inc. measurements made with Sprengnether Model SM - 1 Air Wave Detector. Perini measurements made with Sinco Model Air Wave Detector. Detectors were mounted on Tripod about 4 ft. above the ground.
7) Sound level measured on the A weighting scale would be less than the peak sound level measured by the air wave detectors, due to the low frequency components of the airblast noise. Due to the impulsive nature of the airblast noise, frequency is difficult to determine, so the approximate A scale noise levels given assume a frequency of 50 HZ.

Porter Square Station Pilot Tunnel

ROUND NO.	DATE / TIME	LOCATION OF BLAST (1) STATION AND OFFSET (ft.)	EXPLOSIVE DATA (2)			GROUND VIBRATION DATA					AIR BLAST OVERPRESSURE DATA					
			Total Charge Wt. for Round (lbs.)	Total Number of Delays	Max. Charge Wt. per Delay (lbs.)	Sensor (1) Location Point	(3) Measured by:	Slant (4) Range (ft.)	Peak Particle Velocity (in./sec.)	Direction (5) Of Max. Component	Sensor (1) Location Point	(6) Measured by:	Slant (4) Range (ft.)	Peak PSI	Level dB	Approx. Equiv Noise Level on A-Scale (7) (dB)
FC 2	30 Jan. 79 1025	Sta: 3 + 60	123	18	18.4	H	Perini	173	0.06	V						
						O	Perini	145	0.07	V	O	Perini	145	0.006	126	91
						J	H&A	120	0.14	V	J	H&A	120	0.001	109	74
FC 3	30 Jan. 79 1645	Sta: 1 + 51	130	18	18.4	B	Perini	154	0.335	V						
						C	Perini	257	0.05	V	C	Perini	257	0.007	126	91
						J	H&A	144	0.07	L	J	H&A	144	0.002	116	81
FC 4	31 Jan. 79 1256	Sta: 3 + 67	127	19	15.6	H	Perini	166	0.06	V						
						O	Perini	142	0.07	V	O	Perini	142	0.008	129	94
						I	H&A	83	0.40	V						
SSB 53	31 Jan. 79 1723	Sta: 1 + 46	136	18	15.6	B	Perini	155	0.30	L, T						
						C	Perini	260	0.035	V	C	Perini	260	0.004	123	88
SSB 55	1 Feb. 79 1614	Sta: 1 + 37	137	18	15.6	B	Perini	157	0.35	V						
						C	Perini	262	0.04	V	C	Perini	245	0.005	125	90
						I	H&A	223	0.16	V						
SSB 56	2 Feb 79 1149	Sta: 3 + 80	144	19	14.3	H	Perini	156	0.105	V						
						O	Perini	137	0.085	V	O	Perini	137	0.005	125	90
SSB 57	2 Feb 79 1650	Sta: 1 + 31	147	19	15.0	B	Perini	158	0.25	V						
						C	Perini	265	0.05	V	C	Perini	265	0.010	131	96
FC 5	6 Feb 79 0914	Sta: 3 + 88	128	19	18.4	H	Perini	150	0.19	L						
						O	Perini	135	0.16	V	O	Perini	135	0.004	123	88
						I	H & A	90	0.63	V						
						J	DOT/TSC	142	0.19	V						
						G	DOT/TSC	143	0.12	V						
						K	DOT/TSC	173	0.10	V						

NOTES:
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4) Slant range is radial distance from blast to sensor.
5) Three components of motion measured as follows: T = Transverse (Horizontal), V = Vertical, L = Longitudinal (Horizontal)
6) Haley & Aldrich, Inc. measurements made with Sprengnether Model SM - 1 Air Wave Detector. Perini measurements made with Sinco Model Air Wave Detector. Detectors were mounted on Tripod about 4 ft. above the ground.
7) Sound level measured on the A weighting scale would be less than the peak sound level measured by the air wave detectors due to the low frequency components of the airblast noise. Due to the impulsive nature of the airblast noise, frequency is difficult to determine, so the approximate A scale noise levels given assume a frequency of 50 HZ.

Porter Square Station Pilot Tunnel

SHEET 8 OF 12

ROUND NO.	DATE/ TIME	LOCATION OF BLAST (1) STATION AND OFFSET (ft.)	EXPLOSIVE DATA (2)			GROUND VIBRATION DATA					AIR BLAST OVERPRESSURE DATA					
			Total Charge Wt. for Round (lbs.)	Total Number of Delays	Max. Charge Wt. per Delay (lbs.)	Sensor (1) Location Point	(3) Measured by:	Slant (4) Range (ft.)	Peak Particle Velocity (in./sec.)	Direction (5) Of Max. Component	Sensor (1) Location Point	(6) Measured by:	Slant (4) Range - (ft.)	Peak PSI	Level dB	Approx. Equiv. Noise Level on A-Scale (7) (dB)
FC 5	6 Feb 79 0914	Sta: 3 + 88	128	19	18.4	L M Q	DOT/TSC DOT/TSC DOT/TSC	142 166 140	0.018 0.13 0.13	V V V						
SSB 59	6 Feb 79 1317	Sta: 1 + 25	157	17	20.2	B C	Perini Perini	159 269	0.21 0.045	V V	C	Perini	269	0.008	129	94
FC 6	7 Feb 79 1233	Sta: 3 + 93	123	19	18.4	H O I	Perini Perini H & A	145 134 93	0.11 0.08 0.43	L V V	O	Perini	134	0.006	126	91
SSB 61	7 Feb 79 1719	Sta: 1 + 19	148	18	14.6	B C	Perini Perini	160 273	0.20 0.055	V V	C	Perini	273	0.008	129	94
SSB 62	8 Feb 79 1119	Sta: 3 + 99	147	18	21.6	H O	Perini Perini	140 132	0.105 0.075	L V	O	Perini	132	0.005	125	90
SSB 63	8 Feb 79 1641	Sta: 1 + 12	133	17	13.0	B C	Perini Perini	161 276	0.11 0.03	V V, T	C	Perini	276	0.005	125	88
SSB 64 (Non-electric Delays)	9 Feb 79 1202	Sta: 4 + 05	137	17	13.4	H O H	Perini Perini H & A	135 131 135	0.15 0.065 0.27	L V L						
SSB 65	9 Feb 79 1631	Sta: 1 + 05	144	17	14.5	B C	Perini Perini	163 281	0.09 0.035	V V	C	Perini	281	0.008	129	94
SSB 66	12 Feb 79 1223	Sta: 4 + 11	171	17	17.0	H O	Perini Perini	130 130	0.075 0.07	V V	O	Perini	130	0.009	130	95

NOTES:
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4) Slant range is radial distance from blast to sensor.
5) Three components of motion measured as follows: T = Transverse (Horizontal), V = Vertical, L = Longitudinal (Horizontal)
6) Haley & Aldrich, Inc. measurements made with Sprengnether Model SM - 1 Air Wave Detector. Perini measurements made with Sinco Model Air Wave Detector. Detectors were mounted on Tripod about 4 ft. above the ground.
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Porter Square Station Pilot Tunnel

SHEET 9 OF 12

ROUND NO.	DATE / TIME	LOCATION OF BLAST (1) STATION AND OFFSET (ft.)	EXPLOSIVE DATA (2)			GROUND VIBRATION DATA					AIR BLAST OVERPRESSURE DATA					
			Total Charge Wt. for Round (lbs.)	Total Number of Delays	Max. Charge Wt. per Delay (lbs.)	Sensor (1) Location Point	(3) Measured by:	Slant (4) Range (ft.)	Peak Particle Velocity (in./sec.)	Direction (5) Of Max. Component	Sensor (1) Location Point	(6) Measured by:	Slant (4) Range (ft.)	Peak PSI	Level dB	Approx. Equiv. Noise Level on A-Scale (7) (dB)
SSC 67	13Feb79 1000	Sta: 0 + 98	173	17	17.4	B	Perini	165	0.10	V, T						
						C	Perini	286	0.035	V						
						T	H & A	193	0.07	V						
SSB 68	13Feb79 1549	Sta: 4 + 17	155	18	15.4	H	Perini	126	0.095	V	O	Perini	129	0.006	126	91
						O	Perini	129	0.125	V						
SSB 69	14Feb79 1113	Sta: 0 + 91	152	17	15.0	B	Perini	167	0.11	V	C	Perini	291	0.010	131	96
						C	Perini	291	0.05	V						
SSB 70	14Feb79 1546	Sta: 4 + 23	154	17	19.2	H	Perini	120	0.11	V	O	Perini	128	0.005	125	90
						O	Perini	128	0.09	V						
SSB 71	15Feb79 1115	Sta: 0 + 85	156	18	19.7	B	Perini	169	0.12	V	C	Perini	295	0.007	128	93
						C	Perini	295	0.03	V						
SSB 72	16Feb79 0857	Sta: 4 + 30	175	18	19.8	H	Perini	115	0.14	L	O	Perini	129	0.006	126	91
						O	Perini	129	0.08	V						
						H	H & A	115	0.20	L						
SSB 73	16Feb79 1305	Sta: 0 + 78	155	18	15.6	B	Perini	172	0.11	V	C	Perini	300	0.006	126	91
						C	Perini	300	0.05	V						
SSB 74	20Feb79 1045	Sta: 4 + 36	184	18	20.5	H	Perini	110	0.20	V	O	Perini	130	0.005	125	90
						O	Perini	130	0.10	V						
						J	DOT/TSC	183	0.096	V						
						I	DOT/TSC	120	0.12	V						
						G	DOT/TSC	108	0.13	V						
						K	DOT/TSC	215	0.05	V						
						L	DOT/TSC	172	0.05	V						
						M	DOT/TSC	178	0.033	V						

NOTES:
1) See Blast Monitoring Location Plan, Figure 5 - 1.
2) Explosive data taken from Contractor's "as shot" tunnel round submittals.
3) Haley and Aldrich, Inc. measurements made with Sprengnether Model VS - 1100 Engineering Seismograph. Perini measurements made with Sinco Model S - 5 Engineering Seismograph. Seismometers were bolted to asphalt or concrete surface.
4) Slant range is radial distance from blast to sensor.
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7) *Sound level measured on the A weighting scale would* be less than the peak *sound level measured by the air wave detectors, due to the low frequency components* of the airblast noise. Due to the impulsive nature of the airblast noise, frequency is difficult to determine, so the approximate A scale noise levels given assume a frequency of 50 HZ.

Porter Square Station Pilot Tunnel

SHEET 10 OF 12

ROUND NO	DATE/ TIME	LOCATION OF BLAST (1) STATION AND OFFSET (ft.)	EXPLOSIVE DATA (2)			GROUND VIBRATION DATA					AIR BLAST OVERPRESSURE DATA					
			Total Charge Wt. for Round (lbs.)	Total Number of Delays	Max. Charge Wt. per Delay (lbs.)	Sensor (1) Location Point	(3) Measured by:	Slant (4) Range (ft.)	Peak Particle Velocity (in./sec.)	Direction (5) Of Max. Component	Sensor (1) Location Point	(6) Measured by:	Slant (4) Range (ft.)	Peak PSI	Level dB	Approx. Equiv. Noise Level on A Scale (7) (dB)
SSB 75	20Feb79 1521	Sta: 0 + 70	158	17	20.2	B	Perini	176	0.07	V	C	Perini	294	0.008	129	94
						C	Perini	294	0.03	V						
FC 7	21Feb79 1408	Sta: 4 + 42	147	19	19.6	H	Perini	106	0.21	V	O	Perini	130	0.006	126	91
						O	Perini	130	0.10	V						
						J	DOT/TSC	188	0.09	V						
						I	DOT/TSC	123	0.13	V						
						G	DOT/TSC	104	0.17	V						
						K	DOT/TSC	221	0.048	V						
						M	DOT/TSC	181	0.049	V						
						Q	DOT/TSC	189	0.17	V						
						R	DOT/TSC	487	0.018	V						
FC CUT 1	22Feb79 1059	Sta: 0 + 64	145	18	15.6	B	Perini	179	0.10	V	C	Perini	311	0.008	129	94
						C	Perini	311	0.04	V						
						J	H & A	222	0.06	T						
						J	DOT/TSC	222	0.06	V						
						I	DOT/TSC	293	0.035	V						
						G	DOT/TSC	450	0.036	V						
						K	DOT/TSC	185	0.07	V						
						M	DOT/TSC	343	0.022	V						
						Q	DOT/TSC	207	0.38	V						
						R	DOT/TSC		0.081							
SSB 78	23Feb79 1022	Sta: 4 + 47	176	18	20	H	Perini	102	0.18	V	O	Perini	131	0.009	130	95
						O	Perini	131	0.11	V						
						J	H & A	193	0.08	L						
						J	DOT/TSC	193	0.078	V						
						I	DOT/TSC	129	0.12	V						
						G	DOT/TSC	100	0.16	V						
						K	DOT/TSC	228	0.03	V						

NOTES:
1) See Blast Monitoring Location Plan, Figure 5 - 1.
2) Explosive data taken from Contractor's "as shot" tunnel round submittals.
3) Haley and Aldrich, Inc. measurements made with Sprengnether Model VS - 1100 Engineering Seismograph. Perini measurements made with Sinco Model S - 5 Engineering Seismograph. Seismometers were bolted to asphalt or concrete surface.
4) Slant range is radial distance from blast to sensor.
5) Three components of motion measured as follows: T = Transverse (Horizontal), V = Vertical, L = Longitudinal (Horizontal)
6) Haley & Aldrich, Inc. measurements made with Sprengnether Model SM - 1 Air Wave Detector. Perini measurements made with Sinco Model Air Wave Detector. Detectors were mounted on Tripod about 4 ft. above the ground.
7) Sound level measured on the A weighting scale would be less than the peak sound level measured by the air wave detectors, due to the low frequency components of the airblast noise. Due to the impulsive nature of the airblast noise, frequency is difficult to determine, so the approximate A scale noise levels given assume a frequency of 50 HZ.

Porter Square Station Pilot Tunnel

SHEET 11 OF 12

ROUND NO.	DATE/ TIME	LOCATION OF BLAST (1) STATION AND OFFSET (ft.)	EXPLOSIVE DATA (2)			GROUND VIBRATION DATA					AIR BLAST OVERPRESSURE DATA					
			Total Charge Wt. for Round (lbs.)	Total Number of Delays	Max. Charge Wt. per Delay (lbs.)	Sensor (1) Location Point	(3) Measured by:	Slant (4) Range (ft.)	Peak Particle Velocity (in./sec.)	Direction (5) Of Max. Component	Sensor (1) Location Point	(6) Measured by:	Slant (4) Range (ft.)	Peak Level PSI	Peak Level dB	Approx. Equiv. Noise Level on A-Scale (7) (dB)
SSC 78	23Feb79 1022	Sta: 4 + 47	176	18	20	M Q R	DOT/TSC DOT/TSC DOT/TSC	183 195 494	0.043 0.14 0.009	V V V						
MSB 6/ FC CUT 2	26Feb79 1135	Sta: 0 + 58	121	18	15.6	B C T	Perini Perini H & A	183 316 161	0.20 0.04 0.11	V V L	C	Perini	316	0.008	129	94
SSB 80	26Feb79 1725	Sta: 4 + 53	178	18	19.7	H O	Perini Perini	98 133	0.15 0.06	V V	O	Perini	133	0.005	125	90
SSB 81	27Feb79 1127	Sta: 0 + 52	156	18	19.2	B C	Perini Perini	186 320	0.16 0.04	V V	C	Perini	320	0.006	126	91
SSB 82	28Feb79 0844	Sta: 4 + 59	176	18	20.2	H O	Perini Perini	94 134	0.16 0.09	V V	O	Perini	134	0.005	125	90
SSB 83	28Feb79 1500	Sta: 0 + 45	167	18	21.3	B C	Perini Perini	189 324	0.14 0.035	V V						
SSB 84	1 Mar 79 1715	Sta: 0 + 38	168	18	21.3	U	Perini	147	0.16	V						
SSB 85	2 Mar 79 0858	Sta: 4 + 65	175	18	19.7	H O	Perini Perini	91 137	0.20 0.16	V V	O	Perini	137	0.005	125	90
SSB 86	2 Mar 79 1542	Sta: 0 + 32	157	18	19.9	B C	Perini Perini	197 335	0.22 0.05	V V.	C	Perini	335	0.006	126	91

NOTES:
1) See Blast Monitoring Location Plan, Figure 5 - 1
2) Explosive data taken from Contractor's "as shot" tunnel round submittals.
3) Haley and Aldrich, Inc. measurements made with Sprengnether Model VS - 1100 Engineering Seismograph. Perini measurements made with Sinco Model S - 5 Engineering Seismograph. Seismometers were bolted to asphalt or concrete surface.
4) Slant range is radial distance from blast to sensor.
5) Three components of motion measured as follows: T = Transverse (Horizontal), V = Vertical, L = Longitudinal (Horizontal)
6) Haley & Aldrich, Inc. measurements made with Sprengnether Model SM - 1 Air Wave Detector. Perini measurements made with Sinco Model Air Wave Detector. Detectors were mounted on Tripod about 4 ft. above the ground.
7) Sound level measured on the A weighting scale would be less than the peak sound level measured by the air wave detectors, due to the low frequency components of the airblast noise. Due to the impulsive nature of the airblast noise, frequency is difficult to determine, so the approximate A scale noise levels given assume a frequency of 50 HZ.

Porter Square Station Pilot Tunnel

SHEET 12 OF 12

ROUND NO.	DATE/ TIME	LOCATION OF BLAST (1) STATION AND OFFSET (ft.)	EXPLOSIVE DATA (2)			GROUND VIBRATION DATA					AIR BLAST OVERPRESSURE DATA					
			Total Charge Wt. for Round (lbs.)	Total Number of Delays	Max. Charge Wt. per Delay (lbs.)	Sensor (1) Location Point	(3) Measured by:	Slant (4) Range (ft.)	Peak Particle Velocity (in./sec.)	Direction (5) Of Max. Component	Sensor (1) Location Point	(6) Measured by:	Slant (4) Range (ft.)	Peak Level PSI	Peak Level dB	Approx. Equiv Noise Level on A-Scale (7) (dB)
SSB 87	5 Mar 79 1119	Sta: 4 + 72	181	18	20.5	H	Perini	88	0.37	V	O	Perini	139	0.004	123	88
						O	Perini	139	0.08	V						
SSB 88	5 Mar 79 1650	Sta: 0 + 25	161	18	15.6	U	Perini	137	0.20	V	U	Perini	137	0.003	120	85
SSB 89	6 Mar 79 1136	Sta: 4 + 78	192	18	22	H	Perini	85	0.80	V	O	Perini	142	0.008	129	94
						O	Perini	142	0.11	V						
SSB 90	6 Mar 79 1641	Sta: 0 + 17	181	18	23	U	Perini	130	0.46	V	U	Perini	130	0.004	123	88
SSB 91	7 Mar 79 1101	Sta: 4 + 84	176	18	20.4	H	Perini	83	0.80	V	O	Perini	144	0.005	125	90
						O	Perini	144	0.12	V						
SSB 92	7 Mar 79 1548	Sta: 0 + 10	164	18	20.8	U	Perini	125	0.40	V	U	Perini	125	0.002	117	87
						T	H & A	130	0.44	V						
SSB 93	8 Mar 79 1118	Sta: 4 + 90	168	18	19	H	Perini	82	0.57	V	O	Perini	148	0.008	129	94
						O	Perini	148	0.06	V						
SSB 94 (M.S. Delays)	9 Mar 79 1022	Sta: 0 + 3	141	25	10.2	U	Perini	120	0.46	V	U	Perini	120	0.003	120	85
						T	H & A	126	0.35	V						
						J	DOT/TSC	281	0.15	V						
						I	DOT/TSC	352	0.044	V						
						K	DOT/TSC	247	0.12	V						
						L	DOT/TSC	332	0.047	V						
						M	DOT/TSC	396	0.041	V						
						R	DOT/TSC	110	0.15	V						

NOTES:
1) See Blast Monitoring Location Plan, Figure 5 - 1.
2) Explosive data taken from Contractor's "as shot" tunnel round submittals.
3) Haley and Aldrich, Inc. measurements made with Sprengnether Model VS - 1100 Engineering Seismograph. Perini measurements made with Sinco Model S - 5 Engineering Seismograph. Seismometers were bolted to asphalt or concrete surface.
4) Slant range is radial distance from blast to sensor.
5) Three components of motion measured as follows: T = Transverse (Horizontal), V = Vertical, L = Longitudinal (Horizontal)
6) Haley & Aldrich, Inc. measurements made with Sprengnether Model SM - 1 Air Wave Detector. Perini measurements made with Sinco Model Air Wave Detector. Detectors were mounted on Tripod about 4 ft. above the ground.
7) Sound level measured on the A weighting scale would be less than the peak sound level measured by the air wave detectors, due to the low frequency components of the airblast noise. Due to the impulsive nature of the airblast noise, frequency is difficult to determine, so the approximate A scale noise levels given assume a frequency of 50 HZ.

APPENDIX E
REPORT OF NEW TECHNOLOGY

The work performed under this contract, while leading to no new technology, has allowed field evaluation of several innovative procedures in the field of drill and blast excavation. Fracture control procedures were successfully applied to both perimeter control blasting and to the opening cuts. The Half Cast Factor (HCF) and Specific Half Cast Factor (SHCF) were introduced as valuable aids in assessing the results of perimeter control blasting. Silhouette photographs of tunnel cross sections were found to be an accurate and economical method of estimating overbreak in a tunnel.

GLOSSARY

Advance - Length of additional tunnel excavated as the result of shooting and mucking a round, generally advance per round made in relation to drilled depth.

Air blast - The pressure wave, produced by the explosive energy from blasting, which radiates outward through the atmosphere.

Air overpressure, or air blast overpressure - Air pressure over and above atmospheric pressure, expressed in psi (kPa); a measure of the pressure from air blast.

Back - The roof, crown, or overhead portion of a tunnel.

Bootleg - Unbroken or intact portion of drill hole (usually at bottom of hole) left after the charge has been fired; a drill hole which was not fully blown out. Measurement of bootleg was used in this study to determine advance per round.

Bottom charge - Concentrated charge, generally tamped, in the bottom section of a drill hole.

Burden - The distance from a charged drill hole to the nearest free face, generally measured perpendicular to the axis of the drill hole.

Cap - Detonator.

Collar - The top, or outer portion of a drill hole.

Column charge, or column load - A charge in the column section of the drill hole above or closer to the face than the bottom charge.

Coupling - Placing an explosive charge in direct contact with the rock wall of the drill hole, often done by tamping the charge.

Crown - Back or roof of tunnel.

Cushioned charge - An explosive charge placed in a drill hole so that it is decoupled, or not in contact with the rock wall of the drill hole.

Cut, or opening cut - An artificial opening made in the center of a tunnel face to provide relief for the rock broken in detonating a tunnel round; the drilling pattern used to create the opening.

Cycle time - The time required to complete a drill and blast tunnel round; includes drilling, loading, detonation, venting, mucking, support measures (such as rock bolt installation or shotcrete application) until start of drilling for next round.

Dead press - A process wherein water gel explosive in a drill hole is compressed due to the detonation of other closely spaced drill holes to a degree such that the water gel explosive will not detonate when the delay cap is fired. This process can occur in closely spaced opening cut holes when millisecond (ms) delay caps are used.

Decoupling - Placing an explosive charge in a drill hole so that it is not in direct contact with the rock wall of the drill hole, done to reduce damage to the remaining rock in perimeter holes.

Delay, or delay cap - Detonators used in tunnel blasting that have delay provisions resulting in the charges firing in rotation. Delay caps are used to provide adequate relief (i.e. so the rock will be exploded into an area into which it can expand), and to reduce the total charge weight detonated at any one time so that blasting vibrations will not be excessive.

Delay interval - The elapsed time between the detonation of successive delay caps. Delay intervals vary from less than 0.10 sec. for millisecond (ms) delays to about one second or more for standard tunnel delays.

Detonator - A cap or capsule of sensitive explosive material used to initiate a charge of high energy explosive.

Dike - A tabular body of igneous rock that cuts across the structure of adjacent rocks or cuts massive rocks, generally resulting from the intrusion of magma.

Dip - The angle at which a planar feature or stratum is inclined from the horizontal. The dip is at a right angle to the strike.

Drill hole - A hole drilled into rock to accommodate an explosive charge for blasting the rock.

Face of heading - The free face or exposed vertical (typically) rock surface into which drill holes are drilled in advancing a tunnel.

Fault - A fracture or fracture zone in rock along which there has been displacement of the sides relative to one another parallel to the fracture.

First-row-in (F) holes - In a blasting pattern, the row or column of reliever holes directly adjacent to the perimeter holes.

Flyrock - Rock fragments ejected from tunnel face during detonation of tunnel round.

Fragmentation - The extent to which rock is broken up into small pieces by blasting.

Gelatin explosive - A plastic, high explosive that can be pressed into different shapes. Gelatin explosives have the advantage of being easily tamped in a hole to provide good coupling.

Groove - Notch.

Half cast - The half drill hole remaining at the perimeter of a drill and blast excavation (see Figure 5-13).

Half cast factor (HCF) - Total length of half casts visible after a tunnel round divided by the total length of all perimeter holes in the round. Expressed in percent, the HCF allows a quantitative comparison of the degree of perimeter control achieved (see Section 5.3.5.2).

Heading - Area at the tunnel face.

Hole Factor - Number of drill holes per cubic yard of rock broken in a blasting round; used as an indicator of the number of delay caps used and of drilling costs.

Joint - A fracture in rock along which no appreciable movement has occurred.

Jumbo - A highly integrated, mobile drilling rig on which the drills are mounted on booms, maneuvered (usually) by hydraulic controls.

Lifter (L) holes - In a blasting pattern, the row of drill holes located at the bottom of the round which fragments immediately above the invert. Generally fired near the end of the delay sequence and often loaded more heavily than reliever holes so that detonation will "shake up" and loosen the muck pile and make mucking operations easier.

Look-out - Angling of perimeter drill holes in a tunnel round outside the desired excavation limits in order to provide space to accommodate the drill when drilling for the next round.

Millisecond (ms) delays - Delay caps, or detonators, with delay intervals of less than 100 ms (1 ms = 0.001 sec.)

Modified Smooth Blasting (MSB) techniques - The specified smooth blasting techniques, as modified by the investigators to achieve optimum perimeter control at the site.

Muck - The broken rock resulting from firing one or more charges, as a tunnel round.

Notch, or groove - A V-shaped indentation, cut longitudinally along a drill hole, used to control crack initiation along the drill hole (see Section 4.1.2).

Opening cut - See Cut.

Overbreak - Rock broken beyond the design limits of a tunnel or other underground chamber excavated with drill and blast methods.

Particle velocity - Unit of measurement of magnitude of ground vibration, expressed in in/sec. (cm/sec.).

Pattern - A dimensioned plan of holes to be drilled in a tunnel face in advancing a tunnel by drill and blast methods.

Perimeter - That portion of the final contour, or excavation limits of a tunnel above the invert.

Perimeter control techniques - Those procedures, such as smooth blasting or fracture control, which attempt to produce smooth final contours, reduce damage to the remaining rock, and reduce overbreak.

Perimeter (P) holes - In a blasting pattern, the exterior row or column of drill holes, above the invert, which determines the final contour of the excavation.

Powder factor - Number of pounds of explosives used per cubic yard of rock broken in a blasting round; used as an indicator of the cost of explosives.

Primacord - A detonating cord manufactured by Ensign-Bickford Company, Simsbury, Connecticut; a strong flexible cord containing a core of detonating explosive, generally used for initiating a series of charges simultaneously. It explodes practically instantaneously throughout its length, when initiated with a detonator.

Pull - Length of rock broken when a tunnel round is detonated; advance per round.

Reliever (R) holes - In a blasting pattern, the drill holes between the opening cut holes and the perimeter and lifter holes.

Rib - Sidewall of tunnel, between invert and back.

Roof - Crown, back of tunnel.

Round - The series of drill holes detonated to produce a unit of advance in the tunnel heading.

Scaling - Manually breaking off loose rock from ribs and back of tunnel after detonation of a tunnel round.

Shotcrete - A spray-on concrete used to apply a concrete lining on a tunnel immediately after excavation; used for rock support and as a permanent lining.

Sidewall - See Rib.

Smooth blasting - A method of perimeter control blasting using closely spaced perimeter holes and reduced perimeter hole charges.

Spacing - The linear distance between collars of adjacent drill holes aligned approximately parallel to a free face.

Specified Smooth Blasting (SSB) techniques - The smooth blasting techniques specified in the contract for excavation of the Porter Square Station Pilot Tunnel (MBTA Contract No. 091-301). These techniques were based on current smooth blasting techniques used in the United States (see Section 5.3.1).

Spider tube - A specially manufactured extruded plastic tubing used to support the Primacord column charge in the center of the drill hole (see Figure 4-4). Used in perimeter holes using fracture control (FC) procedures and Primacord loaded modified smooth blasting (MSB) procedures, as well as in cut holes of the FC opening cut.

Stemming - Material used to seal a drill hole after the charge has been placed; generally an inert material such as clay, sand (in paper tamping bags), or water (in plastic water bags). Stemming serves to a) hold the charge in the drill hole so it is not blown out by previous hole detonations; and b) contain the explosive gasses in the drill hole.

Stick - A cartridge, or preformed unit of high explosive wrapped to a predetermined diameter and length.

Strike - The direction or bearing of a horizontal line in the plane of an inclined joint, fault, or other structural plane. It is perpendicular to the direction of dip.

Tamp - Compact or pack an explosive charge into a drill hole with a succession of light or medium blows with a tamping stick.

Throw - The spread of rock fragments in connection with detonation of a round.

Water bag - A plastic bag filled with water under pressure and used for stemming drill holes (see Section 5.1),

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