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INVESTIGATION OF TECHNIQUES IN EXPLOSIVE DRILLING

Walter L. Black

AAI Corporation

Prepared for:

Army Mobility Equipment Research and Development Center

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FINAL REPORT
by.

W. L. BLACK

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AAI CORPORATION
COCKEYSVILLE, MD. 21030

for

U.S. ARMY MOBILITY EQUIPMENT RESEARCH AND DEVELOPMENT CENTER

MECHANICAL TECHNOLOGY DEPARTMENT
CONSTRUCTION EQUIPMENT DIVISION
CONSTRUCTION EQUIPMENT DEVELOPMENT BRANCH
Fort Belvoir, Virginia 22060

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13. ABSTRACT

An exploratory program was conducted for the Army to evaluate the possibility of adapting some particular explosive drilling techniques to the problem of producing emplacements for atomic demolition munitions (ADM). The approach consisted of introducing small encapsulated explosive charges into the bore hole which exploded and fragmented the rock at the bottom of the hole into particles that can be removed by any one of several spoils removal methods.

Discussions are included of the design, development and testing of the explosive capsules, the means of introducing the capsules into the bore hole, and spoils removal techniques. The problems encountered and the solutions achieved or proposed are discussed. The results of the explosive drilling experiments are detailed and projections made as to the explosive requirements to produce an ADM emplacement.

Details of illustrations in this document may be better studied on microfiche

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SUMMARY

The Army has a need for means of rapidly generating bore holes for the emplacement of ADM devices. These emplacements may be required at any worldwide location, therefore, no limits can be predicted as to the type of soil or rock to be drilled or the climatic conditions that might exist at the drilling site. This imposes special requirements on the equipment and techniques employed in drilling these emplacements.

Briefly, the principal requirements are: 1) equipment of modest size and weight to be compatible with the Army's critical logistic requirements, 2) equipment and techniques having a universal capability that can generate emplacements in any soil or rock structure, 3) equipment and techniques that can be employed in any climatic environment, and 4) a rapid emplacement capability.

The large amount of energy required to drill emplacements in rock requires commercial equipment that is much too large and heavy to suit the Army's needs. The chemical energy in explosives, if it can be used effectively, is an efficient source of energy and its use in deep hole drilling has been under investigation in the oil industry for several years. A natural conclusion is that if this source of energy can be applied effectively to the drilling of shallow holes as well, it might provide a solution for the Army's ADM emplacement problem. This program was an exploratory effort concerned with investigating the merits of some explosive drilling techniques as a means of rapidly constructing these emplacements for atomic demolition munitions.

The problem consists of finding a way to introduce the explosives into the bore hole in a safe, efficient, and effective manner so that the in-situ materials are dislodged and broken up into particles or "spoils", then devising an effective way of conveying these spoils to the surface.

It is required that the explosives be used in a controlled manner and in discreet amounts, otherwise large explosions could occur that would destroy the equipment and blast large holes of no value in the drilling process. This can be accomplished by employing small capsules that contain the desired quantity of explosives. Means can be devised for handling these capsules and introducing them into the bore hole at controlled intervals. The effect of the explosions produced by these capsules can be varied by altering the design of the capsules. Different methods of removing the spoils produced

by these explosions can be considered but the method that will accomplish the task with the least bulk and weight of equipment is important in the ADM emplacement problem. An investigation was conducted based upon this approach to the problem. Specific goals of the program can be listed as follows:

1) Develop a basic capsule design to serve as a vehicle for introducing the explosives into the bore hole. Basic considerations are that the capsule be safe to assemble and handle and that it function reliably when it reaches the bottom of the bore hole.

2) Devise a means of introducing the explosive capsules into the bore hole in a safe controlled manner.

3) Investigate the effectiveness of different capsule configurations.

4) Evaluate the effectiveness of a specific spoils removal technique that employed a combination mechanical-pneumatic approach.

Goals number 1 and 2 were satisfactorily achieved. A basic design for the capsule was developed and proven in tests. It was handled safely, provided an effective way of introducing the explosives into the bore hole, and functioned reliably at the bottom of the bore hole. Also the design could be varied easily to permit study of different capsule configurations. The important design considerations were the explosive train, the arrangement of the explosive elements, and the choice of capsule materials. Also, a method of introducing the capsules into the bore hole was developed that proved effective in tests. The equipment employed in this exploratory program was much simpler than envisioned for final versions, but it simulated the idea well enough to indicate that the concept is sound and a system can be automated for introducing the capsules at a high rate.

Goals 3 and 4 were partially satisfied. Sufficient experimentation was completed to demonstrate that hard rock can be drilled effectively with explosives using the particular technique that had been proposed. The experiments were hampered, however, by the lack of a drilling site that provided an extensive in-situ rock structure. As a result, evaluation of the effectiveness of the different capsule configurations was incomplete and the drilling experience was not extensive enough to judge the merits of the scheme for spoils removal.

FOREWORD

This exploratory program was conducted by the AAI Corporation, Cockeysville, Maryland for the Construction Equipment Development Branch, Construction Equipment Division, Mechanical Technology Department, U. S. Army Mobility Equipment Research and Development Center, Fort Belvoir, Virginia. The services were performed under Contract No. DAAK02-72-C-0006, DA Project No. 1G662708DF0103. The program was concerned with evaluating the merits of an explosive drilling technique as a means of rapidly constructing emplacements for atomic demolition munitions. This final report reviews the development efforts, describes features of various designs, and provides information derived from the test activities.

The program was performed under the direction of A. J. Tolbert and H. B. Reese of the Construction Equipment Branch, Fort Belvoir, Virginia. The project was managed at the AAI Corporation by W. L. Black under the supervision of R. G. Strickland, Department Manager. The principal designer was R. M. Quintavalle.

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INTRODUCTION

An exploratory program consisting of analytical, design, manufacture and testing effort was conducted to evaluate the merits of an explosive drilling technique as a means of rapidly constructing emplacements for atomic demolition munitions. These emplacements may be required at any location in the world, hence, there are no limits on the type of soil or rock that must be drilled or the climatic conditions that might exist at the emplacement site. This dictates special requirements for the equipment and techniques employed in producing these emplacements. The principal requirements are: 1) the size and weight of the equipment must be small enough to be compatible with the Army's mobility requirements, 2) equipment and techniques having a universal capability that can generate emplacements in any soil or rock structure is required, 3) equipment and techniques that can be employed in any climatic environment is necessary, and 4) a rapid emplacement capability is necessary.

Techniques based on the use of small explosive charges to disintegrate rock at the bottom of the bore hole have been researched by the oil industry in this country and Russia. These small explosions pulverize the rock and accomplish the same action as the roller cone and diamond bits used in conventional drills. In conventional drilling considerable quantities of mechanical equipment are required to maintain drilling pressures and rotate the drill bit which causes its size and weight to be outside the range of consideration for ADM emplacement use. Explosive drilling is attractive to the oil well driller because it affords a way to sink large increments of hole without withdrawing the drill stem to change the bit. This is highly significant in drilling deep holes for the higher basic costs of explosive drilling are more than offset by reducing the time lost in tool transit. For shallow holes, explosive drilling has not been competitive economically and consequently has attracted little or no attention. However, in the ADM problem, explosive drilling becomes attractive for different reasons, namely, reduction of equipment bulk and weight and the speed at which the drilling can be performed. Also, operating economy is not nearly so important as in commercial applications. It is more important to be able to move the equipment into place readily, construct the emplacement quickly and withdraw from the area rapidly than to dig numerous holes day after day as commercial equipment is required to do. The explosive drilling techniques used in the deep hole drilling have demonstrated conclusively that this method can be used to drill rock. The problem then is to adapt the technique to the particular requirements of ADM emplacement, and further, determine if the tool can also be used to penetrate unconsolidated formations for a universal drilling capability, as required with ADM.

A problem of major proportions in any type of drilling tool is the removal of the spoils from the bore hole. In deep hole applications where explosive drilling has been used to date, hydraulic methods of spoils removal have been employed. Due to the necessity in the ADM problem for drilling in arid and arctic regions, hydraulic methods may not be acceptable and resorting to pneumatic or mechanical means of spoils removal will be necessary. But pneumatics requires heavy compressor equipment, and mechanical techniques, as currently practiced, are not effective in all types of soil so that a very real problem results that will require ingenuity plus some hard development effort to obtain an acceptable solution.

The objective of this program was the examination of some particular explosive drilling concepts and evaluation of their potential as an eventual solution of the ADM emplacement problem. The approach consisted of introducing small explosive charges into the bore hole at discreet intervals and removing the spoils or loosened earth or rock by a combination mechanical-pneumatic scheme. The program was planned to consist of the following tasks:

1. Analysis. Here theoretical aspects of the problem were examined to establish design features such as the size of the explosive charge, the response of the mechanical elements in the explosive train, the compressed air requirements, and estimate the expected performance of the system.

2. Design. This effort produced designs for the explosive capsules, the feeder mechanism, a static test fixture, and the experimental test equipment.

3. Capsule Development. This was an experimental effort using a static test fixture to determine the functional suitability of the capsules and the capsule feeder.

4. Test Rig Modifications. A drilling rig was acquired and modified for use in the drilling experiments and this effort provided for the necessary modifications.

5. Drilling Experiments. This was the experimental portion of the program where experiments in explosive drilling were conducted to provide qualitative and quantitative information used in evaluating explosive drilling techniques.

6. Reporting. The summary and test reports plus other documentary materials were prepared under this task.

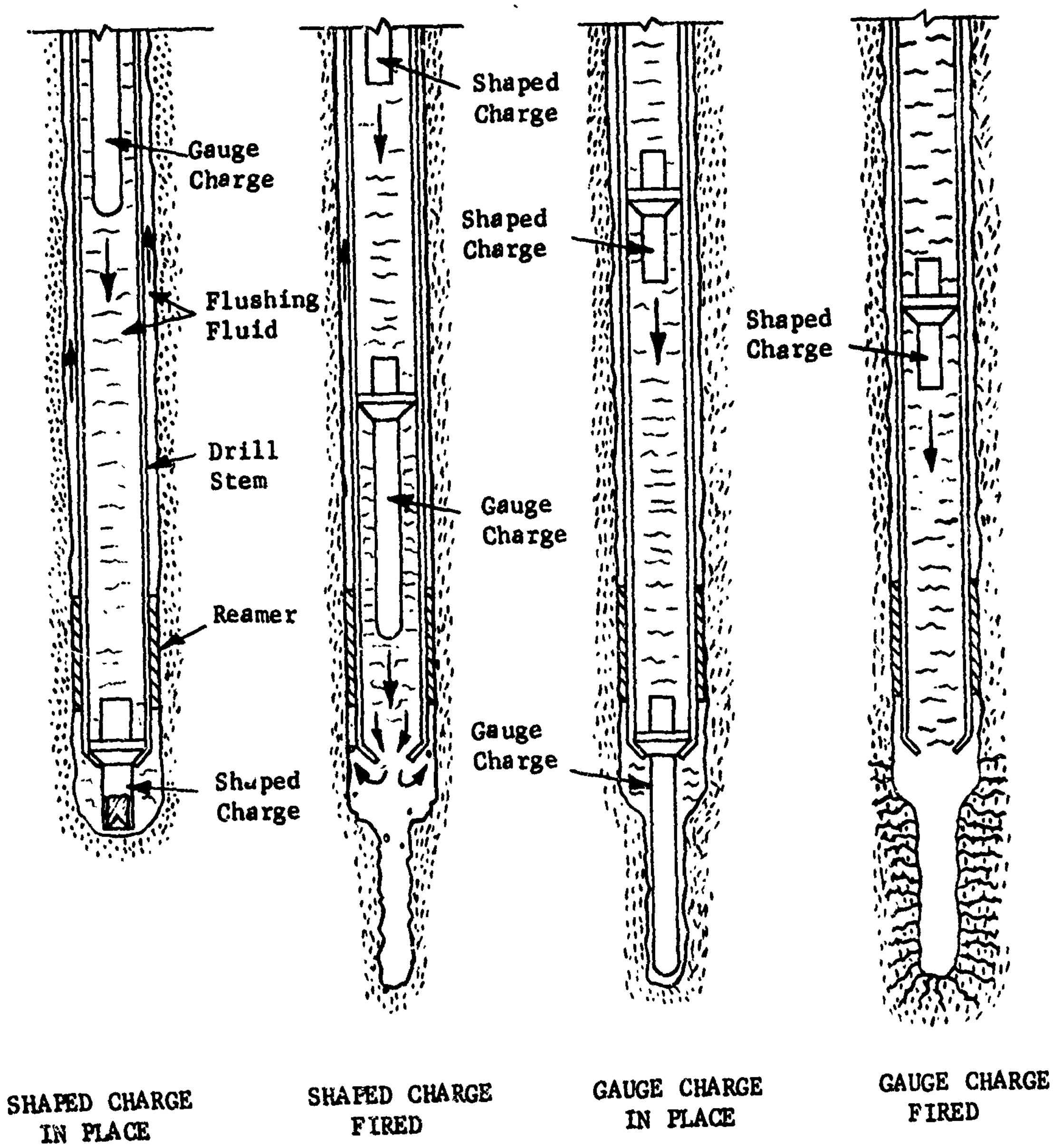
INVESTIGATION

A. Rock Fragmentation by Explosives

The fragmentation of rock by explosives is practiced on a large scale in quarry and mining operations and a wealth of information is available on the use of explosives in these fields. Here the practice is to drill small diameter bore holes by mechanical means, then fill the holes almost completely with explosives prior to detonation. This results in loading densities (the proportion of the hole filled with explosives) that are nearly 1.0. Mathematical relationships have been developed that describe or predict the action of an explosive in this situation with considerable reliability. In explosive drilling the situation, especially with the Russian approach, is considerably different for the practice is to explode small individual charges at or near the bottom of the bore hole, and the loading density in this situation approaches zero. Under this condition, little or no theoretical formulation has been derived that will describe the effects of the explosives on the rock and empirical data must be relied upon to predict results. A principle source of this type of information is the Russian work reported by Ostrovskii.[1]

The Humble Oil Company has also experimented with explosive drilling for several years using an approach based upon a series of patents issued to Robinson.[2] This approach consists of creating a slender hole in the rock with a shaped charge, then introducing a gaging charge in this hole which is used to shatter the rock out to a diameter desired for the finished hole. The hole is then reamed to the finished diameter by mechanical means. This approach is illustrated in Figure 1. This approach resembles the conventional method of drilling a hole and filling it with explosives, and the performance of this scheme can be predicted fairly well by mathematical expressions derived for this purpose. Robinson[3] has reported on controlled experiments designed to examine the effectiveness of this approach and quotes theoretical work which can be used to predict the action of explosives used in this manner.

The information on the Russian approach is reported in Reference 1. This report is eleven (11) years old and covers work performed in that country as much as twenty-five (25) years ago. It covers both laboratory work and actual drilling experience and is one of the most comprehensive sources of information on explosive drilling available in this country. This approach consists of introducing explosive capsules into the bore hole which



HUMBLE OIL EXPLOSIVE DRILLING CONCEPT

FIGURE 1

are exploded at or near the surface of the rock to fragment it into particles that can be removed readily by hydraulic means. The capsules employed were approximately equivalent to a ball of explosives where the energy pulse radiates isotropically from the center of detonation. They conducted experiments with the bore hole filled with water and with air and found the fragmentation effects to be considerably greater in water than air. In fact, they were on the order of ten (10) times greater if the hole was filled with water. The reason for this has been attributed to the incompressibility of the water. This medium will transmit the energy of the shock wave from the source of the detonation without material loss, whereas in air, the medium is compressed and the energy required to compress the air is lost insofar as the effects on the rock is concerned. This factor can have an important bearing on the ADM designs for it is desirable to operate in air. The reason for this is the requirement for worldwide deployment and the necessity to operate in frigid and/or arid regions where the use of water is impractical or perhaps impossible. The inefficiency in air of a charge whose detonation products expand isotropically might be overcome by employing shaped charges, and designs for approaching the problem in this way were developed and experiments run to evaluate this approach.

1. Russian Approach

The Russian experience covers several years of experimentation in the laboratory and the field and much of this information can be utilized in the conceptualization of designs for the ADM application. First, they found that the effect of rock strength on the explosive drilling rate is not significant. This is interesting and of importance in the ADM problem. The results shown in Table I are taken from Reference 1.

Examination of the data shows that the strength of the rock varied by a factor of 14 to 1, but the amount of rock removed varied by a factor of only 2 to 1. Also the rock giving the lowest penetration rate was limestone, having a rather low compressive strength.

Ostrovskii[1] provides data on six (6) different holes driven in various parts of Russia by the explosive drilling technique. One of these holes was a fairly shallow hole, 177 meters, driven in the Moscow area through porous limestones and dolomites using 40 gram charges. This hole varied in diameter from 8 to 16 inches and the average penetration per explosion was 0.8 inches. This gives an average removal rate of about 2.2 in^3 per gram of explosive.

Material	Crushing Strength K_g/cm^2	Density g/cm^3	Porosity %	Pene-tration mm	Diameter of Hole mm	Avg. Vol. of Rock Shattered per Explo-sion - ml
Limestone	130	2.59	18.0	5.2	57	11.6
Concrete	270	2.52	4.8	3.8	52	8.0
Limestone	370	2.60	14.6	2.8	42	3.9
Concrete	400	2.35	4.6	3.0	50	5.9
Sandstone	400	2.66	8.8	4.2	45	6.7
Marble	1400	2.71	0.8	1.5	80	7.3
Granite	1850	2.69	0.6	3.1	48	5.6

Table I. Effect of Rock Strength on Explosive Drilling Rate

In the deeper holes this removal rate decreased somewhat. For example in Hole 855 the average diameter of the hole was about 12 inches and the penetration rate 0.50 inches per explosion. This gives a rock removal rate of about 1.4 in^3 per gram of explosive. The data obtained from drilling this hole is shown in Table II.

Rock	Depth Interval m.	Avg. Penetration Per Explosion mm	Avg. Dia. of Hole mm
Limestones, Dolomites	559-625	13.3	306
Cherry Limestone	625-696	10.7	320
Sandstones & Silt Stones	1642-1651	18.8	300

Table II. Drilling Data - Hole 855

Various comments of interest in the Ostrovskii report[1] include the following:

1. Clay materials at the surface are penetrated effectively by explosive drilling. The effectiveness of an explosion in this material is roughly three times the value in rock materials.

2. Clay or other soft materials such as gypsum interspersed in the rock formation reduces the drilling rate perceptibly.

3. The distribution of the particle size of the rock removed by an explosion shows a preponderence of small particles where the explosion occurs in air.

4. When the penetration rate decreases due to less effectiveness, the diameter of the hole always increases.

5. Explosive drilling produces straight holes with very little drift or curvature.

6. Cleaning the hole of shattered debris is very important. The presence of debris results in a marked reduction in the penetration rate. Penetration will be reduced roughly by the thickness of the debris layer.

7. The diameter of the hole may be varied within broad limits by varying the distribution of the charges on the hole bottom and the size of the charge.

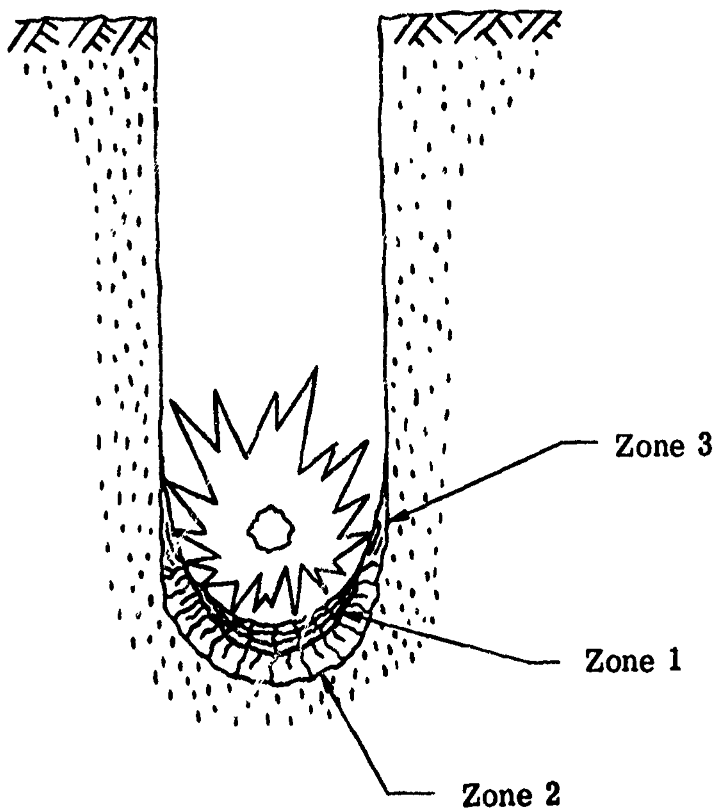
8. As a rule of thumb, the hole diameter is three to four times the diameter of the explosive charge.

9. The explosions should occur eight (8) inches or more from the nozzle for the nozzle to survive.

10. The Russians do not ream their holes. This contrasts with the Humble Oil system where reaming is used to size the hole.

11. Detonation of following charges is a problem if the hole is filled with water. This is not a problem in air-filled holes.

12. Explosive action on the rock is described as follows: Three zones of actions are identified as illustrated in the following sketch. Zone 1 occurs beneath the explosion and consists of crushed material. Zone 2 is the advanced zone of crushing consisting of fractures and other disruptions of continuity. These disruptions are not sufficient to separate fragments from the mass. Zone 3 is the effect of shock waves on the wall of the hole which are considerable if the hole is water filled. In an air filled hole these effects would be minor.



The loss of effectiveness, as reported by Ostrovskii[1] of an isotropically expanding detonation in air is a matter of concern in the ADM application. This might dictate the consideration of shaped charges for the explosive capsule rather than ball charges if the decision holds to operate in air. Shaped charges have a restricted area of coverage but their penetration is extremely good. The problem that arises with their use is how to make them generate a large diameter hole,for they will tend to bore narrow holes no larger than the diameter of the charge itself. Two ideas have been advanced to resolve this problem. One is to use multiple shaped charges in the capsule arranged so the jets radiate at an angle to the axis of the hole. The other is to include a small ball charge in the capsule along with the shaped charges. The objective is to generate a design that will work as well in air as the ball charge does in water. This approach was used in designing some of the capsules and is discussed in detail later in this report. If an equivalent effectiveness can be realized, then the Russian experience can be used to estimate the quantities of explosives required to produce an ADM emplacement.

The experimental holes drilled on this program will be about six (6) inches in diameter which requires the removal of about 340 in^3 of material per foot of hole. Recall that the Russian experience gave a removal rate of 2.2 in^3 per gram of explosive for a shallow hole and 1.4 in^3 per gram for a deep hole. Assuming that performance here will fall within that range, the quantities of explosive required to drill these experimental holes would be:

$$W = \frac{340}{1.4 \times 454} = 0.54 \text{ lb/ft max.}$$

$$= \frac{340}{2.2 \times 454} = 0.34 \text{ lb/ft max.}$$

If these requirements are extrapolated to a full size ADM emplacement, the explosive quantities would be about 5 lb/ft max. and 3 lb/ft min. The quantity of explosive needed to drill an ADM emplacement, therefore, is reasonable which makes the explosive drilling approach attractive.

2. Humble Oil Approach

A second approach that could be considered is the Humble Oil method developed by Robinson. This consists of driving a slender hole into the bottom of the bore hole into which a cylindrical gaging charge is introduced. Detonation of the gaging charge shatters a cylindrical segment of rock out to the desired diameter of the hole. The debris or spoils is then dislodged by mechanical reaming and flushed out of the hole. This approach resembles conventional rock blasting except it is performed on a small scale, and the mathematical models devised to predict the amount of rock shattered can be applied to this method. Robinson conducted a series of laboratory experiments to examine the character of this method which are reported in Reference 3. The results were comparable to those reported by the Russians. In porous berea sandstone the quantity of rock crushed was about 2.1 in^3 per gram of explosive and in non-porous limestone it was 0.8 in^3 per gram. It can be concluded, therefore, that this method would require about the same quantity of explosives as the Russian approach.

Some problems are associated with this process that make it more difficult to implement than the Russian approach. The mode of operation is to explode a shaped charge to drive a slender hole in the rock that has sufficient diameter to introduce a gaging charge that will shatter the rock out to a diameter of the finished hole. Employing this routine, the shaped charge and gaging charge would be alternately fed into the bore hole. The problem arises in being able to create a hole of sufficient diameter with a shaped charge to accommodate a gaging charge that will crush the stone to the desired diameter. For example, the diameter of the required gaging charge can be estimated from mathematical models. The relationship of Hino as reported by Robinson[3] correlates well with experimental results and will be used. The expression is:

$$a = \left(\frac{P_d}{P_r}\right)^{1/n} (r_1)$$

where: a = radius of the crushed rock zone

P_r = shock wave pressure - psi

= 3 x compressive strength of the rock (approx. relationship)

n = a distance exponent - usual value between 2 and 3 (use 2.5)

P_d = detonation pressure = 2,300,000 psi (TNT, Comp. C, others)

r_1 = radius of charge - in.

We wish to compute r_1, so rearranging we have

$$r_1 = a\left(\frac{P_r}{P_d}\right)^{1/n}$$

Say we wish to shatter the rock out to a nine (9) inch radius and the medium is limestone with a compressive strength of 18,000 psi, then

$$r_1 = 9\left(\frac{3 \times 18,000}{2,300,000}\right)^{1/2.5}$$

$$= 2.0 \text{ inches}$$

This means that the hole pierced by the shaped charge needs to be on the order of five (5) inches in diameter to allow ready insertion of the gaging charge. The information to project the exact size of such a shaped charge that will produce this size hole is not available, but enough is known to predict that a charge weighing several pounds would be needed. Such a charge cannot be tolerated because it would wreck the equipment at the bottom of the bore hole. Some technique, such as opening a hole with a small shaped charge and then expanding it with a series of gaging charges might be feasible. This may be difficult to do, so the approach appears to be more complex than the Russian technique when holes of the size needed for ADM are considered.

B. Spoils Removal Considerations

The removal of the spoils, consisting of crushed rock and/or soil and water is a major technical challenge. If a dry hole is to be drilled, the spoils must be removed either mechanically or by air or by a combination of these two methods. It was decided to explore the combination approach in this program, but since a straight air or the pneumatic removal method is also a prime candidate, it was examined analytically. Mechanical removal systems have been developed by industry by a cut and try method and does not lend itself to analysis.

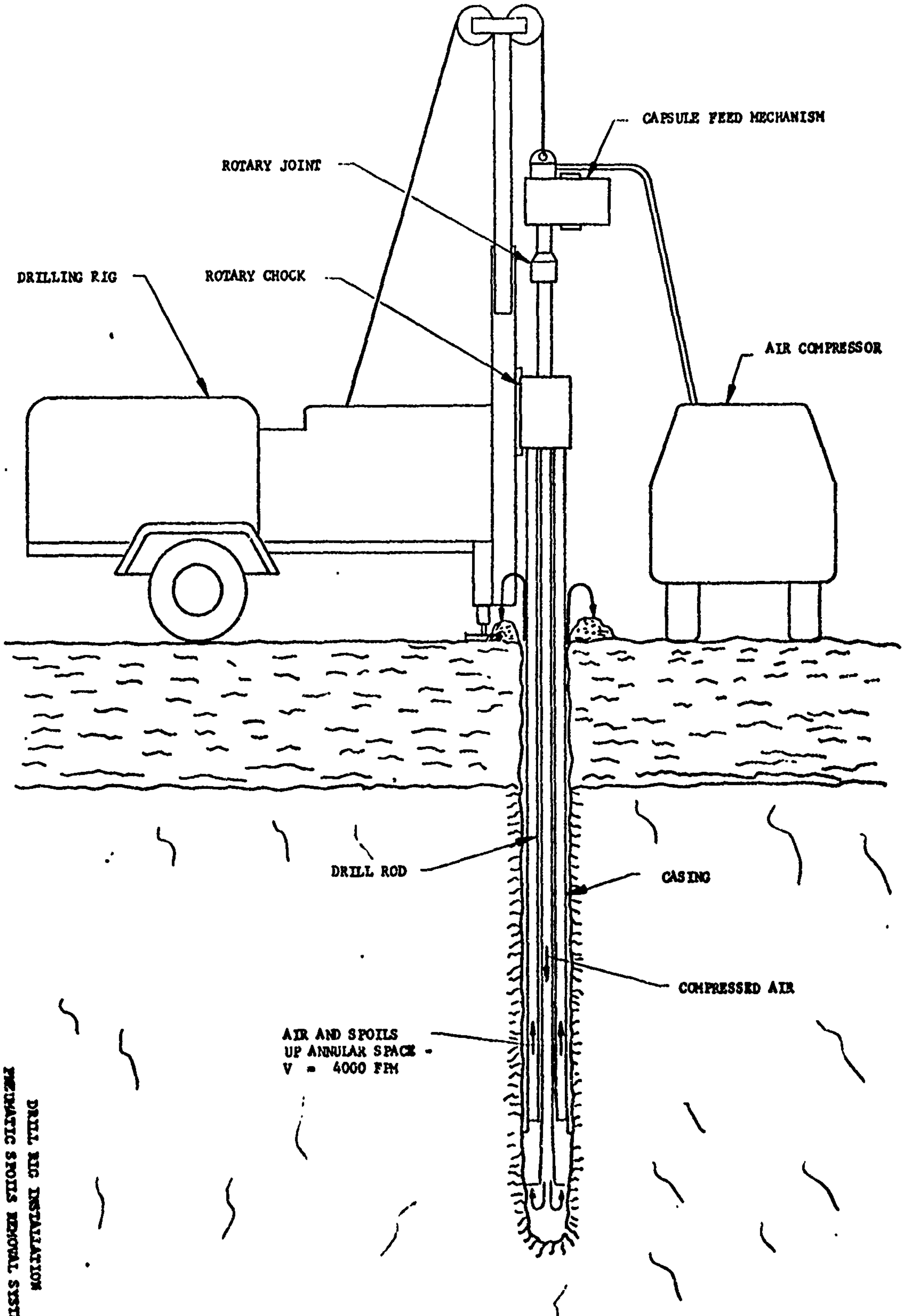
A conventional pneumatic spoils removal scheme is not suitable for ADM because it requires large quantities of compressed air,and the compressors become very large and heavy which cannot be tolerated. The conventional system works as follows: Compressed air is pumped down the drill tube and exits at the bottom of the hole as very high velocity jets. These jets sweep the spoils from the bottom of the hole and carry them up the annular space between the drill tube and the walls of the hole. Experience shows that the air velocity in the annular space must be $\geq$4000 FPM to carry the spoils from the hole. This scheme, adapted to an explosive drilling concept, is illustrated in Figure 2.

There are ways to reduce the magnitude of the problem and one of these is particularly adaptable to ADM equipment since it is proposed to case the hole as it is drilled. This scheme is to block off part of the annulus area so that a number of channels are formed through which the spoils laden air escapes. This reduces the volume appreciably so that the necessary air velocity can be maintained with a reduced compressor capacity. Consider cleaning the small hole that it is planned to drill on this program by pneumatic methods. A cross-section of this hole and the tooling used to drill it are shown in Figure 3. The cross-sectional areas of the drill rod and spoils removal cavities are 4.43 in^2 and 4.6 in^2, respectively. If we wish to maintain a flow velocity of 4000 FPM in the spoils removal cavity, the volumetric rate V_2 is:

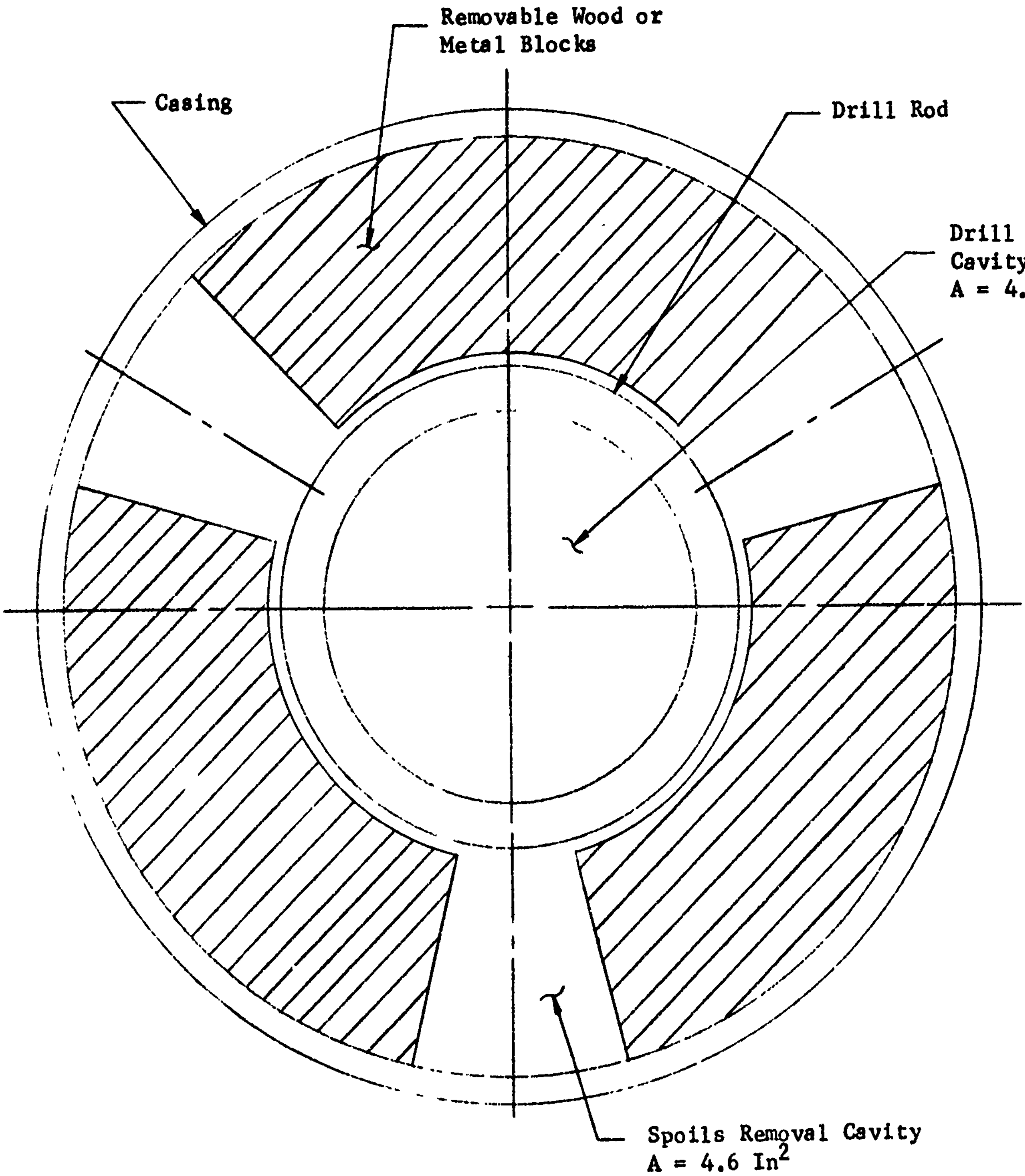
$$V_2 = \frac{U_2 \times A_2}{144}$$

$$= \frac{4000 \times 4.60}{144}$$

$$= 128 \text{ CFM}$$



DRILL RIG INSTALLATION
PNEUMATIC SPOILS REMOVAL SYSTEM
FIGURE 2



CROSS SECTION OF EXPERIMENTAL HOLE

FIGURE 3

where: U_2 = flow velocity - FPM

A_2 = area of spoils removal cavity = 4.60 in^2

V_2 = volumetric rate - CFM

A 128 CFM compressor is reasonable in size and could be tolerated for final ADM use. This scheme of choking down the annular space to make the use of a small compressor practical can also be envisioned for the full-size ADM bore hole.

The considerations discussed above are for a conventional air flushing system. In explosive drilling we have the action of the explosion products assisting to some extent in moving the spoils. Some theoretical work on the benefits that might be derived from this source of energy has been developed in appendix 2 of Reference 4. These calculations are not included here because the effects will be greatly attenuated by the presence of the drill head and not a great deal of practical help is expected from this source in moving the spoils up the spoils cavities. This conclusion was solidified somewhat by calculating the volume of gaseous products produced by a pound of TNT. The explosion products cool very rapidly so it was assumed that the products are at standard conditions of temperature and pressure which are 32°F and 14.7 psi, respectively. From Cook[5], the products of detonation of TNT for a density of 1.11 gm/cc is given as follows:

$$4.4\ C_7H_5N_3O_6 \rightarrow 3.5\ CO + 6.6\ CO_2 + 2.5\ H_2O + 5.5\ H_2 + 0.5\ CH_4$$

$$+ 0.5\ HN_3 + 2.5\ CH_3OH + 2.2\ HCN + 0.2\ C_2H_2 + 10.2C$$

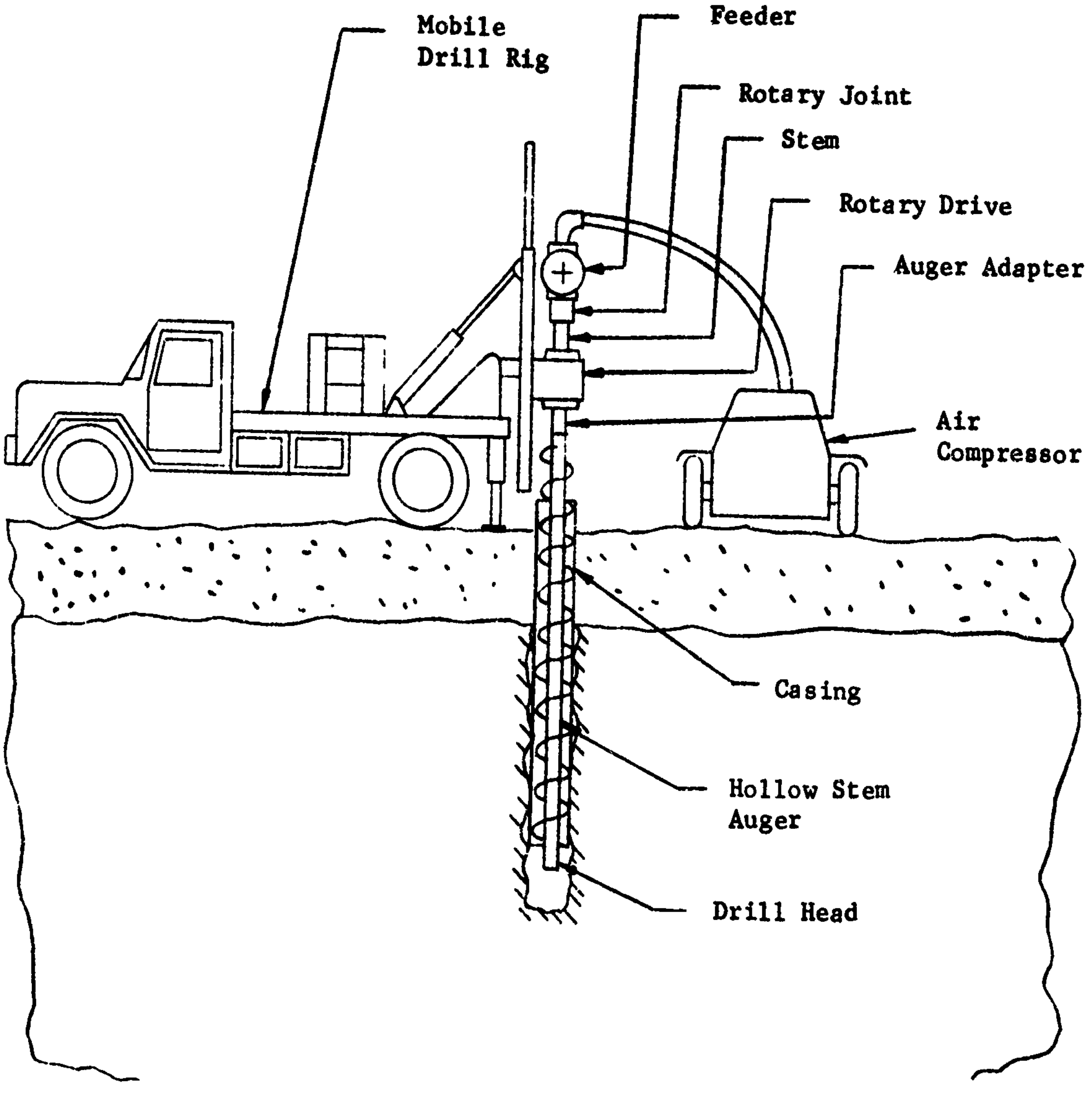
The yield of gaseous products produced from a pound of TNT is summed in Table III and found to be 8.53 cubic feet which is of no consequence insofar as generating a velocity in the gas flow through the spoils removal cavities.

(1) Product	(2) Yield $\frac{gm\ Moles}{K_g}$	(3) Yield cu-ft/lb (2) x .358
CO	8.5	3.04
CO_2	6.6	2.38
C_2H_2	0.2	0.07
H_2	5.5	1.97
CH_4	0.5	0.18
HN_3	0.5	0.18
HCN	2.2	0.79
TOTAL	24.0	8.53

Table III. Gas Volume of 1 Lb. of TNT at Standard Conditions of Temperature and Pressure

Considerable help from the explosions is expected, however, in cleaning the bottom of the bore hole and imparting an initial velocity to the spoils. This action would be highly beneficial to the mechanical scheme for removing the spoils and will be relied upon to raise the spoils into engagement with the flights of the auger. A modest amount of compressed air will be used with the mechanical system also to carry the capsules down the drill rod. This will assist in raising the spoils, but the principle source of energy will be furnished by the explosion.

The resources of the program were limited so a choice was necessary regarding the method of spoils removal to be used in these limited experiments. The choice favored a combination pneumatic-mechanical scheme which is illustrated in Figure 4. The plan employed a truck mounted B-30 drill furnished by the Mobile Drilling Company. The drilling rig in place for the drilling experiments is shown in Figure 5. A hollow stem auger was used that had a 2-1/2 inch opening through the center.



EXPLOSIVE DRILL RIG EMPLOYING A
PNEUMATIC-MECHANICAL SPOILS REMOVAL CONCEPT

FIGURE 4

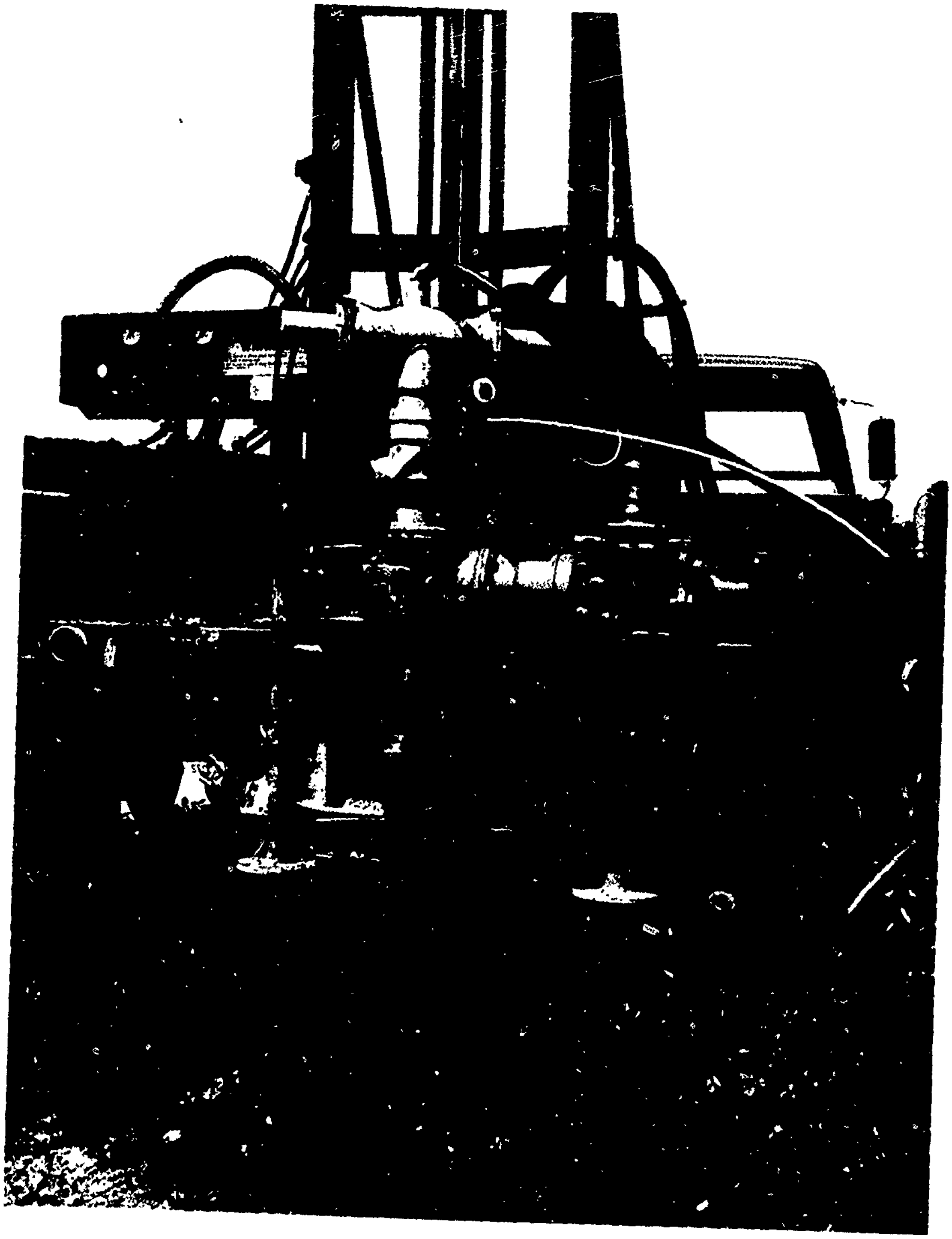


Figure 5. Drill Rig in Place for Experiments

Explosive capsules were injected into this opening by means of a feeder and propelled downward into the bore hole. Compressed air was used to operate the feeder and drive the explosive capsules through the hollow stemmed auger. The auger was raised about 12 inches from the bottom of the hole so that the capsules exited from the auger and traversed the space to the bottom of the bore hole where they exploded on impact. The auger flights were 6-1/2 inches in diameter and ran inside a steel casing that was 7.50 inches O.D. with a .250 inch wall. This left a nominal clearance of 1/2 inch between the diameters of the auger and the inside of the casing.

In this spoils removal system the loosened spoils are lifted from the bottom of the hole by the circulating air and the impetus imparted by the explosions so that they reach the flights of the auger. Once they reach the auger they are conveyed to the surface mechanically. This scheme, if it is found to be satisfactory, could be a solution to the spoils removal problem for the ADM for a modest compressor of 125 to 200 CFM would suffice and a drill rig such as the B-30S made by Mobile Drilling Co. could be used to drive the auger. An illustration of the B-30S drill is shown in Figure 6.

Figure 6. View of Small Drill Rig

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C. Capsule Design

Effort was devoted to the development of capsules of three different configurations. They were designated Types I, II and III. The Type III capsule utilizes a ball of C-4 explosive which has no directional properties and the energy from the explosion expands isotropically from the center of the charge. The other two capsules employ shaped charges which focus the energy in the direction of the narrow jets created by the shaped charges. The Type I capsule employs seven (7) small 1.1 gram shaped charge units and the Type II, three (3) units having 3.7 grams of explosive each. Capsules having different size shaped charges were employed experimentally only to determine which approach would be the more effective, a large number of small units or a small number of larger units. The shaped charge approach was included in the experiments because it is planned to work in an air-filled hole and it is anticipated that this type of charge might be more effective under this condition than the non-directional charge. In the course of development it appeared that the shaped charge capsules might not be producing enough explosive products to aid flushing of the spoils from the hole so a quantity of C-4 explosive was added to the shaped charge configurations to improve this aspect of the design. This results in a combination type capsule and broadened the scope of the experiments. The Type I, II and III capsules are illustrated in Figures 7, 8 and 9, respectively and a photograph of the parts in a Type I capsule are shown in Figure 10.

1. Firing Train Development

The development of the firing train involved the selection and arrangement of the explosive elements, the provisions for safing and arming and the functioning of the train under the dynamic conditions in which the capsule must operate.

Safing and arming was an extremely important factor in the design because the safety of personnel involved in the use of the capsules depends upon the reliability of the methods employed. It was decided to use a bore rider technique where the explosive elements are out of line with the firing pin whenever the capsule is in the feeder or drill stem. During handling this out-of-line condition is maintained by a safety pin which is inserted at assembly and remains in place until after the capsule is inserted in the feeder mechanism. Details of this scheme are illustrated in Figures 7 through 10.

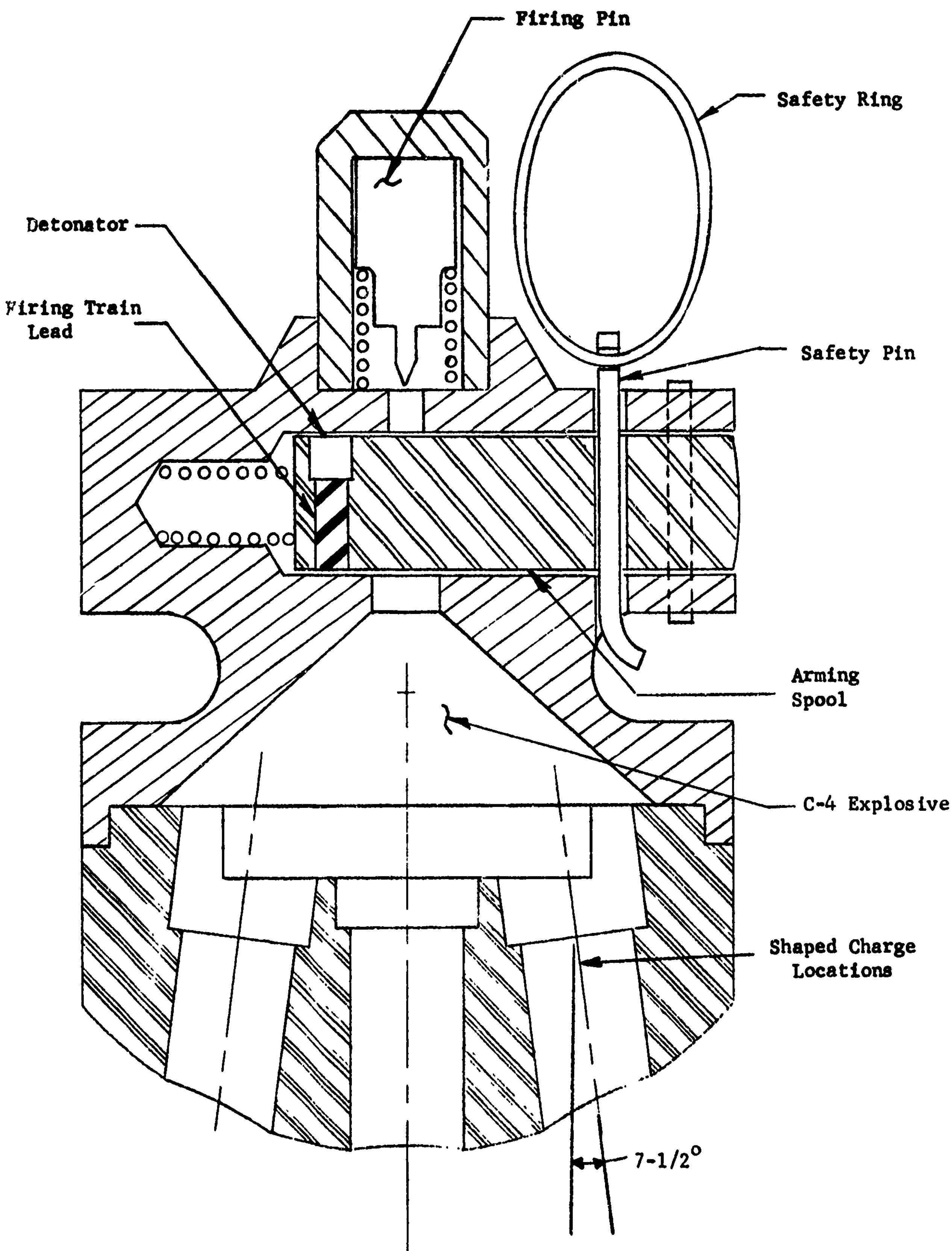


Figure 7. Type I Capsule

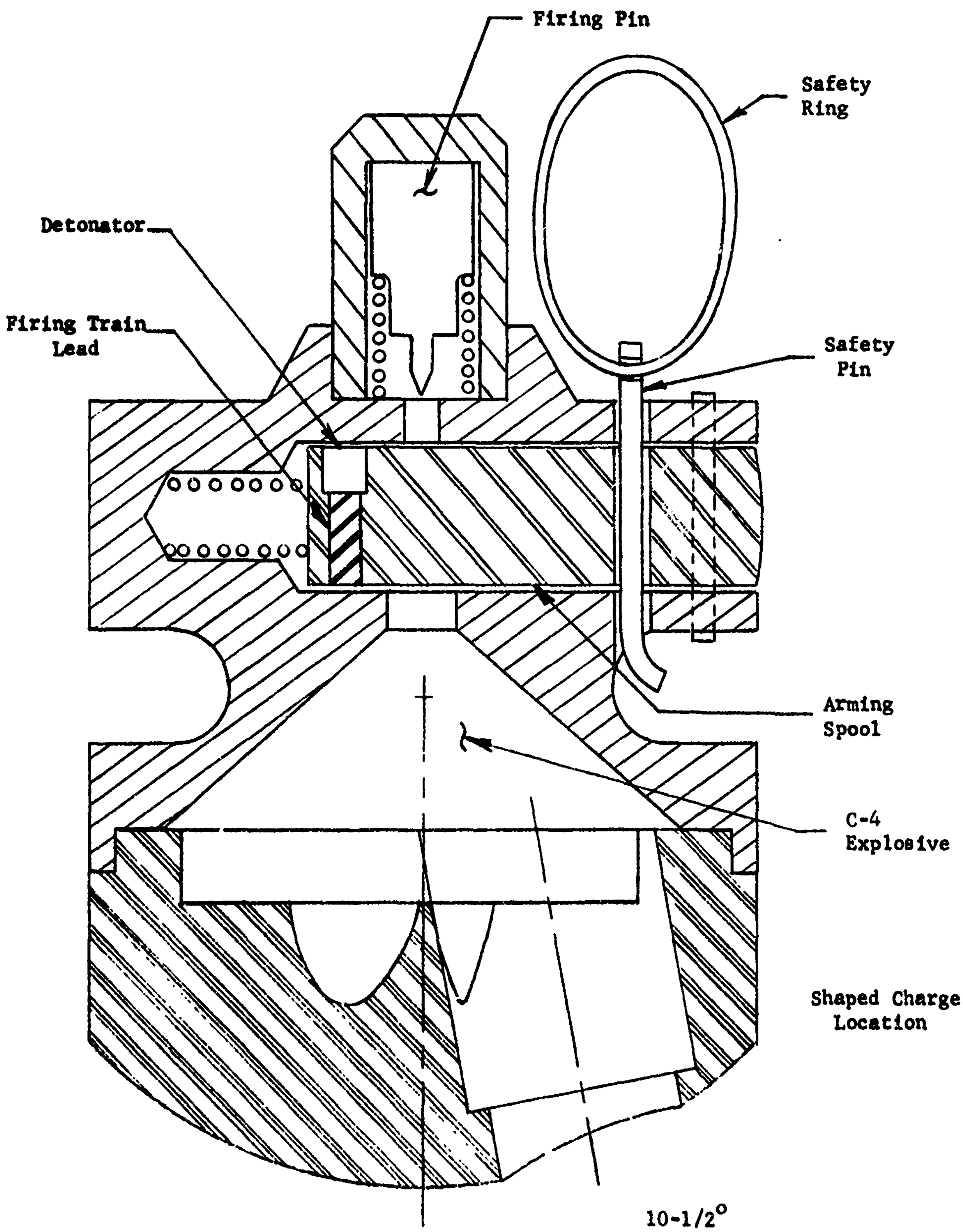


Figure 8. Type II Capsule

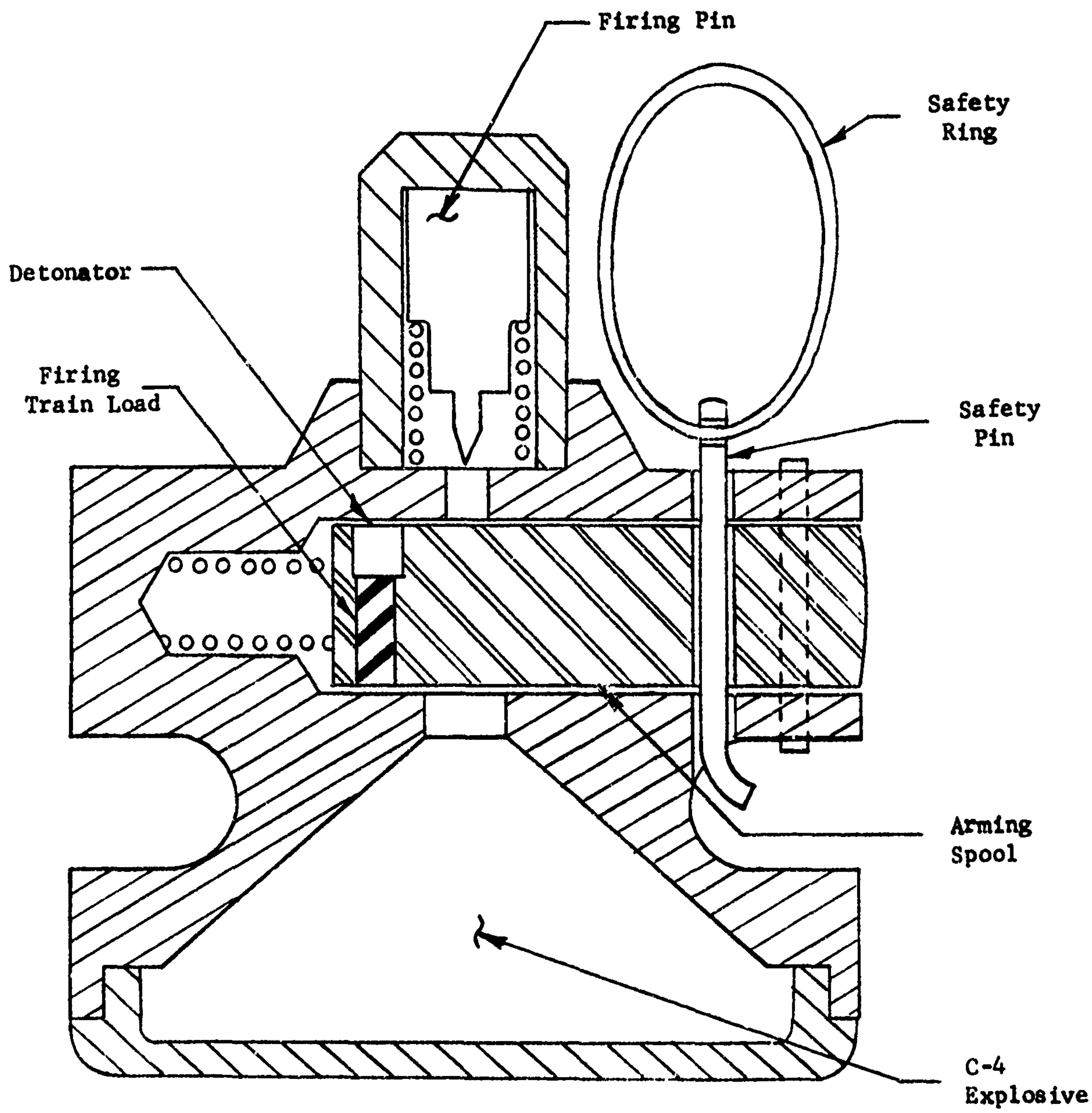


Figure 9. Type III Capsule

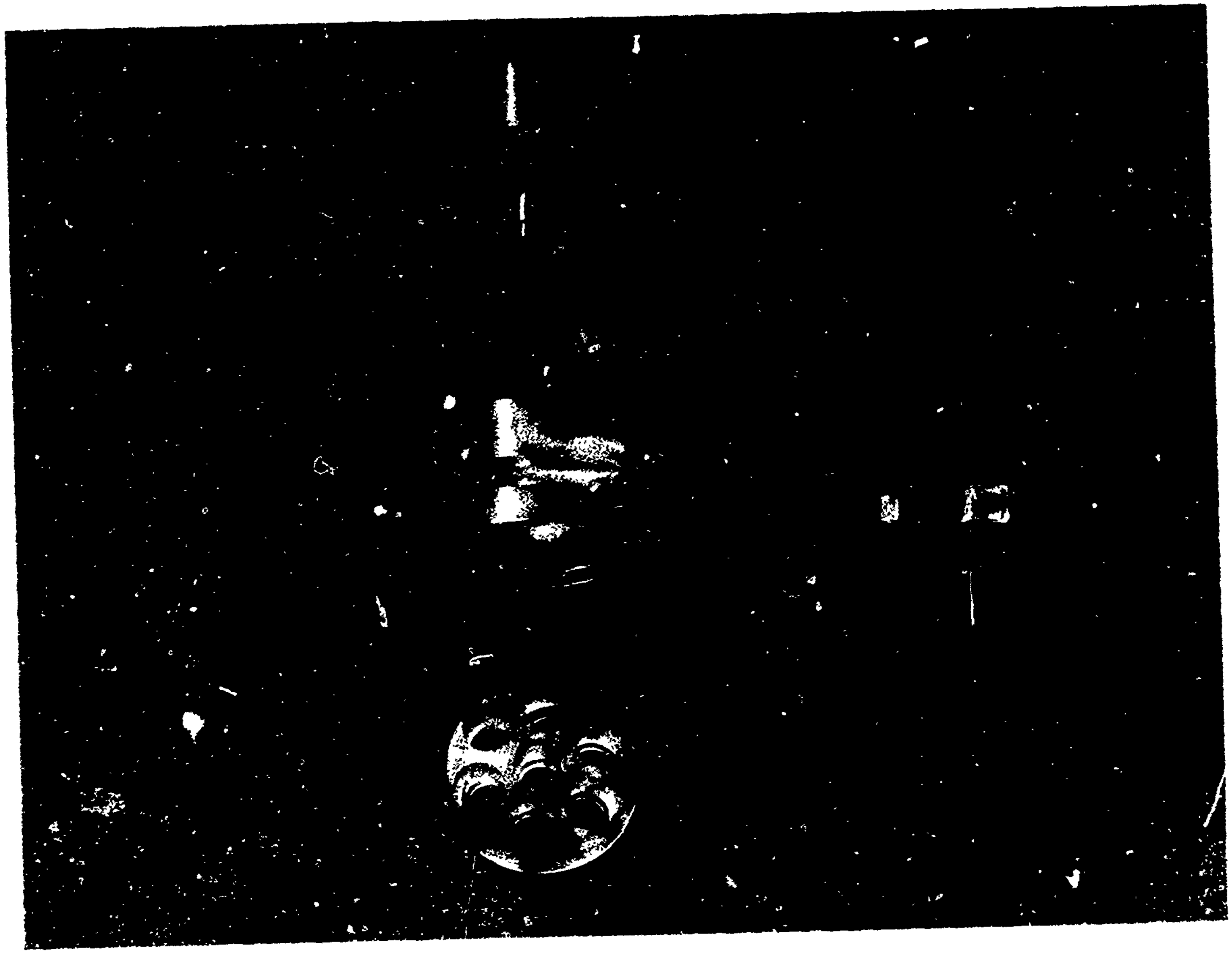


Figure 10. Photograph of Type I Capsule

The firing pin is made of steel and is retained in place by a spring. The firing pin is constrained to move in one direction only against the restraint of this spring and if an acceleration force $\geq$ 1.5 g's occurs in the direction of pin movement, the force of the spring will be exceeded and the firing pin will move, but as long as the firing train elements are out of line with the pin, the pin can strike the arming spool and no explosion will occur. However, if the firing train elements are in line with the pin, and the pin strikes with sufficient energy, the detonator will deflagrate and initiate the explosion.

The arming spool is held in its safe position either by the safety pin during handling, or by the walls of the feeder and drill stem while in the drilling rig. When the capsule exits from the drill stem at the bottom of the hole, the restraint of the arming spool ceases and the arming spring moves the spool to place the firing train in line with the firing pin. The capsule exits from the drill stem at a considerable velocity (estimated to be about 45 fps - see Section D). It traverses a distance of about one foot and impacts the bottom of the hole. This impact drives the firing pin down with sufficient energy to fire the detonator. The time required for the capsule to traverse the one foot from the drill rig to the bottom of the hole is about .022 seconds; therefore, the mass of the arming spool and the force of the spring driving it must be proportioned so that the firing train is in place before the firing pin moves. These mechanical elements were proportioned properly and the train frunctioned reliably in all tests.

The selection of the elements in the firing train and their acquisition was eventually resolved in the following manner. A M-55 detonator is employed which deflagrates when struck by the firing pin. This detonator has sufficient energy to detonate RDX or PETN high explosive if it is immediately adjacent to it. In the final design, RDX explosive was packed in the arming spool adjacent to the detonator. Initially C-4 explosive was tried but its sensitivity was too low to be detonated by the M-55 detonator. The RDX in the arming spool fires into a hole in the lower part of the capsule. The end of a piece of primacord which has been threaded through the shaped charges then knotted in the C-4 charge, is stuffed into this hole and transmits the detonation to the primary explosive charge. Initially a Mark 43 detonator was selected for use because of its high energy output. It detonated the C-4 explosive directly and simplified the train somewhat.

This unit was not immediately available and was expensive ($1.25 per unit) so alternate components were sought. Eventually the M-55 detonator was selected because it is economical ($0.06 per unit) and readily available.

The bulk explosive used in this program was C-4 because it is easy to handle and load. Some explosive energy is sacrificed because the explosive elements are diluted by the carrier or plasticizing material. In production quantities, a cast explosive such as Comp. B would be used.

Some problems were encountered with the reliability of the explosive train when a flexible explosive called Deta-sheet, made by DuPont, was substituted for the Primacord. It appeared that the plasticizer in the C-4 explosive and the Deta-sheet were not compatible and the Deta-sheet became soft. Deta-sheet was tried because it is more flexible than primacord and could be threaded with greater ease through the bases of the shaped charges. The problem was solved by reverting to primacord which apparently is not affected by the C-4 plasticizer. After this correction, the firing train functioned with complete reliability.

2. Explosive Charge Arrangements

As previously indicated, three (3) different style capsules were developed and classified as Types I, II and III. The Type I design utilizes seven small shaped charges containing 1.1 grams of explosive (see Figure 7). Six (6) of the shaped charges are arranged in a ring with their axes inclined 7-1/2 degrees from the longitudinal axis of the capsule. The seventh shaped charge is in the center of the cluster and mounted with no inclination. Approximately thirty (30) grams of C-4 explosive are packed around the shaped charges to provide additional explosive energy to shatter the rock and lift the spoils from the bottom of the hole. The firing train consists of an M-55 detonator and a few grains of RDX pressed into a spool. This fires into a piece of primacrod which is threaded through each of the shaped charges, then knotted in the center of the capsule with C-4 explosive packed around this knot and the shaped charges. Handling safety is maintained by moving the spool to position the detonator and its lead charge out-of-line with the remainder of the explosive train. It is secured in this position by a pin that is not removed until the capsule is in the feeder. After the capsule is in the feeder, the safety pin is removed but the out-of-line condition is maintained because the bore of the chamber will prevent movement of the spool. This bore-riding condition is maintained as long as the capsule is in the feeder and the stem of the auger. When it exits from the auger at the bottom of the bore hole, restraint of the spool is lost and a spring moves the detonator and its small lead charge in-line with the firing pin and the remainder of the firing train. When the capsule strikes the bottom of the bore hole, the firing pin is accelerated and moves to strike the detonator and the explosion is initiated.

All three capsules are similar except for the explosive charge. The Type II capsule contains three (3) shaped charges containing 3.7 grains of explosive. These shaped charges are also arranged in a circle but their axes are inclined 10-1/2 degrees with the longitudinal axis of the capsule. The firing train is similar to that described for the seven (7) jet capsule. It also contains 30 to 35 grams of C-4 explosive. The Type III capsule is packed with about 30 grams of C-4 explosive only; otherwise, it is similar in design to the Type I and II capsules.

The capsules were machined from polystyrene plastic material. This material was chosen because it had good fragmentation properties, is very easy to mold, and is one of the most economical of materials. The fragmentation properties were important because it is necessary that the capsule break up into small pieces so that it becomes part of the spoils and will be flushed from the hole along with the other spoils. The moldability and cost of the material were important because large quantities of capsules will be required if this approach becomes operational. The material does not machine well and tends to crack and craze, but this problem would be avoided if the capsules were molded according to the plans envisioned for quantity production.

The current configuration of the capsules are such that they can be molded in molds having a moderate amount of sophistication. No effort was made to production design the system and there is no question that with some effort of this type, the designs can be made highly producible. In fact, in succeeding discussions, a design for a multi-jet shaped charge capsule is presented that would be highly producible.

The canting of the shaped charges in the Types I and II capsules is an attempt to widen the fragmentation zone reached by the jets. The inclusion of a small ball charge in the shaped charge capsules was to increase the diameter of the fragmentation zone and help the flushing of the spoils from the bottom of the hole. A small standoff, normally about one (1) shaped charge diameter, is desirable to achieve the best efficiency from a shaped charge. A design constraint was encountered due to the desire to work within the 2-1/2 inch inside diameter of the hollow stem auger and to use a simple feeder such as described in the following section. The desired standoff was attained in the seven-jet design but only 1/2 the usual value was possible in the three-jet unit. Both units functioned well and the loss of standoff in the three-jet unit did not appear to be critical.

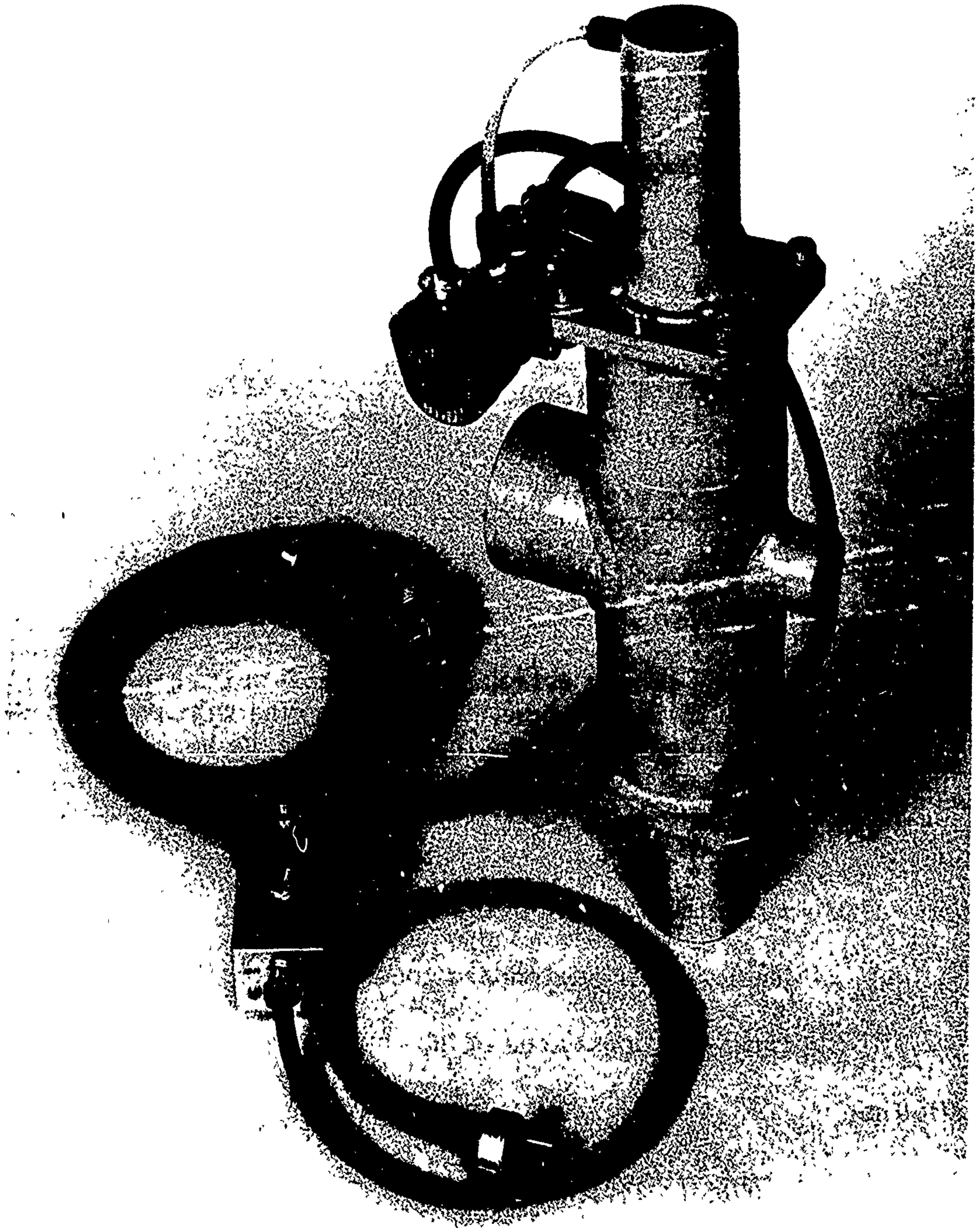
D. Feeder Provisions

A feeder mechanism was designed and fabricated that provided the means of introducing the capsules into the bore hole. A view of the mechanism is shown in Figure 11. It is also shown installed on the test rig in Figure 5.

The feeder consists of a cylindrical housing which contains an internal shuttle piece that is moved back and forth by an air cylinder. The shuttle provides two cylindrical cavities, each sized to accept an explosive capsule. When one cavity is in position to accept a capsule, the other is positioned over the top of the feeder tube. A capsule is introduced into the open cavity and the safety pin in the arming mechanism removed. A solenoid valve is then actuated and compressed air metered to the air cylinder to move the newly loaded capsule to the feeder tube position. When the capsule arrives at this position, it blocks the flow of the compressed air into the feeder tube and pressure builds up to drive the capsule down through the tube. This movement of the loaded capsule to the feeder tube position exposes the other shuttle cavity so another capsule can be introduced. The shuttle may then be stroked back to the original position and in this manner a continuous supply of capsules is supplied to the bore hole.

The feeder tube is connected to the continuous supply of air from the compressor. Air is tapped from this supply just before it enters the feeder tube and in order for the cylinder to generate sufficient force to stroke the feeder, the pressure should be at or near the 100 psi supply pressure of the compressor. To maintain this pressure and also limit the size of the compressor, a washer with a drilled hole 5/16 inch in diameter was placed in the fitting where the supply line connects to the feeder. This creates an orifice through which the air must flow to enter the feeder tube. The flow through this orifice can be predicted (Reference 6) by the following expression:

$$C_o A = \frac{M \sqrt{T}}{0.528 P}$$



VIEW OF CAPSULE FEEDER MECHANISM

FIGURE 11

where: A = orifice area = 5.33×10^{-4} ft^2

$P = 1.64 \times 10^4$ psi - absolute

T = air temperature - degrees rankine = $530^\circ R$

M = mass flow - lbs/sec.

C_o = coefficient of discharge = .60

Rearranging terms and substituting:

$$M = \frac{(0.528)(1.64 \times 10^4)(5.33 \times 10^{-4})(.60)}{\sqrt{530}}$$

$$= .119 \text{ lbs/sec.}$$

This mass flow may be used to calculate the velocity of the air through the 2-1/2 inch opening in the feeder tube. This is also the velocity at which the capsule will be pushed through the tube and enter the bore hole.

$$V = \frac{M}{\rho S}$$

where: V = velocity of the air in the tube - ft/sec.

ρ = density of air at standard conditions - lbs/ft^3 = .0765

S = cross-sectional area of tube opening = .0341 ft^2

Substituting:

$$V = \frac{.119}{(.0765)(.0341)}$$

$$= 45 \text{ fps}$$

The required compressor capacity can also be determined from this information:

$$C = V \times A$$

$$= (45)(.0341)(60)$$

$$= 92 \text{ CFM}$$

A 125 CFM compressor was used in the experiments.

E. Drill Rig Configuration

For the drilling experiments, it was planned to investigate a combined pneumatic-mechanical method of removing the spoils. To implement this approach, a truck mounted drill, Model B-30, was rented from the Mobile Drilling Company. This firm also furnished a hollow stem auger that has an opening through the stem that is 2-1/2 inches in diameter. An auger having flights 6-1/2 inches O.D. was chosen for the experiments.

A number of modifications to the B-30 drill were required to make it suitable for the explosive drilling experiments. First, a mount was made that positioned the shuttle-type feeder over the drill head and held it stationary. A rotary joint was designed and the stationary part was attached to the feeder. A rod extension was attached to the movable part of the rotary joint which extended through the drill head and nested against the top of the hollow stem auger. A special adapter was designed that attached the hollow stem auger to the drill head. This arrangement allowed the capsule feeder to stand stationary but all other parts rotated with the auger. A smooth hole 2-1/2 inches in diameter was provided by this arrangement for passage of the capsules all the way from the feeder to the bottom of the bore hole. Details of this arrangement are illustrated in Figures 4 and 5.

The capsule feeder allows a capsule to be inserted; then, from a remote location through the medium of a solenoid-operated valve and compressed air, the piston in the feeder is moved to position the capsule over the top of the 2-1/2 inch hole in the hollow stem auger. Compressed air flowing through this tube catches the capsule and drives it through the hollow stem auger into the bore hole.

The auger is rotated and located vertically by the feed and drive mechanisms of the drill rig. The auger is used to remove the overburden and rock that is soft enough to drill by this method. When hard rock is encountered the hole is cased with the 7-1/2 inch O. D. steel pipe. The flights of the auger rotate inside this pipe and convey to the surface the spoils that the air and explosions raise from the bottom of the hole.

F. Development Tests

A number of development tests were run to examine the functional properties of the feeder and perfect the design of the capsules prior to manufacturing the capsules for the explosive drilling experiments. The following is an account of this experience.

1. Test Fixture

A static test fixture was designed and fabricated and installed in an explosive test area for testing the feeder and capsules. The capsules were exploded on the surface by mounting the feeder on a scaffold and attaching a 10 foot length of tube that simulated the hollow stem of the auger. Photographs of this arrangement are shown in Figures 12 and 13.

2. Test Experience

The feeder, after adjustment of the valves and plumbing, functioned satisfactorily. Occasionally the feeder would stick and fail to cycle the piston. This was caused by friction which was higher than expected and could have been corrected by installing a larger air cylinder. The trouble was not serious enough to warrant this change so the program was conducted without making this correction.

In the original designs a valve was incorporated at the foot of the drill stem that remained closed except when a capsule passed through and forced the valve to open. This maintained pressure inside the drill stem and conserved the flow of air. Also, the air escaping from the higher pressure region inside the tube to the ambient pressure in the bore hole would gain considerable velocity and eject the capsule at high speed.

The valve functioned satisfactorily in the static tests but there was concern that it would be damaged by the explosions in the confines of the bore hole. The idea was conceived of regulating the pressure and flow rate with a simple orifice as previously described in Section D. This

Figure 12. Feeder Installation on Test Stand

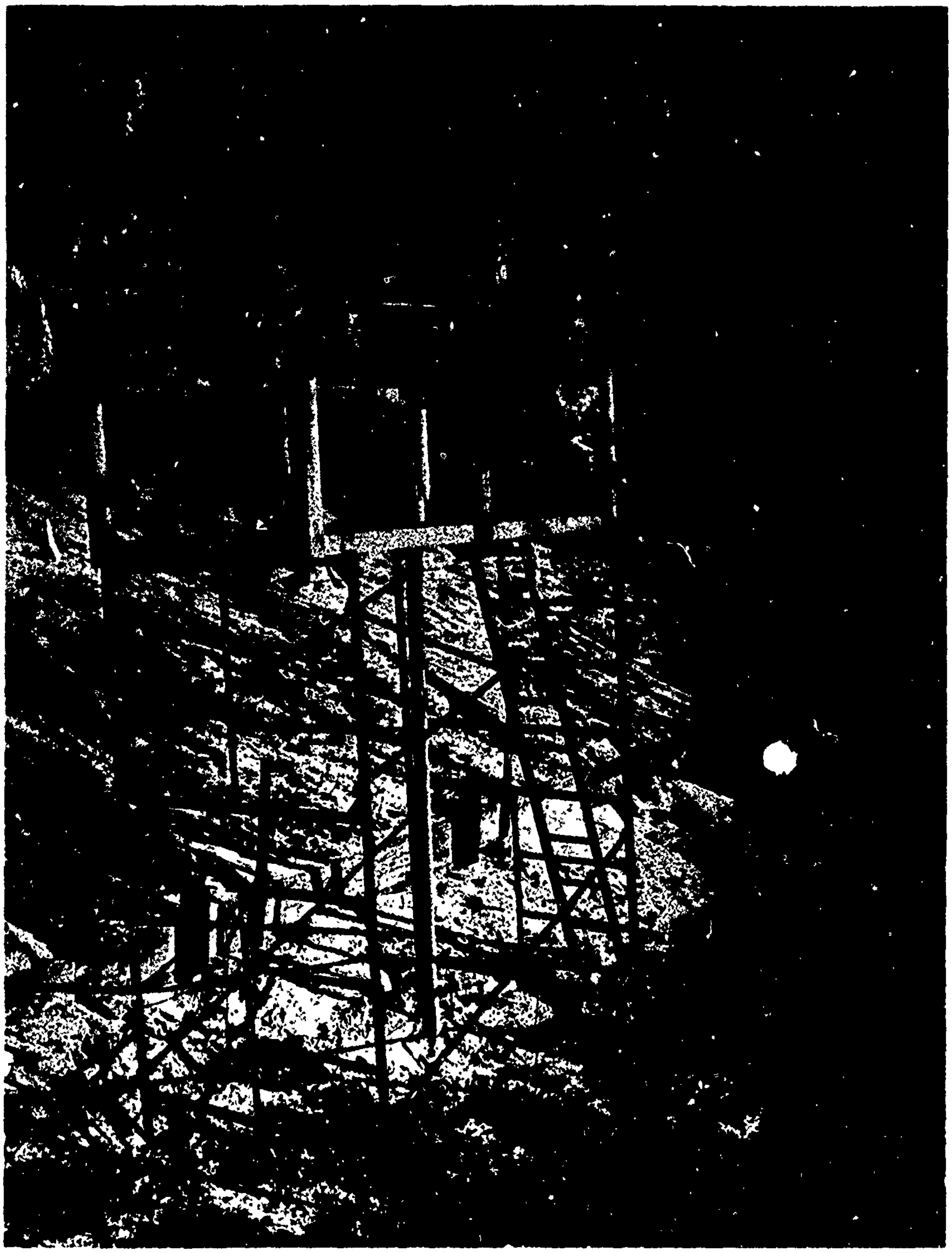


Figure 13. View of Static Test Stand Installation

was tested and found to be satisfactory so the foot valve arrangement was abandoned. This simplified the equipment a great deal and makes it possible to provide a rugged end at the foot of the tube that will withstand a battering from the explosions.

The dynamics associated with the functioning of the firing train proved to be satisfactory. This concerns the movement of the spool to place the detonator in line with the firing pin in the few milliseconds of time it takes the capsule to traverse the space from the end of the drill rod to the bottom of the bore hole. Also there must be sufficient energy in the firing pin to function the detonator. One-hundred percent performance was experienced in this portion of the capsule design.

Some troubles were encountered with the firing train when it was decided to use M-55 detonators to initiate the explosion.. Mark 43 detonators with considerable output energy were originally used. They would explode the C-4 explosive directly but the M-55 units did not have sufficient output. It was found that the M-55 would initiate the purer explosives such as RDX and PETN if it was in close proximity to the detonator. It was necessary to pack these purer explosives in the spool cavity next to the M-55 unit. When this arrangement was provided, the explosive train functioned satisfactorily.

The capsules functioned satisfactorily once the detonator troubles were resolved. Some configuration changes in the method of retaining the shaped charges were recognized that obviously would improve the capsule design. These changes were incorporated in the capsule designs before fabrication for the explosive drilling experiments. These changes also provided space in the capsules to include some C-4 explosive in addition to the shaped charges.

G. Explosive Drilling Experiments

A set of experiments was planned to evaluate a number of features of the particular explosive drilling approach outlined in the preceeding sections. Specifically it was planned to evaluate: 1) the effectiveness of the proposed scheme for introducing the explosive capsules into the bore hole; 2) the functional suitability of the explosive train and a plastic capsule; 3) the capabilities and differences of the three capsule designs; 4) the ability of explosive drilling to advance a drilled hole from both a qualitative and quantitative viewpoint; and 5) the ability to remove spoils by proposed pneumatic-mechanical approach.

The site chosen for the experiments was on company property adjacent to an abandoned limestone quarry. The rock formation lay under an overburden of three (3) to four (4) feet of soil. Three holes were augered through the overburden and casings were inserted in the holes. Figure 4 shows the casing in one of these holes with the auger of the drill rig lowered into the casing.

All the experimental equipment functioned as designed. A few debugging problems were encountered, but once these were corrected the equipment functioned as envisioned. The most troublesome problem was the explosive train in the capsules. In order to ease an assembly problem in the two shaped-charge capsules, Deta-sheet was substituted for Primacord after a preliminary experiment indicated this substitution was satisfactory. Several of the capsules failed to function. This was finally traced back to the use of the Deta-sheet for apparently it had been desensitized by the plasticizer elements in the C-4 explosive. Once Prima-cord was put back into the train, excellent reliability was obtained.

The experiments began using the three (3) jet Type II capsule. Over a period of a few days a total of eighteen (18) of these capsules were exploded in the hole. These experiments were discontinued at this point and the program plan adjusted. Poor penetration was being experienced and it appeared evident that it was due to the weak nature of the rock structure. It was decided to redirect the experiments and expend a number of capsules on hard rock. A good grade granite slab was obtained that measured 5 feet by 4 feet by 8 inches thick, and a series of experiments were performed on the static test stand shown in Figure 14. These experiments were successful in demonstrating the penetration power of the explosive technique in hard rock structure.

Details of the experimental program and its results are described in the following section.

1. Down-the-Hole Experiments

Eighteen (18) of the three jet, Type II capsules were exploded in the bore hole shown in Figure 4. These experiments were interrupted between the 16th and 17th trials to check the effectiveness of the jet formation. The details of this series of tests are described in sequential order of occurrence.

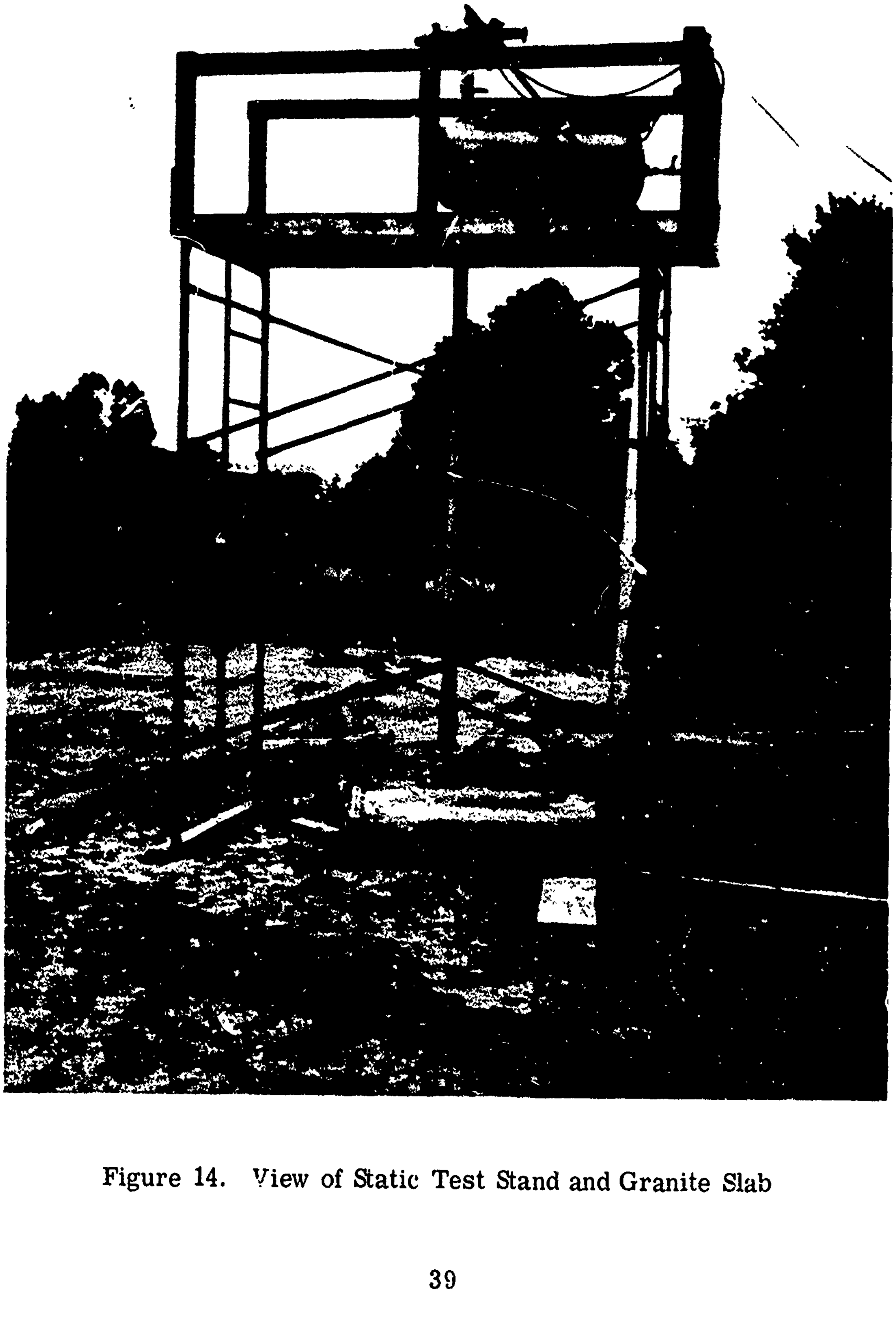


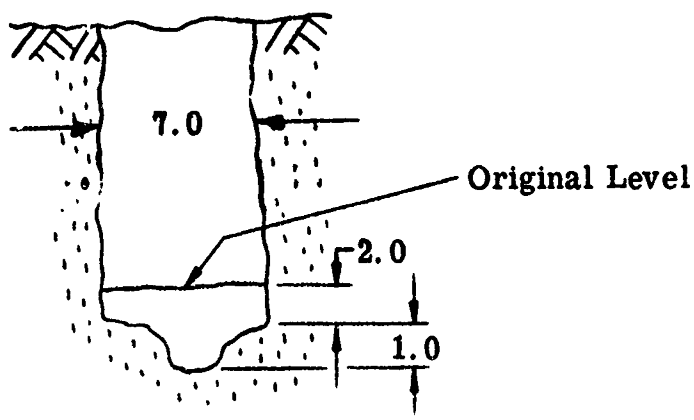
Figure 14. View of Static Test Stand and Granite Slab

Shot No. 1 - A considerable quantity of spoils, mostly soil, that had collected in the bottom of the hole was found in the flights of the auger. The hole deepened about 1.0 inch.

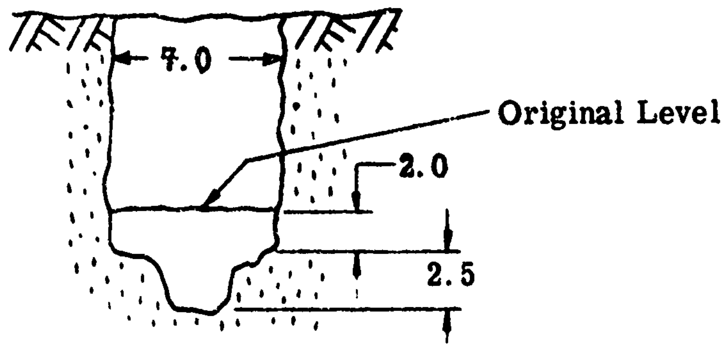
Shot No. 2 - Two no-fire capsules occurred between the No. 1 and No. 2 shots and the hole had collected considerable dirt. This shot cleared the hole of most of this loose soil and about one (1) quart of earth was found in the flights of the auger.

Shot No. 3 - Two no-fire capsules occurred between shots 2 and 3 and this shot served again to clear the collected debris.

Shot No. 4 - The hole had approximately the following form following this shot:

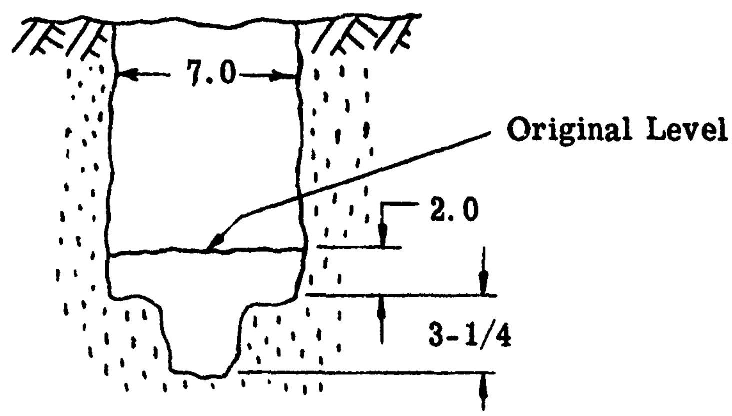


Shots No. 5 & 6 - The hole had deepened slightly after these shots. The additional spoils on the flights of the auger had diminished noticeably. The hole had the following approximate shape.



Shots No. 7 & 8 - The penetration was much less than expected so a search for a reason began. The bottom face of the capsule was taped to prevent any chance of dirt filling the jet holes when the capsule struck the bottom of the hole. This could prevent the effective formation of the jets. This, however, had no noticeable effect on performance.

Shots 9, 10 & 11 - Returned to original capsule configuration but hole deepened very little. After these shots the hole had the following approximate form:



Shots 12 & 13 - Lowered the auger to reduce the stand-off from the bottom of the hole to eight (8) inches. No measurable deepening detected following these shots.

Shots 14 & 15 - Cleaned the bottom of all debris before each of these shots. Had no measureable effect in deepening the hole.

Shot No. 16 - Removed C-4 from the capsule. Had no measureable effect on performance.

The experiments were interrupted here to check the performance of the capsules against aluminum witness plates. No evidence could be observed by visually examining the bottom of the hole that the jets were being formed by the shaped charges. To check this, units of both the Type I and Type II capsules were exploded against a 3/8" thick aluminum plate in an above-ground test. These tests indicated excellent jet formation as shown in the photographs of Figures 15 and 16. To be sure that equivalent performance was occurring in the bore hole, an aluminum plate was placed at the bottom of the bore hole and a Type II capsule produced the results shown

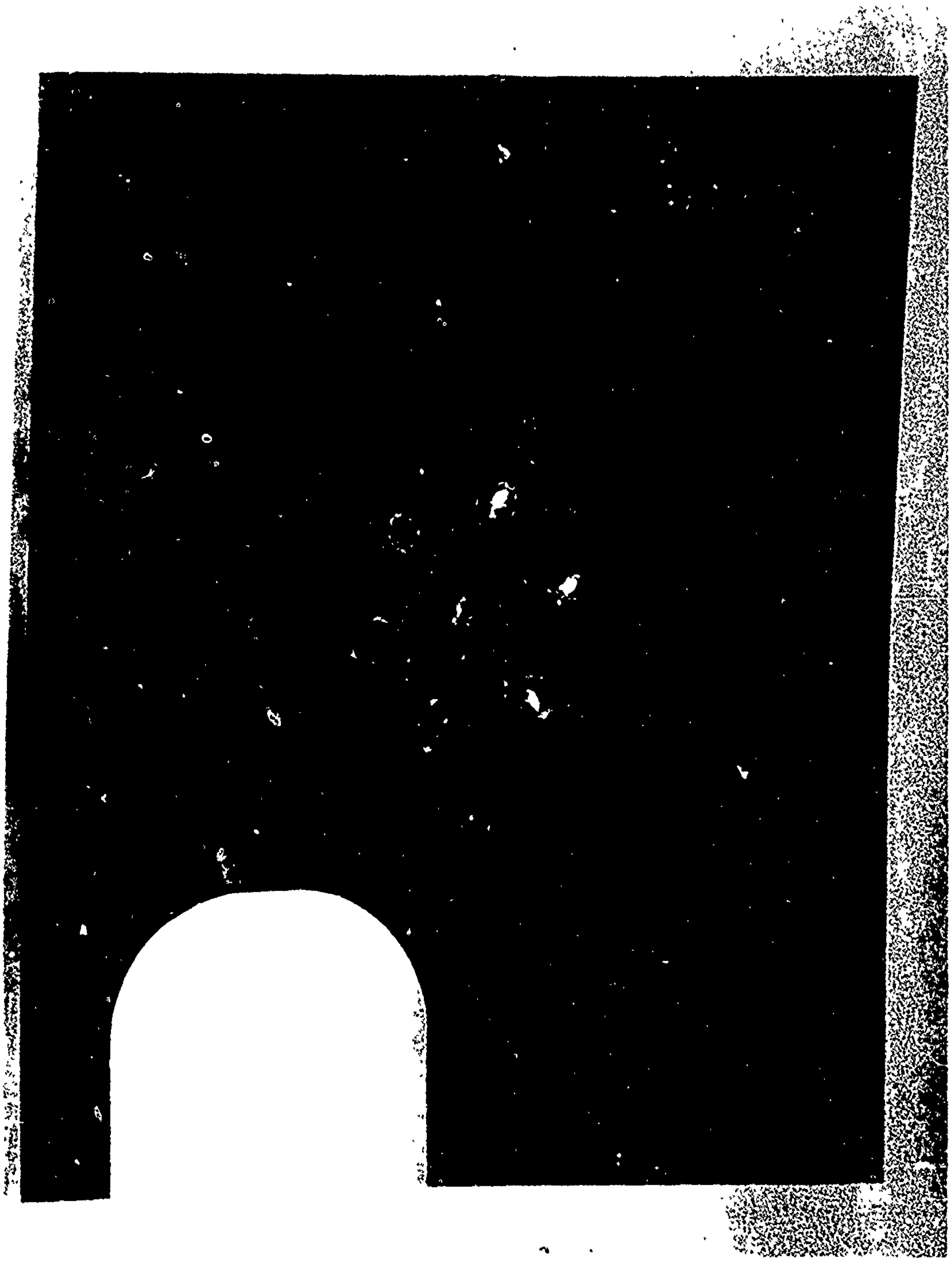


Figure 15. Witness Plate Penetration
With Type I Capsule

Figure 16. Witness Plate Penetration With Type II Capsule

in Figure 17. These results indicated that the capsules were performing properly so the shots were resumed.

Shot No. 17 - Removed considerable soil from the hole and deepened it to its former level. Careful probing revealed the presence of jet formed holes in the bottom of the hole. They had filled with loose dirt and were not detectable by visual inspection.

Shot No. 18 - No measurable deepening occurred. The rock formation was very poor quality and the spoils that were removed could be crumbled by hand with very little effort. It was concluded that the failure of explosive drilling to penetrate was due to the poor structure of the rock. Actually this rock could be removed by drilling with the auger at a fairly high rate. Apparently the rock yields under the effects of the explosion rather than shatter and very little progress was realized. It was anticipated that the process would be much more effective if the rock structure were hard. To check this theory, a block of hard granite was obtained and a group of experiments was conducted above ground in the static test stand shown in Figure 14. The results of this series of experiments is reported as follows.

2. Hard Rock Experiments

Series No. 1 - The first test series was conducted using the Type I or seven-jet capsule. Nine (9) shots were required to drill a clean hole 2-3/4 inches in diameter through the center of the granite block. A photograph of this hole is shown in Figure 18 and the shot-by-shot progress is illustrated in Figure 19. The lower half of the hole sheared out on the ninth shot. Shearing in this manner was anticipated because of the finite thickness of the slab, but before this occurred, measurements were obtained that provides some quantitative data on the penetration of hard rock with this style capsule. If the sheared out lower chunk is not included, the average quantity of stone removed is approximately 2.55 cc/gram of explosive. The 2-1/2" diameter hole began to form with the third shot so, disregarding the stone removed by the first two shots, the average quantity of stone removed was 1.14 cc/gram of explosive which is indicative of the true down-the-hole capability of this style capsule.

Figure 17. Witness Plate Penetration
Type II Capsule in Bore Hole

Figure 18. View of Drilled Hole in Granite Slab

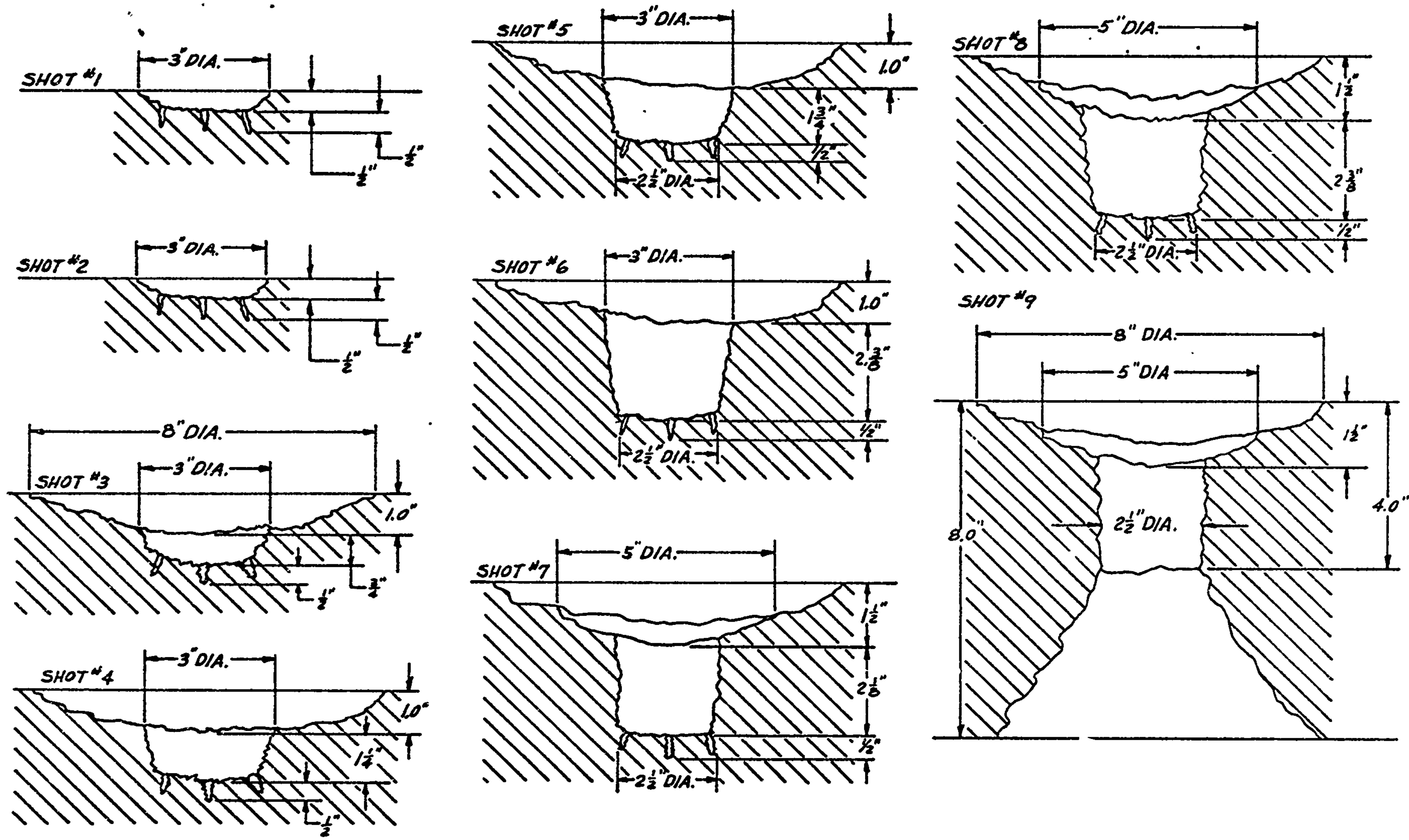


Figure 19. Shot-by-Shot Progress of Drilled Hole

Series No. 2 - This series was a repeat of the first series using the Type I seven-jet capsule. Progress was comparable to the experience of the No. 1 series but unfortunately the slab began to crack apart with the fourth shot and broke badly with the sixth shot so that complete development of the hole was not accomplished. A shot-by-shot photographic record of this series was made and is shown in Figures 20 through 26. The penetration of the jets from the shaped charges is clearly seen in these photographs. Also the beginning of a hole about 2-1/2 inches in diameter can be seen with the third shot. There is a clear indication that a clean hole similar to that obtained from the first series would have been obtained if the crack in the slab had not occurred.

Series No. 3 - This series employed the Type II capsule which is designed around three 3.7 gram shaped charges. Unfortunately the only locations available on the slab to drill were near the edge and a crack developed with the second shot and a large split was created with the third shot. A photographic record of shots 1 and 2 is shown in Figures 27 and 28. The beginning of a hole is clearly evident but the early splitting of the slab prevented the acquisition of reliable quantitative data on the penetration power of this capsule.

Series No. 4 - This was a repeat of Series No. 3 using a Type II capsule. The results were the same as the previous series with a crack starting with the second shot and a bad split occurring with the third.

Series No. 5 - A repeat of series No. 3 and 4 was attempted at a new location but a crack appeared with the first shot and a split with the second shot.

The experiments were terminated because the slab no longer presented a sound area for drilling. The limitations of experimenting with rock having finite dimensions such as this granite slab is typical of the experience reported by Robinson and others. Extensive in-situ formations are the only thoroughly satisfactory sites to conduct experiments of this type. No known site such as this was available in the area; therefore, experimentation was terminated.

This series of experiments did show that the technique is effective in removing hard rock in an efficient manner and some quantitative information was obtained.

Figure 20. Penetration of Shot No. 1
Type I Capsule

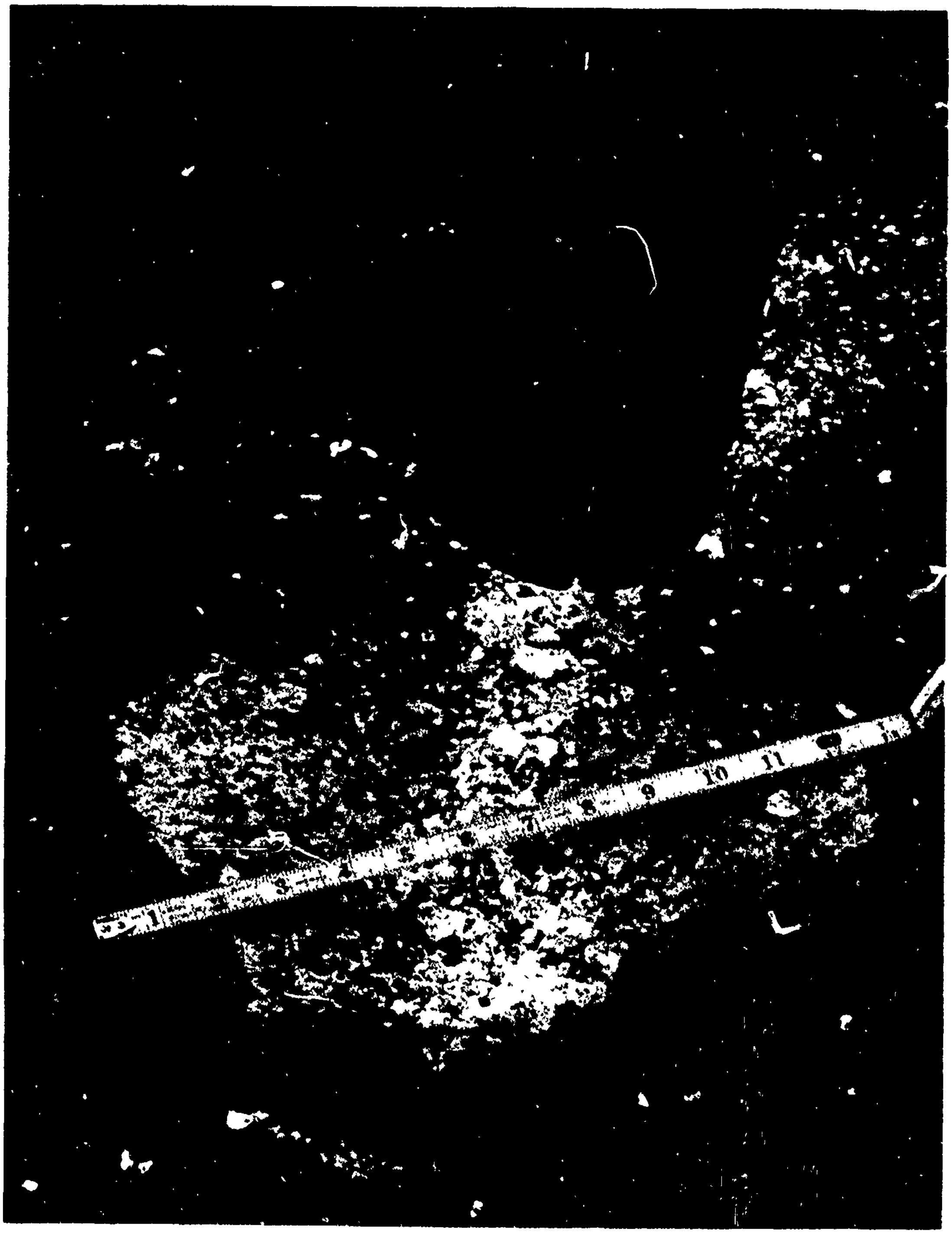


Figure 21. Penetration After Shot No. 2
Type I Capsule

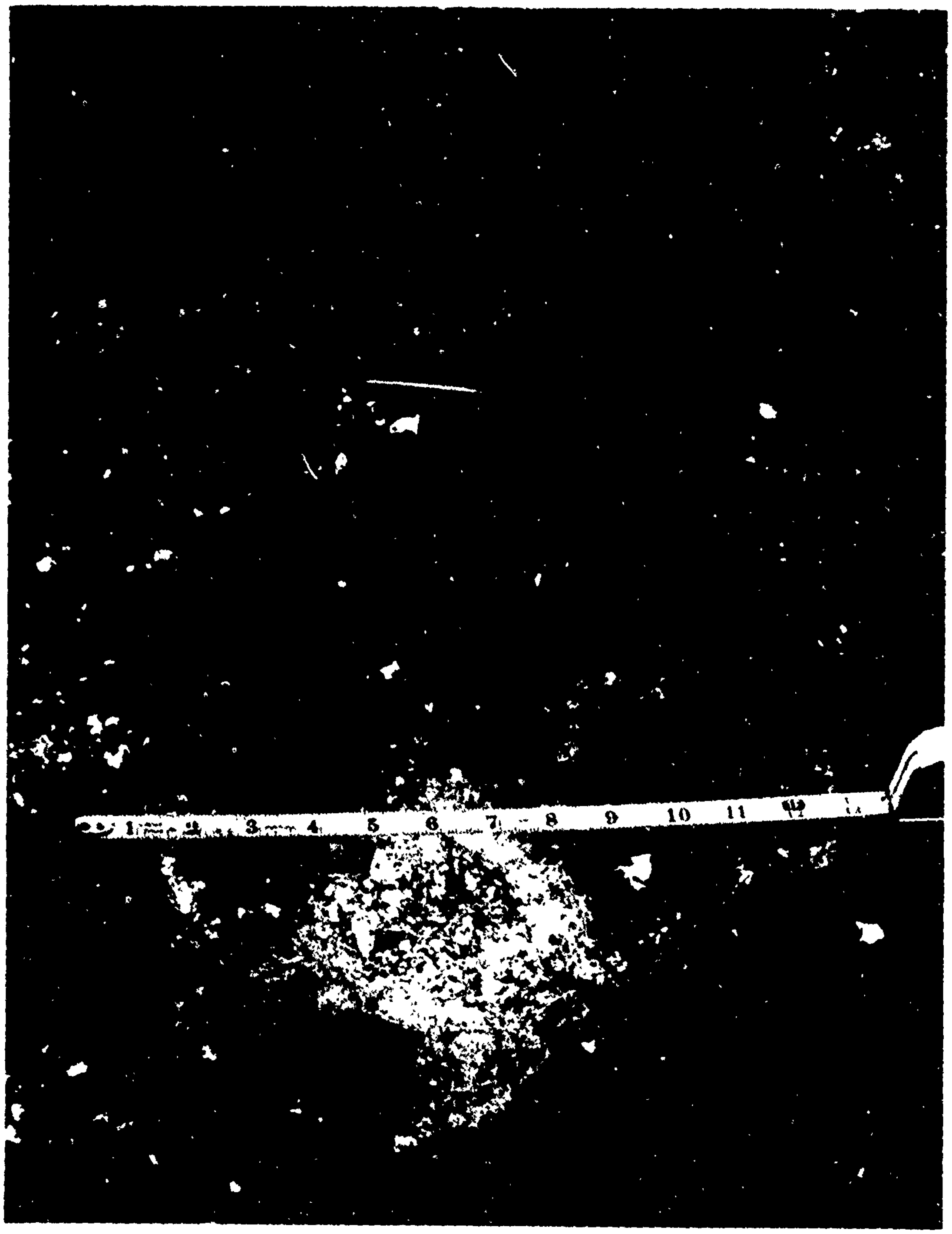


Figure 22. Penetration After Shot No. 3
Type I Capsule

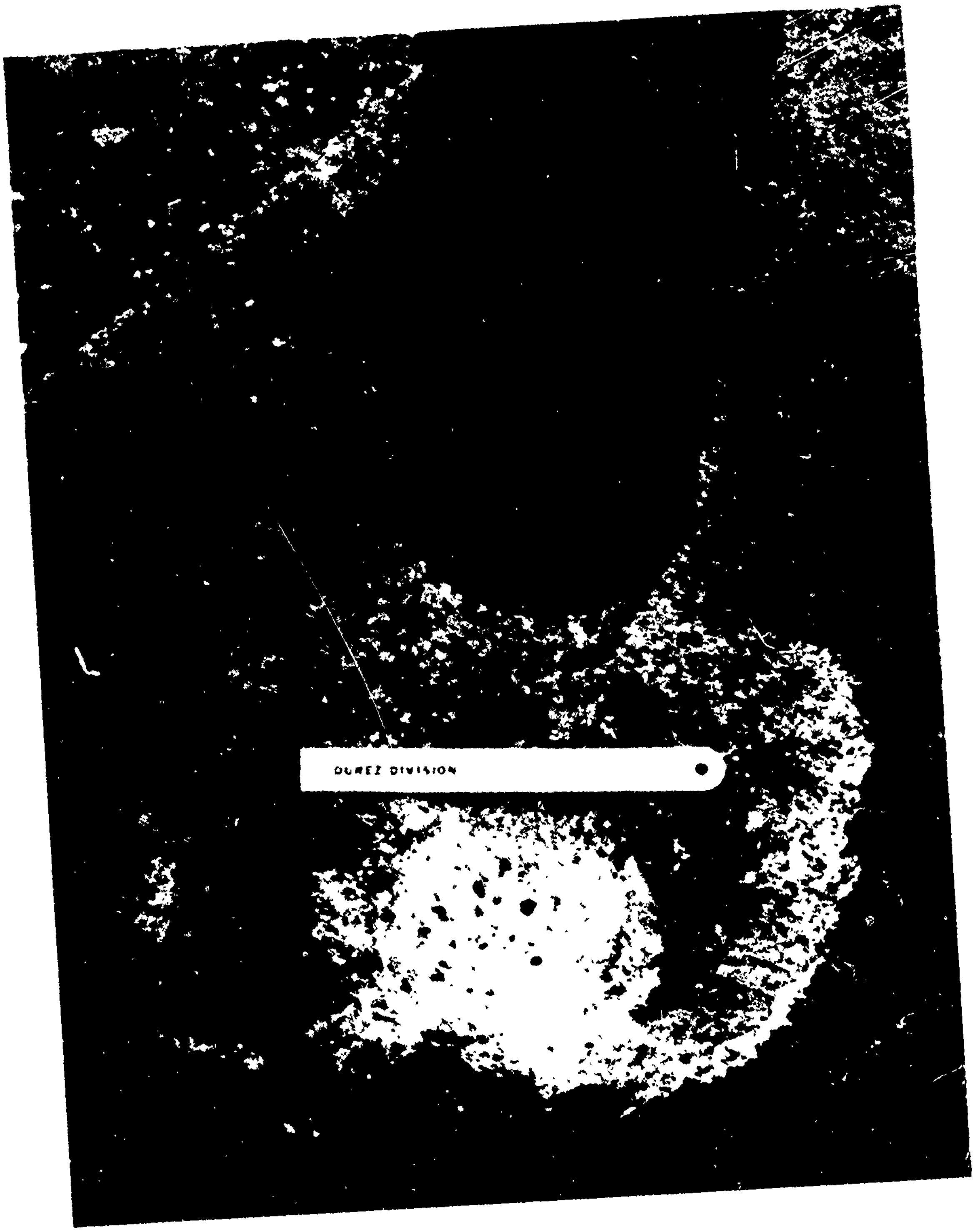


Figure 23. Penetration After Shot No. 4
Type I Capsule

Figure 24. Penetration After Shot No. 5
Type I Capsule

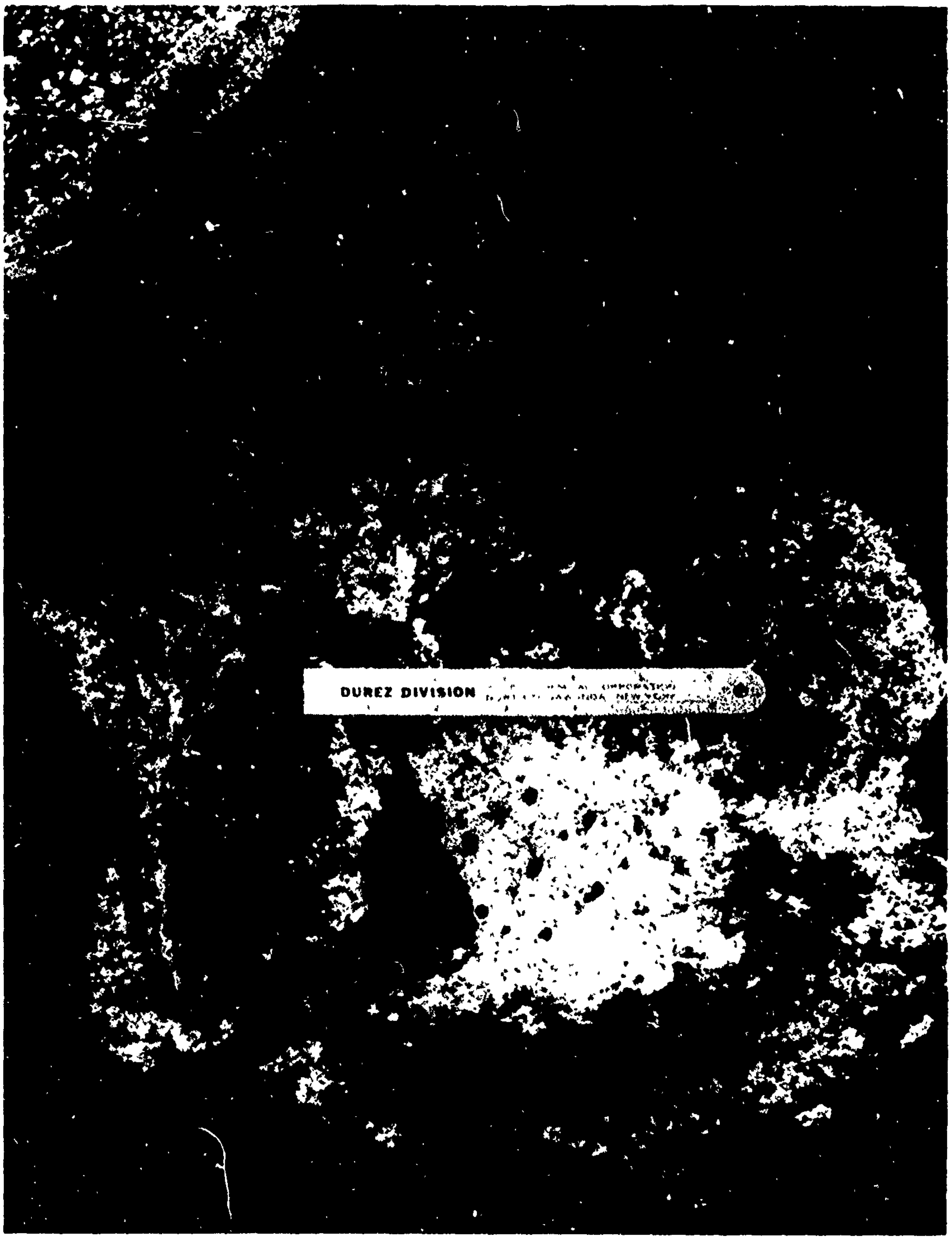


Figure 25. Penetration After Shot No. 6
Type I Capsule

Figure 26. Fractured Slab After Shot No. 7
Type I Capsule

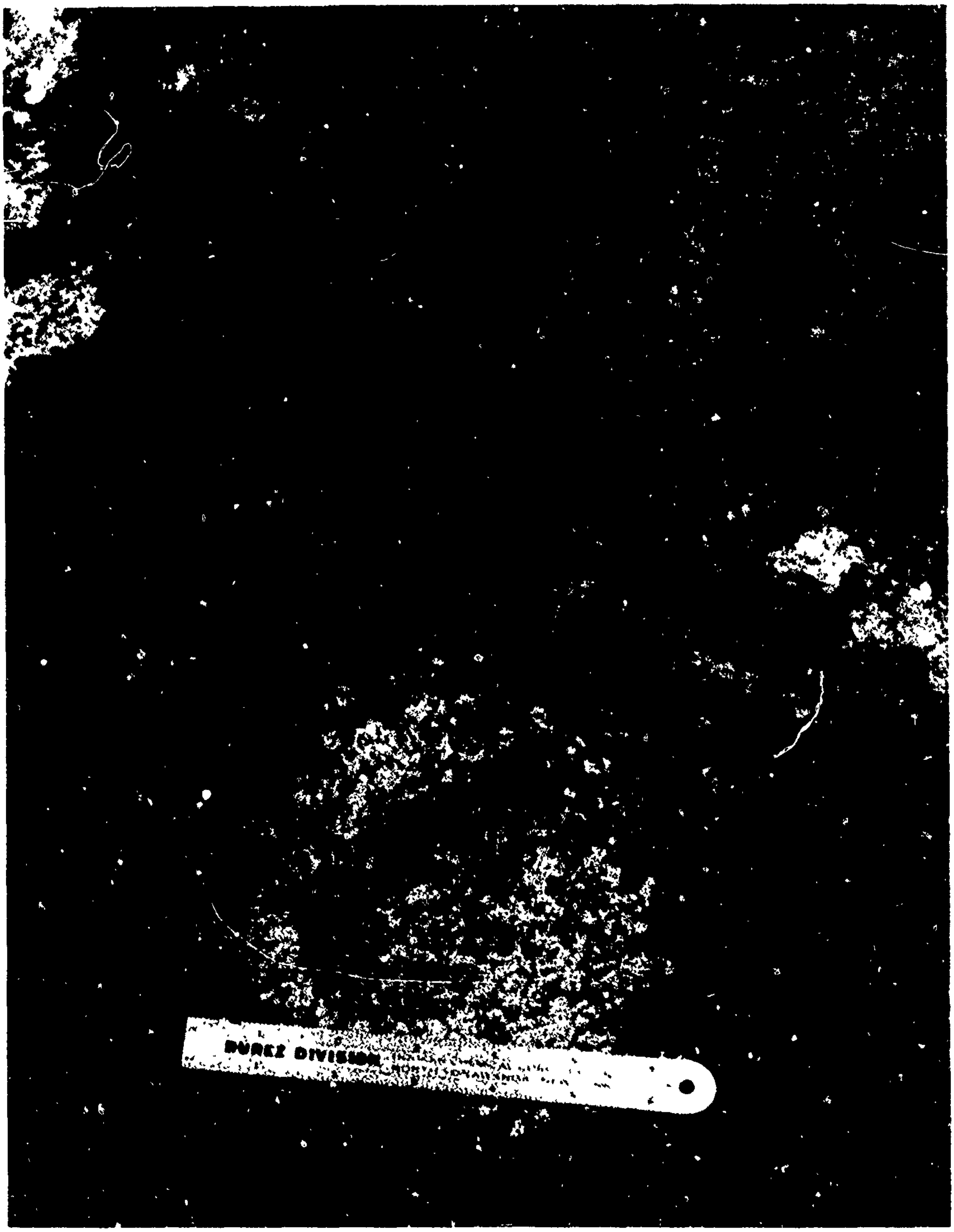


Figure 27. Penetration After Shot No. 1
Type II Capsule

Figure 28. Damage After Shot No. 2
Type II Capsule

DISCUSSION

The program fell short of some of its objectives primarily because the drilling site proved to be unsuitable. Before the drilling experiments began it appeared that the choice of sites, with the rock covered with a few feet of overburden, would be ideal. The unforeseen factor was the quality of the rock. There is ample evidence that the down-the-hole experiments failed to advance the hole because the quality of the rock was so poor that the explosive energy was absorbed and very poor penetration was realized. Using rock-cutting tips on the drill head, the rock could have been drilled at a substantial rate with the auger equipment alone.

The above ground experiments on the granite block demonstrated that explosive drilling can be effective in drilling hard rock. Unfortunately, these experiments were limited due to fracturing of the block and precluded a comparative evaluation of the effectiveness of the different capsule designs. Clearly, the most disappointing factor in the program was the lack of a suitable test site and, in any future efforts, a test site providing large in-situ formations of quality rock covered with some overburden must be located. Preferably the type of rock should vary to widen the scope of the experiments, and if this variation cannot be found in a single locality, then testing at different localities must be considered.

The only hole that was drilled completely through the granite block before break-up began was drilled with the Type I, seven-jet capsule. Examination of the step-by-step photographs, Figures 20 through 26, indicates this capsule was functioning in a manner anticipated. The shaped charges were piercing the rock ahead of the hole and each capsule explosion shattered a considerable portion of rock in the zone that had been pierced by the previous explosion. The particle size of the shattered rock was rather small, indicating that the explosions will break the rock fine enough to bring the spoils to the surface with air or drilling mud. Whether or not they are so fine that they would run downward through the flights of the auger and inhibit the mechanical spoils removal scheme could not be determined. The quantity of rock removed per unit of explosive was about 1.14 cc/gram which is in fair agreement with the experience of other experimenters who have reported results on drilling in air (references 1 and 3). This result was disappointing, for other experimenters had employed ball charges and it was anticipated that using the explosives in the form of shaped charges would improve the efficiency and bring the fragmentation rate in line with a ball charge operating under water. This experience, however, is by no means conclusive for a number of reasons, and the concept of obtaining good efficiency using shaped charges may well be sound. First, the quantity of bulk C-4 explosive in the capsule compared to the explosives in the shaped charges was at a ratio of about 4/1. It may be that this ratio is much too high for optimum efficiency. If the bulk explosive is not very effective, its reduction or possible elimination would improve the efficiency perceptibly. Second, nothing was learned on optimizing the size of the shaped charges. It had been planned to explore this factor in a limited way with the two shaped charge capsule designs, but the lack of suitable rock for drilling prevented these experiments. Third, the configuration of the shaped charges in the capsule needs additional study to increase the diameter of the fracture zone. The need for attention to this facet of the design was evidenced by the size and nature of the hole drilled in the granite block. The hole was straight and round but its diameter was only slightly larger than the capsule. This seems to indicate that the inclination of the outer ring of jets should be increased to enlarge the diameter of the fracture zone. Further investigation of employing shaped charges in the capsules appears to be justified.

Efforts concentrated in the areas listed above are certain to advance performance beyond that experienced in these preliminary tests. The degree of improvement that can be realized should be determined before considering abandoning the air-filled hole approach in favor of a wet process.

The proposed pneumatic-mechanical method of spoils removal could not be evaluated because of the poor penetration rate experienced in the down-the-hole experiments. There were some indications that the scheme might function satisfactorily, for in the initial explosions where there was a considerable quantity of loose material in the bottom of the hole, the explosives raised the loose material well up into flights of the auger. As much as a quart of spoils were collected from the flights of the auger after some of the initial explosions. The scheme affords so many advantages for ADM if it is found to function satisfactorily that it should be fully evaluated under realistic drilling conditions.

The method of introducing the capsules into the bore hole was evaluated sufficiently to indicate that the approach is sound. When the feeder moved a capsule into place over the 2-1/2 inch opening in the hollow stem auger, the compressed air caught it and moved it down the tube at a considerable rate. This velocity was not measured but it was assumed to be approximately equal to the 45 fps average flow rate of the compressed air. In future experiments this velocity could be measured without great difficulty.

The capsules were ejected from the bottom of the tube in the proper attitude and at sufficient velocity to function reliably when they impacted the bottom of the hole. Some duding was experienced during the experiments, but as previously explained, this was traced to the sensitivity of the explosives and was not the fault of mechanical elements. The feeder used in this program was simple and required manual loading and control. It is easy to envision an automatic or semiautomatic feeder utilizing the same principle of capsule feeding. The shuttle arrangement could be replaced with a rotary mechanism that functions like the rotating chambers of a revolver. The empty chambers would be replenished with capsules by automatic means so that a continuous high capacity method of introducing the capsules to the bore hole would result.

The choice of polystyrene for the capsule material appeared to be sound. The material fragments well and breaks into particles small and light enough to be removed from the hole along with the other spoils. This material is among the most economical class of plastics and is easy to mold. It does have a tendency to crack and craze and has poor dimensional stability when machined. This was the source of some trouble in this program but these troubles should disappear when fabricated in production quantities by molding.

The mechanical features of the firing train including the safety arrangements functioned satisfactorily throughout the program. The explosive elements, after some debugging, also performed properly and the capsules in their finalized version were completely reliable.

Safety in any device containing high explosives is extremely important. The capsules used in this program have only a single safety; namely, the out-of-line arrangement of the firing train. It is recognized that a second safety that operated from some event in the loading or injection sequence would be desirable. In ammunition, set-back accelerations or spin, or both, are commonly used to control the safety measures. There are some set-back accelerations involved in the injection process that might be used. This matter should receive attention in any further development effort on the capsule.

A multi-jet shaped charge fabricated in a single unit as opposed to the multi-unit arrangement employed in this program should receive serious attention in any future effort.

A proposed configuration for a capsule of this type is shown in Figure 29. This configuration was conceived and the feasibility of the approach established on another company program. It has been clearly demonstrated on this program that effective jets can be generated from a single explosive charge configured in a manner shown in the sketch. This is quite significant from a cost-effectiveness viewpoint for the use of a plastic liner makes the entire capsule a moldable item that can be produced at a very reasonable cost. An approach such as this should be given serious consideration in any future work.

If explosive drilling is to become effective as an ADM emplacement method, the effectiveness or amount of hole driven per unit weight of explosive must be at an acceptable level. This has been repeatedly touched upon throughout this report and several suggestions have been offered centered upon the use of a capsule employing the shaped charge principle. If it is assumed that this effort will be successful and the effectiveness of such a capsule in air can be brought into line with a ball-type charge in a water-filled hole, then the quantity of explosives required to drill an ADM emplacement would be on the order of 3 to 5 pounds per foot (see Section A). If the quantity of explosive in each capsule is 40 grams, then about 57 capsules would be needed to furnish 5 pounds of explosive. If a drilling rate of 100 feet per hour could be achieved, a capsule feed rate of 1.6 capsules per second would be required. Recall that the down-the-hole capsule velocity in the experimental rig was estimated at 45 feet per second; then at the 1.6 capsule feed rate, the separation between the capsules in the tube would be 28 feet. This is sufficient separation to avoid sympathetic detonation of the following charge if the hole is air-filled. It would be sufficient in water also, but if water is used the flow rate is much less than 45 fps. This is a major problem in explosively drilling a water-filled hole for the water transmits the detonation wave effectively; therefore, the separation distance should be as large as possible. The circulation rate is much lower so the capsules have to be spaced closer together to maintain the drilling rate. Thus the drilling rate and capsule separation requirements are at odds with each other and the drilling rate is the parameter that is adjusted. This has been a real problem in deep hole explosive drilling experience and is another very solid reason for perfecting a suitable drilling capability in an air-filled hole.

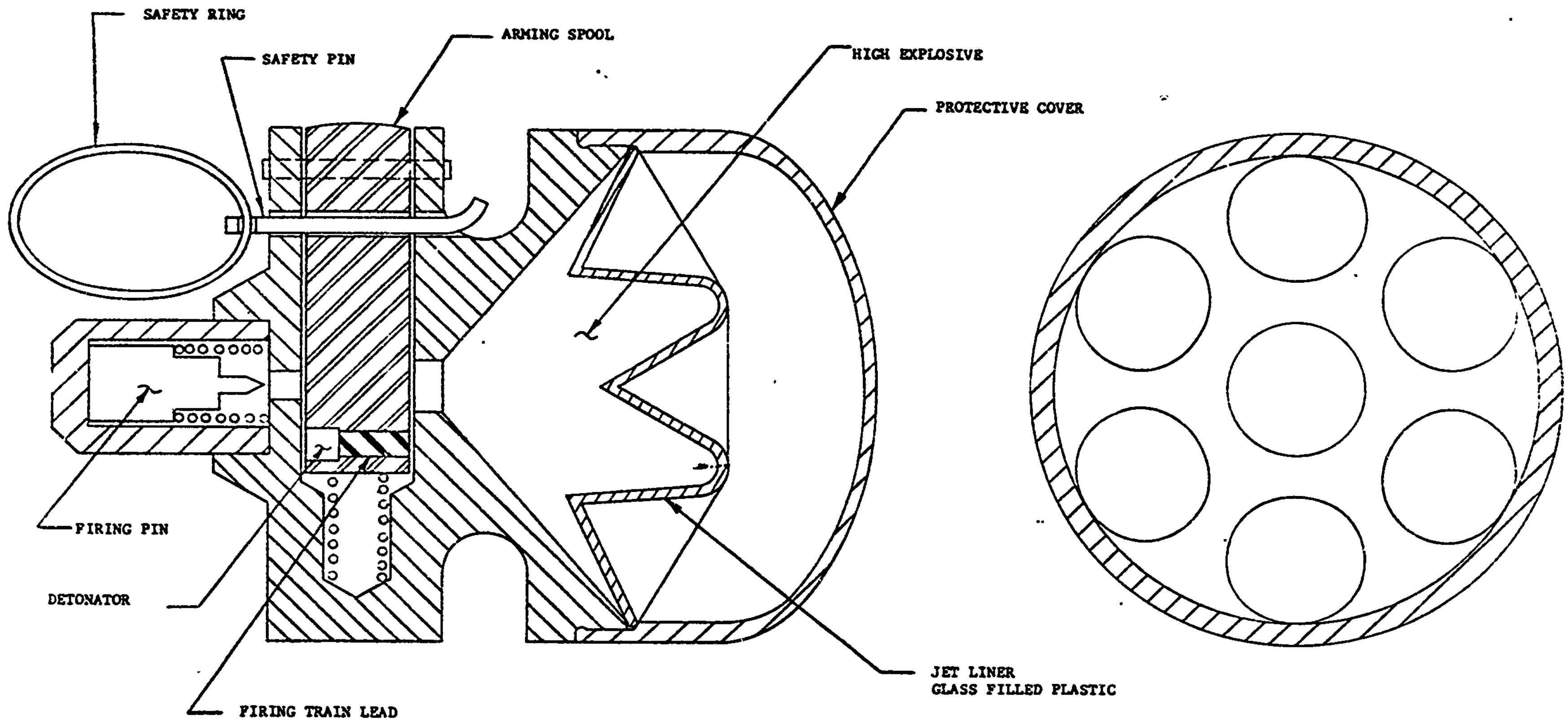


Figure 29. Single Unit Multi-Jet Shaped Charge Configuratio-

CONCLUSIONS

The following conclusions are drawn from the experience and findings of this program.

- Explosive drilling as conceptualized by this particular technique is effective in drilling hard rock. It is not effective in soft rock that could perhaps be removed efficiently by other means such as an auger equipped with hardened cutting bits.

- The experimental data obtained was insufficient to quantitatively evaluate and differentiate the merits of the three capsule designs. Qualitatively, however, it appeared that the shaped charges performed their function well in penetrating the rock at the bottom of the borehole. The hard rock fragmented well and there were indications that the combination of a shaped charge with a small ball charge was a sound concept for the explosive capsule.

- The quantity of rock fractured per unit weight of explosive was disappointing and must be improved considerably to make it practical to explosively drill an air-filled hole. Several features of the capsule design require study and development to achieve a marked improvement in efficiency. One feature in particular that may have lowered the efficiency of the capsules was the large amount of C-4 explosive in the ball charge relative to the explosive in the shaped charges.

- The multi-jet shaped charge developed on another program appears to be ideally suited to this problem. It would provide the combination effects in a single unit that could be fabricated at a very reasonable cost.

- The method of introducing the capsules into the borehole functioned well and advanced equipment, based upon this technique, designed to automatically feed the capsules can be envisioned.

- The safing and arming provisions for the capsule functioned well and advanced designs based upon these concepts can be envisioned for production capsules. It would be desirable to have an additional safing arrangement on the capsule and advanced concepts that provide an additional safing arrangement should be generated and evaluated.

RECOMMENDATIONS

The results of this program led to the following list of recommendations regarding future investigation of explosive drilling as a means for producing ADM emplacements.

o It was demonstrated that the technique of using explosive capsules to drill hard rock is sound. Several features of the concept require additional study to fully evaluate its potential and establish the physical character of equipment that could produce ADM emplacements. It is recommended that a modest program be organized to continue to investigations. Specific areas for continued study are indicated below.

o The combination auger-explosive capsule technique including the pneumatic-mechanical method of spoils removal should be evaluated further under drilling conditions that make the auger alone impractical. This requires in-situ rock formations that cannot be penetrated effectively with the auger alone. A situation where hard rock is covered with soft overburden to some depth is needed. It would be ideal if the site were extensive enough to provide rock of different quality and character at different locations. This matter needs careful consideration in any future planning.

o Efforts to achieve a practical drilling rate in an air-filled hole through the use of shaped charges in the capsule should be continued. Working in an air-filled hole is viewed as important in the ADM application to be compatible with worldwide deployment. Also, operating in air makes it much easier to achieve a high capsule feed rate and, therefore, a high drilling rate provided satisfactory capsule effectiveness can be achieved.

o Work with capsules of different configurations should be continued. The single-unit multi-jet design should be included in the investigations. The combination of a ball charge and a shaped charge in the capsule requires additional study and should be included in future investigations.

o The concept of a capsule molded in plastic materials appears to be sound and should be continued.

o The tests yielded little information on the effectiveness of the pneumatic-mechanical concept of spoils removal. This was due to the poor penetration rate experienced in the soft rock. This concept should not be discarded for its potential in being able to limit the bulk and weight of the ADM drilling equipment is extremely attractive and it should be fully evaluated.

o The concept of a plastic capsule appears to be sound. The capsule fragmented well when the capsule exploded and was a suitable vehicle for the explosives. Designs can be configured for injection molding the capsule to provide an economical method for quantity production.

o The principle difficulties and disappointments of the program were caused by the poor quality of rock at the drilling site. Any future investigations of explosive drilling must include careful consideration and selection of the drill site. Large in-situ formations of rock of varying quality covered with a layer of overburden would be ideal.

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- o An effort should be made to provide a second means of assuring safe handling and use of the capsule.

- o The method of feeding the capsules into the bore hole appears to be sound and should be refined to approach the ultimate goal of automatic operation.

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