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Rock Mechanics and Rapid Excavation Using Explosives

AAI Corp.

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(4 FEBRUARY 1972 - 24 MARCH 1973)

ROCK MECHANICS AND RAPID EXCAVATION USING EXPLOSIVES

PREPARED FOR:
U. S. DEPARTMENT OF INTERIOR
BUREAU OF MINES
TWIN CITIES MINING RESEARCH CENTER
TWIN CITIES, MINNESOTA 55111

PREPARED BY:
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WEAPONS & AERO SYSTEMS DIVISION
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13. ABSTRACT

An exploratory program was conducted to prove the feasibility of a high rate, explosive drilling system to significantly increase the rate of rock excavation and disintegration. Basically, the system utilizes a unique multi-jet explosive capsule, incorporating 7 GRP shaped charge liners with a common explosive charge and detonator. The capsules are transported automatically at a high rate down the drill tube by the use of water and high pressure air, between the capsules. The capsules are ejected from the tube, travel through the water in a filled borehole and is detonated against the working face at the bottom of the borehole. The ultimate system will incorporate an automatic and continuous capsule feed to obtain the high rate of fire in excess of 600 SPM and will recycle the water. Each capsule produces 7 jet penetrations into the rock. When capsules are fired at 600 SPM, the total rate will be 4,200 jet penetrations per minute. The shock of the multi-jet penetrations, coupled with the capsule underwater detonation shock, will rapidly advance the rock working face. The pressurized air and water located between the capsules exits from the drill tube into the borehole and removes the spoils which are pulverized by the detonation of the capsules.

Discussions are included of the design, development and testing of the multi-jet capsule, including the hydroballistic test rig, the drill rig and 3-capsule feed; anti-sympathetic detonation buffer; water and air injection subsystems; fire control and support equipment. The problems encountered and solutions achieved or recommended are discussed.

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Fire Control						
Support Equipment						
Spoils Removal						
Rock Excavation and Disintegration						
Shaped Charges						

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I. TECHNICAL SUMMARY

A recent study program conducted by a committee of the National Academy of Science emphasizes the need for major advances in the technology of underground excavation. The need is most acute for hard rock tunneling and mining, which are presently accomplished almost exclusively by drill-and-blast methods. Although these methods have improved over the years, their inherently cyclic nature imposes fundamental limitations on the excavation rates attainable and on the means of reducing costs. To increase speed and reduce costs significantly, it is necessary to develop equipment that operates continually.

The functional operations in the rock excavation process may be broken down into three basic classes; the rock disintegration directly associated with advancing the working face (the actual disintegration of in situ rock); the rock disintegration associated with the secondary breaking and grinding of disintegrated material into a size that can be efficiently handled; and the spoils or muck removal subsystem.

To an appreciable extent, rock disintegration is the key to the actual process of excavating. It is the major cost factor, representing 1/3 to 1/2 of the present total excavating costs; the <u>rate of excavation</u> basically is the factor that ultimately limits the rate of advance.

AAI considered that the most practical approach to the rock excavation problems was the selection of an explosive drilling system that is capable of performing the excavation functions rapidly and continuously. The only interruption to continuous operation would be the addition of a new length of drill tube, as the borehole depth is advanced. However, this operation could ultimately be automated to reduce the equipment downtime. AAI originally proposed a fully automatic, high rate, explosive drilling system concept and the feasibility of this concept was investigated under this program.

The purpose of this project was to develop an improved explosive drilling system to significantly increase the rock excavation rate. Basically, the system utilizes a unique multi-jet explosive capsule, incorporating seven shaped charge cone liners with a common explosive charge. These capsules are rapidly transported down a drill tube at a steady rate, and the system includes other new drilling techniques. This system is considerably improved over the low rate explosive systems developed by the Soviet and presently being studied by U. S. oil companies.

Under this program, AAI developed the multi-jet explosive capsules and drill rig hardware, capable of automatically firing a three-capsule burst, which was considered adequate to prove the feasibility of the concept. This approach was to serve as the basis for future development of an ultimate explosive drilling system.

The explosive drilling approach was selected because of its high terminal effectiveness against the rock working face and the explosives produce a secondary effect of breaking up the disintegrated material into very small fragments and pulverized particles. The explosive effect against the working face is greatly increased since the explosive capsules are detonated underwater at the bottom of the water-filled borehole. The train of capsules in the drill tube are propelled through the tube to the bottom of the borehole by pressurized water and air, which are injected between the capsules in the drill tube. This water/air combination between the capsules acts as an anti-sympathetic detonation-buffer to protect the following capsule from sympathetic detonation and mechanical damage due to the overpressure effect when the leading capsule is detonated. The length of the water/air buffer required to afford this protection establishes the spacing between capsules and the rate of fire or shots per minute (SPM) of the system. The water/air buffer system that propels the capsule down the drill tube, exits from the end of the tube behind the capsule and into the water-filled borehole. The impulse of the water/air discharge into the water-filled borehole is sufficient to flush the disintegrated spoils (small fragments and pulverized particles) from the borehole. This provides the muck removal subsystem which continually occurs in pulses equal to the rate of firing the capsule in shots per minute. The detonation of the capsules in rapid sequence will also assist the muck removal function. In the ultimate system the capsule rate of fire is expected to exceed 600 SPM and the water will be recycled through the system. To make the proposed system economically feasible at these rates of fire, it will be necessary to fabricate the capsules from low cost injected molded glass-reinforced plastic (GRP). The final capsules under this feasibility program were fabricated from spun and machined aluminum components with GRP shaped charge cone liners.

The work performed under this program involved: literature search; comprehensive shaped charge testing; development and testing of 7-jet capsule test specimens; the conduct of capsule hydroballistic tests to establish capsule configuration, stability, exit and impact velocities; the development of a capsule fuze, involving the safe and arm device and explosive train; final multi-jet capsule; the design and fabrication of the drill rig components with its various subsystems, drill tube and support, water and air injection systems, water pump and compressed air supply systems; the three-capsule automatic feed magazine; automatic fire control system; etc.

The successful development of the GRP jet liners and the 7-jet capsule with a common explosive charge were considered to be a technological breakthrough during this program. To our knowledge, neither of these achievements was previously performed.

The capsule produces seven-jet penetrations per unit into the rock. When capsules are fired at 600 SPM, the total rate will be 4,200 jet penetrations per minute. The shock of the multi-jet penetrations coupled with the capsule underwater detonation shock will rapidly advance the rock working face.

The work items described above were completed; however, the remaining work on some of the drill rig hardware, the erection of the rig and final test of the system could not be completed due to insufficient contract funds.

AAI was notified by the U. S. Bureau of Mines (USBM) that they in turn had been informed by Advanced Research Projects Agency (ARPA) that the latter's financial support for the FY-1973 Rock Mechanics and Rapid Excavation Programs had been terminated. Both the USBM and AAI personnel made efforts to solicit financial support from other Government agencies for the completion of the remaining program work. Since the explosive drilling system has high potential use in both civilian and military applications, AAI contacted cognizant personnel in the Army, Navy/Marine Corps, and the National Science Foundation for financial support of the system. Although considerable interest was generated during these contacts, no definite commitment has been received from these other agencies at the time of this writing. The USBM extended the contract end date four months to allow the other agencies time to evaluate the subject drilling concept and take whatever action they deemed necessary.

The following sections of this report describe the work performed to date on the development and test of the subject explosive drilling system, subsystems, and components. In addition, the report presents discussions in the following sections: future research indicated; Government agency implications; conclusions; technical reference; abbreviations; acknowledgements; subject inventions, and DD Form 1473.

It was unfortunate that we encountered the contract financial problem; however, this should in no way reflect on the high potential use and technical capability of the explosive drilling system in the rapid hard rock excavation field. The characteristics of the explosive drilling system are as follows: high rate of fire, continuous operation, full automatic operation, high terminal effects against the rock working face and in disintegration of the spoils; automatic flushing of muck from the borehole; economical fabrication of capsules from injection molded glass-reinforced plastic; a capsule fuze requiring 4 deliberate actions prior to arming for maximum safety, etc. This system has all the characteristics required to advance rock excavation technology by a high factor rather than a small improvement of 30% which is considered acceptable at the present. Due to the advanced capabilities of the proposed drilling concept, it is highly recommended that its development be continued.

II. GENERAL DISCUSSION

A. Background

For many years AAI Corporation has been engaged in the study of explosive devices including utilization of these devices for the penetration of reinforced concrete structures and the excavation of soil and rock for military purposes. In the course of these studies, investigations have been made of the latest state-of-the-art methods of deep well and hole drilling by explosives; in particular, the unconventional methods of drilling at high rates primarily utilized in the Soviet Union and for some oil field drilling in the United States.

Having first evaluated the present state of the art, AAI has engaged in some experimental R&D work to establish methods of speeding up the drilling and excavating of rock. The Russians have long utilized a practical system for delivering explosive cartridges to the bottom of a well. These cartridges, delivered at a steady rate, explode at the bottom, digging the well deeper while a stream of water or "mud" propels the charges downward and flushes the rock chips out of the bottom. Our reports of their system indicate that it is limited to a rate of about 12 charges per minute because of the danger of sympathetically detonating the following charge by the explosion of the first. In the United States several systems like it are being studied under independent research activity of certain oil companies. One system utilizes shaped charges and regular charges to take out more rock per explosion.

B. Concept Description

Our basic concept utilizes the same general principles as the Russian and U. S. methods but with two major improvements. (1) The explosive charge that we direct downward has a drilling face composed of a single liner shaped like a series of small individual shaped charge conical sections in a single explosive charge. The resultant explosion sends out a series of small jets into the rock in a conical pattern. This type of device will drill more rock per unit of explosive than either of the types previously mentioned. (2) By utilizing a pumping system working through a revolver-like feed system and using a combination of water and air, the explosive rate can be increased 10 to 100 times that of present systems, i.e., 120 to 1200 SPM.

Since the limiting factor often is the sympathetic detonation of a close-following charge, the addition of air under high pressure to the water or "mud" used for pumping creates an air bubble just below the following charge. This air bubble prevents hydrostatic shock from causing a detonation even with charges 5 to 10 feet apart. This device in full-scale operation could result in a drilling rate of 10 to 40 feet per minute. While the charge feed system is of course capable of continuous operation, it still would require stopping and adding additional lengths of pipe which could be automated to reduce the equipment downtime to approach a more continuous operation.

C. Program Discussion

Under the requirements of the subject contract, AAI conducted a research program to develop a preliminary explosive drilling system to prove the feasibility of the principles of the original concept. The work included experimentation to develop a typical multi-jet capsule, drill rig and capsule feed magazine to establish the system's rate of fire or the number of explosions per minute. Exploratory tests were conducted on components, subsystems, and total system for verification of the concept. The purpose of the program was to establish the basic criteria for the design of an ultimate system which would incorporate a fully automatic capsule feed system for sustained operation, until a section of pipe is to be added to the drill tube.

In addition to the above, some of the parameters to be determined during this program are outlined below:

- Safety/handling requirements
- Rock fracture effects of submerged explosions
- Anti-sympathetic detonation effects of the water/air buffer
- Capsule and air/water injector systems
- Arming and detonation of the capsule
- Flushing of spoils from the borehole.

In June, AAI successfully fired the first multi-jet capsule into an aluminum target. The capsule, which contained seven glass-reinforced plastic (GRP) liners, was fired with a common explosive charge and produced seven individual jet penetrations into the target plate. We consider this achievement to be a technological breakthrough. Since that time, several multi-jet capsules have been successfully fired in the air against aluminum witness plates and underwater against rock. The terminal results obtained from all the capsule firings are considered to be extremely effective.

To our knowledge, molded glass-reinforced plastic has not been previously used for shaped-charge liners, nor guessed to be so effective against such targets as rock, concrete and aluminum.

The major effort was directed toward the development of an effective multi-jet capsule. This work involved design, fabrication, investigation of materials, exploratory testing and it is believed that we have pushed the state of the art in shaped-charge development. A Hydroballistic Test Rig was designed and fabricated to observe the underwater performance of the capsule in regard to attitude, stability, and striking velocity. The data generated from this test rig was used to finalize the design of the multi-jet capsule configuration. It was planned to fabricate the capsule from injection-molded GRP to achieve the economical production costs required for the ultimate high rate of fire system.

Concurrent with the capsule development, preliminary designs and engineering investigations were conducted on the development of other system components and subsystems. These included the fuze, drill rig, capsule loader, water and air injection systems, anti-detonation buffer, flushing of spoils, etc. It was necessary to finalize the capsule design prior to finalizing the designs of the related components and subsystems. The final capsule design was established after the completion of the capsule hydro-ballistic tests.

The target test materials used in the program to evaluate the performance of the capsule shaped-charge development were rock, concrete, and aluminum plates. All rock disintegration tests were conducted in a quarry on the AAI property. The rock type at the quarry is considered to be coarse grained, partially weathered, Cockeysville marble. It was believed that an "over-kill" approach in the capsule design against the target rock available would provide satisfactory results when the developed system is ultimately evaluated against hard rock, such as granite and/or basalt. Unreinforced concrete target pads were poured and aged to provide a fairly constant target for the evaluation of individual shaped-charge candidates. A stack of 3 one-inch thick aluminum plates were used to evaluate the performance of the initial multi-jet capsules.

The explosive drilling concept developed under this program has great potential use, wherever rapid rock excavations are required. These include both civilian and military public works applications. In addition, the civilian uses include rapid deep hole drilling for land and off-shore oil wells, rescue operations for trapped underground workers, drilling for construction work, etc. The most outstanding military application, based on our background experience, is for Rapid Atomic Demolition Munition (ADM) Emplacement. It is recommended that the rapid explosive drilling system development be continued beyond this present exploratory program.

III. DEVELOPMENT AND EXPLORATORY TESTS

A. General

This section describes the work performed to date on the design, development, and test of the explosive drilling system components. These involve the multi-jet capsule, hydroballistic test rig, fuze for the capsule, and the drilling rig. These component discussions are presented in chronological order, with slight deviations to group similar accomplishments.

The major effort was directed toward the development of the multi-jet capsule, which involved the design and test of shaped charges with variations in linear configuration, material, wall thickness, stand-off distance, terminal effects against rock, explosive charge weights, etc. As the development progressed, groups of 7-unit clusters using the miniature shaped charges were tested for effect against rock and the development ultimately evolved into the 7-unit multi-jet capsule, which performed exceptionally well against aluminum and rock targets.

The final multi-jet capsule design was based on a set of parameters generated as a result of the explosive firing tests, capsule tests performed under simulated bore hole drilling environment provided in the hydroballistic test rig, compatibility with the fuze and the drill rig subsystems. The hydroballistic test rig was designed and fabricated to simulate the drilling environment. The purpose of these tests was to establish the following: the external capsule configuration; weight and c.g. location; the exit velocity of the capsule as it leaves the end of the drill tube; the underwater stability of the capsule during its path from the drill tube to the bottom of the borehole; and the capsule striking velocity at the bottom of the bore hole.

The fuze developed for the multi-jet capsule was based on the data generated during the performance of the hydroballistic tests and was designed to be compatible with the final multi-jet capsule configuration. The fuze concept used was based on electromechanical operational modes and requires that four deliberate actions be performed in sequence in order to fire the capsule. These four deliberate actions are performed automatically when the capsule is placed in the drill pipe, the capsule exits from the drill pipe, and the capsule strikes the bottom of the bore hole.

The drilling system components are discussed in detail in the following paragraphs of the report.

B. Multi-Jet Capsule

1. Discussion of the Problem

The purpose of this effort was to design, develop and test a multi-jet capsule, which will include seven shaped-charge liners with a common explosive charge and fuze, and prove its effectiveness in rock excavation.

Since the predicted rate of firing the capsules down the drill tube is in excess of 600 SPM, it is required that the capsule components, including the liners, be fabricated by the most economical means. The Navy has proven the structural integrity and overall performance of glass-reinforced plastic (GRP) components to withstand extremely high external pressures in their deep submergence vehicles; AAI decided to adapt this approach in the fabrication of the capsule components. Ultimately, the capsule will be fabricated from 50% GRP material in the high production, low unit cost capability of the injection molded process. Therefore, the liners developed in this exploratory program shall be injection molded GRP components, in order to be compatible with future capsule design.

Based on the above approach, the objectives were to develop an effective GRP conical liner, develop a multi-jet test capsule with seven GRP liners, and verify the feasibility of the capsule concept.

Prior to the design and fabrication of the injection mold for the GRP liners, AAI procured a quantity of three different types of commercial miniature shaped charges. These charges were procured for use as control units and to determine their terminal effects against rock, based on the respective shaped charge type, size, and characteristics. These units were tested individually and the optimum type was selected. Seven 7-charge cluster units, using the optimum miniature shaped charges, were fabricated and tested against rock, above and underwater.

Using the data generated in the above test the GRP liners were sized and work was initiated on the design and fabrication of an injection mold to produce the GRP liners. The mold was sufficiently flexible to vary the wall thickness of the basic GRP liner, without modification to the tool. The GRP conical liners were produced, loaded, and test fired. These liners were test fired, using specimens of various wall thicknesses and stand-off distances, against a specially poured, homogeneous, concrete target pad of known strength to obtain uniform test data for comparable evaluation.

Multi-jet test capsules were fabricated using the GRP liners. These specimens were originally fired against three 1-inch-thick aluminum target plates to assure that the test capsule liners produced seven individual jet holes in the target plates. These tests were repeated after minor modifications to the test capsules and improved results were obtained. In addition to firing four test capsules against aluminum plate targets, seven units were statically fired underwater, in sequence, against rock.

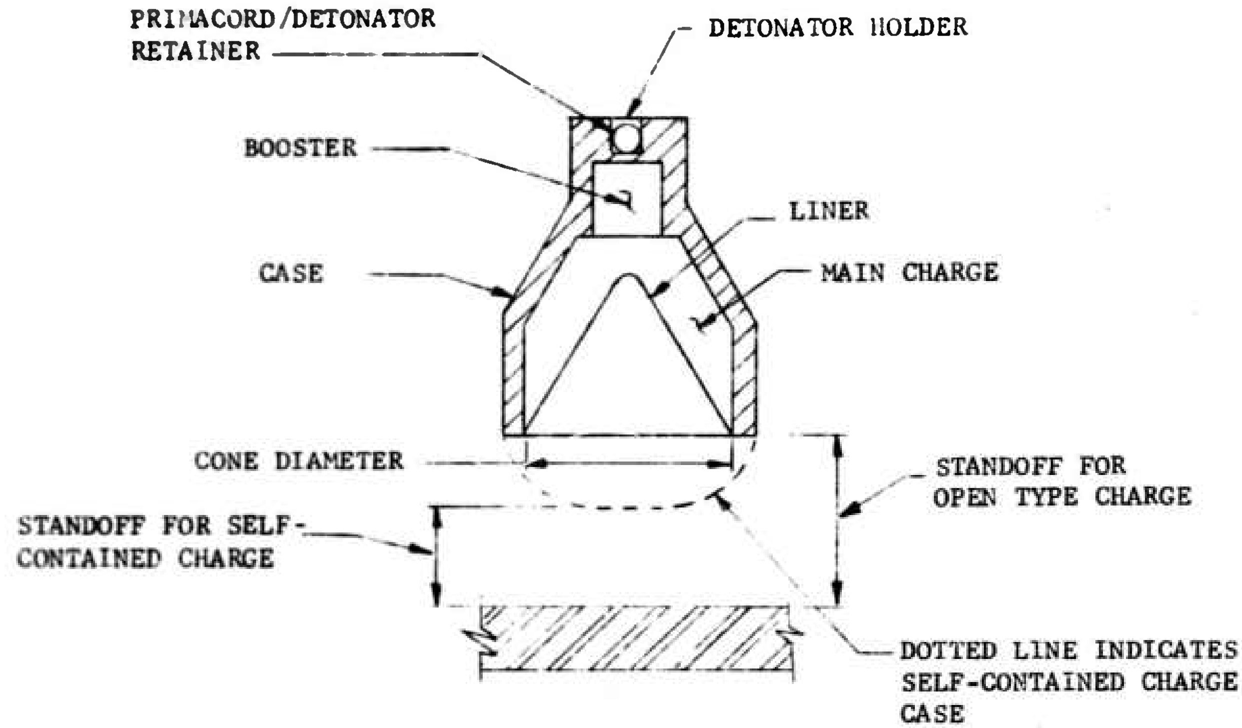
The final multi-jet capsule design is presented at the end of this section, although its development was based on the results of the hydro-ballistic tests, fuze design, and drilling rig subsystems which are discussed later in the report.

2. Exploratory Test Results

a. Miniature Shaped Charges

The miniature shaped charges, ordered from the Jet Research Center, Inc., of Arlington, Texas, were of three different types under vendor's part numbers Y1005, Y1006, and Y1007. A sketch of a miniature shaped charge with tabulated data on the types procured are presented in Figure 3-1. All three charges used copper liners, however, their liner configurations were different. The liner configurations of Y1005, Y1006 and Y1007 are hemispherical, conical and semi-parabolic, respectively. A series of tests were fired using the three different types with varying stand-off distances, against hard, coarse-grained Cockeysville marble. The results of firing three charges of each type is shown in Figure 3-2. Shots #1, #2, and #3 were charge #Y1005; shots #4, #5 and #6 were charge #Y1006; and shots #7, #8 and #9 were #Y1007. Figure 3-2 illustrates the test set-up and results; however, the liner diameter and configuration are shown but the rest of the shaped charge has been omitted.

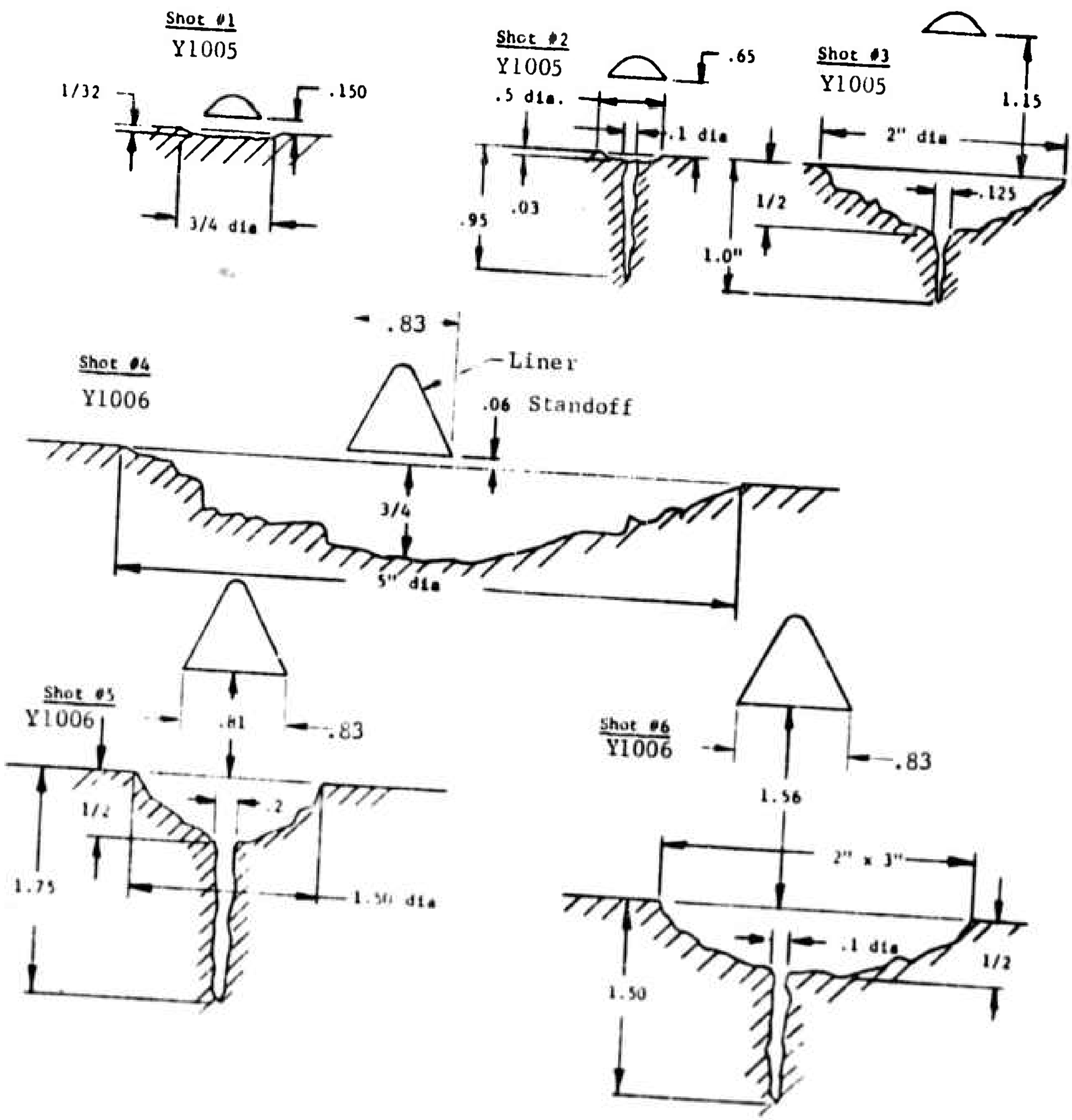
In addition to the above test, three of the largest shaped charges (Y1007) were subsequently fired individually into rocks which were placed in a 55-gallon drum and filled with water. The rocks selected for the underwater tests were approximately 25 lbs. weight and of a convenient size to place in the 55-gallon drum. In each test, the target rock was penetrated and split. This was due primarily to the small size of the rock, the lack of rock confinement, and the hydrostatic effects. Other than noting the above results, no other data could be recorded due to the terminal condition of the target rocks.



						Performance in Mild Steel		
JRC Charge Number	Explosive Weight (Grams)	Gross Weight (Grams)	Approximate Outside Diameter (In.)	Approx. Charge Length (In.)	Approx. Standoff (In.)	Penetration (In.)	Hole Diameter (In.)	Cone Diameter (In.)
Y1005	1.1	20	.63	.83	1/2	0.75	0.20	.50
Y1006	3.7	48	1.00	1.32	3/4	2.00	0.30	.80
Y1007	8.5	96	1.61	1.74	1	2.50	0.30	1.30

MINIATURE SHAPED CHARGES

FIGURE 3-1



A SERIES OF FIRING TESTS USING 3 TYPES OF
MINIATURE SHAPED CHARGES AGAINST
HARD, COARSE GRAINED, MARBLE

FIGURE 3-2 (Cont'd)

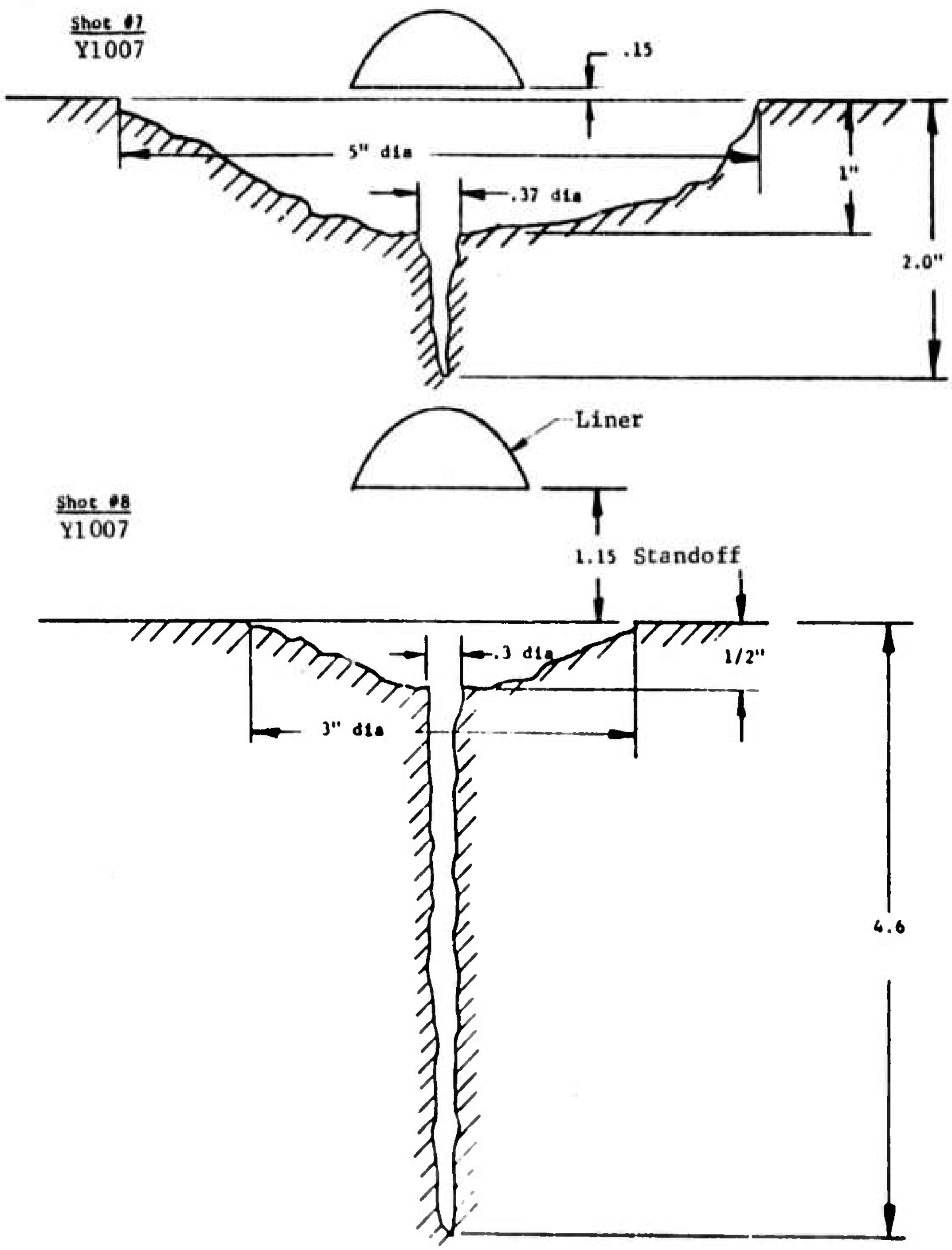


FIGURE 3-2

(Continued From Previous Page)

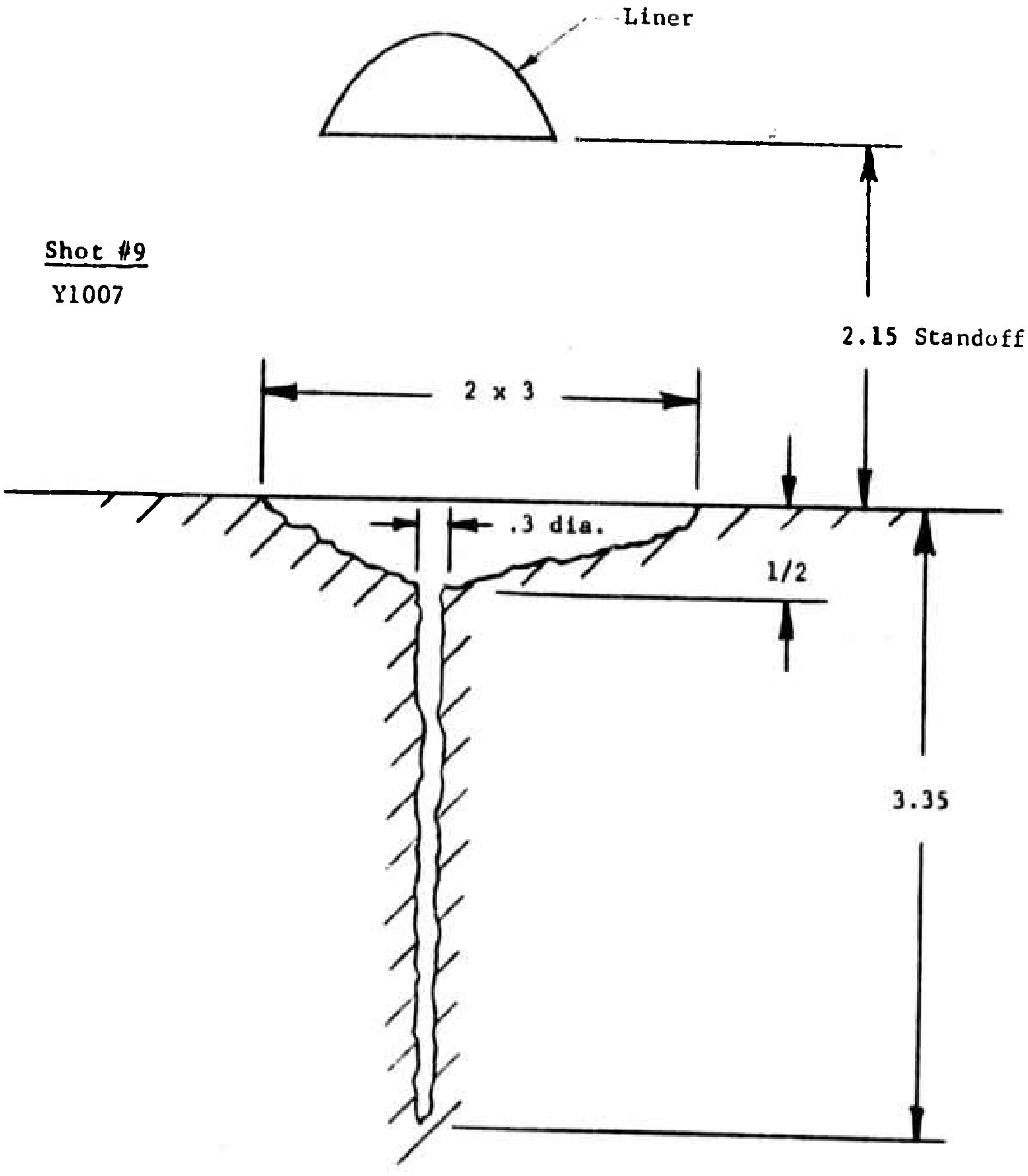


FIGURE 3-2
(Continued From Previous Page)

b. Seven Shaped Charge Cluster Unit

Selecting the Y1007 miniature shape charge as the optimum in the above tests, seven 7-shaped-charge-cluster units were fabricated. The general arrangement of the charges in the cluster units is shown in Figures 3-3 and 3-4. One charge is placed in the center. The remaining six charges are arranged in an outer circle, around the center charge, and provide a conical array of 6 jets. An equal length of detonating cord is inserted into each shaped charge and their leads are clustered in the center. Figure 3-5 shows one of the cluster units placed in the hole provided by the previous shot and is ready to fire.

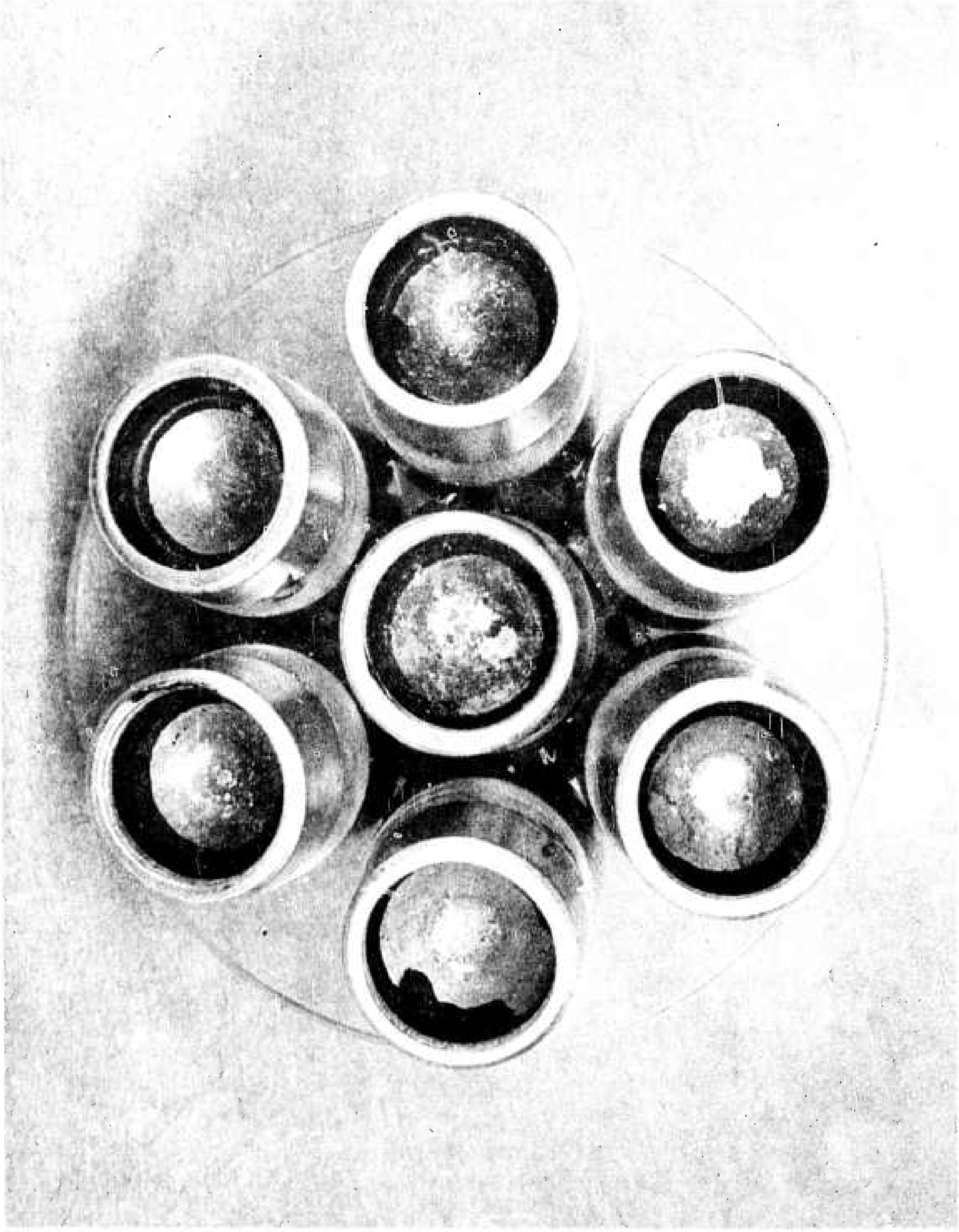
Two of the seven cluster units were test fired in air against the exposed surface of a buried rock boulder. These two charges were manually placed and fired individually into the same position of the boulder and results of the sequence shot are shown in Figure 3-6.

The remaining five explosive clusters were test fired in sequence in an underwater environment. One of the test sites, which were prepared by removing the soil overburden with a backhoe, was filled with water. One of the explosive clusters was lowered into the water, placed on the base rock, and fired. After the shot the hole was siphoned dry and the remaining spoils were removed to allow measurement of the results. The second cluster was lowered into the refilled test site and placed in the hole produced by the first shot. This procedure was repeated for the remaining cluster shots and the hole was siphoned and measured after each shot. The final result of firing the five of these cluster units in sequence is presented in Figure 3-7.

c. GRP Liner Development

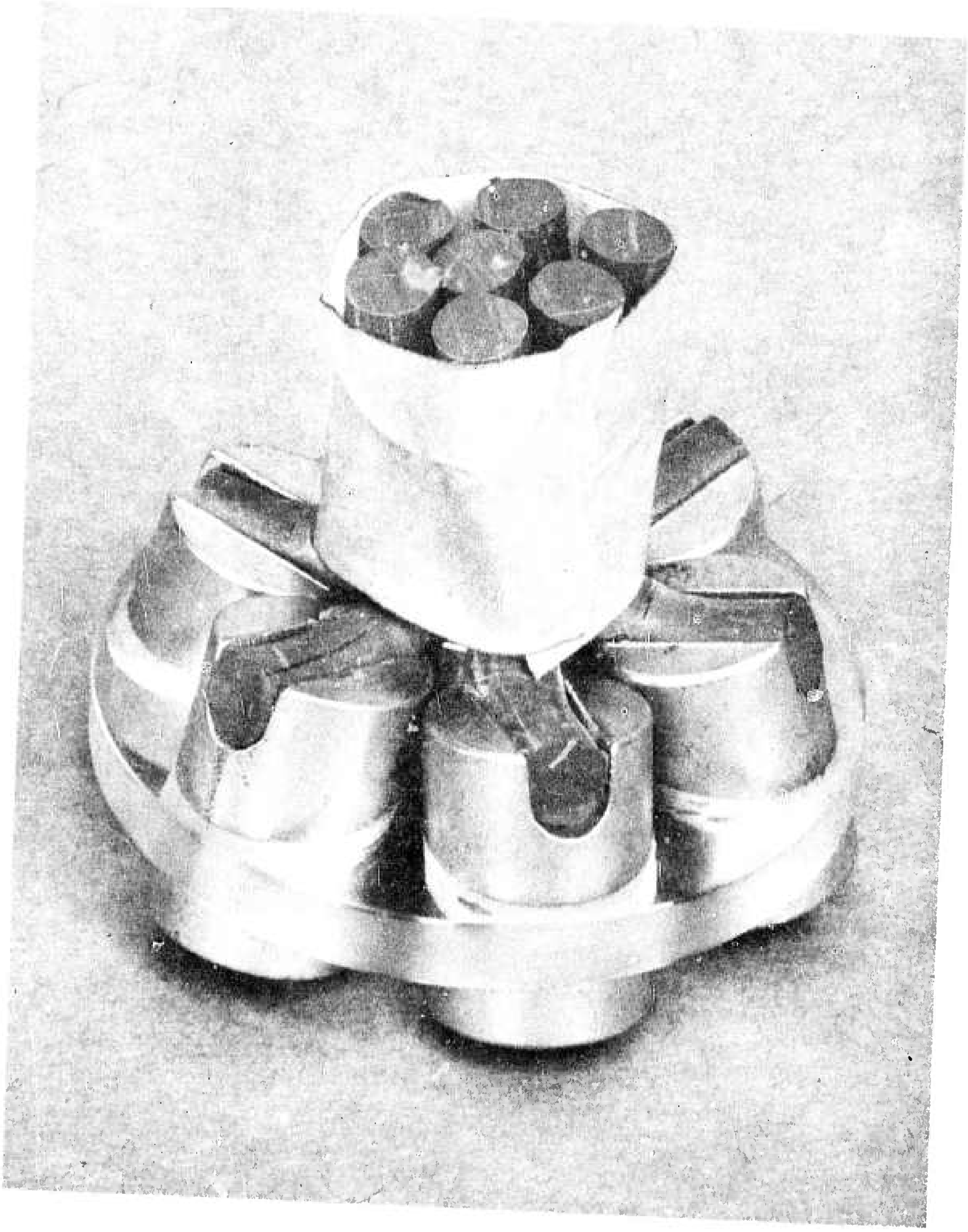
The criteria for the development of the GRP liners required for the economical production of the multi-jet capsule was based on the data generated during the performance of the above individual and cluster unit tests, and on the results of our literature studies, regarding shaped charge design and performance. The parameters selected for the design of the GRP liners are as follows: 1.3" cone diameter; 60^{o} included cone angle; variable wall thickness for test, and attempt to achieve greater terminal effects against rock than was achieved by the copper-lined miniature shaped charge of the same size. Preliminary design indicated that seven 1.3" cone diameter liners could be housed within a 4" O.D. multi-jet capsule. Our literature search revealed that various materials have been used in the fabrication of shaped charge liners, however, to our knowledge, this is the first time that GRP liners have been used.

Injection molding tools were designed and fabricated to produce the GRP cone liners in four sizes, identical except for wall thicknesses. The molds were flexible so that various cone wall thickness could be obtained without modification of the tooling. The liners were 1.3" in diameter with a 60^{o} cone. The cone thicknesses of the liners were .040", .080", .160", and .200".



7-Charge Cluster Unit - End View

Figure 3-3

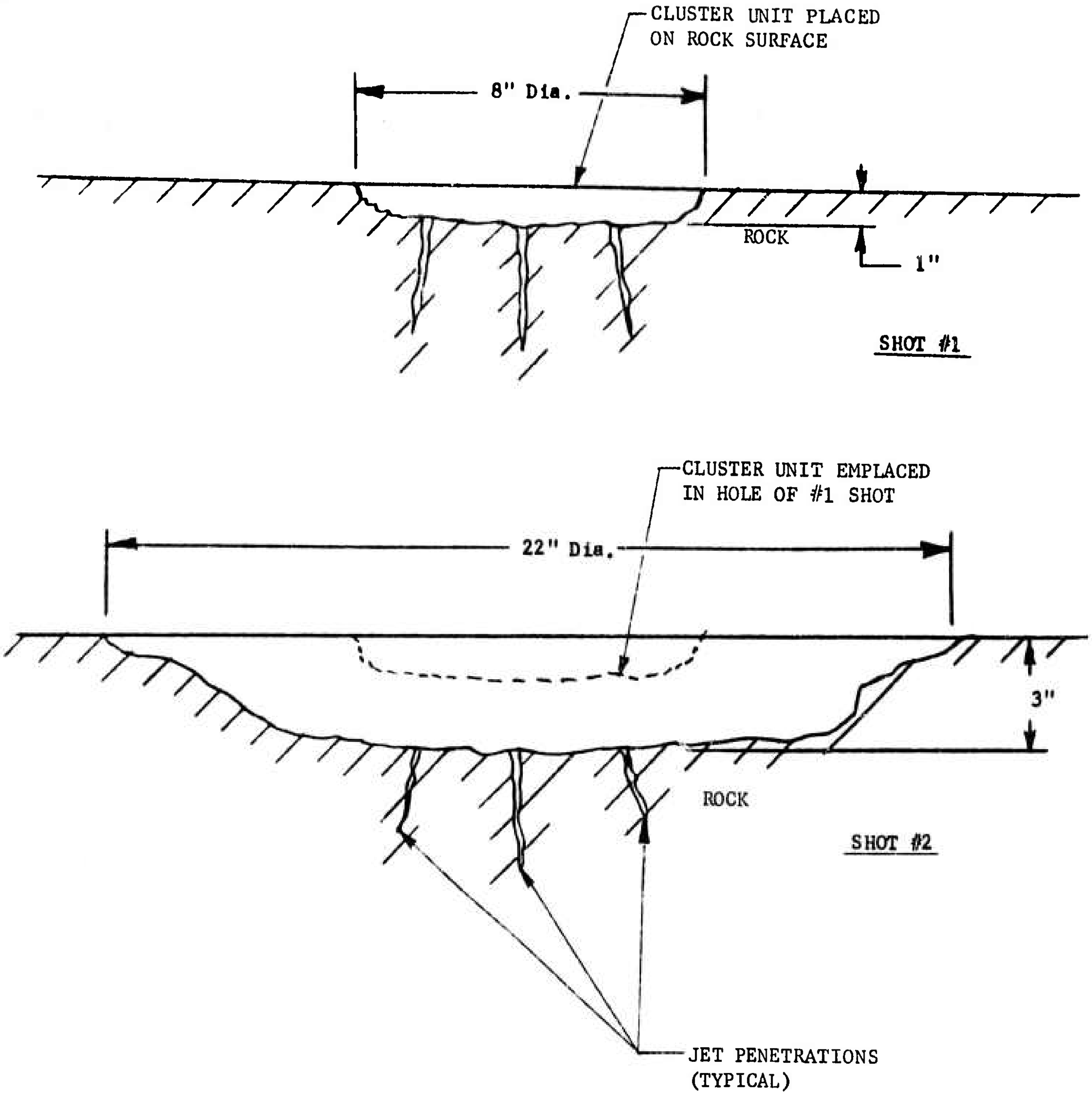


7-Charge Cluster Unit, Side View

Figure 3-4

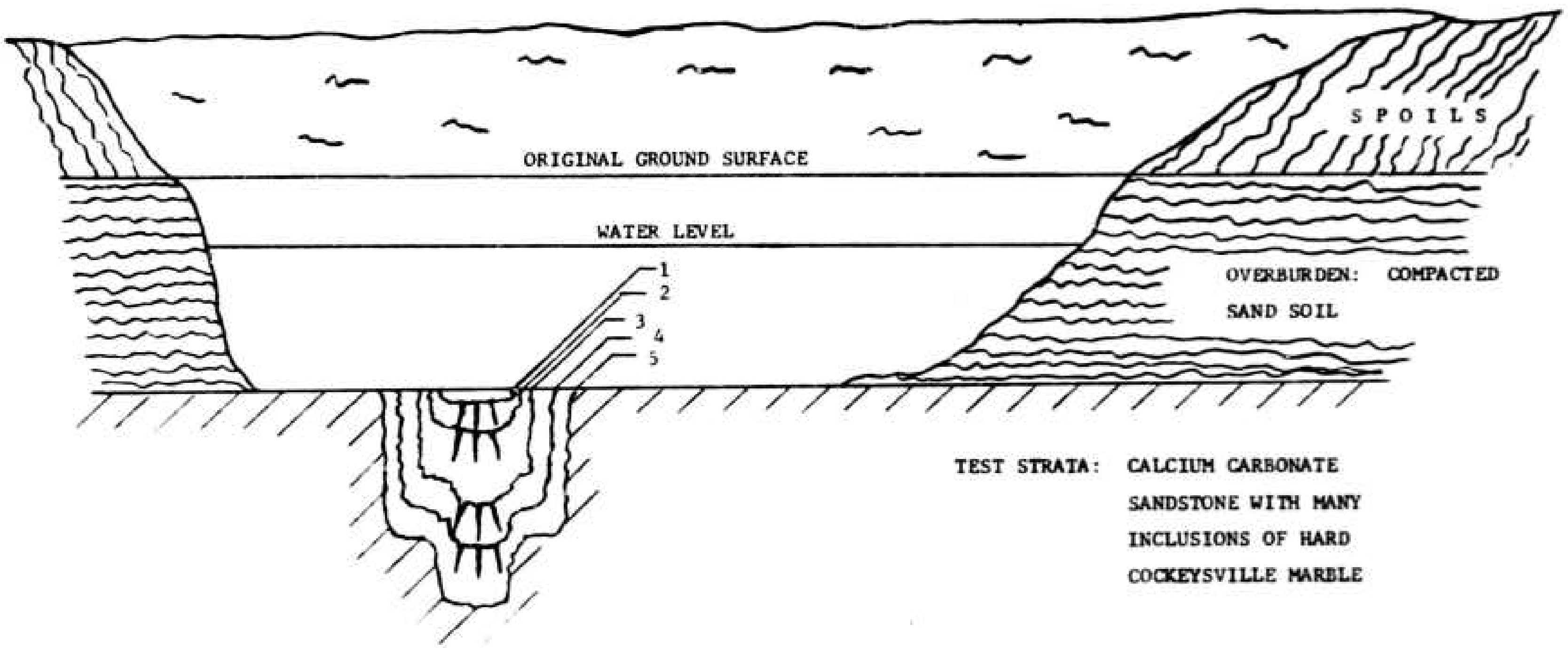
7-Charge Cluster Unit - Emplaced on Rock Prior to Firing

Figure 3-5



7-CHARGE CLUSTER UNITS. SHOTS #1 and #2
FIRED IN AIR AGAINST ROCK IN SEQUENCE

FIGURE 3-6



Shot #	Diameter At Top	Depth To 7" Dia.	Total Depth
1	6"	1" *	1"
2	8"	3½"	3½"
3	9"	6½"	10"
4	13½"	10"	14"
5	15"	12"	18"

* At 6" Diameter

FIVE 7-CHARGE CLUSTER UNITS
FIRED UNDERWATER AGAINST ROCK
IN SEQUENCE

FIGURE 3-7

Another liner, procured commercially, was also test fired in this series of tests. This liner was fabricated from 35% glass-reinforced plastic having a hemispherical configuration with a 2" diameter base and .062 wall thickness.

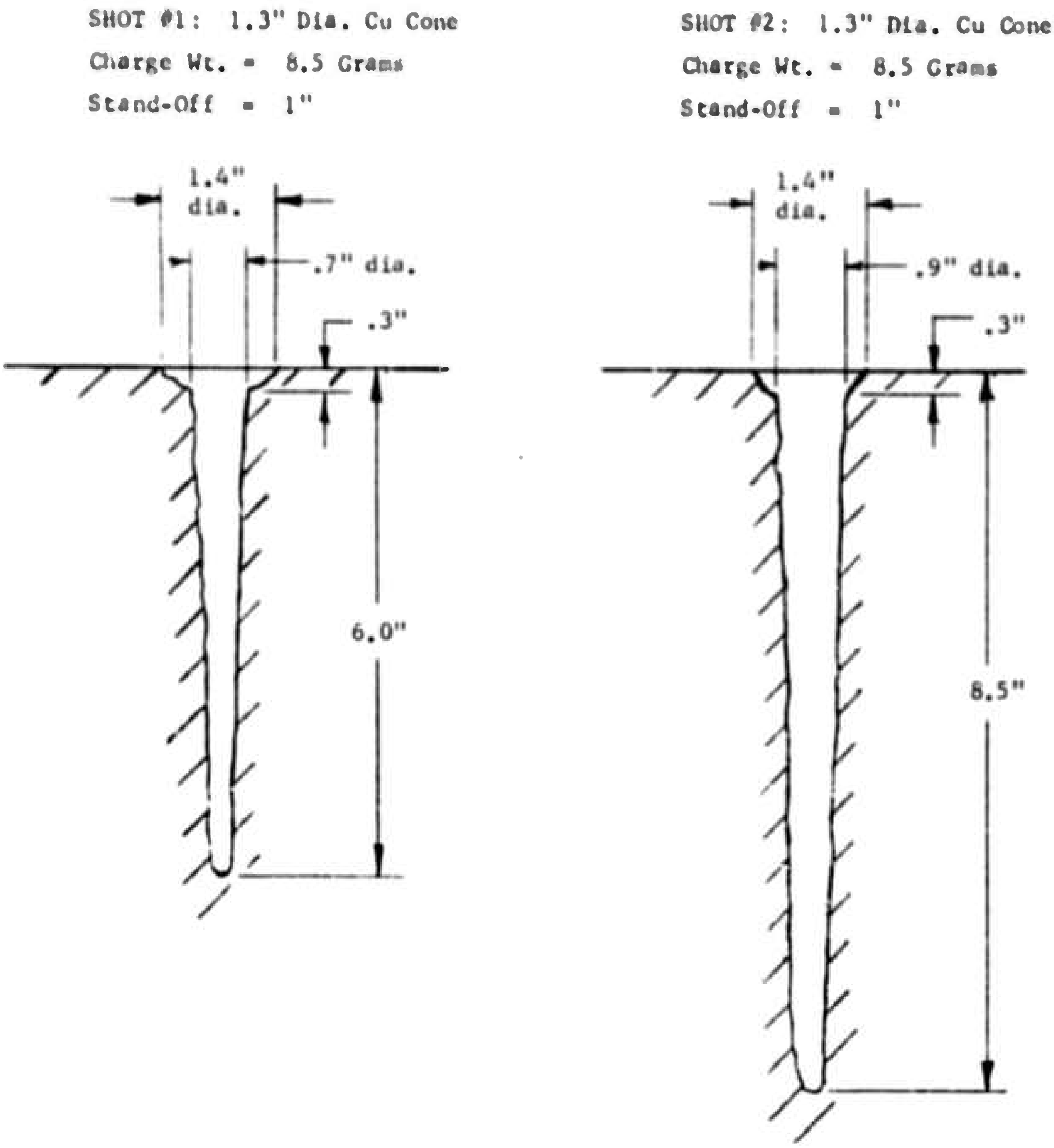
Each of the candidate GRP liner charges was loaded with C-4 explosive to the maximum effective charge length. According to our literature search, the maximum effective charge length is established at a ratio of 2.25/1 times the liner cone diameter. Since no empirical data was available regarding the performance of shaped charges using GRP liners, the maximum charge length was used in these tests. The charge length was adjusted later to be compatible with the requirements of the final multi-jet capsule design.

In conjunction with the GRP liner tests, a concrete pad, 4 ft. wide, 6 ft. long, and 1 ft. thick, was poured to provide a consistent 3,000 psi compressive strength target. No aggregate was used in the concrete to assure uniformity throughout the test pad.

In this series, shots #1 and #2 (Y1007 miniature shaped charges) were fired into the concrete pad as test control items and the results are shown in Figure 3-8.

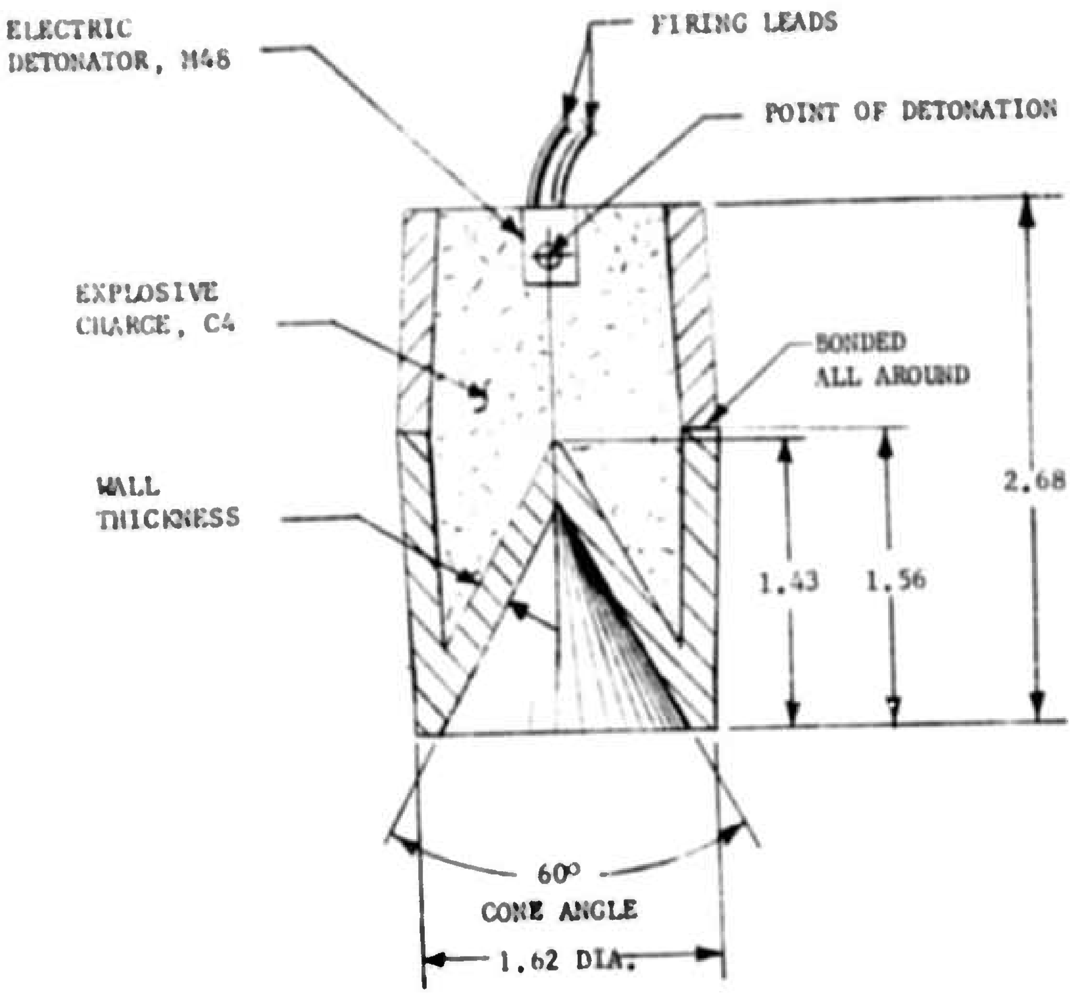
The GRP liner test specimen used in these individual liner tests is shown in Figure 3-9. This unit is made by bonding the upper and lower injection molded GRP sections. The lower portion is as molded. The upper section is what remains after the liner cone is machined from a lower portion. The machined cone liners are used in the multi-jet capsule. The results of firing shots #3, 4 and 5 are shown in Figure 3-10 and a composite sketch of the five shots is shown in Figure 3-11.

Sixteen (16) additional individual glass-reinforced plastic shaped charge tests were conducted. These tests involved shaped charges having liners of various configurations; liner materials, cone diameters, charge weights and lengths were variables. These units also incorporated other parameters such as liner wall thickness, internally copper plated cones and varying stand-off distances. All of these tests were fired against the concrete pad. The unit parameters and test data are tabulated for all shots from #1 through #21 as shown in Figure 3-12. Evaluation of these data indicates that the units with the greatest wall thickness produced the maximum penetrations; the slight gain of the copper plated units does not justify their increased cost; and the longer stand-offs produce the greatest penetrations.



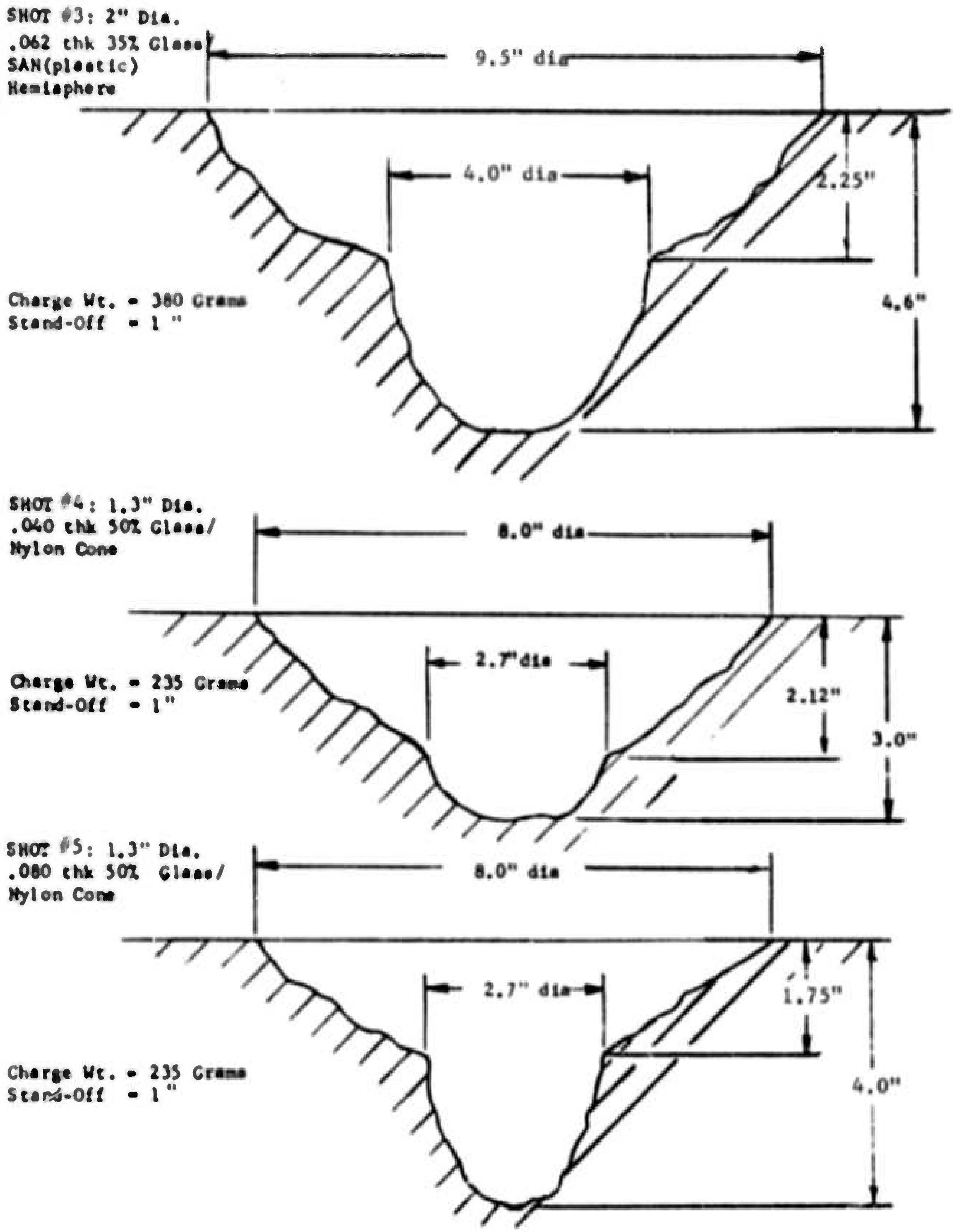
TESTS OF Y1007-MINIATURE SHAPED CHARGES AGAINST CONCRETE

FIGURE 3-8



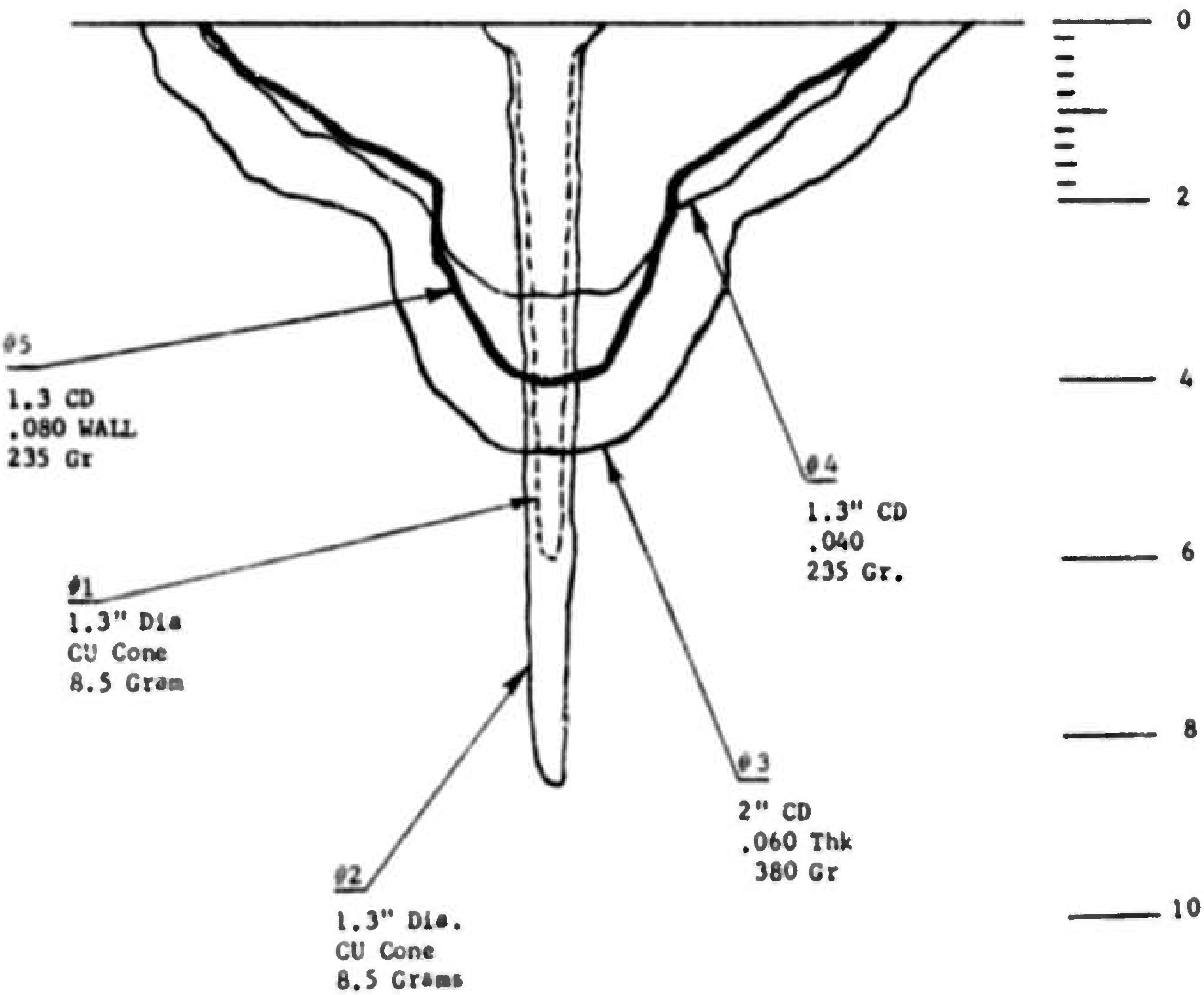
GRP-LINER TEST SPECIMEN

FIGURE 3-9



TEST SHOTS #3, 4 and 5 HAVING GRP LINERS

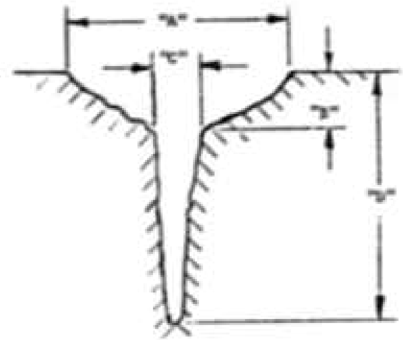
FIGURE 3-10



COMPOSITE RESULTS OF PREVIOUS 5 SHOTS

FIGURE 3-11

Test No.	Liner Data				Explosive Data		Stand-off	Crater		Jet		Total Water Volume (ml.)
	Liner Shape	Dia. (In.)	Liner Thickness		Weight (gm)	Length (In)		A Dia. (In.)	B (In.)	C Dia. (In.)	D (In.)	
			GRP	Cu.								
1	SP	1.3	-	.03	8.3	-	1.00	1.40	.30	.70	6.0	50
2	SP	1.3	-	.03	8.3	-	1.00	1.40	.30	.90	8.3	40
3	HS	2.0	.06	-	380	9.0	1.00	9.50	2.25	4.00	4.6	1950
4	C	1.3	.040	-	235	3.10	1.00	8.00	2.13	2.70	3.0	1000
5	C	1.3	.080	-	235	3.10	1.00	8.00	1.75	2.70	6.0	800
6	C	1.3	.140	-	238	3.10	1.00	3.75	1.25	1.75	5.0	420
7	C	1.1	.040	-	69.2	2.10	1.25	4.75	1.00	1.75	3.5	275
8	C	1.1	.080	-	67.6	2.10	1.25	4.00	.95	1.60	4.8	270
9	C	1.1	.140	-	68.3	2.10	1.25	2.75	.30	1.30	5.9	140
10	C	1.3	.040	.001	67.9	2.10	1.25	6.00	1.11	2.00	5.75	300
11	C	1.1	.080	.001	67.3	2.10	1.25	5.25	1.25	1.38	5.75	225
12	C	1.1	.040	.0042	67.4	2.10	1.25	6.00	1.25	1.80	3.94	400
13	C	1.3	.040	.0042	67.4	2.10	2.00	6.00	1.18	1.88	3.06	260
14	C	1.3	.040	.0042	64.9	2.10	2.75	6.00	1.25	1.75	4.06	200
15	C	1.3	.080	.0042	64.2	2.10	1.25	4.75	1.50	1.50	5.19	300
16	C	1.3	.080	.0042	64.0	2.10	2.00	3.62	.75	1.50	5.75	150
17	C	1.3	.080	.0042	67.3	2.10	2.75	3.50	1.25	1.38	5.62	270
18	C	1.3	.200	-	69.3	2.10	1.25	2.50	1.19	1.00	6.44	180
19	C	1.3	.200	-	70.3	2.10	2.00	1.75	1.38	.75	8.19	115
20	C	1.3	.200	-	64.2	2.10	2.75	3.00	.94	.62	10.00	125
21	C	1.3	.200	-	69.2	2.10	3.50	2.75	1.25	.62	11.50	125



Legend

GRP = Glass Reinforced Plastic

CU = Copper

HS = Hemisphere Liner

C = 60° Cone Angle Liner

SP = Semi- Parabolic

Note:

1. All firing tests against concrete pad.

COMPARISON OF INDIVIDUAL SHAPED CHARGE TESTS
(WITH VARIOUS CONE PARAMETERS AND CHARGE WEIGHTS)

FIGURE 3-12

The chart also indicates that the greater the wall thickness of the cone, the greater the penetration depth; whereas the thinner the wall thickness of the cone, the greater volume of target material removed. As the test program continues into rock targets, we shall determine the tradeoff between maximum penetration or maximum target material removal.

To our knowledge, the use of molded glass-reinforced plastic has not been previously used for shaped charge liners nor guessed to be so effective against such targets as rock, concrete and aluminum. This may be considered a new development. It is planned to ultimately injection mold the seven liners into one GRP piece for the economical production of the future multi-jet capsule.

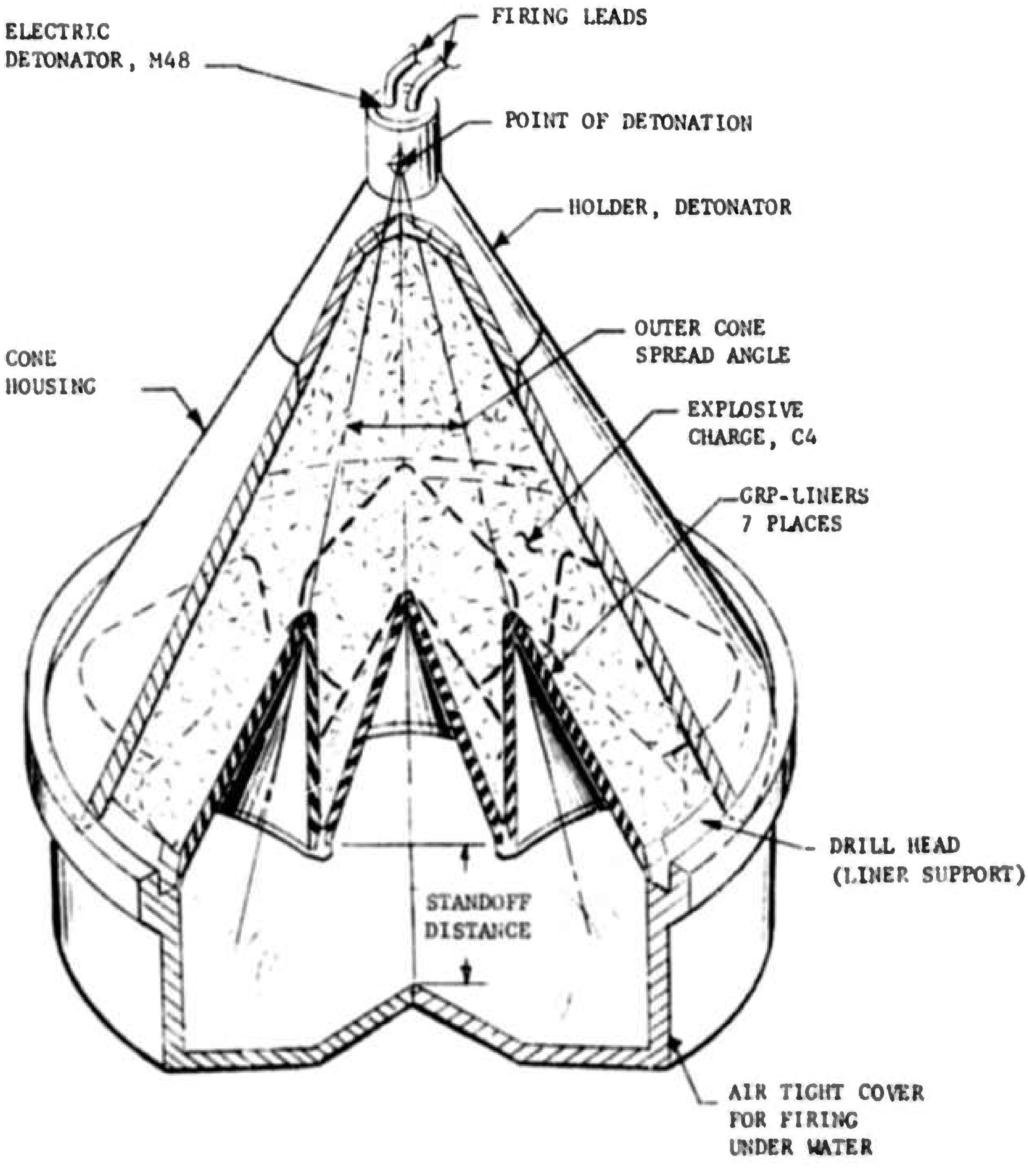
The rock disintegration performance of the charges with GRP liners is considerably increased over that of the copper lined control charges, primarily due to their large explosive charges. These tests proved that a GRP liner is practicable and effective.

d. Multi-Jet Test Capsule

This section describes the design, development and test of the multi-jet test capsule. Its basic design evolved from the evaluation of the foregoing development, test, and literature studies. The test capsule was designed basically to be used as a statically fired test specimen to prove the feasibility of the seven-jet concept, determine its terminal effects against rock, and provide additional empirical data to be used in the final multi-jet capsule design.

A cutaway sketch of the test capsule, with callouts, is shown in Figure 3-13. Eleven test capsules were designed and fabricated for test. Four test capsules were fired in the air against 3 stacked 1" thick aluminum plate targets to evaluate the seven-jet concept, and seven were fired underwater, in sequence, against rock. The sketch in Figure 3-13 illustrates the test capsule that was fired underwater and requires an air-tight cover over the seven liners. Shaped charges that are fired underwater without the airtight cover are ineffective, since the jets have no space to develop; in other words, no stand-off. The four test capsules, fired in air against the aluminum targets, used three stand-off posts to provide the stand-off required in lieu of the air-tight cover which is not required for shaped charge shots fired in the atmosphere.

All of the eleven test capsules were basically the same, except for certain variations that were deliberately incorporated for test. These variations consisted of the following parameters: liner wall thickness, .040" and .160"; spread angle of the six cones in the outer ring of liners included spread angles of 40° and 60°; and finally, minor variations in explosive charge weights, which were small and ranged from 255.5 to 294.6 grams. The variations in the characteristics of the eleven test capsules is shown in Figure 3-14.



MULTI-JET TEST CAPSULE

FIGURE 3-13

Number	Spread Angle	Cone Wall Thickness	Target	Charge Wt. (Grams)	
1	60°	.040	Alum	286	
2	60°	.040	Alum	255.5	
3	40°	.040	Alum	294.5	Air
4	40°	.160	Alum	294.5	
5	60°	.040	Rock	262.5	
6	60°	.160	Rock	260.2	
7	60°	.040	Rock	257.2	Underwater
8	60°	.160	Rock	262.4	
9	40°	.040	Rock	294.6	
10	40°	.160	Rock	294.5	
11	40°	.160	Rock	293.4	

MULTI-JET TEST CAPSULE

DELIBERATE PARAMETER VARIATIONS

FIGURE 3-14

The following paragraphs describe the test capsules and their test results.

(1) #1 Test Capsule

The #1 test capsule and its terminal effects are best described by referring to the following six figures.

The components of the #1 capsule are shown in Figure 3-15 and consist of an aluminum head, seven GRP liners, outer cover and three standoff posts. The head is machined with seven counterbored holes and arranged with one in the center and six equally spaced holes on a circle concentric with the center hole. The six outer holes are on a 60° spread angle which is subtended from the detonation point on the capsule longitudinal axis. It is also to be noted that the seven liners have a flange at their base to match the counterbored holes in the machined head. The outer cover is sheet metal cut from a lamp shade to expedite fabrication. The liners were fabricated from injection molded 50% glass-reinforced nylon. These liners form a 60° cone angle, 1.300 inch cone diameter with a .040 inch wall thickness.

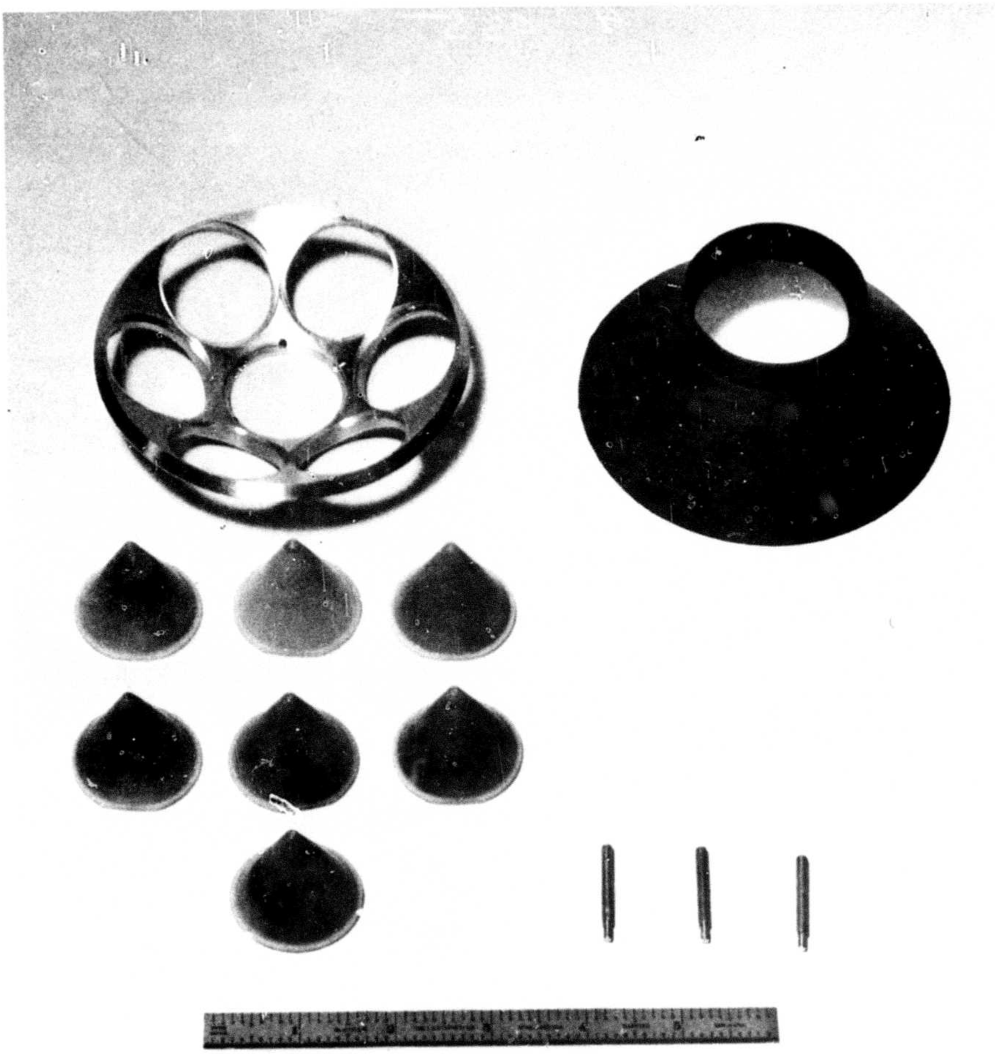
Figure 3-16 shows the same components with the seven liners positioned into the counterbored holes in the head.

Figure 3-17 presents an elevation view of the assembled capsule with its three standoffs in position and ready for static firing. The outside diameter of the capsule is four inches. The lower part, the head with its seven liners in place, is first bonded to the charge housing and all loading operations are then performed through the hole in the top of this housing. The #1 multi-jet capsule was loaded with 286 grams of C-4 explosive.

The bottom view of the capsule is shown in Figure 3-18 and presents the view seen by the target.

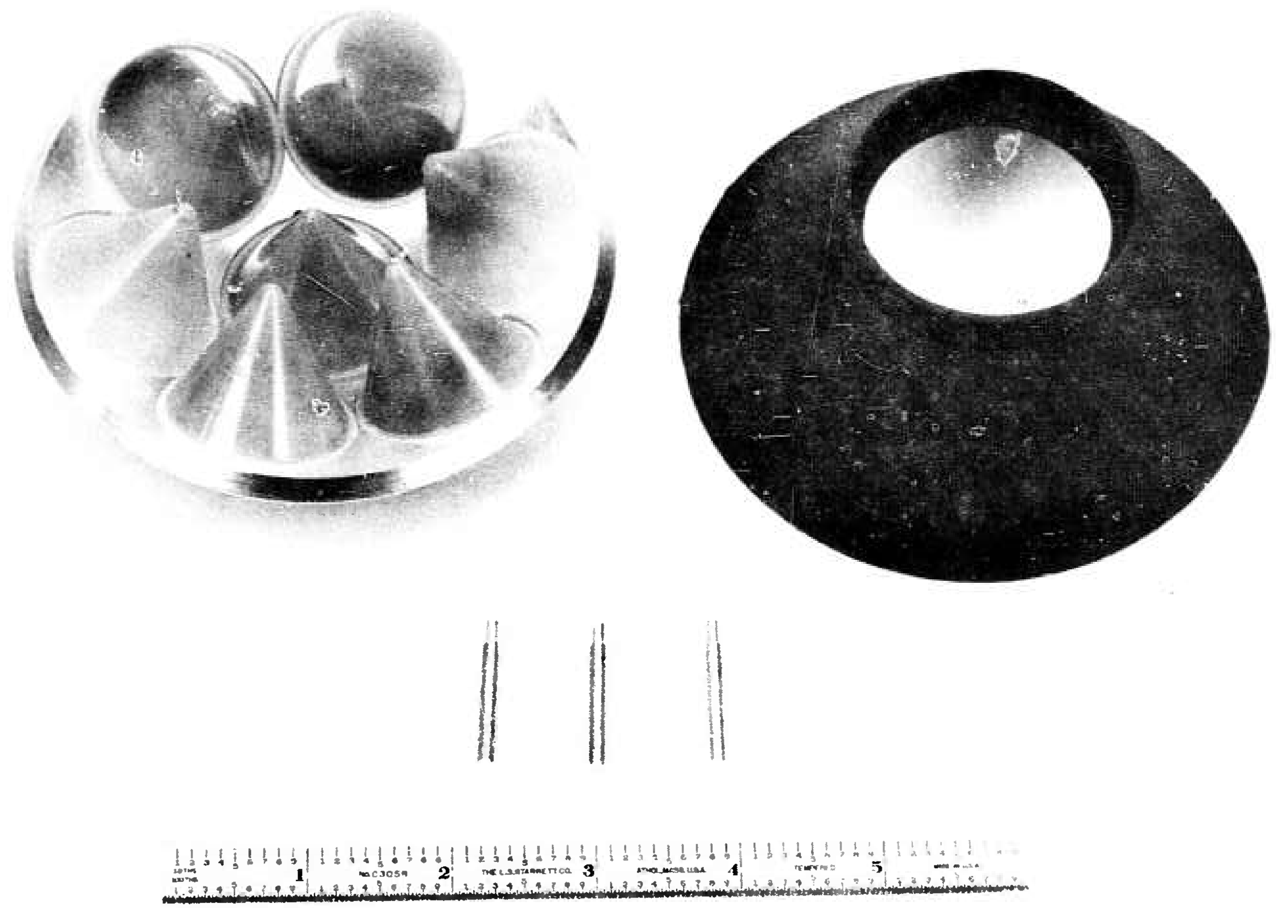
The multi-jet capsule was placed on the target with a one-inch standoff. The target consisted of a stack of 3 one-inch thick, 6061-T6 aluminum plates that were 12 inches square. The results of the firing tests are shown in Figures 3-19 and 3-20.

In Figure 3-19 the #1 capsule is shown on the right side of the first plate. This test proved that the multi-jet capsule was capable of producing seven individual jet penetrations into the target. The center and the 3 upper jets completely perforated the plate, while the remaining 3 only penetrated into the plate.



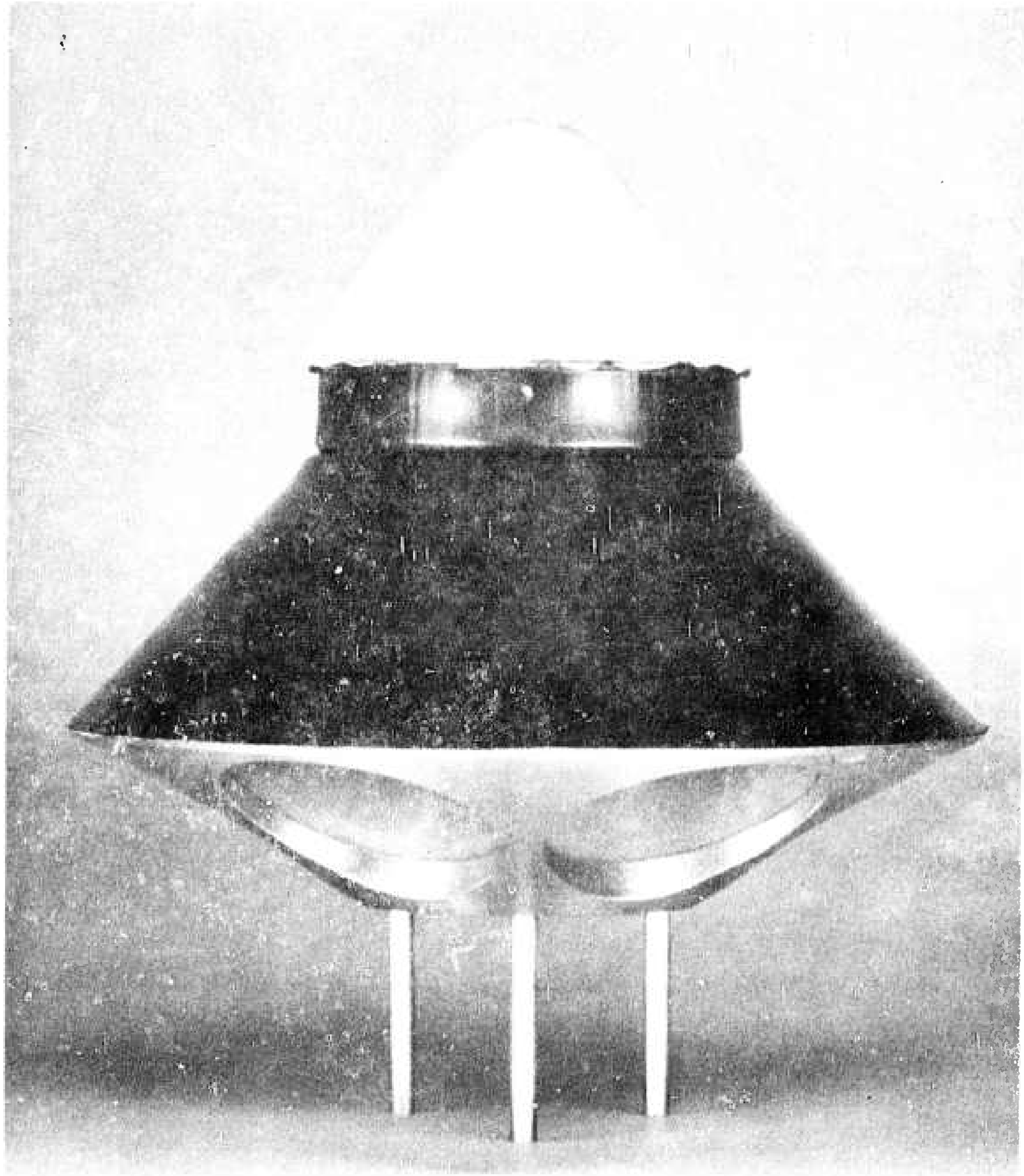
#1 MULTI-JET TEST CAPSULE COMPONENTS

FIGURE 3-15



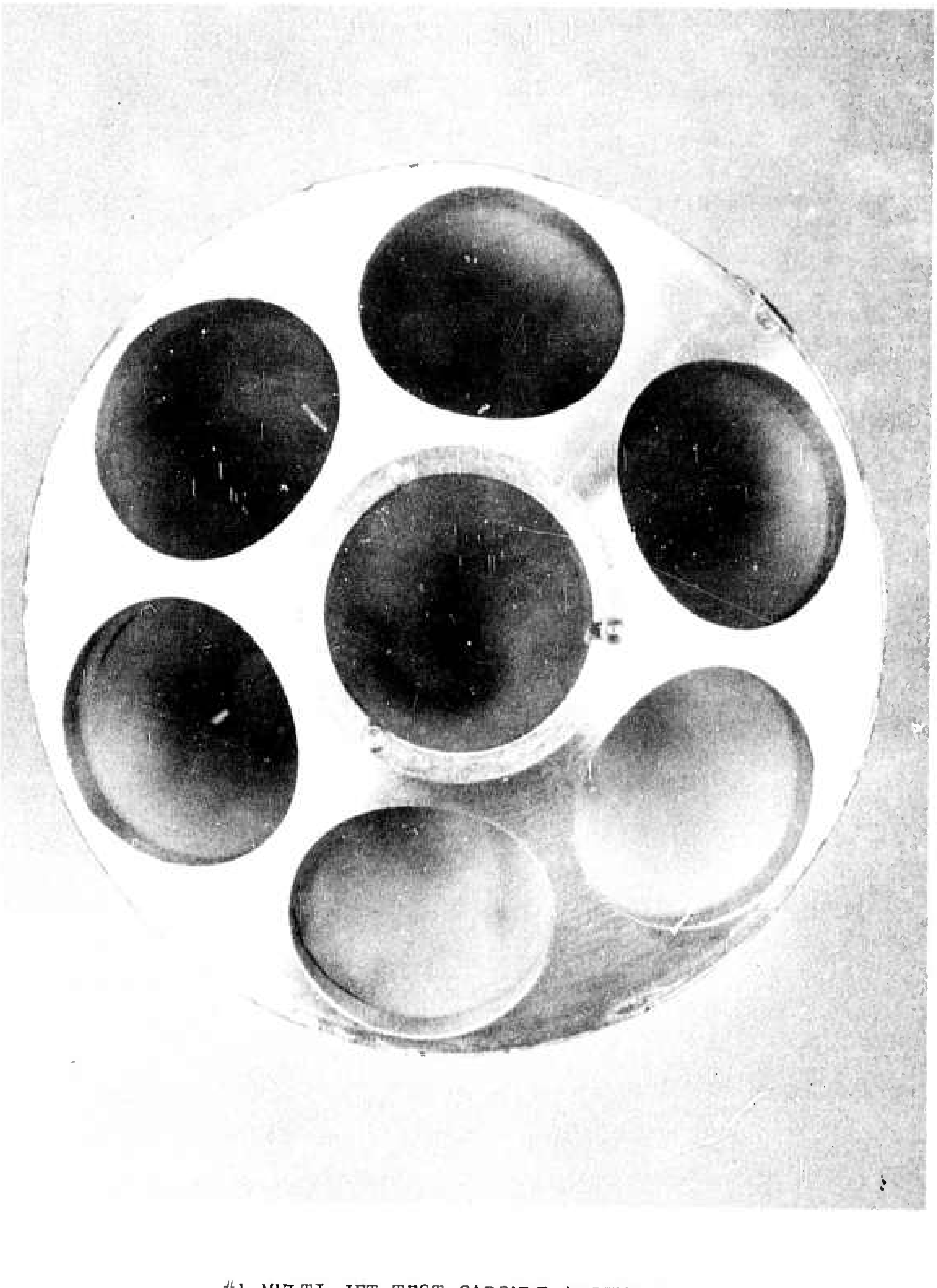
#1 TEST CAPSULE WITH GRP LINERS
POSITIONED IN THE CAPSULE HEAD

FIGURE 3-16



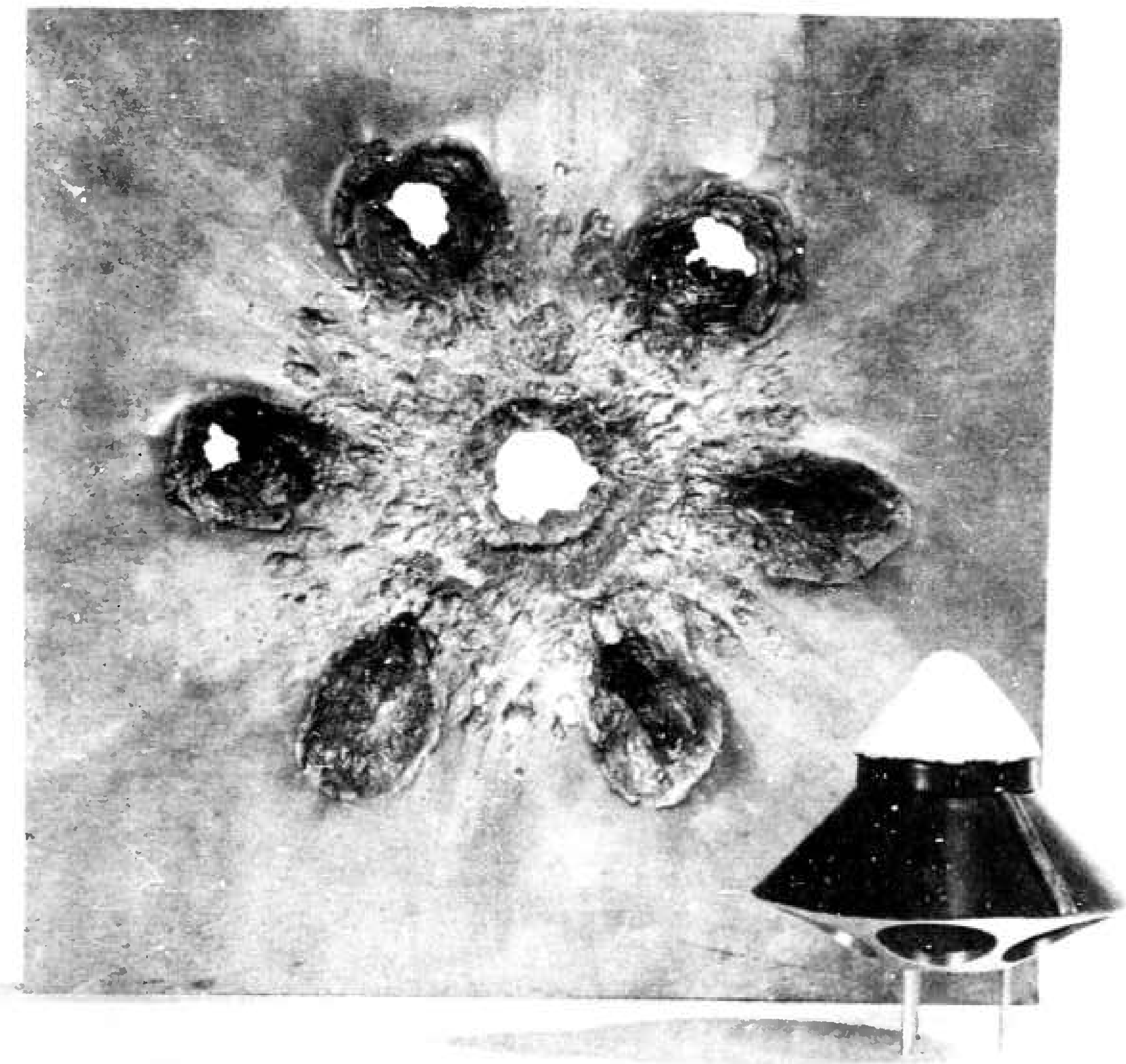
#1 MULTI-JET TEST CAPSULE ASSEMBLY
SIDE VIEW WITH STANDOFFS FOR STATIC FIRING

FIGURE 3-17



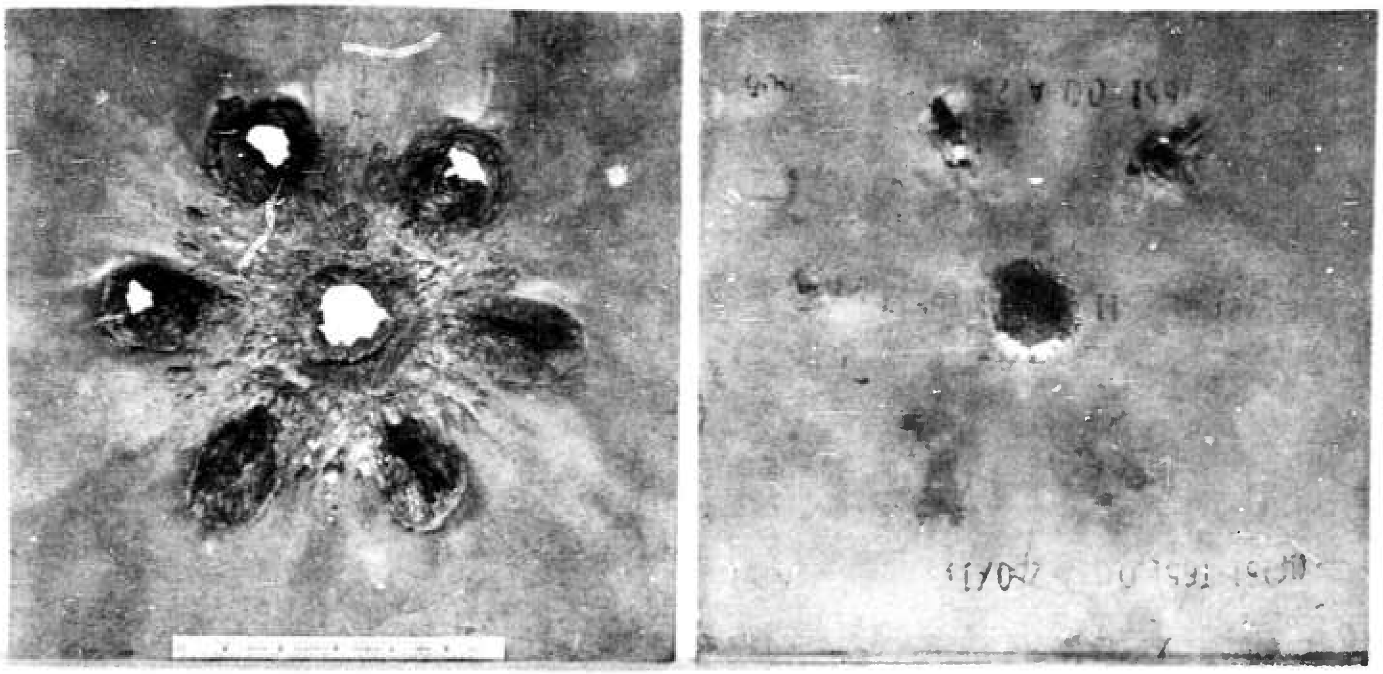
#1 MULTI-JET TEST CAPSULE ASSEMBLY
BOTTOM VIEW OF HEAD END

FIGURE 3-18



#1 MULTI-JET TEST CAPSULE AND 1st TARGET PLATE

FIGURE 3-19



#1 MULTI-JET TEST CAPSULE RESULTS
FRONT FACES OF 1st & 2nd TARGET PLATES

FIGURE 3-20

Figure 3-19 shows the front face of the first target plate on the left and the jet penetrations produced in the second target plate. The third plate was warped with indent marks from jet force and blast effects conducted through the first and second plates.

(2) #2 Test Capsule

The #2 capsule design and its terminal effects against the aluminum target plates are described in the following six figures.

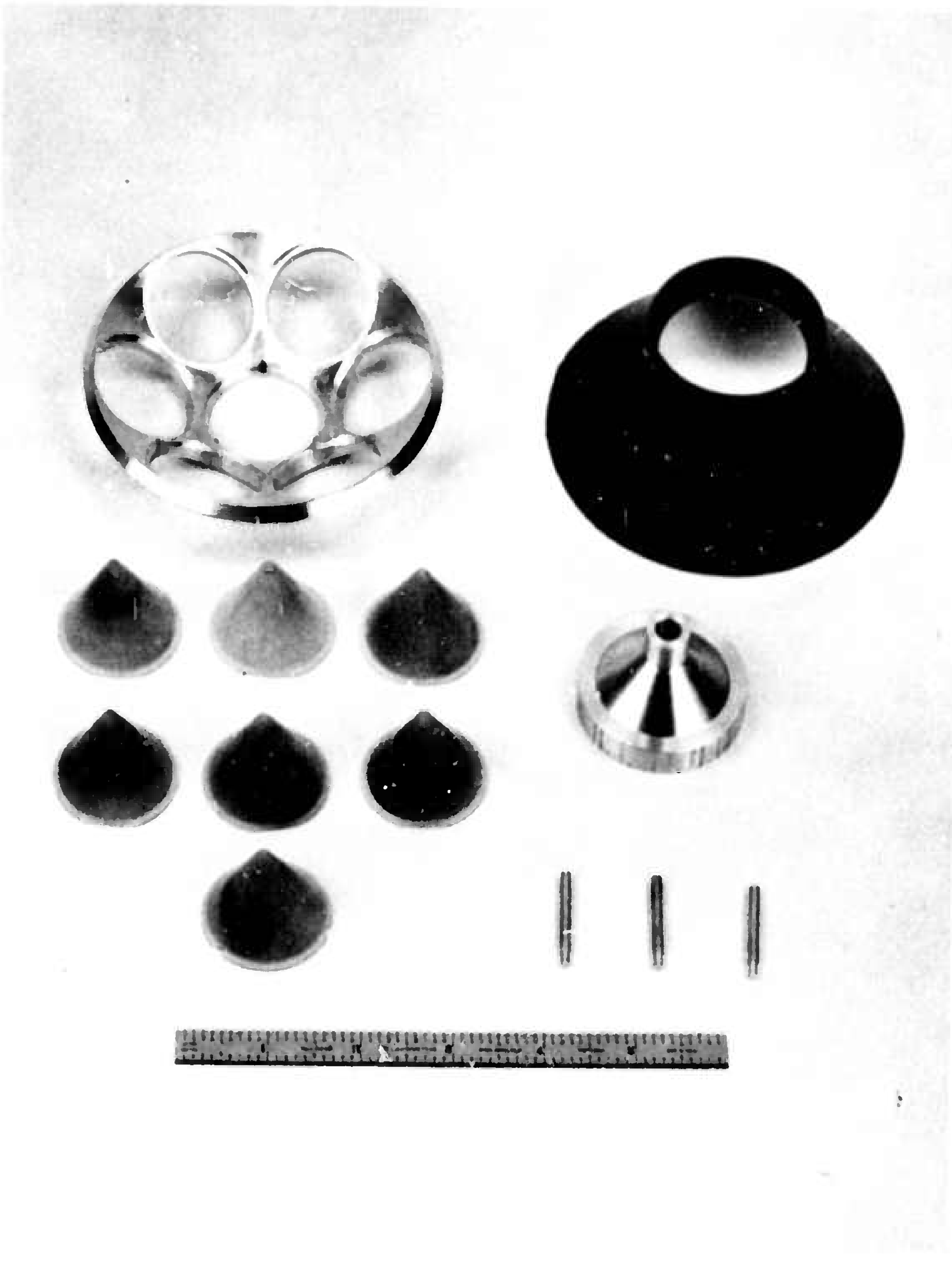
The components and assembly of the #2 capsule, shown in Figures 3-21 through 3-23 inclusive, are identical with those of the #1 capsule except for two modifications. The first change involved the bonding of the seven GRP liners to the counterbored holes of the head to prevent possible movement of the liners during the capsule loading operation. The second revision involved the fabrication of a detonator holder to accurately position the detonator in relation to the liners and thus assure improved shape of the detonation wave. The #2 capsule was loaded with 255.5 grams of C-4 and was also fired into 3 one-inch thick 6061-T6 aluminum plates. In this case the 3 plates were bolted together to provide a more homogeneous target, however, the bolts failed.

The #2 capsule was fired into the target plates with a one-inch standoff on the center liner. The terminal effects of the #2 capsule shot are shown in Figures 3-24 through 3-26, inclusive.

Figure 3-24 shows the front face of the first target plate. The refinements incorporated into the #2 capsule considerably improved the terminal effects over the #1 capsule shot. The 7 jets completely perforated the first plate (Figure 3-24) and penetrated the second plate, whereas the third plate, not shown, was warped and dented by the 7 jets. Figure 3-25 shows the back face of the first plate and Figure 3-26 shows the front faces of the first and second plates.

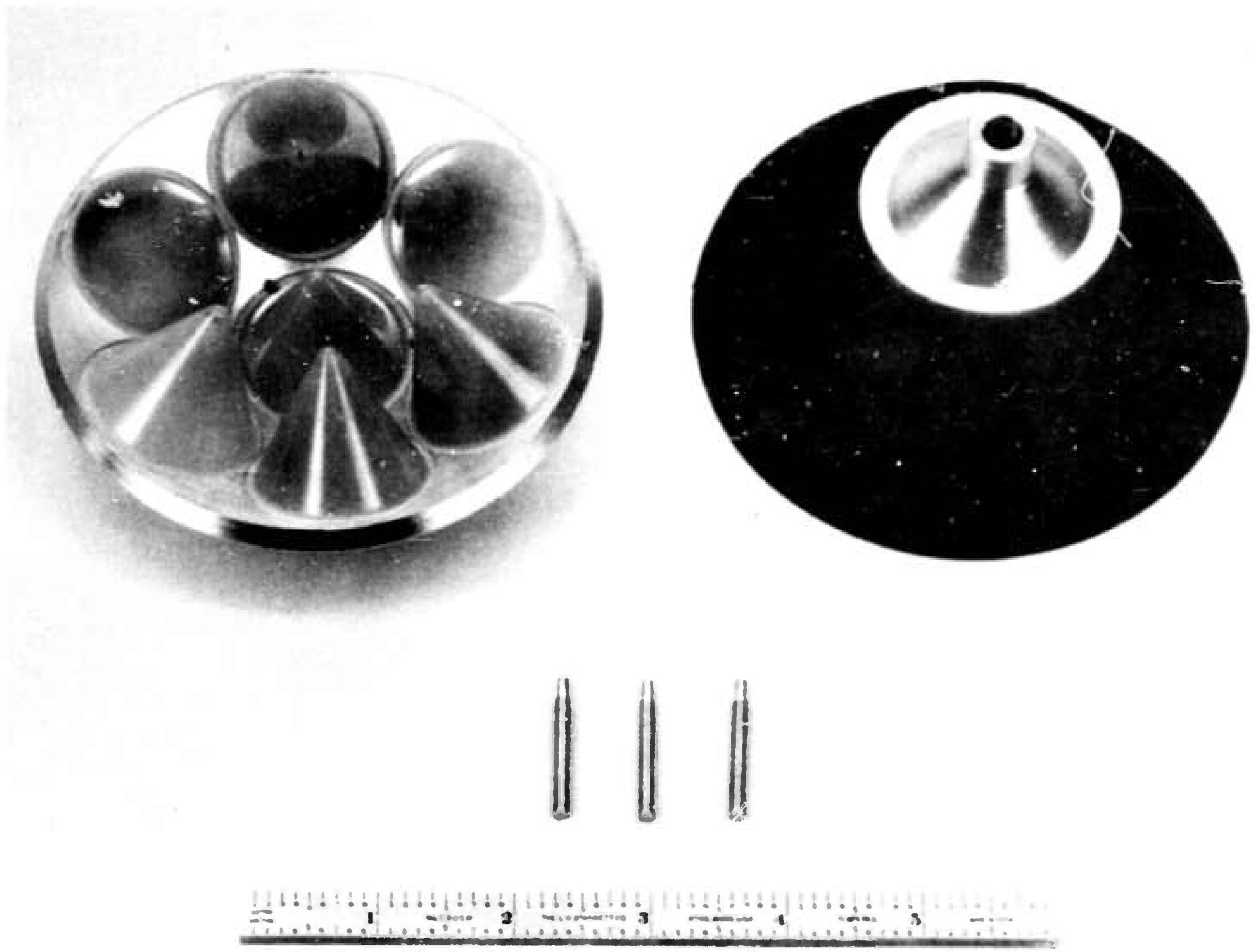
(3) #3 Test Capsule

In order to increase the downward penetration rate and to decrease the bore diameter that would be produced, new configuration capsules were built in which the conic liners were mounted at 40° included spread angle instead of 60°. Due to the smaller angle the explosive column became somewhat longer in order to place the detonator at the intersection of the axes of the liner cones. The explosive weight was thus increased slightly.



#2 MULTI-JET TEST CAPSULE COMPONENTS

FIGURE 3-21



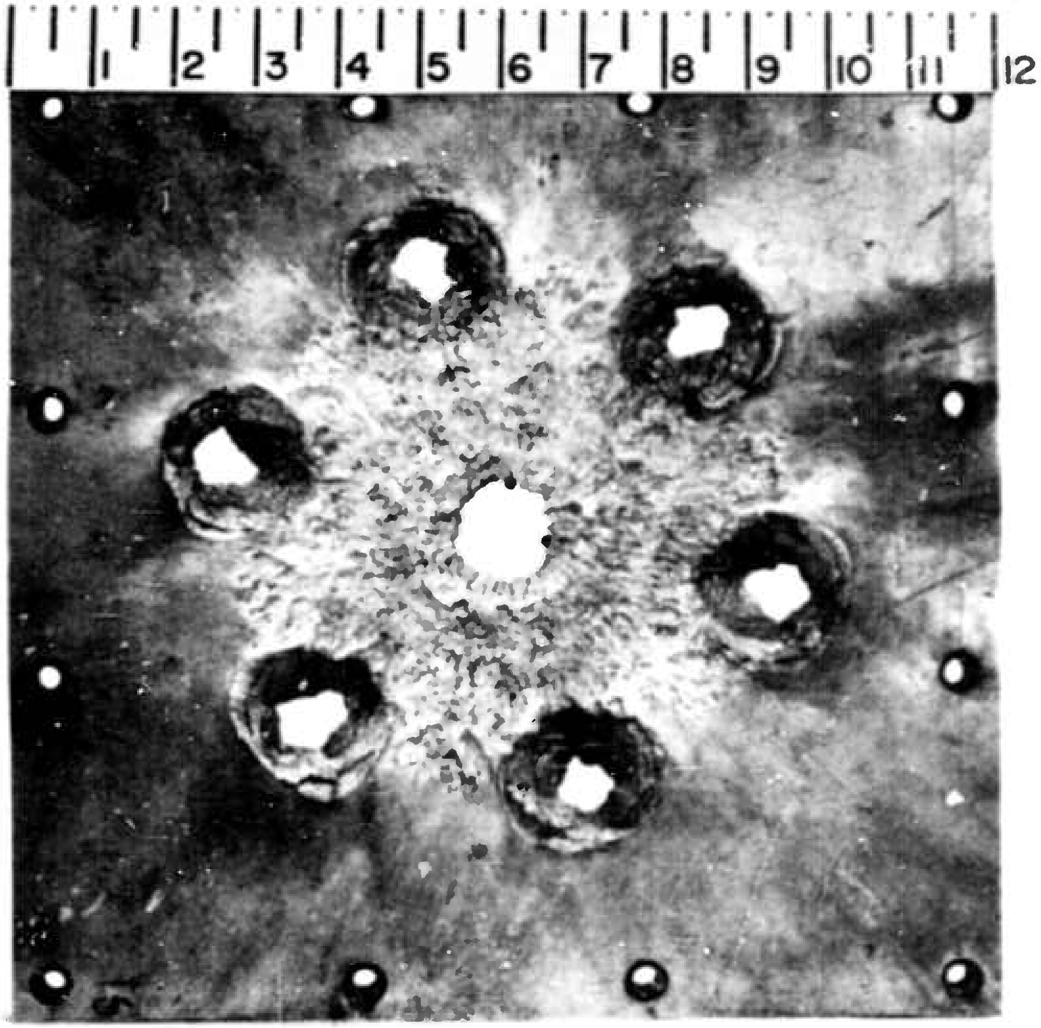
#2 MULTI-JET TEST CAPSULE COMPONENTS
WITH GRP LINERS BONDED TO HEAD

FIGURE 3-22

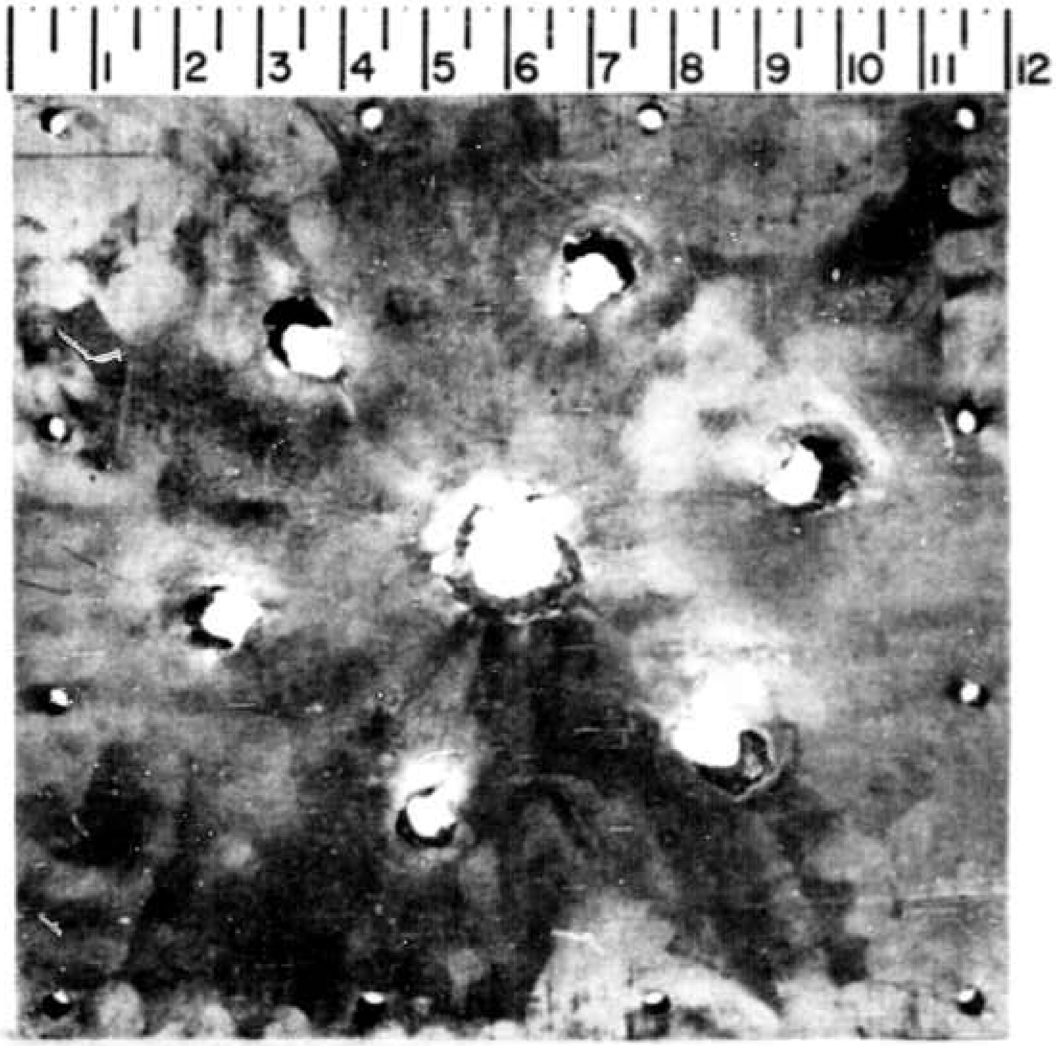
#2 MULTI-JET TEST CAPSULE ASSEMBLY

SIDE VIEW

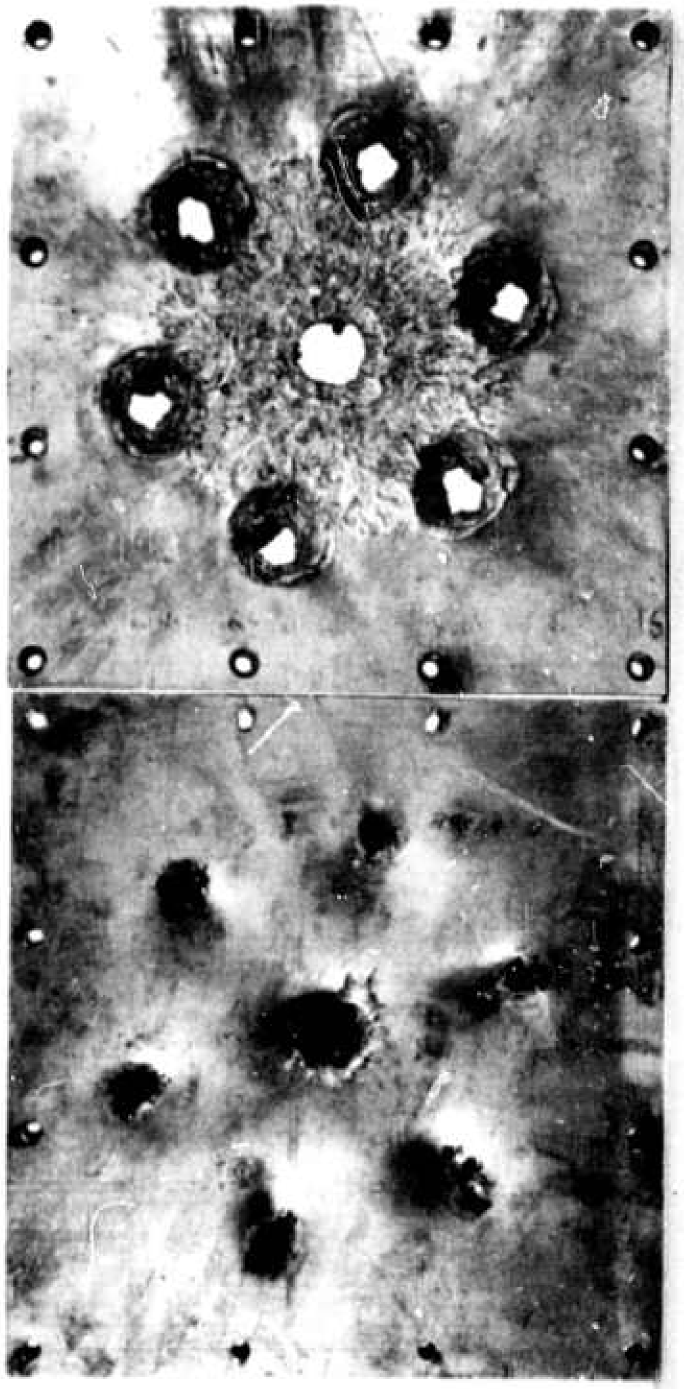
FIGURE 3-23



#2 MULTI-JET TEST CAPSULE
FRONT FACE OF 1st TARGET PLATE
FIGURE 3-24



#2 MULTI-JET TEST CAPSULE
BACK FACE OF 1st TARGET PLATE
FIGURE 3-25



#2 MULTI-JET TEST CAPSULE

FRONT FACES OF 1st & 2nd PLATES

FIGURE 3-26

The #3 capsule was loaded with 294.5 grams of C-4 and contained seven .040" thick molded GRP conic liners. Figure 3-27 is the face surface view of the first of the three plate stack of witness plates. The witness plates for this test were not bolted together as the results of capsule test #2 showed that there is no value to this practice. Stand-off was increased from 1.00" to 1.25". Figure 3-28 shows all three witness plates. Notice that the results are very similar to the previous test except that the pattern was reduced by the change of spread angle to 40°.

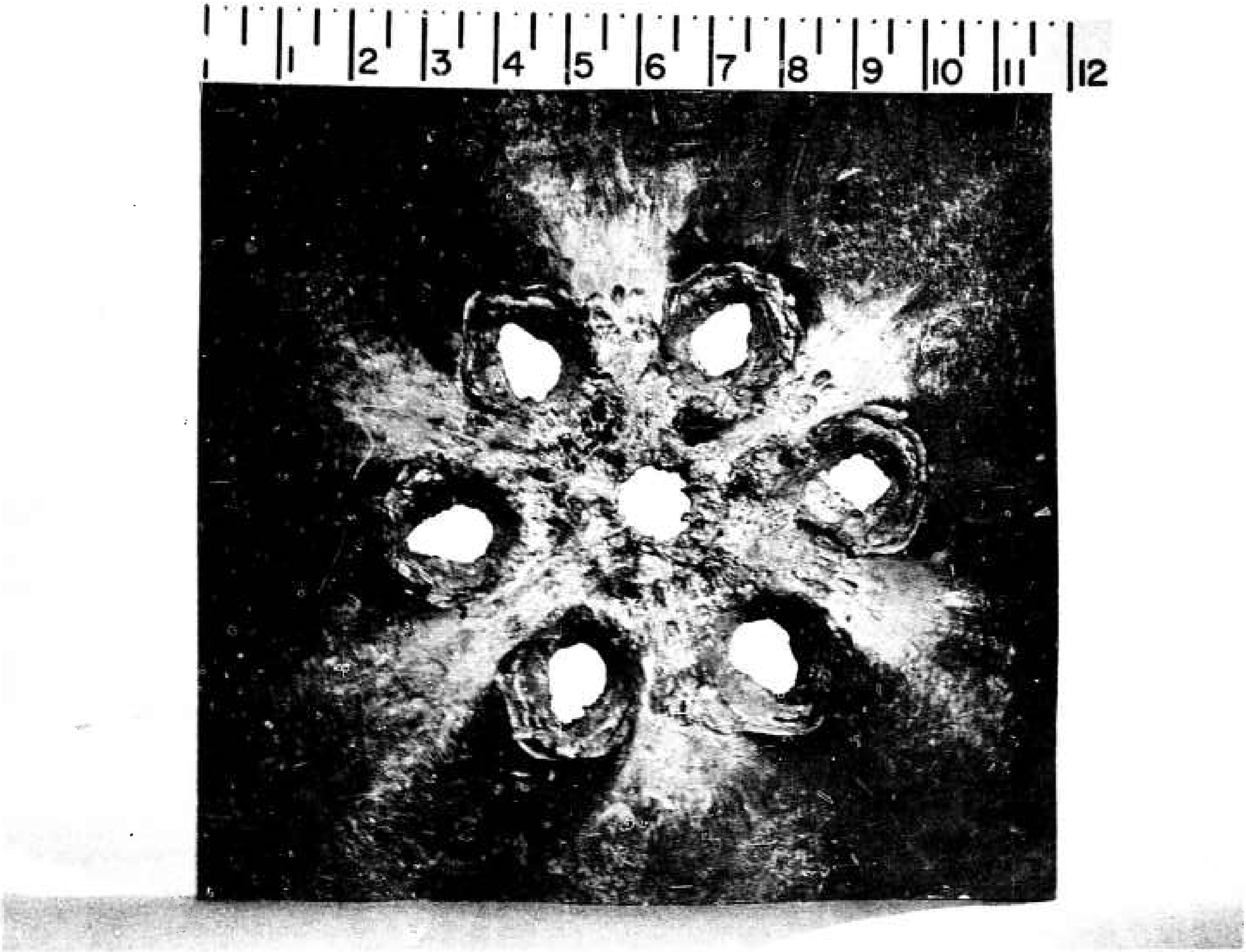
(4) #4 Test Capsule

The fourth capsule was practically identical to the #3 capsule except that the shaped charge cones were made .160 thick instead of .040 as in all the previous capsules. The results of this change are shown in Figures 3-29 and 3-30. Notice that instead of merely penetrating the second inch of 6061-T6 aluminum, the second plate is completely perforated in all seven places. The third plate was penetrated six places up to .6" deep. The center jet did not penetrate the third plate but produced larger holes in the first two plates than the peripheral jets. This indicates that stand-off should be greater than 1.25".

(5) Test Capsules (5 through 11) Fired Underwater

After the foregoing tests, seven additional multi-jet capsules were test fired underwater. The tests started at the bottom of an 18" deep hole in the quarry rock previously made by five cluster units of commercial shaped charges. The first capsule was placed at the 18" depth, the hole was filled with water and the capsule was fired. The hole was drained, the remaining loose spoils were removed and the hole dimensions measured. Each of the remaining capsules was fired in sequence in the same manner. The results of these tests are graphically presented in Figure 3-31 which shows that the seven multi-jet capsules extended the depth of the bore-hole from 18" to 60". The total excavation depth of 42" in rock for the seven multi-jet test capsules provides an average of 6" depth per capsule. The legend shown in Figure 3-31 indicates the variation in parameters for each of the seven multi-jet test capsules (#5 through #11).

The test results presented in Figure 3-31 illustrate that the greatest depth of penetration was produced by capsule #8 with #10 as a close runner up. Both capsules used the .160" wall thickness cones. The difference in effect, if any, in regard to the outer cone ring spread angle of 60° on #8 and 40° on #10 is considered insignificant. It is noted that the explosive charge weight of #8 capsule was smaller than that used in #10. However, the 40° spread angle does have the advantage of concentrating the jets in a more downward direction.



#3 MULTI-JET TEST CAPSULE TARGET PLATE

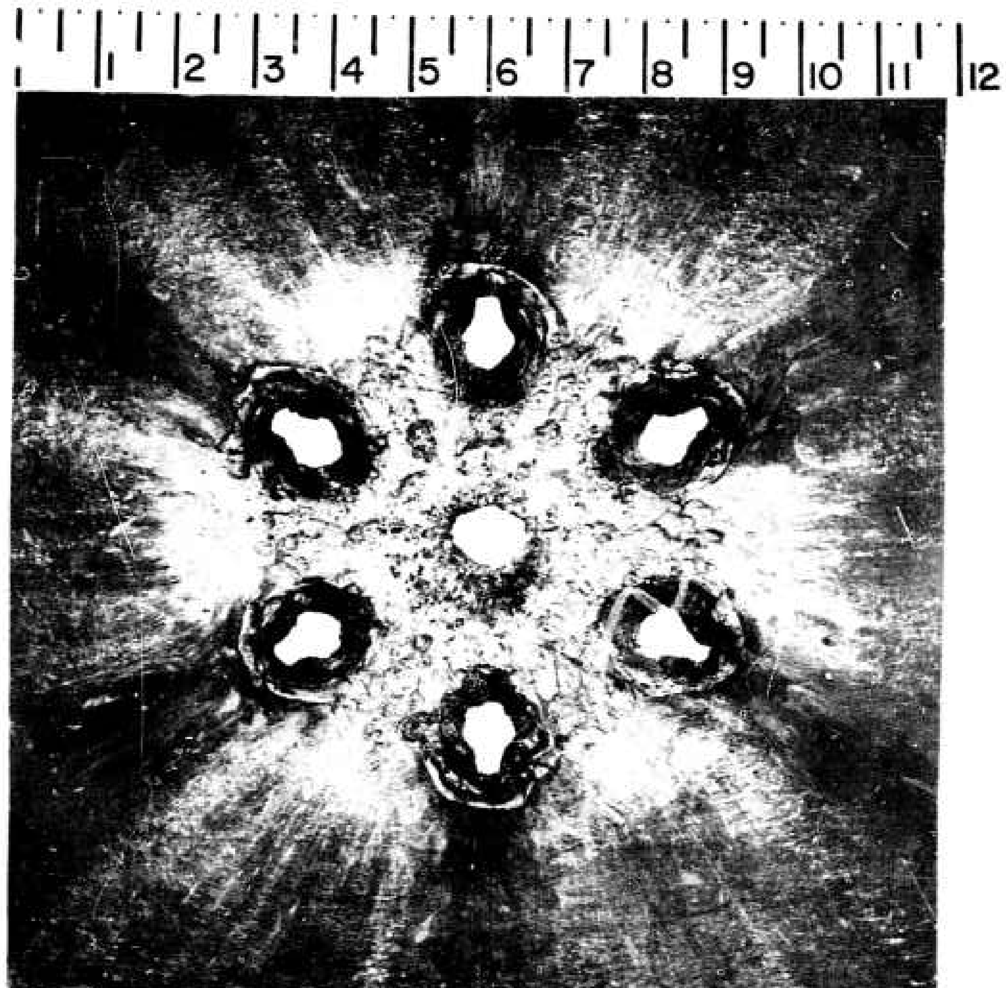
PLATE #1 - FRONT FACE

FIGURE 3-27

#3 MULTI-JET TEST CAPSULE TARGET PLATES

FRONT FACES - PLATES 1, 2 AND 3

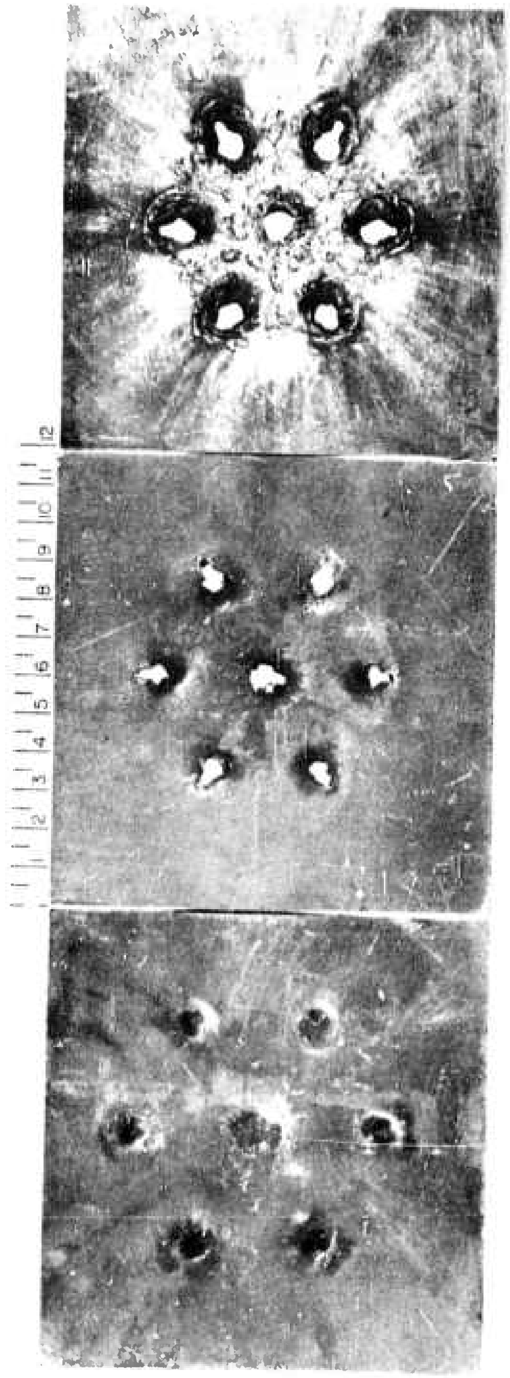
FIGURE 3-28



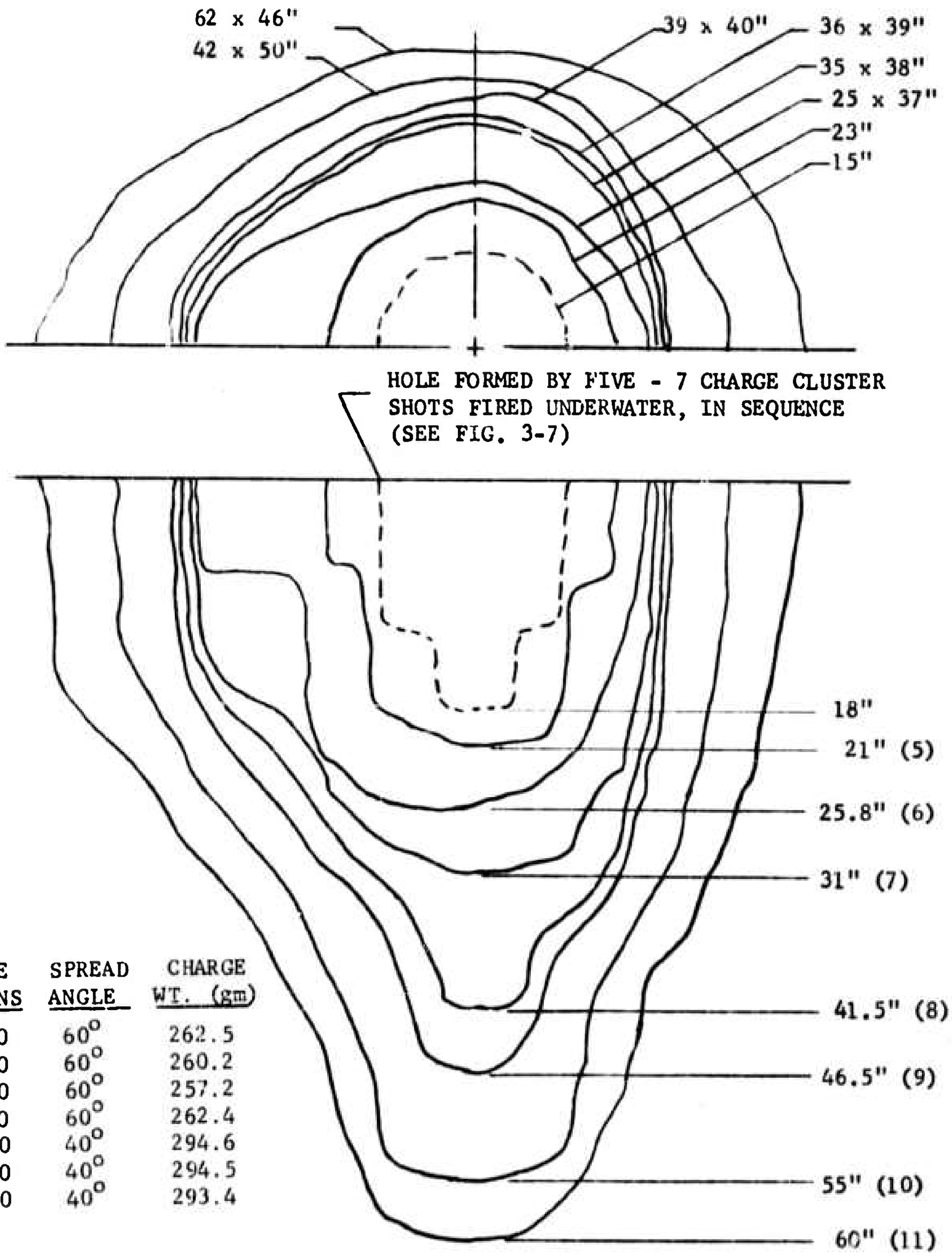
#4 MULTI-JET TEST CAPSULE TARGET PLATE

PLATE NO. 1 - FRONT FACE

FIGURE 3-29



#4 MULTI-JET TEST CAPSULE TARGET PLATES
FRONT FACES - PLATES 1, 2 AND 3
FIGURE 3-30



TEST NO.	CONE THKNS	SPREAD ANGLE	CHARGE WT. (gm)
5	.040	60°	262.5
6	.160	60°	260.2
7	.040	60°	257.2
8	.160	60°	262.4
9	.040	40°	294.6
10	.160	40°	294.5
11	.160	40°	293.4

MULTI-JET DRILLING TEST

CAPSULES #5 THRU 11 INCLUSIVE

FIGURE 3-31

The multi-jet test capsule firings "over killed" the Cockeysville marble at our test site as planned; therefore, we predict that the multi-jet capsule will be very effective against granite and basalt. In the explosive drilling of hard rock, such as granite and basalt, the hole diameters will be considerably smaller than those achieved in the Cockeysville marble of Figure 3-31. The smaller hole diameters will be extremely beneficial in the removal of the disintegrated material or muck from the borehole. The rate of advancing the working face at the bottom of the borehole when drilling the harder rock will be less than the 6" depth average capsule. However, when the final drilling rig transports the capsules down the drill tube at a rate of 600 SPM or 10 shots per second, the working face will be advanced more rapidly. The best way to destroy any target is to place the maximum number of shots against the target in the shortest time possible. This should also apply to rock drilling. The first capsule will provide the 7 jet penetrations which will fill with water, the second capsule will provide 7 more jet penetrations and its detonation wave will act against the water in the jet penetrations and the overpressure will cause the rock to rupture and disintegrate between the jet holes.

3. Final Multi-Jet Capsule

a. General Discussion

The final capsule design is described in this section to maintain continuity with the development of the multi-jet capsule described above. The work performed in the hydroballistic tests, the fuze development and the development of the drill rig, contributed to the final capsule design and are discussed later in the report.

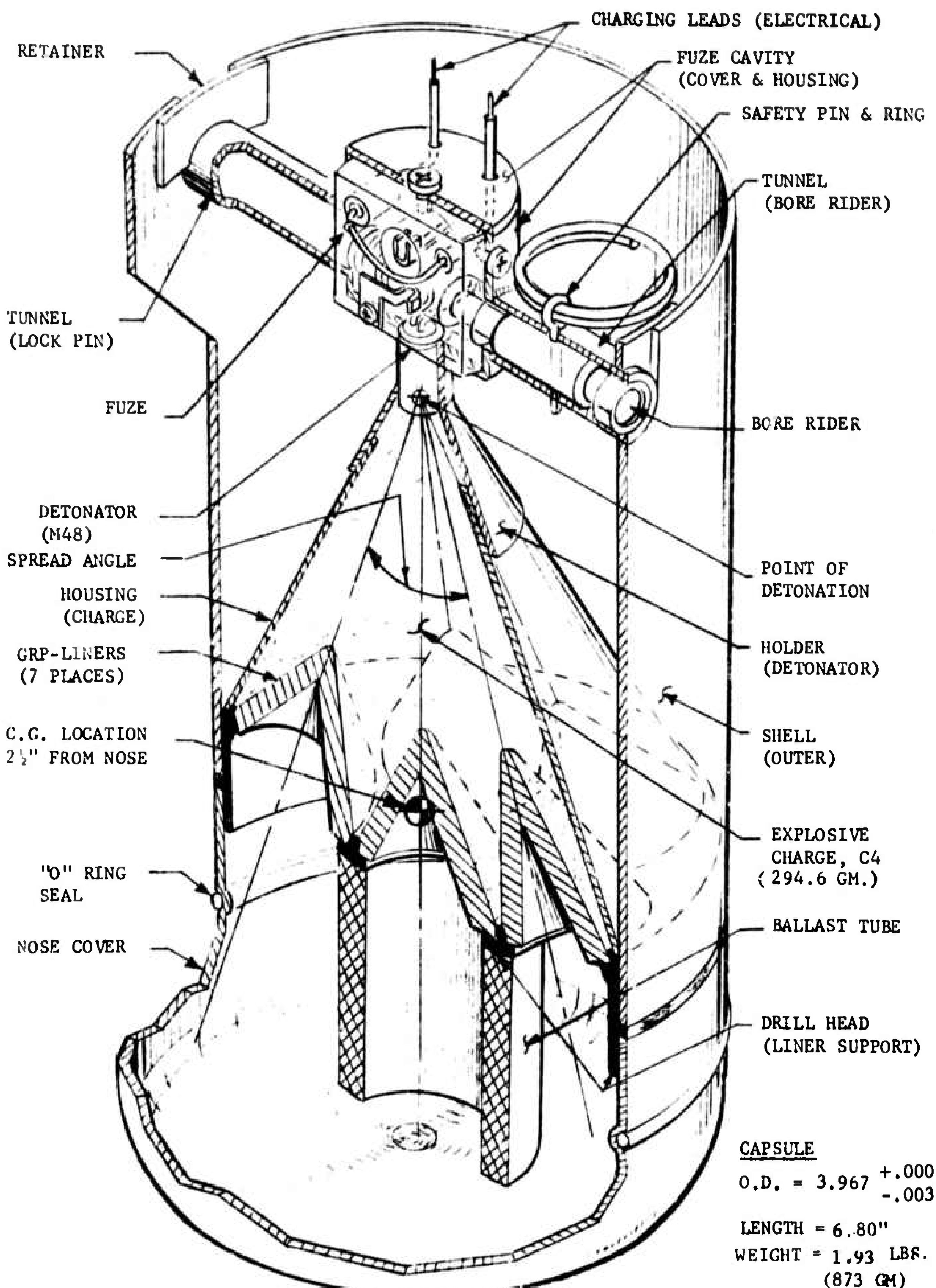
The final capsule was designed and fabricated from aluminum components, incorporating seven glass-reinforced plastic (GRP) liners. We were unable to fabricate the ultimate capsule with the all GRP components due to lack of contract funds. However, due to the high rate of fire predicted for the ultimate explosive drilling system, the all GRP component capsule will be required to take advantage of the economical capsule production inherent in the injection molding process. Using this process, the number of capsule components could be reduced by integrating two or more parts in a single mold. Due tothe funding problems, the fabrication of the ultimate GRP-type capsule was set aside and we proceeded with the design and fabrication of the final aluminum component capsule described herein. The cognizant USBM personnel concurred with this change in plan. A limited quantity of the aluminum capsules were specifically designed for dynamic testing of the capsule in the experimental drill rig developed under this exploratory program.

An artist's sketch of the final capsule is shown in Figure 3-32. A disassembled view of the capsule components is shown in Figure 3-33 and an external view of the assembled capsule is presented in Figure 3-34.

The capsule was designed to withstand the dynamic loads it will encounter during the drilling system operations. The capsule loads are induced during the following operations: handling, loading, feeding, and while being transported down the drill tube. The capsule must be capable of withstanding the external overpressure applied through the water/air buffer to the following capsule, when the leading capsule is detonated. In addition, the capsule is required to take the external pressure during its underwater path from the end of the drill tube to impact at the bottom of the borehole. Since the water/air anti-sympathetic detonation buffer is provided between the capsules in the drill tube, the capsule loads at this point are small, and depends on the pressure differential between the buffers above and below each capsule. The train of water/air buffers between the capsules is transported down the drill tube, as a column, at about 50 feet per second. As the train proceeds, the leading capsule will exit from the bottom of the drill tube and strike the bottom of the borehole, initiating the fuze and detonating the capsule. The resulting overpressure force on the water in the dril tube will compress the air in the buffer, against the face of the following capsule. It is to be noted that this force will also be transmitted to all other capsules and buffers in the tube and help to dissipate the force. The value of the compressed air force against the capsules is a function of capsule spacing and the length of the water/air buffers between the capsules. It was planned to determine the optimum capsule spacing during the drill rig tests. After analysis of the loads, the capsule was designed to withstand an external pressure of 2,000 pounds per square inch (psi), which is far greater than any load to be experienced by the capsule. The 2,000 psi design load represents a pressure at an underwater depth of 4,500 ft., which would be encountered in deep hole drilling. The design pressure could be increased for greater depth if desired.

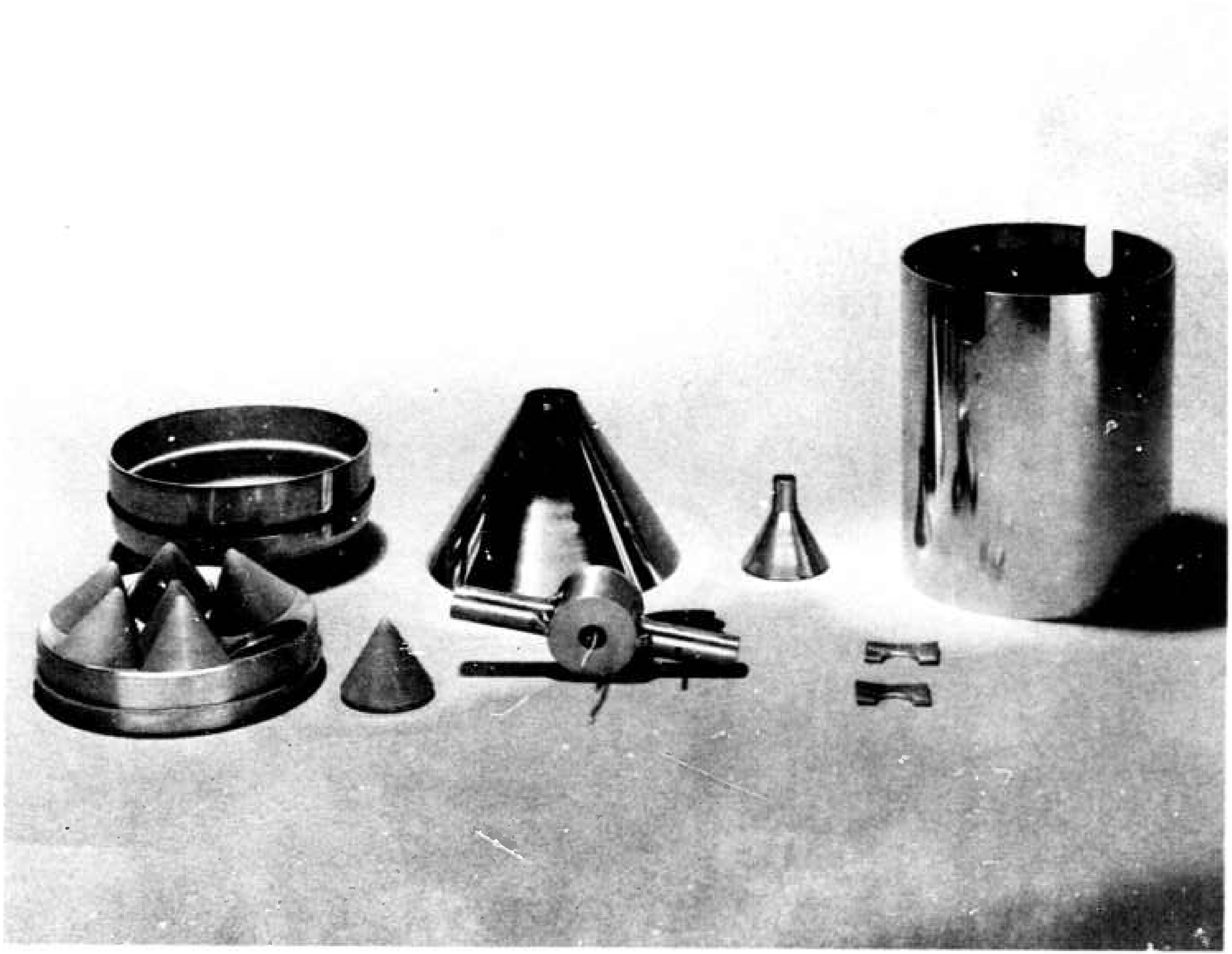
The following describes the capsule components and their fabrication methods (refer to Figures 3-32, 3-22, & 3-34).

The nose cover, charge housing, and detonator are spun from aluminum sheet and are heat-treated and aged to a final condition of 6061-T6. The nose cover thickness varies from .083" at the center of the header dome to .066" at the side walls. A bead is provided around the periphery of the cover for an "O" ring seal and also adds strength to the cover. The charge housing and the detonator holder are .032" thick. The outer shell is machined from a 4" O.D. x .083" wall aluminum tube. The outer surface of the tube is machined to 3.967 (+.000, -.003) diameter and its remaining thickness is .066. The fuze cavity is machined from round aluminum (6061-T6) bar stock and the two aluminum tube extensions are welded to the fuze cavity.



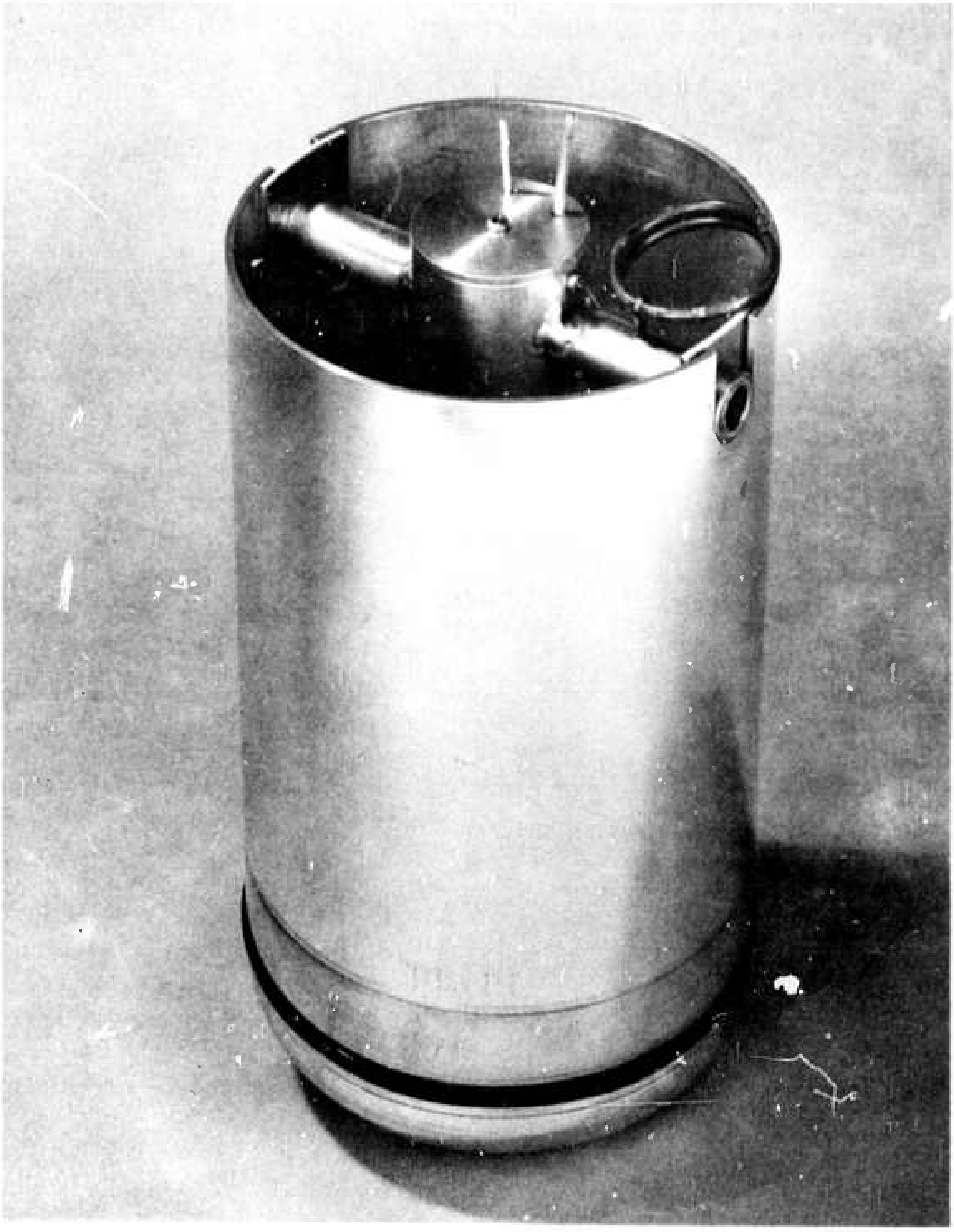
FINAL MULTI-JET CAPSULE

FIGURE 3-32



FINAL MULTI-JET CAPSULE COMPONENTS

FIGURE 3-33



FINAL MULTI-JET CAPSULE
EXTERNAL VIEW

FIGURE 3-34

The fuze cavity/tube subassembly is welded in position to the outer shell using the two curved retainer plates as shown in Figure 3-32. A special fixture is required for this welding operation to assure that the counterbored hole in the base of the fuze cavity will align with the detonator holder during final assembly of the capsule. The extension tubes provide tunnels for the bore rider on one side and a lock pin on the other. The solenoid operated lock pin mentioned here is provided in the magazine feed on the top of the drill tube.

The drill head is machined from 2024-T4 aluminum round bar stock. Seven counterbored holes are machined into the head for the seven GRP liners. The counterbore for the center hole is 1.300" and the six equally spaced counterbored holes in the outer circle are 1.260". The drill head incorporates an outer flange and an external shoulder ring which separates the cover and outer shell during assembly. The drill head also incorporates a notched groove to receive the bottom of the charge housing cone.

The seven GRP shaped charge liners were machined from molds produced in the same injection mold previously used to make the test specimens for the individual GRP liner tests. The liners selected for the final capsule are the same as previous liners, except these liners have wall thicknesses of .200". The cone diameter of the center liner is 1.300" diameter whereas the six liners in the outer circle are 1.260" diameter. The latter cone diameters were reduced from 1.300" to 1.260" diameter in order to stay within the 3.967 (+.000, -.003) O.D. of the capsule. Liners with .200" thick walls were not available at the time the multi-jet test capsules were fabricated and tested. The .200" thick liners were made and tested at a later date and the average results of these tests are shown as items 18 through 21 inclusive in Figure 3-12 on page 3-19. These units produced the deepest jet penetrations into the concrete pad and were selected for use in the final capsule design. The six liners in the outer ring are aligned on a 40° included spread angle with its apex located at the point of detonation on the longitudinal axis of the capsule.

A ballast tube is added between the bottom of drill head and the inside of the nose cover at the center line of the capsule (see Figure 3-32). The purpose of the ballast tube is to add weight to the nose end of the capsule to bring its c.g. location to 2-1/2" from the nose to approach the 2.44" c.g. location of the most successful capsule model in the hydroballistics tests. The c.g. location is of prime importance in providing capsule stability during its underwater path from the end of the drill tube to impact on the bottom of the borehole. The performance of the center liner jet or any other jet is not affected by the addition of the ballast tube. It also provides additional support to the nose cover structure when the capsule nose impacts the bottom of the borehole.

The following paragraphs present a description of the loading and final assembly of the capsule.

b. Capsule Loading & Assembly

This section describes the procedures for the loading and final assembly of the multi-jet capsule. The work shall be performed in accordance with the applicable Government and facility standard safety procedures. These procedures are not presented herein, since this operation is a straight-forward loading operation. Any safety procedures specifically peculiar to this operation will be presented in the following description.

Prior to proceeding with the loading and final assembly operations, all capsule components shall be thoroughly cleaned and the following subassemblies should be made to expedite the procedure. In the following discussions reference will be made to Figure 3-32.

The welded subassembly of the outer shell, fuze cavity, and extension tubes and the two retainers has been previously described.

The 7 GRP liners are bonded in their respective counterbored holes in the drill head and the bottom of the charge housing cone is placed in its notch and also bonded to the drill head (see Figure 3-32).

The fuze is completely assembled including the installation of the M48 electric detonator. The lead wires from the M48 to the fuze shall be 1-1/2" long to facilitate its installation on the capsule.

The loading operations and final assembly of the capsule are described below.

(1) Start with the subassembly consisting of the drill head, 7 liners, and the charge housing cone. The internal cavity formed by these parts are to be loaded with 296 grams of C-4 explosive. The drill head subassembly and the detonator holder should be weighed and recorded.

(2) The internal cavity is loaded through the access hole provided at the top of the charge housing cone. The C-4 is a plastic explosive and is hand loaded. The C-4 shall be loaded tightly around the 7 liners and wooden dowels may be used for tamping. The charge shall be packed solid and every effort should be made to avoid inclusions. During the loading operation, the partially loaded subassembly and the detonator should be weighed to determine progress. The drill head subassembly is loaded flush with the top of the charge housing cone.

(3) The detonator holder shall be placed on the charge housing cone as shown in Figure 3-32 and bonded in place. The C-4 loading operation is continued through the hole at the top detonator holder. The C-4 is loaded until the level of the bottom of the M48 detonator or slightly higher.

(4) The subassembly, consisting of the outer shell, fuze cavity and tubes, and the two retainer plates, is installed over the drill head subassembly until the bottom of the shell slides over the drill head flange and the counterbored hole in the base of the fuze cavity is positioned onto the top of the detonator holder. The outer sleeve is pushed over the drill head flange until it bottoms against the shoulder ring on the flange. These two subassemblies are bonded together as shown in Figure 3-32, at the drill head flange and the detonator holder.

(5) The bore rider plunger is passed through the lock pin tunnel, across the fuze cavity and into position in its own tunnel. The hole in the bore rider is aligned with the through hole in the tunnel tube and the safety pin is installed. The safety pin is attached to a ring to facilitate its extraction at the required time in the cycle.

(6) The fuze assembly is the next unit to install. The fuze is oriented to align its slide piston with the bore rider. With the fuze held in this position, the M48 is passed through the fuze cavity housing and into the top of the detonator holder. The wires between the fuze and the M48 are of sufficient length to allow the M48 to be installed. The M48 should be pushed into the detonator holder to contact the C-4. The fuze is then installed into its cavity. Any excess wire from the M48 may be coiled in the counterbored space at the inside bottom of the fuze cavity housing. After the fuze is positioned, a screw is passed through the hole in the side of the cavity and threaded into the fuze plastic housing to retain the fuze in alignment. The head of the retaining screw may be seen in Figures 3-32 and 3-34.

(7) Complete the fuze installation by passing the two electric charging wires, coming out the top of the fuze, through the two holes provided in the cover. The cover is held down by a screw and the cover is bonded to the rim of the fuze cavity housing.

(8) The ballast tube is aligned and bonded to the inside of the nose cover.

(9) Adhesive is applied to the top of the ballast tube and the inside of the straight side walls on the cover. The cover is slid over the drill head flange until it contacts the shoulder on the drill head flange.

(10) The "O" ring seal is installed in the groove provided by the bead on the nose cover.

It is noted that the above procedure is based on hand loading a limited quantity of capsules. In production the capsules could be loaded by casting an improved high explosive charge into its cavity.

The high strength rapid bonding adhesive used to bond the capsule components has performed very well in this application. Its trade name is "Vigor Aron Alphia", distributed by B. Jadow & Sons, Inc., New York, New York, and manufactured by Toagosei Chemical Industry Co., Ltd. This adhesive cures at room temperature in less than a minute and develops a tensile strength of 5,000 psi.

C. HYDROBALLISTIC TEST RIG

1. General

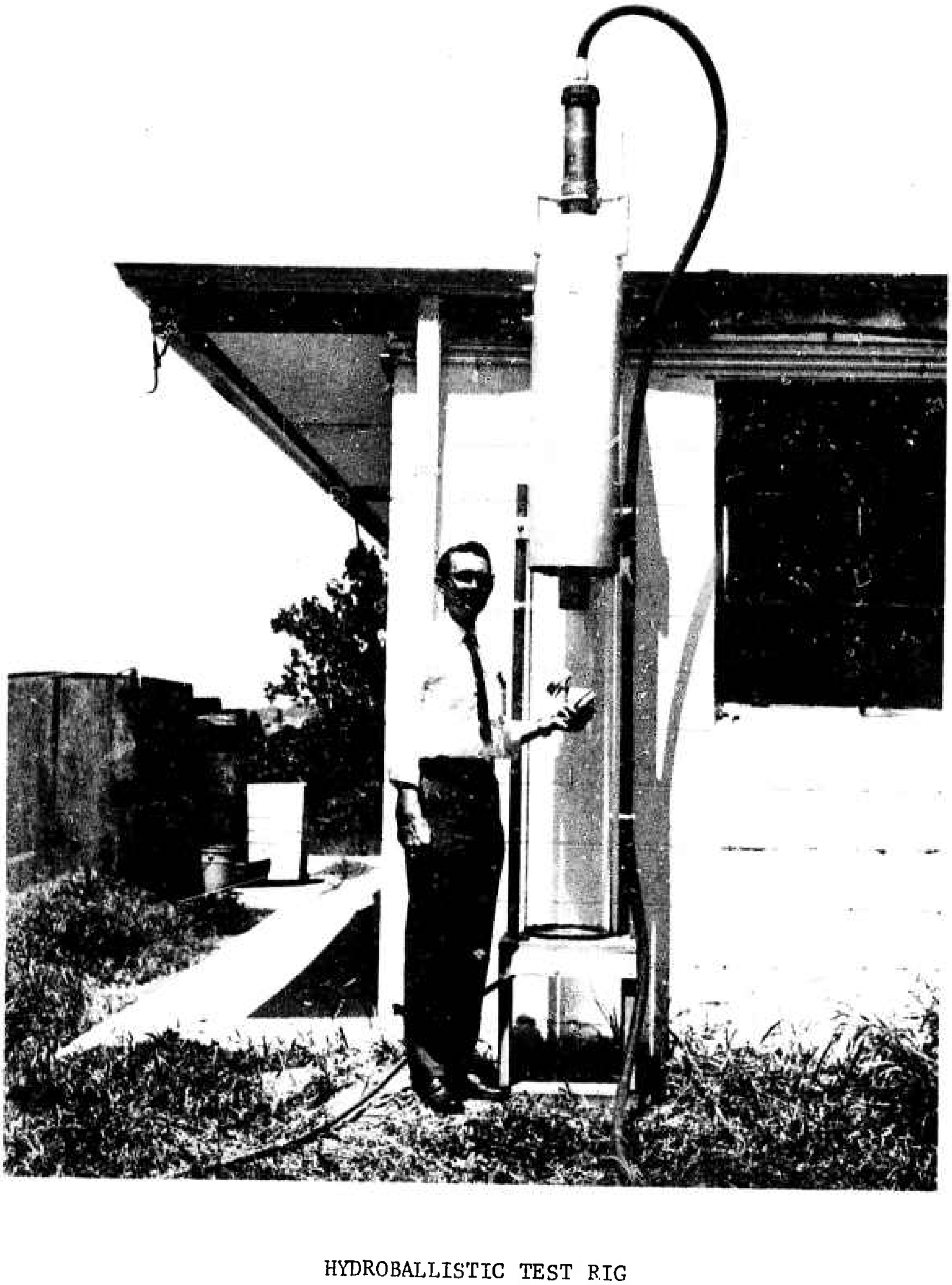
The hydroballistic test rig was designed, fabricated, assembled, and mounted vertically on the wall of one of our buildings, as shown in Figure 3-35. The purpose of the test rig was to determine the underwater stability and ballistics of various multi-jet capsule model configurations. The test rig was designed to simulate the underwater environment of the bore-hole and the drill rig. The parameters to be determined by the test rig were as follows: external capsule configuration; c.g. location; capsule weight; capsule velocity at exit from the drill pipe; capsule velocity and stability throughout its underwater trajectory; capsule impact velocity on striking the bottom of the borehole; and effects of the various injection pressures and test rig set-ups on the capsule performance.

Prior to initiation of hydroballistic testing, explosive tests were conducted to determine the safe proximity of the drill tube and the charge detonation at the bottom of the bore hole. A 290 gram C-4 ball charge was placed at the bottom of the water-filled bore hole. The drill tube was lowered to a distance of 4 feet from the charge. The distance was 2 feet for the second test. The tube was inspected after each test and no distortion or damage was detected. It was determined that the tube in the hydroballistic rig would be located at a distance of 4 feet to provide maximum distance for observation of the capsule trajectory.

2. Test Rig Description

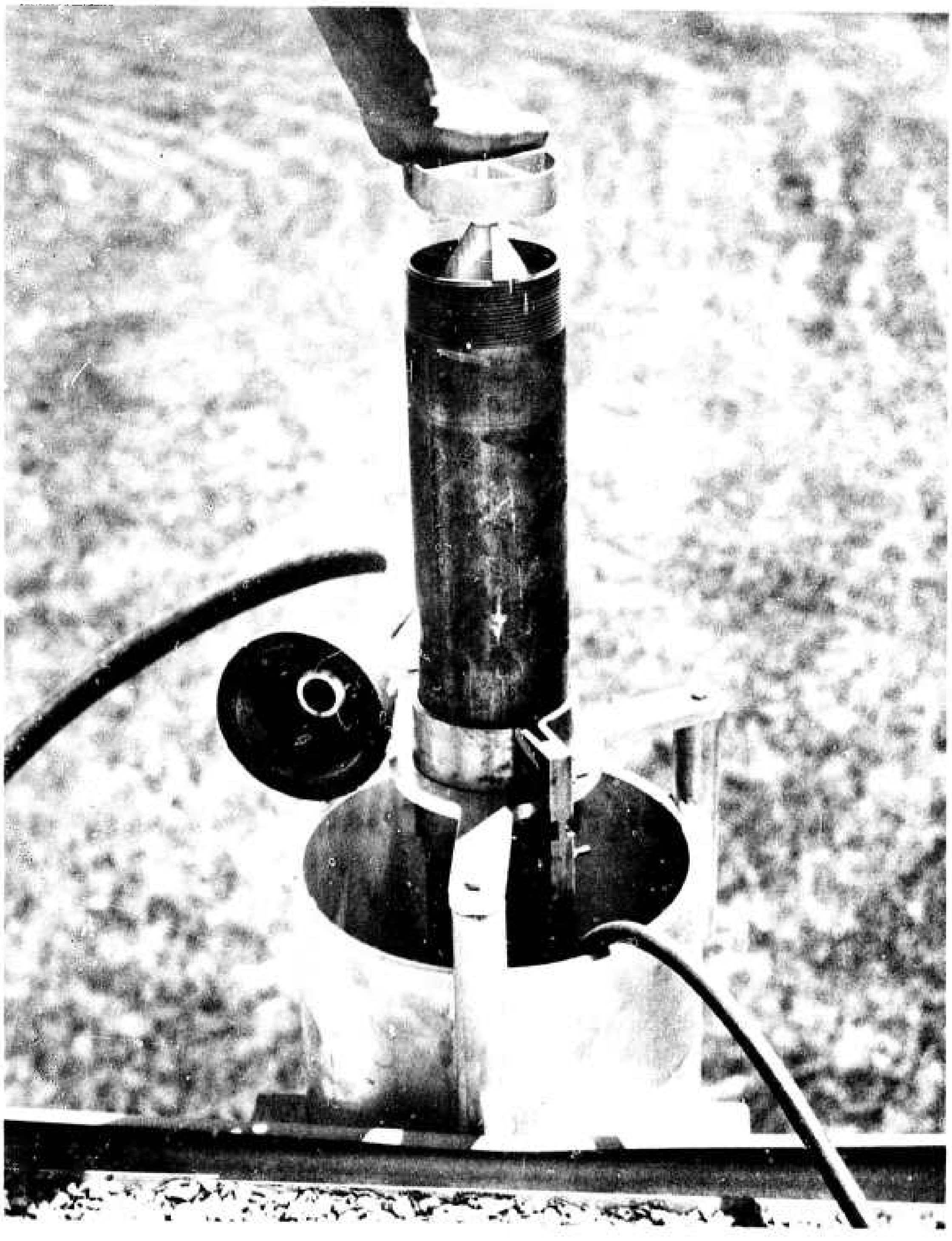
Basically, the test rig consists of an 8-foot long composite tube, 12 inches in diameter, closed at the bottom and open at the top. The upper 4-foot length consists of an aluminum pipe and the lower 4-foot section is a transparent plexiglass tube, which is used for observation of the capsule during test. A 4-inch I.D. steel tube, mounted coaxially with the large tube, is suspended so that its lower end protrudes into the plexiglass tube to provide a means of observation of the capsule model exit (see Figure 3-35).

Figure 3-36 shows the upper breech end of the drill tube that is mounted coaxially with the 12" aluminum pipe through a clamp and spider fitting. The lower end of the drill tube is held concentric with the outer tube by the use of three equally spaced rods. The rods are screwed into the wall of the 4" tube and extend radially to contact the I.D. of the outer tube. Figure 3-36 shows a capsule model being loaded into the drill tube and the breech cap with its flexible air hose attached.



HYDROBALLISTIC TEST RIG

FIGURE 3-35



UPPER BREECH END
HYDROBALLISTIC TEST RIG

FIGURE 3-36

The length of the drill tube was 6 feet long in the test rig shown in Figure 3-35. However, as the test program progressed, it was necessary to extend the length of the drill tube to 9 feet and later to 11 feet long. The additional drill tube lengths were required to conduct tests under various conditions, regarding the capsule model position in the drill tube in relation to the lengths of water and compressed air columns in front of, or aft of, the capsule model. The various test conditions are defined later in this section of the report.

In operation the test rig is filled with water, both the 12" pipe and the 4" I.D. drill tube, to a predetermined level. The capsule model is positioned in the drill tube in relation to the water and air columns forward or aft of the capsule as specified in the test request. The breech cap is installed and a high-speed camera is set up to view through the 12" diameter plexiglass tube. The high-speed camera records the underwater trajectory of the capsule model from its drill tube exit until it strikes the bottom of the simulated borehole. On firing, the high-speed camera is started, a manual control valve is opened, and the pressurized air from the compressor accelerates the capsule and water columns through the drill tube and into the simulated borehole water.

Tne high-speed film is developed and reviewed to determine capsule stability, exit and impact velocities, and effects of the air injection pressures. These data were evaluated and the next test was set up.

The data generated from the hydroballistic test were used in the final design of the multi-jet capsule, the fuze, and the drill rig. With this test rig design, we were able to determine capsule model velocity at any point, observe its attitude, stability, and striking velocity. The striking velocity is an important factor in the design of the fuze/detonator initiation system.

The capsule configuration and other related parameters were developed in the hydroballistic test rig. The following comments are presented to give the reader an understanding of the difficulties overcome during the hydroballistic tests.

The capsule weight of about 1.93 lbs. (873 grams) incorporates positive buoyancy, since an equal volume of water displaced by the capsule is 3.2 lbs. It was planned to conduct hydroballistic tests on the final capsule design to assure the integrity of its underwater performance. However, due to lack of contract funds, the work was stopped. The weight of the final capsule could be readily increased, if necessary, by increasing the weight of the ballast tube in the nose of the capsule and further improve its underwater stability.

The underwater environment created in the test rig during a test cycle provides a turbulent medium for the trajectory of the capsule. Assume the following test condition is set up in the test rig. The test rig is filled with water to a predetermined level above the bottom of the drill tube. Starting from the bottom, the drill tube is loaded as follows: a four-foot water column, the capsule, a four-foot water column on top of the capsule, the remaining length of tube is an air void and the breech is screwed on the end of the drill pipe. The water in the 12" tube of the test rig simulates the borehole water which is at rest, prior to initiating the test cycle. When the test is initiated, the compressed air is applied through the breech and propels the train of water column, capsule model and forward water column down the tube. The forward water column exits from the drill tube and impacts the static borehole water, creating considerable turbulence. The capsule exits from the tube into the turbulent borehole water and starts its trajectory toward the bottom. The aft water column and the compressed air column exit in turn from the tube, against the rear of the capsule in its trajectory. Although this turbulent underwater environment existed in the test rig, we were successful in developing an optimum capsule model configuration that was stable and developed the required exit and striking velocities. In fact, the striking velocity of the capsule models against the bottom of the test rig were high; the capsule models were being damaged and it was necessary to increase the bottom hard rubber pad from 1" to 3".

Another point emphasized by this test was that the spacing between capsules in the drill tube shall be of sufficient length to assure that the following capsule shall be in the tube, with its anti-detonation water/air buffer when the proceeding capsule is detonated.

The following paragraphs describe the capsule models, test results and the selection of the optimum capsule configuration.

3. Capsule Test Models

Several capsule model configurations were designed and fabricated to simulate the characteristics of the current capsule design at that time. The capsule models were made from hard wood and metal and also incorporated provisions for changing the nose shape, density, weight, and center of gravity (c.g.). One capsule model was fabricated to conduct preliminary tests to check out the functioning of the test rig. As the tests progressed, the remaining capsule models were fabricated and tested. One or two "O" ring seals were installed on the capsule models to seal against the I.D. of the drill tube.

The final capsule shape and weight must satisfy two necessary goals. First, the capsule must strike the hole bottom in a nose-down, vertical position. This is the stability requirement. Second, the capsule must penetrate as much water as possible at any reasonable ejection velocity and hit the hole bottom with enough remaining velocity to actuate the fuze/detonator system. This goal is set to allow the greatest flexibility of the overall drilling system.

The six capsule model configurations used in the hydroballistic tests are shown in Figures 3-37 through 3-42.

4. Test Results

Extensive hydroballistic testing was performed during this exploratory program. In all, a total of fifty-three (53) tests were conducted. Six different capsule model configurations were used, nine test rig set-ups, and various compressed air injection pressures were implemented. The six capsule test models were of various configurations as shown in Figures 3-37 through 3-42 and each had the capability of varying the weight and c.g. location. The capsule nose shapes, in most cases, were interchangeable and were varied to determine their effect on the capsule underwater stability.

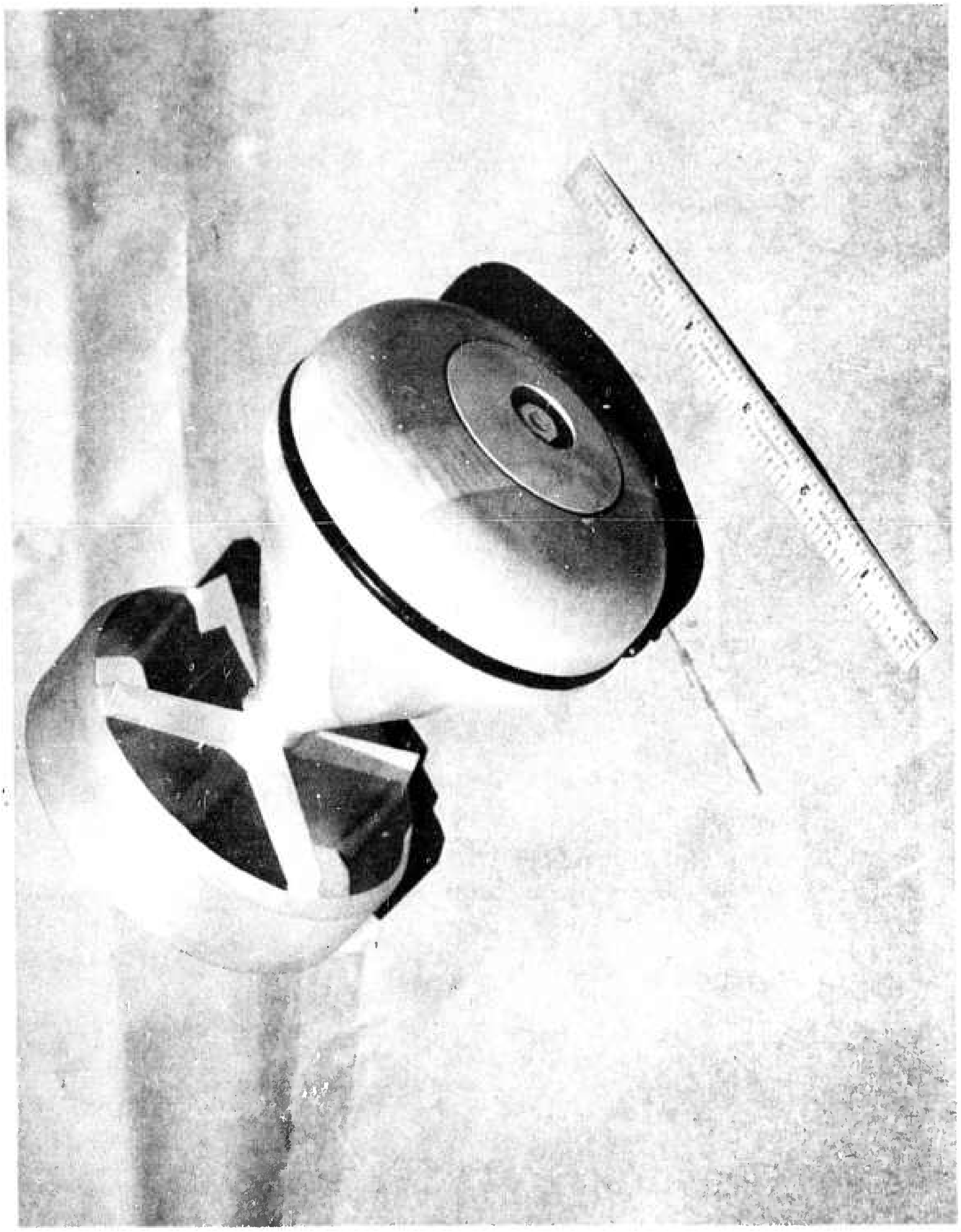
High-speed movies of each test were taken and carefully evaluated to determine the following parameters:

(a) Optimum Capsule Configuration
(b) Capsule Velocity at Exit from Drill Tube
(c) Capsule Velocity & Stability Throughout its Trajectory
(d) Capsule Velocity at Impact with Bottom of Rig
(e) Effects of Various Compressed Air Injection Pressures

and test rig setup conditions on the capsule performance.

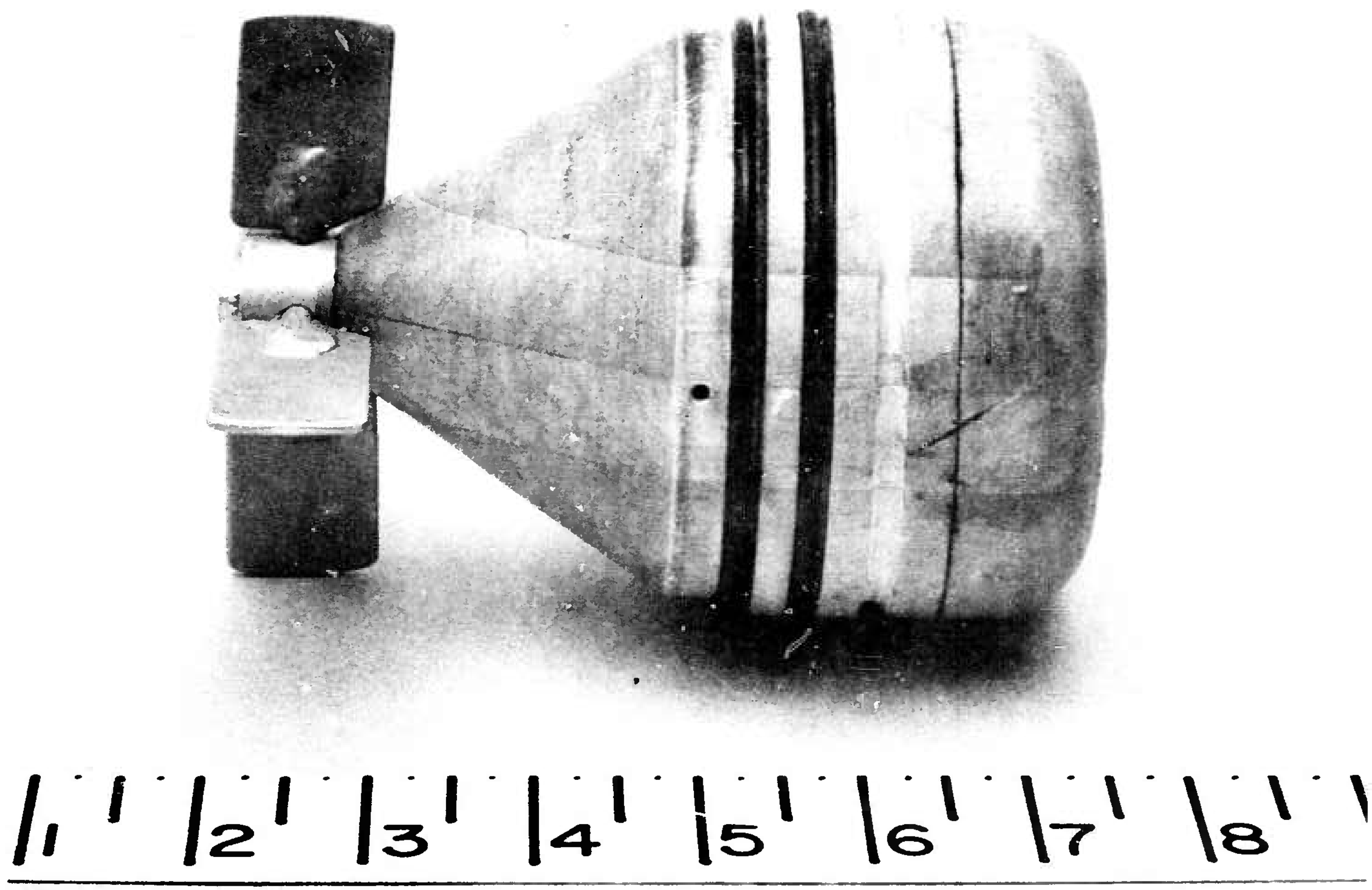
Attempts to obtain high-speed color movies by putting different dye colors in the borehole water and the water column above the capsule, were unsuccessful.

The results of the hydroballistic tests are tabulated and presented in Figures 3-43 (models #1 and #2) and 3-44 (models #1, #2, #3, #3A, #4, and #4A). These two figures include capsule model configurations used and the test rig setup diagrams.



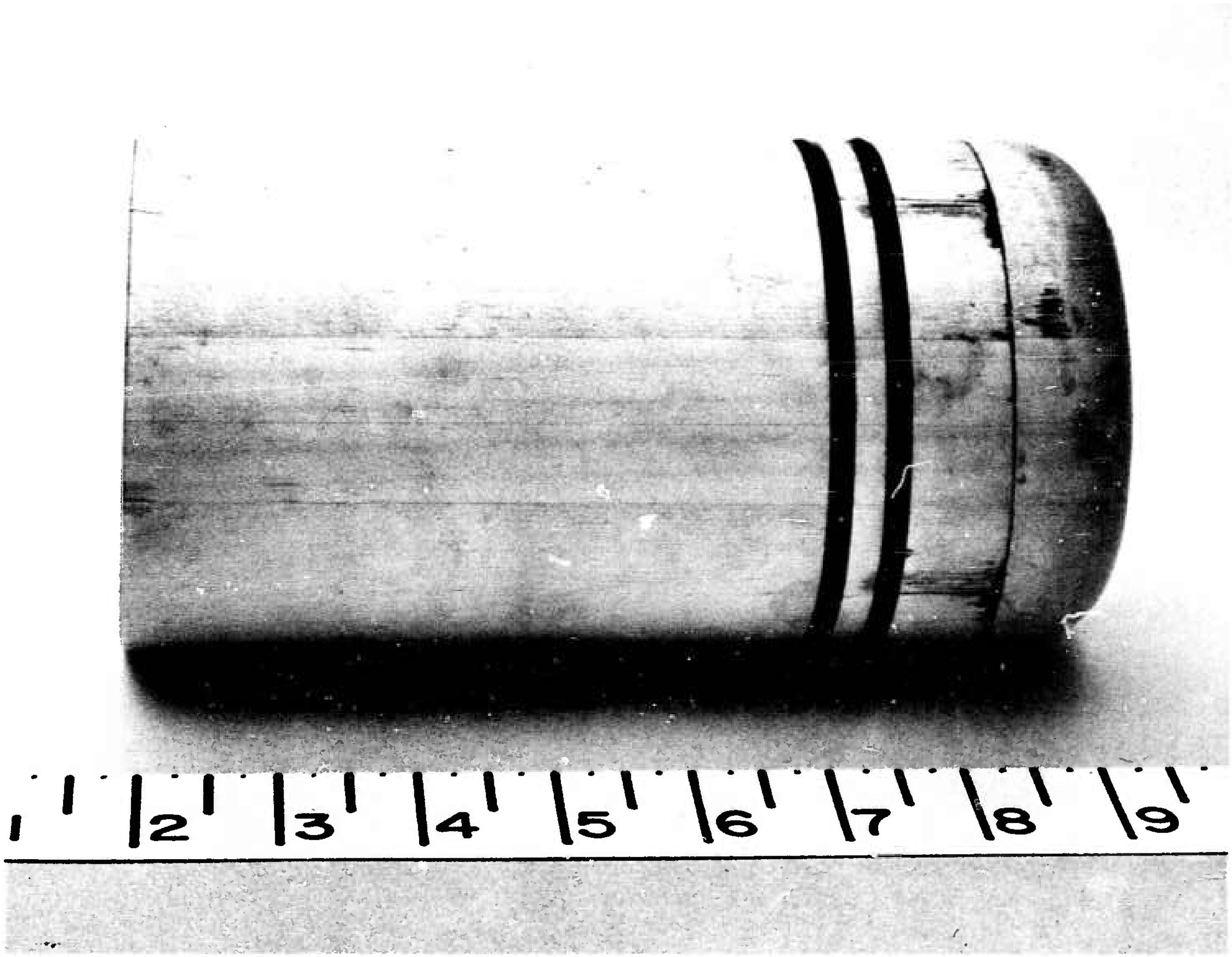
CAPSULE TEST MODEL #1

FIGURE 3-37



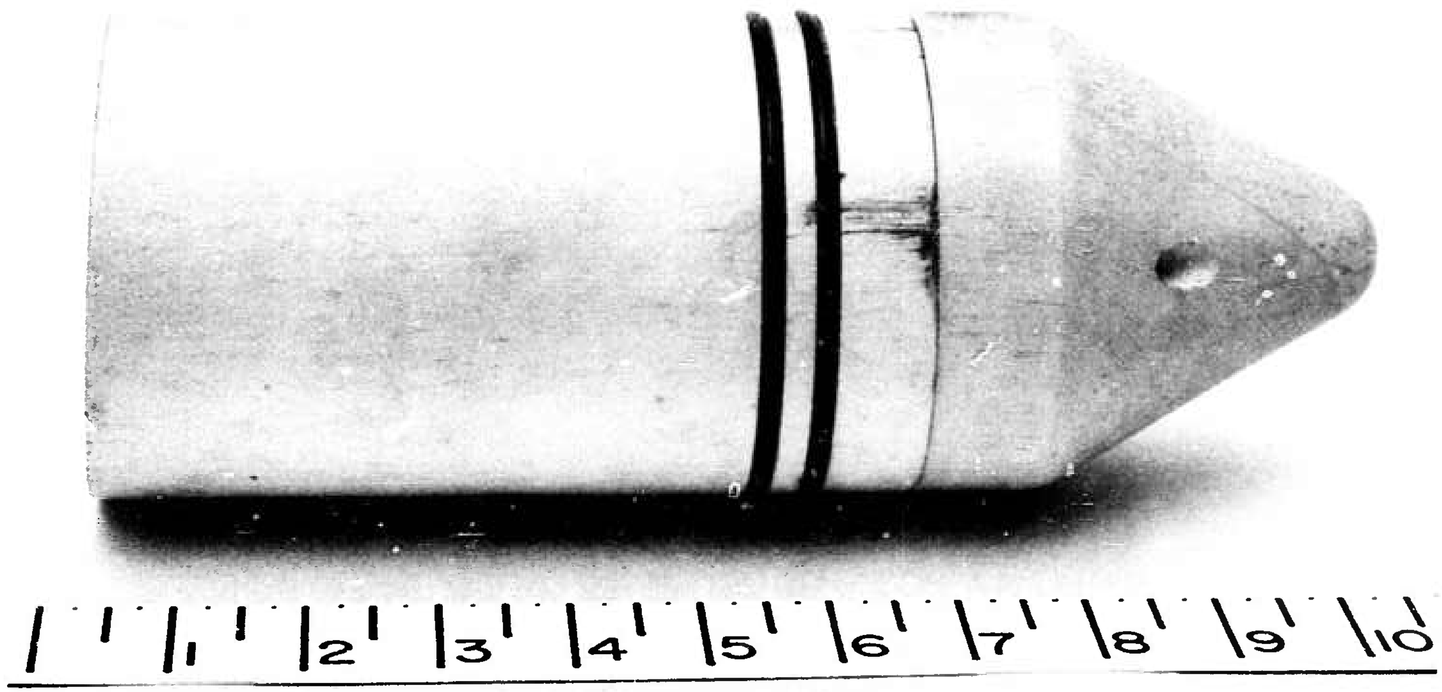
CAPSULE TEST MODEL #2

FIGURE 3-38



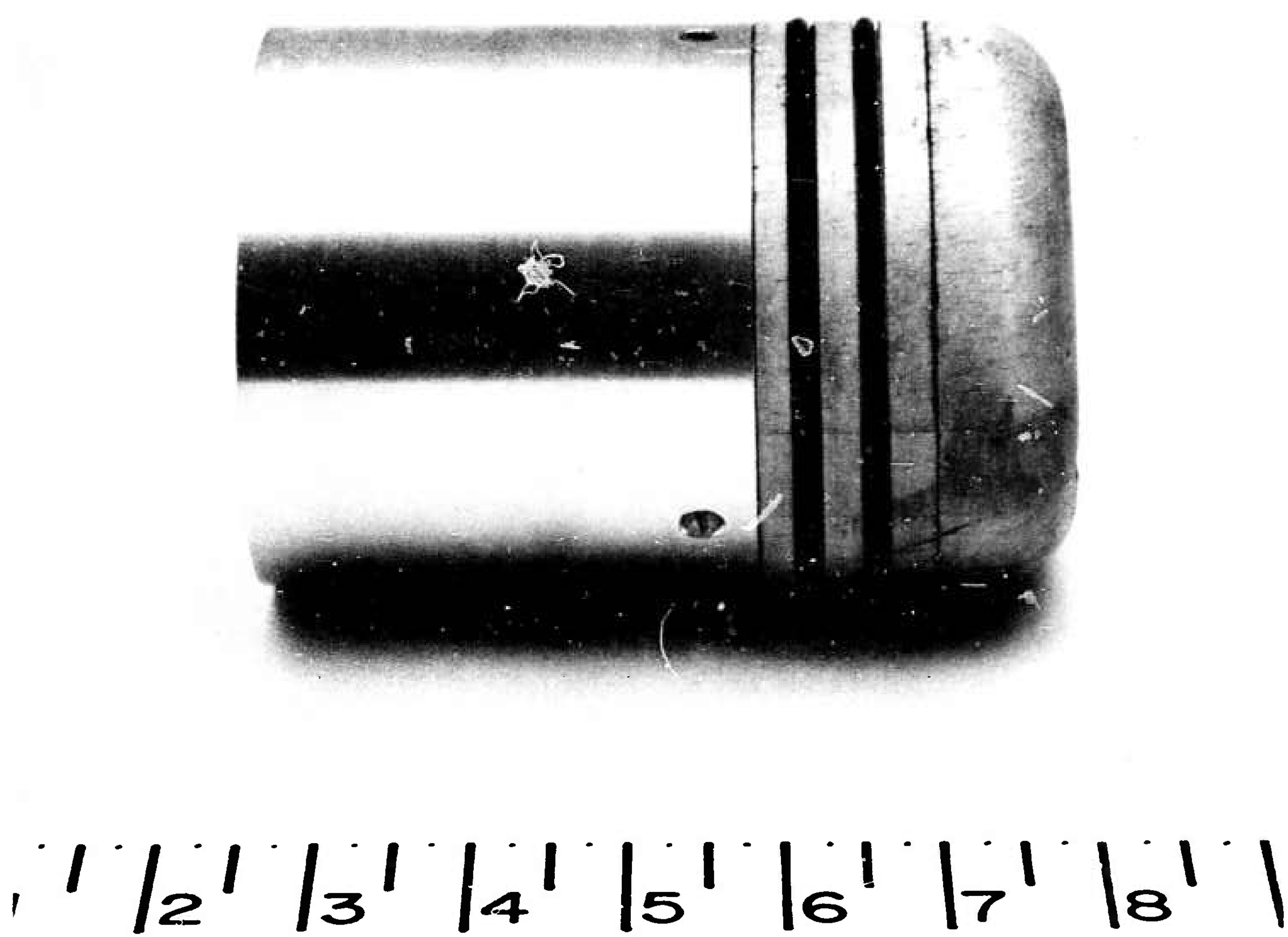
CAPSULE TEST MODEL #3

FIGURE 3-39



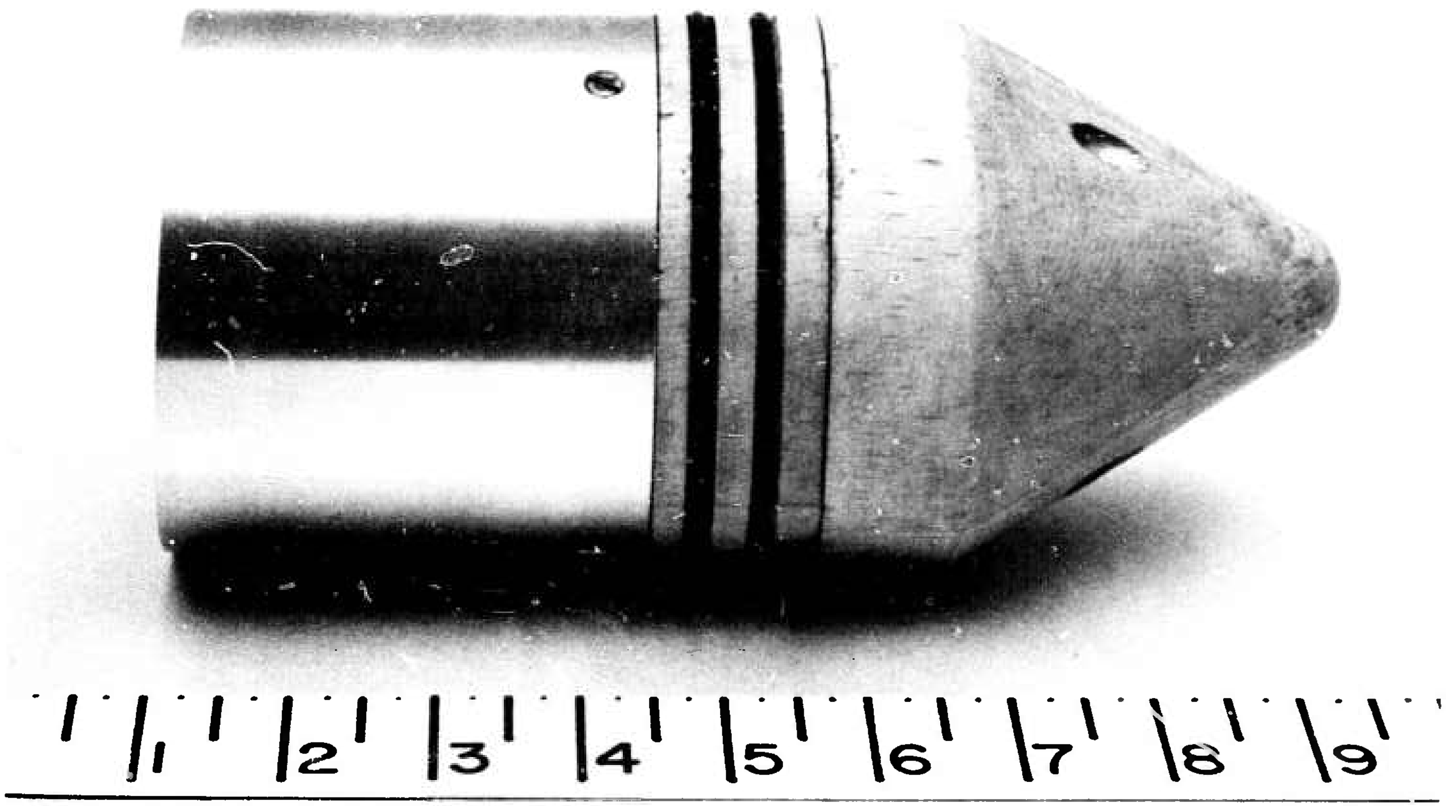
CAPSULE TEST MODEL #3A

FIGURE 3-40



CAPSULE TEST MODEL #4

FIGURE 3-41

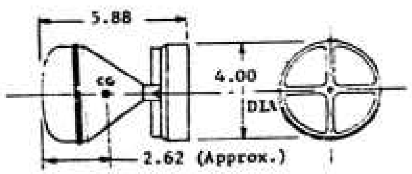


CAPSULE TEST MODEL #4A

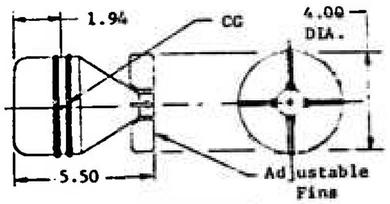
FIGURE 3-42

DATE NO.	TEST NO.	TRUE AIR PRES-SURE	CAPSULE DATA				VELOCITY DATA (fps)								TRAVEL	
							DISTANCE SEGMENT FROM EXIT POINT (In.)									
			SET-UP NO. ○	TYPE NO.	WEIGHT (grams)	SEE NOTE NO.	0-6	6-12	12-18	18-24	24-30	30-36	36-42	42-48	STABLE DISTANCE	MAX. DISTANCE PERPENDICULAR
8/1/72	1	14.5	1	1	768											
	2	14.5	1				27.5	27.5	22.5	17.8	13.1	10.7				
	3	24.7	1				35.2	35.2	30.6	21.1	19.0	14.6				
	4	34.4	1				41.7	39.8	33.6	25.0	18.2	16.8				
	5	44.3	1				44.0	45.9	39.3	26.8	21.6	19.0				
8/11/72	1	53.3	2			3										
8/18/72	1	34.4	3				56.8	29.1	15.9	10.7	6.3	4.6				
	2	53.3	3				84.6	52.3	26.8	16.7	9.6	7.2	4.1	3.9		
	3	53.3	4			3										
	4	53.3	5			3										
3/21/72	1	53.3	5			3										
	2	34.4	6			3										
	3	34.4	7			3										
	4	53.3	7			3										
	5	53.3	8	1	768	3										
8/29/72	1	53.3	5	2	686	1	70.0	70.0	70.0	61.8	33.8				1.5 Ft.	2.5 Ft.
	2	53.3	5	2	686	2	78.5	78.5	68.7	64.6	47.7	25.0			1.5 Ft.	3.0 Ft.
	3	34.4	5	2	686	2	64.3	64.3	56.3	54.0	21.2				1.5 Ft.	2.5 Ft.
	4	53.3	2	2	686	2	50.0	50.0	47.5	30.6	25.7	22.1			2.5 Ft.	3.25 Ft.

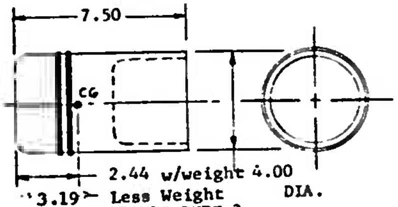
NOTES:
1. Fins are at 40° to centerline axis.
2. Fins are at 0° to centerline axis.
3. Instrument error - timing marks did not register on film.



CAPSULE TYPE 1

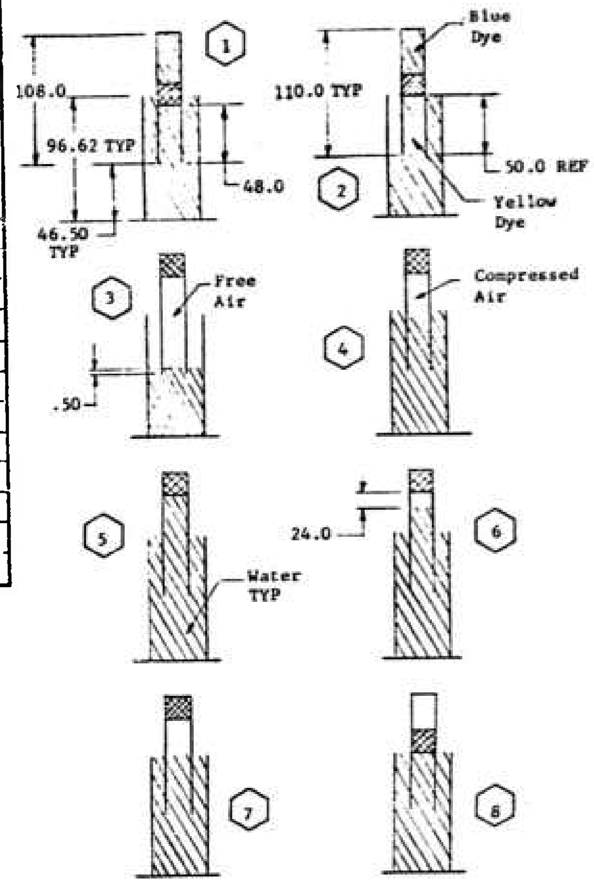


CAPSULE TYPE 2



CAPSULE TYPE 3

TEST RIG SET-UPS



ALL DIMENSIONS ARE IN INCHES

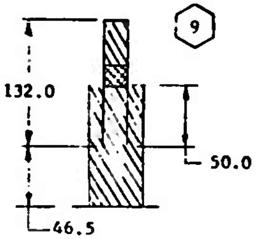
HYDROBALLISTIC TESTS
(MODELS #1 & #2)

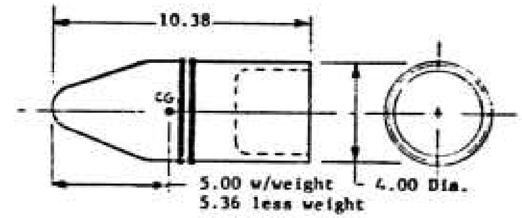
FIGURE 3-43

DATE 1972	TEST NO.	TRUE AIR PRES-SURE	CAPSULE DATA SET-UP NO. ○	TYPE NO.	WEIGHT (grams)	SEE NOTE NO.	VELOCITY DATA (fps) DIST. SEGMENT FROM EXIT POINT (in) 0-6	6-12	12-18	18-24	24-30	30-36	36-42	42-48	TRAVEL (ft) STABLE DISTANCE	MAX. DISTANCE PERPENDICULAR
9/6	1	53.3	9	1	768		40.5	47.2	36.9	28.3	22.4	17.7	11.6		3.25	Full Run
	2	53.3		1	768		42.4	50.0	38.6	28.3	21.8	15.4			2.0	3.0
	3	53.3		3	873		42.4	47.2	40.5	38.6	32.7	30.4	29.3		Full Run	Full Run
	4	53.3		2	686	1	40.5	47.2	38.6	25.7	18.5				1.25	2.75
9/8	1	82.0		3	873		53.0	55.3	55.3	50.0	47.4	45.0	37.5		Full Run	Full Run
	2	64.5			873		49.4	52.5	52.5	46.7	44.2	42.0	35.0		Full Run	
	3	45.5			873		46.7	46.7	46.7	44.2	38.2	35.0	32.3		2.50	
	4	26.3			873	2	-	-	-	33.6	30.0	28.0	23.3		2.25	
	5	64.5			559	2,4	-	-	-	52.5	42.0	38.2	31.1		2.0	
	6	26.3		3	559	4	36.5	40.0	35.0	35.0	29.0	24.7	18.3		Full Run	Full Run
9/22	1	82.0		4	857	2,3	-	-							1.25	3.75
	2	64.5			857		60.2	52.8	44.4	35.2	33.8	31.3	24.1		Full Run	Full Run
	3	45.5			857	3	49.1	41.3	39.3	37.4	31.4	30.2	17.5		1.25	3.25
	4	26.3			857	3	41.6	37.8	33.2	28.7	27.7	22.5	10.5		2.25	3.38
	5	64.5			543	3,4	45.6	42.5	37.5	33.6	30.4	24.5	14.8		2.0	3.12
	6	26.3		4	543	3,4	40.0	38.1	33.3	27.6	25.8	21.0	11.8		1.75	3.0
9/25	1	82.0		4A	975	3	53.3	49.5	49.5	46.2	38.5	34.7	30.1		2.0	3.25
	2	64.5			975	2	-	-	-	-	-	-	-		2.50	Full Run
	3	45.5			975	3	50.0	44.7	44.7	42.5	34.0	31.5	25.0		1.25	3.0
	4	26.3			975		37.0	35.4	35.4	32.7	28.3	25.7	22.4		3.01	Full Run
	5	64.5			653	4	52.8	50.0	50.0	45.2	39.0	36.5	29.7		Full Run	Full Run
	6	26.3		4A	653	3,4	36.9	36.9	36.9	34.0	25.7	22.4	12.7		2.25	3.38
	7	82.0		1	477	4	50.0	50.0	44.7	Level					1.50	1.75
	8	82.0		1	477	4	53.2	61.4	38.0	19.9	Stopped 60°				1.25	2.12
9/26	1	82.0		3A	981		56.7	53.0	56.7	50.0	44.7	40.4	34.0		2.50	Full Run
	2	64.5			981		50.0	47.2	44.7	44.7	37.0	35.4	30.4		Full Run	Full Run
	3	45.5			981		47.3	40.8	40.8	39.1	34.6	32.1	25.7		2.50	Full Run
	4	26.3			981	3	35.0	33.6	33.6	32.4	27.3	25.0	21.8		2.0	3.50
	5	64.5			666	3,4	50.0	50.0	53.0	47.2	40.4	35.4	28.3		1.75	3.50
	6	26.3		3A	666	4	39.1	31.0	34.6	32.1	27.3	25.0	22.5		Full Run	Full Run
	7	82.0		1	768		56.7	51.0	47.2	27.4					1.75	2.38
	8	64.5		1	768		52.9	50.0	36.0	20.9					3.25	2.25
	9	45.5		1	768		44.7	36.9	40.4	25.7	14.7				2.0	2.62
	10	26.3	9	1	768		33.3	33.3	27.3	16.7	14.3	11.4			1.75	3.25

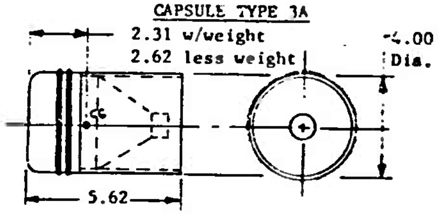
FIGURE 3-44. HYDROBALLISTIC TESTS (MODELS #1,2,3,3A,4,4A)

TEST RIG SET-UP

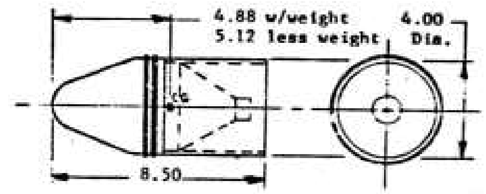




CAPSULE TYPE 3A



CAPSULE TYPE 4



CAPSULE TYPE 4A

NOTES:
1. Fins set at 0° to centerline axis.
2. Air obscured capsule during part (or all) of run.
3. Capsule hit wall at max perp. dist.
4. Capsule fired without weights.

HYDROBALLISTIC TESTS (MODELS #1,2,3,3A,4 & 4A)
FIGURE 3-44

5. Optimum Model Configuration

After extensive evaluation of the test results, it was determined that capsule test model #3 (873 grams) produced the most stable and effective underwater performance. The velocities and other parameters generated on the #3 model met or exceeded our general requirements and were compatible with the designs of the subsystems of the overall explosive drilling system. The blunt nose and large L/D (length-to-diameter) ratio repeatedly proved to be more stable than the other capsule configuration candidates. It was also determined that the hydroballistic test rig setup No. 9 (water column in front of and aft of the capsule in the drill tube) was most conducive to good performance, and was used exclusively throughout the remaining portion of testing (see Figure 3-44). The No. 9 test setup is the one that is most compatible to the conditions that will exist in the drill rig during actual explosive drilling operations.

The following observations may be made by reviewing the test results of the #3 capsule model with (873 grams) and without (559 grams) weights as shown in Figure 3-44.

The variable parameters in these tests consisted of capsule weight, c.g. location, and compressed air pressures. The capsule weights were 873 grams with weights and 559 grams without weights and the corresponding c.g. locations (measured from the nose) were 2.44" and 3.19", respectively. The compressed air pressures were varied from 82 to 26.3 psi. The constant parameters in these tests were capsule external configuration and the No. 9 test setup condition.

Under these conditions, six test shots were conducted: four with the heavier capsule (873 grams) with a c.g. location of 2.44" and air pressures at 82, 64.5, 45.5 and 26.3 psi; and two shots with the lighter capsule (559 grams) with a c.g. location of 3.19" and at air pressures of 64.5 and 26.3 psi.

The results indicate that the heavier capsule (873 grams) with the most forward c.g. location of 2.44" and fired at the highest air pressure of 82 psi, produces the greatest underwater performance in regard to the highest exit velocity, the greatest stability and the highest impact velocity. It is pointed out that the #3 model (873 grams) impacted the bottom of the borehole at an acceptable impact angle and velocity at all air pressures, including the lowest at 26.3 psi. The capsule stability and impact velocity are of the greatest importance. In order for the capsule to function the last mode of fuze operation (impact switch), the impact velocity shall exceed 12 fps and the lowest impact velocity obtained in the heavier capsule test was 23.3 fps at 26.3 psi.

Therefore, the #3 capsule model (873 grams) was selected as the optimum capsule configuration and the final capsule design shall match this capsule model's configuration and characteristics. By referring to Figure 3-32, it will be noted that the final capsule design weighs 873 grams (1.93 lbs.) and its c.g. location is 2.50".

D. Fuze Development

1. General

This section presents a discussion of the fuze investigations, conducted by AAI during the program, to determine the fuze requirements, methods of operation and safety considerations. The fuze concepts covered include mechanical, electrical and electromechanical modes of operation. The fuze development effort was coordinated with the design of the capsule, hydroballistic tests, and the drill rig, and these units contributed to the development of the fuze. This section also presents a description of the fuze selected and developed in this program.

2. Fuze Investigation

a. Mechanical Types

(1) Out of line detonator, bore rider armed as the capsule exits from the drill tube and inertia pin fired as the capsule strikes the bottom of the borehole.

(2) Out of line detonator, centrifugally armed as the capsule is spun by the rifling at the bottom end of the drill pipe and inertia pin fired as the capsule strikes the bottom of the borehole.

b. Electrical Types

(1) Centrifugal Arming

This fuze uses an electrical system consisting of a diode, a capacitor connected in parallel and two special switches in series with a M48 electric detonator. In operation, the capsule is positioned into the drill tube by the loader. A rammer, which includes the electrical power source, rams the capsule down the drill tube, the safety pin is mechanically removed by the downward action of the capsule and the rammer charges the capacitor through the diode. The two special switches are spring loaded "open" at this time. The capsule is propelled down the tube by water and compressed air, and through the rifling section attached to the bottom of the tube. This action causes the capsule to spin and the components of the first switch rotate outward from the fuze axis and close this switch. The rotational force on the centrifugal switch will maintain it closed or a lock can be provided. The second switch is an inertia type and will fire the M48 when the capsule strikes the bottom of the borehole.

(2) Bore Rider Arming

This fuze concept is similar to the centrifugal type described above, except that the arming is achieved by a bore rider. This approach eliminates the need for spinning the capsule and for the rifling section at the bottom of the drill tube.

This fuze concept utilizes an electrical system composed of the following components: a diode; a capsule in parallel; and two special switches in series with the M48 detonator. When the capsule is completely loaded into the drill tube, the rammer, which includes the electric power source for the fuze, contacts the capsule and the fuze electrical terminals, and launches the capsule down the tube. The safety pin is mechanically removed by the downward action of the capsule, and the rammer circuit charges the capacitor through the diode. The fuze block assembly contains a spring loaded, two piece piston which provides a radial force against the end of the bore rider, trying to move it out of the capsule. However, the bore rider is restrained by the I.D. of the drill tube and no action occurs. The two piece piston is composed of a metal and a plastic portion. At this time in the cycle, the bore rider leaf switch is spring loaded against the plastic (insulator) piston and switch is open. As the capsule exits from the drill tube, the piston spring moves the bore rider plunger to protrude slightly from the capsule, since it is out of the drill tube. As the bore rider plunger is pushed outward, the spring force slides the metal part of the piston under the bore rider switch and the switch is closed. The second or impact switch is spring loaded away from the metal piston. However, as the capsule strikes the bottom of the borehole, the impact switch closes, the capacitor discharges, initiating the M48, and detonating the capsule explosive charge.

c. Electromechanical Type

This fuze concept combines two independent methods of operation - electrical and mechanical - and either system is capable of firing the M48 detonator. The incorporation of two fuze systems into a single fuze assembly is redundant and more costly; however, it provides maximum reliability. For the electrical system, either the centrifugal or bore rider arming or other concepts could be used. For a preliminary investigation of this type of fuze, we selected the electrical system with the bore rider arming device. For the mechanical system, we selected the graze lever action which is locked by the bore rider mechanism while the capsule is in the drill tube. The mechanical components would consist of a graze lever, graze lever spring, a spring loaded firing pin which is locked by the graze lever, and a T-96 stab primer mounted beside or against the M48 detonator used in the electrical system. When the capsule strikes the bottom of the borehole, the graze would pivot about its axis due to the set forward force. The rotation of the graze lever releases the spring loaded firing pin, firing the T-96 primer which in turn initiates the M48. If the electrical system is the prime functioning mode of the fuze, the mechanical backup system should be designed to utilize as many of the existing electrical system parts and functions as possible to minimize fuze costs.

The electromechanical fuze concept was investigated on a preliminary basis; however, the approach is considered feasible and has potential for future capsule programs. The dual fuze approach offers the highest reliability and just about eliminates the possibility of duds.

The fuze was not pursued further due to lack of contract funds and the limited number of capsules and fuzes required to prove the feasibility of the explosive drilling system.

d. Safety and Other Considerations

The electrical types, both centrifugal and bore rider arming modes, are considered to be extremely safe, since four (4) separate and deliberate functions must be performed in the proper sequence to detonate the M48. The safety pin is removed, the capacitor is charged, the spin or bore rider switch is functioned at the bottom of the drill tube and the impact switch is closed to initiate the M48 when the capsule strikes the bottom of the borehole.

AAI is familiar with reliable performance of the M48 from experience on other projects. The M48 is capable of firing the C-4 explosive directly without the need for a lead and booster pellet which simplifies the fuze explosive train. The M48 was used to fire all the individual GRP shaped charges and the test capsule firing tests previously described.

In all the fuze concepts described above, it is mandatory that the capsule with fuzes must be positioned inside the drill tube, prior to removing the safety pin and charging the capacitor.

3. Final Fuze Design

a. Selection

After careful evaluation of the various fuze concepts, AAI selected the electrical type using the bore rider arming technique. The selected fuze is considered safe. It requires four (4) independent actions to occur in sequence, at the established dynamic loads. This fuze meets our basic requirements for testing in the drill rig of this program. It is small, lightweight and economical to develop and fabricate. The selection of this fuze eliminates the need for spinning the capsule and for the rifling section at the end of the drill tube. The following paragraphs describe the selected fuze in detail.

b. Fuze Description

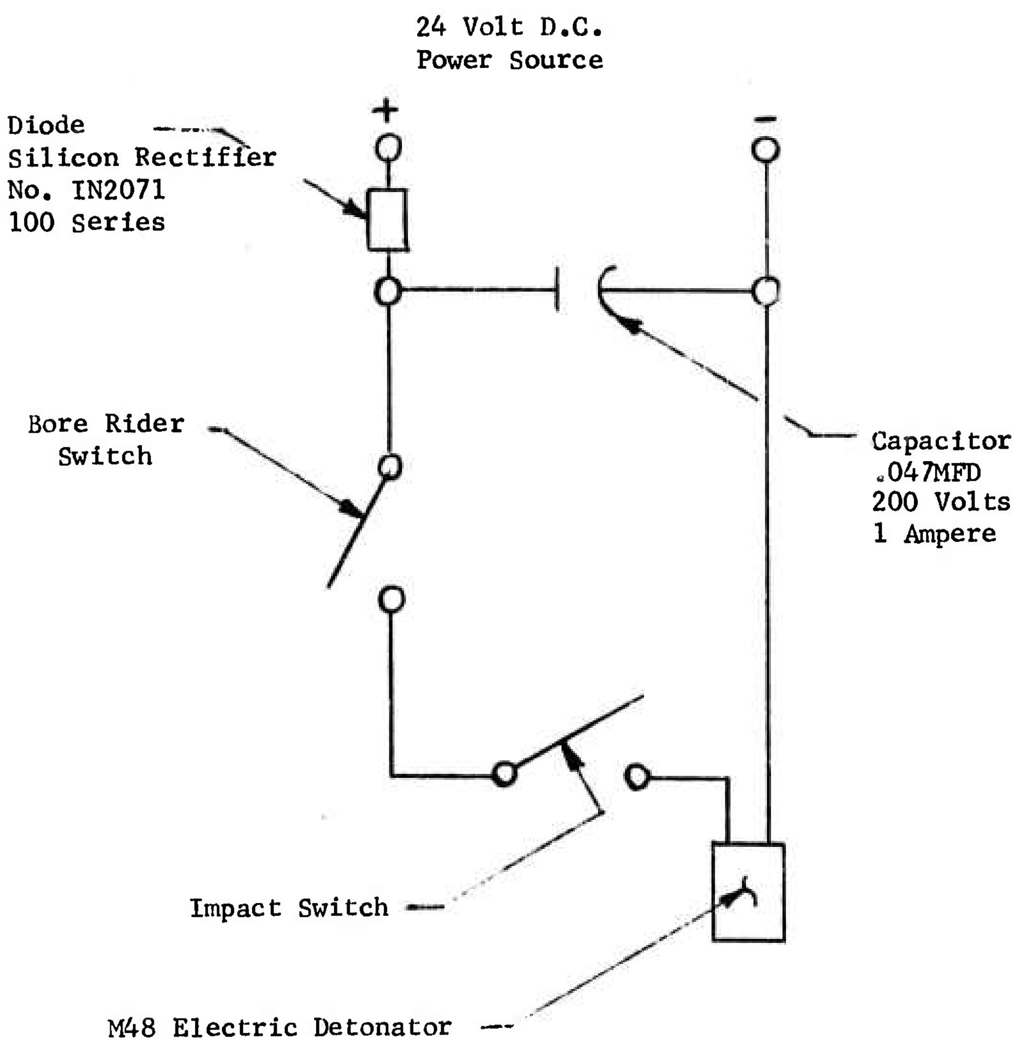
The wiring diagram for the electrical fuze with the bore rider arming device is shown in Figure 3-45. The components consist of a diode, a capacitor, two switches and a M48 detonator. The diode acts as a check valve to prevent the discharge of the capacitor. It is seen that both the bore rider switch and the impact switch must be closed in order for stored electrical charge in the capacitor to discharge and initiate the M48 detonator.

The fuze component breakdown is shown in Figure 3-46 and the nomenclature of each part is incorporated into this figure.

The fuze block and the bore rider mechanism are shown in the lower portion of the figure. The fuze block was machined from a polystyrene block and has provisions for mounting the various components. A bottomed drilled hole is provided to receive the bore rider mechanism in this order - spring, metal piston with "O" ring, and plastic piston with "O" ring. The bore rider plunger is also machined from polystyrene and is installed in its respective tunnel tube in the fuze cavity assembly above and the safety pin may be installed. The diode and capacitor are installed into holes provided in the block. The leaf type bore rider and impact switches are assembled to the block with their retaining screws and the components are wired up. A complete fuze block assembly with all of the above mentioned parts except the bore rider plunger and safety pin is shown at the center of the figure. Both the front and rear faces of the fuze block assembly are shown in Figure 3-47. Some of the installed parts may be seen in position through the transparent plastic block.

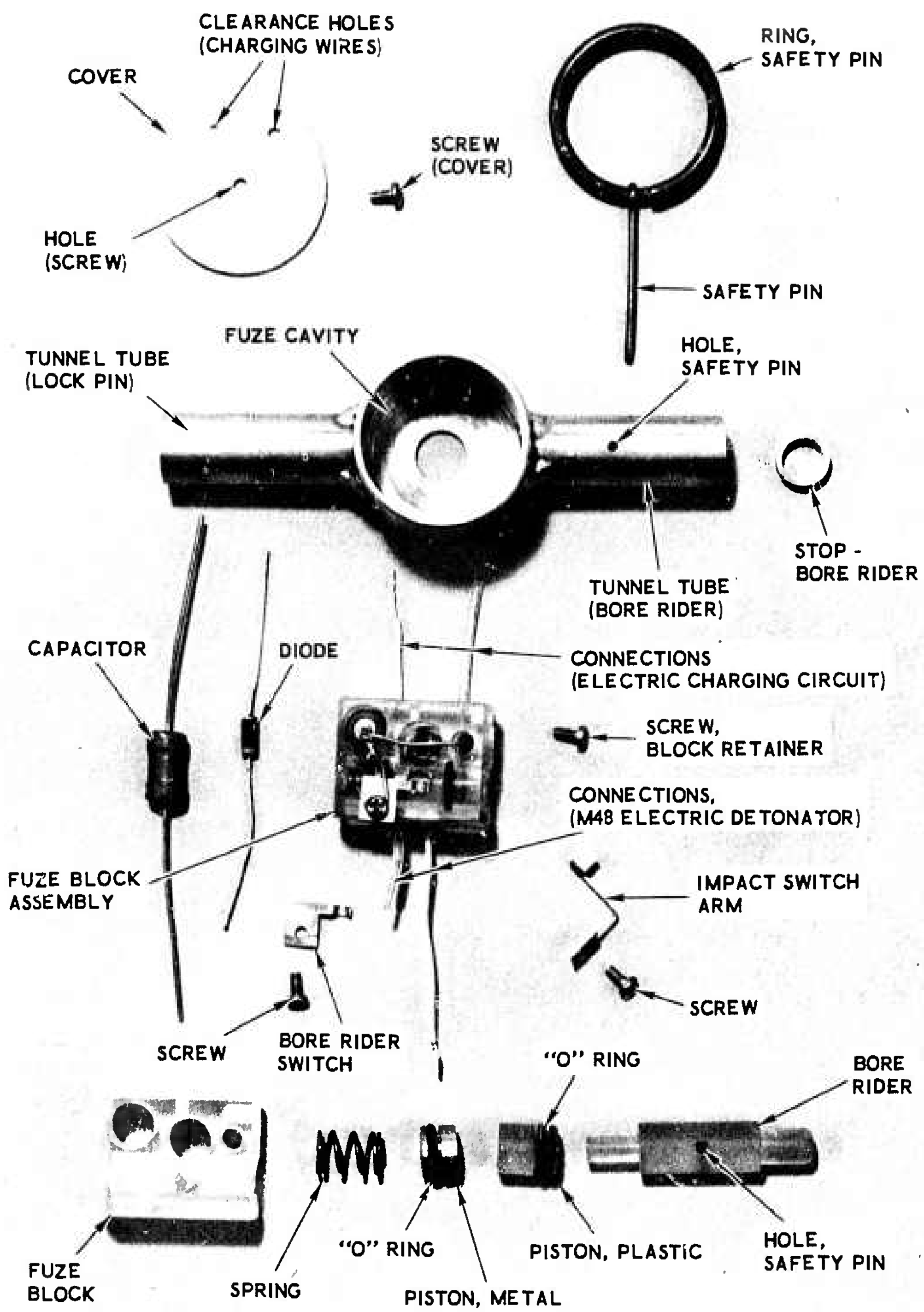
The fuze block assembly installed in the fuze cavity is shown in Figure 3-48. The bore rider plunger must be installed prior to the installation of the fuze block assembly. The fuze block must be oriented so that the bore rider spring and piston arrangement in the block is aligned with the bore rider plunger in the tunnel tube.

Figure 3-49 shows the final fuze assembly completely installed. A screw is installed through a hole in the side of the fuze cavity housing and is tapped into the fuze block to retain it in position. The two wires coming out of the top of the fuze block threaded through the holes provided in the cover and the cover is bonded to the cavity housing and retained by a screw in the center of the cover. The two wires protruding from the bottom of the assembly will be used for connection to the lead wires of the M48 detonator.



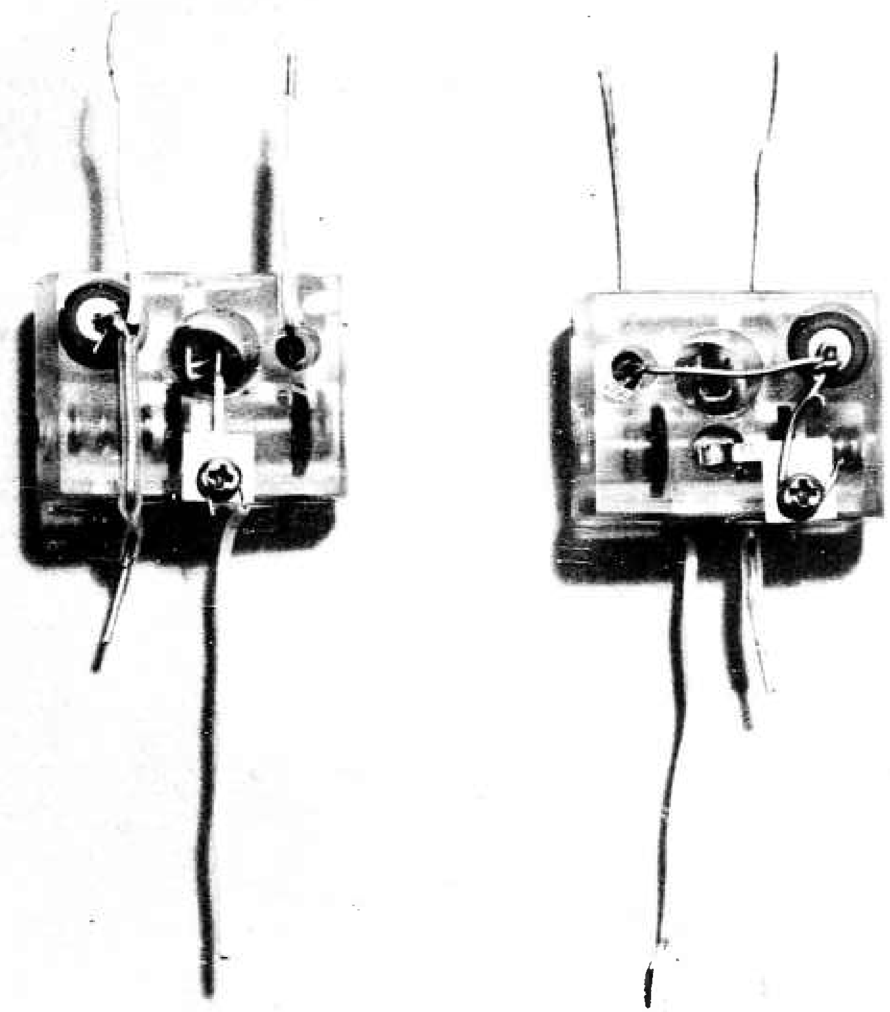
FUZE WIRING DIAGRAM

FIGURE 3-45



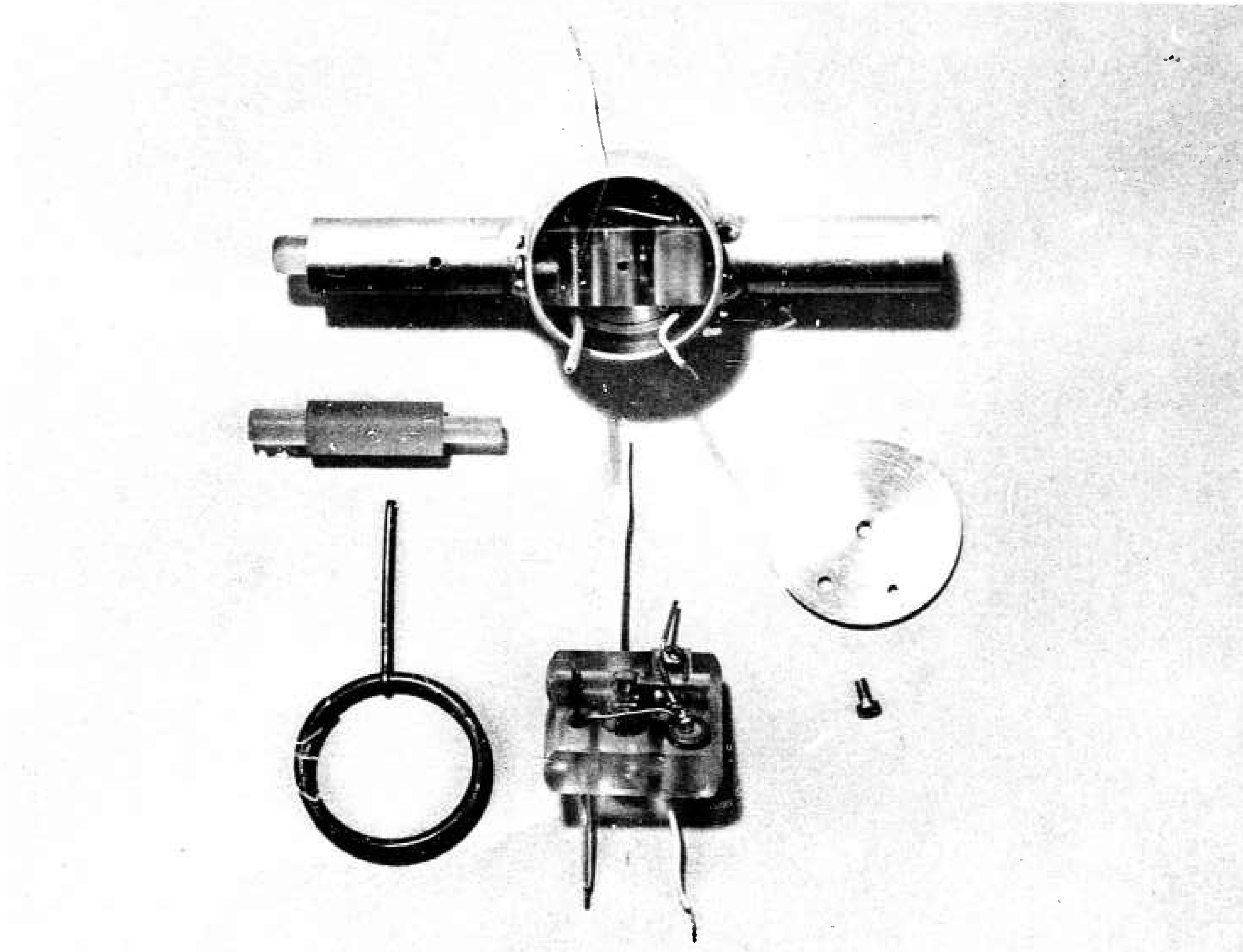
FUZE COMPONENT BREAKDOWN

FIGURE 3-46



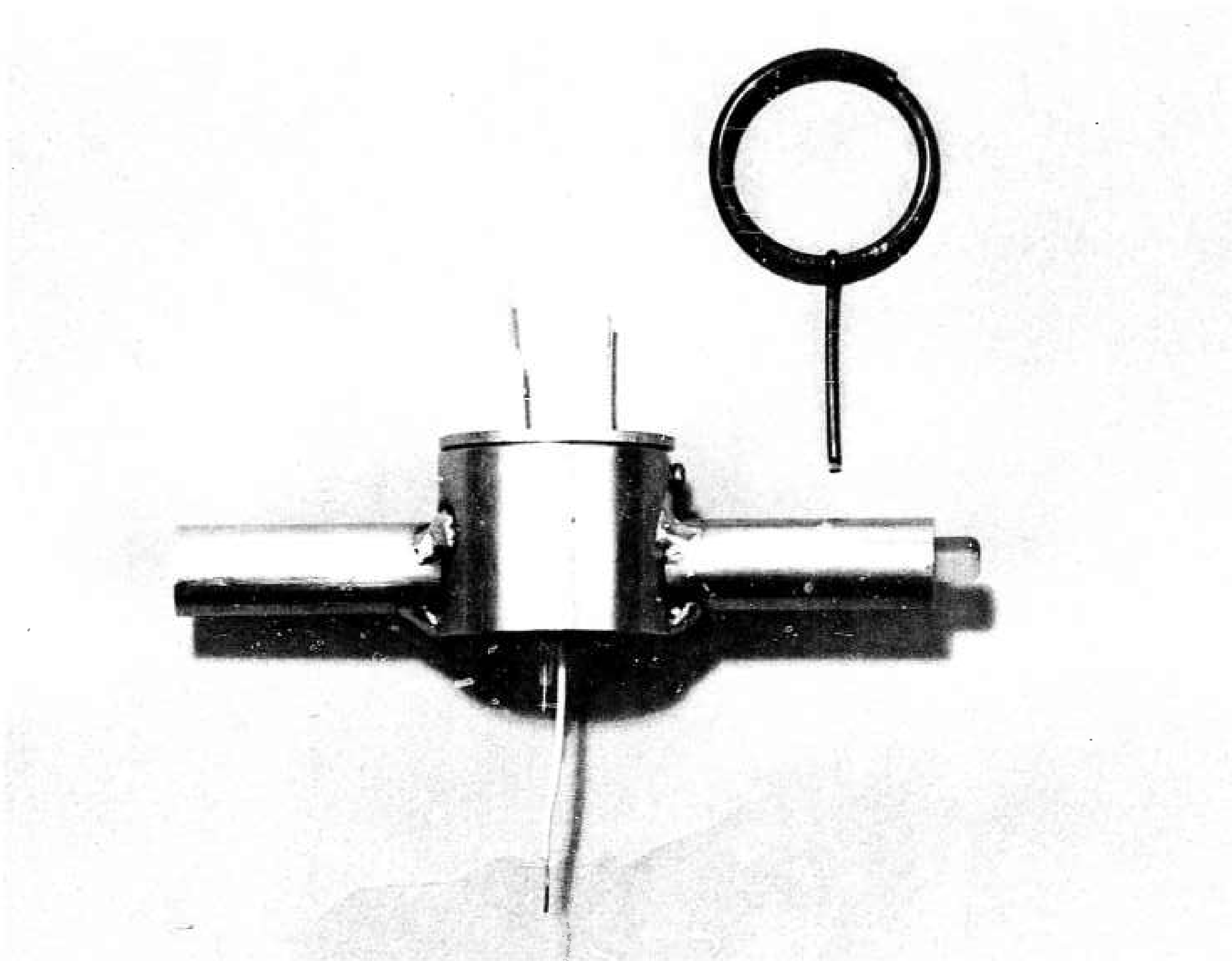
FUZE BLOCK ASSEMBLY - FRONT & REAR VIEWS

FIGURE 3-47



FUZE BLOCK INSTALLED

FIGURE 3-48



FINAL FUZE ASSEMBLY

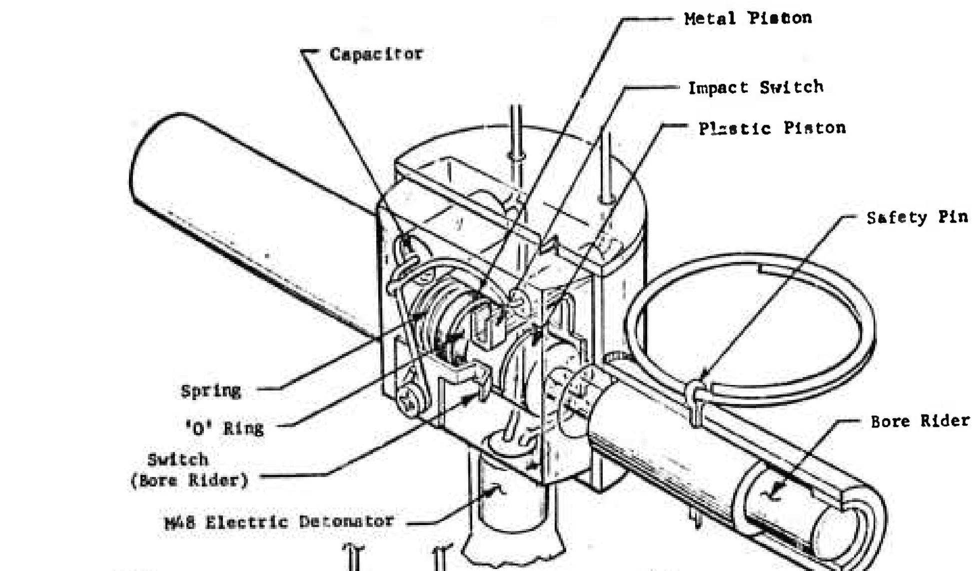
FIGURE 3-49

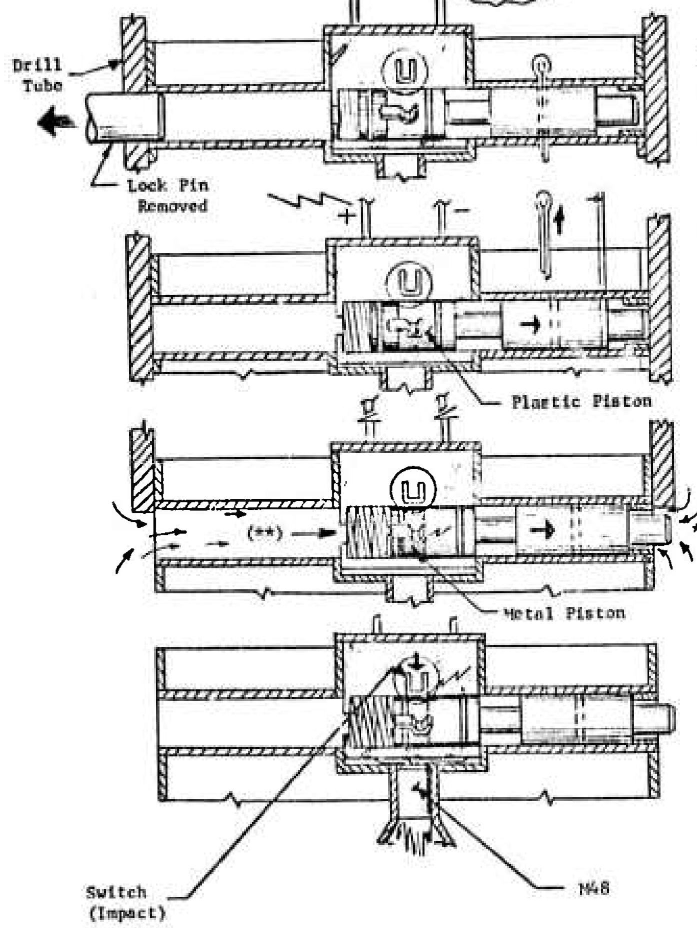
In actual practice, the fuze cavity and tunnel tube assembly are welded to the capsule shell and bonded to the detonator holder. The M48 would be installed on the respective wires from the fuze block assembly. On the final installation the M48 would be placed into the detonator holder prior to orienting and installing the fuze block into the cavity.

The cover and loose charging wires protruding from the top of the fuze and cover arrangement shown are adequate for the purpose of this program. However, in the ultimate design, a cover cap, similar to that used on a lightbulb would be installed and the wires would be attached to the cap. A rammer, having the electrical power source, would contact this cap and charge the capacitor.

c. Sequence of Operation

The fuze sequence of operation is described with the use of artist sketches and write-up in Figure 3-50. After the foregoing discussions on the fuze and its components it is believed that the sequence of operation data presented in Figure 3-50 is self-explanatory.





Step 1
Capsule in drill tube, bore rider and impact switches are open and are positioned against and away from the plastic piston, respectively.

Step 2
Capsule starts to move down tube. Safety pin is removed and spring moves bore rider to I.D. of tube. Both switches remain open as in Step #1. Capacitor is electrically charged.

Step 3
Wires are cut as capsule moves down drill tube.
Capsule exits from drill tube. Spring moves bore rider out of capsule and metal piston slides under and closes bore rider switch. Borehole water pressure at (**) balances (*) on bore rider and spring moves bore rider and piston.

Step 4
Capsule strikes bottom of bore hole. Resulting set forward force causes impact switch to overcome its spring force and contacts metal piston. With all switches closed, the capacitor initiates the M48 and detonates the capsule explosive charge.

FUZE: SEQUENCE OF OPERATION

FIGURE 3-50

E. Drill Rig and System Equipment

1. General

This section describes the drill rig and system equipment developed during this exploratory program. The drill rig and system equipment installation at the AAI facility is shown in Figures 3-51 (Plan View) and 3-52 (Elevation). This equipment is capable of launching the final capsules in accordance with the explosive drilling concept and will be utilized to prove the feasibility of the total system.

During the feasibility tests, the performance of the following parameters shall be determined:

a. Capsule velocity down drill tube.
b. Effectiveness of anti-detonation water/air buffer.
c. Injection of capsules, water, compressed air into the system.
d. Safety of system.
e. Fuze performance.
f. Capsule effectiveness in rock excavation.
g. Removal of spoils from borehole.

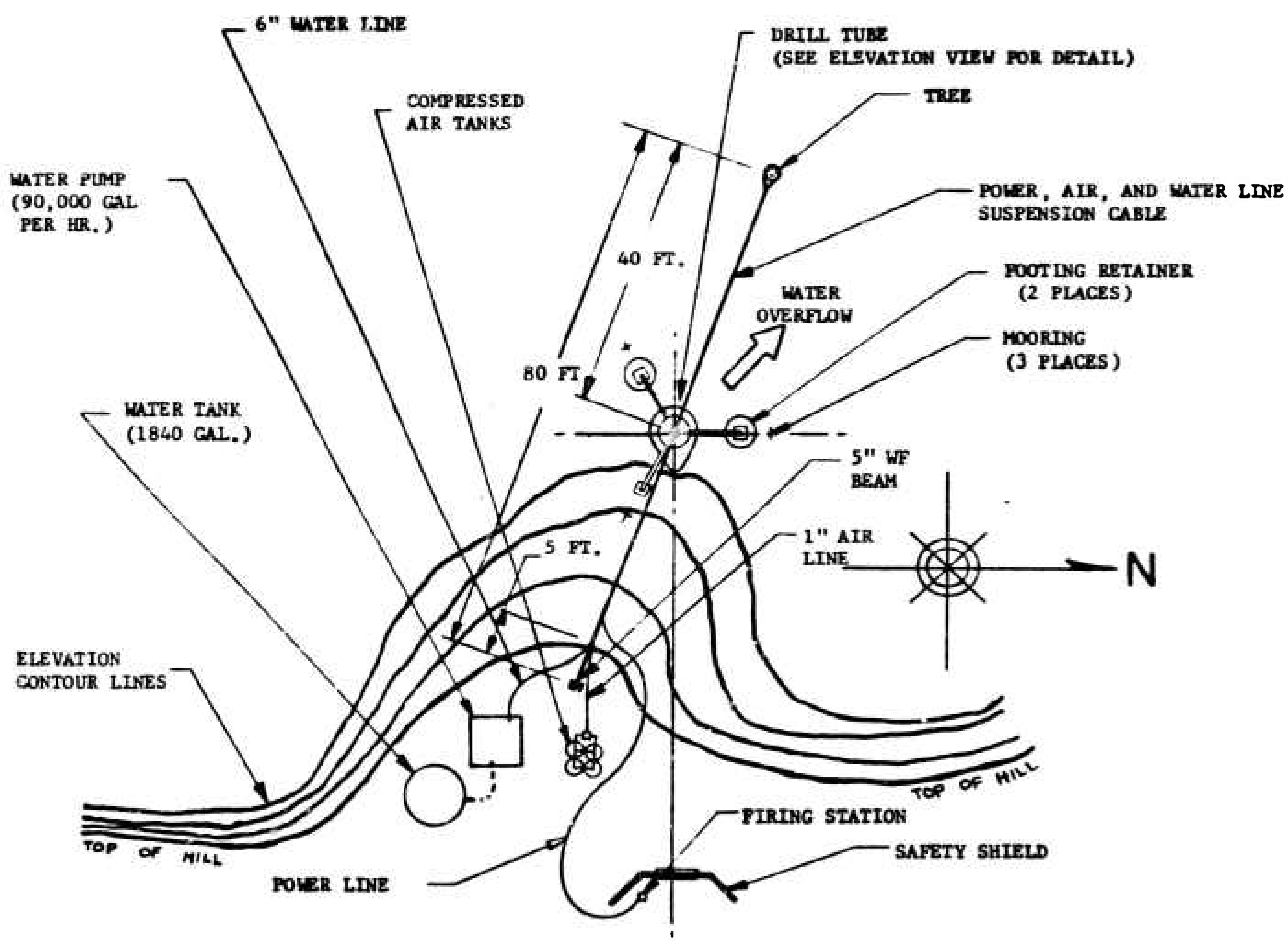
The drilling equipment developed for this program and that of the ultimate system are identical in operation except as indicated below. The ultimate drilling system will incorporate an automatic capsule feed system that will be operated on a continuous basis and recycles the water used. The exploratory drilling system incorporates a three-capsule feed system and the capsules can be fired singly, semiautomatic or full automatic in a 3-round burst. This approach is adequate to prove system feasibility and to generate the required data on the parameters listed above.

2. Description

a. Drill Rig

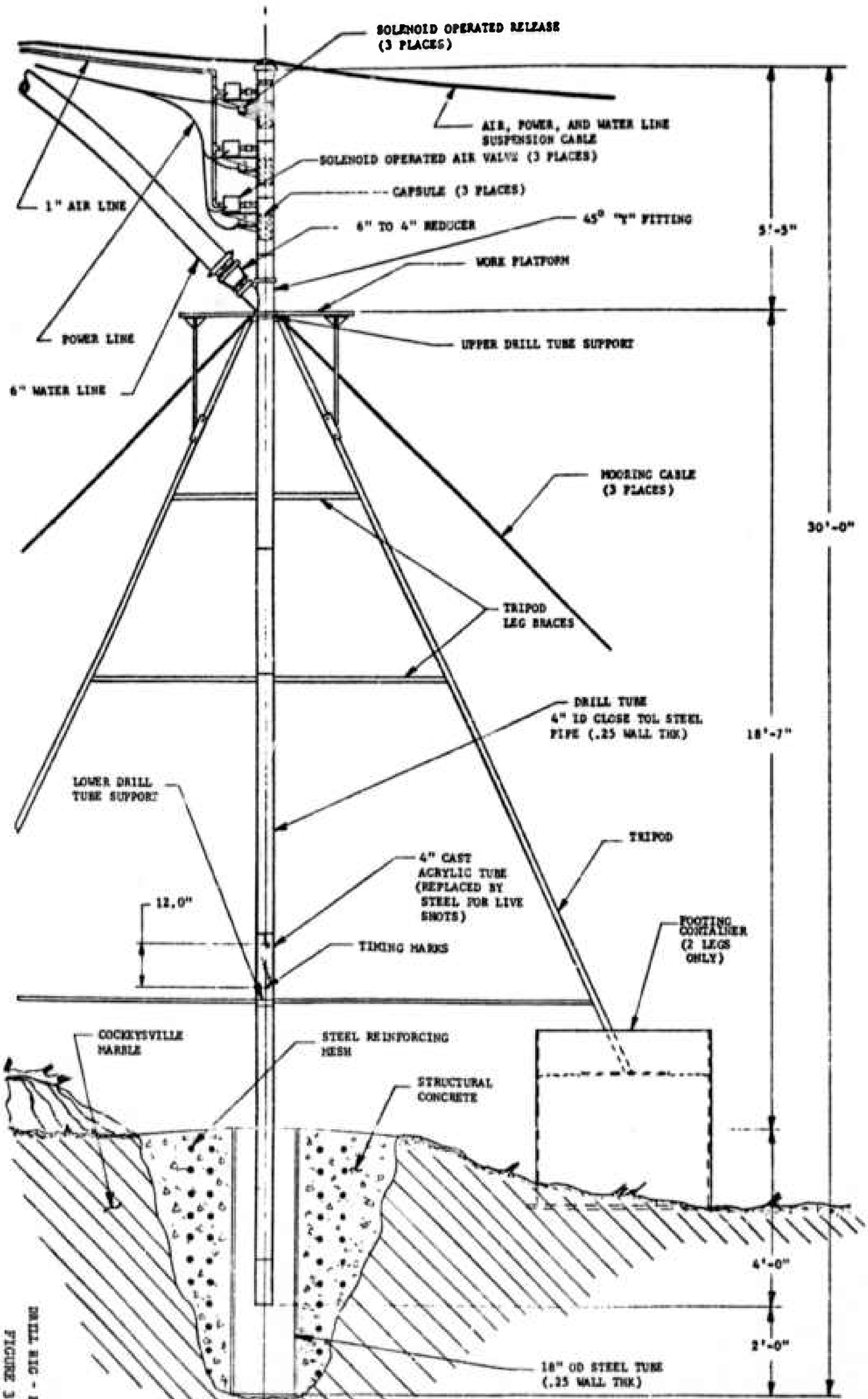
The drill rig assembly consists of the following basic components: tripod, drill tube, Y pipe fitting, work platform, 3-capsule magazine feed, fire control device, and provisions for water and compressed air injection systems and electrical power.

A previously used borehole was selected for these tests and was reinforced by installing a 18" O.D. x 6 foot long steel tube liner and reinforced concrete as shown in Figure 3-52.



DRILLING SYSTEM EQUIPMENT: PLAN VIEW

FIGURE 3-51



DRILL RIG - ELEVATION
FIGURE 3-52

A tripod assembly was fabricated and erected over the 6-foot deep, water-filled borehole and was leveled by adding footings under two of its legs. The drill tube is supported by the tripod apex fitting at the top and the lower support about 3 feet above the ground line. The centers of the apex fitting and the lower drill tube support on the tripod are aligned with the center of the borehole, with a plumb line. The tripod is tied down at its three legs and also by the 3 mooring cables. The work platform and its supporting braces are assembled to the tripod.

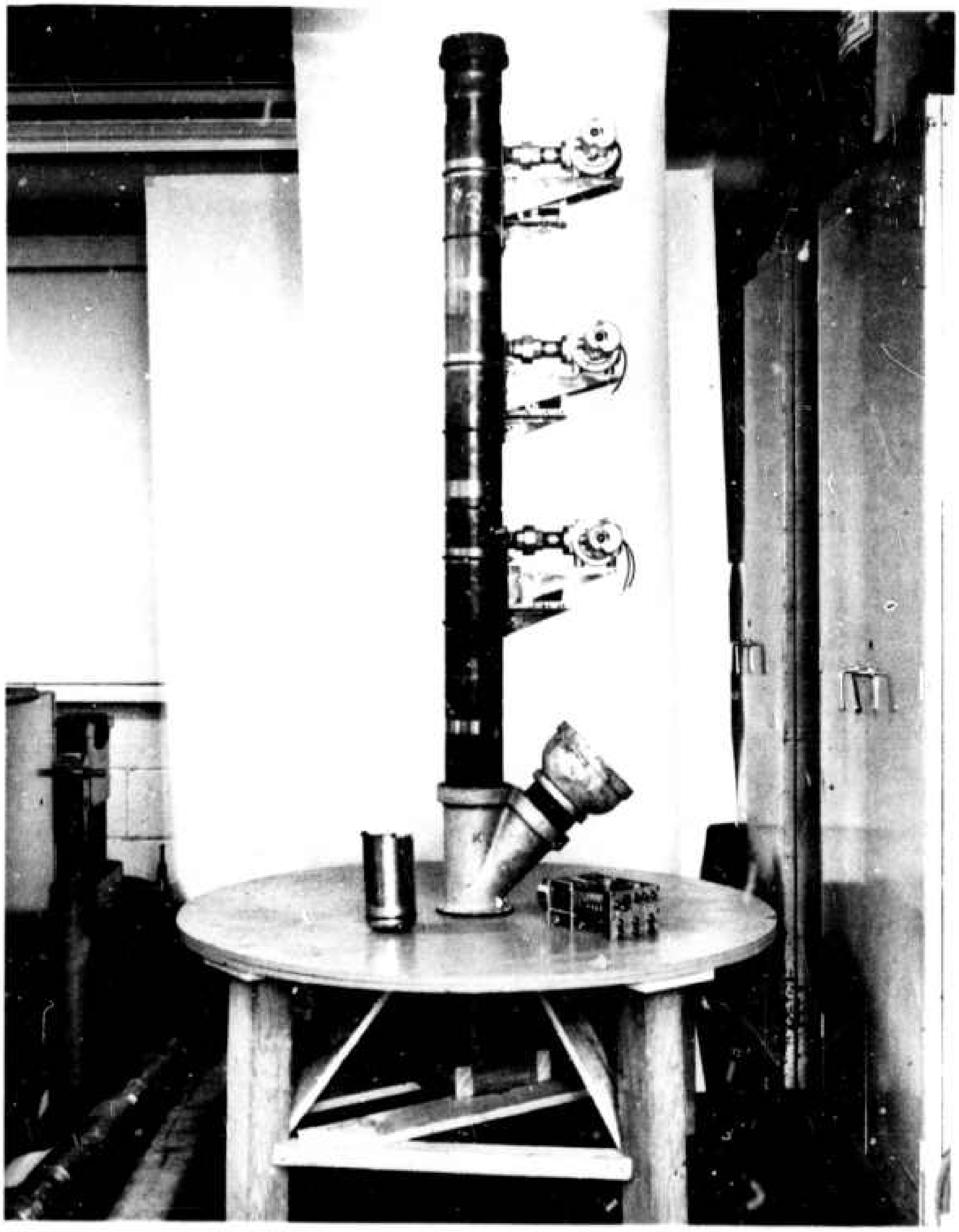
The basic drill tube and the tubes used in the 3-capsule feed magazine were made from 4" I.D. smooth bore steel pipe. The drill tube was made in sections since some of the pipes were salvaged from the hydro-ballistic test rig. The drill tube is supported at the apex fitting and the lower tripod support and the lower end of the tube is set 2 feet from the bottom of the borehole.

After the drill tube is attached tothe tripod, a "Y" pipe fitting is installed on top of the drill tube. A 6" to 4" pipe reducer is installed in the side inlet of the "Y" fitting for connection of the water injection hose.

The 3-capsule feed magazine is mounted in the "Y" pipe fitting at the top of the drill tube. It is composed of three breech assemblies. Each breech assembly consists of a 16" long, 4" I.D. smooth bore steel pipe section, which accommodates one multi-jet capsule, a solenoid operated air flow valve, and a capsule retaining pin with a solenoid retractor.

The capsule is secured in its prelaunch position in the breech by the stainless steel retainer pin which is retracted prior to injection of the air pulse. The air pulse is controlled by means of the solenoid operated air valve which feeds air behind the capsule, through a one-inch pipe to an opening in the wall of the breech. After the capsule is launched, it travels down the drill tube to the 45° Y fitting. It is at this point that the capsule enters the water stream and travels with it down the remaining length of the drill tube to the bottom of the borehole. Each of the three capsules is launched in succession. It is estimated that the total time for launching three capsules in the exploratory drill rig will be in a range of 0.5 (360 SPM) to 2.0 (90 SPM) seconds. However, in the ultimate drilling system with a fully automatic capsule feed, we still predict a rate of fire of 600 SPM (Shots per Minute). The necessary sequencing of events to accomplish this will be provided by the fire control system.

The 3-capsule feed magazine is shown assembled in Figure 3-53. The magazine is composed of three identical breech assemblies, one for each capsule. Each breech mounts two solenoid mechanisms, one for retracting the lock pin from the capsule and the other controls the flow of compressed air to drive the capsule into the water injection flow.



3-CAPSULE AUTOMATIC FEED LAUNCHER

FIGURE 3-53

This figure also shows the work platform, the "Y" pipe fitting, the 6" to 4" pipe reducer and the upper end is closed by a pipe cap. An eye fitting is attached to the pipe cap to support the cable for suspending the air, water, and power lines. A final capsule and fire control mechanism are shown on the work platform. The breeches are numbered in their order of firing, #1 breech is the lowest breech (closest to the work platform); #2 is in the middle; and #3 is the highest breech. These breech numbers are carried over to the fire control system. The fire control system can fire all three capsules automatically by throwing all three sets of switches to "ON" prior to throwing the firing switch. It can also fire the capsules singly or semiautomatically.

The first capsule fired will not have the water/air buffer in front of it, since it is not required for the first round. However, the subsequent capsules will have the water/air buffer in front of each capsule as required.

Figure 3-52 shows that a 4" I.D. acrylic plastic tube section is installed about 4 feet above the ground line. The purpose of the transparent tube section is to permit observation and high-speed photography of dummy or inert capsules to determine capsule velocity in the drill tube. The plastic tube will be replaced with a 4" I.D. smooth bore steel tube when live capsules, loaded with the explosive charge, are tested in the rig.

b. System Support Equipment

The drilling system support equipment installation is shown in Figure 3-51. The support equipment is basically composed of the following subsystems: water pump; water supply tank; compressed air supply; firing station with safety shield and fire control device; and power, water, and air hose lines.

The water pump subsystem consists of a centrifugal water pump with a capacity of 90,000 gallons per hour (GPH) or 1500 gallons per minute (GPM) at 60 psi; water storage tank, since we are not recycling the water; three 6" diameter hose assemblies, one length of suction hose and two lengths of pressure hose. AAI planned to rent all the water pump equipment except the water storage tank which is available at our facility.

Sequencing and activation of the drilling system is accomplished remotely from a shielded observation area on top of the hill overlooking the test site. The compressed air cylinders, water pump and water reservoir are located on the hill in the vicinity of the observation area.

The compressed air supply for the air injection system is provided by cascading 4 or more high-pressure industrial air cylinders. The cylinders are manifolded together with one regulator and a solenoid shut-off valve. The compressed air is supplied from the cylinders to the 3-capsule feed launcher by 1" diameter hose. At the drill rig the supply hose branches into 3 sections which are connected to the 3 air flow solenoid valves. The air cylinder supply approach was used in lieu of the air compressor due to its remote location and the pressure drop encountered in a long supply line. Another advantage of the air cylinder approach is that it is capable of supplying higher air injection pressures if required during test.

The remote firing station is located behind the observation shield, and power cables from the station are routed to the water pump, solenoid shut-off valve at the compressed air source, and to the 6 solenoid valves on the 3-capsule feed magazine on the drill tube.

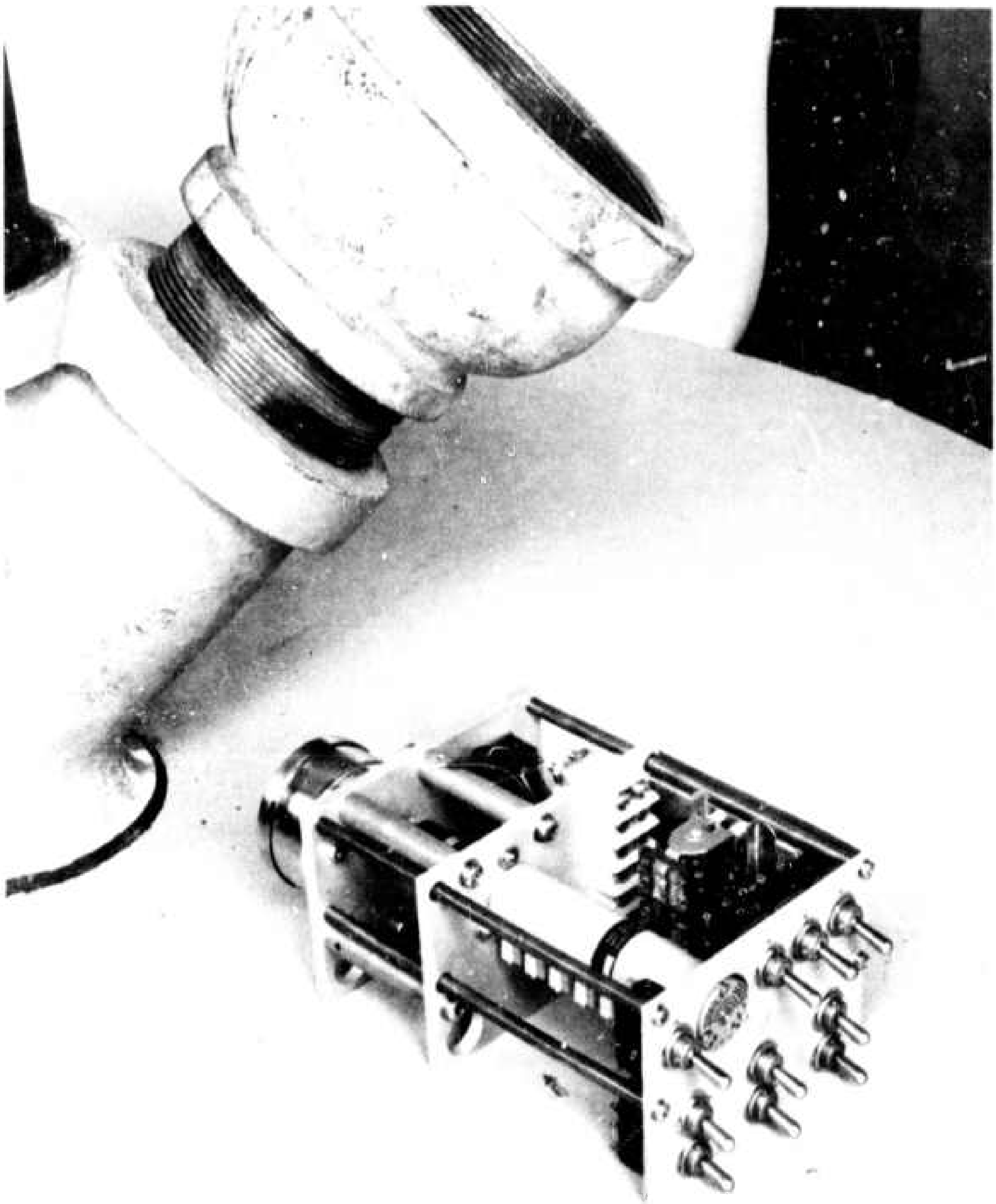
After assuring the equipment is ready and all personnel are under protective cover, the following firing procedures will be performed at the remote firing station:

a. Power switch "ON"
b. Main air supply solenoid switch "ON"
c. Water pump is initiated and flow established
d. Fire control device

    (1) Arming switch turned "ON" and "OFF" to charge capacitors in capsule fuzes.
    (2) The retracting lock pin and the air flow valve solenoid switches are set to the "ON" position.
    (3) Motor switch is turned "ON", motor is allowed to come up to speed, and
    (4) Firing switch is turned "ON" and returned to the "OFF" position after the last capsule explosion.

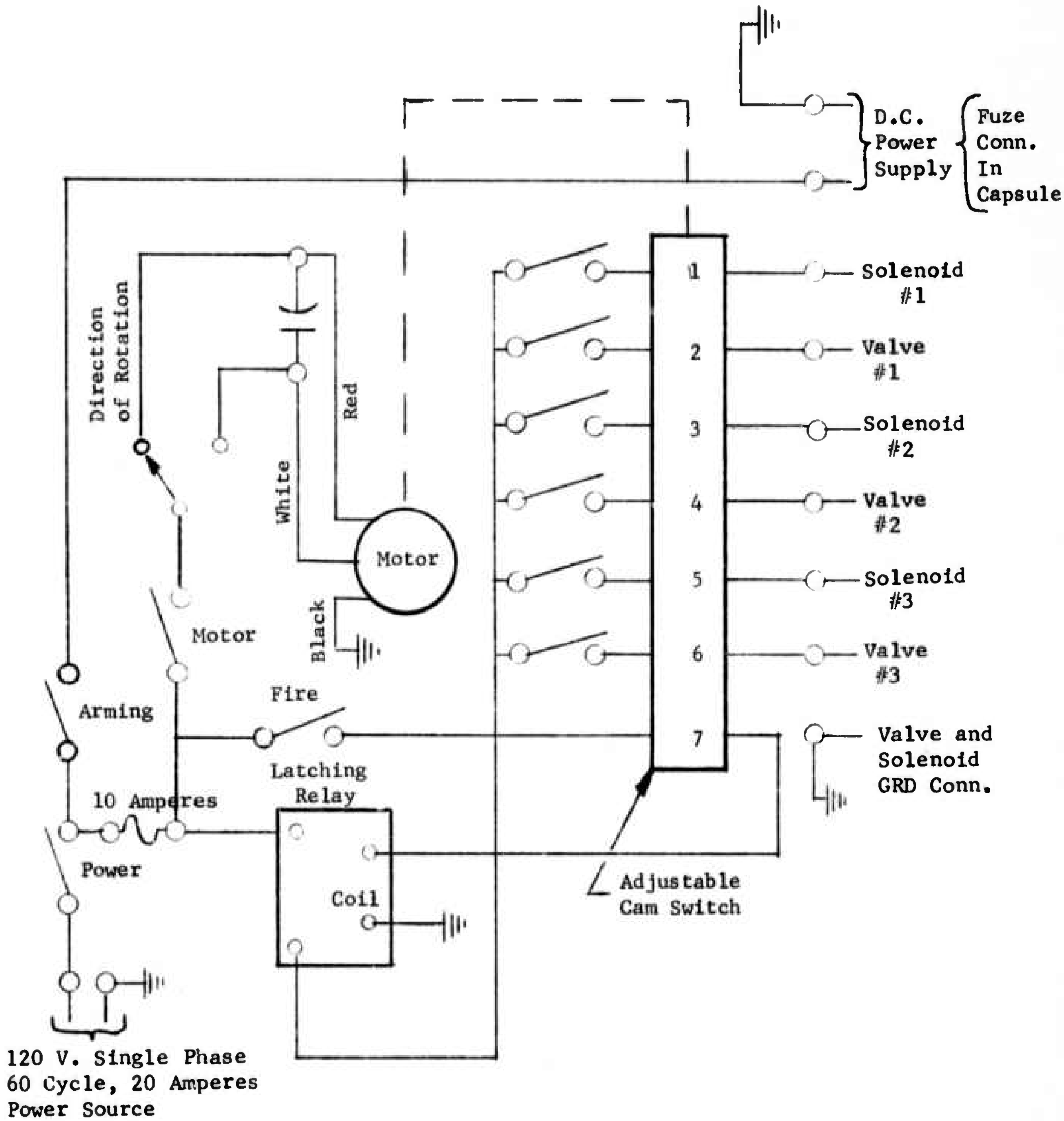
Although the solenoid switches are turned to the "ON" position in (2) above, the solenoids are not actuated until the firing switch is turned "ON". The sequencing of these solenoids is controlled by the adjustable cam switches in the fire control device.

The major component in the firing station is the motor driven adjustable cam switch in the fire control device. A photograph of the fire control device is shown in Figure 3-54 and its wiring diagram is illustrated in Figure 3-55.



FIRE CONTROL DEVICE

FIGURE 3-54



WIRING DIAGRAM - FIRE CONTROL DEVICE

FIGURE 3-35

The fire control device includes the following components: adjustable cam switch; latching relay; capacitor; motor; terminal blocks; and several switches. The switches shown on the front face of the device are shown in Figure 3-54. Starting with the top row, the switches from left to right are as follows: firing; arming; motor and power switches. The 6 switches in the 2 lower rows are used to control the 6 solenoids on the 3-capsule breeches of the feed magazine. The upper row of switches controls the 3 air flow solenoids and the lower row controls the 3 lock-pin retracting solenoids. The upper and lower switches of each of the three sets of two are grouped together for feed breeches #1, #2 and #3, respectively, and are shown in Figure 3-55.

The drive motor, power connections and the motor rotation direction switch are installed on the rear face of the device.

The adjustable cam switch is composed of eight individual cam switches stacked on a common shaft which is driven by an electric synchronous timing motor through a flexible coupling. Each cam switch has an adjustable dwell angle from 3^{o} to 357^{o}; and switch activation point infinitely adjustable throughout the 360^{o} range. Only seven of the eight cam switches are used in this device.

When the firing switch is turned "ON", current is supplied only to the seventh cam switch. When the seventh switch rotates to its closed position (indicating that the first six cam switches are properly oriented for the sequence to begin), current is furnished to the coil of the latching relay. The latching relay contacts are locked in the closed position providing power for cam switches one through six. These six cam switches are adjusted to activate the solenoid capsule release and air flow valve on each breech assembly in the proper sequence.

The remaining portion of the support equipment consists of the installation of the air, water and power lines which are supported by a suspension cable to the drill rig. The suspension cable is routed from a buried steel beam dead-man through the eye fitting of the pipe cap on top of the drill tube and is attached to a tree trunk on the far side.

F. Current Program Status

In various sections of the report we have mentioned that the available contract funds were inadequate to complete the program scope of work. We also stated that the USBM and AAI personnel, considering the great potential of the explosive drilling system, solicited other Government agencies for the financial support to complete the remaining work on this program. No definite commitment has been received from the agencies contacted at the time of this writing; however, considerable interest has been generated at these agencies and they may respond at a future date.

The purpose of this section is to briefly outline the remaining work required to complete the program.

1. Component Details and Assembly

a. Final Capsules (8)

All details complete - loading and assembly required.

b. Fuzes (8)

All details complete - loading and assembly required.

c. Drill Rig System

(1) All drill tube components are complete.
(2) Additional work required on 3-capsule breeches.
(3) Tripod assembly and footings complete.
(4) Work platform details complete.
(5) 3 mooring cables for tripod - details complete.
(6) Borehole rework shown in Figure 3-52 is complete.
(7) Fire control device - electric wiring required.
(8) Suspension cable for supporting air, water, and power lines - details complete.
(9) Rent water pump and three 6" diameter hoses.
(10) Set up compressed air cylinders, manifolds and solenoid shut-off valve.

d. Functional Check-Out

(1) Fuze with dimple motor in lieu of M48 detonator under simulated conditions in hydroballistic test rig.
(2) 3-capsule feed magazine/launcher with dummy capsules, air and power lines connected.
(3) Fire control device.

(4) Combined 3-capsule feed magazine/launcher with fire control device and air and power lines connected.
(5) Water pump pressure and output capacity.

e. Installation

(1) Erect tripod assembly for final leveling and aligning with borehole.
(2) Assemble work platform to tripod.
(3) Install and anchor the 3 mooring cables to tripod.
(4) Assemble drill tube components and install on tripod.
(5) Install suspension cable.
(6) Position water pump and water reservoir.
(7) Position compressed air cylinders.
(8) Set up firing station behind protective shield.
(9) Install firing device and other controls at station.
(10) Route and install all air, water and power lines.

f. Feasibility Tests

The final functional check-out and the feasibility testing of the explosive drilling system shall be in accordance with the test procedures set forth in Part III, Section G of this report.

G. Drilling System Test Plan

After the fabrication of all component details and assemblies are completed, the subsystems will be tested individually and in conjunction with their associated subsystems to assure their operation, prior to final installation. The drill rig will be erected as shown in Figure 3-52, all supporting subsystems and equipment will be positioned as illustrated in Figure 3-51 and all air, water, and power lines will be routed and installed. All functions of the completed drilling system will be tested, prior to initiating the firing tests of the overall system.

Safety procedures will be established, documented, approved and adopted for use during the conduct of the tests. Copies of the safety procedures will be distributed to the cognizant engineering and test personnel and Government representatives observing the tests.

AAI prepared a test plan to prove the feasibility of the explosive drilling system. The number of tests to be conducted are limited to the quantity of capsule/fuze assemblies available for test, due to lack of contract funds. The initial tests will be conducted using dummy capsules to check out the operation of the equipment and generate initial test data. The total number of capsule/fuze assemblies and dummy capsules are eight (8) and six (6), respectively.

The objective of these tests is primarily to prove the feasibility of the overall system. In addition, functional data will be determined on the following: capsule/fuze assembly; capsule velocity and spacing in the drill tube; effectiveness of the anti-sympathetic detonation (water/air) buffer; cyclic rate of fire; rock excavation; and the performance of the air and water injection subsystems.

The test plan is presented below. The requirements for each basic test must be satisfied prior to proceeding with the subsequent tests.

1. <u>System Check-Out</u>

a. Conduct a minimum of 3 tests using one, two, and three dummy capsules.

b. Check out operation of 3-capsule launch system with the fire control device, using the 3 different electric synchronous motors available to check out cyclic operations at 0.5 (360 SPM), 1.0 (180 SPM), and 2.0 (90 SPM) seconds.

c. Confirm established operating procedures.

d. Take high speed movies through plastic drill tube section to record capsule velocities and spacing between capsules per sequencing cycle time.

e. Review the movies and select cyclic time as a function of capsule spacing.

2. Fuze Function

a. Use 3 dummy capsules with fuzes installed; however, dimple motors will be used in lieu of the M48 electric detonators.

b. Conduct tests at selected sequence cycle time.

c. Function 3 dummy capsules (with fuze/dimple motors) through drilling system.

d. Take high-speed movies of c above through plastic drill tube section to confirm capsule velocity, spacing and cycle time.

e. After test, inspect capsule/fuze assemblies to assure that the fuzes functioned and dimple motors were fired and salvage fuzes for live capsule tests.

3. Anti-Sympathetic Detonation Buffer (Water/Air)

a. Replace plastic tube section in drill tube with 4" I.D. smooth bore steel pipe section.

b. Proof test for drill rig structural integrity by detonating a 360 gram explosive proof charge placed underwater at the bottom of the borehole, directly below the lower end of the drill tube.

c. Conduct two firing tests as follows:

(1) First test using 2 live capsule/fuze/M48 assemblies.
(2) Second test using 3 live capsule/fuze/M48 assemblies.
(3) In both tests, use selected cyclic time and capsule spacing, determined above.
(4) Take high-speed movies of both tests, with camera at a remote distance so that the view will show the complete drill rig.
(5) Determine effectiveness of water/air buffer, fuze function and examine rock excavation results.

4. <u>Demonstration Test for Government Representatives</u>

a. Replace 4" I.D. steel pipe section in drill tube with the transparent plastic tube to take high-speed movies.

b. Conduct First Test With:

(1) 3 Dummy capsules loaded into feed magazine.
(2) Use selected cyclic time and capsule spacing.
(3) Fire automatically in 3-dummy-capsule burst.
(4) Take high-speed movies and review.

c. Replace transparent plastic tube in drill tube with 4" I.D. steel pipe section.

d. Conduct second test with:

(1) 3 live capsule/fuze assemblies loaded in feed magazine.
(2) Use selected cyclic time and capsule spacing.
(3) Fire automatically in 3-capsule burst.
(4) Take high-speed movies at a remote position.
(5) Review movies and determine effectiveness of water/ air buffer, fuze function, rock excavation and spoils removal.

IV. FUTURE RESEARCH INDICATED

The foregoing sections of this report have thoroughly described the explosive drilling system and its potential and capabilities are further discussed under Part V, "GOVERNMENT AGENCY IMPLICATIONS."

The work performed under this contract advanced the explosive drilling system, however we were unable to complete the program work, due to lack of contract funds. We have completely developed the multi-jet capsule, determined its terminal effectiveness against rock, established its final configuration through the hydroballistic tests to provide stability for its underwater trajectory and provide the exit and striking velocities required. The capsule used glass-reinforced plastic liners in its tests in order that the ultimate capsule can be completely fabricated in GRP and produced in high quantity under the low unit cost of the process of injection molding.

A new electric fuze was developed for the capsule. This fuze is considered to be safe, since four deliberate actions are required to detonate the fuze. These four actions will occur in sequence, as the capsule is moved down the drill tube.

The drill rig and system supporting equipment have been designed, selected and/or procured and a major portion of the components have been fabricated and some have been assembled. In general, the remaining work involves the completion of the details, assembly and subsystem functional tests and performance of the tests prescribed above to prove overall system feasibility.

Assuming that the work performed to date is classified as Phase I, the immediate research indicated is presented below in Phase II. Two follow-on Phases, III and IV, are also presented below; however Phases II and III could possibly be combined.

<u>Phase II</u>

1. Complete the remaining program work as specified in Part III, Section F of this report.

2. Conduct explosive drilling system tests set forth in Part III, Section G of this report to prove feasibility.

<u>Phase III</u>

1. Fabricate additional quantities of final capsule/fuze assemblies for tests.

2. Transport the drilling system and its equipment from AAI facility to a new test site having hard rock such as granite and/or basalt. Erect the drilling system and support equipment on this site, conduct tests to evaluate system effectiveness against hard rock.

Phase IV

1. Design, fabricate and test the optimum explosive drilling system having a fully automatic feed system capable of continuous operation.

2. Design and fabricate injection molding tools for the production of all glass-reinforced plastic capsule components and for all of the fuze polystyrene components.

3. Fabricate a quantity of capsule/fuze assemblies required for test.

4. Research and development effort shall be continued throughout the program to improve function and to lower component production costs.

5. Conduct tests on all subsystems and overall system against hard rock.

6. Evaluate the optimum explosive drilling system with other systems in regard to rock excavation and disintegration, drill speed, cost per foot, etc.

V. GOVERNMENT AGENCY IMPLICATIONS

There is a need for a drilling system that can perform various tasks of rock excavation and disintegration rapidly and at a low cost. The need exists in both civil and military applications involving the Government, public works, private companies and the military. Shafts and tunnels for water, sewerage, and transportation, mining, oil and gas well drilling are a few civil applications. A few military uses are: rapid atomic demolition munition (ADM) emplacement; missile silos; underground defense control centers; underground storage facilities; and a great variety of military construction work.

AAI considers the explosive drilling system to be capable of advancing the state of the art in the field of rapid rock excavation by a large factor when the capsules are fired at a rate in excess of 600 shots per minute (SPM). The multi-jet capsule head technique is capable of simultaneously producing seven craters and jet penetrations per capsule into the rock working surface. Each capsule contains a 300 gram (.662 lb.) charge of high explosive and when fired at a rate of 600 SPM, the rock face will be advanced rapidly.

A properly designed shaped charge fired at its optimum standoff will penetrate any known material. When a shaped charge is detonated, the liner collapses, a portion of the liner forms a small diameter jet, which shoots forward at a velocity from 6,000 fps to 30,000 fps. The jet is followed by a slug, also formed from the liner material, which travels at a velocity of 1500 fps to 3000 fps. This shaped charge action requires less than five microseconds. The long thin jet, at these velocities, causes the forcing aside of the target material (similar to a high pressure water hose against soil or mud) by the extremely high pressure of 0.3 million atmospheres or 4.5 million psi, which is produced by the impact of the high velocity jet against the target material. It is readily seen that the strength of the target material in this case rock can be neglected.

The above describes the capability of a single shaped charge. The significance of the multi-jet capsule terminal effectiveness can be appreciated when it is considered that a single shaped charge capability against the target is increased by a factor of seven. The capsule incorporates seven shaped charge liners within a common explosive charge which is fired by a single detonator. When the multi-jet capsule is fired at 600 SPM and each capsule provides seven simultaneous jet impacts against the target, the total will be 4,200 jet penetrations per minute (7 x 600) against the rock working face. If the rate of firing the capsules were ultimately increased to 1200 SPM, which is considered within the state of the art, the total would be 8,400 jet penetrations per minute against the rock. In the ultimate system, the capsule O.D. could be increased to accommodate a greater number of shaped charge liners and could be fired at 1200 SPM and produce any number of jet penetrations per minute desired. The anti-sympathetic detonation (water/air) buffer, previously described, is the key to the high rate of fire capability of the explosive drilling system.

In addition to shock of the jet penetrations, the rock will also be severely shocked by the detonation of the capsules underwater in the borehole. The underwater detonation of the capsules increases the rate of rock excavation and disintegration and facilitates spoils removal.

The purpose of the foregoing discussion on terminal effects was primarily to re-emphasize the rapid rock excavation and disintegration capabilities offered by the multi-jet capsules, fired at a high rate and detonated underwater.

When initially starting a borehole for a shaft or tunnel, the drilling system can be operated in the atmosphere, without the water injection subsystem, and the capsules would be fired at an extremely low rate of about 12 SPM. The terminal effectiveness of the capsule is reduced when fired in the atmosphere. This reduction is due to the dissipation of a portion of the capsule explosive energy to the atmosphere, which is also true of any explosive component fired in the air.

We believe that the best way to achieve low cost, rapid rock excavation and disintegration is by the rapid use of explosives. We also believe that the unique explosive drilling system, firing the multi-jet capsules at a high rate, is capable of successfully performing the civil and military applications mentioned at the outset of this section.

VI. CONCLUSIONS AND RECOMMENDATIONS

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

o The glass-reinforced plastic (GRP) shaped charge liners test specimens were successfully test fired against concrete, aluminum plate, and rock targets and the terminal effects exceeded our expectations. The GRP liner specimens utilized a variety of wall thicknesses (.040, .080, .160, and .200 inches) and standoff distances (1.00 to 3.50 inches) in these tests. The tests confirmed that the thicker wall liners and maximum standoff, produced holes with the smallest craters, deepest jet penetrations and smallest volumes. Conversely, the thinner wall liners, at the minimum standoff, produced holes with the largest craters, shortest jet penetration depths and the maximum volume.

o The feasibility of the multi-jet capsule, incorporating seven GRP liners mounted in a housing with a common explosive charge and detonator, was proven in test. The feasibility was initially proven by firing four (4) multi-jet test capsules, in the atmosphere against three (3) inch thick aluminum target plates. The capsule produced seven individual jet penetrations in each target.

o The capsule feasibility was further confirmed by statically firing seven multi-jet capsules underwater in a previously started borehole in situ Cockeysville marble. The original borehole was 15 inches in diameter at the top and 18 inches deep. The capsule was placed on the bottom of the water-filled borehole and fired. After firing, the borehole water was drained, the remaining spoils were removed, and the new borehole was measured. This procedure was followed after each shot. After firing the seven test capsules, the rock working face of the borehole was advanced to 60 inches from the ground surface and the borehole at the top extended to an ellipse with a major and minor diameter of 62 inches and 42 inches, respectively. The bottom of the borehole was advanced from 18 inches to 60 inches or 42 inches for seven capsules to provide an average of 6 inches advance per capsule. A composite sketch of the borehole profiles after each shot is shown in Figure 3-31. The capsule was designed to "over kill" the Cockesyville marble so that it will be effective against harder rock, granite and basalt.

o The final multi-jet capsule design was completed in this program. To establish the capsule's final external configuration, its stability during the underwater trajectory from the drill tube to the bottom of the borehole, its exit velocity from the drill tube, and its impact velocity at the bottom of the borehole, the hydroballistic test rig was designed and fabricated. The test rig simulates the borehole environment and incorporates both compressed air and water injection subsystems of the drill rig. Fifty-three (53) tests were conducted in the test rig using six (6) different capsule model configurations, nine (9) test conditions in regard to the capsule position in the drill tube in relation to the air and water columns, and various air injection pressures. The #3 capsule model configuration was selected as the optimum in these tests and the following parameters were established: external configuration, weight, c.g. location for underwater stability, exit velocity, and striking velocity. The striking velocity is important in the fuze design. The air injection pressure and the position of the capsule in regard to the air and water columns in the drill tube were determined in these tests.

o The final multi-jet capsule design was based on the characteristics of the #3 capsule model configuration. The capsule uses seven GRP liners and the remaining components were fabricated from aluminum spinnings and machined parts. These capsules are to be used in the drill rig tests.

o It is recommended that the ultimate capsule be fabricated from all GRP components in a follow-on program phase. These capsules will be fabricated by using the injection molding process. This process is capable of high quantity production at a low unit cost and this is required for the economy of the high rate explosive drilling system.

o A new electric fuze was developed for the capsule. The fuze is considered safe, since four arming functions are required prior to capsule detonation. These arming functions are performed in sequence, as the capsule travels down and out of the drill tube. Preliminary tests of the fuze, using a dimple motor in lieu of the M48 detonator, will be mounted in a dummy capsule and fired down the drill tube, were planned.

o The drill rig and system support equipment was designed and a major portion of the components were fabricated; however, the complete system has not been erected. The anti-sympathetic detonation buffer has not been tested and the spacing between capsules in the drill tube has not been determined. The drill rig incorporates a 3-capsule feed magazine and these are launched in sequence, singly, semi- and fully automatically, by the fire control device.

o The seven-jet capsule produces seven jet penetrations into the rock and, when fired underwater, produces additional shock to the rock. This capsule may be compared to a shotgun cartridge, since it has more than one "kill mechanism" per cartridge whereas a rifle cartridge contains only one. Therefore, when the capsules are fired down the drill tube at a rate in excess of 600 SPM (minimum predicted for the ultimate system) the number of jet penetrations per minute into the rock working face will be in excess of 4,200 per minute.

o The development of the GRP liners and that of multi-jet capsules with seven shaped charge liners and a common explosive charge and detonator are considered to be technological breakthroughs.

o Due to the lack of contract funds, all work was stopped on 6 November 1972. The development of the explosive drilling system and components were advanced considerably by this exploratory program. Since the planned tests were not conducted, certain development areas are unresolved. The remaining work to be performed, in addition to the proposed follow-on programs, are presented in Part IV. The system potential and its practical applications are discussed in Part V.

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VIII. ABBREVIATIONS

ADM	Atomic Demolition Munition
FPS	Feet Per Second
Ft. or '	Foot or Feet
Gal.	Gallon
GPH	Gallons Per Hour
GPM	Gallons Per Minute
GRP	Glass Reinforced Plastic
I.D.	Inside Diameter
In. or "	Inch(es)
Lbs.	Pounds
O.D.	Outside Diameter
PSI	Pounds Per Square Inch
SPM	Shots Per Minute

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X. SUBJECT INVENTIONS

In accordance with Appendix "B" to this contract entitled "Patents and Inventions Article," AAI has no "Subject Inventions" to report.