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Distributed Explosive-Driven Six-Foot Diameter by Two-Hundred Fot Long Shock Tube

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DISTRIBUTED EXPLOSIVE-DRIVEN SIX-FOOT DIAMETER by TWO-HUNDRED FOOT LONG SHOCK TUBE

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Abstract

The blast parameters for the 6-foot diameter by 200-foot long, explosively driven shock tube are presented in this report. The purpose, main characteristics, and blast simulation capabilities of this PETN Primacord, explosively driven facility are included. Experimental data are presented for air and Sulfurhexaflouride (SF6) test gases with initial pressures between 0.5 to 12.1 psia (ambient). Experimental data are presented and include shock wave time of arrival at various test stations, flow duration, static or side-on overpressure, and stagnation or head-on overpressure. The blast parameters calculated from the above measured parameters and presented in this report include shock wave velocity, shock strength, shock Mach number, flow Mach Number, reflected pressure, dynamic pressure, particle velocity, density, and temperature. Graphical data for the above parameters are included. Algorithms and least squares fit equations are also included.

Acknowledgments

Tom Hendrickson's and Lloyd Bonzon's support toward the documentation of this work is greatly appreciated. Thanks to Mike Kaneshige's and Gary Rivera's for their efforts in a timely review of this report. Thanks to Patricia Sanchez for her efforts in getting this report finalized and published in a timely manner.

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Nomenclature

A_o	Test gas sound velocity (fps)
a_o	Sound velocity behind the shock wave (fps)
Co	Test gas sound speed (fps)
C_p	Specific heat at constant pressure
C_v	Specific heat at constant volume
D	Shock tube diameter (ft)
CTU	Calibration Test Unit
I	Static impulse (psig-ms)
LTU	Laboratory Test Unit
Mf	Flow Mach number
Ms	Shock Mach number
N_R = Re	Reynold's number
$P = P_2$	Static or Side-on pressure (psia)
$P_o = P_1$	Initial test gas pressure (psia)
P_t	Stagnation or head-on pressure (psia)
P_r	Reflected pressure (psia)
ΔP	Static overpressure (psig)
Q = q	Dynamic pressure (psia)
T	Temperature behind shock
T_a	Shock arrival time relative to the initiation of explosive (ms)
T_d	Flow duration time (ms)
T_1	Temperature behind the shock wave (F)
T_o	Initial test gas temperature (F)
Tt	Stagnation temperature
U = u	Flow velocity behind the shock wave (fps)
V_s	Shock wave velocity (fps)
W	Explosive weight (lb)
$\rho_1 = \rho$	Density behind the shock wave (lb/ft^3)
ρ_o	Initial test gas density (lb/ft^3)
γ	Test gas specific heat ratio
μ	Viscosity
(P/P_o)	Shock strength
FREON-C318	Octofluorocyclobutane
SF6	Sulfurhexaflouride

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1.0 Introduction

Sandia National Laboratories (SNL) has been extensively engaged in the design of aerodynamic structures to withstand blast loading. As part of this program, SNL has devoted a considerable effort to the development of facilities for blast simulation, instrumentation to measure structural response and blast environment, and analytical techniques to analyze structure-environment interactions as documented in References 1 through 20.

Current interest in the blast testing of the W76-1/MK-4 system has required that available explosively driven shock tube facilities be evaluated to conduct this program. Sandia National Laboratories (SNL) explosively driven shock tube facilities were last used on the W88/MK-5 blast program in about 1986. Therefore, SNL must make a decision whether to re-start or refurbish the shock tube facilities here or to conduct the W76-1/MK-4 blast program at an outside facility if a qualified site is found. As part of the evaluation of shock tube facilities and to help in the decision-making, this report is one of several (Reference 1 and 20) documenting SNL shock tube facilities and their performance parameters.

This report is similar to and compliments the report documented in reference 1 for a 6-foot diameter by 60-foot long, concentrated explosive-driven shock tube and reference 20 for a 19-foot diameter explosively driven blast simulator. The distributed, PETN Primacord, explosively-driven and longer shock tube described in this report differs from the shock tube described in reference 1 as follows:

1. Distributed, PETN Primacord, explosive with much lower density (1.0 versus 1.65 g/cc),
2. Re-usable, thick-walled, driver section,
3. Longer flow duration times (25 ms versus 5 ms),
4. Longer static impulses, and
5. Lower static and stagnation pressures.

Designing any structure to survive a dynamically applied load such as blast is a complex task. In terms of re-entry vehicles, the blast loads on the structure are caused by the vehicle velocity, as well as by the density, pressure, and particle velocity of the blast wave. The complexity of the blast environment experienced by the structure demands that design be experimentally verified and proof tested.

There are two general methods for blast testing structures: move the structure through the blast environment, or hold the structure stationary in a blast environment. SNL chose the approach of combining a stationary vehicle (and hard-wire instrumentation) with an explosive-driven flow environment in a shock tube.

Loading Characteristics of Stationary Structures

The loads imposed on a stationary structure in a shock tube are caused only by conditions behind the shock wave. These conditions, and the load pulse shape, depend upon the initial conditions in the tube, tube configuration, and load level. The important considerations in this type of blast-loading can be summarized as follows:

1. The maximum load level prescribes a limit to the shock strength and velocity,
2. The shock velocity controls the load rise time,
3. The length of the shock tube and the shock strength determine the duration of the load pulse, and
4. The flow Mach number behind the shock wave, which influences the pressure distribution on the structure, depends upon the driven gas, initial test gas pressure, and the shock strength.

These interdependent parameters determine the nature and configuration of a shock tube for a given application. However, considerable control over the shock tube performance at a given load level can be exercised by appropriate selection of the test gas and initial pressure in the tube.

For example, one major limitation of shock tube testing, or for that matter, any other blast simulation technique, is in obtaining a pressure distribution around the structure that is representative of actual high-velocity flight intercepts. This pressure distribution depends upon the Mach number of the flow. Thus, relatively high Mach numbers are desirable behind the shock for blast testing of aerodynamic structures.

Purpose

The six-foot diameter by two-hundred foot long explosively driven shock tube at Sandia National Laboratories has been used to simulate the blast environment on a Re-entry Vehicles (RV) resultant from the detonation of an enemy RV in the vicinity. The ability of the components within the RV to survive this hostile blast environment is verified by subjecting the RV to similar blast environments in the shock tube. This shock tube has been in service since the fall of 1964.

Shock Tube Blast Parameters

The blast parameters for the 6-foot diameter by 200-foot long, explosively driven shock tube are presented in this report. The purpose, main characteristics, and blast simulation capabilities of this PETN Primacord, explosive driven facility are included. Experimental data are presented for air and Sulfurhexaflouride (SF6) test gases with initial pressures between 0.5 to 12.1 psia (ambient). Experimental measured data are presented for the following blast parameters:

1. Shock wave time of arrival at various distances,
2. Test gas sound velocity measurements,
3. Flow duration,
4. Static or side-on overpressure, and
5. Stagnation or head-on overpressure.

The blast parameters calculated from the above measured parameters and presented in this report include:

1. Shock wave velocity,
2. Shock strength,
3. Shock Mach number,
4. Flow Mach Number,
5. Reflected pressure,
6. Dynamic pressure,
7. Particle velocity,
8. Density behind the shock, and
9. Temperature behind the shock.

Graphical data for the above parameters are included. Algorithms and least squares fit equations are also included.

2.0. Shock Tube Configuration

General

The 6-foot diameter by 220-foot long shock tube configuration is shown in Figures 1 - 3. Figure 1 shows the pre-test configuration. Figure 2 shows this shock tube and the 6-foot diameter by 60-foot long shock tube documented in reference 1. Figure 3 shows the detonation product gases venting from the driver end shortly after initiation of the explosive and also shows the shock tube shortly after the blast wave has propagated beyond the muzzle end. The total shock tube length can vary between 200 to 220 feet depending on the test section used at the muzzle end. Table 1 lists some of the shock tube sections along with length, weight, and wall thickness data.

Driver

The driver section is 50 feet long with a 3-inch thick wall. The driver is made of T-1 steel. The yield stress for this material is 120,000 psi. The driver has steel pad eyes welded to the top and bottom of the driver that are used to suspend and distribute the PETN Primacord explosive strands. The driver end has an "O" ring groove machined into the 3 inch wall thickness used to seal between the one in thick steel, closure plate and the driver for reduced test gas pressure tests. The driver end has threaded holes in the 3 inch was face that are used for the bolts that hold the 1 inch thick steel plate to seal the driver end. The shock tube sections are suspended by adjustable screw jacks as shown in Figure 4.

Driver End/Tamping Mass

The driver end tamping mass has been used to prevent the early venting of the high-test gas pressures until after the blast wave has reached the test section. The driver end blows out when the explosive is detonated, eliminating the thrust to the pipe. This no thrust feature is an important part of the design. Since small wall discontinuities are not important compared to the six-foot diameter, flanges or other mechanical joint fastenings were eliminated at a considerable savings in cost and fabrication time.

The tamping mass configurations have included the following on any given test:

1. One inch thick steel plate(1300 lb),
2. Nine to 18 inch thick plywood plug (1600 lb) attached to the 1 inch steel plate to be cantilevered inside the driver section, and
3. Plywood plug, 1 inch steel plate, and 5 or 6-foot cube concrete blocks.

One to three concrete block blocks have been used. The weight of each concrete block is about 27,000 to 30,000 pounds. The maximum tamping weight has been about 91,000 pounds. The driver, 18-inch plywood plug, one-inch steel plate and two concrete blocks are shown in Figure 5 prior to being installed. Figure 6 shows these tamping masses installed behind the driver. Plywood sheets are used between the tamping masses to distribute the loads over the area of the concrete blocks to minimize the chipping of the block surfaces.

<u>Explosive Loading</u>

Four hundred grain per foot (0.0571 lb/ft), PETN Primacord explosive is used to drive this shock tube. The PETN explosive density is about 1.0 gram per cubic centimeter. The explosive is housed in a 0.5 inch outside diameter nylon tube or cord with about a 0.014-inch wall thickness. Therefore the explosive diameter is about 0.47 inches. The explosive and nylon tubing weigh about 0.076 lb/ft.

The PETN Primacord is evenly distributed over the cross-sectional area of the driver, and various charge lengths have been used. The maximum explosive loading, linear density is 8 pounds per foot. The maximum loading generates stresses in the T-1 steel, 3-inch thick wall driver that are at the safe operating levels. Previous tests have limited the explosive loading to 7.4 pounds per foot. Typically, 100 grain/foot PETN Primacord explosive stringers are installed vertically to support 400 grain/foot horizontally positioned strands. The 100 and 400 grain/foot explosive has a thin, nylon re-enforced sheath to provide strength or support. The vertical stringers are tied in knots to steel eyebolts welded to the top and bottom of the driver.

Figure 7 shows the Primacord strands installed in the driver section. Per Figure 7, the ends of the Primacord strands are grouped into two bundles. An SE-1, RP-1, or similar detonator is taped in the center of each bundle to be used to initiate the explosive in each bundle. The distribution geometry of the Primacord strands of explosive in the six foot-diameter driver is shown in Figure 8.

<u>Test Section</u>

The driver is 50 feet long with a 3-inch wall thickness, the next 42 foot long section has a 1.0-inch wall thickness, and the remainder of the shock tube has a 0.75-inch wall thickness. The tube sections are not rigidly joined: however, a vacuum seal is provided by rubber boots placed over the joints. The total shock tube length can vary between 200 and 220 feet. The last section and typically the test section can include a 45 or 90-degree muzzle end as shown in Figures 9 and 10, respectively. The 45-degree end section is used to allow larger test units at large angles of attack to fly free after blast arrival and to clear the test section. The 45-degree test section end also tends to reduce the relatively high base pressure, which is a result of reflections from the diaphragm (for reduced initial test gas pressure tests only) on the muzzle end.

Test Unit Suspension

Lighter test units are typically suspended from the top of the test section by light fiberglass straps, which are broken or sheared by the blast wave. Heavier test units are typically suspended from the top of the test section by a wire rope or cable. The cable is explosively cut when the blast wave arrives at the nose of the test unit. The test unit is then free to respond to the blast wave. Figure 11 shows a conical test unit suspended the test section.

Test Unit Soft Recovery

When it is desired to have the test unit free to response to the blast wave, ejected from the test section and to be soft recovered, a sawdust recovery pit is used. The length, width, and depth depend on the trajectory and geometry of the test unit. Nylon parachutes vertically suspended along the trajectory of the test unit have been used to decelerate the test unit and reduce the length of the test unit flight. Sand bags or other masses have been attached along the edges and bottoms of the parachute to aid in the deceleration process. This technique has been used on a 19-foot diameter shock tube and is shown in Figure 12.

Reduced Pressure Tests

The shock tube can be sealed for reduced initial test gas pressure tests. Initial test gas pressures from 0.5 to 12.1 (ambient) psia have been used. Test gases have included air, sulfurhexaflouride (SF6), and Octofluorocyclobutane (FREON C-318). A 1-inch thick steel plate and rubber "O" ring have been used to seal the driver end. Strands of thick rubber have been used to seal at the interfaces between sections of the shock tube. Two large radiator type clamps are used to hold the rubber strands on the shock tube surface. A thin (0.04 inches thick) aluminum diaphragm along with a steel ring holder and an "O" ring has been used to seal the muzzle end of the shock tube. Puddy has been used to seal any small air leaks throughout the shock tube. Figure 13 shows the muzzle end sealed with an aluminum diaphragm.

3.0. Test Gas

Explosively driven shock tubes are used to simulate the effects of blast waves on structures. Successful simulation depends upon attaining a desired load level, duration, and spatial distribution. The flow parameters behind a shock wave which determine the character of loads on structures are uniquely determined by the shock velocity and the initial conditions and chemical composition of the test gas. The maximum load level in a test may easily be altered by changing the initial pressure. However, the spatial load distribution depends upon the flow Mach number behind the shock; and, thus, upon the shock strength and the specific heat ratio (k) of the gas. The variation in flow Mach number versus shock strength and specific heat ratios is illustrated in Figure 14 [3].

The maximum Mach number (M_f) in an ideal gas at very high shock strengths is approximated by the following equation [3]:

$$M_f = \{(2)/[k(k-1)]\}^{0.5}$$

Where,

$k = c_p/c_v$

Thus, it is obvious that heavy gases, which have low specific heat ratios, are desirable test gases to approximate the pressure distributions, which are associated with blast waves encountered in high-speed flight.

Though heavy, nontoxic gases are the more favorable for testing, they have several disadvantages. Their lack of equilibrium under shock tube conditions and their chemical instability frequently lead to solid deposits or burning; moreover, these factors make it difficult to calculate the conditions that will exist behind the shocks.

Previous experience for testing with Freon C-318 has shown that significant amount of graphite is produced behind the initial moving shock wave. This graphite production causes the values of the stagnation pressures to be uncertain since the graphite particles impacting the transducers can cause unrealistic spikes on the measured pressure profiles. In addition, the arbitrariness of the reaction and its probable spatial non-homogeneity may well account for the large fluctuations in static pressures. Freon C-318 is stable only at temperatures below 1000 ° K and therefore, the gas is suitable for use only in cold driven shock tubes or explosive driven shock tubes long enough to permit cooling of the combustion or detonation product gases below 1000 ° K.

Shock tube tests have shown that for shock mach numbers greater than 4 (shock strength = 20), Freon C318 decomposes resulting in a non-planar shock front at the test station. The thermal decomposition value is approximately 1200 degrees Kelvin for Freon C-318.

Previous development work at Sandia National Laboratories has shown that Sulfurhexaflouride (SF6) is chemically stable in an explosively driven shock tube blast environment. For SF6, shock photographs in the shock tube indicate more planar shock fronts (using PETN Primacord distributed explosives) with transparent shocked gas. SF6 was analytically determined to be thermally stable to twice the temperature of Freon C-318.

Shock tube tests indicate that Freon C-318 and SF6, molecular weights of 200 and 144, respectively, were capable of producing flow Mach numbers twice that obtained in air for equivalent shock strengths.

4. Measurements and Instrumentation

Typically, measurements for a test include static (side-on) and stagnation (head-on) pressures along the total length of the shock tube, shock arrival times, test gas sound velocity, shadowgraphs of the shock wave to measure planarity, photography including the trajectory of the test unit from the test section to the soft recovery pit, and flow duration measurements. Measurements on the test unit include surface pressures, accelerations, velocities, and strains. Previously, a maximum of 200 channels of data per test have been recorded. These have included about 150 channels of piezoresistive and about 50 channels of piezoelectric measurements.

The instrumentation cables are routed out of the center of the test unit base plate. A 3 or 4-inch diameter radiator hose is used to protect the instrumentation bundle from the blast wave. The cable bundle is explosively cut after the blast wave has propagated beyond the test unit. For tests where the impulse induced on the test unit is relatively short and the test unit trajectory is short and directed downward, the instrumentation bundle is not cut. For this case, the test unit can be re-suspended in the test section and tested again without having to re-splice the instrumentation cables.

5. Calibration Test Unit (CTU)

The CTU is typically a thick, walled boilerplate model of the actual Laboratory Test Unit (LTU) or Re-entry Vehicle (RV). The CTU geometry, total weight, and center of gravity are identical to the LTU. The CTU is usually made of aluminum. Typically about 150 pressure measurements have been made on the surface of the CTU. For a typical CTU test, about 50 channels are used to record shock tube pressures, CTU internal component accelerations, velocities, and strains.

6. Laboratory Test Unit (LTU)

The LTU is a prototype vehicle of the actual Re-entry Vehicle (RV). Total instrumentation includes about 150 channels of data. A few surface pressure measurements are recorded (about 25). A few shock tube static and stagnation pressure measurements are recorded primarily in the test section area. The remainder of the recorded channels include accelerometer, velocity, and strain gage measurements.

7. Measured Static and Stagnation Pressure Profiles

A typical, measured static pressure versus time profile is shown in Figure 15. A typical, measured stagnation pressure versus time profile is shown in Figure 16. These pressure measurements were obtained from a shock tube test with air as the test gas and a 12.1 psia (ambient) initial test gas pressure. The measurements were obtained at a test station of 210 feet from the driver end.

8. Maximum Performance Blast Parameters

The blast wave generated in an explosively driven shock tubes is a shock wave followed by a rarefaction wave. The flow duration is dependant on the explosive weight, distribution in the driver section, driver tamping mass, test gas, and initial test gas pressure. The duration also strongly depends on the shock tube length.

The distribution of the explosive over the various lengths requires a shock tube length of at least 15 diameters before a good planar shock front is formed.

The maximum PETN Primacord explosive charge weight was 320 pounds uniformly distributed over a 40 foot length. The maximum explosive linear loading density is 8.0 pounds per foot. The maximum blast parameters at a test station about 210 feet from the driver end are as follows:

1. Shock velocity: 8000 feet/second,
2. Shock Mach number: 11.0
3. Flow Mach number: 6.0
4. Overpressure: 200 psi
5. Shock strength: 130
6. Flow duration: 30 milliseconds
7. Flow duration to 50% of maximum pressure: 10 milliseconds

The above maximum conditions are not all obtained with the same initial shock tube parameters (test gas, initial test gas pressure, explosive weight, etc.).

9. Shock Tube Blast Parameters

The Rankine-Hugoniot equations used to calculate some of the blast parameters are listed in Table 2. Constants for various gases are listed in table 3.

Test Gas: Air

The shock tube parameters for air as the test gas are shown in Figures 17 – 25. Figure 17 shows the static overpressure (Ps), flow duration (Td), and static overpressure impulse (I) versus driver explosive weight (W). Figures 18 through 20 show static overpressure (Ps), shock mach number (Ms), and shock time-of-arrival (Ta) versus driver explosive weight, respectively.

Figure 21 shows the static overpressure (Ps), shock mach number (Ms), flow mach number (Mf), and static to stagnation pressure ratio (Ps/Pt) versus driver explosive weight to initial test gas pressure ratio (W/Po). Figures 22 through 25 show shock strength [(Ps/Po) = static pressure to initial test gas pressure ratio), shock mach number (Ms), flow mach number (Mf), stagnation to static pressure ratio (Pt/Ps), and shock time-of-arrival (Ta) versus driver explosive weight to initial test gas pressure (W/Po), respectively.

Measured Time-Distance Data/air

Table 4 lists the measured time - distance data for a test with a relatively low explosive weight (72 pounds) in the driver. Table 5 lists the blast parameters calculated from the shock velocity which was calculated from the measured time-distance data. This table lists the calculated shock velocity, shock and flow Mach numbers, static pressure P(S), stagnation pressure P(T), dynamic pressure p(D), density ratio across the shock ETA, and shock strength (static to initial test gas pressure ratio).

Table 6 lists the measured time - distance data for a test with a relatively higher explosive weight (160 pounds) in the driver. Table 7 lists the blast parameters calculated from the shock velocity which was calculated from the measured time-distance data. This table lists the calculated shock velocity, shock and flow Mach numbers, static pressure P(S), stagnation pressure P(T), dynamic pressure p(D), density ratio across the shock ETA, and shock strength (static to initial test gas pressure ratio). Table 8 lists a summary of the shock tube flow parameters for the above 72 and 160 pound explosive weight tests.

Test Gas: Sulferhexafluoride (SF6)

The shock tube parameters for sulferhexaflouride as the test gas are shown in Figures 26 – 29. Figures 26 through 29 show shock strength [(Ps/Po) = static pressure to initial test gas pressure ratio), shock mach number (Ms), flow mach number (Mf), stagnation to static pressure ratio (Pt/Ps), and shock time-of-arrival (Ta) versus driver explosive weight to initial test gas pressure (W/Po), respectively.

10. Test Gas Sound Speed

Test gas: Air

The sound speed in air (Co) versus initial test gas temperature (To) is shown in Figure 30.

Test gas: Sulferhexafluoride (SF6)

The sound speed in sulferhexafluoride (Co) versus initial test gas temperature (To) is shown in Figure 31.

11. Shock Wave Planarity

The measured shock wave planarity across the 6 foot diameter cross-section is shown in Figure 32. The shock wave was measured through a one quarter inch gap between tube sections. The test parameters for this test were as follows:

1. Test gas: air
2. Initial test gas pressure: 12.1 psia (ambient)
3. Distance from driver end: 150 feet
4. Static overpressure: 130 psig
5. Shock velocity: 3550 feet/second
6. Test No.: E72-159
7. Test Date: (10/11/72)

12. Structural Dynamic Model Correlation

Two major objectives of the blast programs conducted at SNL have been:

1. Evaluation of the structural dynamic model from known forcing functions, and
2. Partial "proof" testing of vehicle structures in a blast environment.

Computer programs have been developed to transform the measured pressure data in digitized form from a CTU test into calculated forcing functions. To minimize the perturbation to the structural response from transducer systems, a two step process has typically been used to obtain forcing functions for structural analysis.

First, a CTU, which is extensively instrumented with pressure transducers, along with some accelerometers, is used to fully define the low environment and prove the test condition acceptable for the LTU of the prototype vehicle. Acceleration and strain transducers are the primary instrumentation for an LTU, with only a few pressure transducers to confirm the equivalency of the LTU test conditions to that of the CTU test.

Typically, with the use of a mean value theorem computer program, digitized "continuous" pressure data is transformed into discrete points for a given time span. Each vehicle pressure for a given test is sampled similarly, so that only one set of time values is needed to describe the pressure points with respect to the pressure rise or shock front arrival.

After a uniform time scale has been obtained from the measured shock velocity and vehicle geometry, these faired pressures from multiple locations on the CTU are interpolated linearly in time and space by a second program. The resulting time-space pressure distribution is integrated by this program over aerodynamic areas corresponding to masses in the structural dynamic model to obtain force and moment time functions. These forcing functions are then used as the inputs into the spring-mass structural model of the prototype vehicle, the objective being the prediction of vehicle response equivalent to that of the LTU when subjected to the same environment. Typically, one CTU test has been required to define the environment and obtain the forcing functions for an LTU test.

Besides the forcing functions, a "rigid body" load history can also be calculated from the CTU pressure measurements and compared with the on-board accelerometers to further verify the defined environment. Measured strain data from the LTU test can be compared to the calculated strain from a structural dynamic model to confirm the match of pulse shape and peak values.

13. Summary and Conclusions

Sandia National Laboratories (SNL) has developed a 6-foot diameter by 200-foot long, explosive driven shock tube for blast simulation on aerodynamic structures. Tailoring of the shock tube design and the test gas (pressure and molecular weight) will produce a wide range of load pulses. The 6-foot diameter by 200-foot long shock tube historical background, characteristics, and flow parameters has been presented in this report.

SNL has developed methods for blast testing structures and verifying analytically and experimentally their capabilities in blast environments.

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Table 1. Six foot diameter by 200 foot long shock tube sections, lengths, and weights

DRIVER MATERIAL: USS T-1 STEEL, YIELD STRENGTH: 105,000psi, TENSILE STRENGTH: 118,000 psi

SECTION NUMBER	DESCRIPTION	LENGTH (feet)	TOTAL LENGTH (feet)	WEIGHT (lb)	WALL THICKNESS (inches)
1	DRIVER	22.18	22.18	53,430	3.0
2	DRIVER	14.8	36.98	35,653	3.0
3	DRIVER	14.8	51.78	35,653	3.0
4		42.0	93.78	32,826	1.0
5		49.0	142.78	28,625	0.75
6		35.0	177.78	20,446	0.75
7	TEST SECTION	28.0 *	205.78 *	16,357	0.75

*** - Length varies depending on whether 45 or 90 degrees test section is installed**

Table 2. Rankine-Hugoniot Relations across the shock

Parameter	Equation
Shock Mach No.	$M_s = \left[1 + \frac{\gamma+1}{2\gamma}\left(\frac{P}{P_0} - 1\right)\right]^{\frac{1}{2}}$
Shock Strength	$\left(\frac{P}{P_0}\right) = \left(\frac{P_m+P_0}{P_0}\right) = \frac{2\gamma M_s^2-(\gamma-1)}{\gamma+1}$
Flow Mach No.	$M_f = \frac{2(M_s^2-1)}{\left\{\left[2\gamma M_s^2-(\gamma-1)\right]\left[(\gamma-1)M_s^2 + 2\right]\right\}^{\frac{1}{2}}}$
Dynamic Pressure	$q = \frac{2\gamma P_0(M_s^2-1)^2}{(\gamma+1)\left[(\gamma-1)M_s^2+2\right]}$
Flow Velocity Ratio	$\left(\frac{u}{a_0}\right) = \left(\frac{2}{\gamma+1}\right)\left(M_s - \frac{1}{M_s}\right)$
Density Ratio	$\left(\frac{\rho}{\rho_0}\right) = \frac{(\gamma+1)M_s^2}{(\gamma-1)M_s^2+2}$
Temperature Ratio	$\left(\frac{T}{T_0}\right) = \frac{\left[\gamma M_s^2-\left(\frac{\gamma-1}{2}\right)\right]\left[\left(\frac{\gamma-1}{2}\right)M_s^2+1\right]}{\frac{(\gamma+1)^2}{2}M_s^2}$
Reflected Pressure Ratio	$\left(\frac{P_t}{P_0}\right) = \left[\frac{2\gamma M_s^2-(\gamma-1)}{(\gamma+1)}\right]\left[\frac{(3\gamma-1)M_s^2-2(\gamma-1)}{(\gamma-1)M_s^2+2}\right]$
Reflected to Static Overpressure Ratio	$\left(\frac{P_t}{P_m}\right) = \frac{\left[2\left(\frac{\gamma-1}{\gamma+1}\right)+1\right]\frac{P}{P_0} + 1}{\left(\frac{\gamma-1}{\gamma+1}\right)\frac{P}{P_0} + 1}$

Table 3. Ideal gas parameters

GAS PARAMETERS

GAS	MOLECULAR WEIGHT	γ (1 ATM. 0-25°C)	R (BTU/LBM-°R)	C_p (BTU/LBM-°R)	C_v (BTU/LBM-°R)	μ VISCOSITY (MICROPOISE)	η INDEX OF REFRACT.	BOILING POINT (°C)	R (FT/LBF / LBM-°R)	SYMBOL
AIR	28.8	1.404	.0695	.2415	0.172	185	1.00029		53.34	AIR
ARGON	39.94	1.667	.05	0.125	0.075	222	1.00028	-185.7	38.66	A
CARBON DIOXIDE	44.01	1.300	.045	0.196	0.151	150	1.00045	- 78.5	35.1	CO_2
CARBON TETRACHLORIDE	153.84	1.130	.0153	0.132	0.1167	100	1.00188	76.8		CCl_4
ISOPETANE	72.15	1.086	.0358	.0452	0.416	67	1.0017	28		C_5H_{12}
ETHANE	30.05	1.22	.0695	.3855	0.316	95	1.0008	-88.3		C_2H_6
ETHYLENE	28.03	1.255	.0729	.3592	0.2862	100	1.00072	-103.9		C_2H_4
FREON 12	120.90	1.139	.018	.1477	0.1297	123		-28		CCl_2F_2
HELIUM	4.003	1.667	.4975	1.244	0.746	195	1.000035	-268.9	386	He
HYDROGEN	2.016	1.407	.985	3.404	2.42	88	1.000140	-252.8	766.4	H_2
KRYPTON	82.9	1.689	.0248	.0608	0.036	246	1.00043	-152.9		K_r
METHANE	16.03	1.313	.1258	.5278	0.402	109	1.00045	-161.5		CH_4
NEON	20.18	1.642	.0956	.2446	0.149	312	1.00067	-245.9		Ne
NITROGEN	28.02	1.404	.0715	.2485	0.177	176	1.00030	-195.8		N_2
SULFUR HEXAFLUORIDE	146.06	1.096	.0135	.1545	0.141	150	1.00078	-63.8	10.59	SF_6
XENON	131.3	1.667	.0153	.0383	0.023	226	1.00070	-107.1		Xe
OXYGEN	32.0	1.395	.062	0.2177	0.1554				48.28	O_2
FREON-C318	200.04	1.055	0.00992	0.195	0.184				7.72	C_4F_8

Table 4. Measured time – distance data/Test 1

Explosive weight : 72 lb, PETN Primacord
Explosive length: 10 feet
Tamping mass: 18 in. plywood plug, 1 in. steel plate, & 56,900 lb concrete (2 blks)
Test gas: air
Test gas pressure: 12.1 psia (ambient)
Initial test gas temperature: 548 degrees Rankine
Test gas sound speed: 1147 feet per second
Test Number: Event 71-176

DISTANCE FROM DRIVER END	TIME AFTER EXPLOSIVE INITIATION
(feet)	(milliseconds)
108.26	23.25
116.25	25.29
120.28	26.34
124.81	27.52
132.11	29.39
158.46	36.24
163.48	38.19
168.48	39.62
193.00	47.06
198.00	48.52

Table 5. Shock tube flow blast parameters calculated from measured time – distance data/Test 1

-27-71, EVENT 71-176
72 LBS., PRIMACORD, 10 FT.,
1 IN.,2BLKS,PLUG, AIR, 12.1 PSIA, 548R,
1147 FT/SEC, G = 1.4, 100 PERCENT AIR.

POSITION FEET	TIME MS	VELOCITY FT/SEC	MACH NO(S)	MACH NO(F)	P(S) PSIA	P(T) PSIA	P(D) PSIA	ETA	SHOCK STRENGTH
60.0	12.317	4733	4.126	1.687	243.1	986.0	459.8	5.0	20.093
64.0	13.167	4675	4.076	1.677	237.0	949.7	443.4	4.9	19.589
68.0	14.028	4618	4.027	1.667	231.0	915.9	427.1	4.9	19.090
72.0	14.899	4562	3.978	1.658	225.0	882.5	411.1	4.8	18.598
76.0	15.781	4507	3.929	1.648	219.3	850.4	395.7	4.8	18.122
80.0	16.674	4452	3.881	1.637	214.1	823.0	382.4	4.8	17.695
84.0	17.578	4398	3.834	1.626	209.0	795.9	369.4	4.7	17.273
88.0	18.493	4345	3.738	1.615	204.0	769.1	356.4	4.7	16.857
92.0	19.420	4292	3.742	1.604	199.0	742.7	343.7	4.7	16.445
96.0	20.358	4240	3.696	1.594	194.1	716.5	331.1	4.6	16.039
100.0	21.307	4188	3.651	1.584	189.2	690.7	318.6	4.6	15.637
104.0	22.268	4137	3.607	1.573	184.4	665.2	306.3	4.5	15.240
108.0	23.241	4087	3.563	1.563	179.8	641.5	294.9	4.5	14.863
112.0	24.225	4037	3.520	1.551	175.6	620.4	284.6	4.5	14.512
116.0	25.222	3988	3.477	1.541	171.4	599.6	274.5	4.4	14.165
120.0	26.231	3940	3.435	1.530	167.3	579.1	264.5	4.4	13.823
124.0	27.253	3892	3.393	1.519	163.2	558.7	254.6	4.3	13.485
128.0	28.287	3844	3.352	1.507	159.1	538.7	244.9	4.3	13.151
132.0	29.334	3798	3.311	1.496	155.1	518.8	235.2	4.3	12.821
136.0	30.394	3752	3.271	1.485	151.2	499.3	225.7	4.2	12.495
140.0	31.466	3705	3.231	1.473	147.3	479.9	216.3	4.2	12.173
144.0	32.552	3661	3.192	1.463	143.7	463.1	208.2	4.2	11.878
148.0	33.652	3616	3.153	1.451	140.3	447.3	200.6	4.1	11.595
152.0	34.765	3572	3.115	1.439	136.9	431.6	193.1	4.1	11.314
156.0	35.891	3529	3.077	1.427	133.5	416.1	185.7	4.0	11.037
160.0	37.032	3486	3.039	1.415	130.2	400.8	178.4	4.0	10.763
164.0	38.186	3444	3.002	1.404	127.0	385.7	171.1	4.0	10.493
168.0	39.355	3402	2.966	1.392	123.7	370.8	164.0	3.9	10.226
172.0	40.538	3361	2.930	1.381	120.5	356.1	156.9	3.9	9.962
176.0	41.735	3320	2.894	1.370	117.4	341.5	149.9	3.9	9.701
180.0	42.948	3279	2.859	1.358	114.3	327.5	143.2	3.8	9.449
184.0	44.175	3240	2.824	1.345	111.6	316.3	138.0	3.8	9.227
188.0	45.417	3200	2.790	1.332	109.0	305.3	132.7	3.7	9.007
192.0	46.675	3161	2.756	1.319	106.4	294.4	127.6	3.7	8.791
[illegible]	47.948	3123	2.723	1.306	103.8	283.6	122.5	3.6	8.577
[illegible]	49.237	3085	2.690	1.294	101.2	272.9	117.4	3.6	[illegible]

Table 6. Measured time – distance data/Test 2

Explosive weight : 160 lb, PETN Primacord
Explosive length: 21.5 feet
Tamping mass: 18 in. plywood plug, 1 in. steel plate, & 56,900 lb concrete blocks(2ea)
Test gas: air
Test gas pressure: 12.1 psia (ambient)
Initial test gas temperature: 545 degrees Rankine
Test gas sound speed: 1142 feet per second
Test Number: Event 71-137

DISTANCE FROM DRIVER END	TIME AFTER EXPLOSIVE INITIATION
(feet)	(milliseconds)
92.75	15.92
100.29	17.57
108.26	19.27
116.25	21.42
120.28	22.53
124.76	23.61
132.11	25.41
139.95	27.35
147.84	29.33
153.47	30.78
158.46	32.09
163.48	33.40
168.48	34.90

Table 7. Shock tube flow blast parameters calculated from measured time – distance data/Test 2

```
...1E71-137
100 LB, PRIMACORD, 21.5K, AIR,
18IN PLUG,1IN PLATE,2 CON BLKS,56900 LB
12.1PSIA,543R,1142FT/SEC,1.4G,100PCT AIR
```

POSITION FEET	TIME MS	VELOCITY FT/SEC	MACH NO(S)	MACH NO(F)	P(S) PSIA	P(T) PSIA	P(D) PSIA	ETA	SHOCK STRENGTH
60.0	8.458	4569	4.001	1.662	227.9	898.4	418.7	4.9	18.832
65.0	9.557	4526	3.963	1.655	223.3	872.8	406.4	4.8	18.455
70.0	10.657	4484	3.926	1.647	218.9	848.7	394.8	4.8	18.095
75.0	11.787	4442	3.889	1.639	215.0	827.6	384.6	4.8	17.766
80.0	12.918	4400	3.853	1.630	211.0	806.6	374.5	4.7	17.440
85.0	14.060	4359	3.817	1.622	207.1	785.9	364.5	4.7	17.118
90.0	15.213	4318	3.781	1.614	203.3	765.3	354.6	4.7	16.798
95.0	16.376	4278	3.746	1.605	199.4	745.0	344.8	4.7	16.481
100.0	17.550	4238	3.711	1.597	195.6	724.8	335.1	4.6	16.167
105.0	18.736	4198	3.676	1.589	191.9	704.8	325.4	4.6	15.857
110.0	19.933	4158	3.641	1.581	188.1	685.0	315.9	4.5	15.549
115.0	21.141	4120	3.607	1.573	184.4	665.4	306.4	4.5	15.244
120.0	22.360	4081	3.573	1.565	180.9	646.6	297.3	4.5	14.947
125.0	23.591	4043	3.540	1.556	177.6	630.3	289.4	4.5	14.676
130.0	24.834	4005	3.507	1.548	174.3	614.1	281.6	4.5	14.407
135.0	26.088	3967	3.474	1.539	171.1	598.2	273.8	4.4	14.141
140.0	27.355	3930	3.441	1.531	167.9	582.3	266.1	4.4	13.877
145.0	28.633	3893	3.409	1.522	164.8	566.6	258.4	4.4	13.616
150.0	29.923	3857	3.377	1.514	161.6	551.1	250.9	4.3	13.357
155.0	31.226	3821	3.346	1.505	158.5	535.7	243.4	4.3	13.101
160.0	32.541	3785	3.314	1.497	155.4	520.4	236.0	4.3	12.847
165.0	33.868	3749	3.283	1.489	152.4	505.3	228.6	4.2	12.599
170.0	35.208	3714	3.252	1.481	149.4	490.3	221.4	4.2	12.346
175.0	36.560	3679	3.222	1.473	146.4	475.5	214.2	4.2	12.039
180.0	37.926	3645	3.192	1.463	143.7	463.1	208.2	4.2	11.878
185.0	39.304	3611	3.162	1.454	141.1	450.9	202.4	4.1	11.659
190.0	40.695	3577	3.132	1.445	138.5	438.8	196.6	4.1	11.443
195.0	42.100	3543	3.103	1.435	135.9	426.8	190.8	4.1	11.228
200.0	43.517	3510	3.074	1.426	133.3	414.9	185.1	4.0	11.015

Table 8. Six foot diameter by 200 foot long shock tube test / example data

TEST SECTION: 200 feet
EXPLOSIVE: PETN Primacord, 400 grain/foot
Po = INITIAL TEST GAS PRESSURE: 12.1 psia (air)
To = INITIAL TEST GAS TEMPERATURE = 545 degrees Rankine
Co = TEST GAS SOUND SPEED = 1145 feet/second

W H.E. WT. (lb)	L H.E. LEN. (ft)	Ta ARR. TIME (ms)	Vs VEL. (fps)	Ms MACH NO.	Mf FLOW MACH NO.	Ps STATIC PRESS. (psia)	Pt STAG. PRESS. (psia)	Pd DYN. PRESS. (psia)	RHOr DEN. RATIO	Ps/Po SHOCK STREN.	Td * FLOW DUR. TIME (ms)
72	10	47	3085	2.69	1.29	101.2	272.9	117.4	3.6	8.37	6.5
160	22	42	3510	3.07	1.42	133.3	414.9	185.1	4.0	11.02	7.0

* - FLOW DURATION TIME TO 50% of peak static pressure
W = EXPLOSIVE WEIGHT
L = EXLOSIVE LENGTH
Ta = SHOCK ARRIVAL TIME
Vs = SHOCK VELOCITY
Pt = STAGNATION PRESSURE
RHOr = DENSITY RATIO ACROSS SHOCK
Ps/Po = SHOCK STRENGTH = STATIC TO INITIAL TEST GAS PRESSURE RATIO

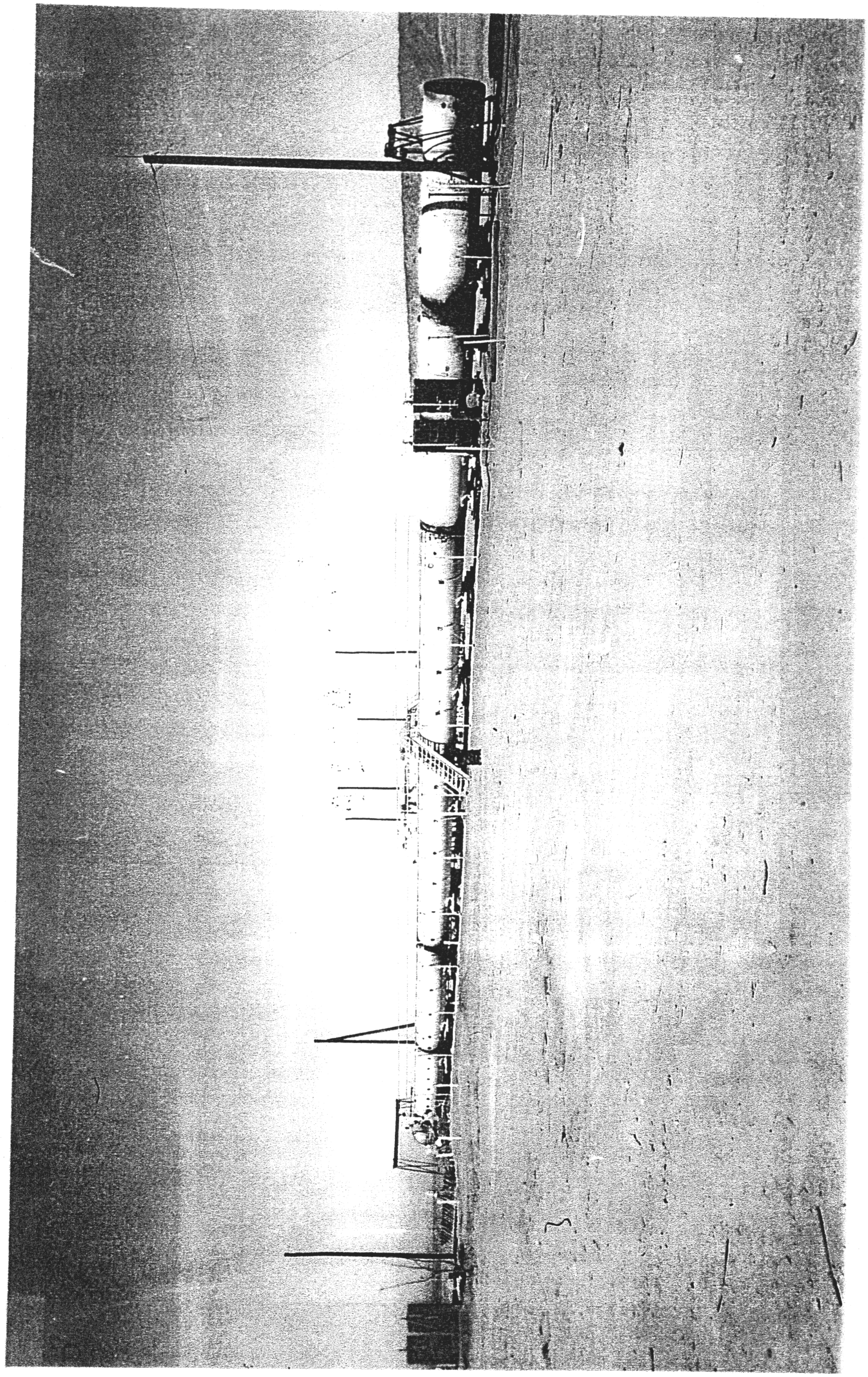

Figure 1. Six foot diameter by 200 foot long shock tube

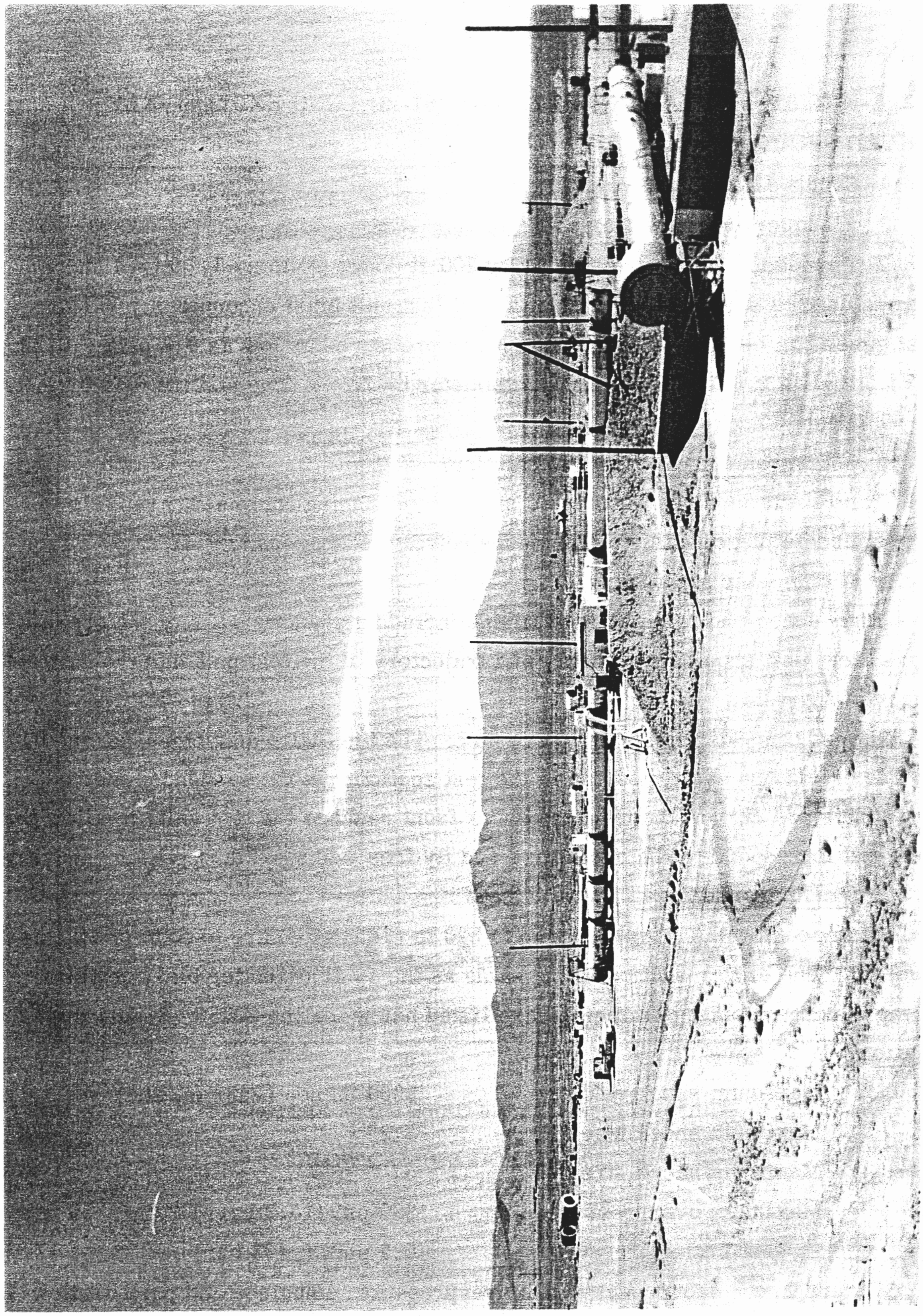

Figure 2. Six foot diameter by 200 and by 60 foot long shock tubes

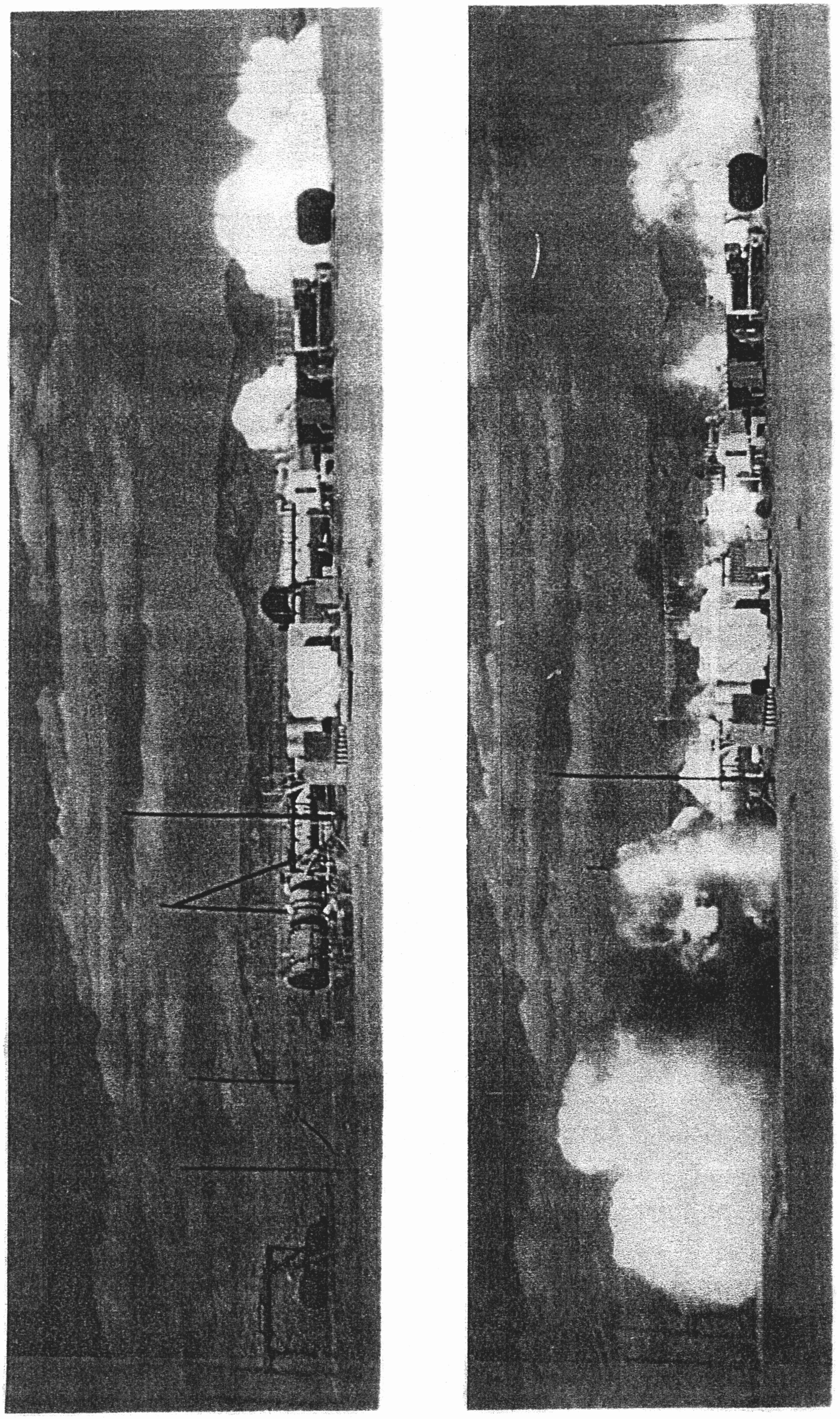

Figure 3. Shock tube shortly after detonation (top) and after shock reaches muzzle end (bottom)

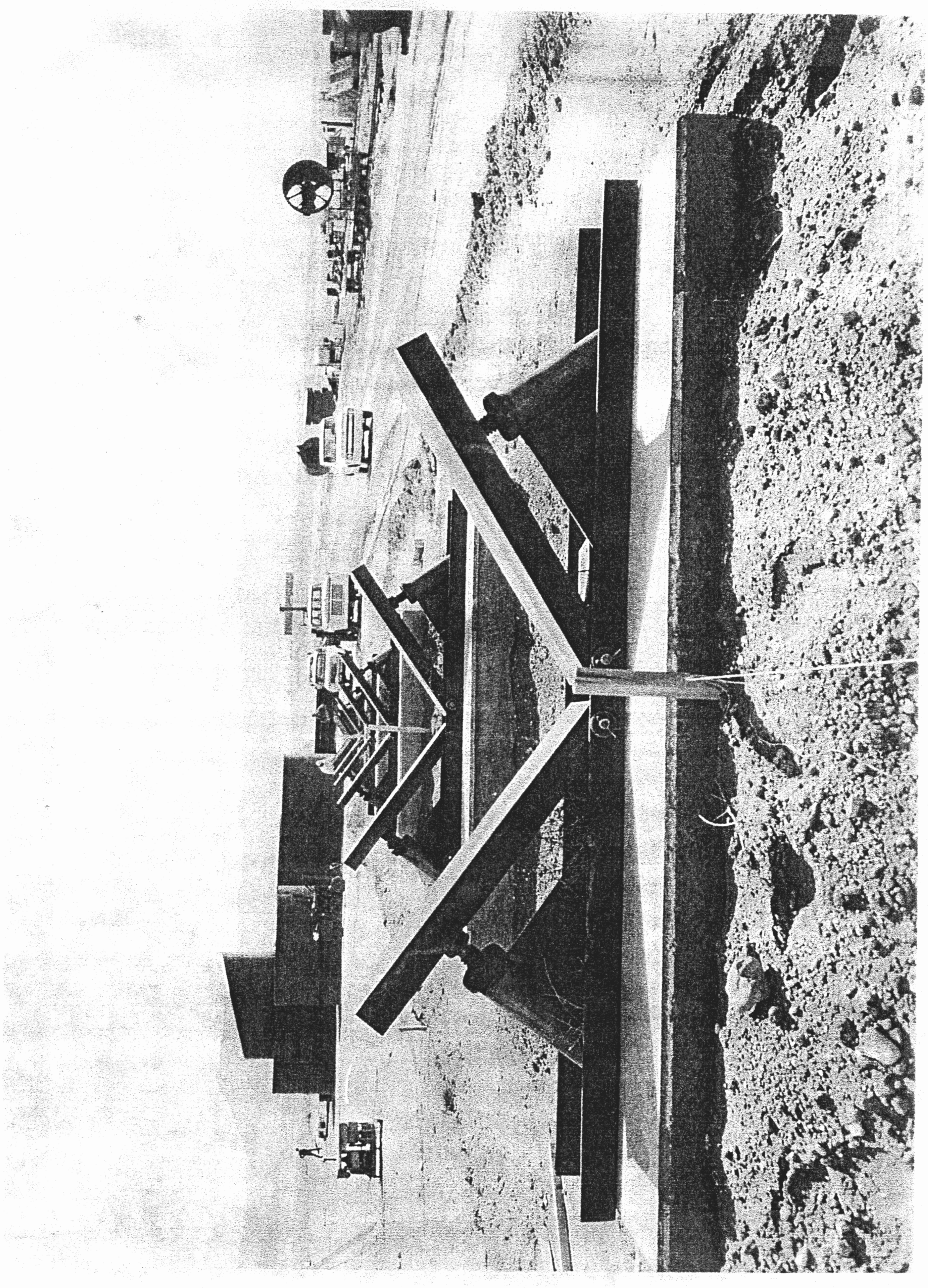

Figure 4. Shock tube section, screw jack supports/stands

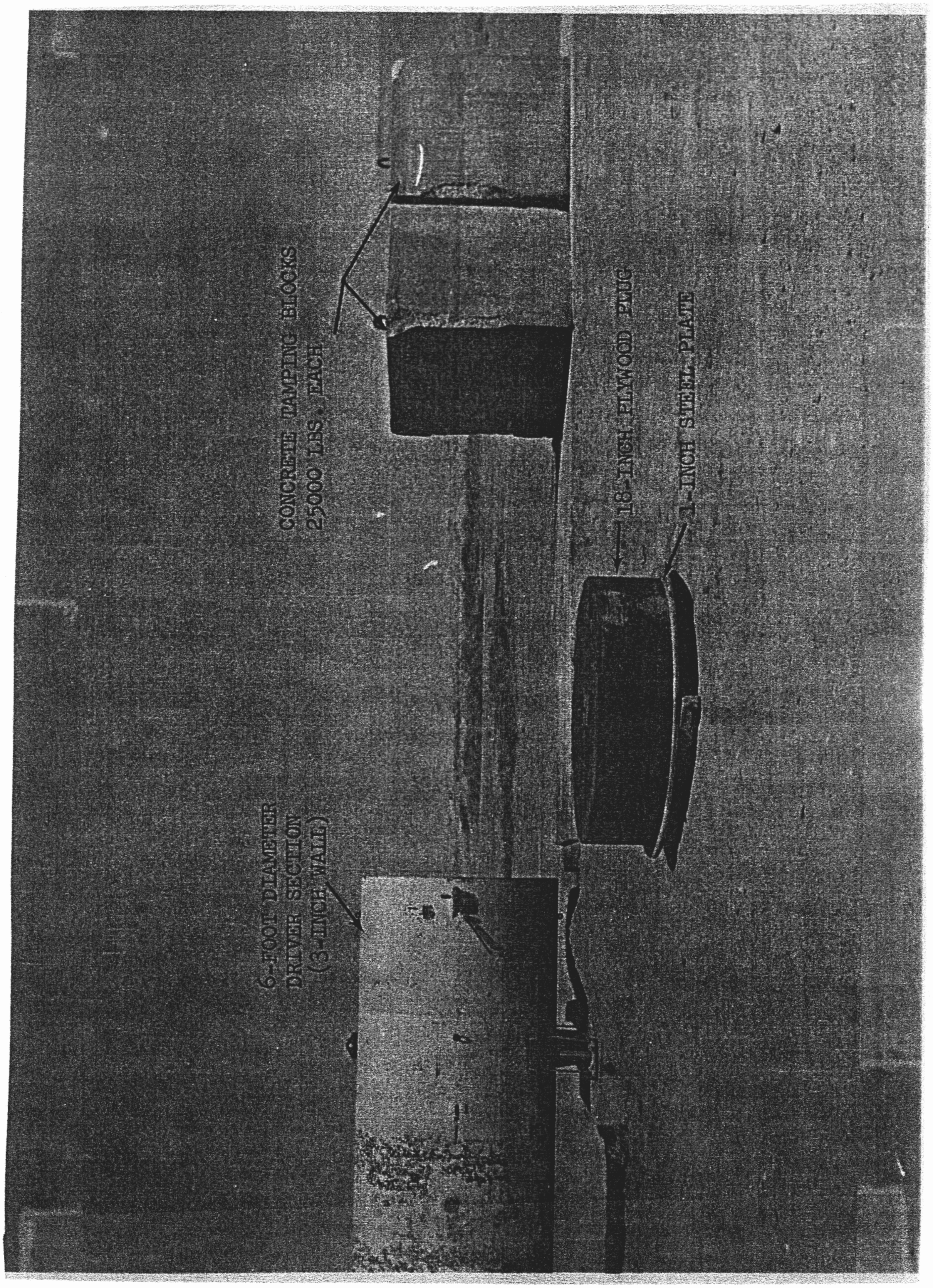

Figure 5. Driver tamping (Eighteen inch plywood plug, 1 " steel plate, and two concrete blocks)

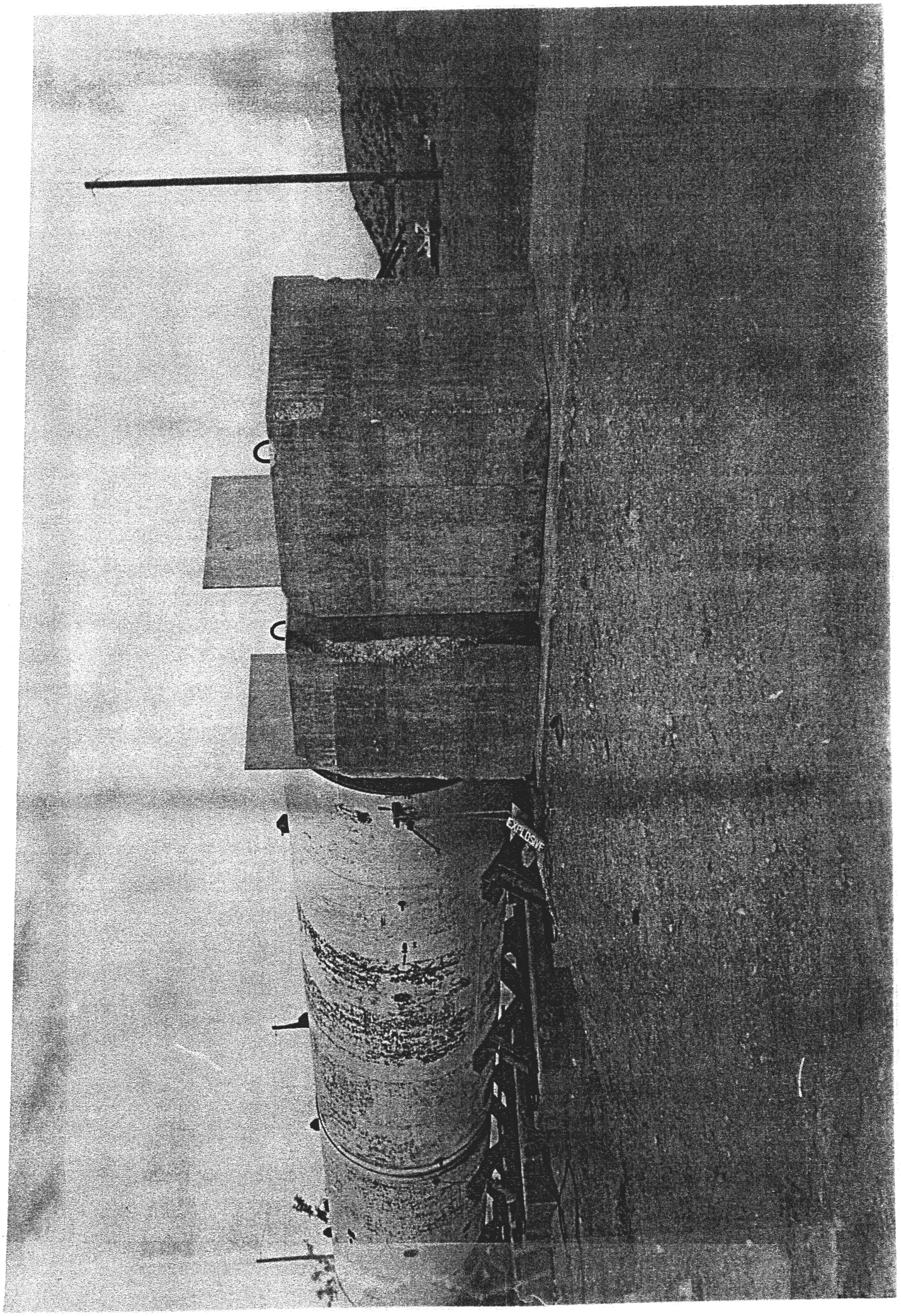

Figure 6. Driver tamping masses installed

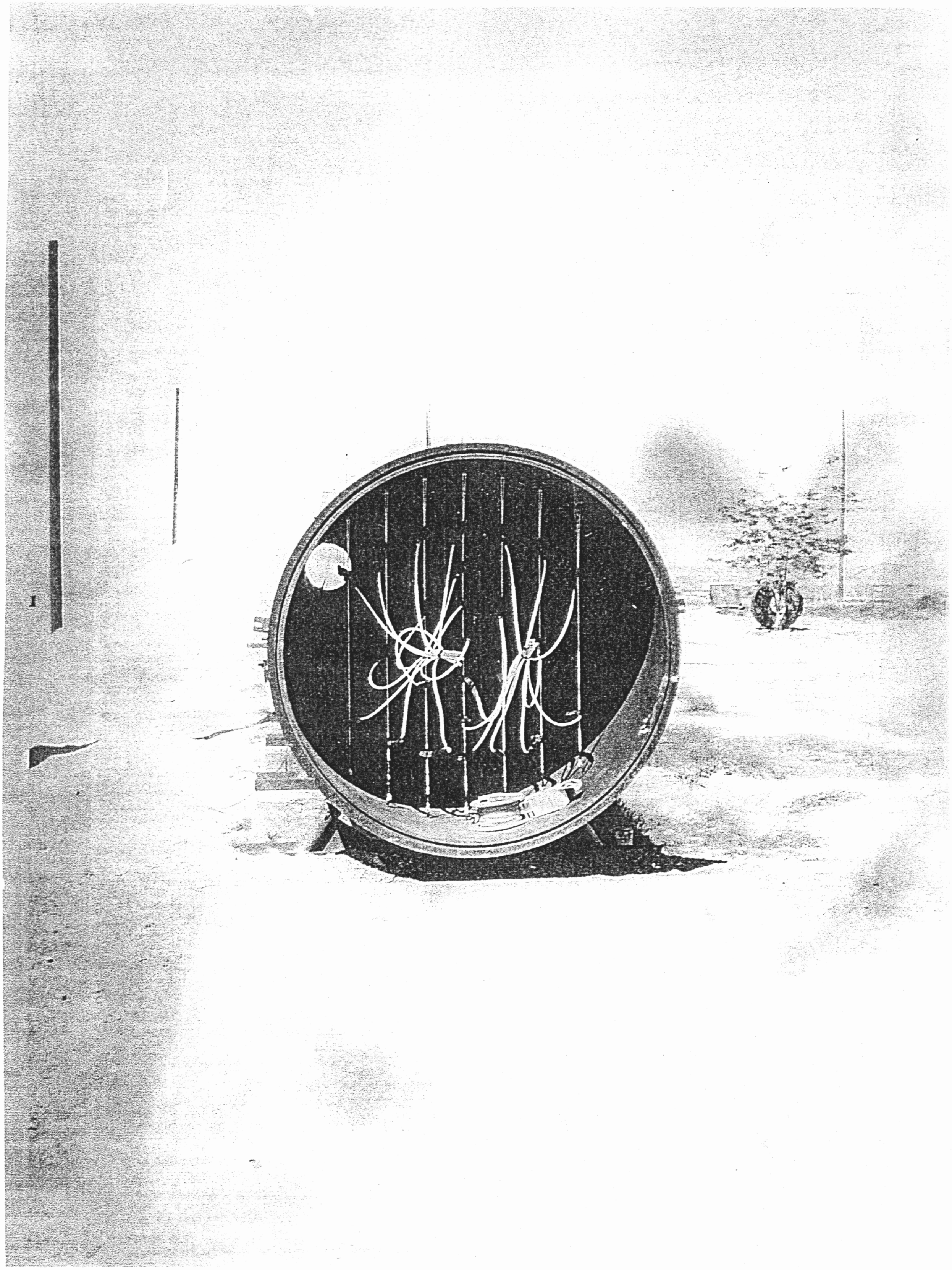

Figure 7. Distributed, Primacord explosive installed in driver

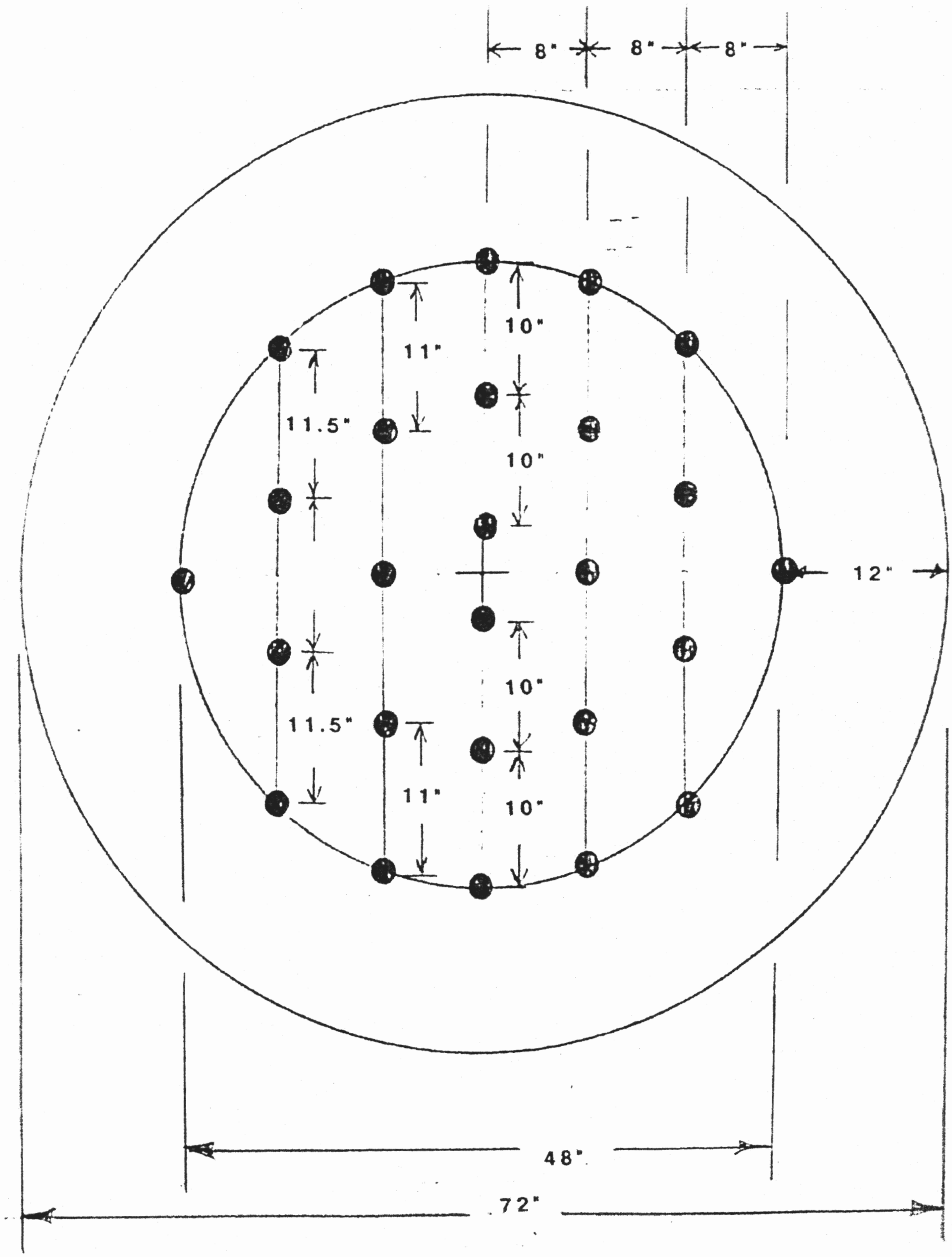

Figure 8. Primacord explosive geometrical configuration over cross-section

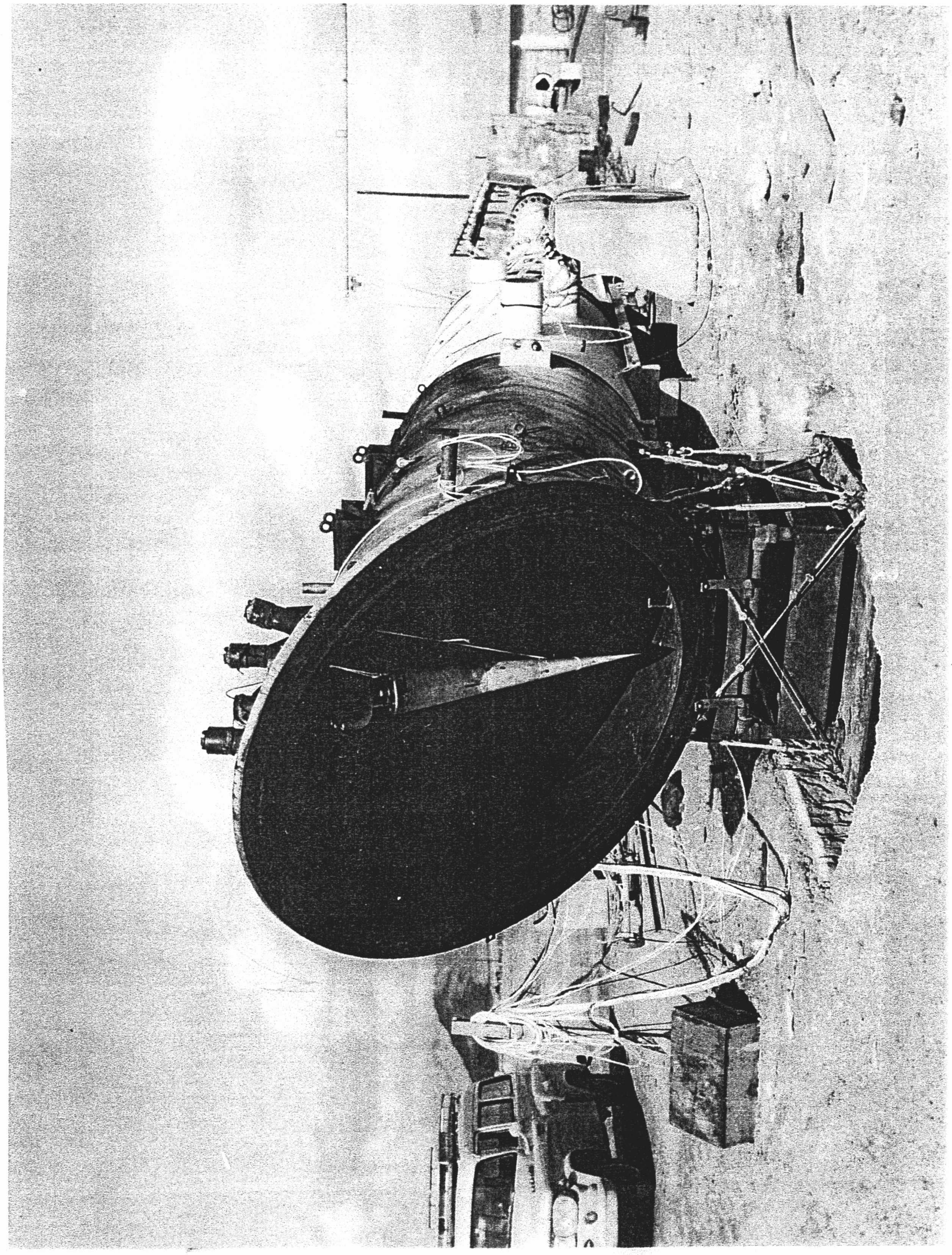

Figure 9. Forty five degree test section/muzzle end

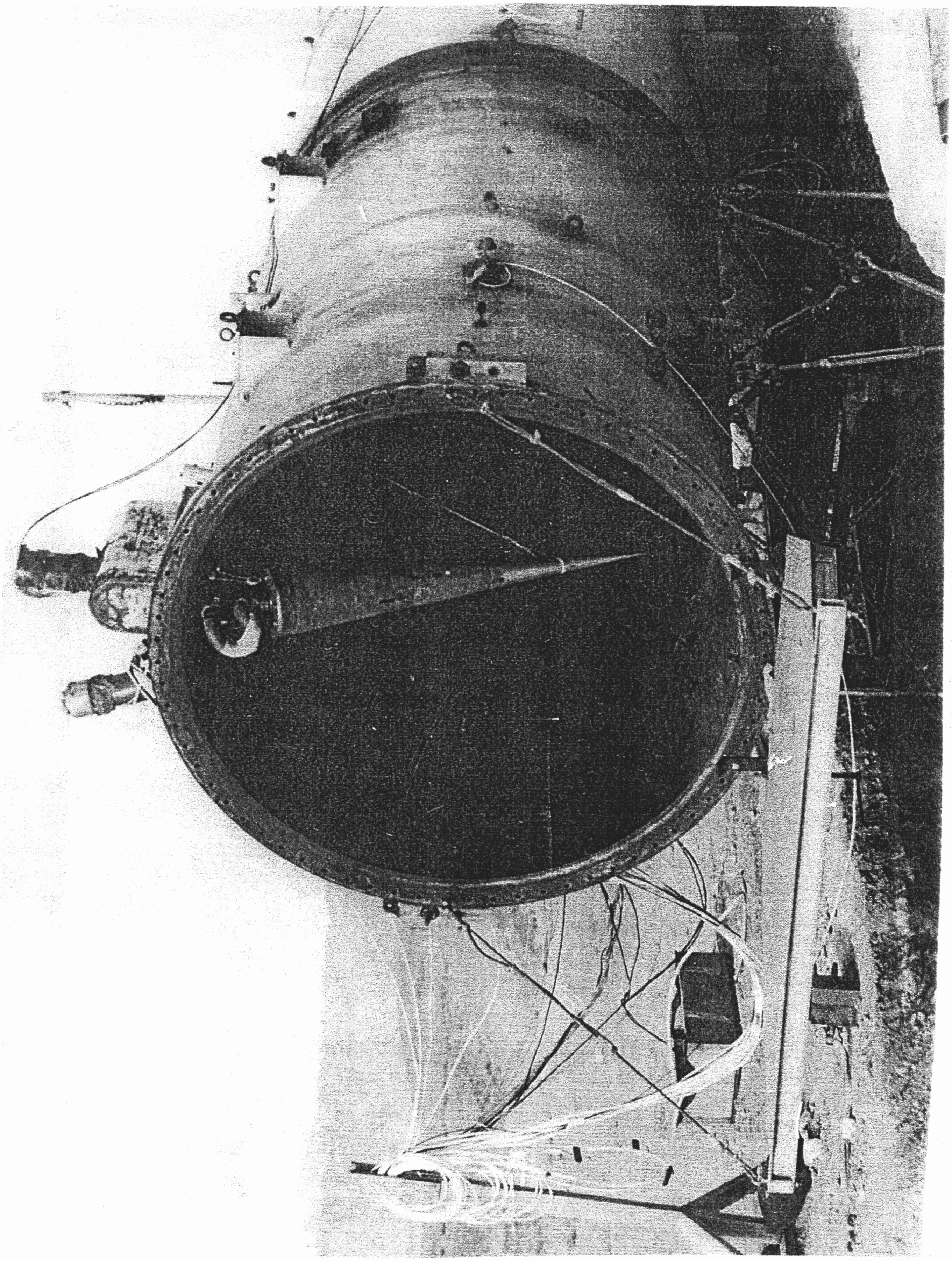

Figure 10. Ninety degree test section/muzzle end

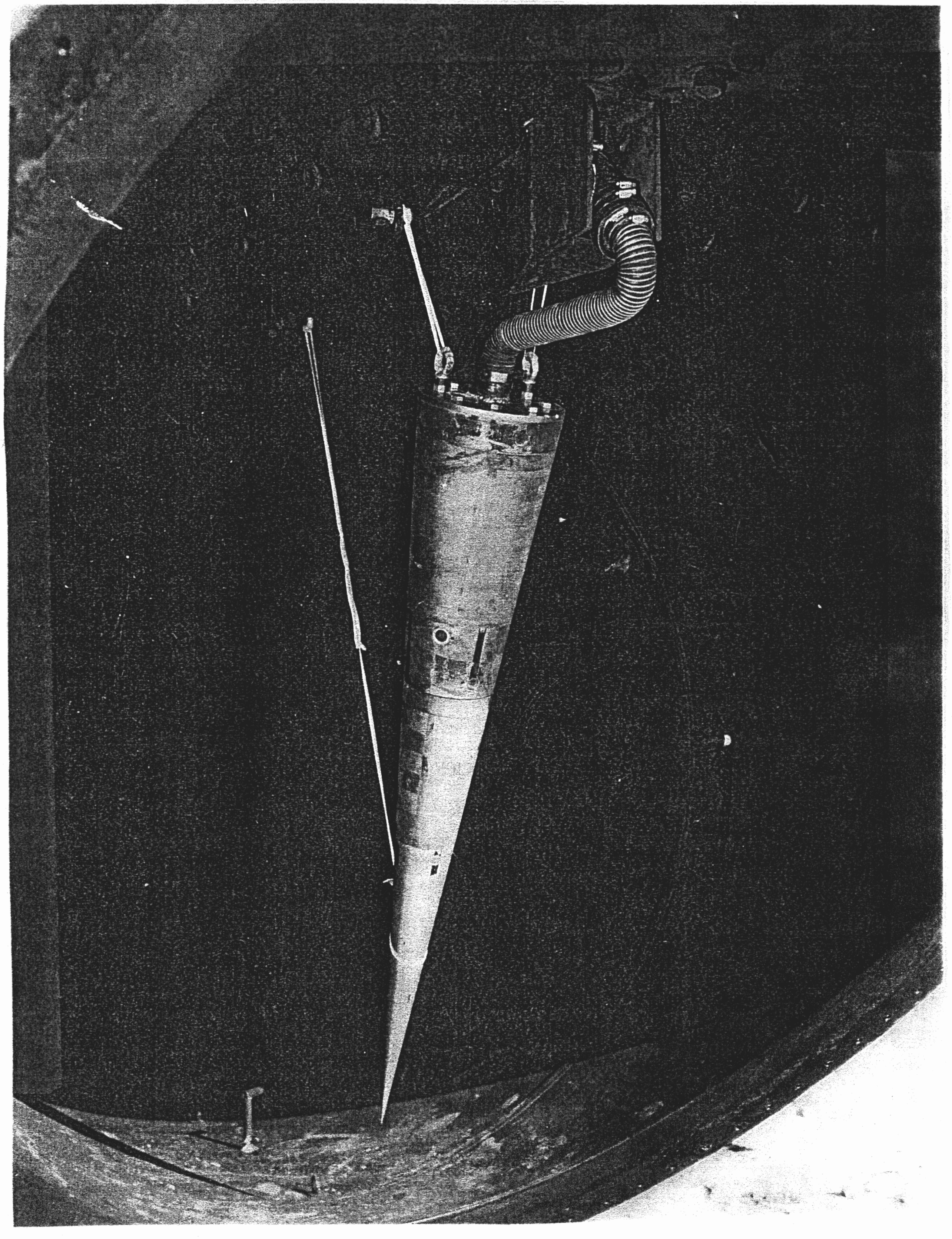

Figure 11. Suspension, instrumentation cable in radiator hose, and conical test unit

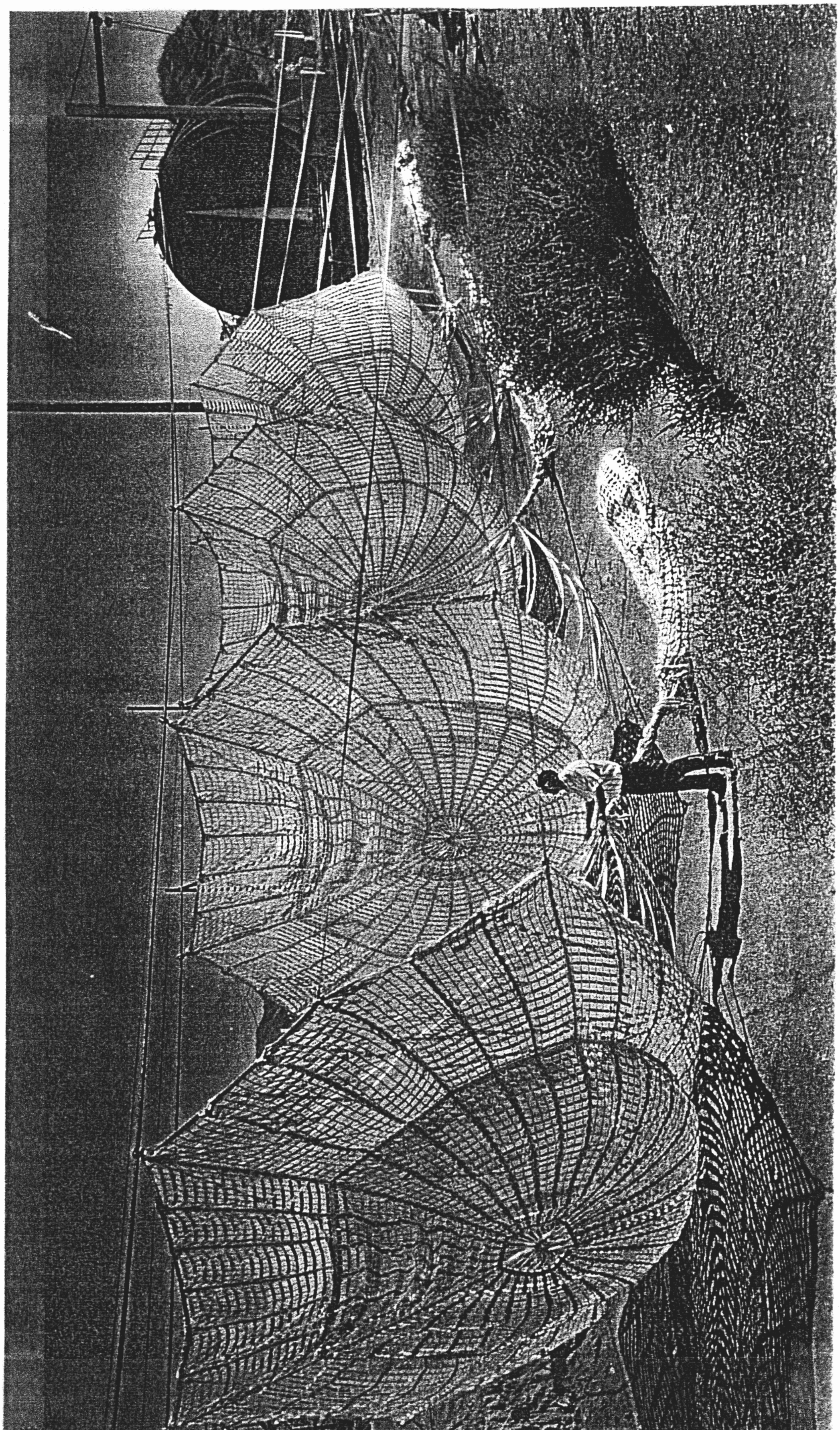

Figure 12. Test unit soft recovery, sawdust pit, parachute deceleration system

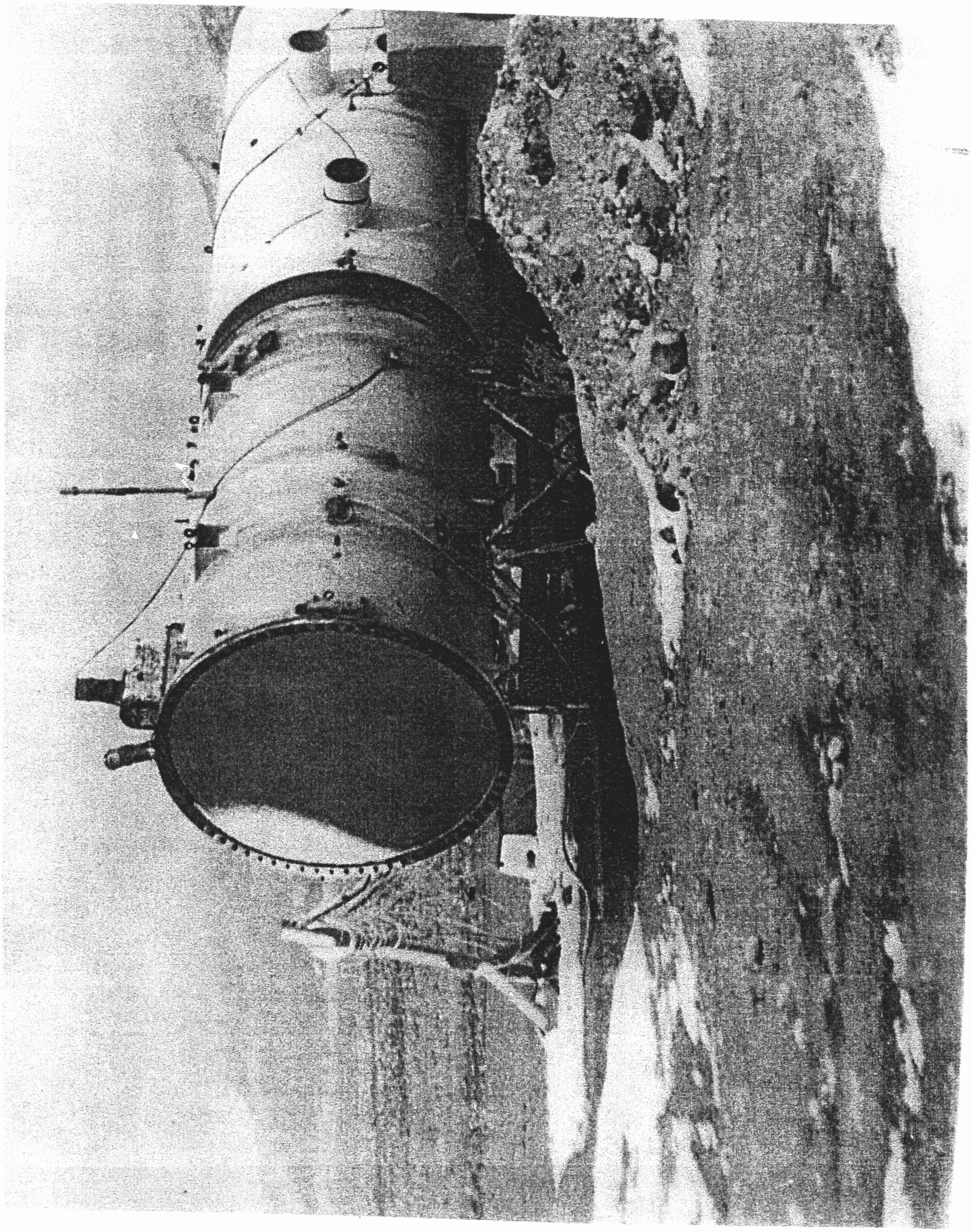

Figure 13. Aluminum diaphragm (0.040 " thick) used to seal muzzle end

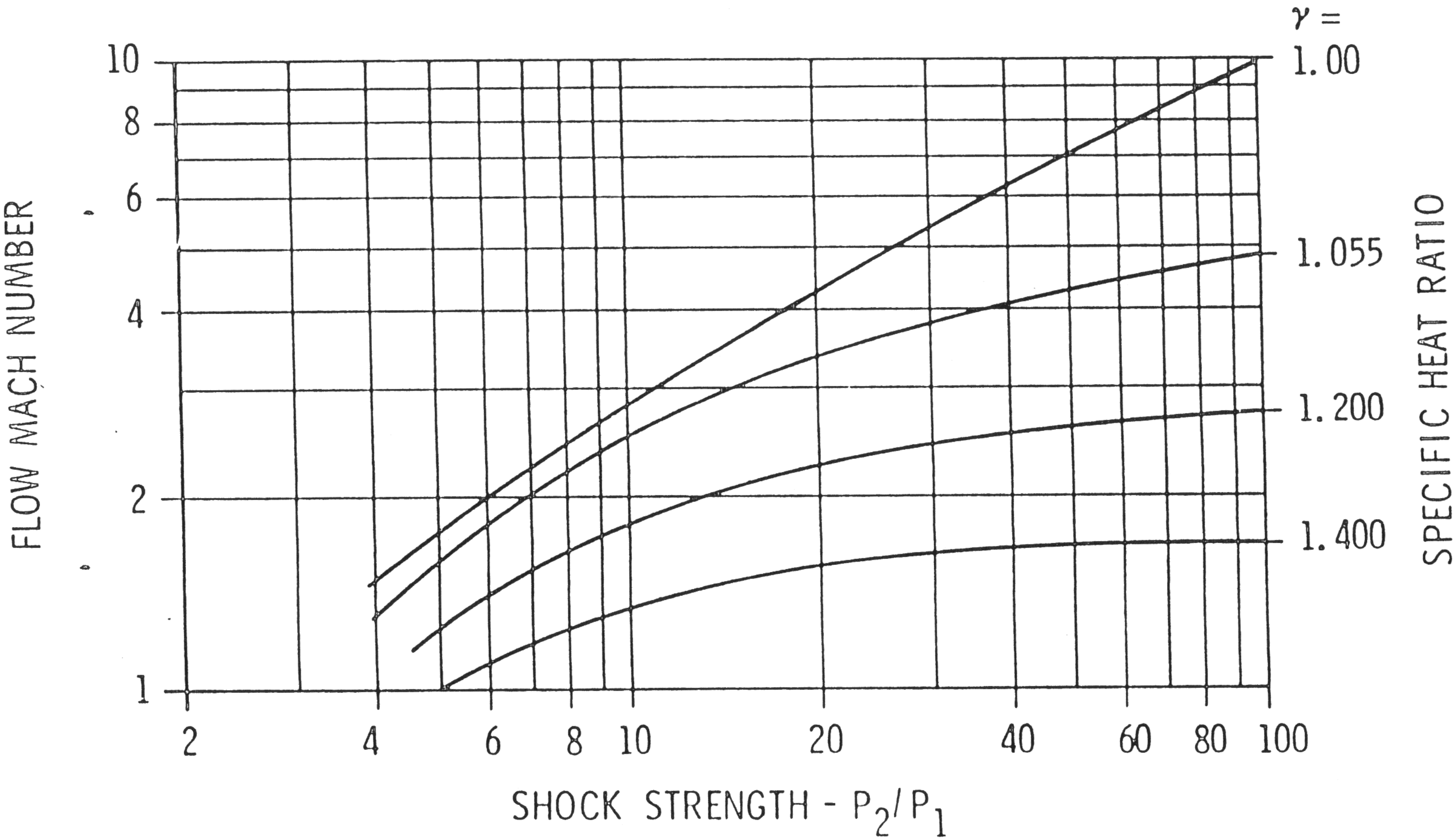

Figure 14. Flow Mach number versus shock strength and specific heat ratio

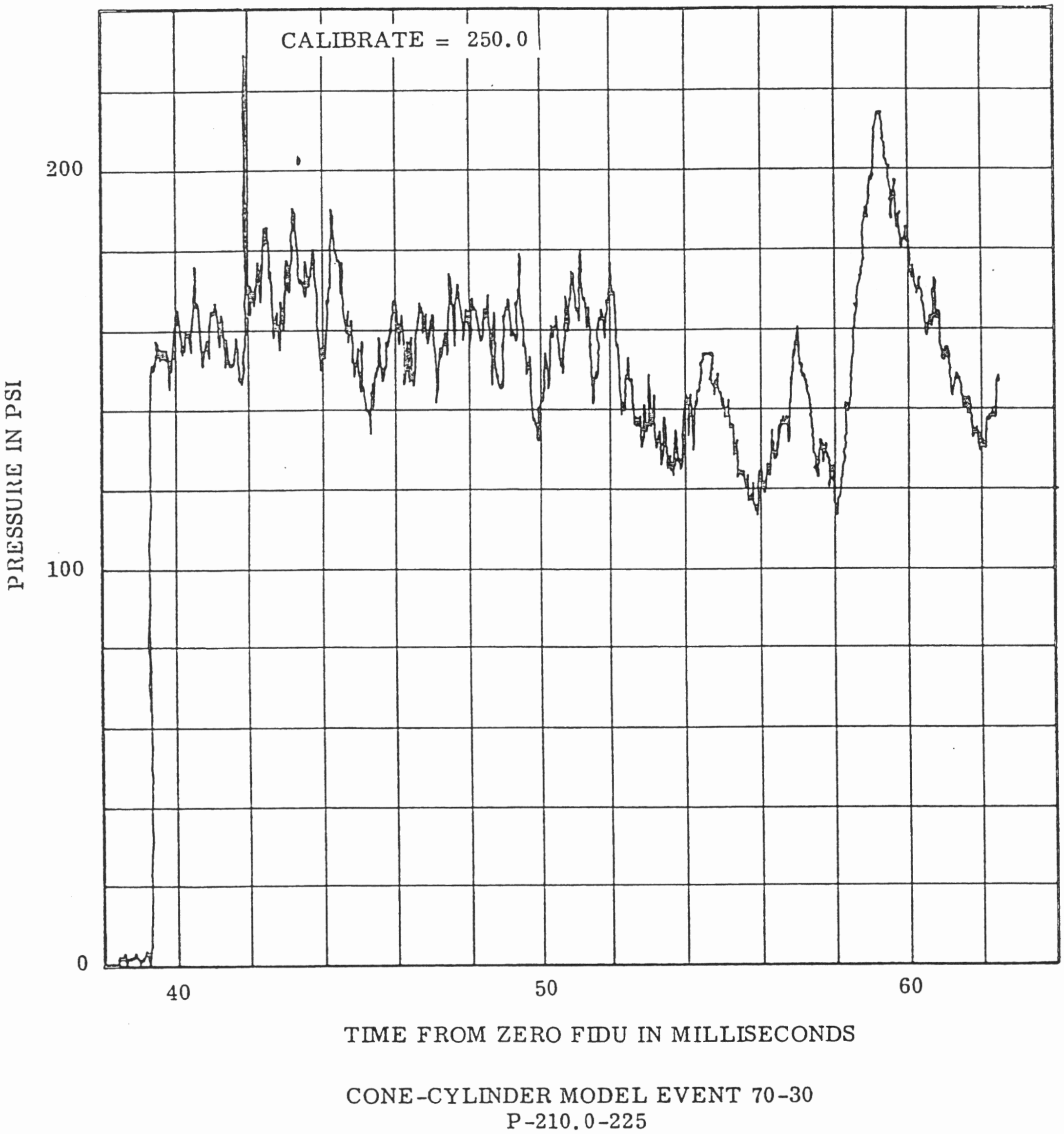

Figure 15. Measured static overpressure – time profile at test station 210 feet

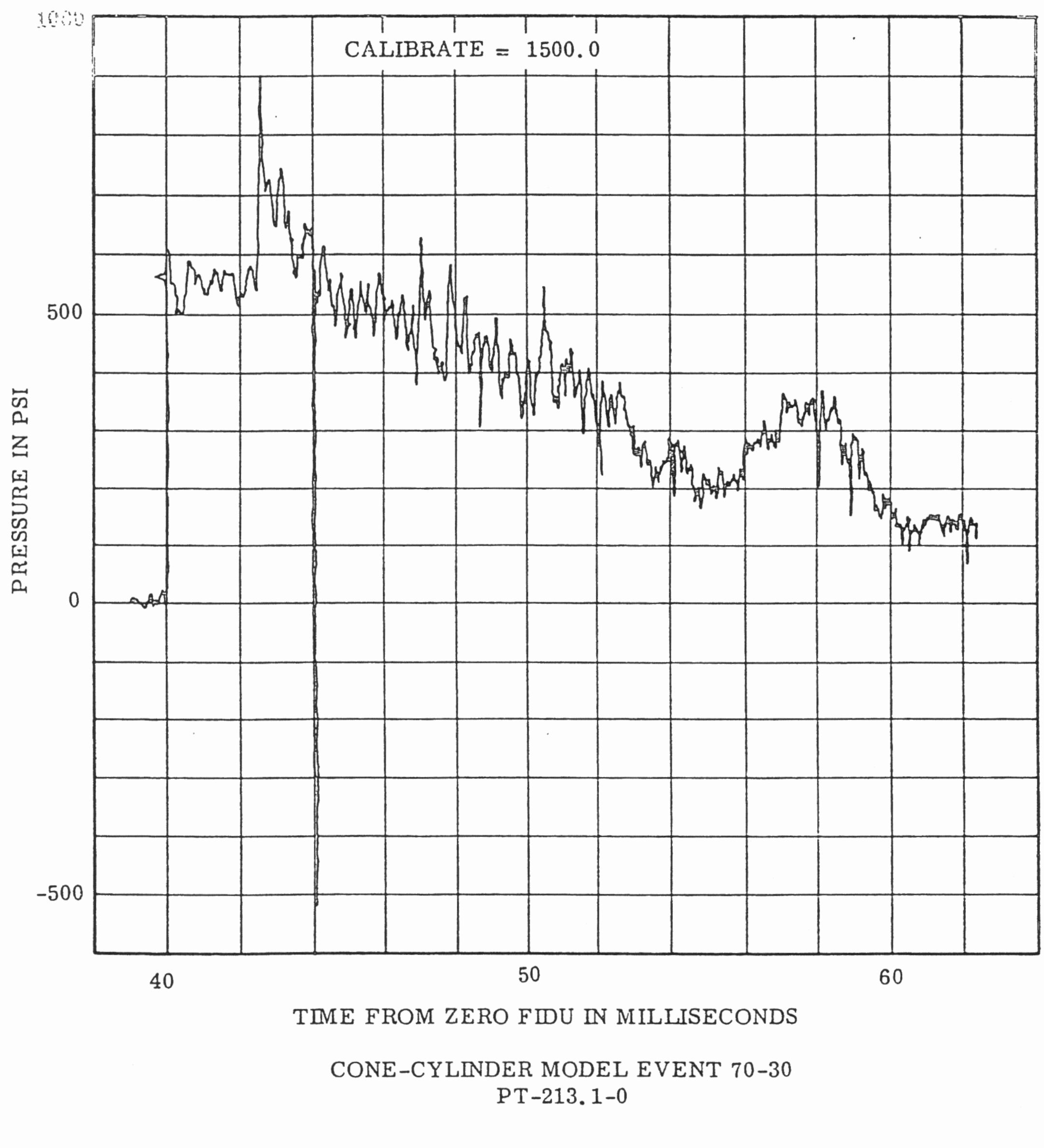

Figure 16. Measured stagnation overpressure – time profile at test station 213 feet

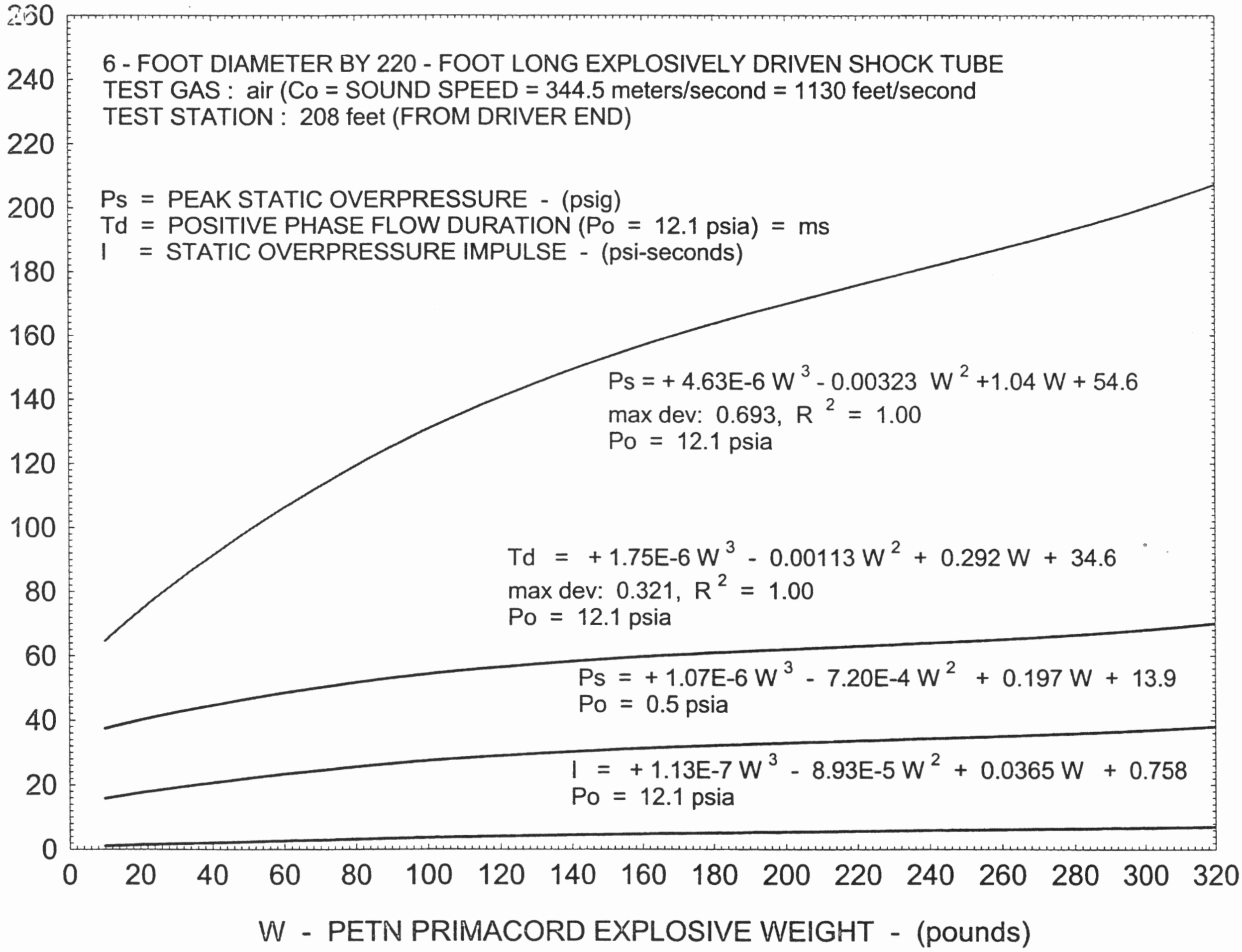

Figure 17. Static overpressure, flow duration, and impulse versus explosive weight

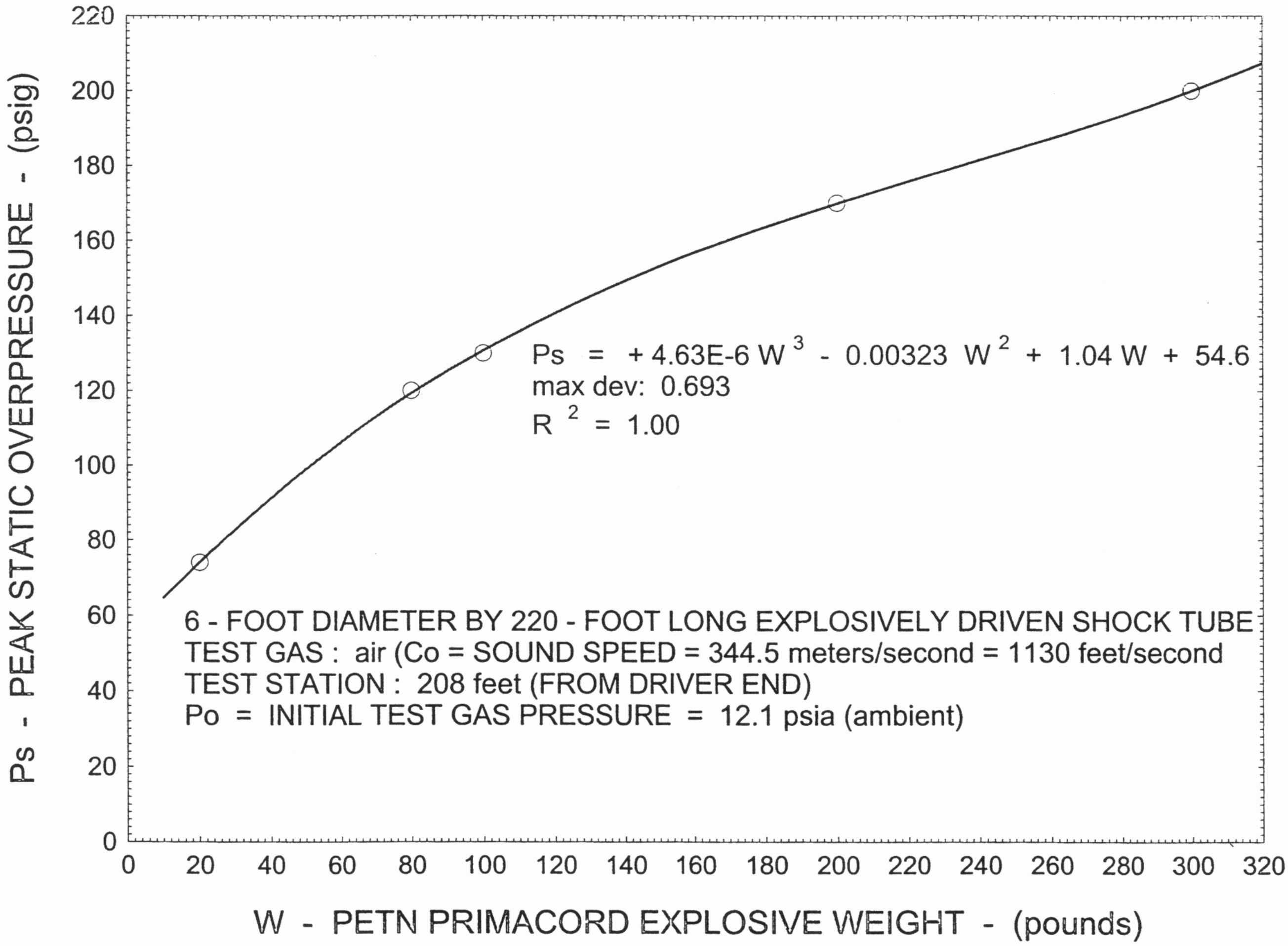

Figure 18. Static overpressure versus explosive weight

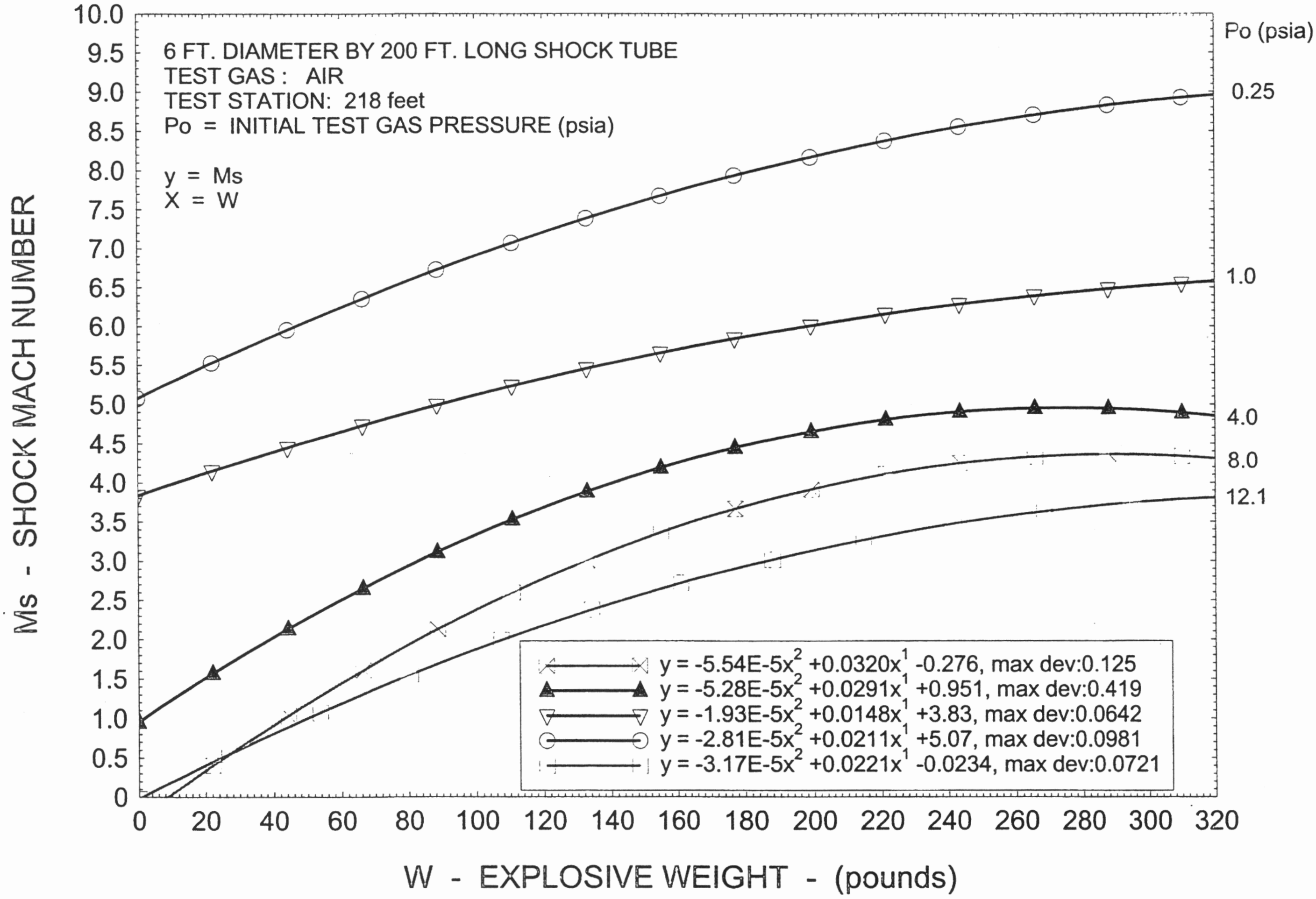

Figure 19. Shock Mach number versus explosive weight

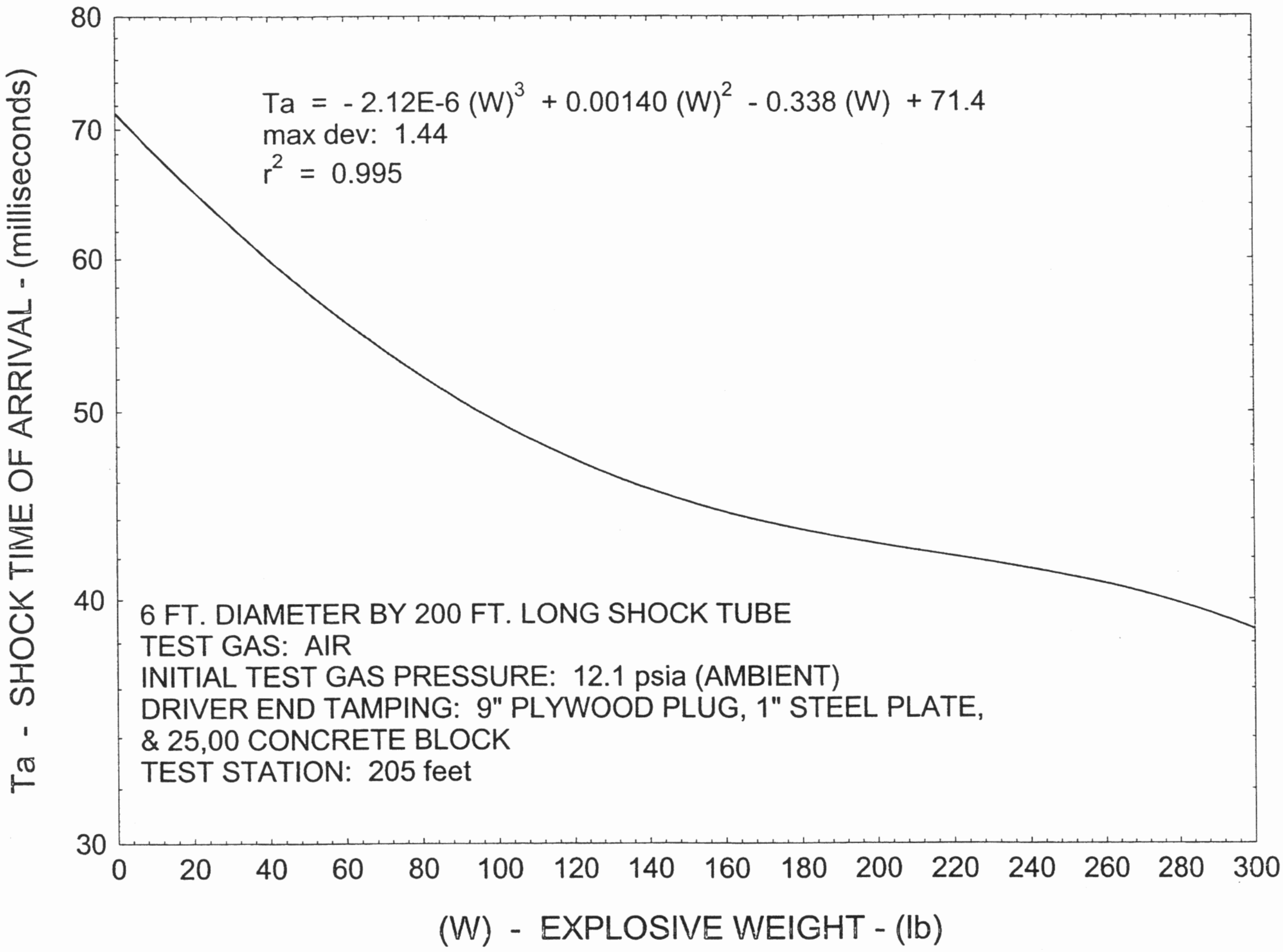

Figure 20. Shock time of arrival versus explosive weight

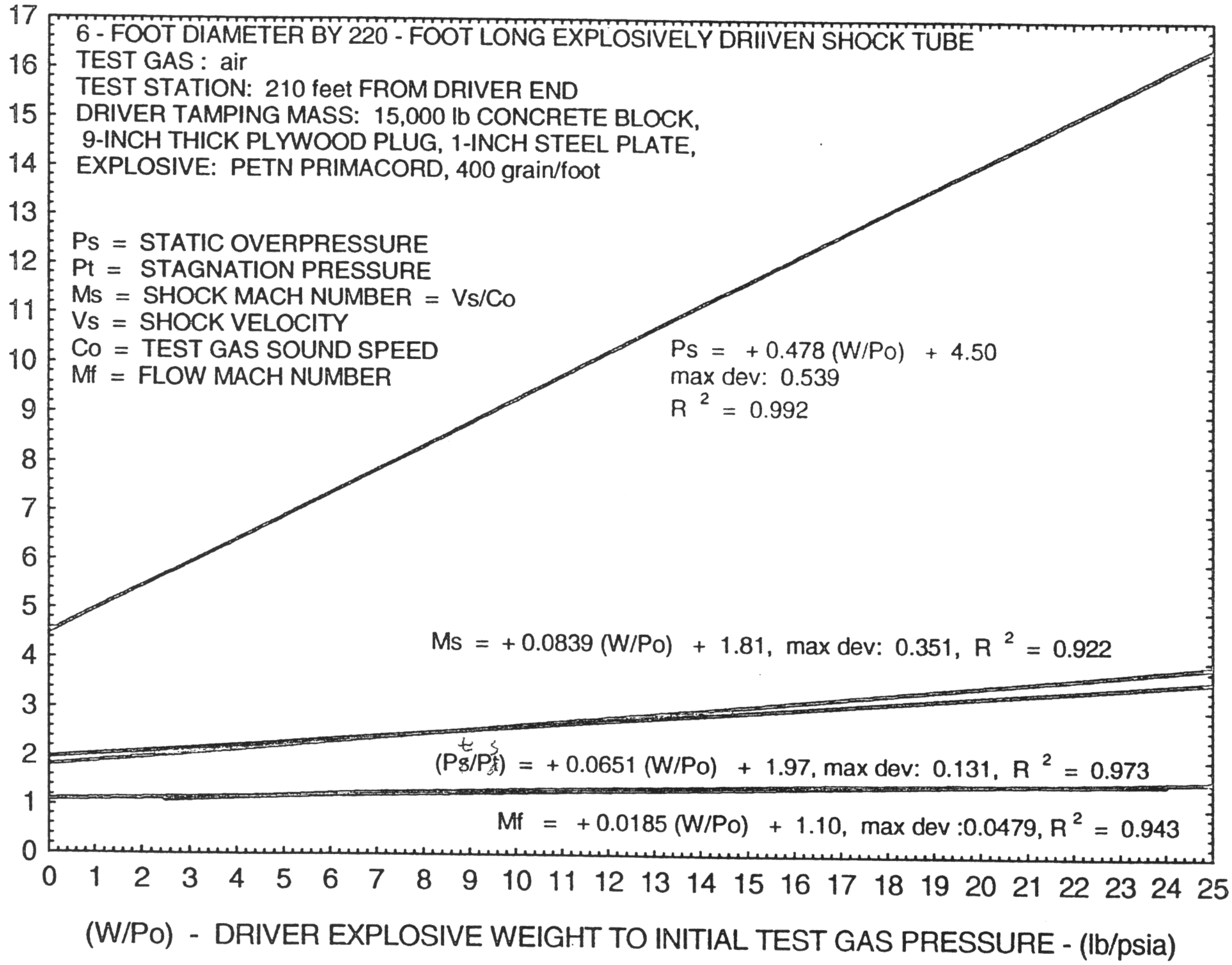

Figure 21. Static overpressure, shock Mach number, flow Mach number & stagnation to static pressure ratio versus explosive weight to initial test gas pressure

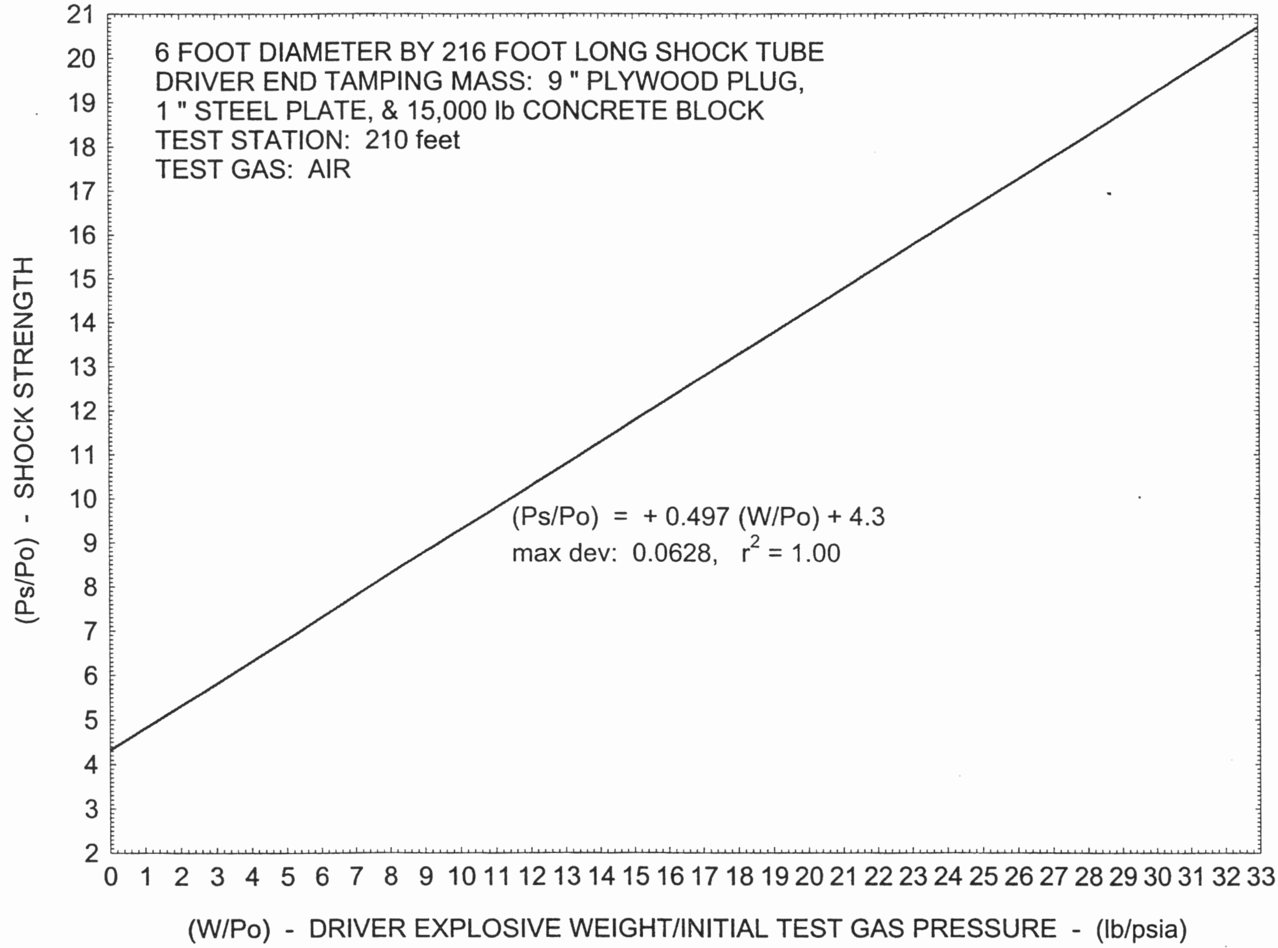

Figure 22. Shock strength versus explosive weight to initial test gas pressure

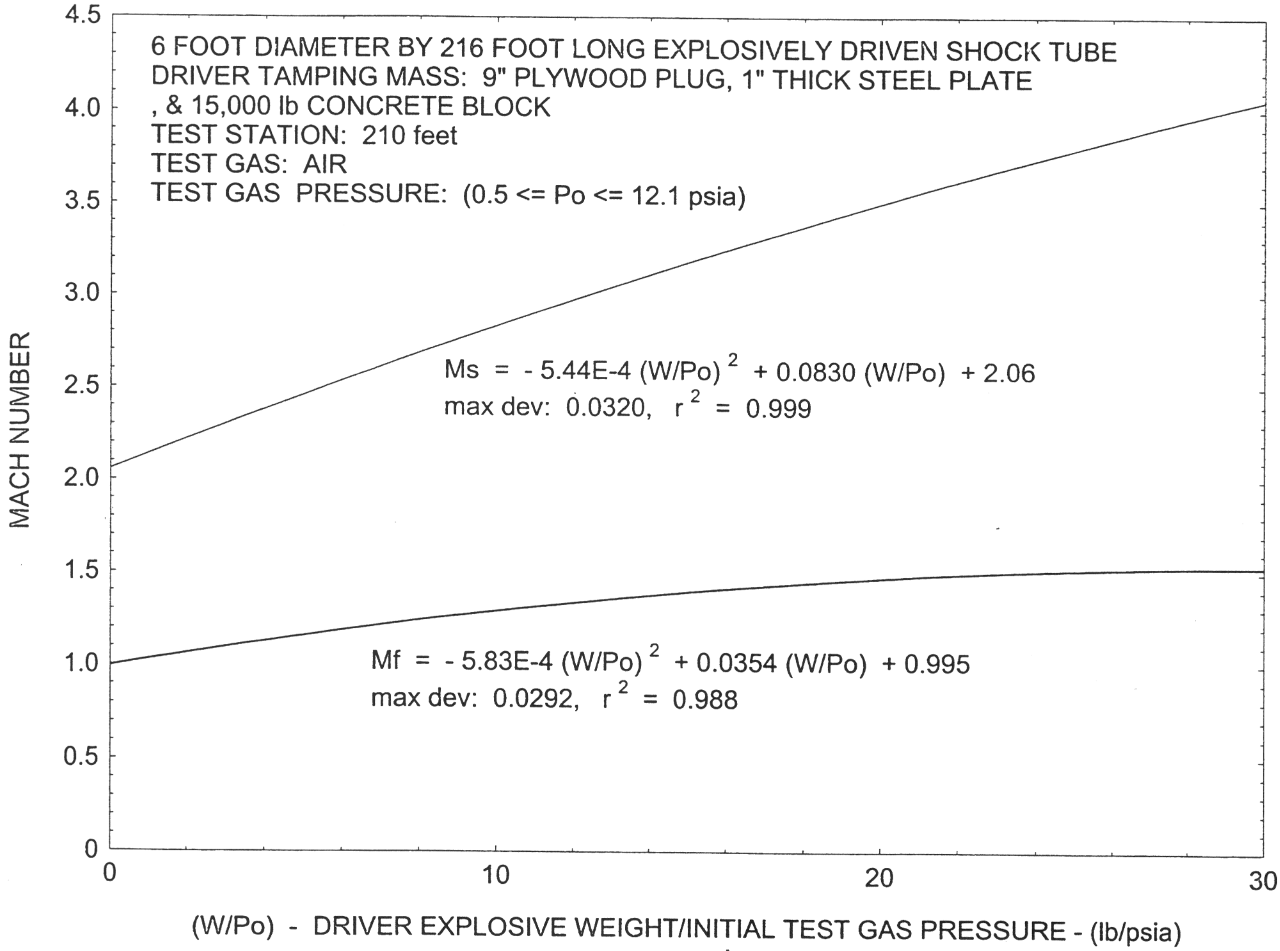

Figure 23. Shock and flow Mach number versus explosive weight to initial test gas pressure

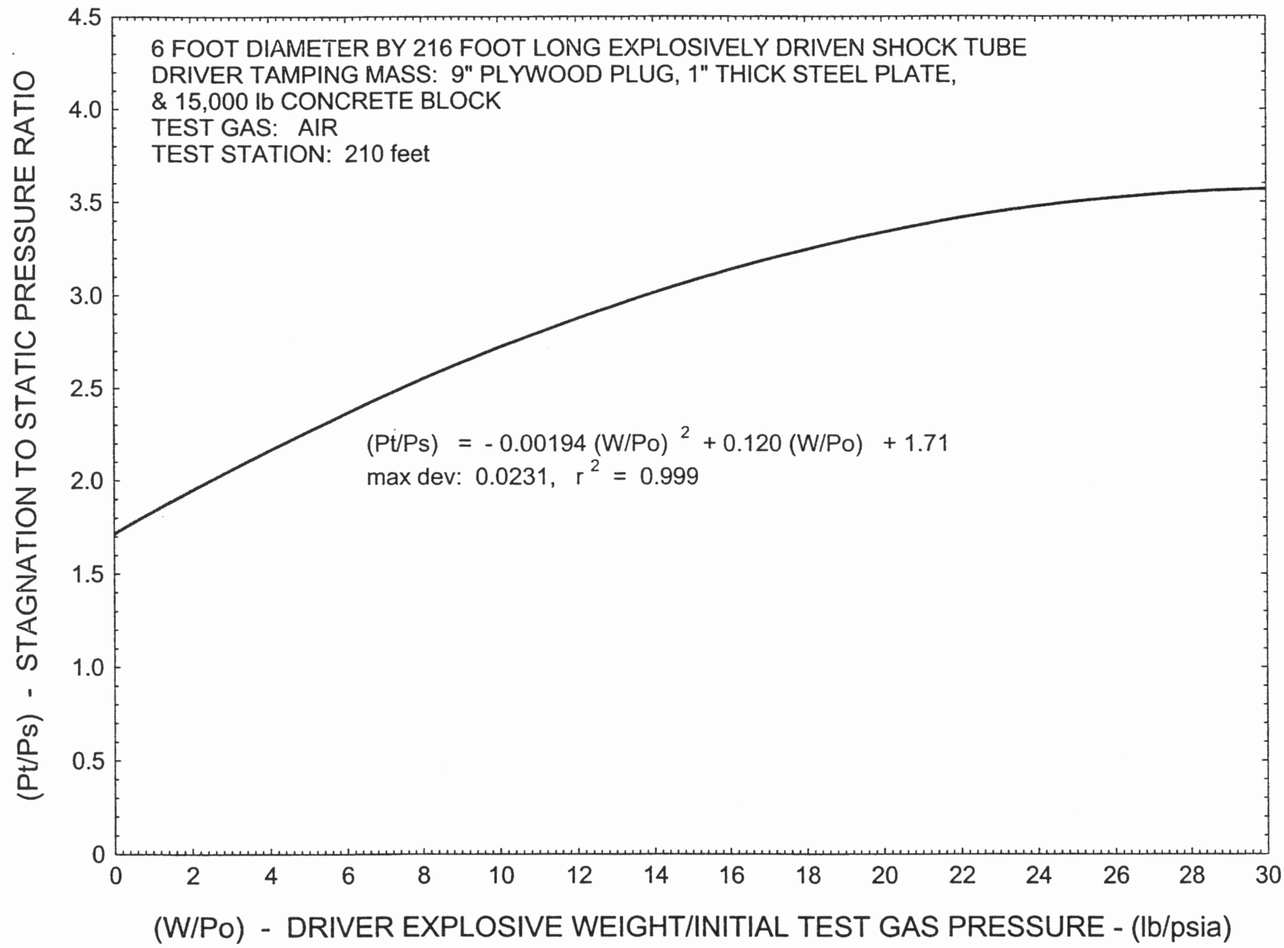

Figure 24. Stagnation to static pressure ratio versus explosive weight to initial test gas pressure

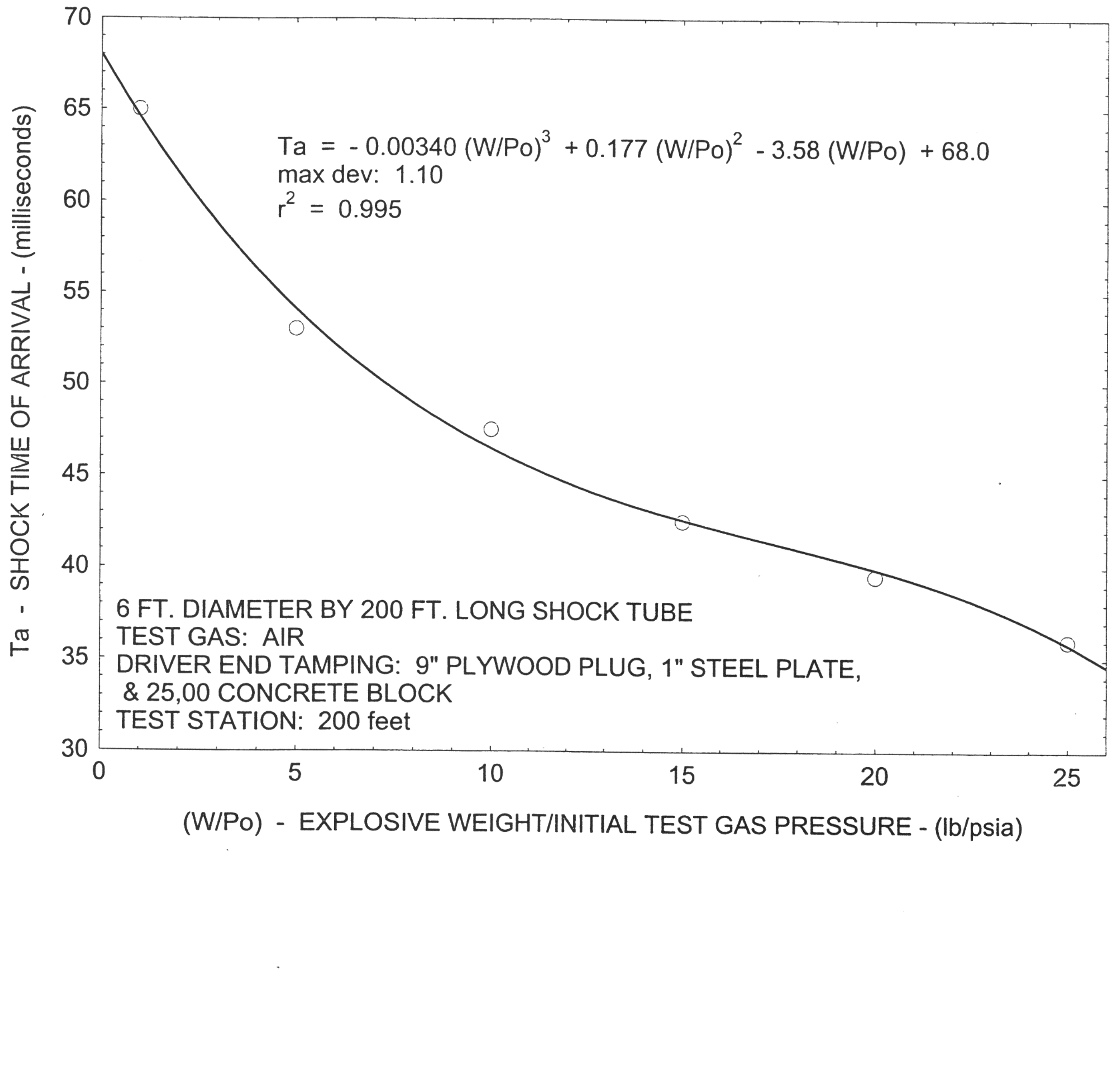

Figure 25. Shock time of arrival versus explosive weight to initial test gas pressure

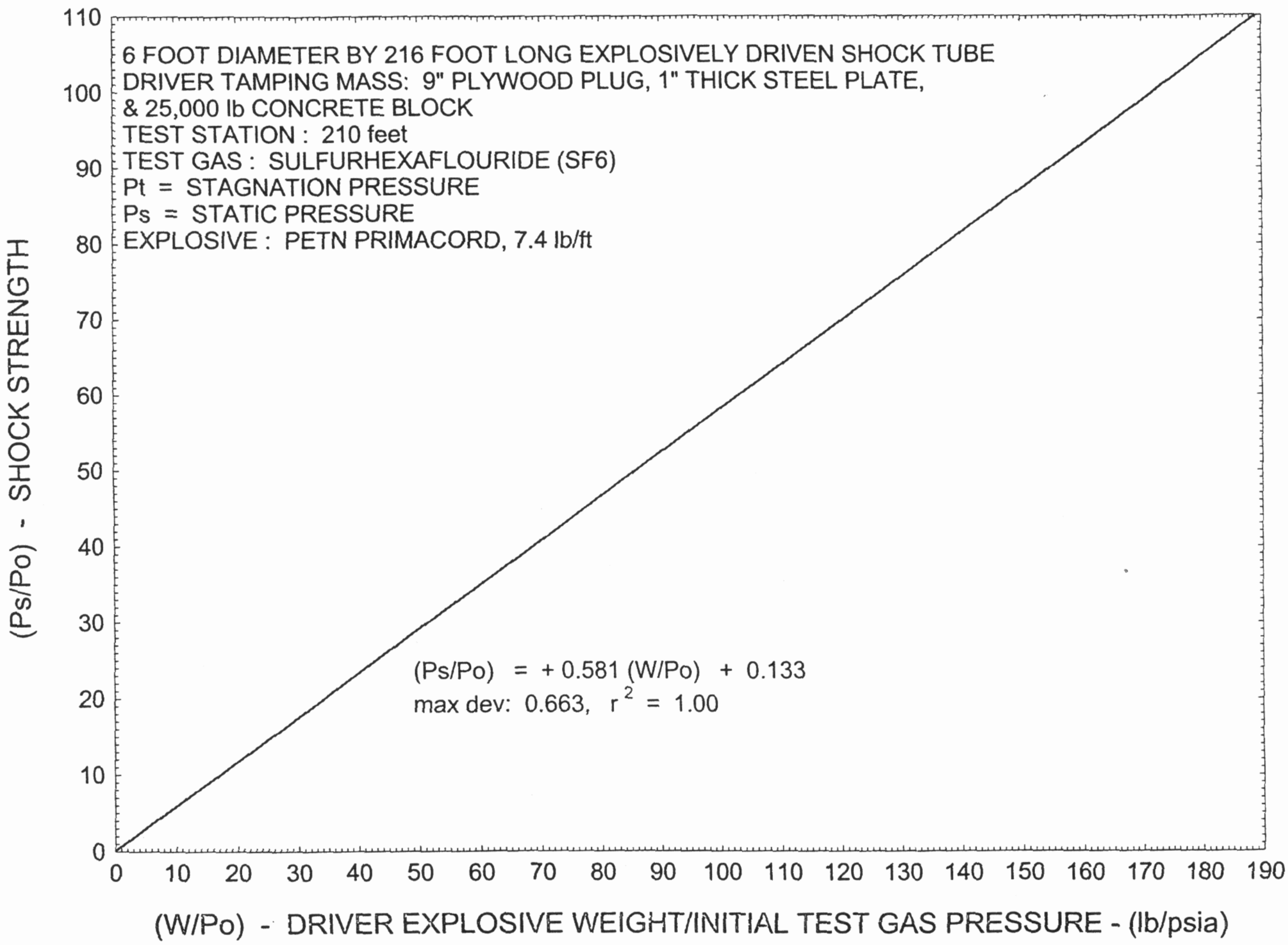

Figure 26. Shock strength versus explosive weight to initial test gas pressure/SF6

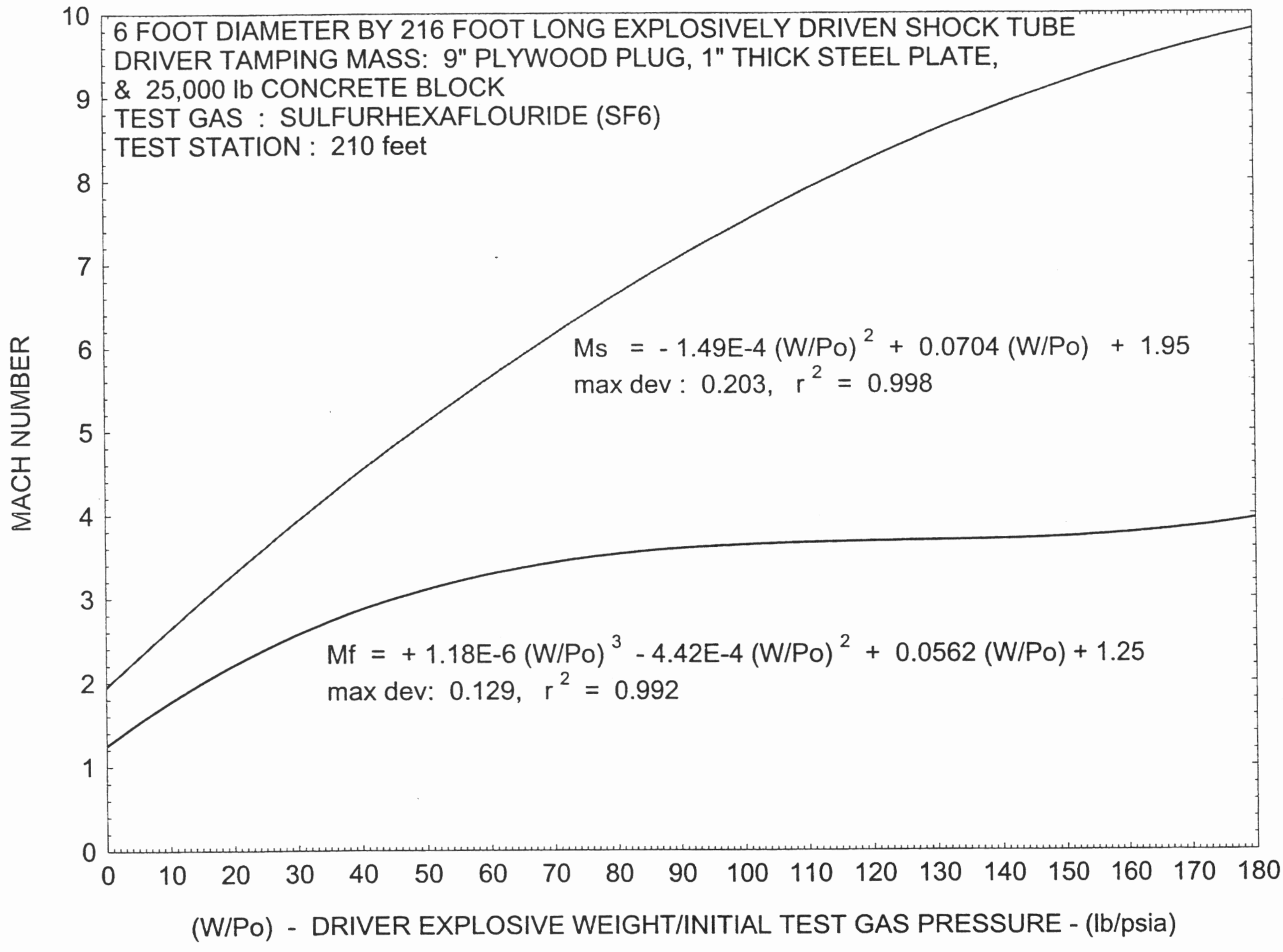

Figure 27. Shock and flow Mach number versus explosive weight to initial test gas pressure/SF6

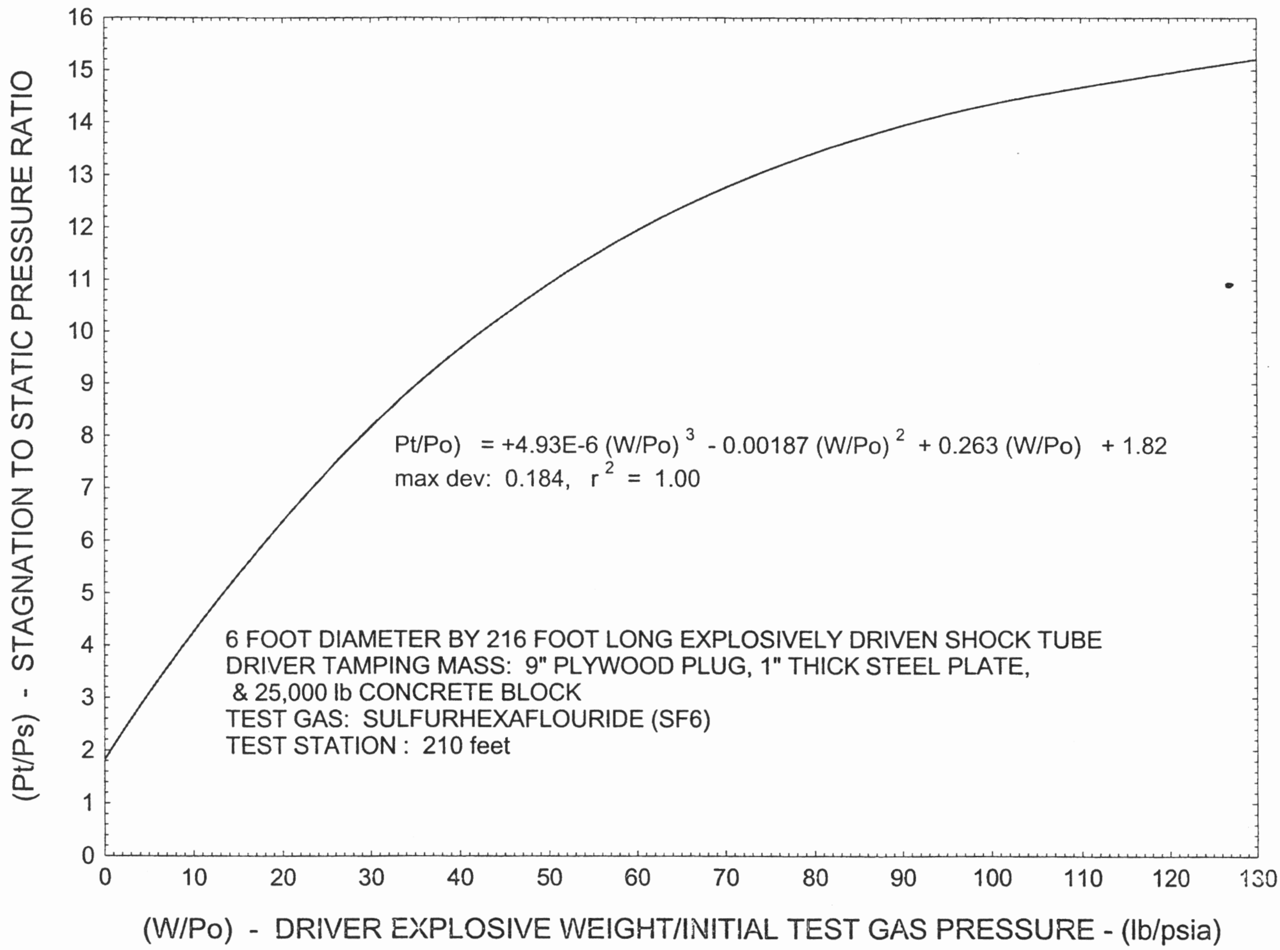

Figure 28. Stagnation to static pressure ratio versus explosive weight to initial test gas pressure/SF6

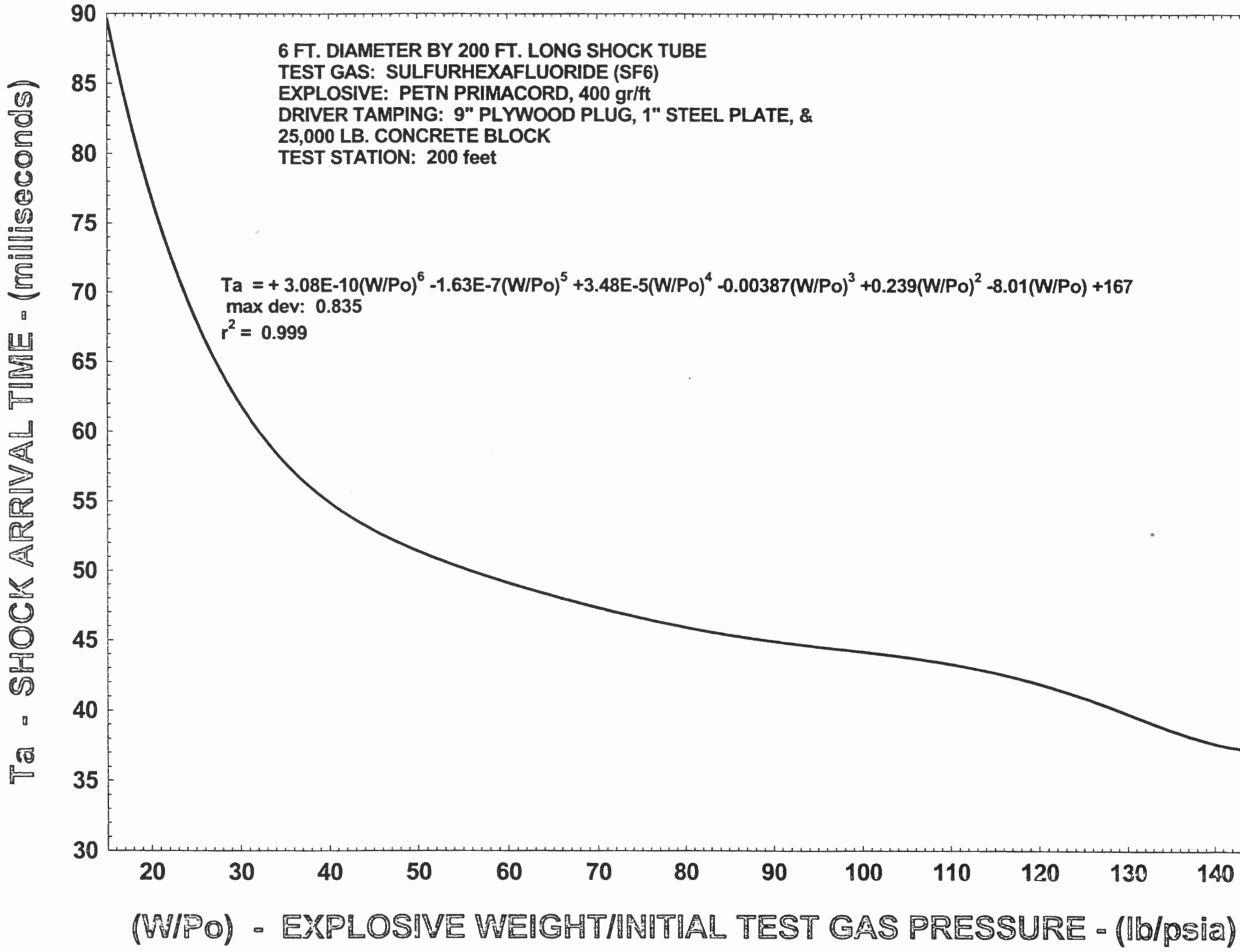

Figure 29. Shock arrival time versus explosive weight to initial test gas pressure/SF6

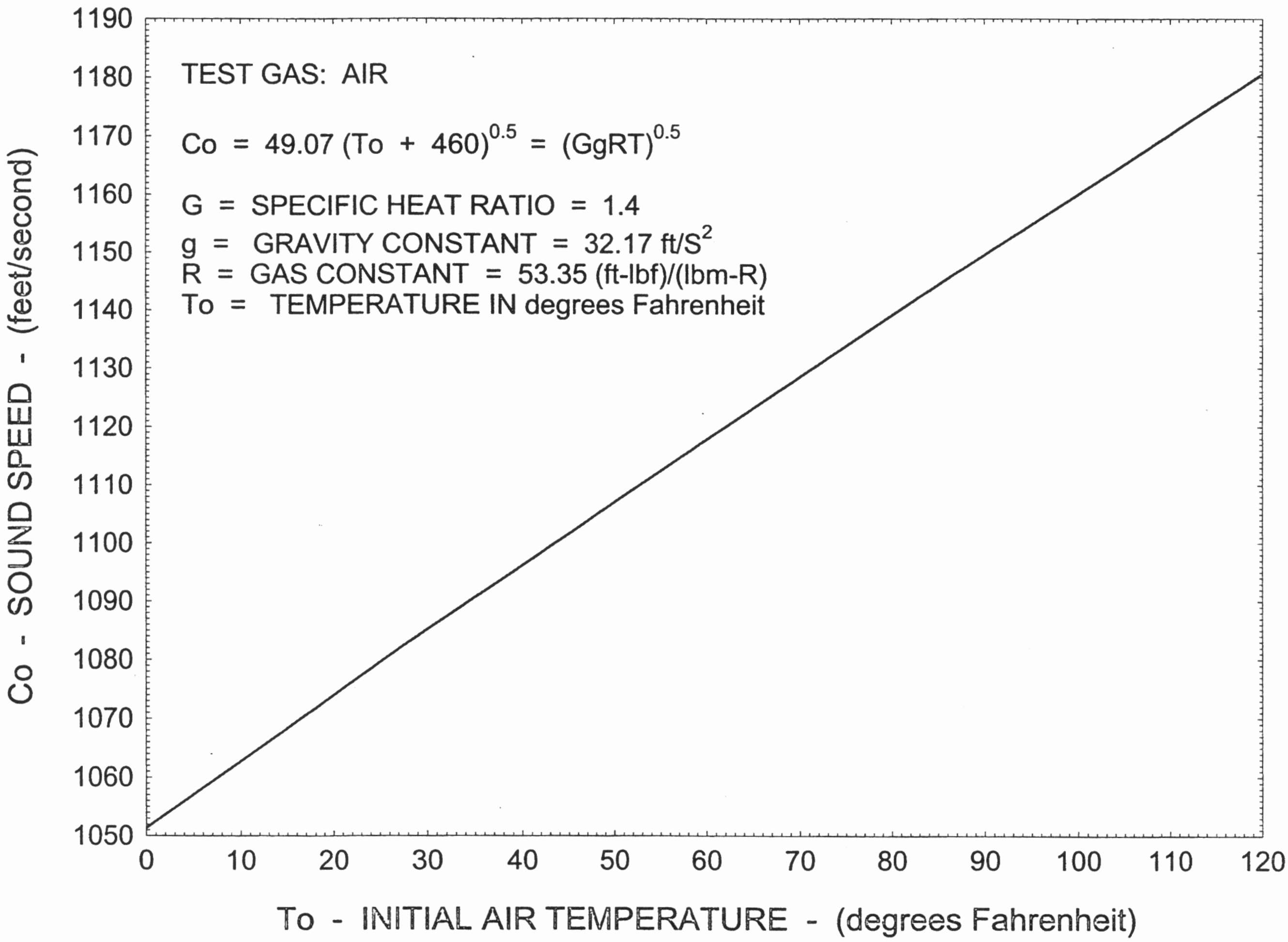

Figure 30. Sound speed versus initial test gas temperature/air

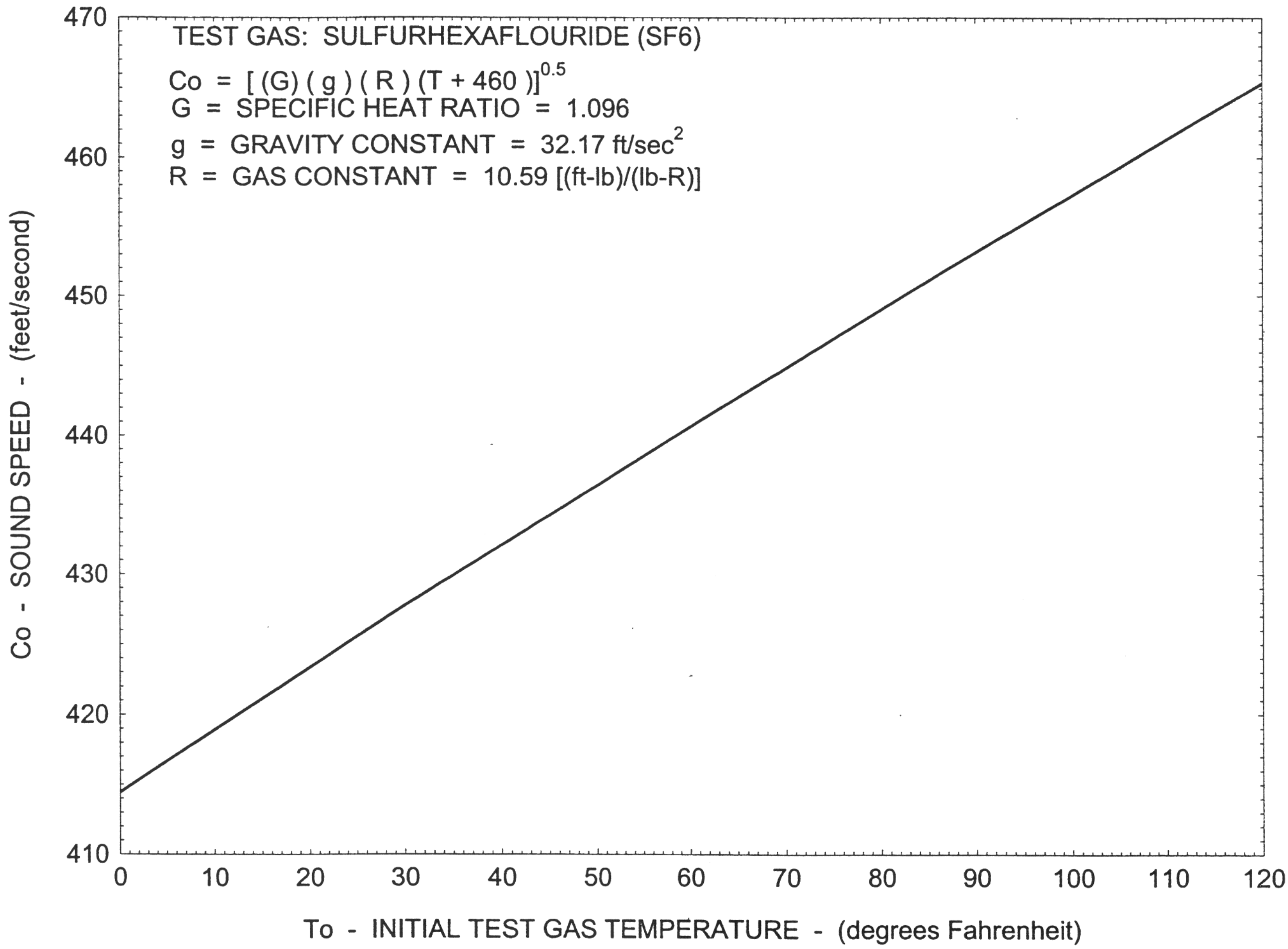

Figure 31. Sound speed versus initial test gas temperature/SF6

Figure 32. Shadowgraph of shock wave at a distance of 150 feet from driver end

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