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Six-Foot Diameter by Sixty Foot Long Concentrated Explosive-Driven Shock Tube

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SIX-FOOT DIAMETER by SIXTY FOOT LONG CONCENTRATED EXPLOSIVE-DRIVEN SHOCK TUBE

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Abstract

The blast parameters for the 6-foot diameter by 60-foot long, concentrated explosive driven shock tube are presented in this report. The purpose, main characteristics, and blast simulation capabilities of this concentrated explosive driven facility are included. Experimental data are presented for air as the test gas with initial pressures between 1.0 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 are presented in this report and 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 and Linda Ainsworth for their efforts in getting this report finalized and published in a timely manner.

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Nomenclature

A_o or C_o	Test gas sound velocity (fps)
a_o	Sound velocity behind the shock wave (fps)
CTU	Calibration Test Unit
g	Gravity constant (ft/s^2)
I	Static impulse (psig-ms)
LTU	Laboratory Test Unit
Mf	Flow Mach number
Ms	Shock Mach number
P = Ps	Static or Side-on pressure (psia)
Pm	Measure static overpressure (psig)
P_o	Initial test gas pressure (psia)
P_t	Stagnation or head-on pressure (psia)
Ptm	Measured stagnation overpressure (psig)
P_r	Reflected pressure (psia)
Prm	Measured reflected overpressure (psig)
Q	Dynamic pressure (psia)
R	Universal gas constant [(ft-lb)/(lb-°R)]
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)
U	Flow velocity behind the shock wave (fps)
V_s	Shock wave velocity (fps)
W	Explosive weight (lb)
ρ_1	Density behind the shock wave (lb/ft^3)
ρ_o	Initial test gas density (lb/ft^3)
γ	Test gas specific heat ratio
(P/P_o)	Shock strength

SIX-FOOT DIAMETER by SIXTY FOOT LONG CONCENTRATED EXPLOSIVE-DRIVEN SHOCK TUBE

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 19.

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 documenting SNL shock tube facilities and their performance parameters.

This report is similar to and compliments the report documented in reference 1 for a six-foot diameter by 200-foot, distributed, PETN, Primacord explosively-driven shock tube. The concentrated explosive shorter shock tube described in this report differs from the shock tube described in reference 1 as follows:

1. Concentrated, much higher density (1.65 versus 1.0 g/cc),
2. Expendable, non-reusable driver section,
3. Shorter flow duration times (5 ms versus 25 ms),
4. Shorter static impulses, and
5. Larger 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 designs 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 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 sixty foot long concentrated explosive driven shock tube at Sandia National Laboratories has been used to simulate the blast environment on a Re-entry Vehicle (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 July 1966.

Shock Tube Blast Parameters

The blast parameters for the 6-foot diameter by 60-foot long, concentrated explosive driven shock tube are presented in this report. The purpose, main characteristics, and blast simulation capabilities of this concentrated explosive driven facility are included. Experimental data are presented for air as the test gas with initial pressures between 1.0 to 12.1 psia (ambient). Experimental measured data are presented for the following blast parameters:

1. Flow duration,
2. Static or side-on overpressure, and
3. Stagnation or head-on overpressure.

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

1. Static impulse,
2. Shock Mach number,
3. Flow Mach Number,
4. Reflected pressure,
5. Dynamic pressure,
6. Particle velocity,
7. Density behind the shock, and
8. 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 60 foot long shock tube configuration is shown in Figures 1 - 3. Figure 1 shows the shock tube pre-test configuration with the water filled annular tank at the explosive driver end. Figure 2 shows the shock tube along side of the 6 foot diameter by 200 foot long shock tube [1]. Figure 3 shows the shock tube geometry with a different explosive driver end tamping. The total shock tube length can vary between 50 to 80 feet depending on the desired impulse required. The shock tube sections have been suspended by adjustable screw jacks as shown in Figure 4.

Expendable Driver

The expendable driver consists of a 6 foot inside diameter by a 10 foot outside diameter by 6 foot long section as shown in Figure 1. The volume between the ID and OD is filled with water. A 1 inch thick steel plate closes the driver end and supports the blocks of concentrated explosive.

Driver End/Tamping Mass

A minimum amount of driver end tamping mass is used with concentrated explosive shock tubes. First, it is very difficult to contain concentrated, high density, secondary explosive charges. Second, the total required shock tube length is relatively short and therefore, it is not necessarily important to delay the venting of high pressure gases at the driver end.

More recent tests using 6 foot or 12 foot diameter shock tubes with lengths less than 80 feet have simply used concentrated explosive charges (cylindrical in geometry) suspended just outside the driver end.

Explosive Loading

TNT, Composition C4 (COMP C4), or nitroguanadine explosive charges have been used to drive this shock tube. The explosive density was about 1.6 grams per cubic centimeter for all types of explosive.

An SE-1, RP-1, or similar detonator is taped in the center of the explosive charge. If several blocks or charges are used, then a similar detonator is attached to each block. A Tetryl pellet of explosive may be used as a booster charge between the detonator and the

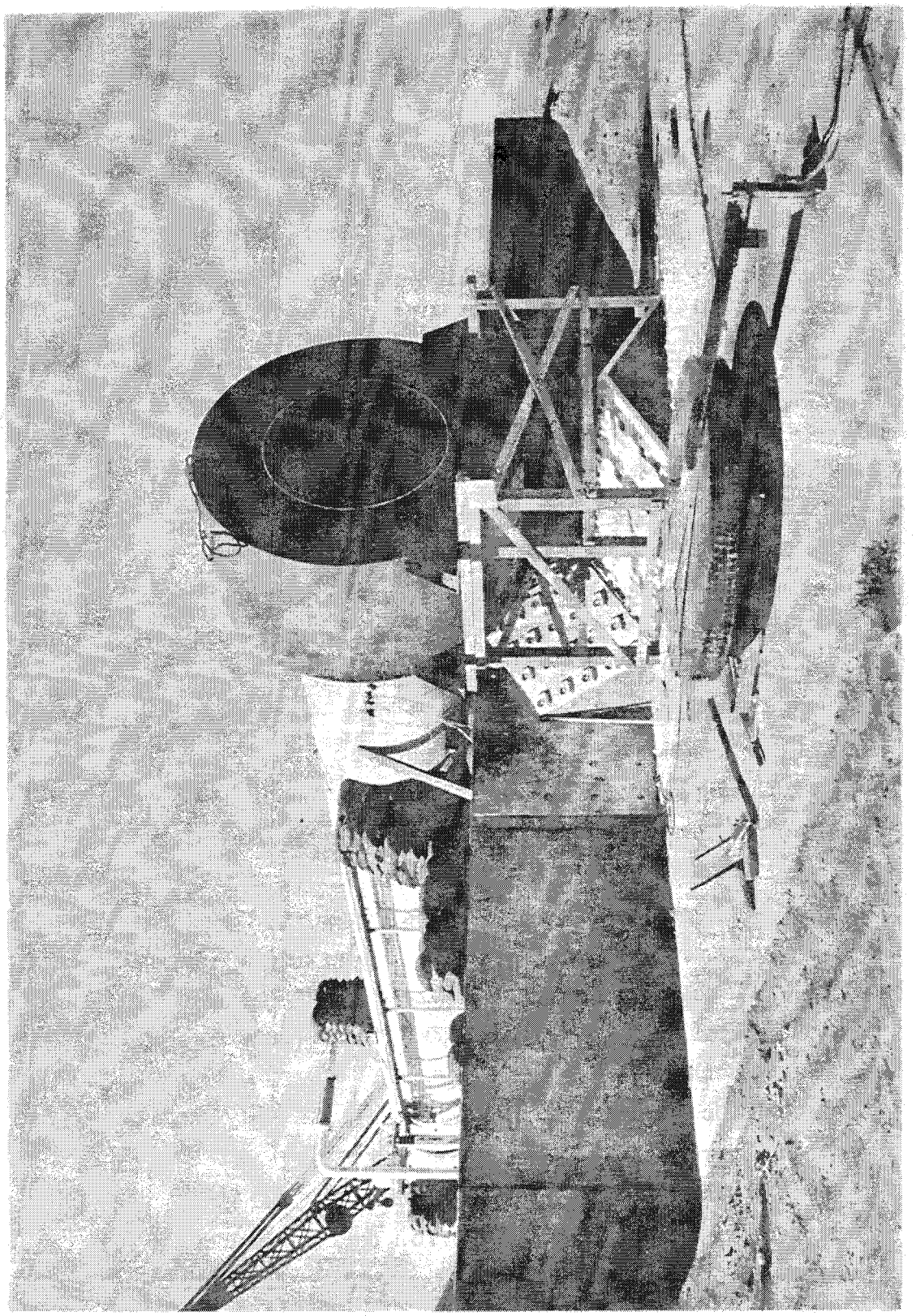

Figure 1. Six foot diameter by 60 foot long concentrated explosive driven shock tube

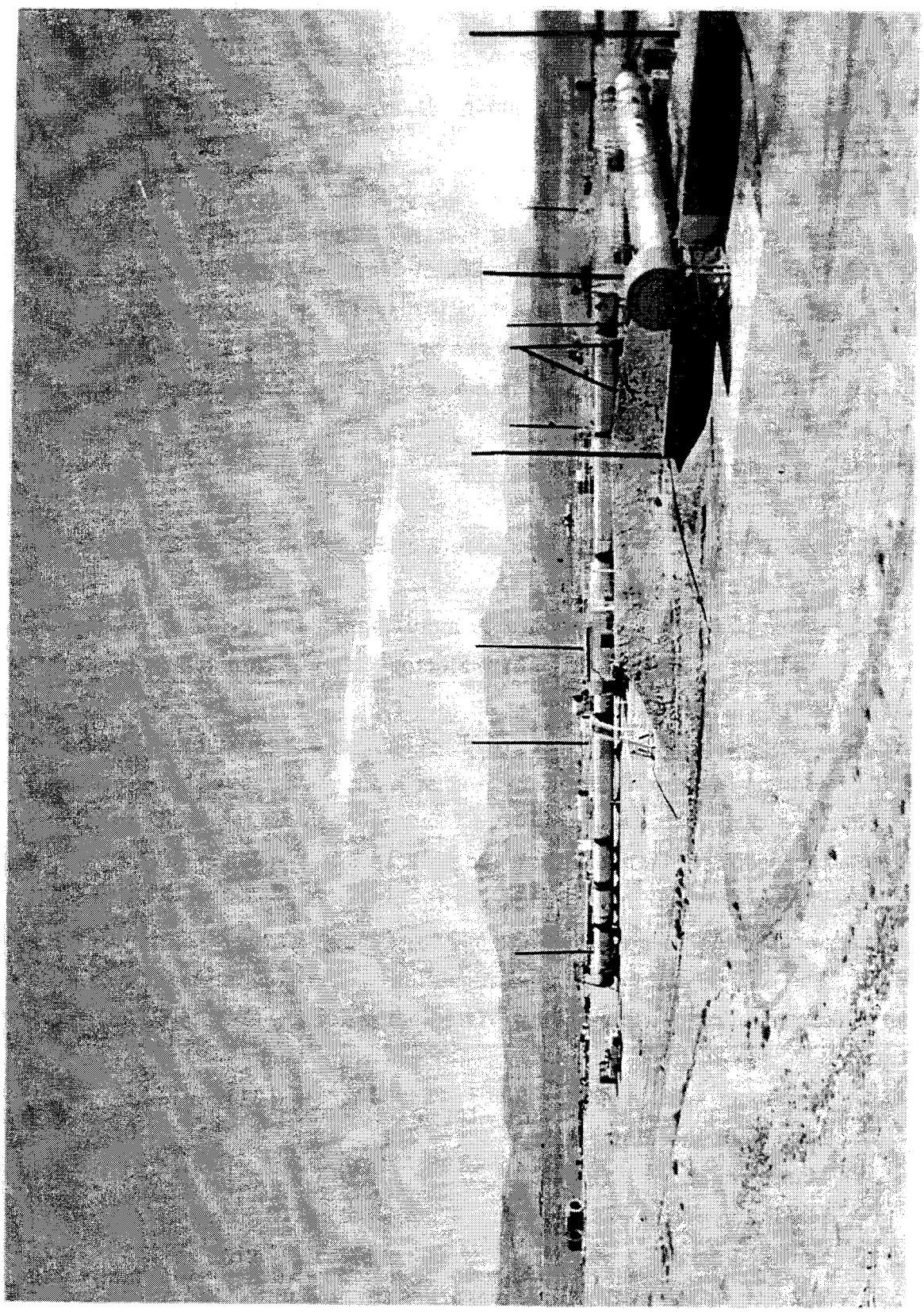

Figure 2. Six foot diameter by 60 foot long concentrated explosive driven shock tube along side 6 foot diameter by 200 foot long, distributed explosive driven shock tube

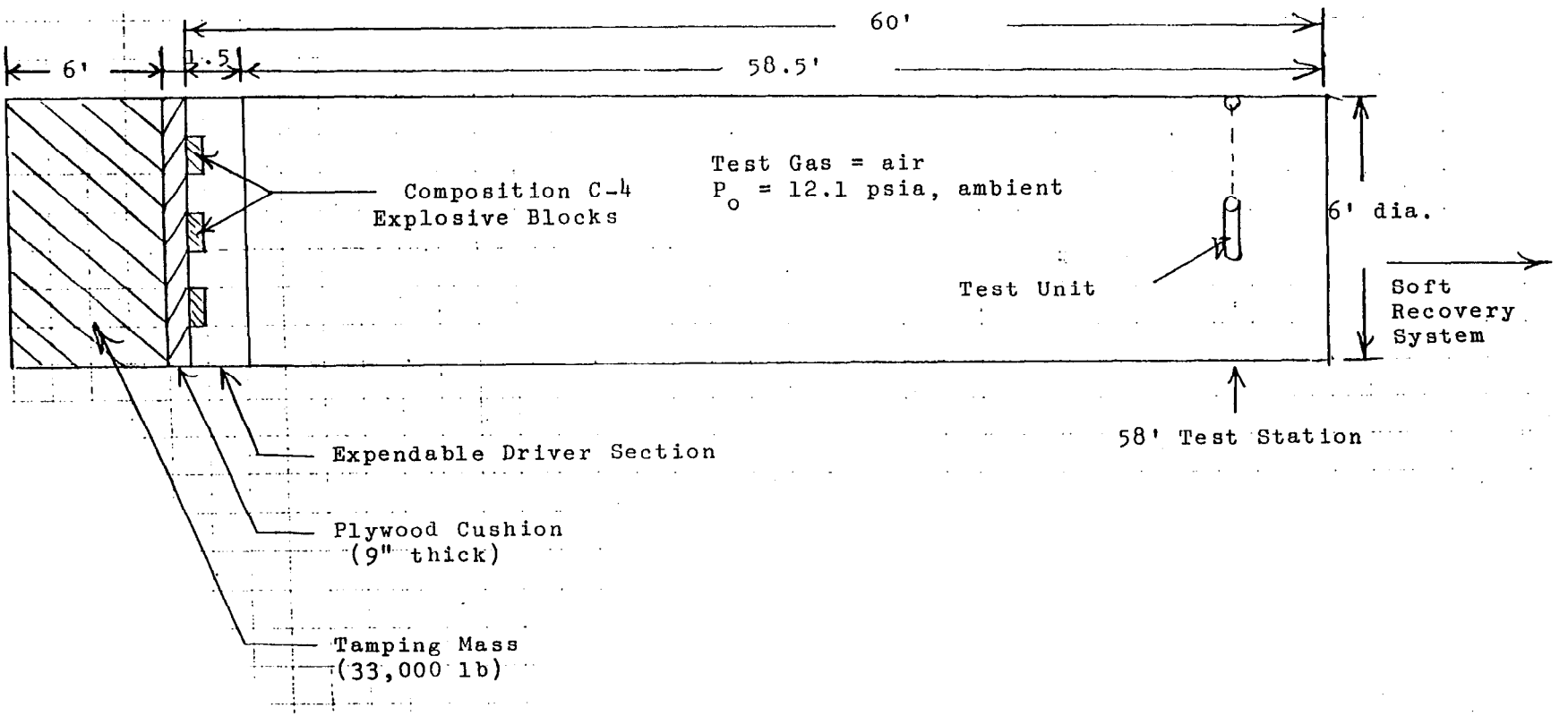

Figure 3. Shock tube configuration/expendable driver and tamping mass

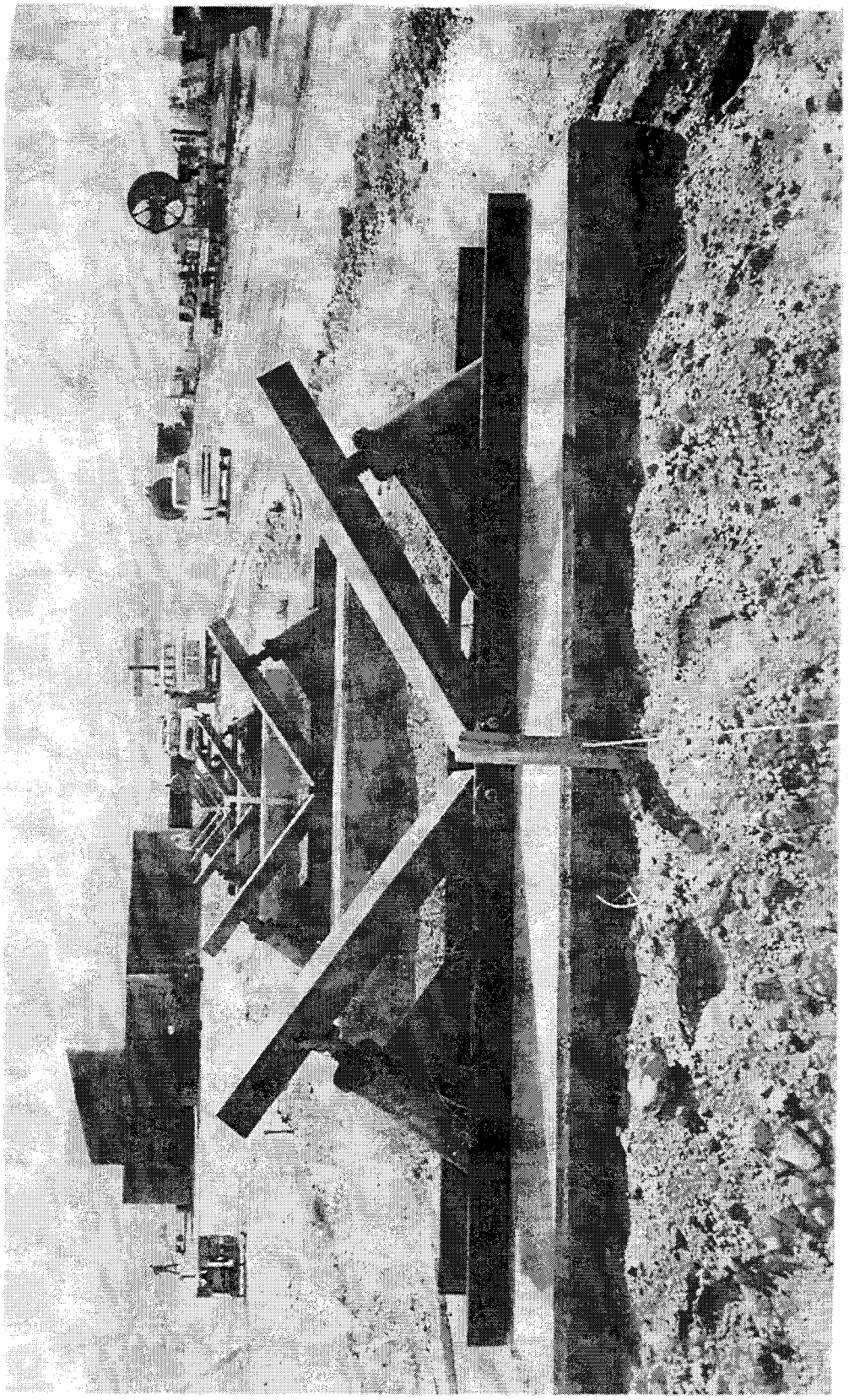

Figure 4. Screw jack, shock tube support system

main explosive charge in some cases if necessary to initiate the particular explosive charge.

Test Section

The total shock tube length can vary between 50 and 80 feet. The last section and typically the test section can include a 45 or 90 degree muzzle end. 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 concentrated explosive 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 5 shows a conical test unit suspended the test section. The radiator hose used to protect the instrumentation wires is shown in Figure 5. The conical test unit is shown in the ninety degree muzzle end or test section in Figure 6. The conical test unit is shown in the forty five degree muzzle end or test section in Figure 7.

Test Unit Soft Recovery

When it is desired to have the test unit free to respond 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 8.

Reduced Pressure Tests

The shock tube can be sealed for reduced initial test gas pressure tests. Initial test gas pressures from 1.0 to 12.1 (ambient) psia have been used. For this shock tube, the test gas has been air. A thin (0.04 inches thick) aluminum diaphragm along with a steel ring holder and an "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 have 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 9 shows the muzzle end sealed with an aluminum diaphragm.

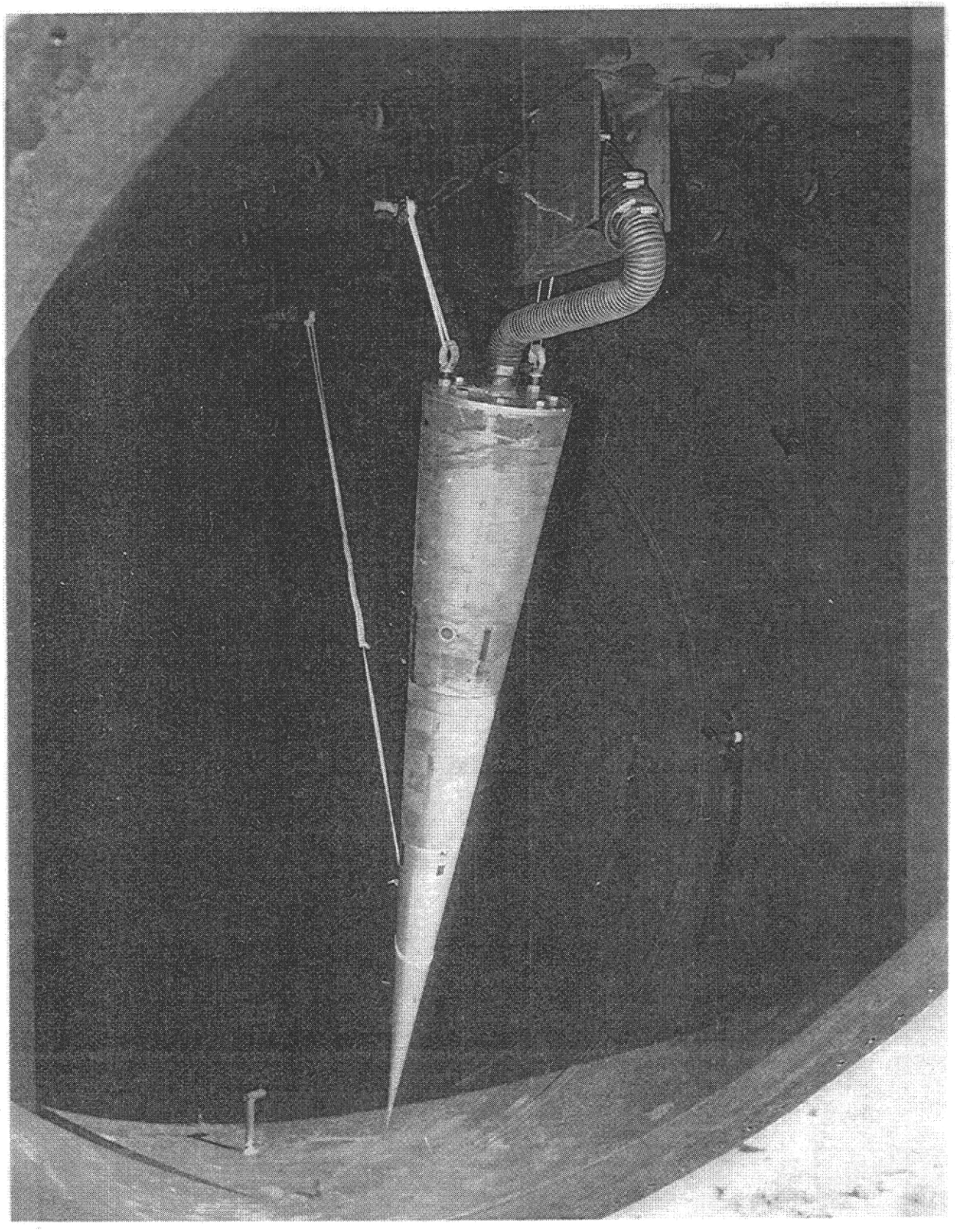

Figure 5. Conical test unit, support straps, and radiator hose housing for instrumentation wires

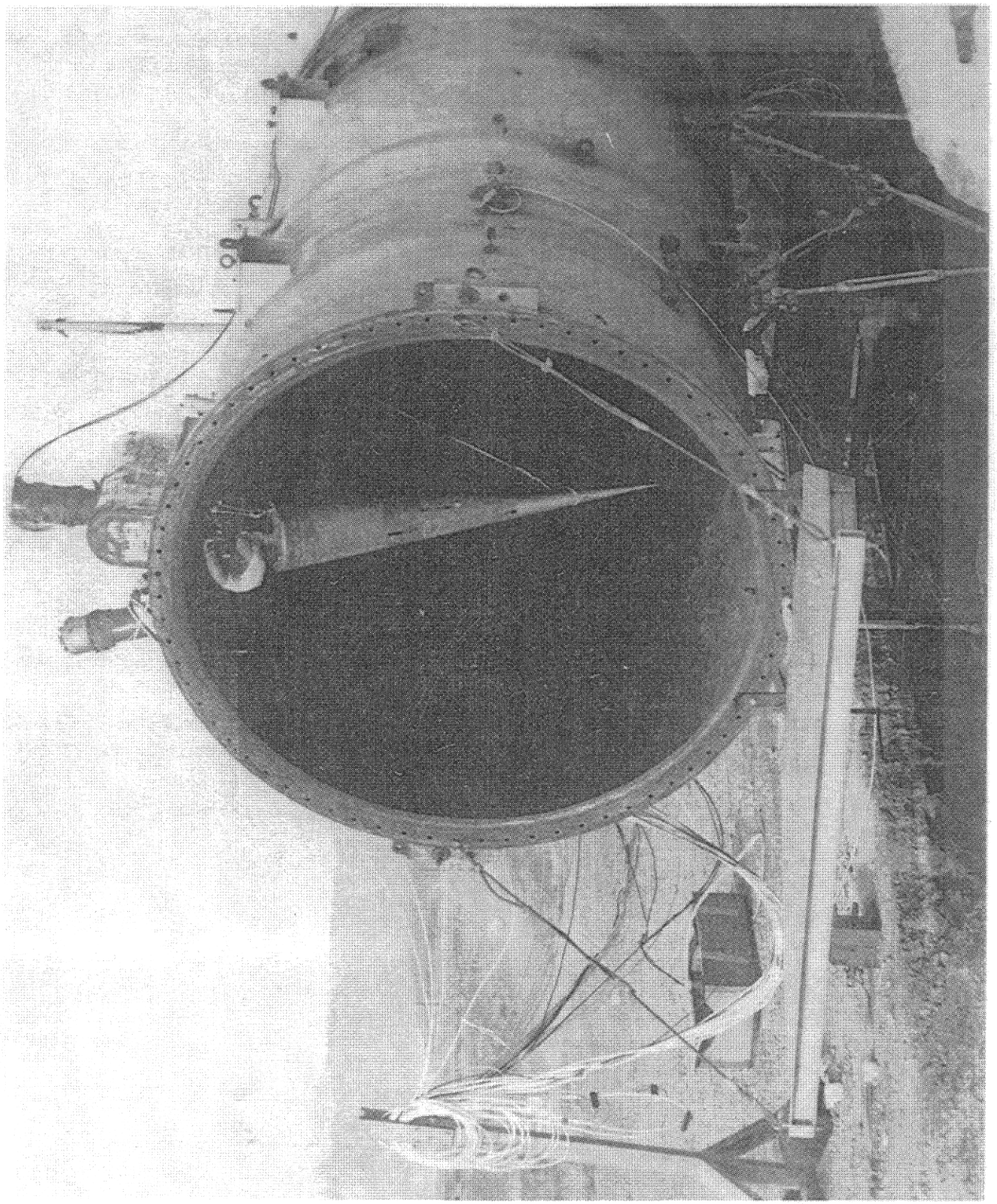

Figure 6. Test unit in 90 degree test section

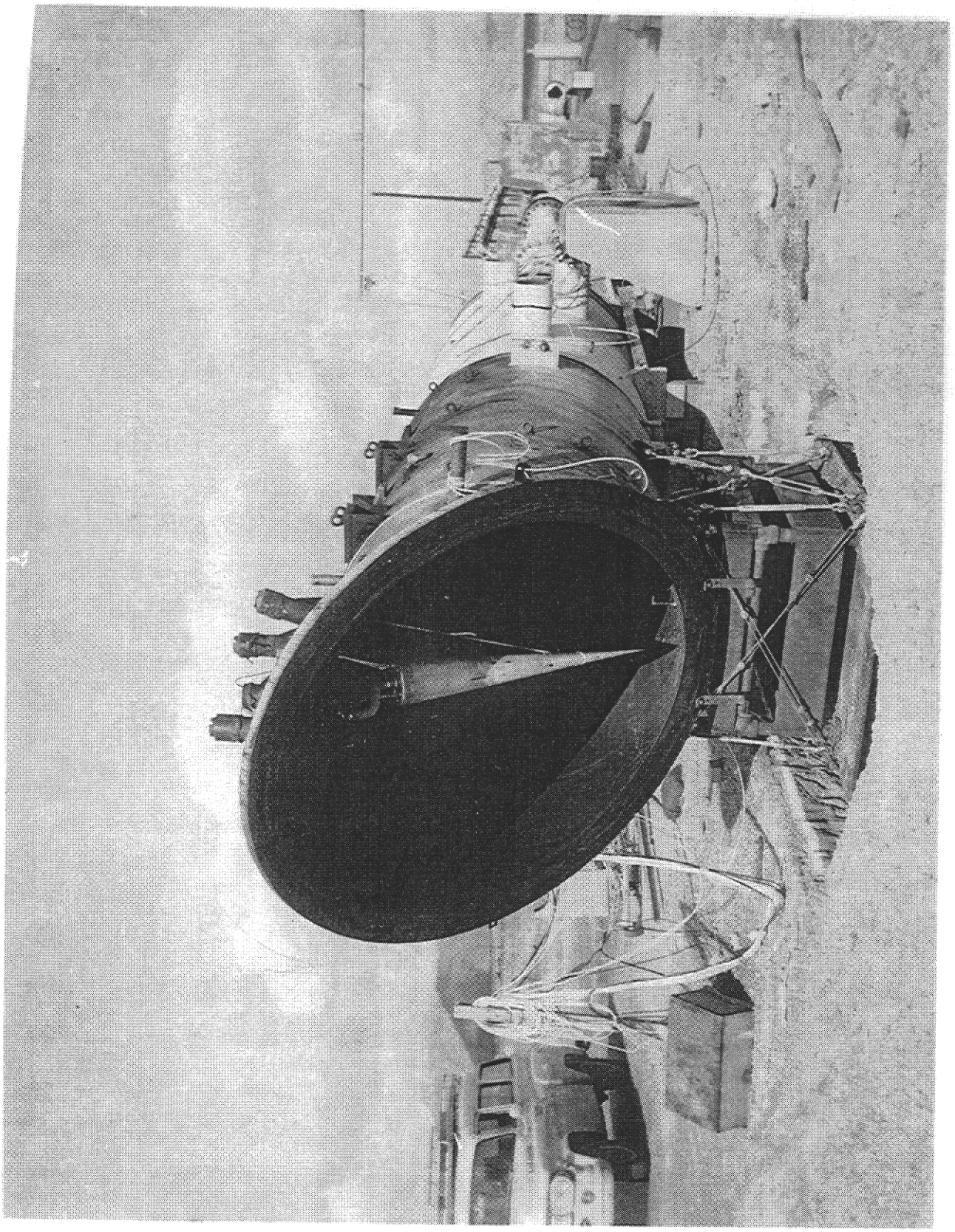

Figure 7. Test unit in 45 degree test section

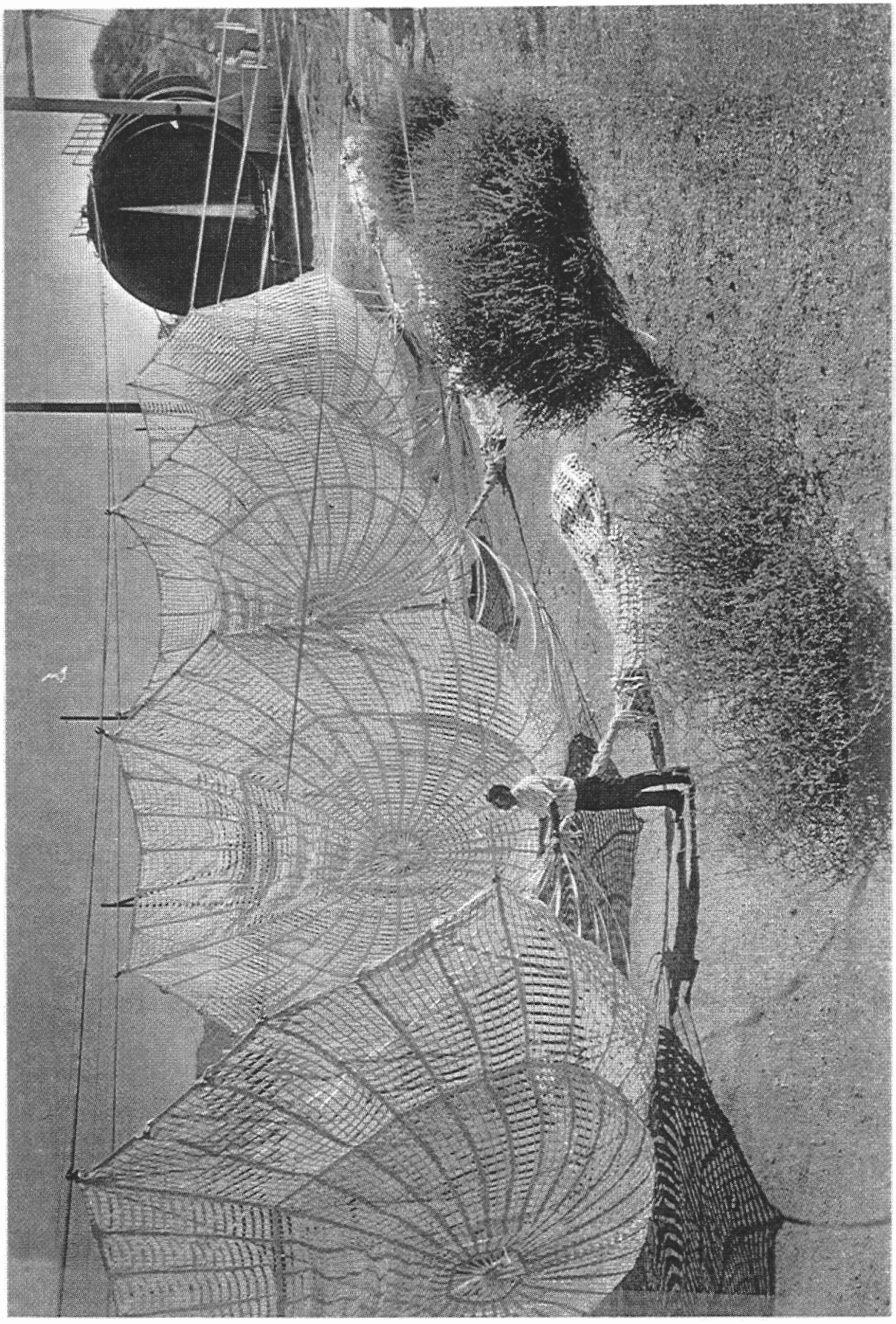

Figure 8. Vertically suspended, 20 foot diameter, nylon parachute, test unit catcher system

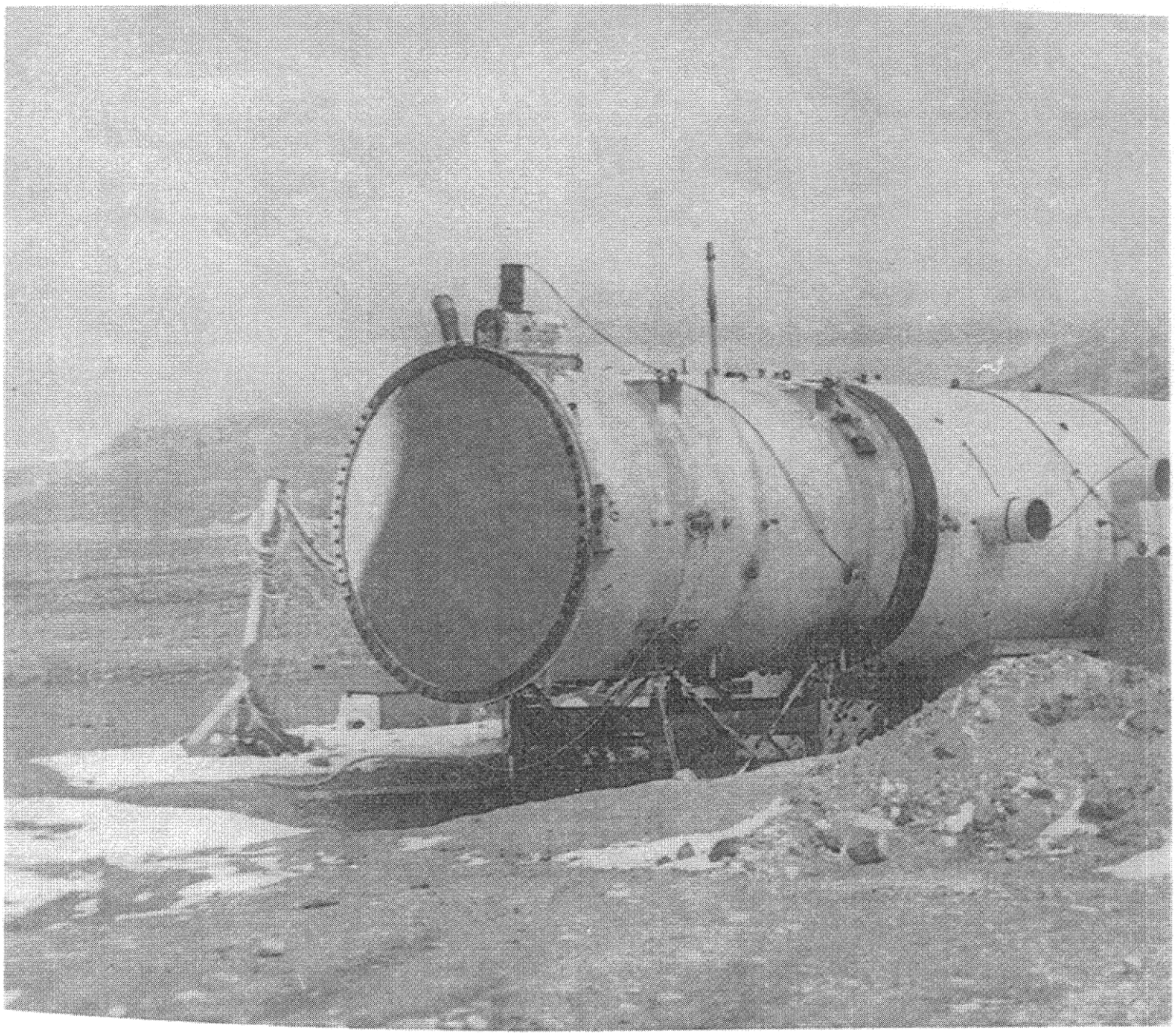

Figure 9. Thin, aluminum diaphragm used to seal shock tube muzzle end

3. 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.

4. Calibration Test Unit (CTU)

The CTU is typically a thick, walled boiler plate model of the actual Laboratory Test Unit (LTU) or Re-entry Body (RB). 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 channel are used to record shock tube pressures, CTU internal component accelerations, velocities, and strains.

5. Laboratory Test Unit (LTU)

The LTU is a prototype vehicle of the actual Re-entry Body (RB). 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.

6. Measured Static and Stagnation Pressure Profiles

Typical, measured static pressures versus time profile is shown in Figure 10 for a test gas initial pressure of 1.0 psia. Typical, measured stagnation pressures versus time profile is shown in Figure 10 for a test gas initial pressure of 1.0 psia. The measurements were obtained at a test station of 55.68 feet from the driver end.

7. Maximum Performance Blast Parameters

The blast wave generated in a concentrated explosive driven shock tubes is a shock wave followed by a rarefaction wave. The flow duration is dependent 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.

For a 6 foot diameter by 60 foot long blast tube and a concentrated explosive charge weight of 295 pounds of TNT , and initial test gas pressure of 1.0 psia, the maximum blast parameters at a test station about 55 feet from the driver end are as follows:

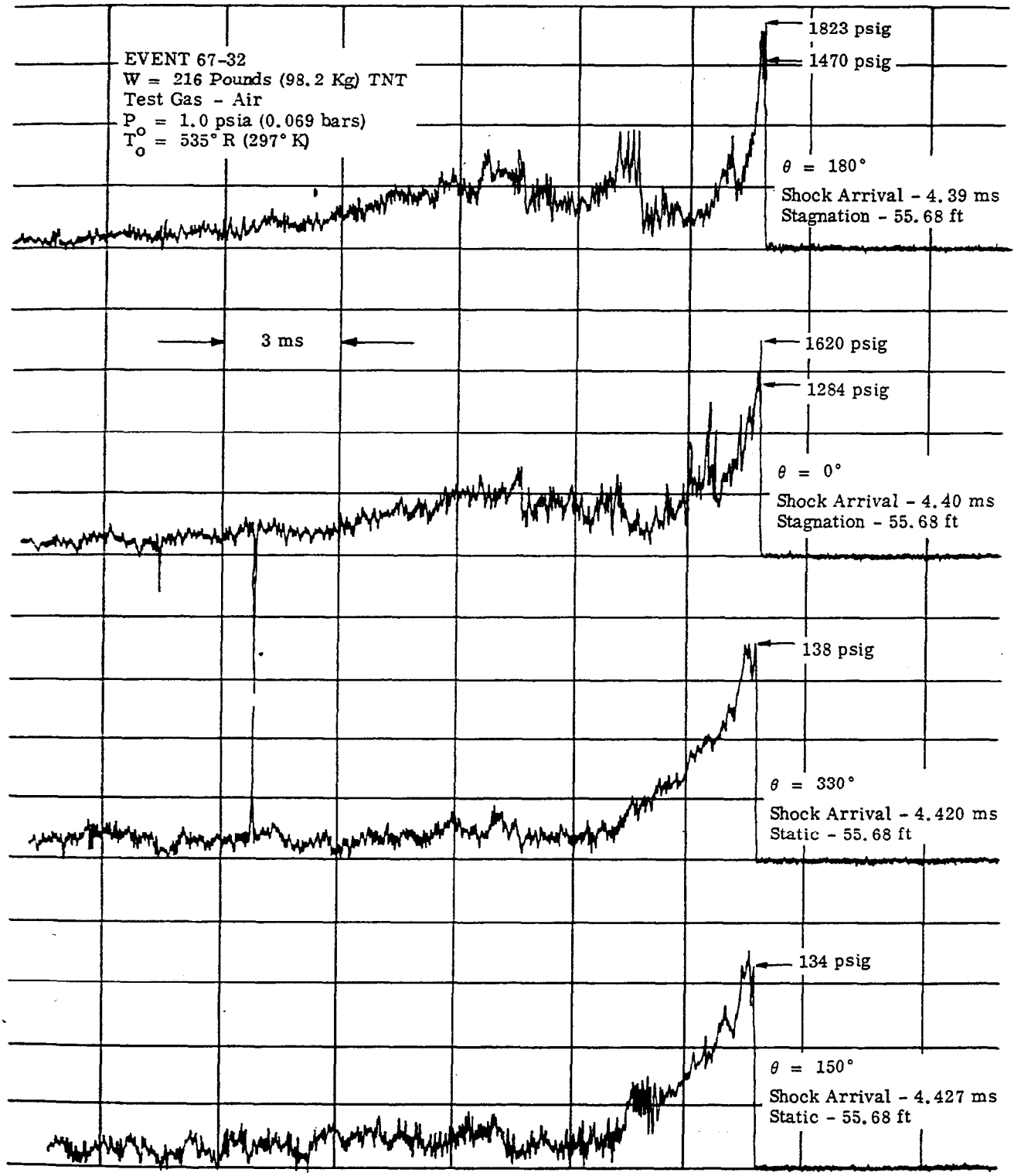

Figure 10. Measured static and stagnation pressure - time profiles(Test station: 55.68 feet from explosive charge)

1. Shock velocity: 12,000 feet/second
2. Shock Mach number: 10.6
3. Static pressure: 1000 psia
4. Flow duration: 4 milliseconds to 10 % of peak pressure

Blast parameters for a similar, temporary, 6.5 foot diameter by 40 foot long, blast tube are include in Appendix A. The test gas was air at an initial test gas pressure of 12.1 psia (ambient). Blast parameters for a temporary, plywood blast tube are included in Appendix B.

8. Shock Tube Blast Parameters

The equations used to calculate some of the blast parameters are listed in Table 1. The equations listed in Table 1 and documented in references 1 - 18 have been used to generate the shock tube flow parameters shown in Appendix C. The graphs in Appendix C can be used to determine desired flow parameter from any given or known parameters. The shock tube parameters for air as the test gas are shown in Figures 11 – 20. The least squares fit equations for the measured data are included are included in each plot. For an initial test gas pressure of 12.1 psia (ambient), Figures 11 through 17 show measured static overpressure (Pm), stagnation overpressure (Ptm), reflected overpressure (Prm), calculated dynamic pressure (Q), impulse (I), measured shock wave arrival time (Tam), and measured positive phase flow duration time (Tdm) versus driver concentrated explosive weight. The test or measurement distance from the explosive face was 58 feet.

For an initial test gas pressure of 1.0 psia , Figures 18 through 20 show measured static overpressure (Ps), impulse (I), and measured positive phase flow duration time (Tdm) near the muzzle end versus driver concentrated explosive weight. The test or measurement distance from the explosive face was 58 feet.

The measured data for the above shock blast parameters are listed in Table 2.

9. Test Gas Sound Speed

The sound speed in the test gas must be measured or calculated in order to calculate the shock Mach number that in turn used to calculate most of the rest of the blast parameters in the shock tube. For this facility, only air has been used as the test gas. For air as the test gas, the sound speed (Co) is calculated as follows:

$$Co = (\gamma g R To)^{0.5} = 49 (To)^{0.5}$$

Where, for air,

γ = Specific heat ratio = 1.4
g = Gravity constant = 32.17 feet/sec^2
R = Universal gas constant = [(ft-lb)/(lb-°R)]
T0 = Gas temperature = °R

The sound speed in air (Co) versus initial test gas temperature (To) is shown in Figure 21.

10. 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.

Table 1. Rankine-Hugoniot Relations for Calculating Blast Flow Parameters

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	$\left(\frac{P_t}{P_m}\right) = \frac{\left[2\left(\frac{\gamma-1}{\gamma+1}\right)+1\right]\frac{P}{P_0} + 1}{\left(\frac{\gamma-1}{\gamma+1}\right)\frac{P}{P_0} + 1}$

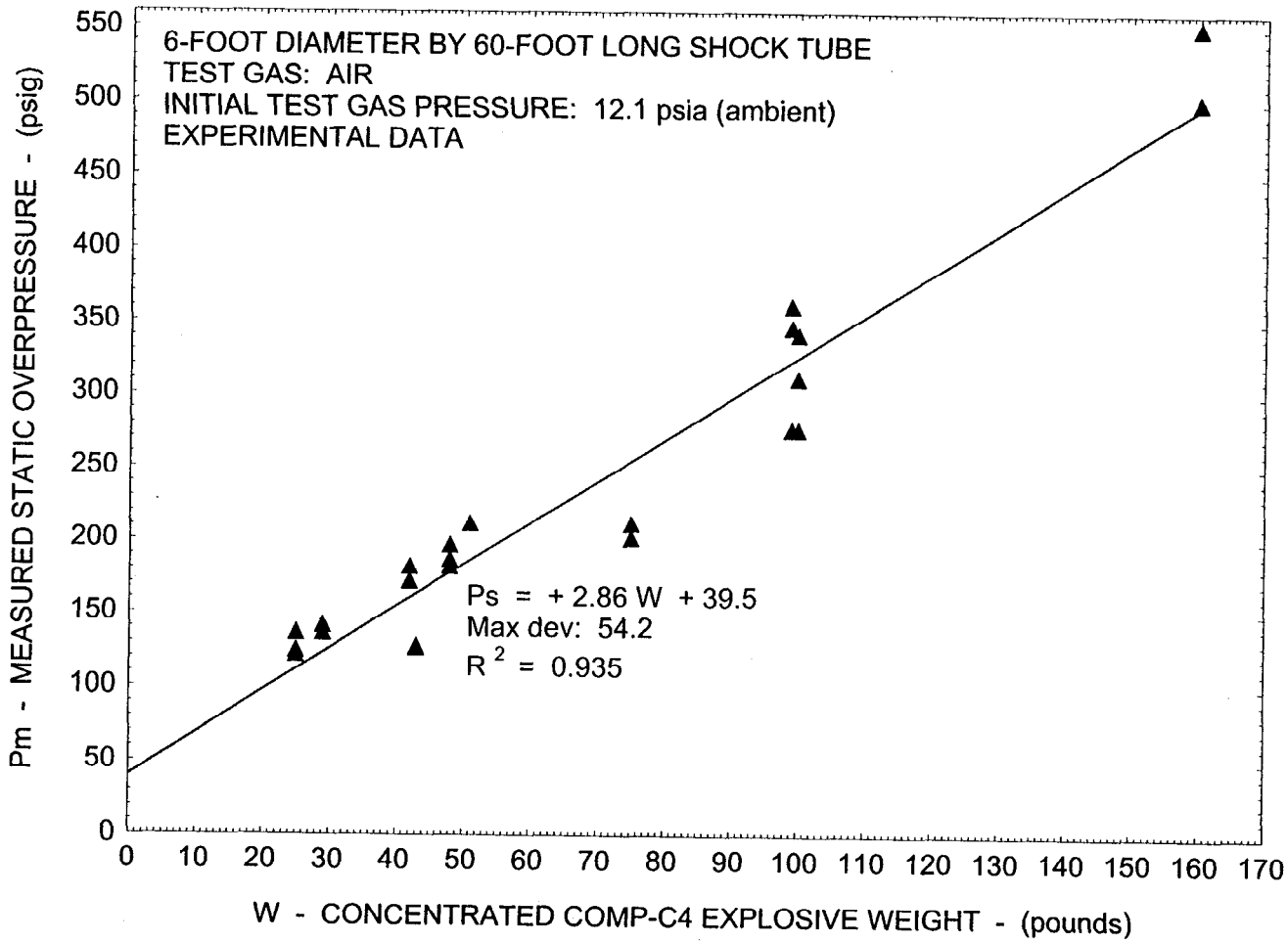

Figure 11. Measured static overpressure versus driver explosive weight

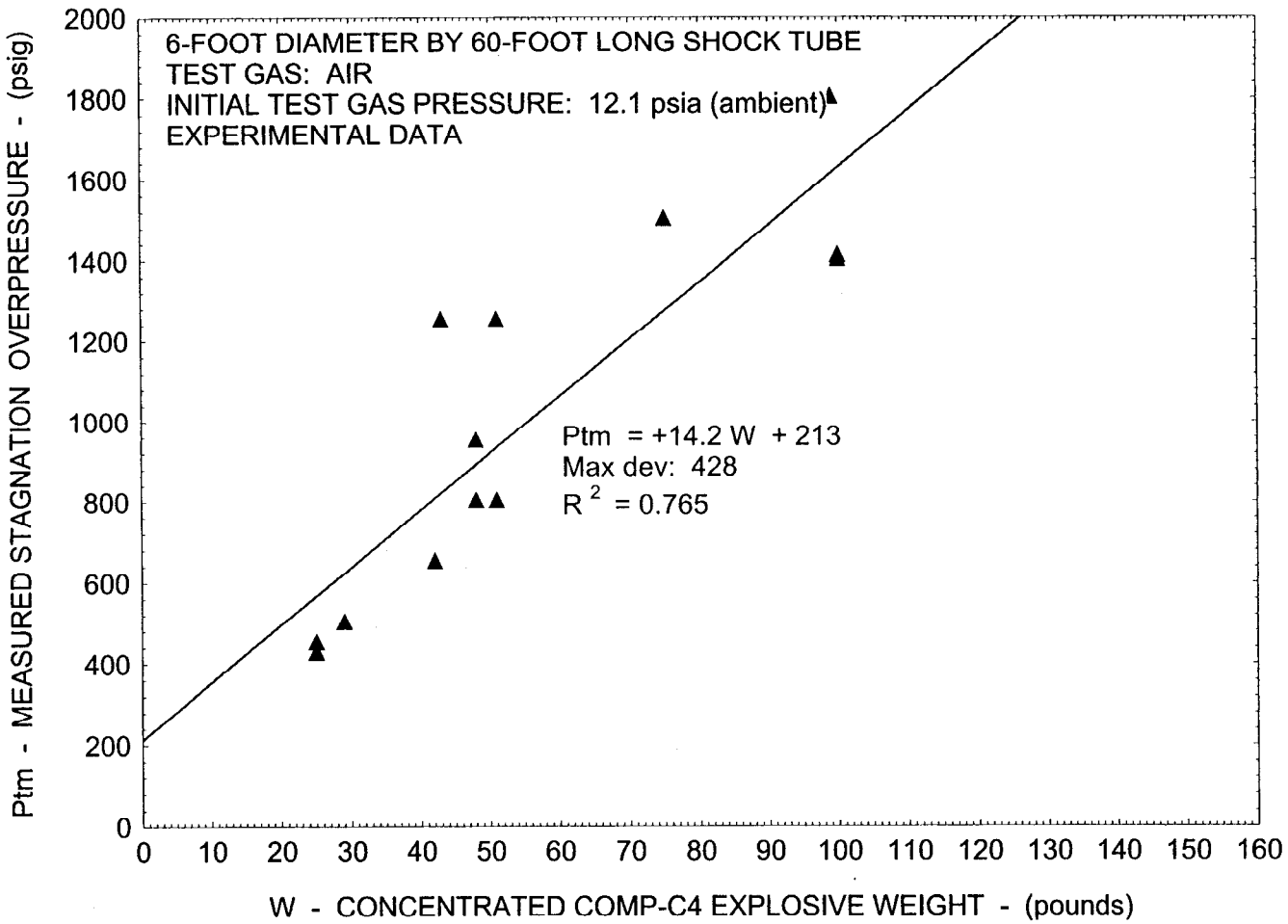

Figure 12. Measured stagnation overpressure versus driver explosive weight

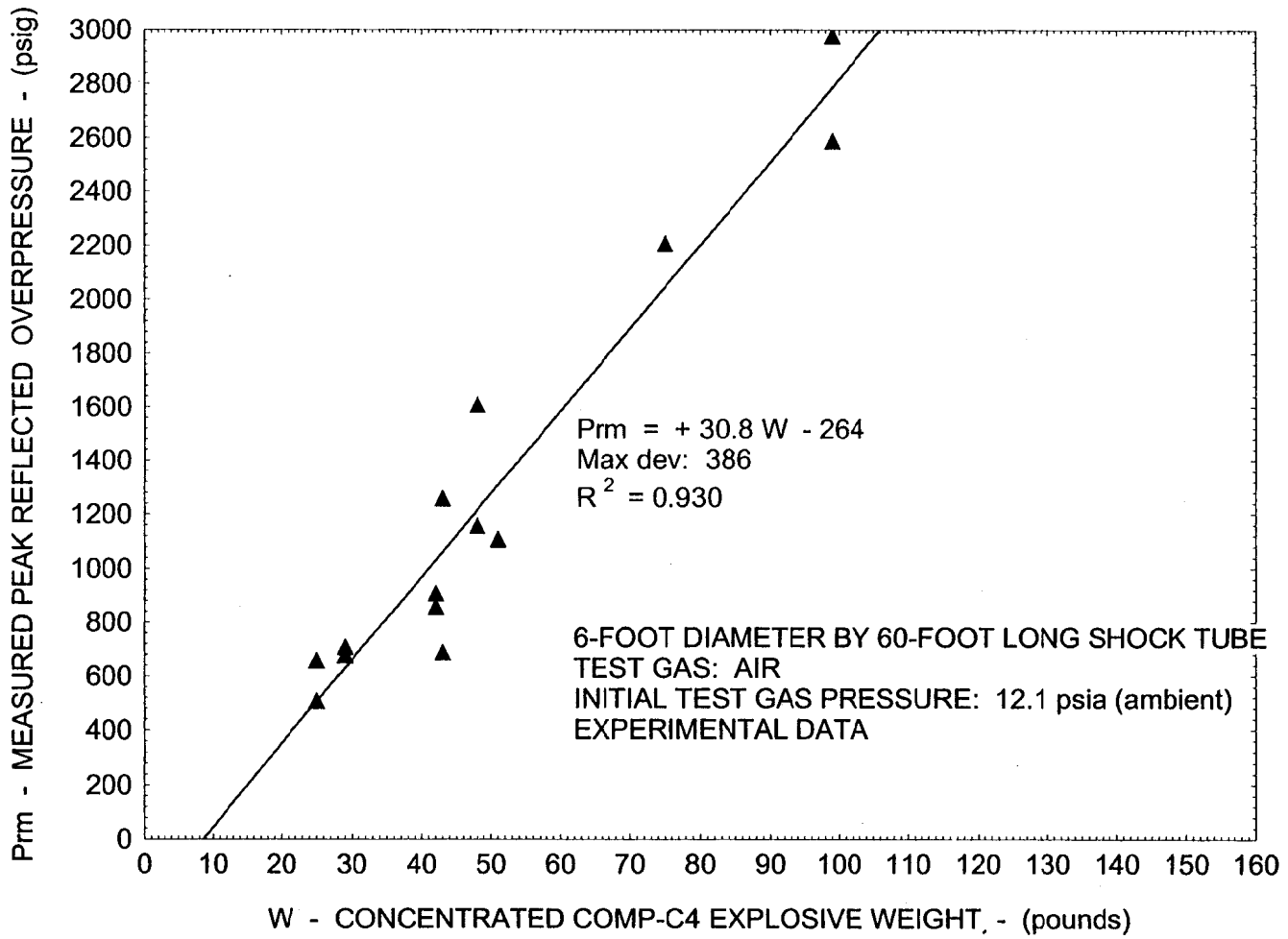

Figure 13. Measured peak reflected overpressure versus driver explosive weight

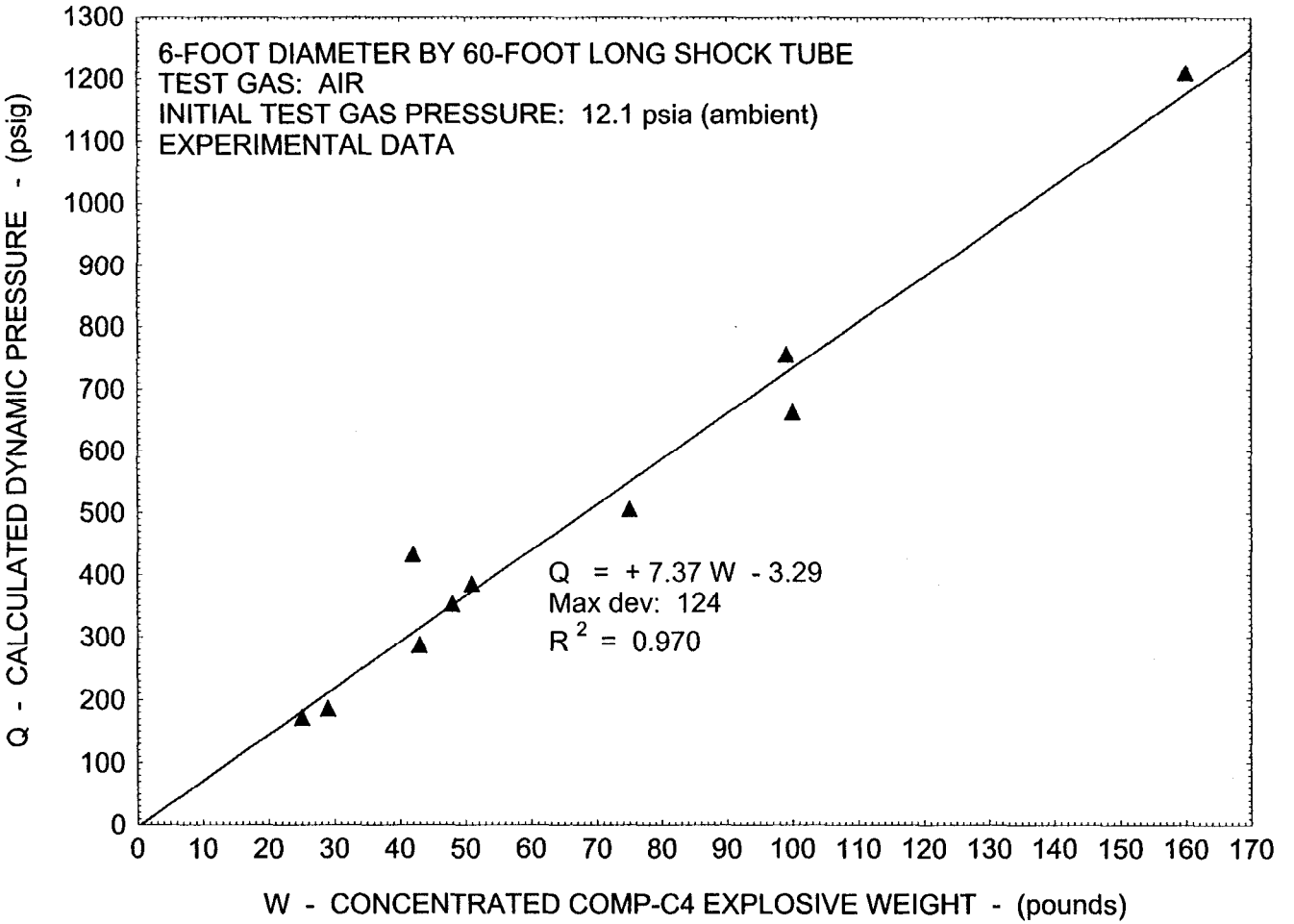

Figure 14. Dynamic pressure versus driver explosive weight

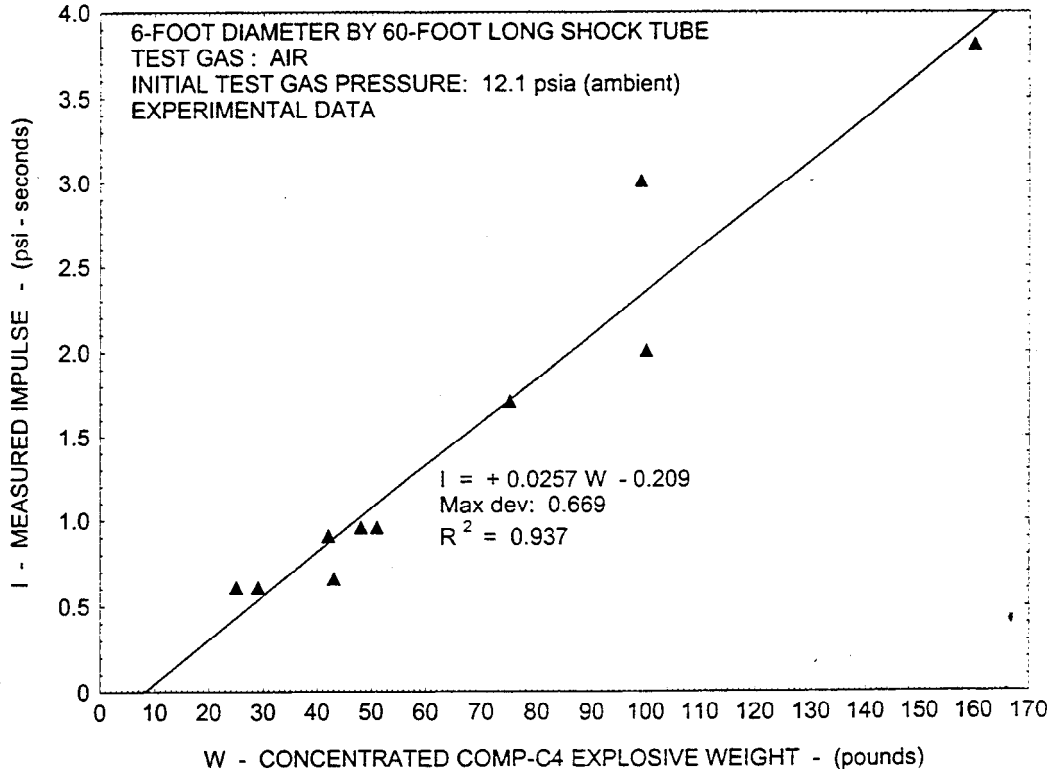

Figure 15. Impulse versus driver explosive weight

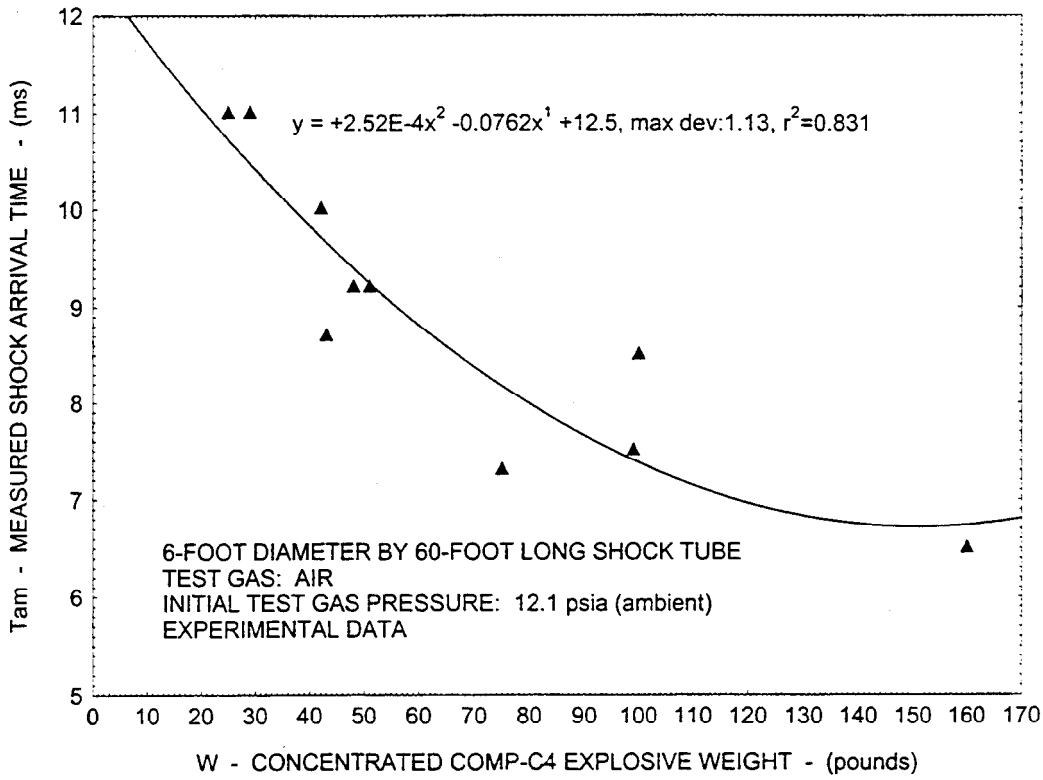

Figure 16. Measured shock arrival time versus driver explosive weight

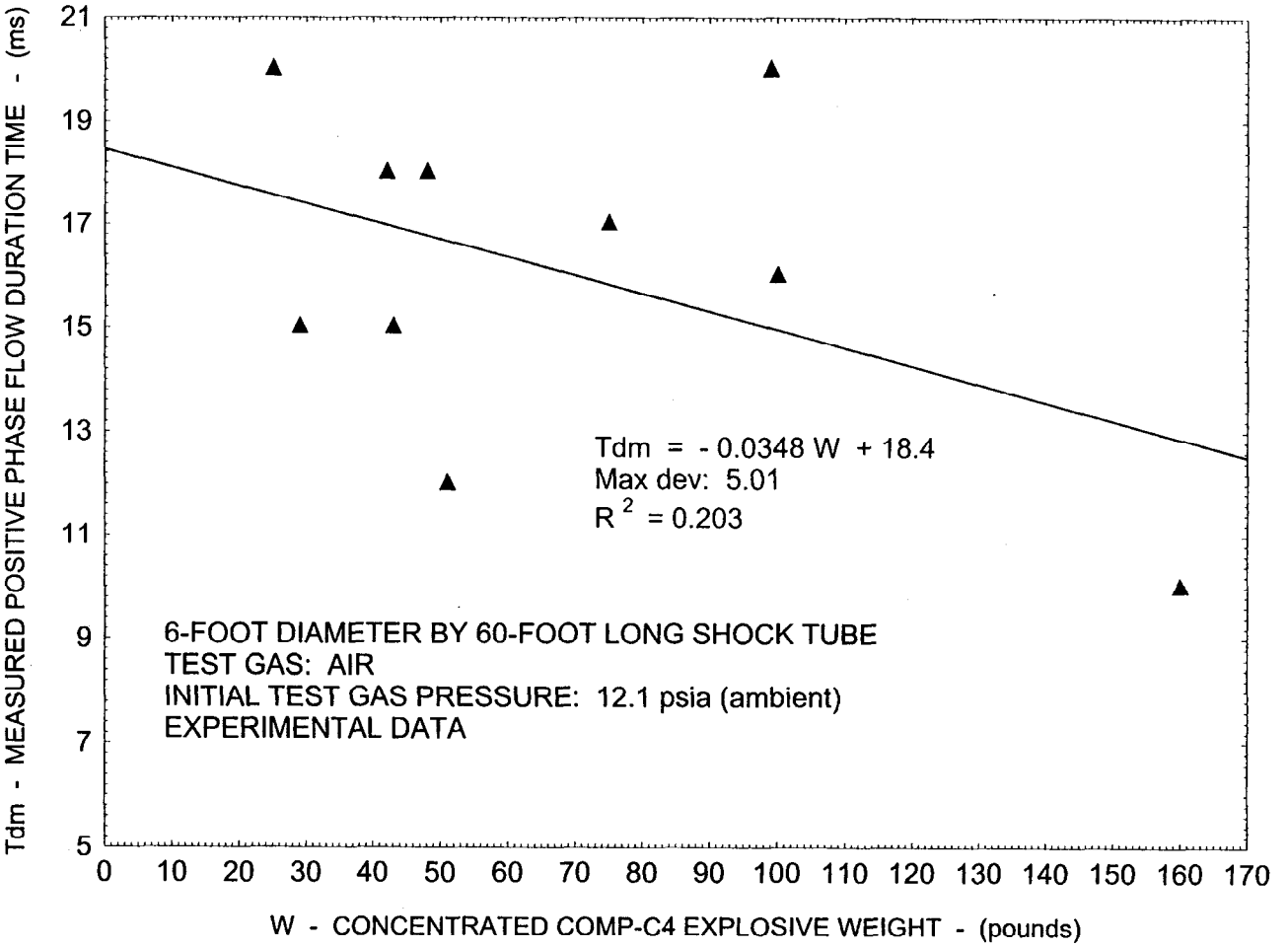

Figure 17. Measured positive phase flow duration time versus driver explosive weight

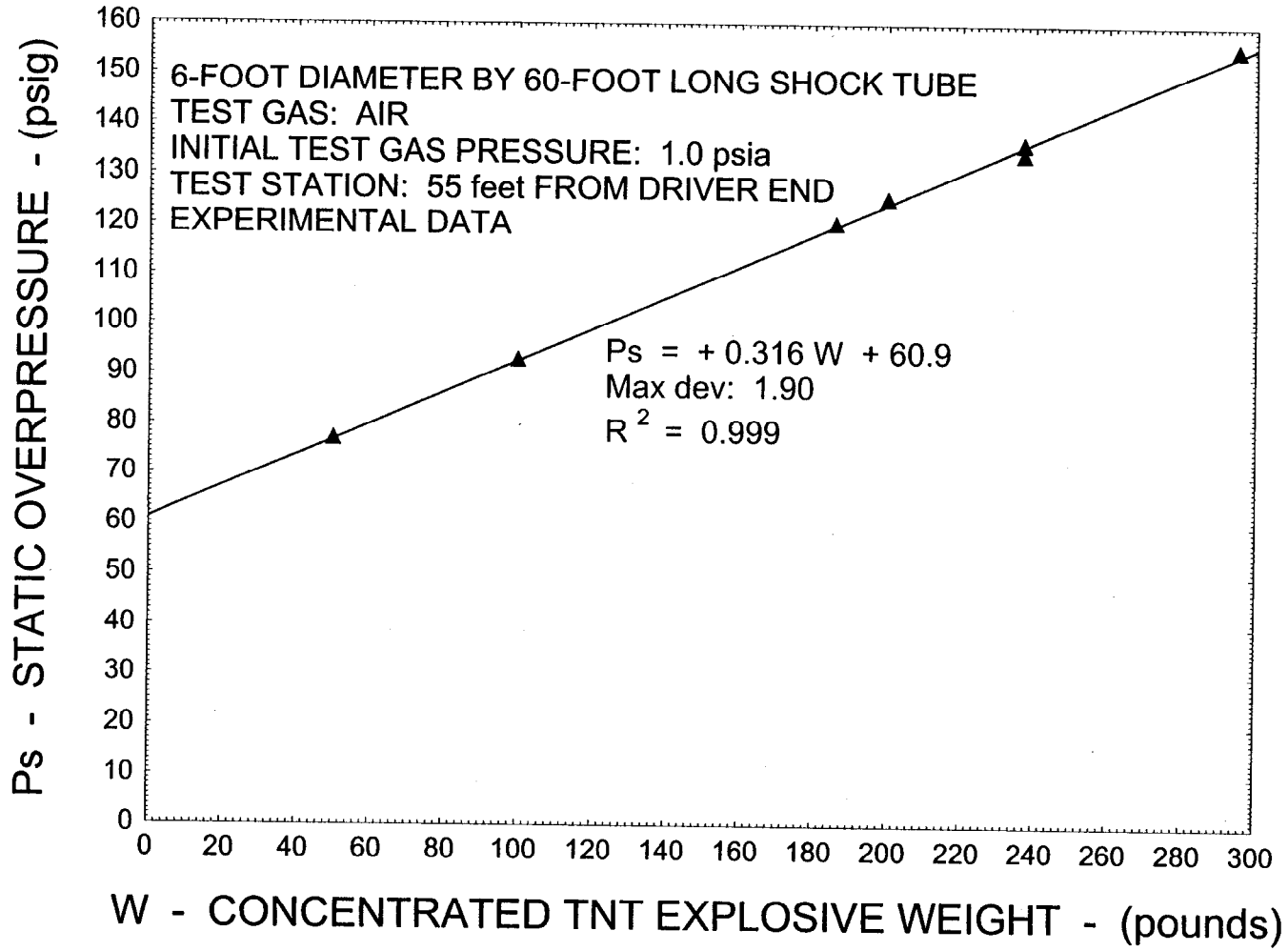

Figure 18. Measured static overpressure versus driver explosive weight/Po = 1 psia

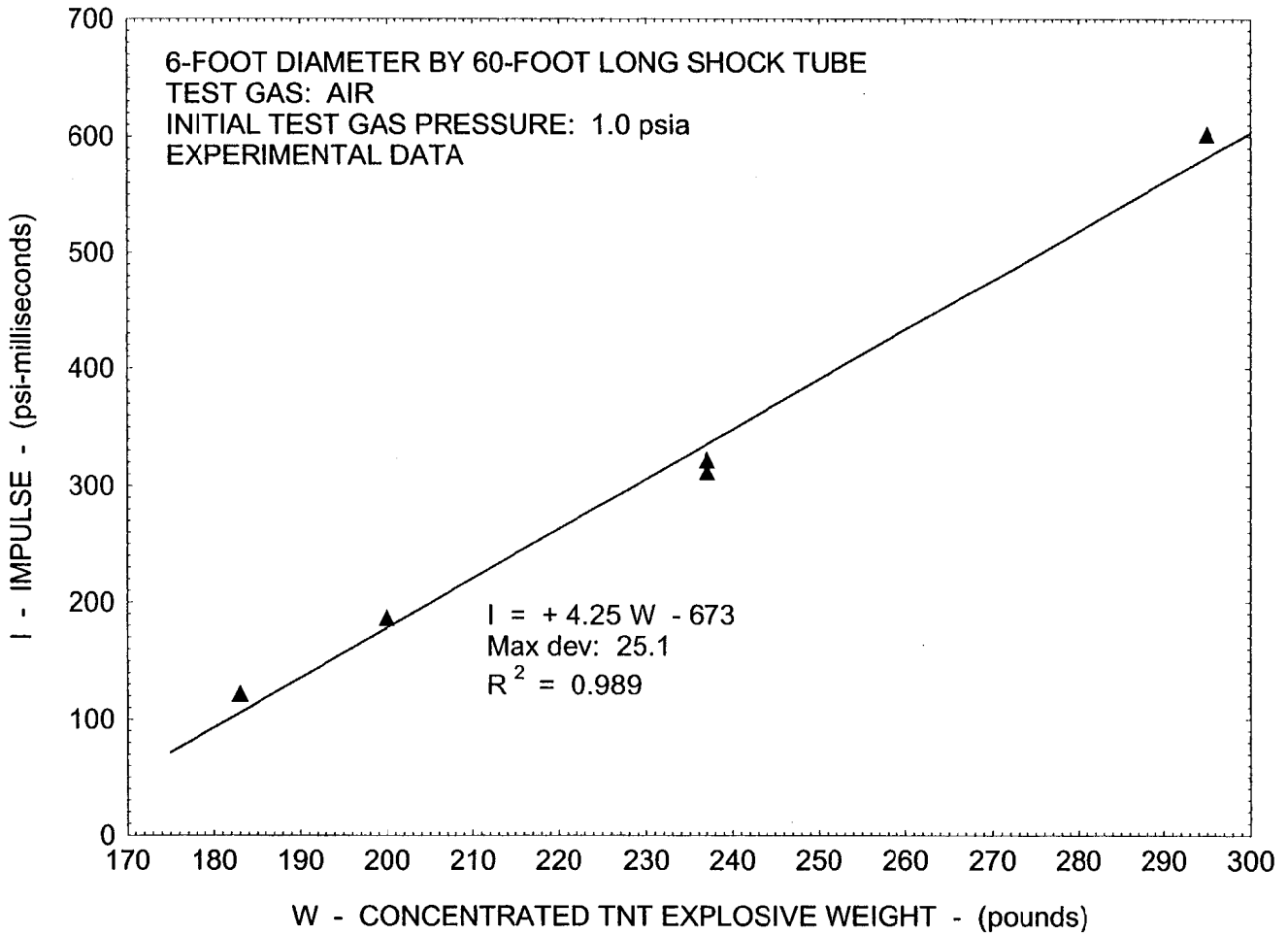

Figure 19. Measured impulse versus driver explosive weight/P0=1 psia

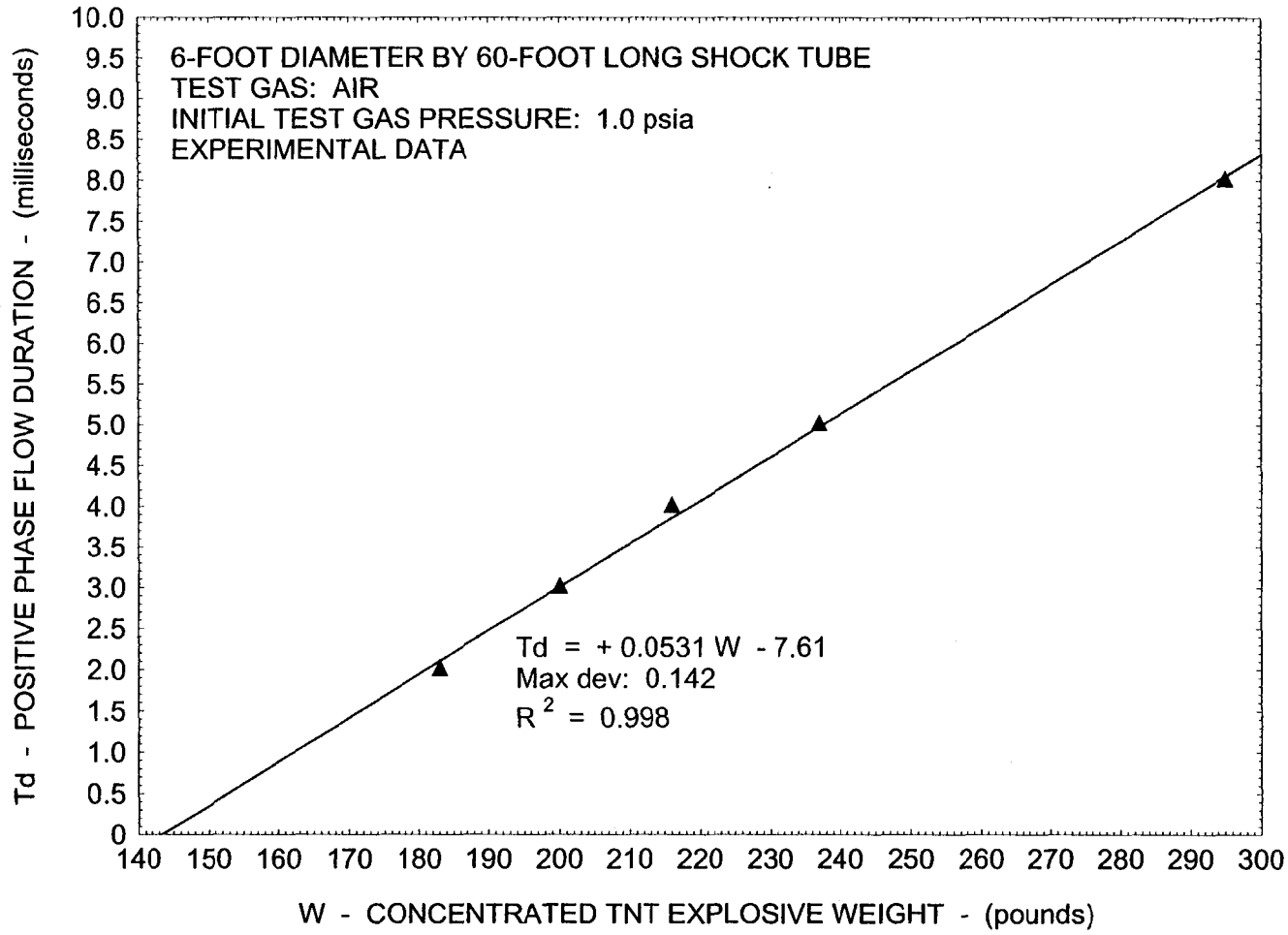

Figure 20. Measured positive phase flow duration versus driver explosive weight/Po=1 psia

Table 2. Measure and calculated blast parameters

TEST STATION: 58 feet
INITIAL TEST GAS PRESSURE: 12.1 psia (ambient)

TEST NO.	W (lb)	Pm (psig)	Prm (psig)	Psm (psig)	Q (psi)	Tam (ms)	Tdm (ms)	I (psi-Sec)	Co (FPS)
1	160	500	3400	2600	1208	6.5	10	3.8	1098
		500							
		550							
2	99	345	2580	1800	753	7.5	20	3.0	1117
		360	2970	1800					
		275							
3	75	200	2200	1500	503	7.3	17	1.7	1144
		2210							
4	43	125	950	680	284	8.7	15	0.65	1140
		126	1500	1250					
5	100	310		1400	660	8.5	16	2.0	1108
		275		1410					
		340							
6	48	195	1600	800	350	9.2	18	0.95	1153
		180	1150	950					
		185							
7	51	210	1100	1250	382	9.2	12	0.95	1149
8	29	140		500	183	11	15	0.60	1148
		135		500					
9	42	180	850	650	320	10	18	0.90	1133
		170	900						
10	25	120	500	425	169	11	20	0.60	1144
		123	650	450					
		135							

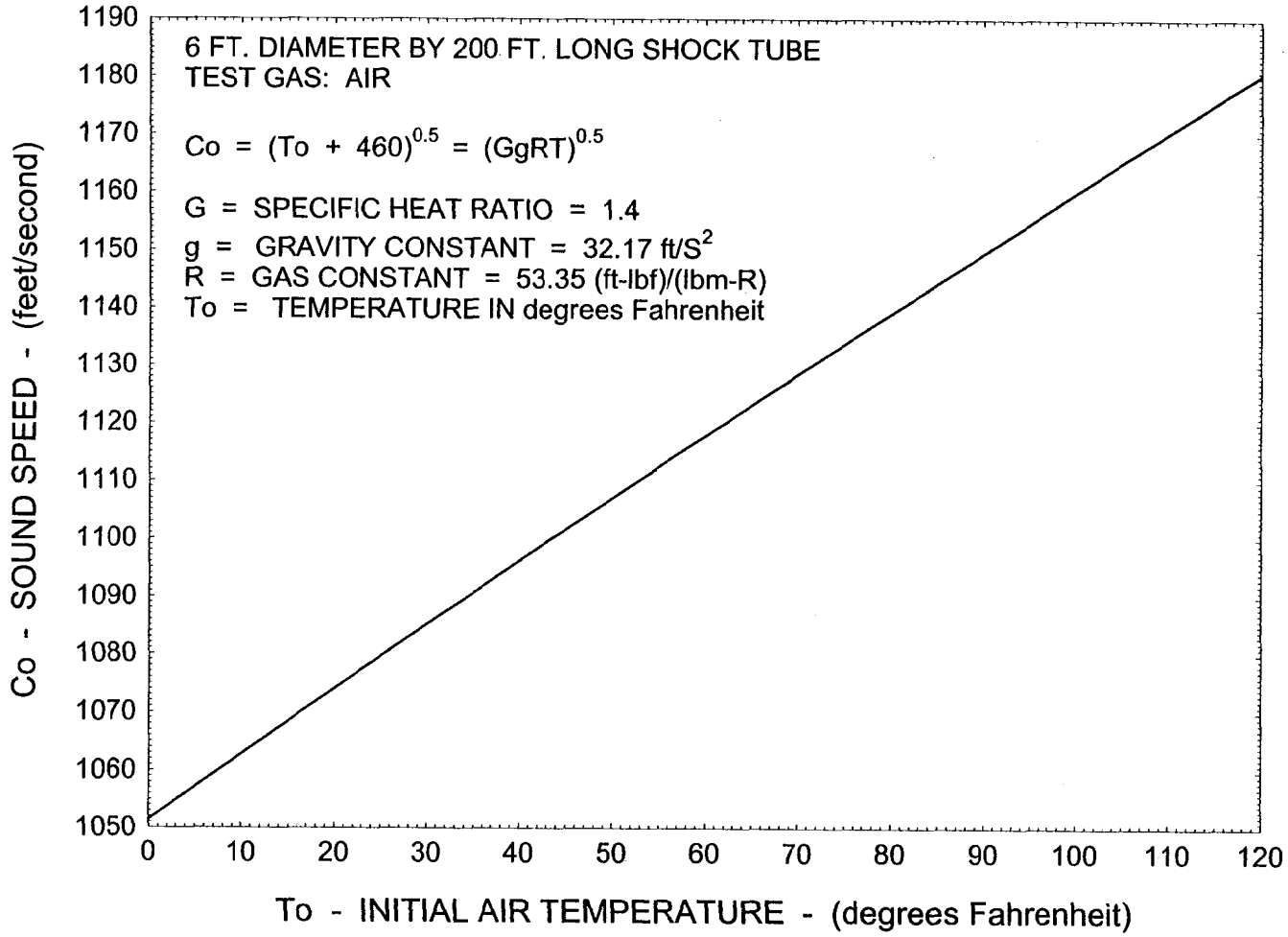

Figure 21. Calculated test gas sound speed versus initial test gas temperature

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.

11. Summary and Conclusions

Sandia National Laboratories (SNL) has developed a 6-foot diameter by 60-foot long, explosive driven shock tube for blast simulation on aerodynamic structures. Tailoring of the shock tube design and the test gas initial pressure will produce a wide range of load pulses. The 6-foot diameter by 60-foot long shock tube historical background, characteristics, and flow parameters have 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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5. Vigil, M.G., et.al., "Primacord Explosive-Driven Shock Tubes and Blast Parameters in Air, Sulferhexaflouride and Octofluorocyclobutaine (Freon C-318), 39th Shock and Vibrations Symposium, Pacific Grove, California, October 22-24, 1968.

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13. Vigil, M.G., et.al., "Sandia National Laboratories' 19-Foot Diameter Blast Simulator", Third International Symposium on Military Applications of Blast Simulators, Schwetzingen, Germany, September 19-21, 1972.

14. Vigil, M.G., "Calibration of Sandia Laboratories' 19-Foot Diameter Concentrated explosive Driven Blast Simulator," 19th Annual Technical Meeting of the Institute of Environmental Sciences, Anaheim, California, April 1973.

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Appendix A

Temporary Shock Tube/6.5 foot diameter by 40 foot long steel tube

Purpose

When desired pressures are too high for the use of permanent or re-usable blast tubes, temporary tubes can be used. These type blast tubes may be expended in one test or re-usable for a few tests. Common tube materials are plywood, cardboard, corrugated steel culvert pipe, and salvaged pipe from other government facilities. Temporary blast tubes have been used at Sandia National Laboratories since 1964.

Shock tube driver sections

All temporary shock tubes have used concentrated explosive charges of TNT, COMP-C4, IRAGEL, and Nitroguanidine. The shock tube lengths have varied between 40 and 90 feet.

Performance Data

As an example, the blast flow parameter for a 6.5 foot diameter by 40 foot long explosively driven shock tube are as follows:

Shock tube wall thickness: 0.32 inches
Test gas pressure: air
Initial test gas pressure: 12.1 psia (ambient)
Initial test gas temperature: 60 degrees Fahrenheit
Test or measurement station: 35 feet from explosive charge face
Explosive: TNT, Density = 1.5 g/cc
Explosive weight: 160 pounds

Shock velocity: 7346 feet/second
Shock mach no.: 6.6
Static overpressure: 550 psig (Figure A1)
Static impulse: 1.6 psig-seconds
Stagnation overpressure: 2750 psig (Figure A2)
Stagnation impulse: 4.8 psig-seconds
Reflected overpressure: 3450 psig (Figure A3)
Stagnation pressure, positive phase flow duration time: 4 milliseconds (to 10% of peak pressure)

The first 10 feet of the blast tube was damaged beyond reuse, but the remainder of the tube was reused.

Table 1A lists the shock parameters calculated from the measure time-distance data along the length of the shock tube. Table 2A lists the shock parameters calculated from the measure time-distance data along the length of the shock tube for a similar test in the same shock tube and for the following parameters:

Shock tube wall thickness: 0.32 inches
Test gas pressure: air
Initial test gas pressure: 12.1 psia (ambient)
Initial test gas temperature: 42 degrees Fahrenheit

Test or measurement station: 35 feet from explosive charge face
Explosive: TNT, Density = 1.5 g/cc
Explosive weight: 100 pounds

Shock velocity: 5701 feet/second
Shock mach no.: 5.2
Static overpressure: 311 psig

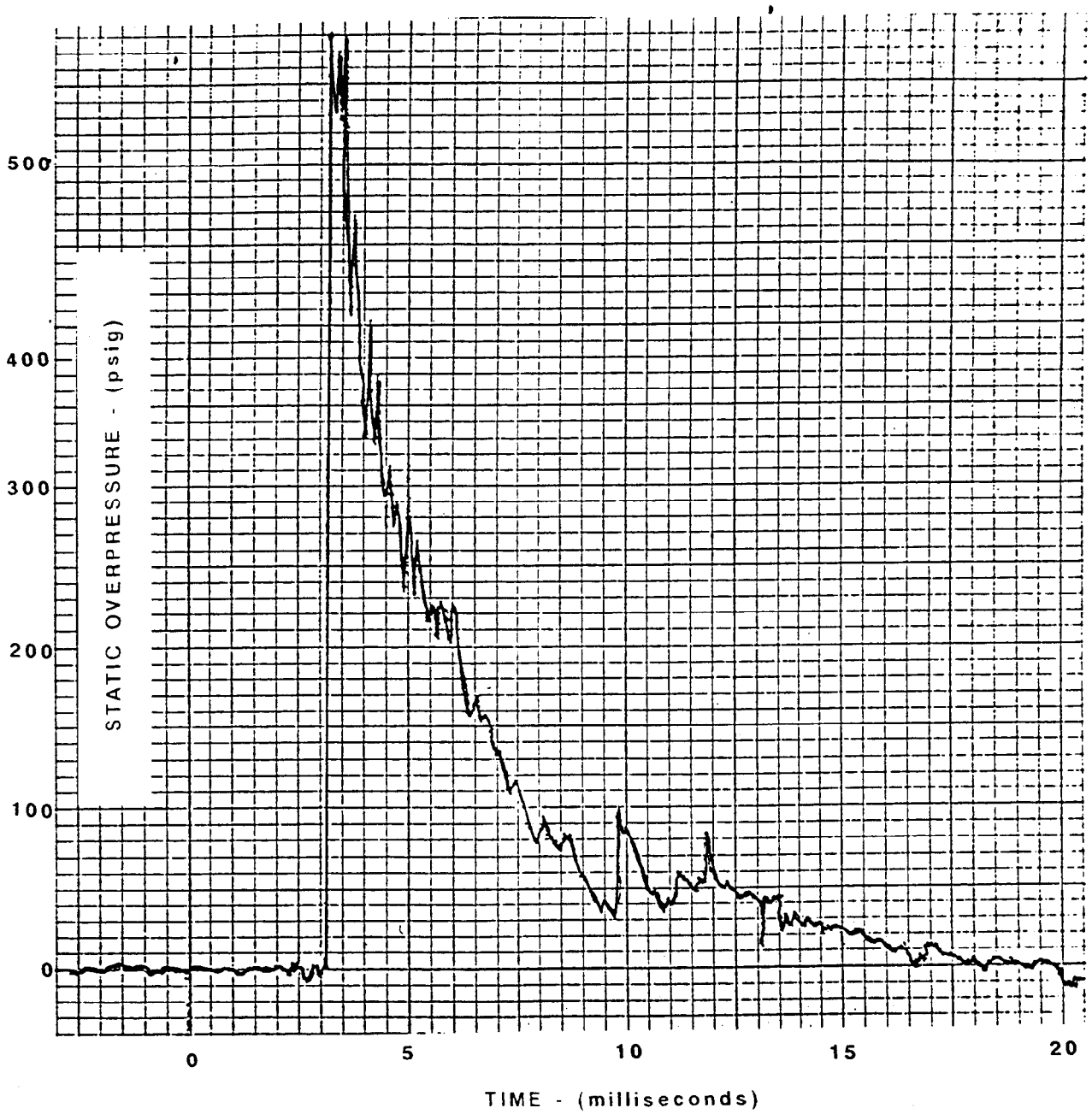

Figure A1. Measured static overpressure versus time/test station = 35.24 feet

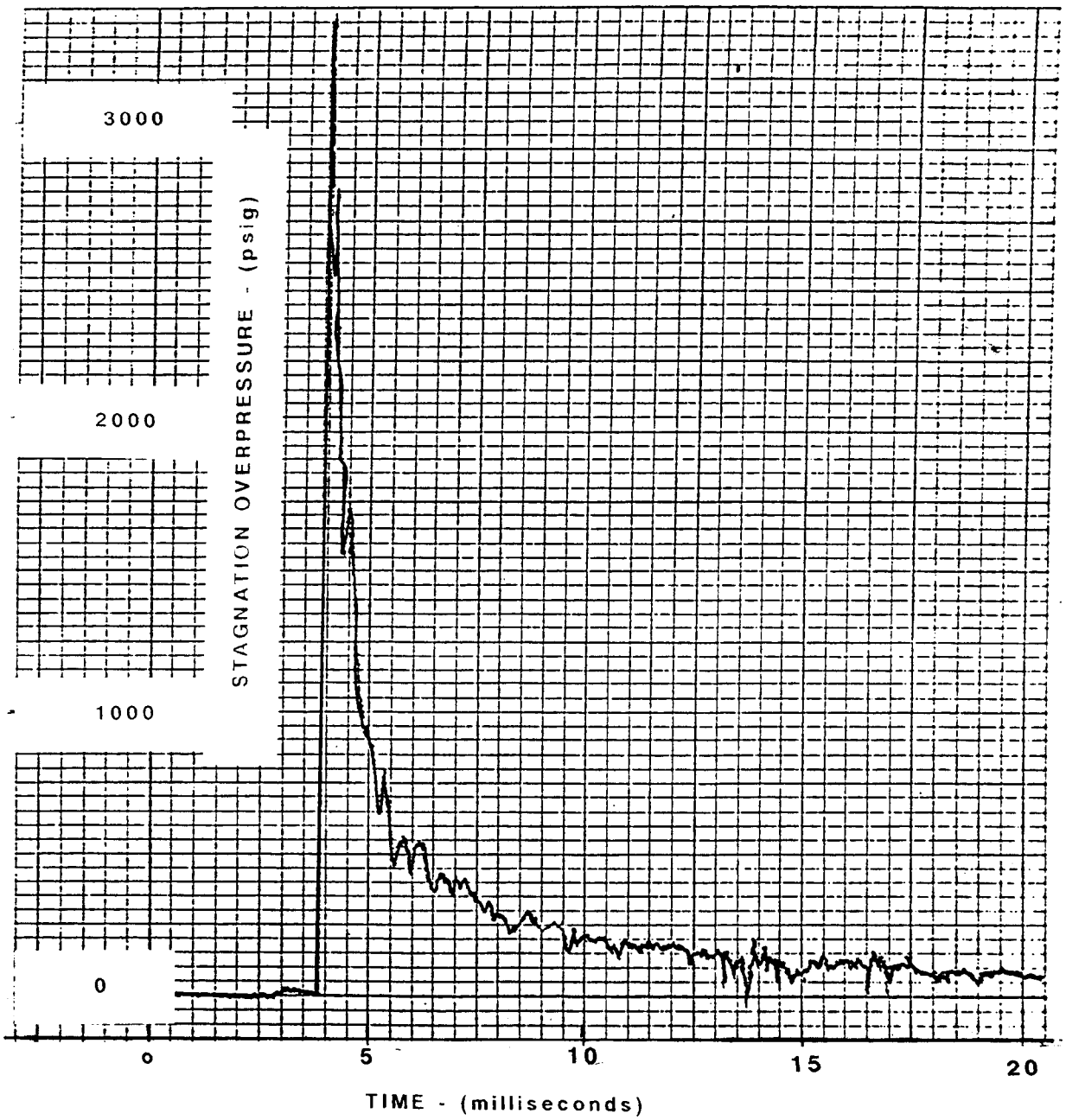

Figure A2. Measured stagnation overpressure versus time/test station 35.24 feet

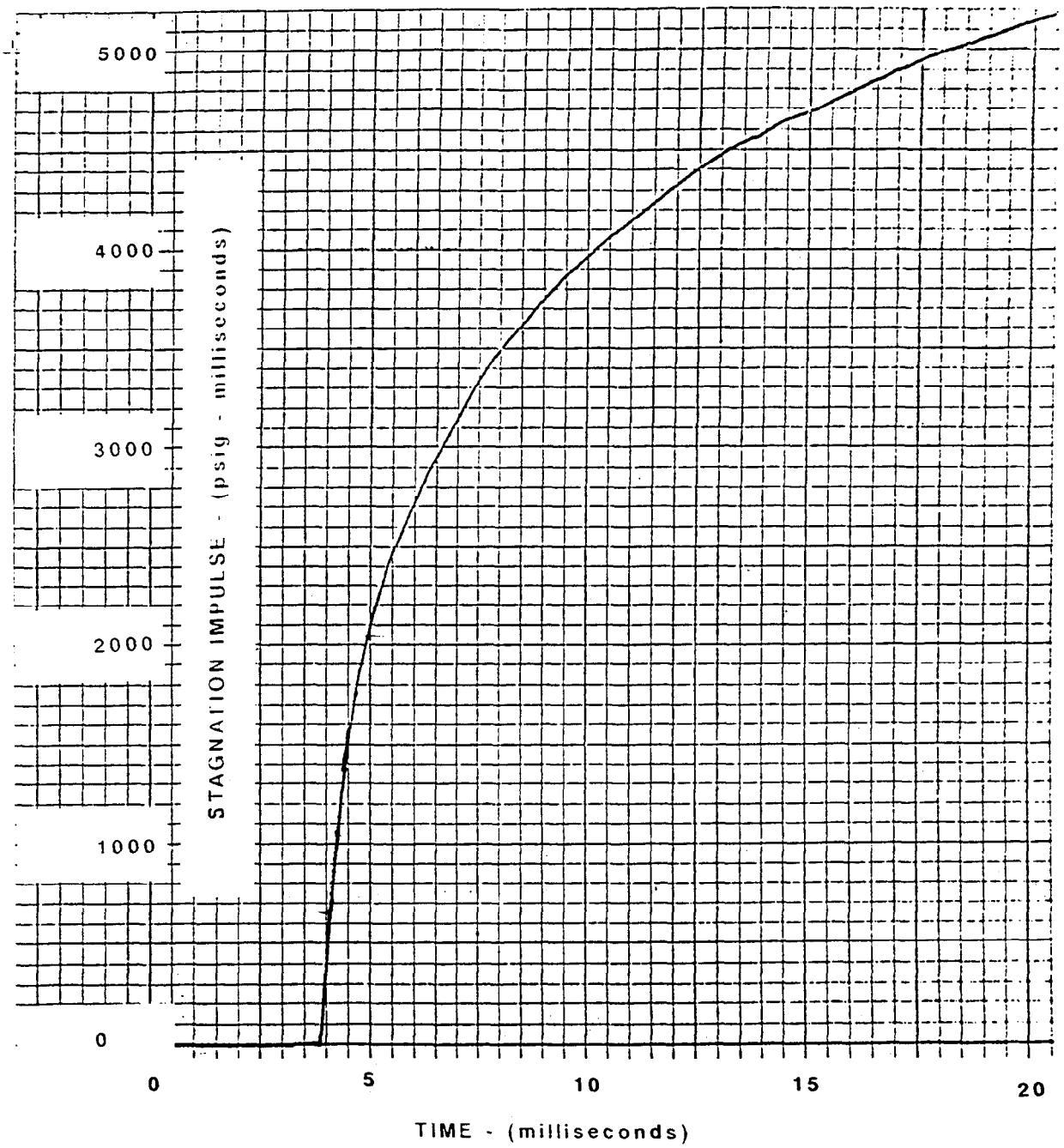

Figure A3. Measured stagnation pressure derived impulse versus time/test station 35.24 feet

Table 1A. Shock parameters calculated from measure time-distance data/160 lb TNT explosive

TEST NO.: E70-262, DATE: (10-19-70)
TEST GAS: AIR, 12.1 psia (ambient), T = 520 R, Co = 1120 FPS
DRIVER TAMPING: 1" STEEL PLATE + 25,000 lb CONCRETE BLOCK

X	T	Vs	Ms	Mf	Ps	Q	Ps/Po
(ft)	(ms)	(FPS)			(psia)	Psi	
5	0.318	9864	8.8	2.3	929	20	77
9	0.732	9484	8.5	2.2	861	18	71
13	1.162	9118	8.1	2.2	795	16	66
17	1.609	8767	7.8	2.2	732	14	61
21	2.074	8429	7.5	2.1	671	12	55
25	2.558	8104	7.2	2.1	612	11	51
29	3.062	7792	7.0	2.0	567	10	47
33	3.585	7492	6.8	2.0	526	9	43
35	3.855	7346	6.6	2.0	505	9	42
37	4.130	7203	6.4	2.0	486	8	40
39	4.41	7063	6.3	2.0	467	8	39

Table 2A. Shock parameters calculated from measure time-distance data/100 lb TNT explosive

TEST NO.: E70-279, DATE: (10-27-70)
TEST GAS: AIR, 12.1 psia (ambient), T = 502 R, Co = 1098 FPS
DRIVER TAMPING: 1" STEEL PLATE + 17,700 lb CONCRETE BLOCK

X	T	Vs	Ms	Mf	Ps	Q	Ps/Po
(ft)	(ms)	(FPS)			(psia)	Psi	
6	0.500	9070	8.3	2.2	814	17	67.8
10	0.954	8533	7.8	2.1	714	14	59.5
14	1.438	8019	7.3	2.1	620	12	51.7
18	1.953	7537	6.9	2.0	548	10	45.7
22	2.500	7084	6.5	2.0	484	8	40.4
26	3.083	6658	6.1	1.9	428	7	35.7
30	3.703	6257	5/7	1.9	374	6	31.2
32	4.027	6066	5.5	1.8	351	5	29.2
36	4.708	5701	5.2	1.8	311	5	25.9

Appendix B

Temporary Plywood Shock Tube/Square area by (40-136) foot long

Concentrated explosive charge, plywood shock tubes were used for tests requiring very high overpressure, short flow duration or impulse blast parameters. Table B1 lists some plywood shock tube parameters. For the algorithms documented in reference 6:

$X = [x(Po/Por)] / Wr$
$T = \{t[(ao)/(aor)] [Po/Por]\} / Wr$

Where: $Wr = [(W/A)/(W/A)_r]$
Po = Initial test gas pressure
Por = Reference initial test gas pressure = 1.0 psia
$(W/A)_r$ = Reference explosive to shock tube area ratio = 7.08 lb/ft^2
aor = Reference test gas sound speed = 1123.2 FPS

For Po = 12.1 psia (ambient) = Initial test gas pressure
$X = [(85.67) (A) (x)]/W$ = Scaled distance for any shock tube cross-section (A)
And, $T = [(0.0763) (a0) (A) (t)]/W$ = Scaled time for any shock tube cross-section (A)

Where: A = Shock tube area,
W = Explosive weight,
x = Actual distance,
t = Actual time

The above scaled X and T values are listed in Table 1. The measured time (t) and distance (x) values used to calculate the above scaled X and T values are shown graphically in Figure B1 for all tests listed in Table 1.

The X and T values were used to calculate the flow Mach number (Ms) as follows: The X-T data shown in Figure B1 were least squares fitted to the power-law equation below:

$$T = 0.0000237 (X)^{1.2437}$$

The shock velocity (Vs) is given by:

$$Vs = (dX/dT) = (4199.741) / [T^{(0.196)}]$$

The shock Mach number is given by:

$$Ms = Vs/aor = Vs/1123.3$$

Therefore,

$$Ms = 3.739 / [T^{(0.196)}]$$

The shock Mach number (Ms) is shown in Figure B2 versus scaled distance (X). The Rankine-Hugoniot relations for conditions across the shock front were used to calculate the shock strength or static to initial test gas pressure ratio. Figure B3 shows the shock strength versus scaled distance (X). Figure B4 shows the calculated stagnation to static pressure ratio versus scaled distance (X).

The data of Figures B1 through B4 can be used to scale the concentrated shock tube flow parameters to any desired shock tube cross-section, explosive weight, initial test gas pressure, etc.

Table B1. Plywood shock tube parameters

TEST NO.	H.E. WEIGHT (lb)	H.E. TYPE	DIM. (ft)	LENGTH (ft)	Co (FPS)	X (ft)	T (ms)
64-220-9	280	CYCLOTOL	2 x 2	96	1121	1.224x	1.22t
64-220-7	560	CYCLOTOL	2 x 2	96	1115	0.612x	0.608t
64-220-3	280	CYCLOTOL	2 x 2	96	1150	1.224x	1.254t
64-220-4	280	CYCLOTOL	2 x 2	96	1136	1.224x	1.238t
64-220-5	280	CYCLOTOL	2 x 2	136	1100	1.224x	1.20t
64-220-10	1160	CYCLOTOL	4 x 4	96	1119	1.182x	1.18t
64-191	790	TNT	6.5 x 6.5	40	1135	3.90x	3.95t
64-213	220	TNT	6.5 x 6.5	60	1143	1.40x	1.427t
64-239	220	TNT	6.5 x 6.5	65	1122	1.40x	1.40t

X = [(85.67) (A) (x)]/W = SCALED DISTANCE
T = [(0.0763) (a0) (A) (t)]/W = SCALED TIME
Where:
A = SHOCK TUBE AREA, W = EXPLOSIVE WEIGHT,
x = ACTUAL DISTANCE, t = ACTUAL TIME
H.E. = HIGH EXPLOSIVE (SECONDARY EXPLOSIVE)
DIM. = SHOCK TUBE CROSS-SECTION DIMENSION

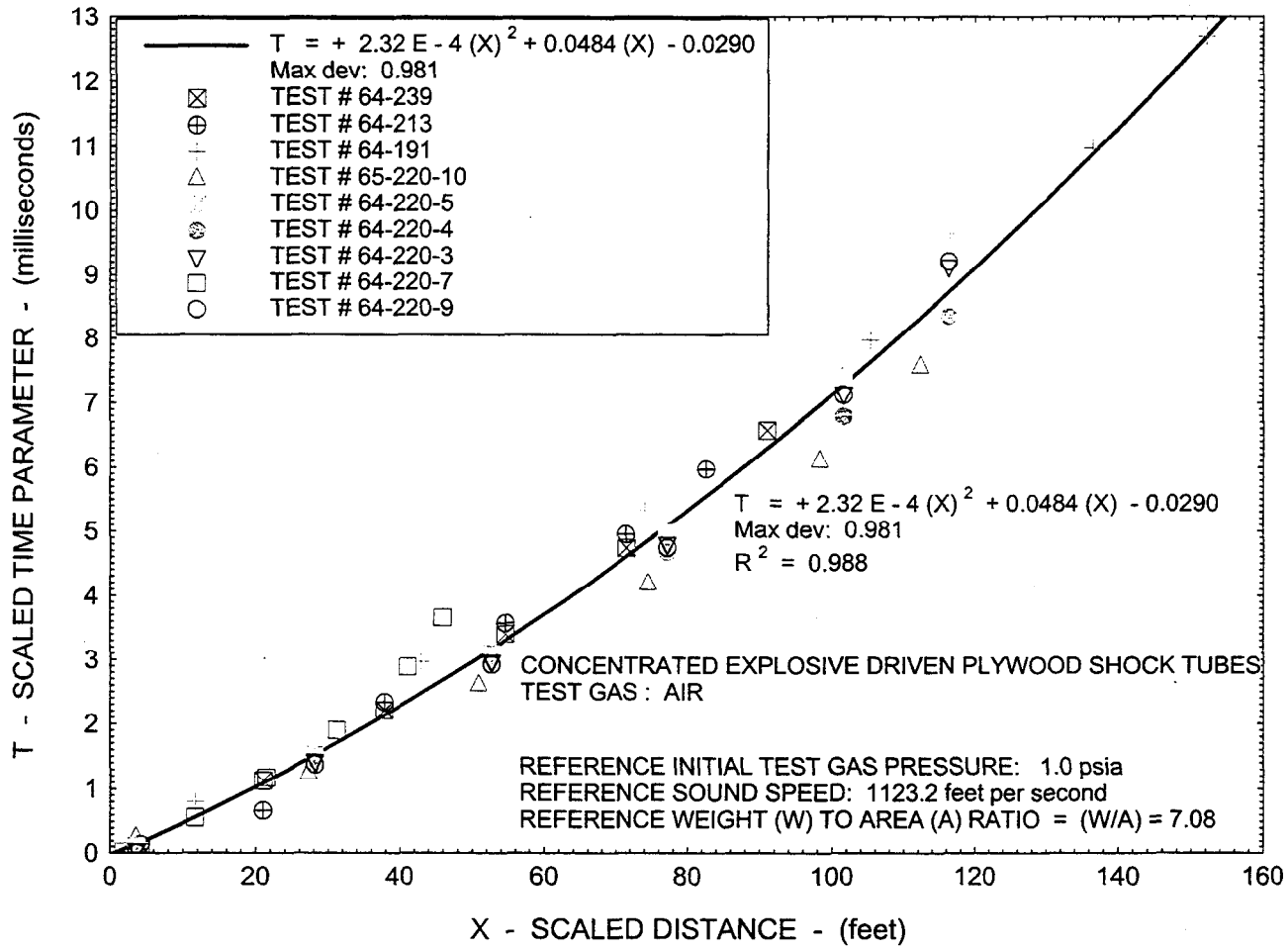

Figure B1. Scaled time versus scaled distance

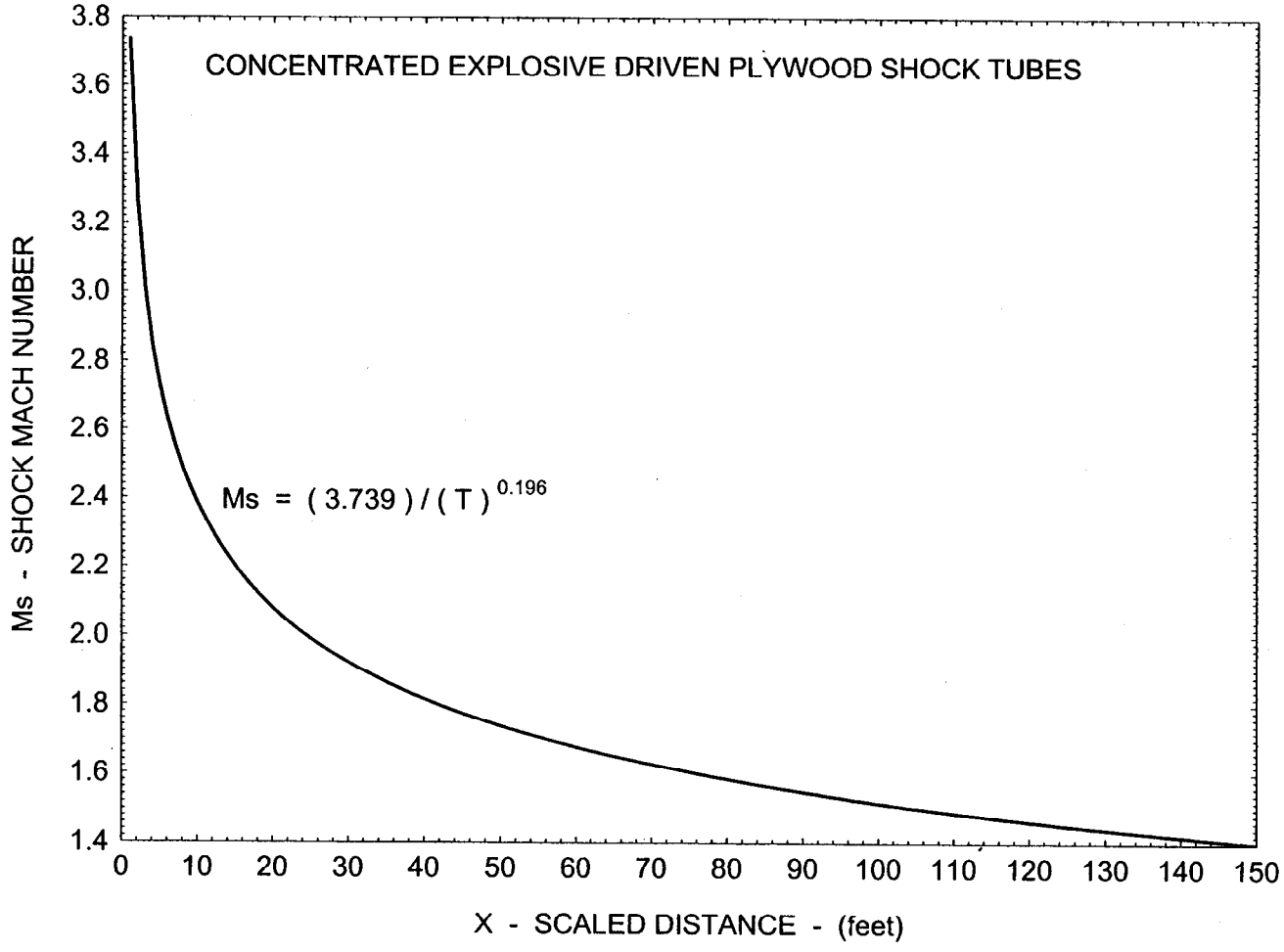

Figure B2. Shock Mach number versus scaled distance

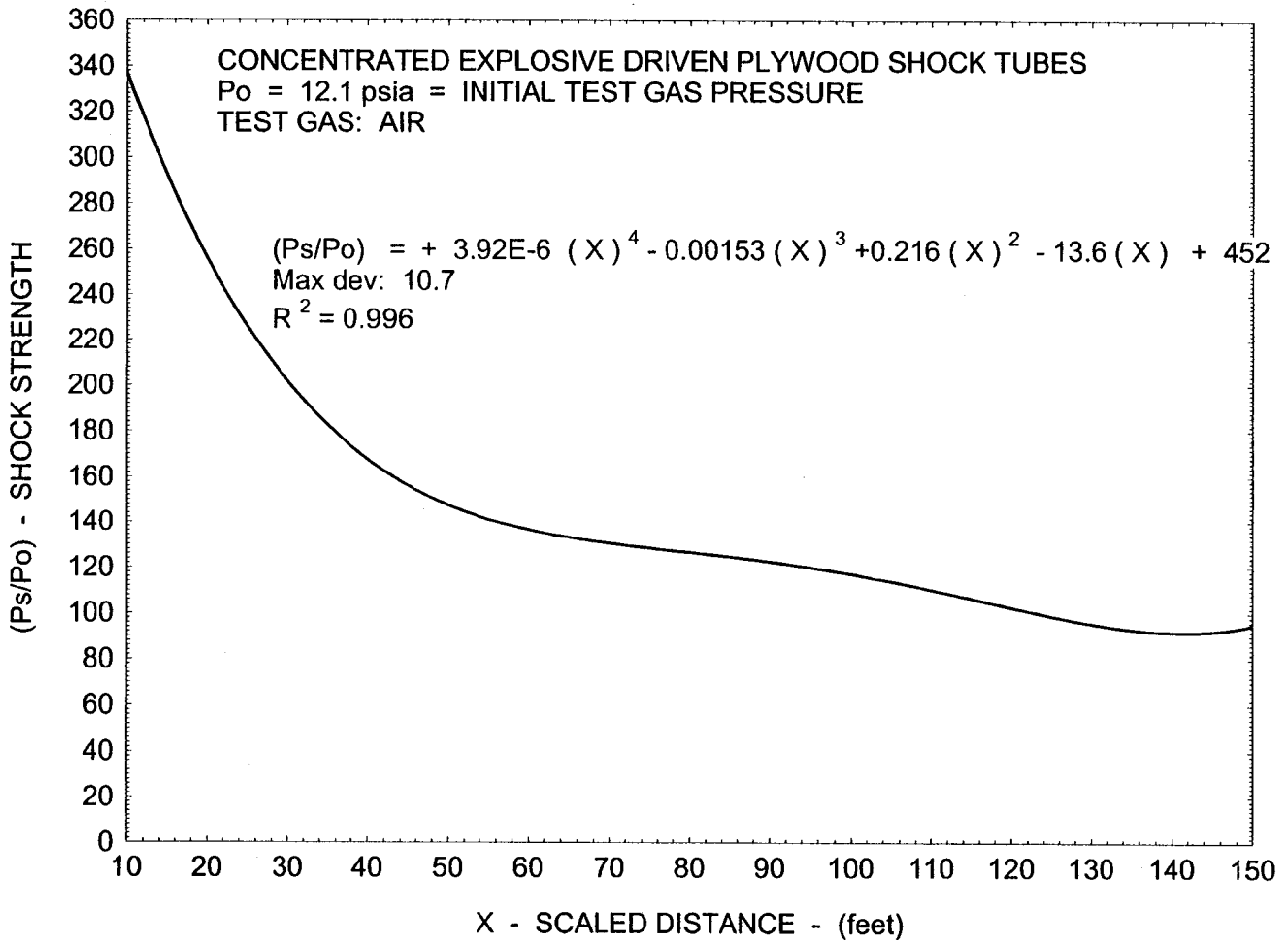

Figure B3. Static pressure to initial test gas pressure versus scaled distance

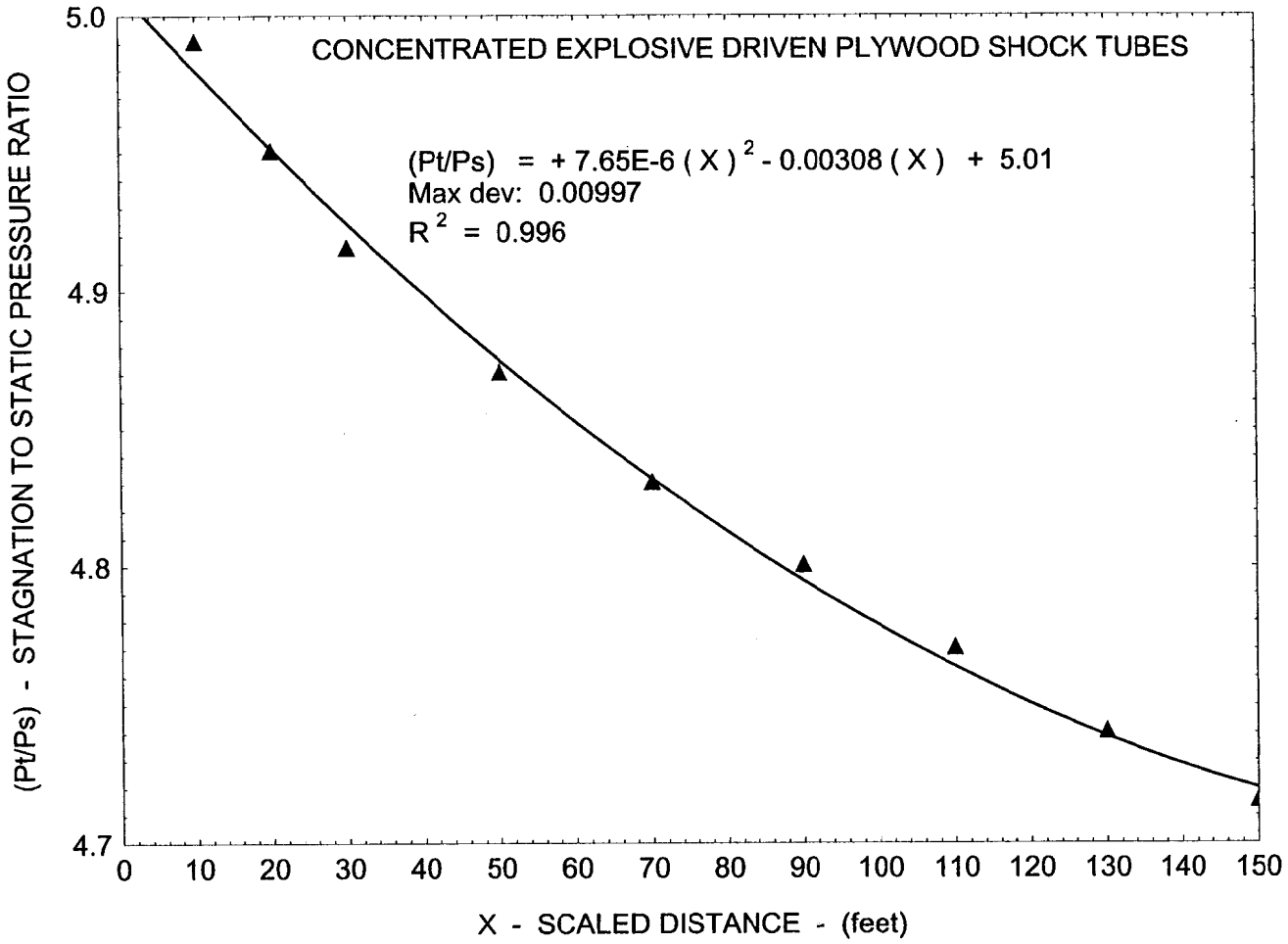

Figure B4. Stagnation pressure to static pressure ratio versus scaled distance

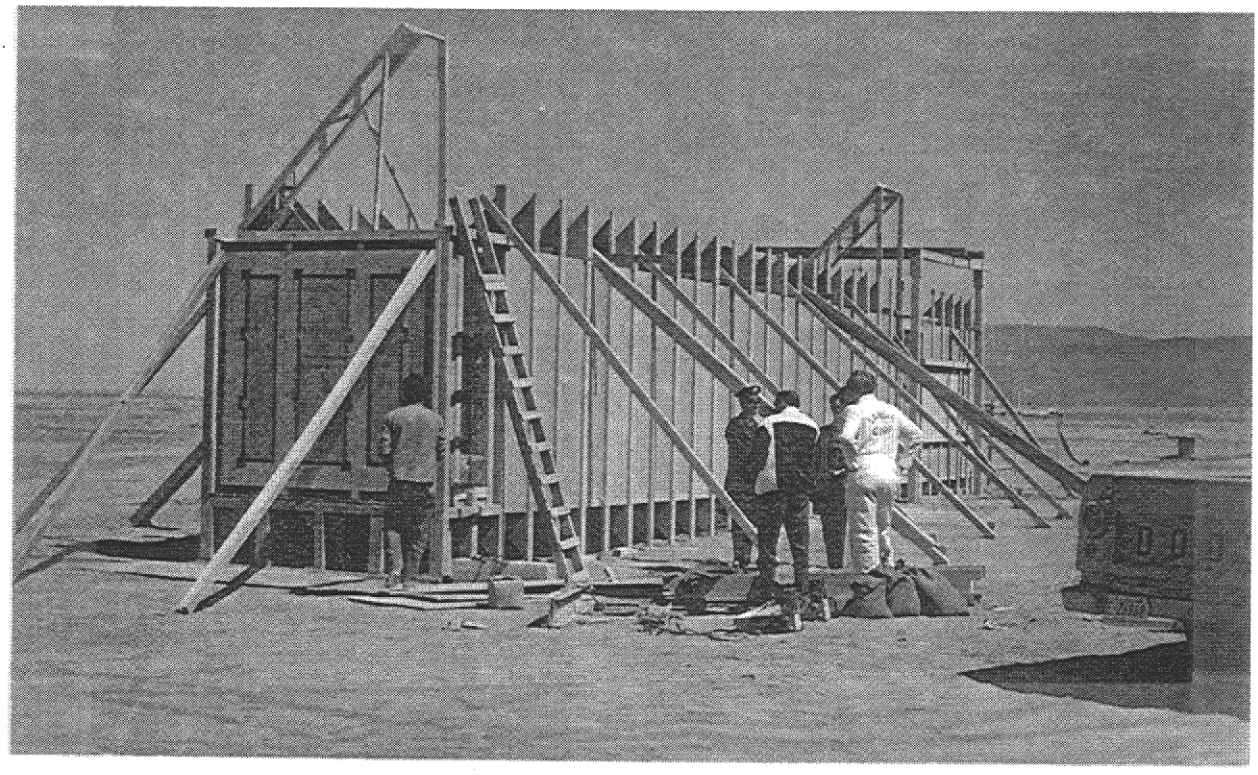

Figure B5. Plywood Shock Tube Configuration (6.5 X 6.5 X 60 ft. Long)

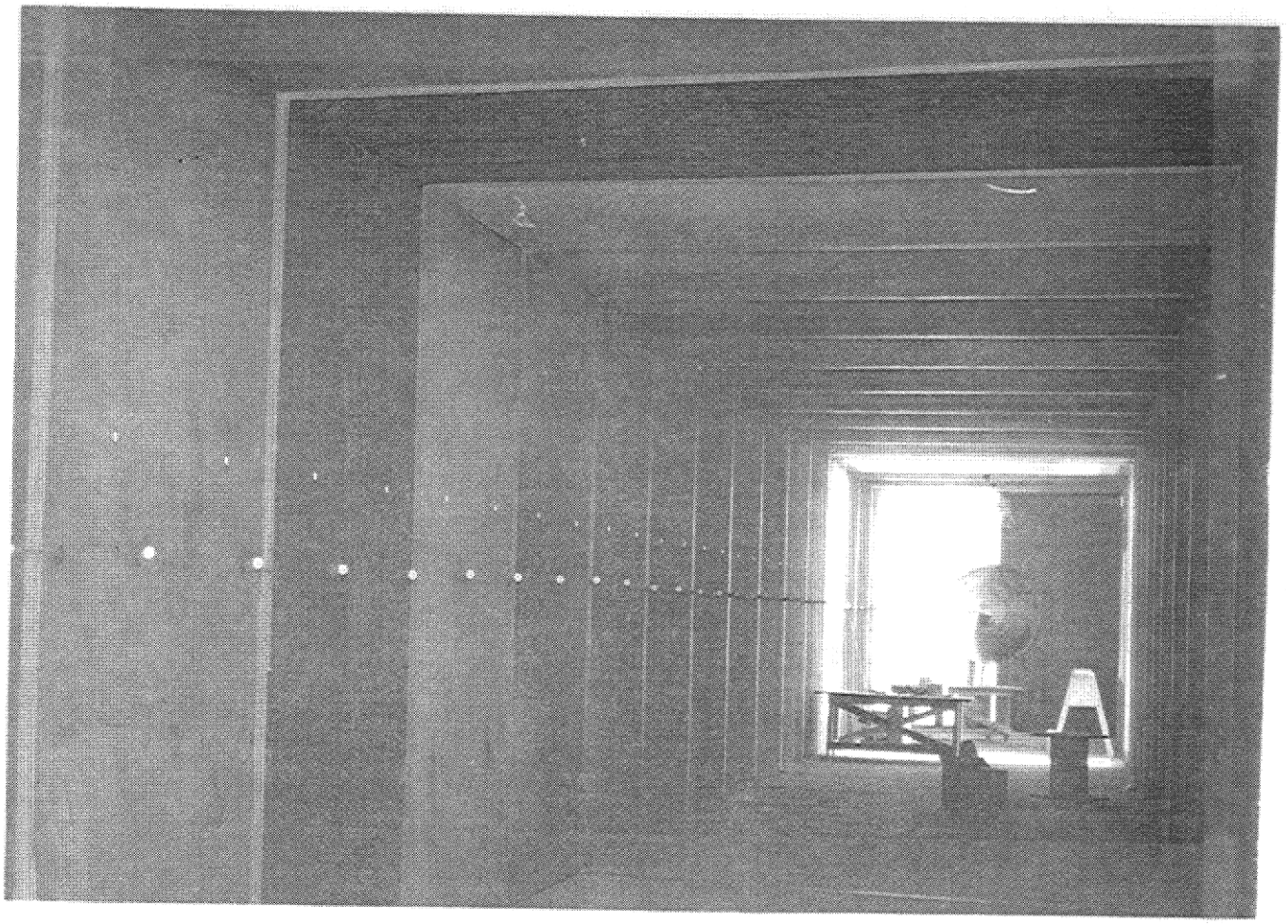

Figure B6. Conical Unit in Test Section of Plywood Shock Tube

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Appendix C

Rankine-Hugoniot shock parameters

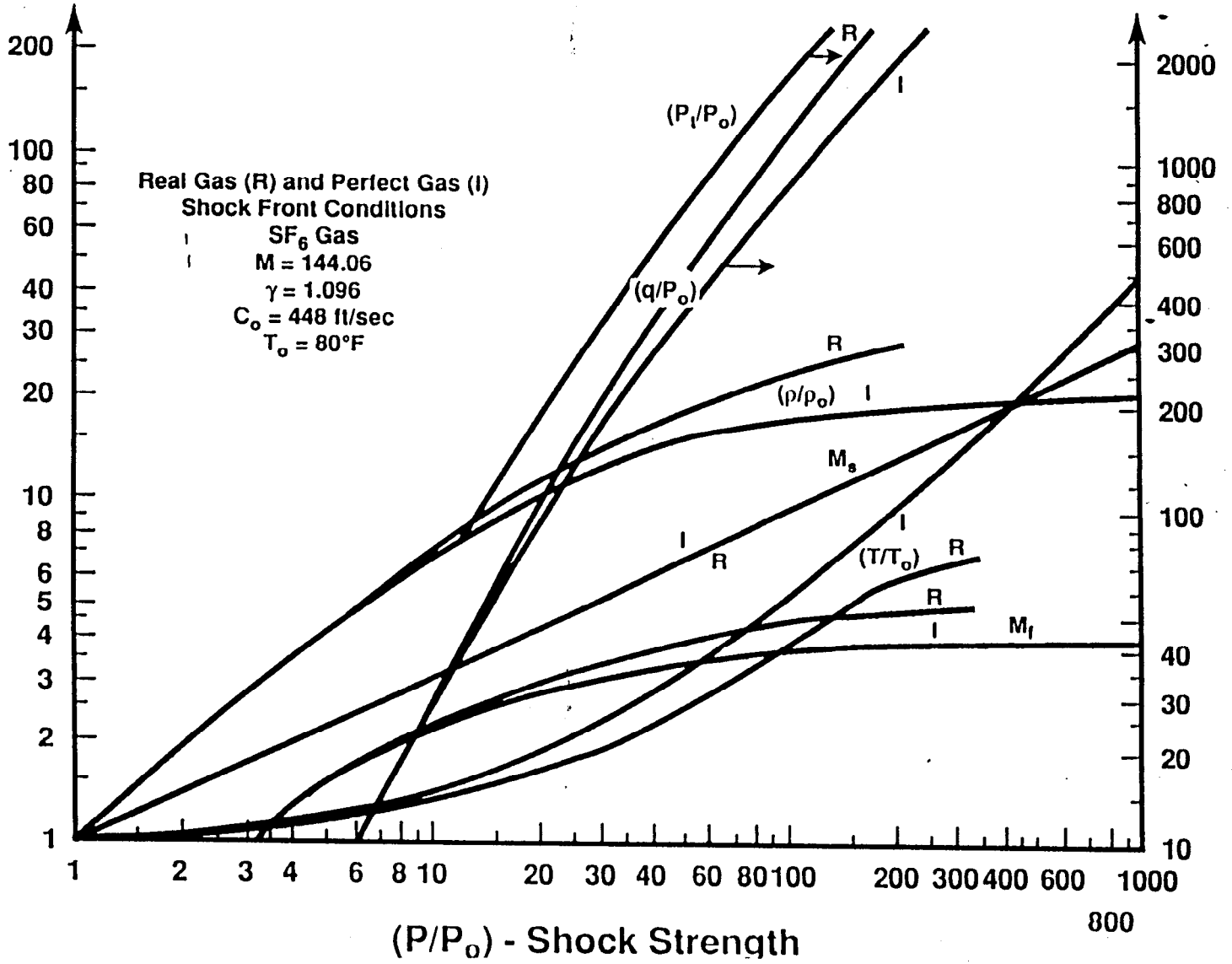

Figure C1. Real and perfect gas parameters versus shock strength

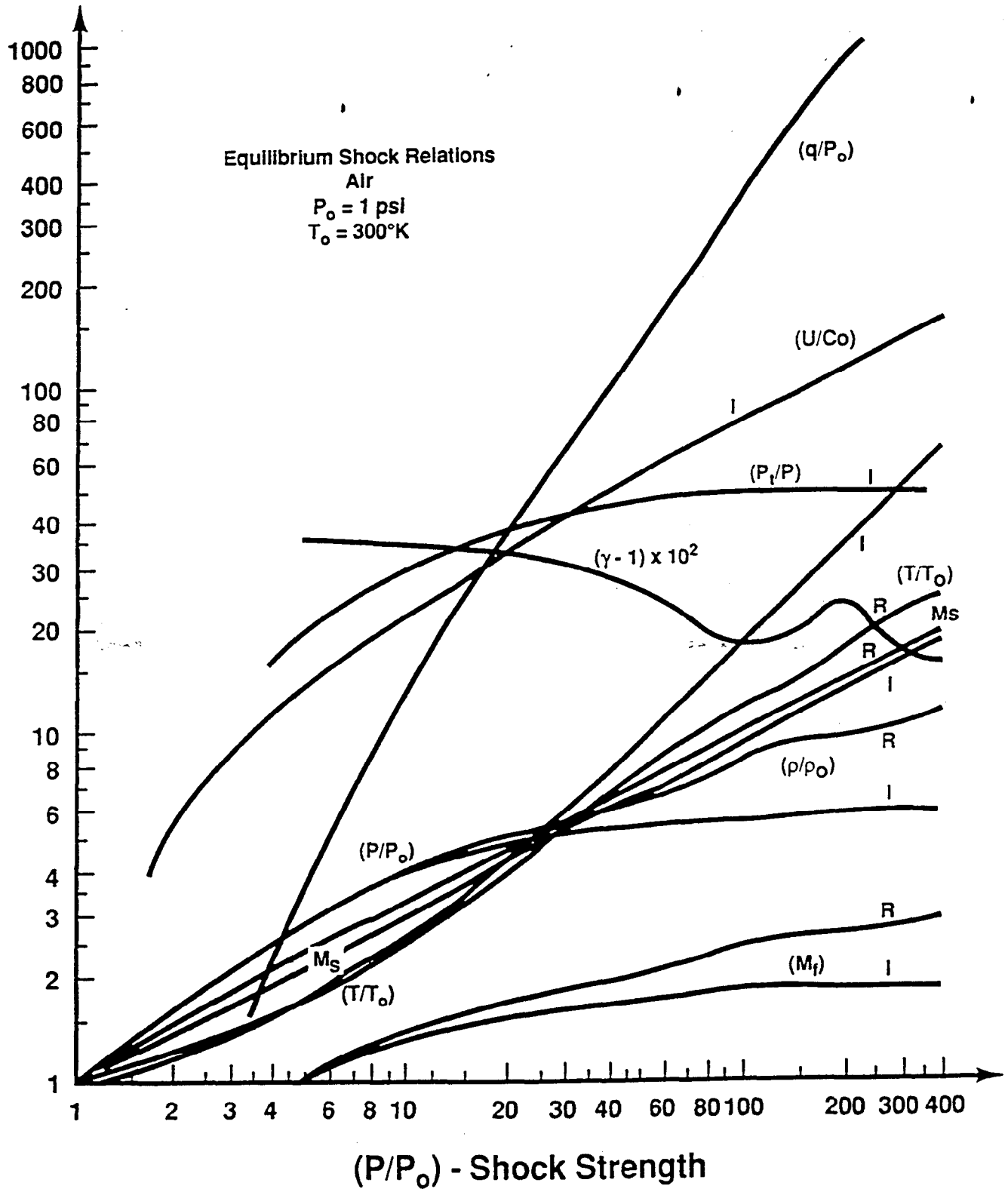

Figure C2. Equillibrium shock relations versus shock strength

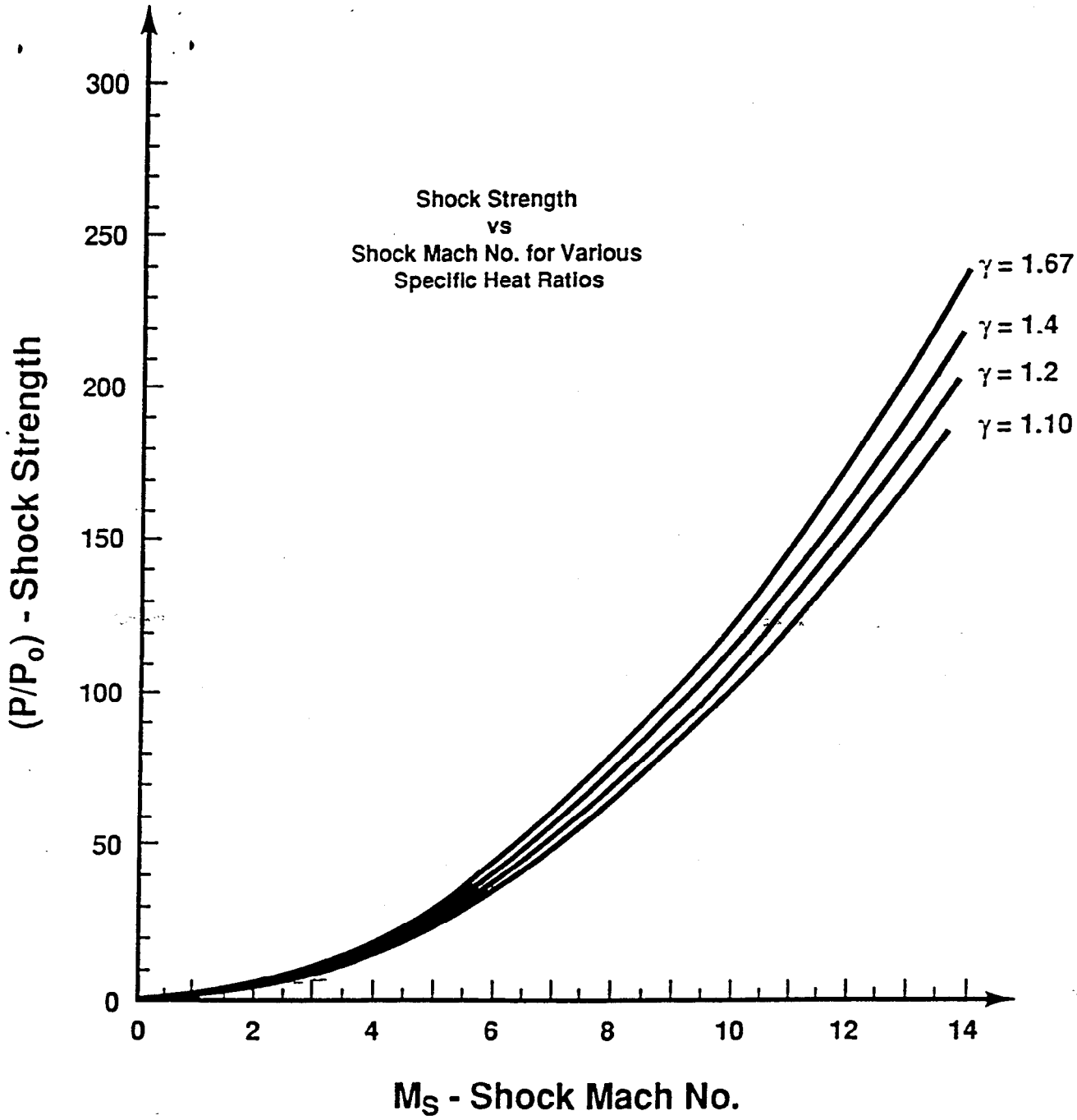

Figure C3. Shock strength versus shock mach number and specific heart ratio

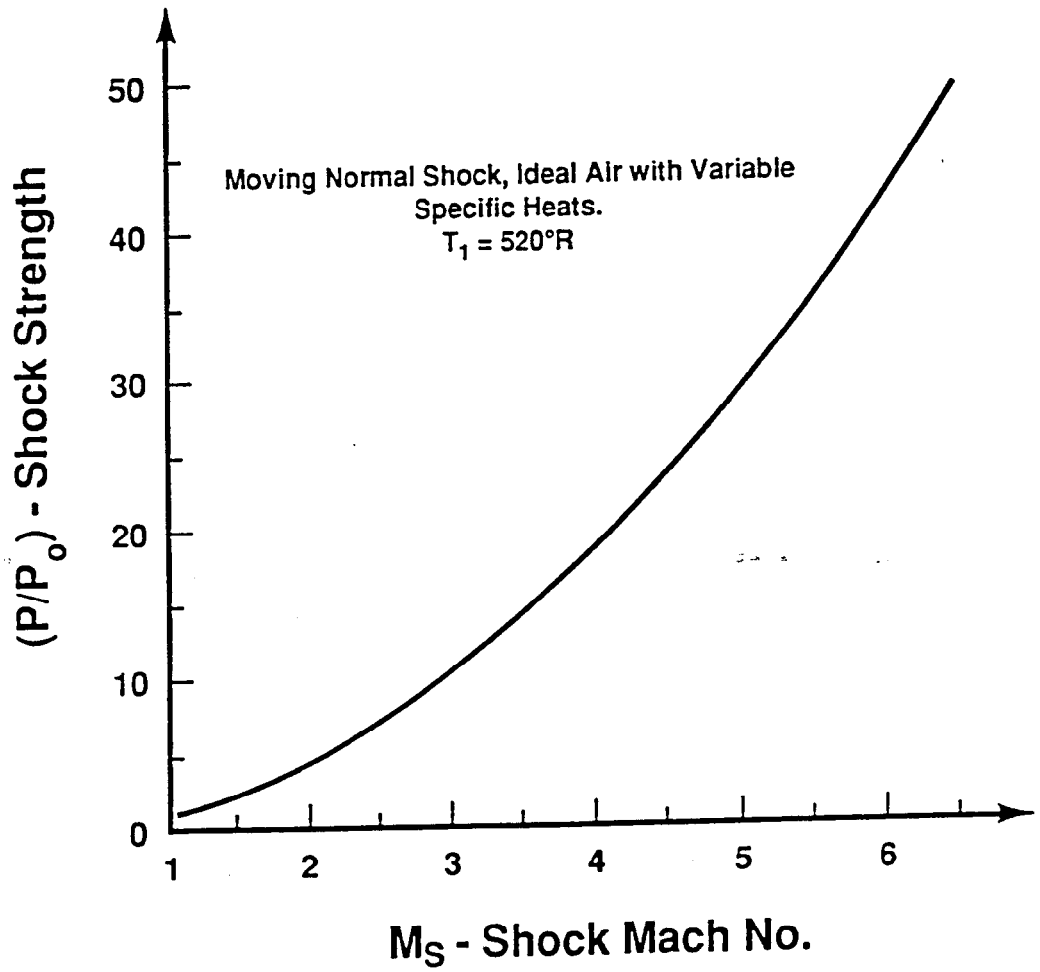

Figure C4. Shock strength versus shock mach number

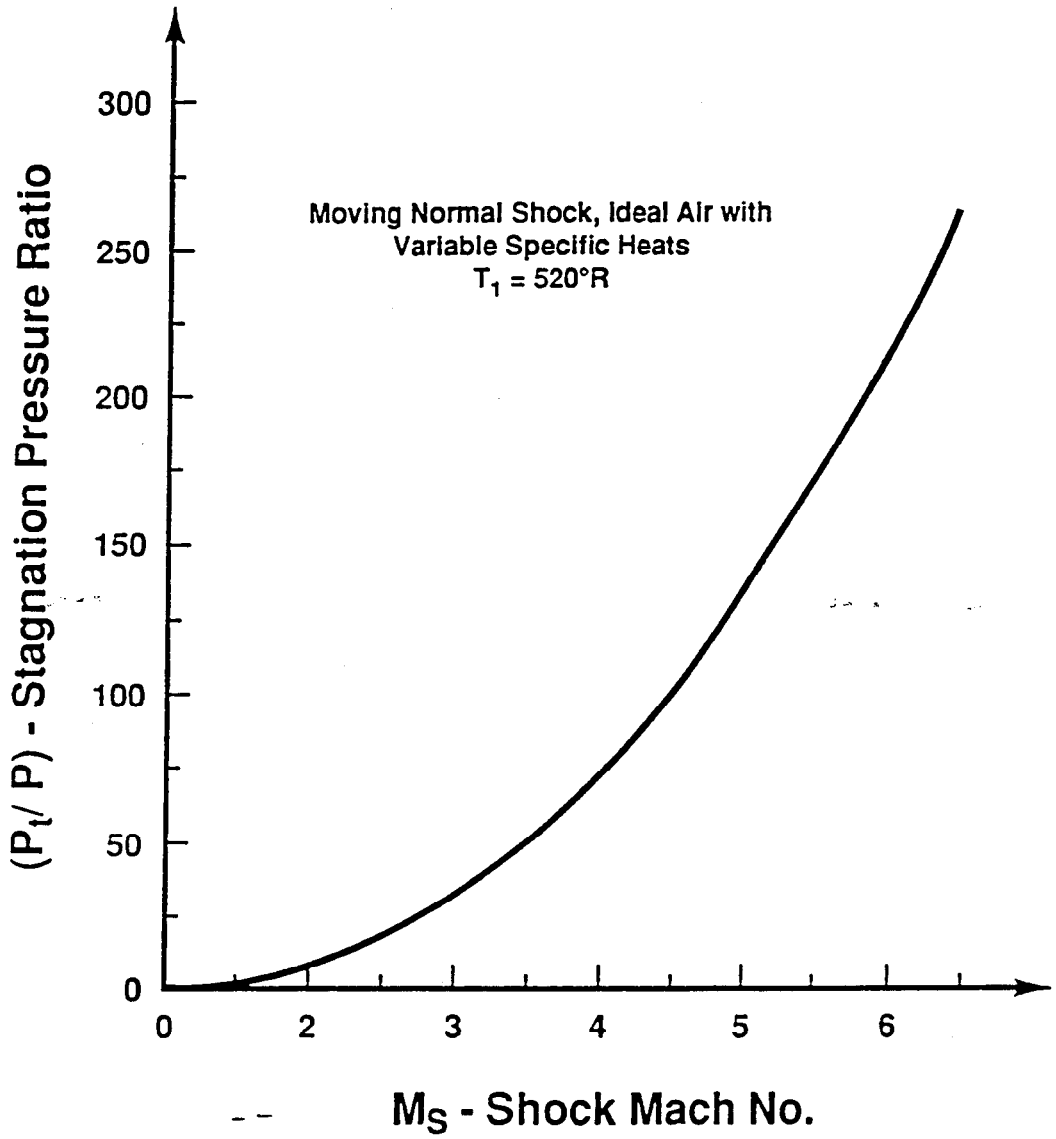

Figure C5. Stagnation pressure ratio versus shock mach number

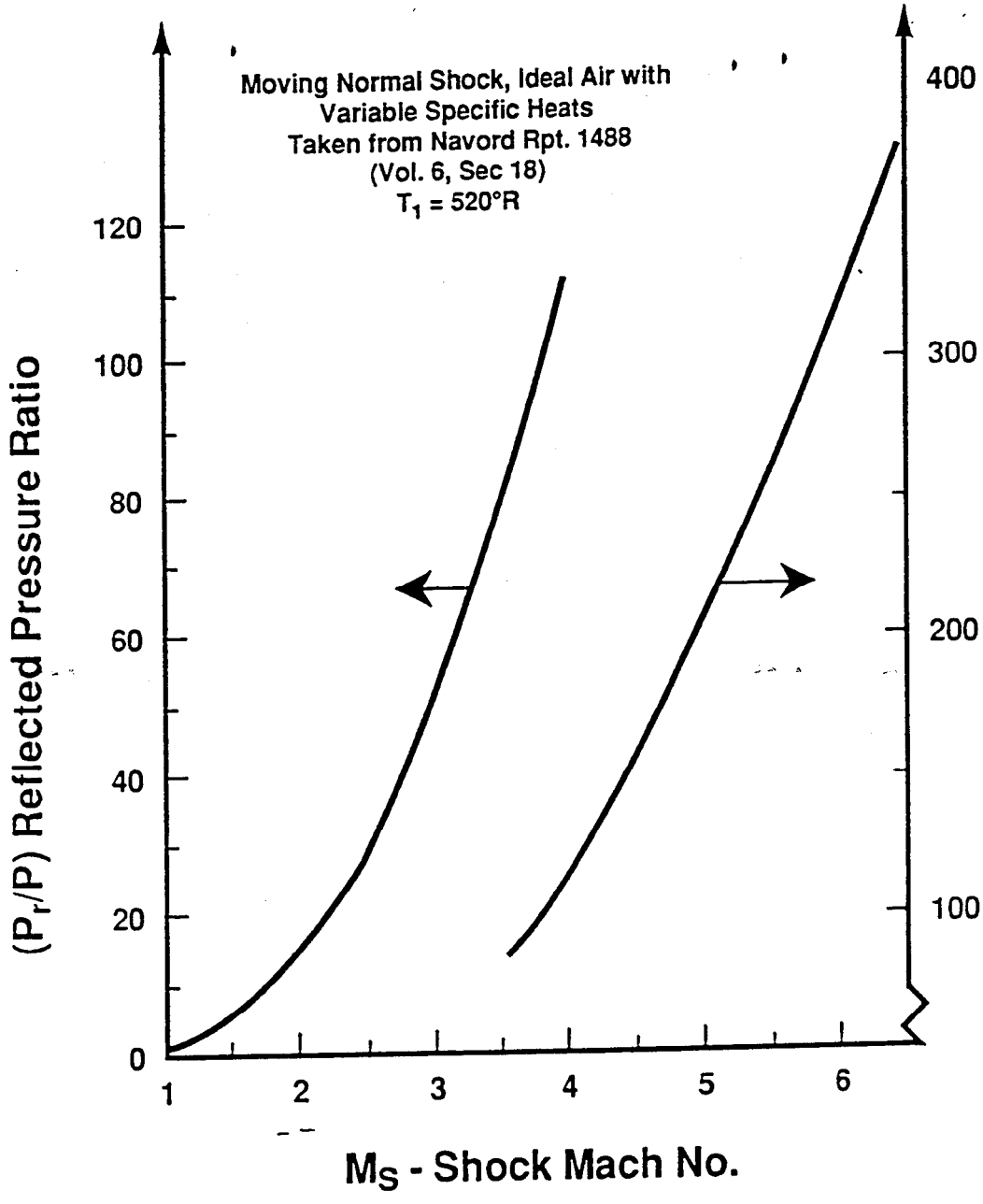

Figure C6. Reflected pressure ratio versus shock mach number

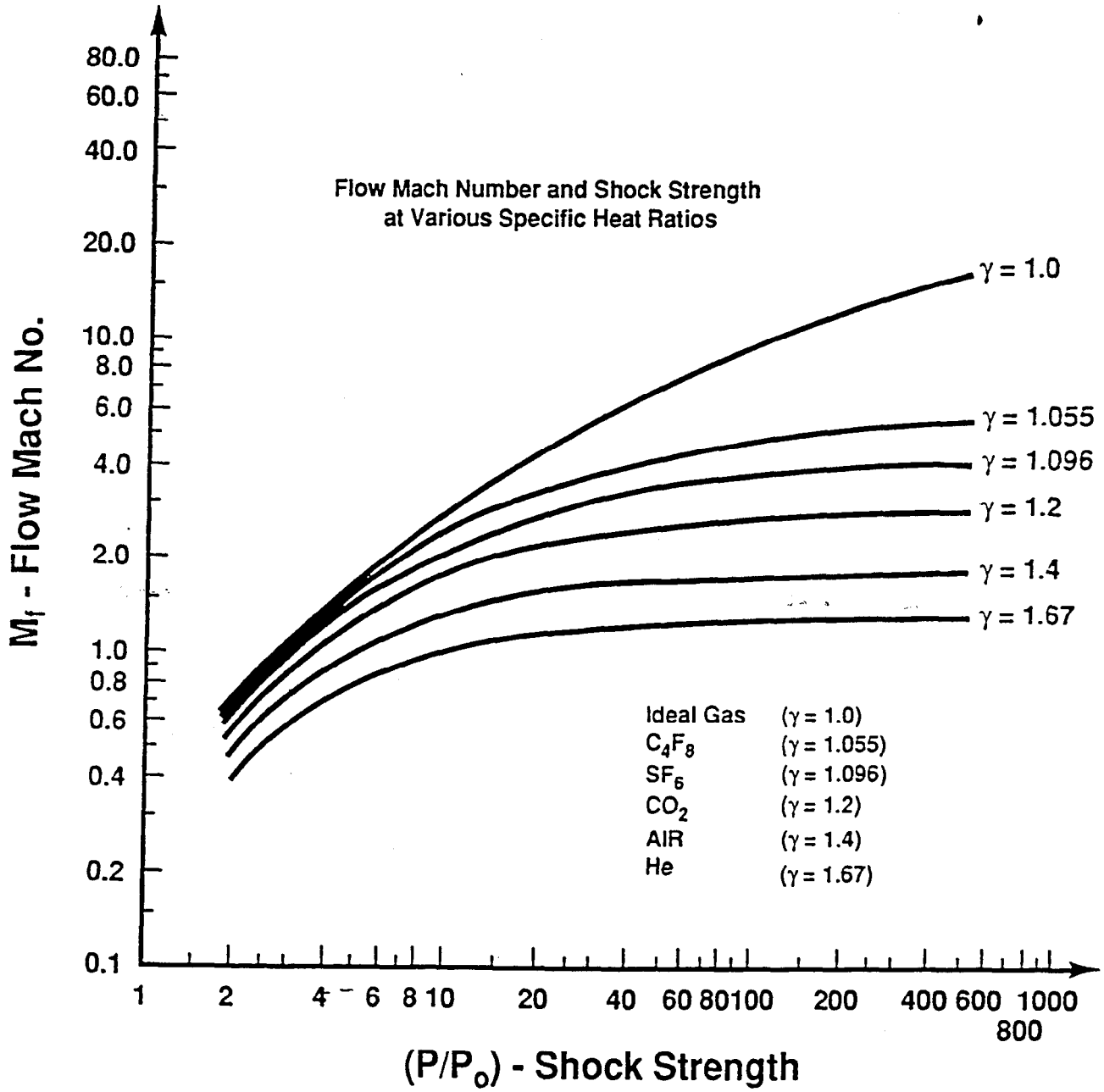

Figure C7. Flow mach number versus shock strength and specific heart ratio

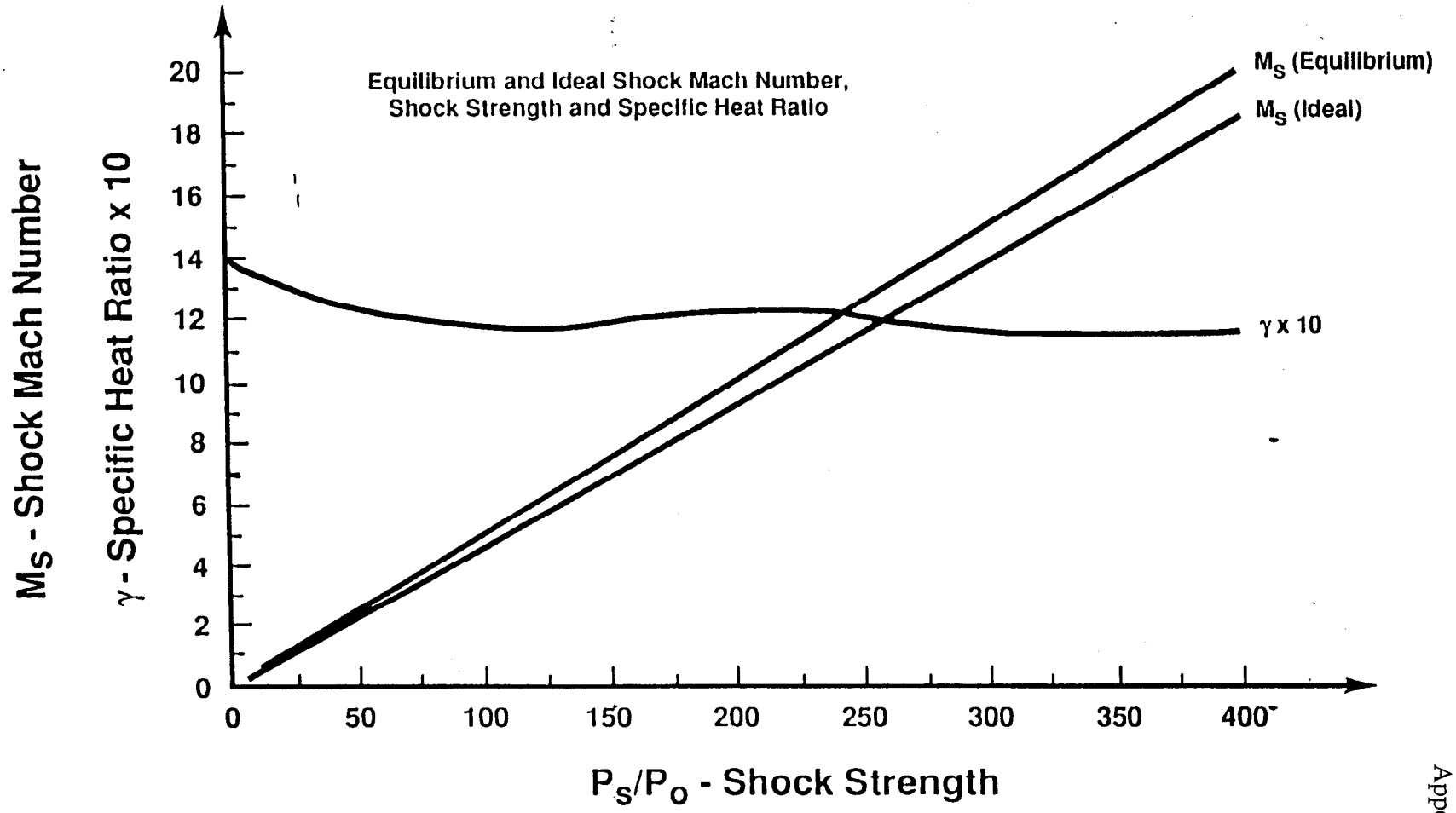

Figure C8. Shock mach number and specific heart ratio versus shock strength

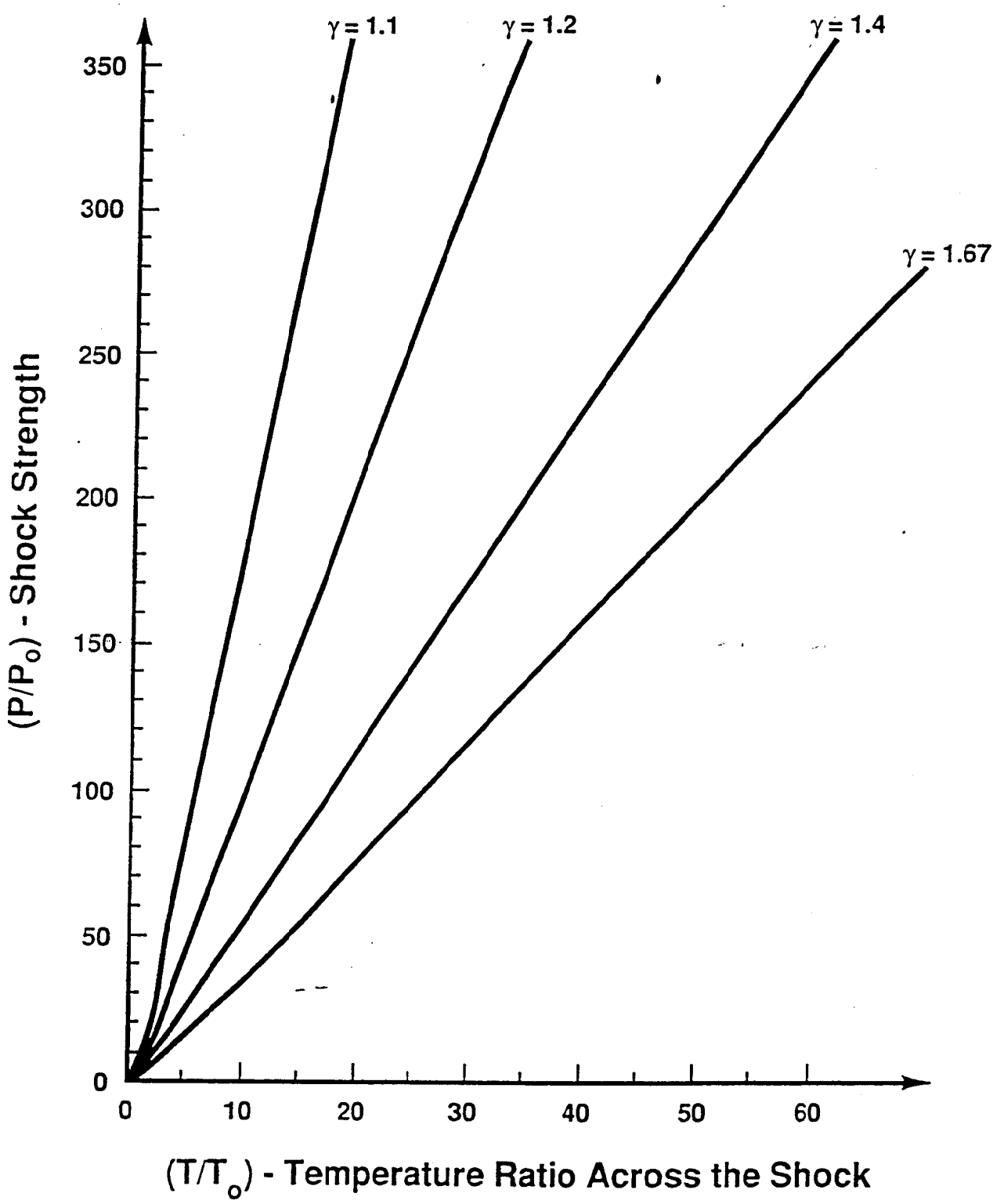

Figure C9. Shock strength versus temperature ratio

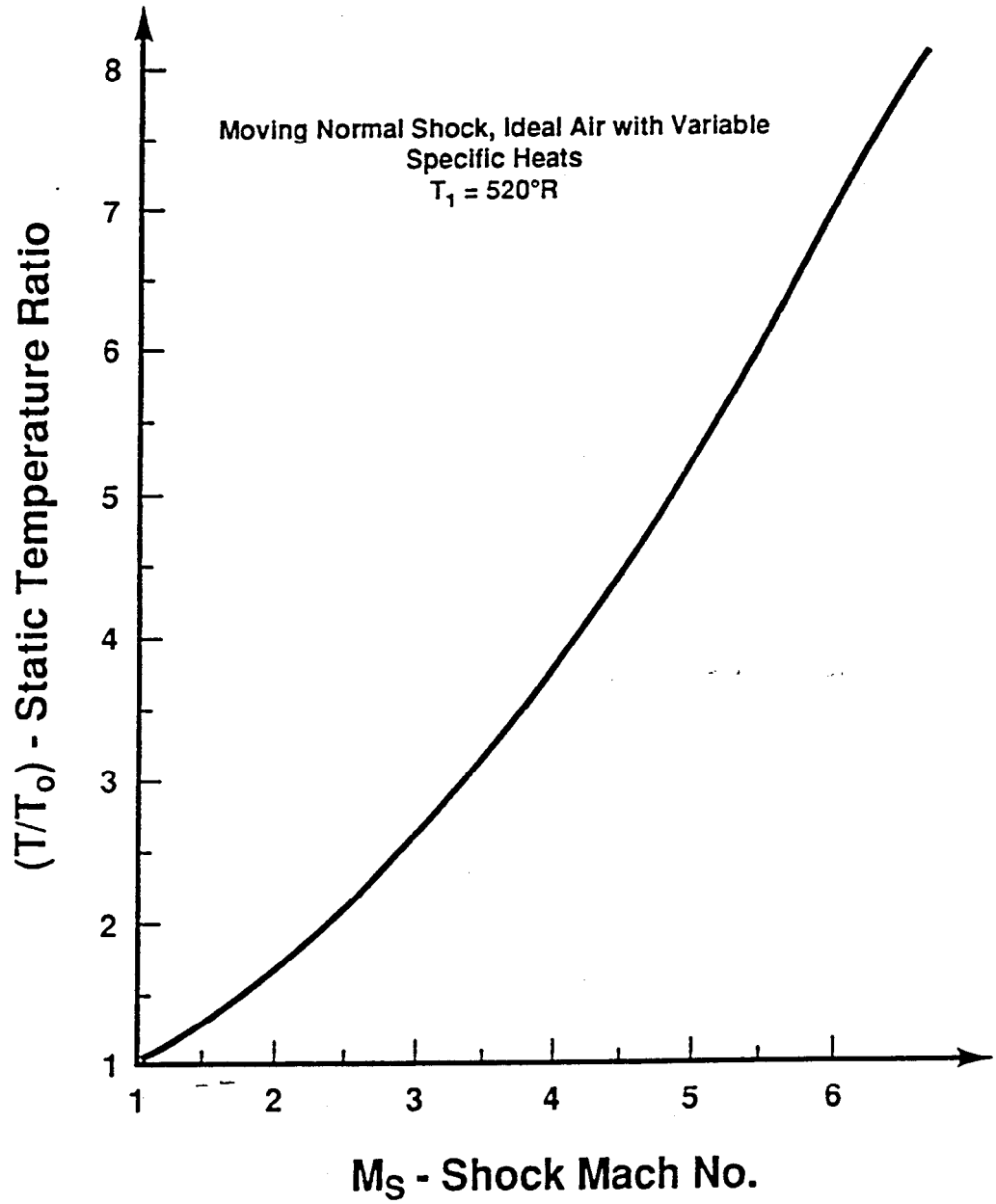

Figure C10. Temperature ratio versus shock mach number

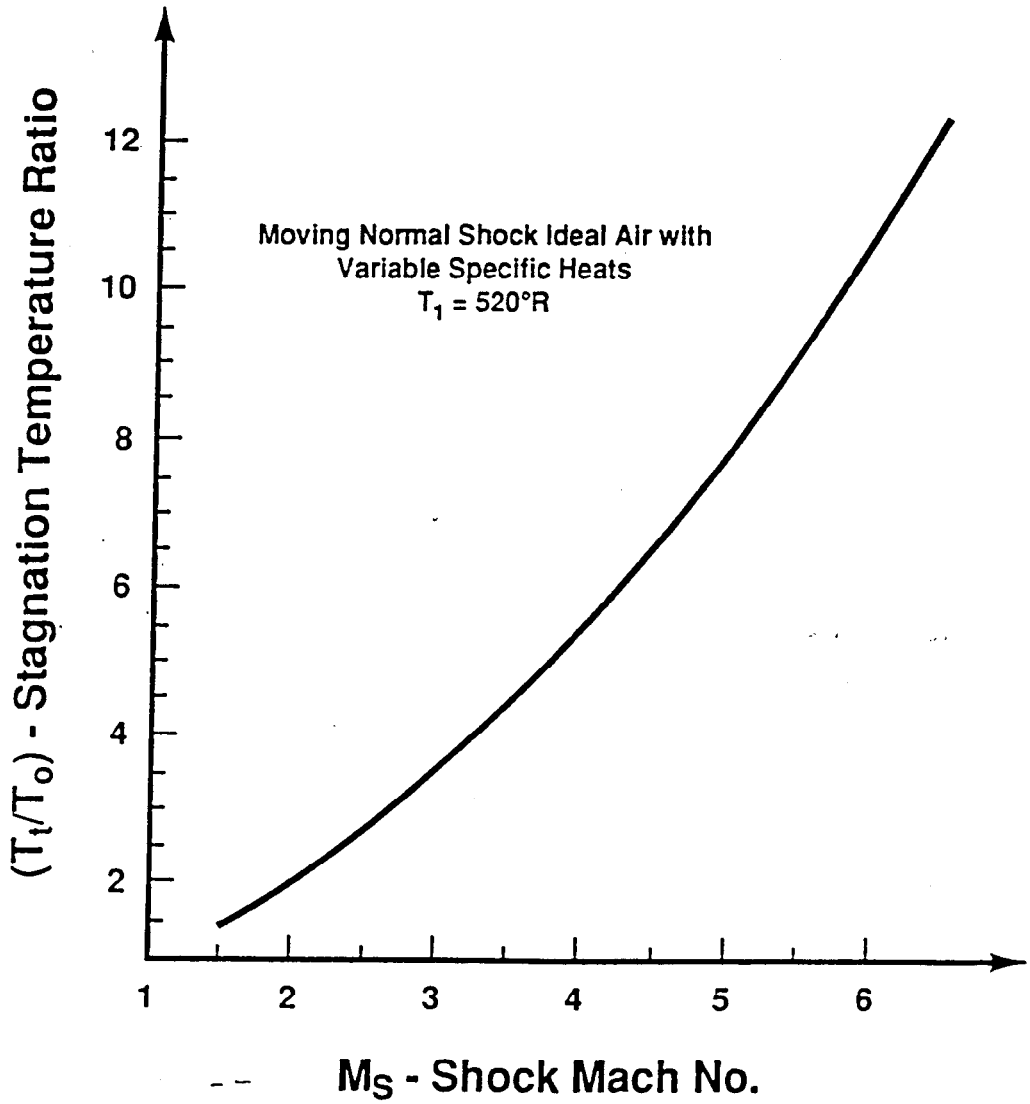

Figure C11. Stagnation temperature ratio versus shock mach number

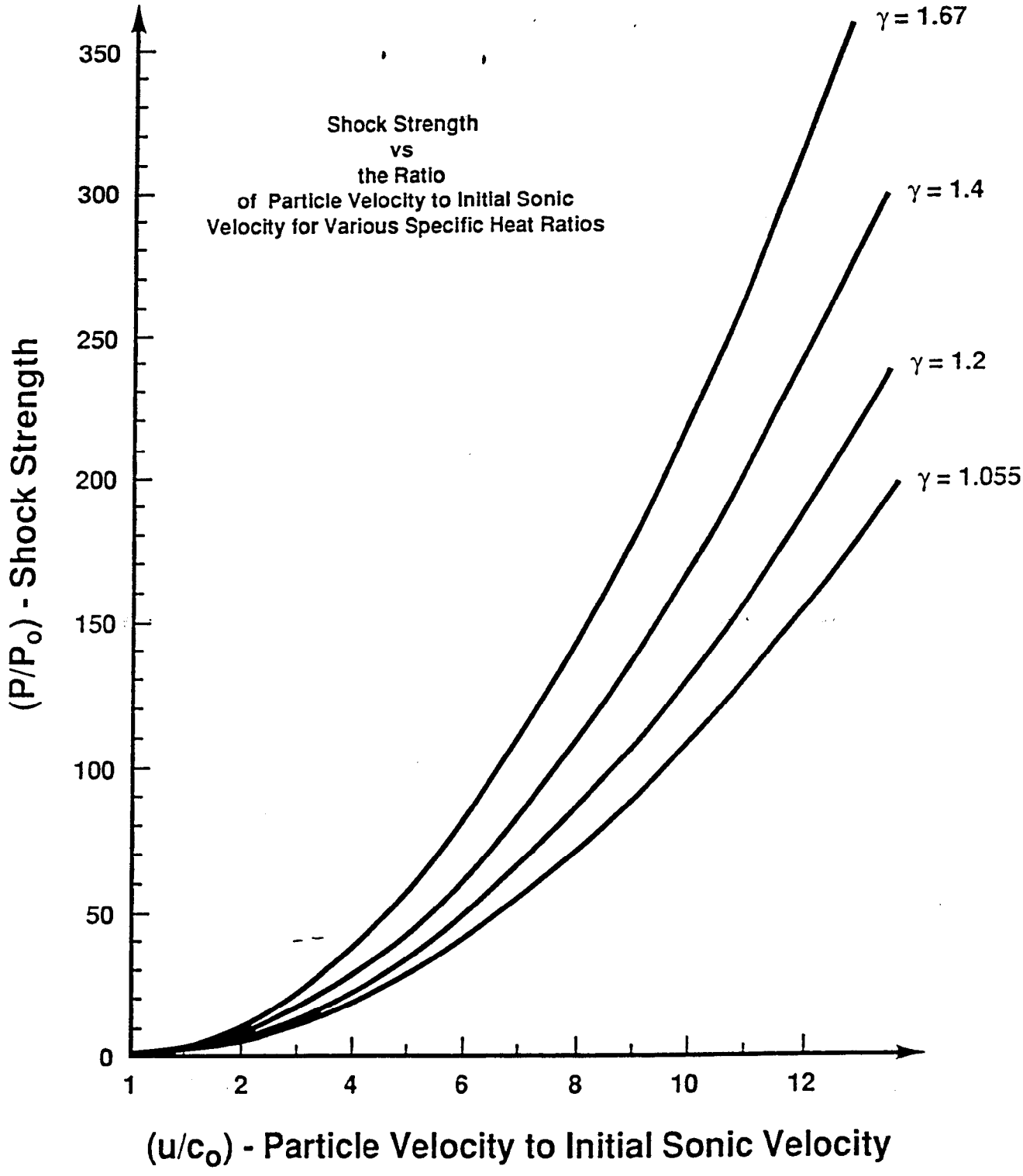

Figure C12. Shock strength versus particle velocity and specific heart ratio

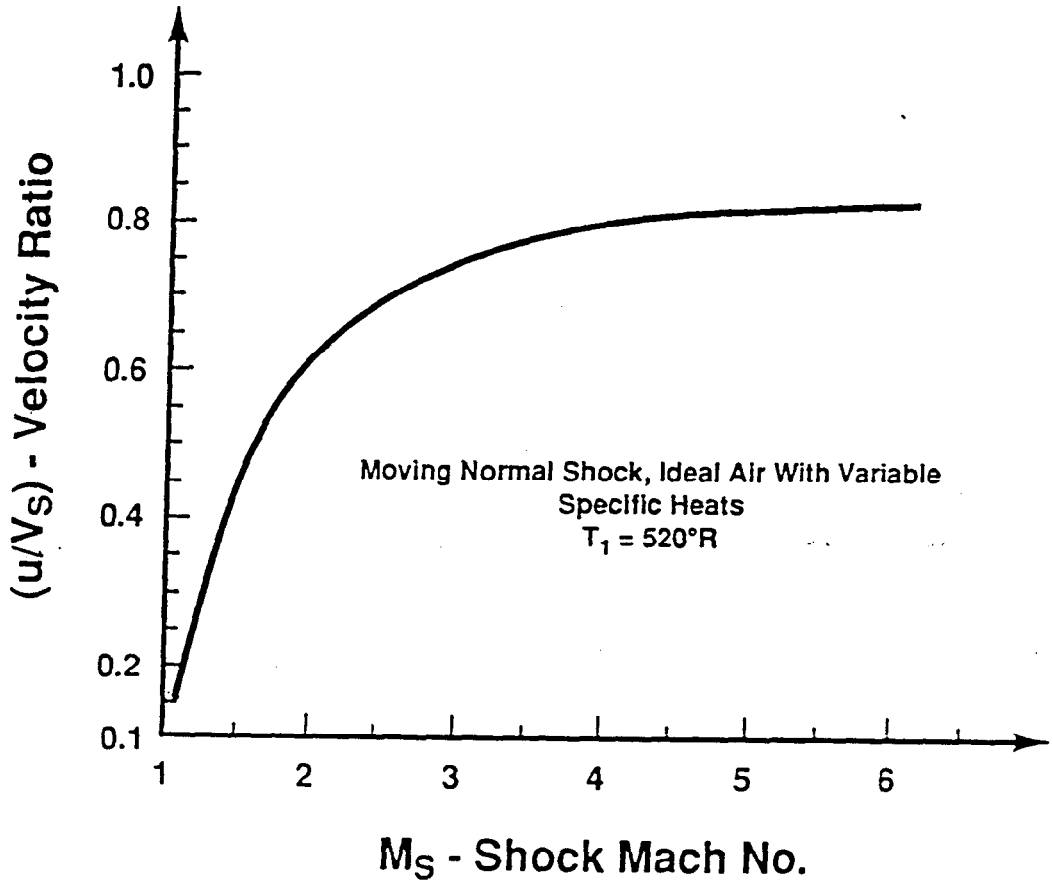

Figure C13. Particle to shock velocity ratio versus shock mach number

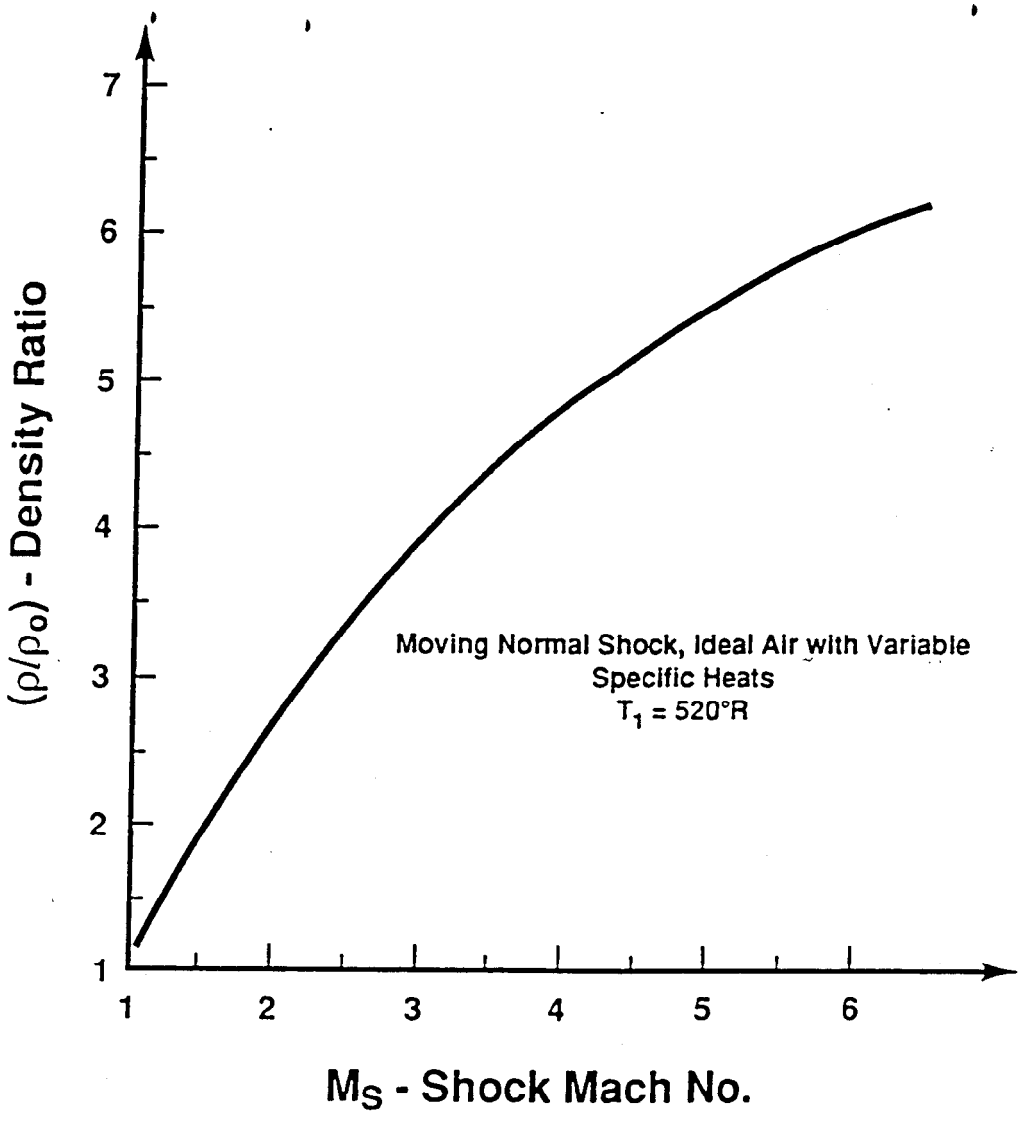

Figure C14. Density ratio versus shock mach number

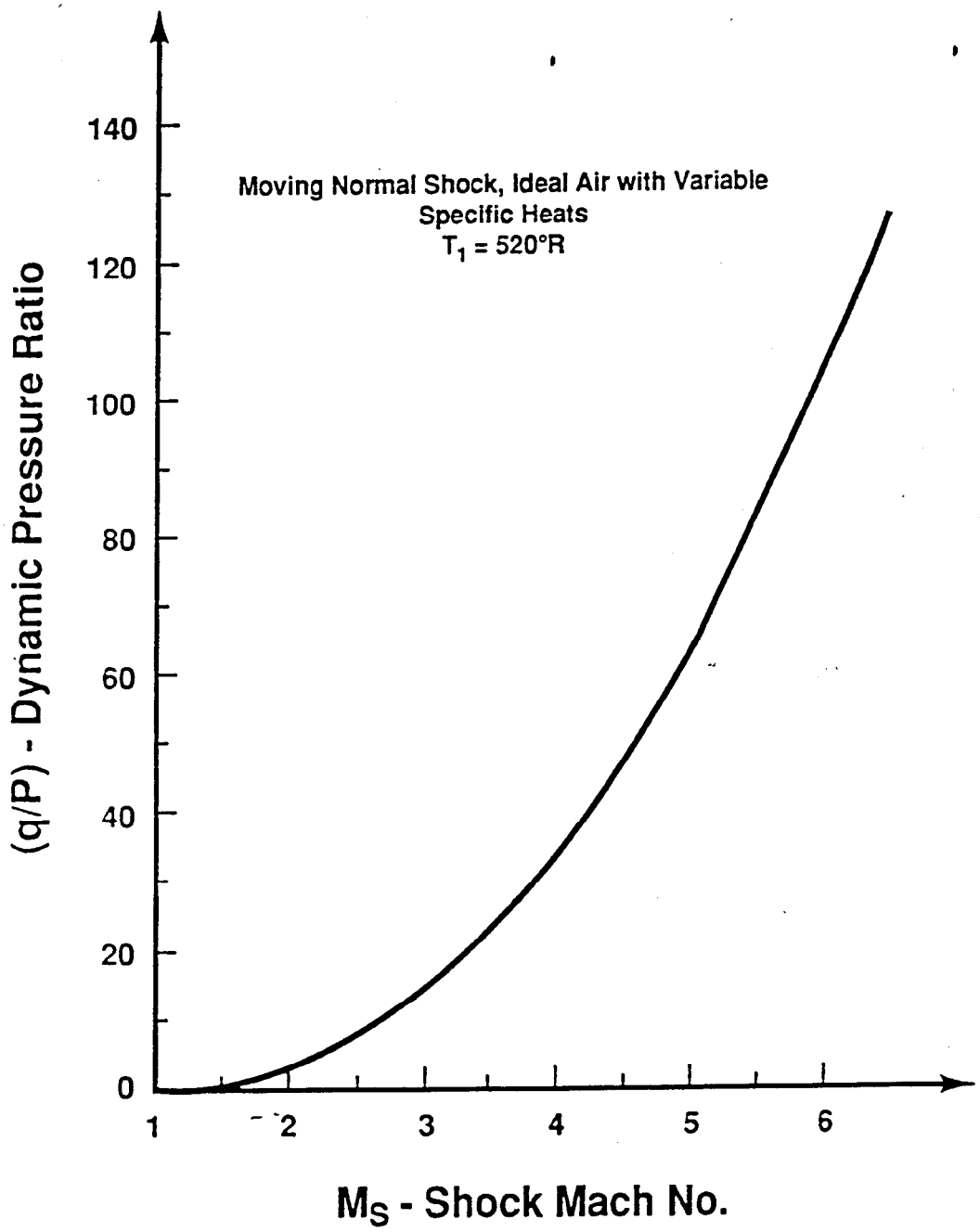

Figure C15. Dynamic pressure ratio versus shock mach number

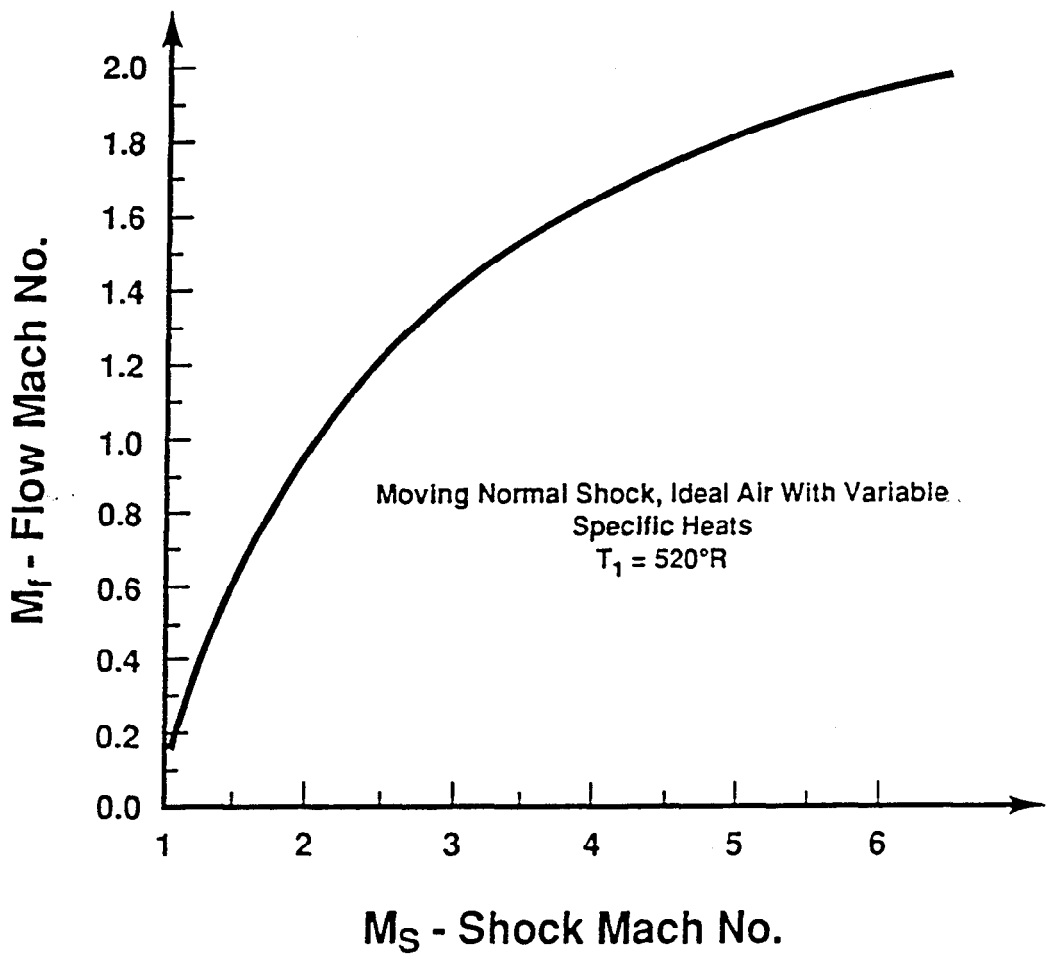

Figure C16. Flow mach number versus shock mach number

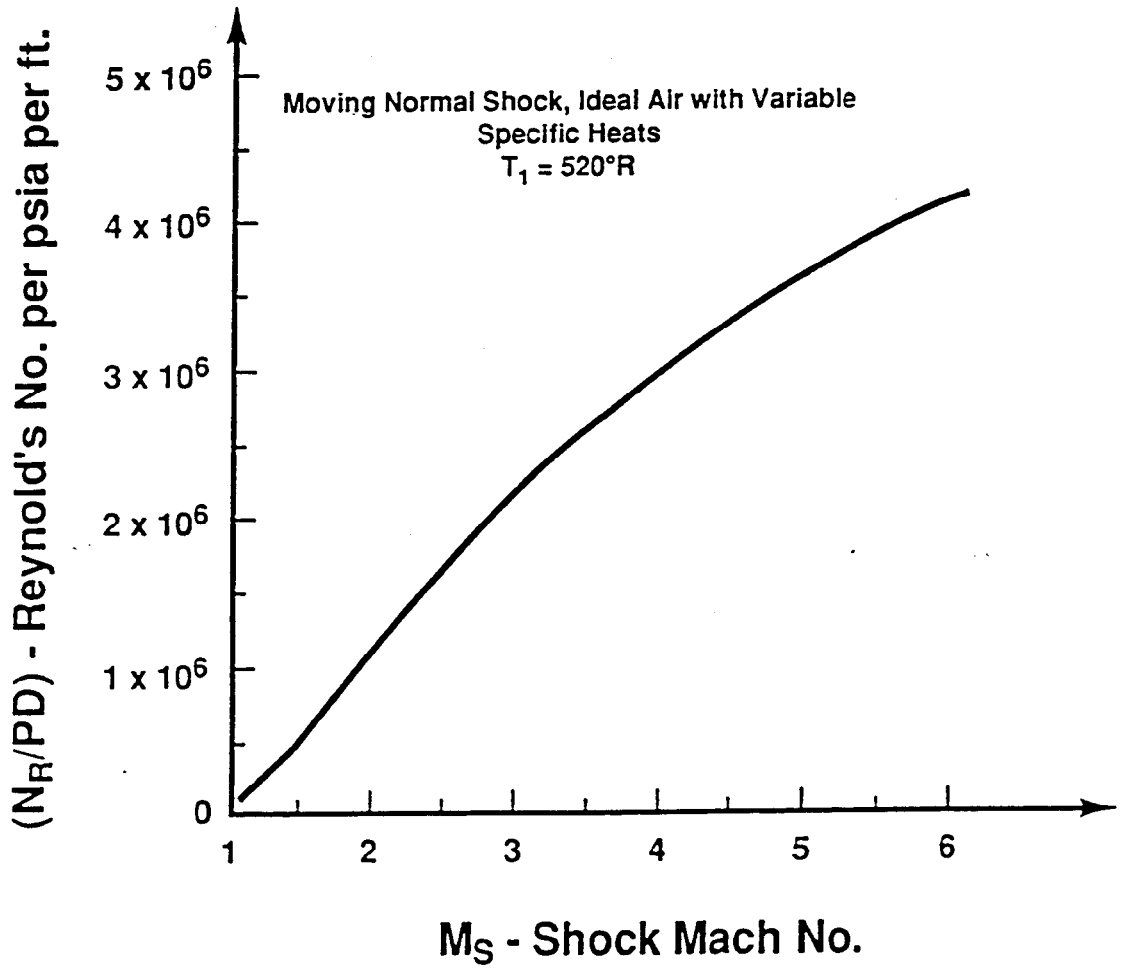

Figure C17. Reynold's number versus shock mach number

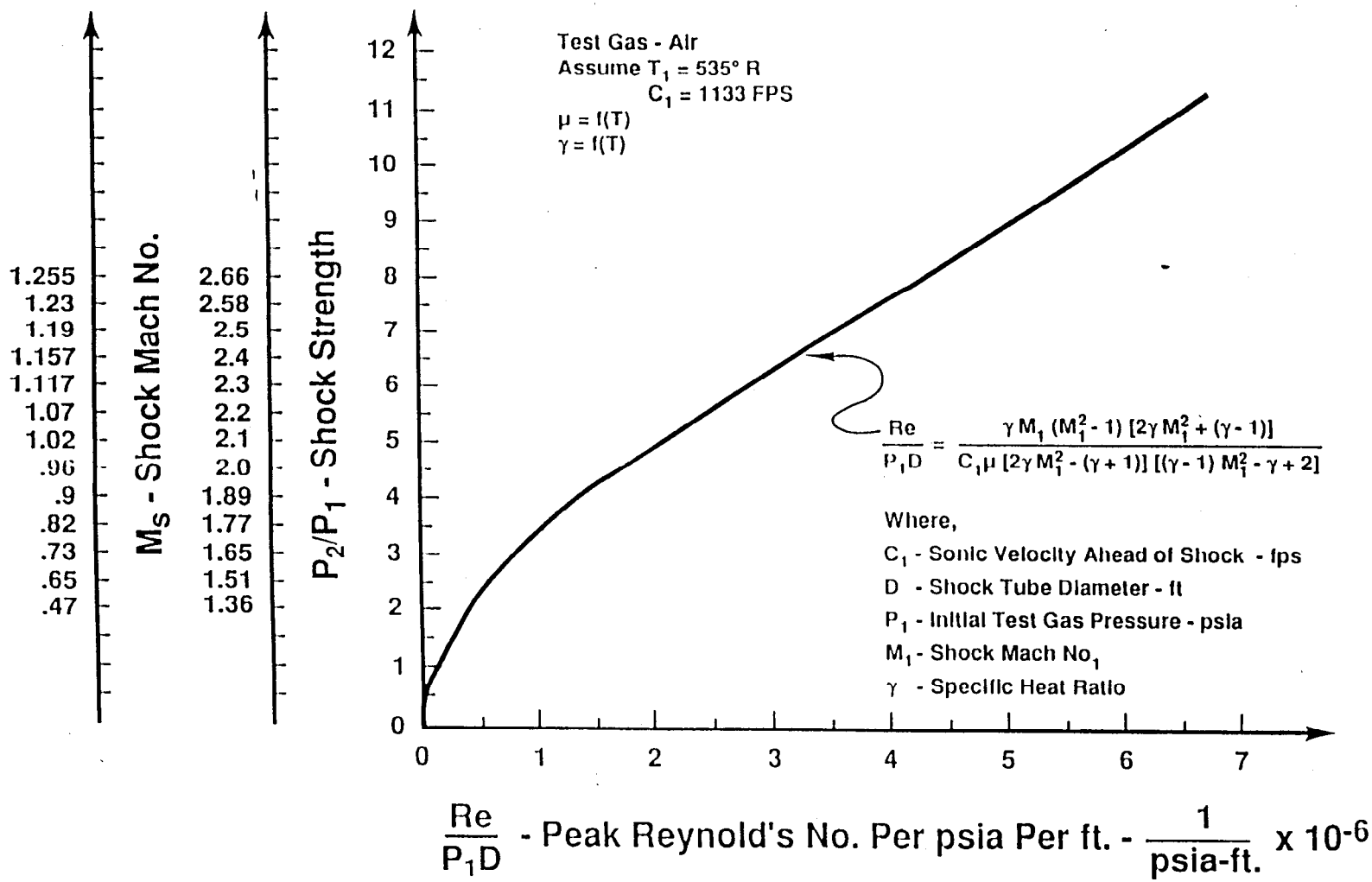

Figure C18. Flow and shock mach number and shock strength versus Reynold's number

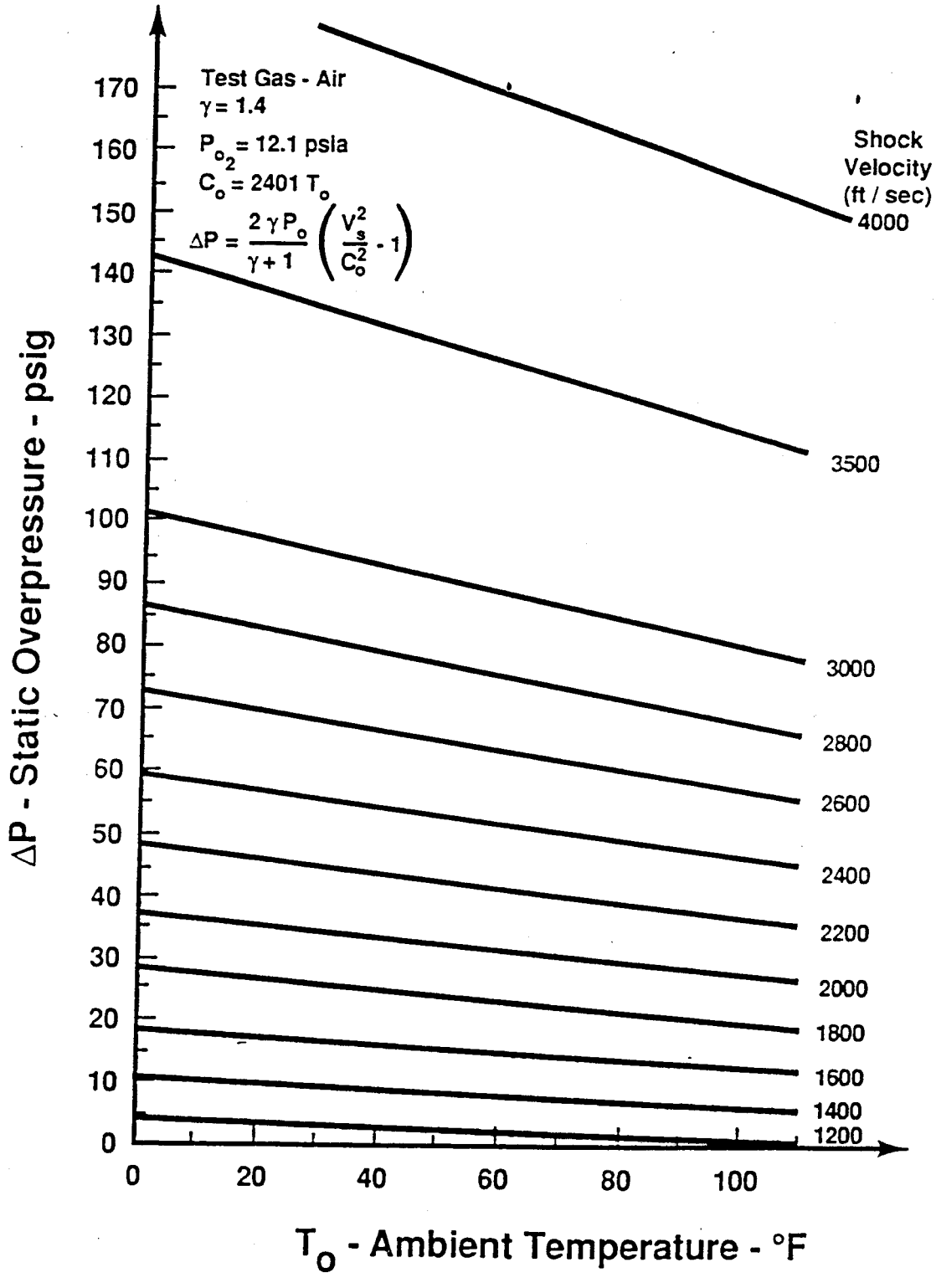

Figure C19. Static overpressure versus ambient temperature (F) and shock velocity

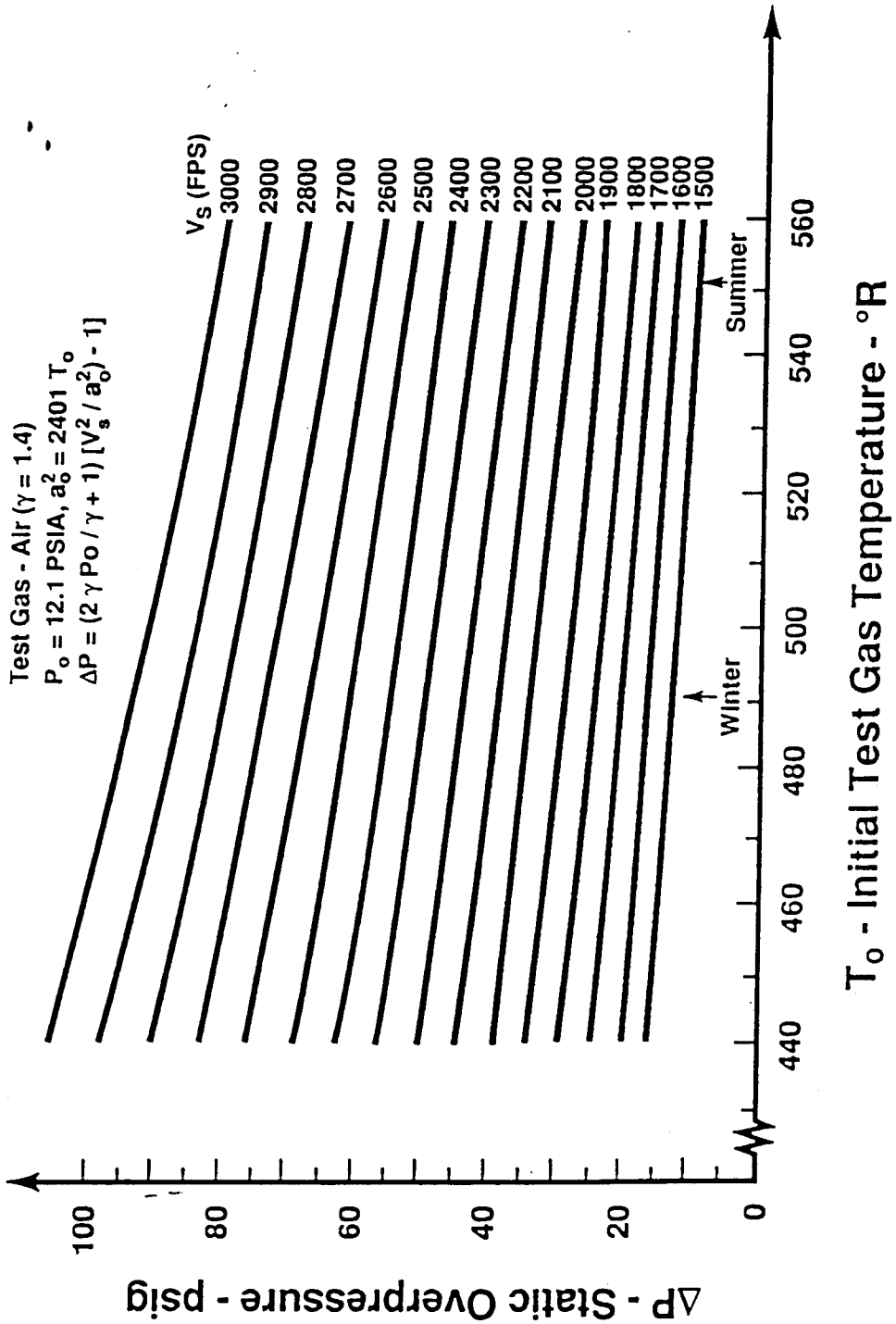

Figure C20. Static overpressure versus initial test gas temperature and shock velocity

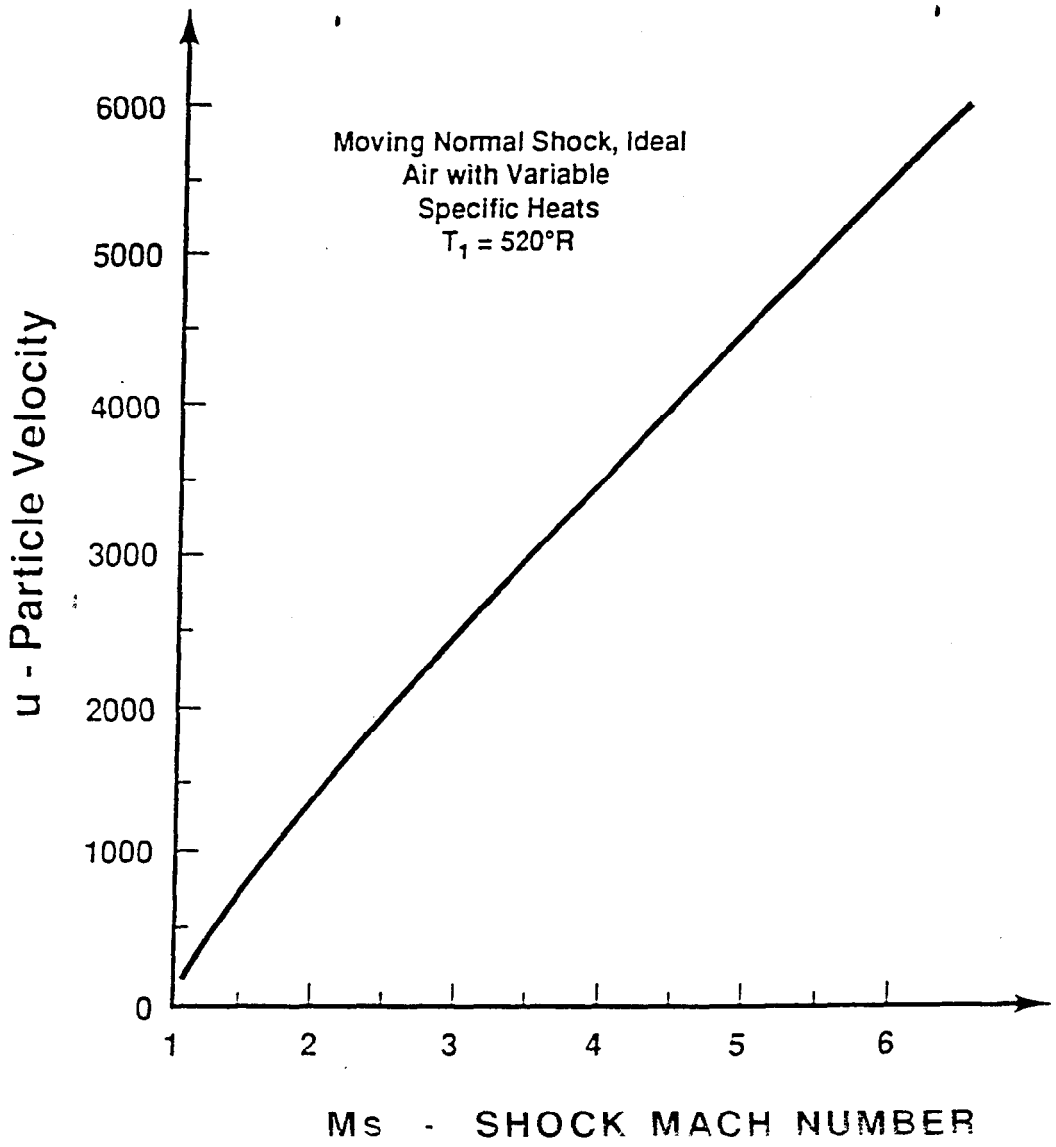

Figure C21. Particle velocity versus shock mach number

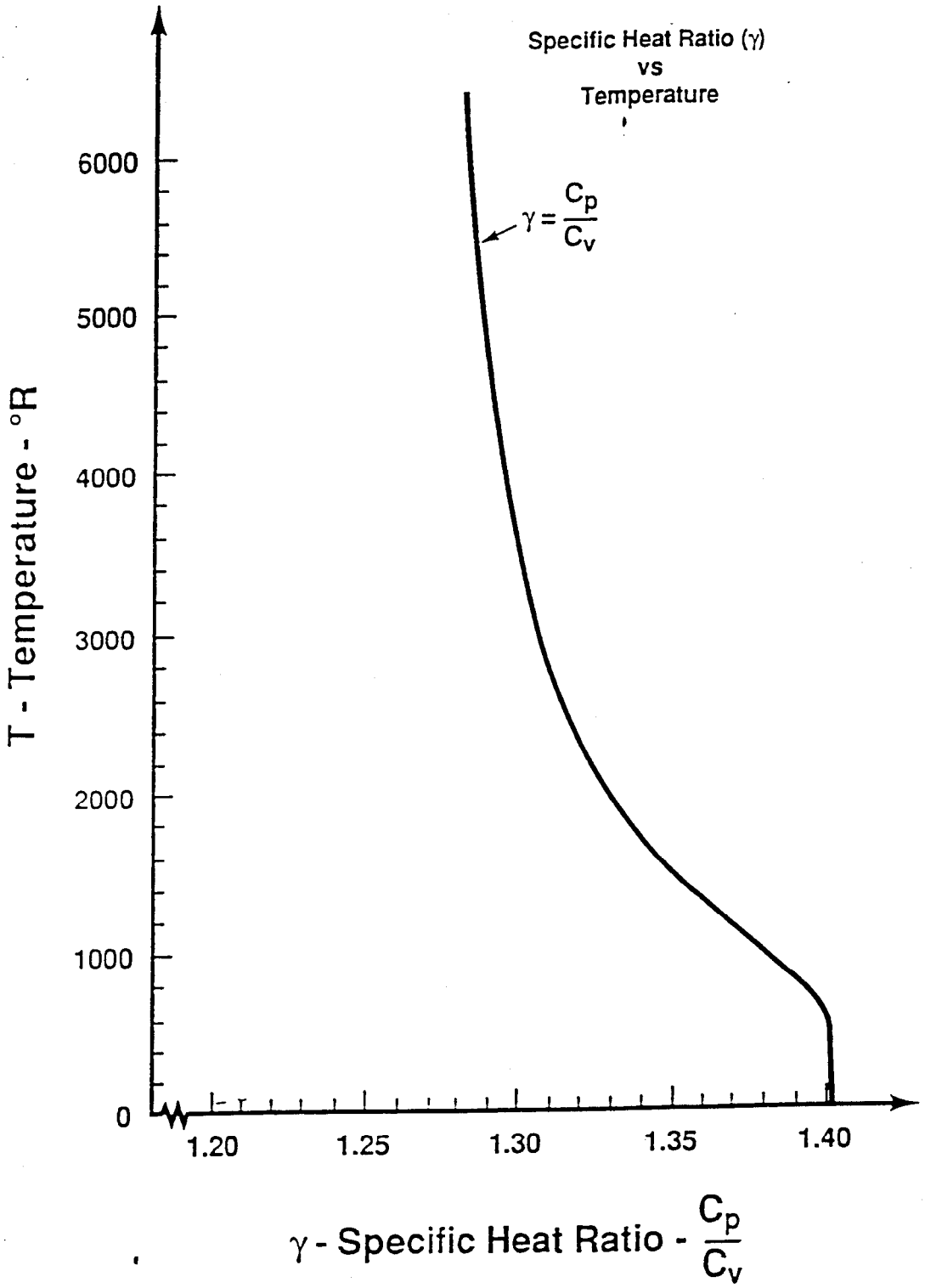

Figure C22. Temperature versus specific heart ratio

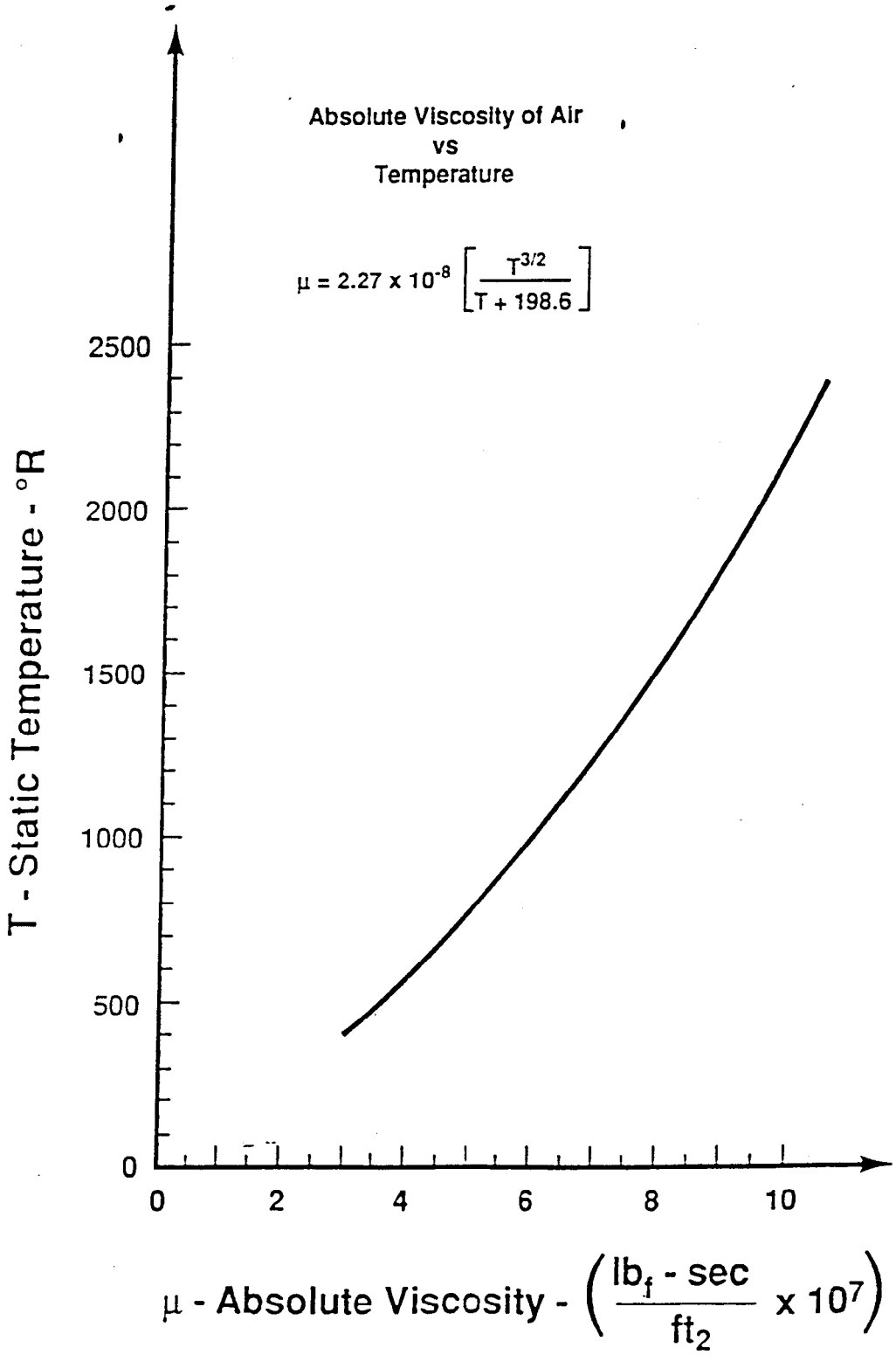

Figure C23. Static temperature versus absolute viscosity

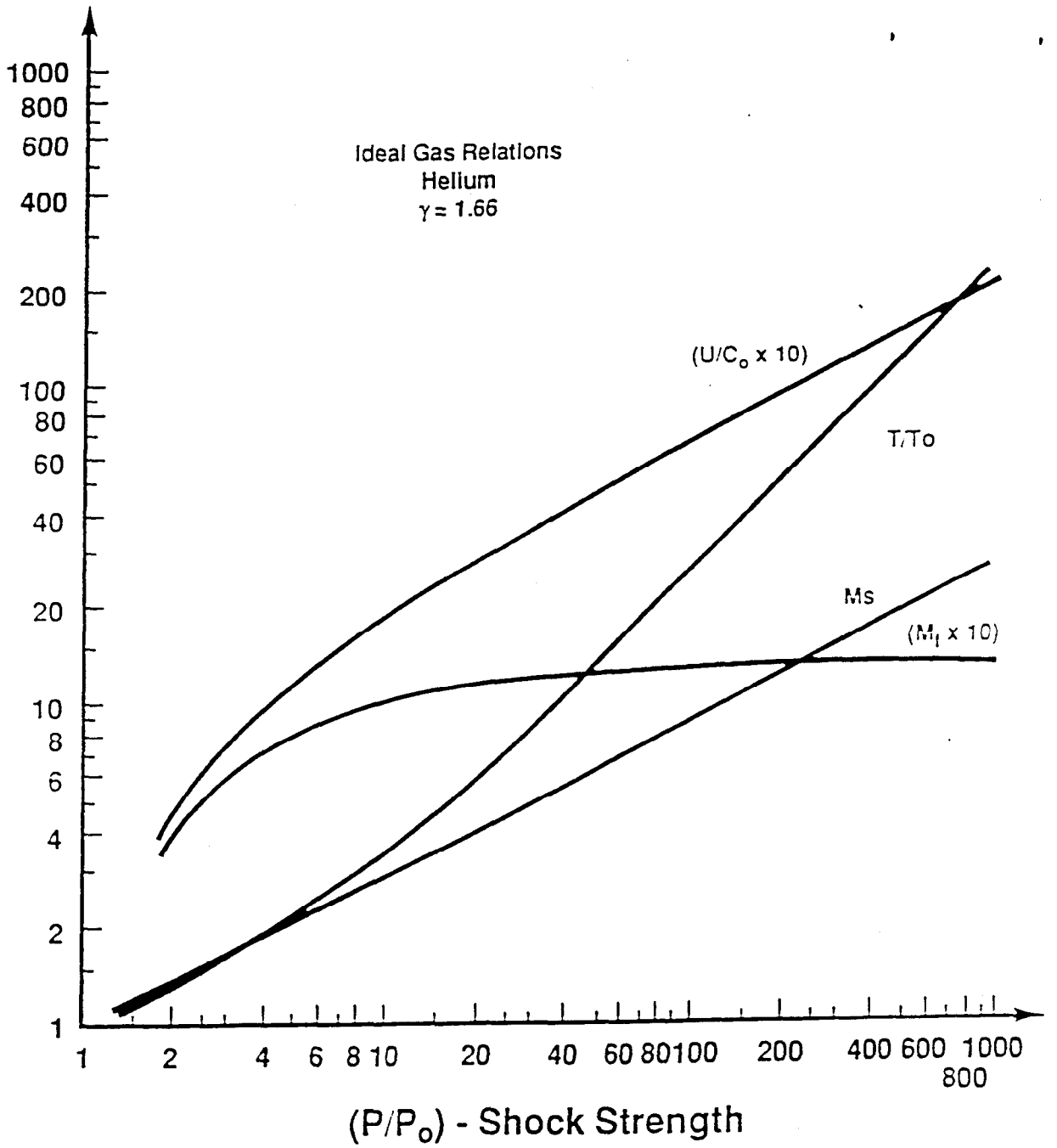

Figure C24. Shock parameters in helium versus shock strength

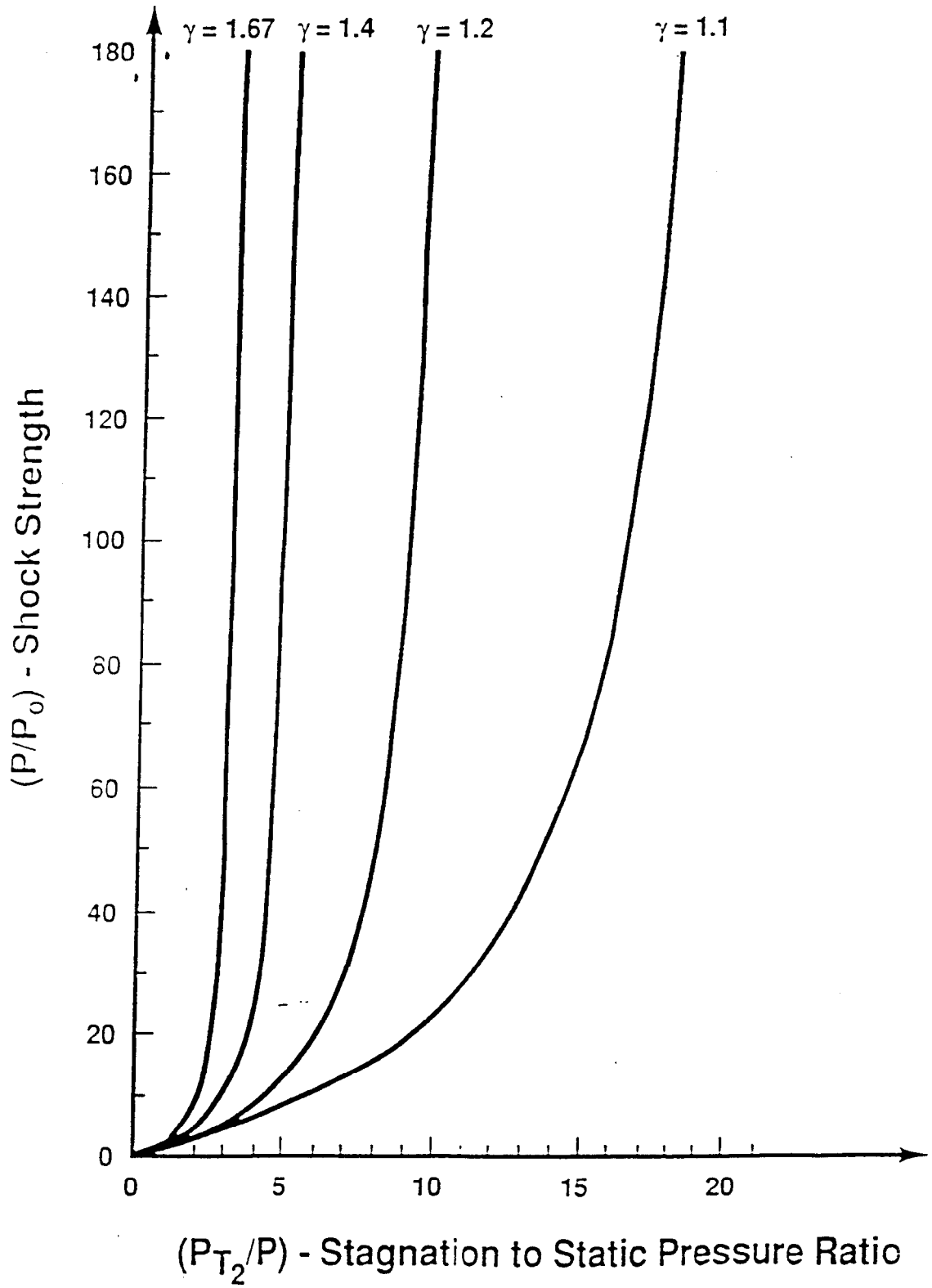

Figure C25. Shock strength versus stagnation to static pressure ratio

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