(2)

ESL-TR-91-25

OPERATION MAINTENANCE, AND SAFETY MANUAL FOR A SHOCK TUBE PRESSURE CALIBRATION FACILITY

D. B. SMITH, S. W. ALLISON, J. D. MUHS, B. L. JOHNSON SR.

OAK RIDGE NATIONAL LABORATORY
P. O. BOX 2003
OAK RIDGE TN 37831-7294

MAY 1991

FINAL REPORT

OCTOBER 1988 - MAY 1991

APPROVED FOR PUBLIC RELEASE. DISTRIBUTION UNLIMITED.

AFESC

AIR FORCE ENGINEERING & SERVICES CENTER
ENGINEERING & SERVICES LABORATORY
TYNDALL AIR FORCE BASE, FLORIDA 32403

NOTICE

PLEASE DO NOT REQUEST COPIES OF THIS REPORT FROM HQ AFESC/RD (ENGINEERING AND SERVICES LABORATORY). ADDITIONAL COPIES MAY BE PURCHASED FROM:

NATIONAL TECHNICAL INFORMATION SERVICE
5285 PORT ROYAL ROAD
SPRINGFIELD, VIRGINIA 22161

FEDERAL GOVERNMENT AGENCIES AND THEIR CONTRACTORS REGISTERED WITH DEFENSE TECHNICAL INFORMATION CENTER SHOULD DIRECT REQUESTS FOR COPIES OF THIS REPORT TO:

DEFENSE TECHNICAL INFORMATION CENTER
CAMERON STATION
ALEXANDRIA, VIRGINIA 22314

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704 0188

1a. REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT
~~DISTRIBUTION LIMITED TO AIR FORCE~~

4. PERFORMING ORGANIZATION REPORT NUMBER(S)

5. MONITORING ORGANIZATION REPORT NUMBER(S)
ESL-TR-91-25

6a. NAME OF PERFORMING ORGANIZATION
OAKRIDGE NATIONAL LABORATORY

6b. OFFICE SYMBOL *(If applicable)*
APPLIED TECHNOLOGY

7a. NAME OF MONITORING ORGANIZATION
AIR FORCE CIVIL EINGINEERING SUPPORT AGENCY

6c. ADDRESS *(City, State, and ZIP Code)*
POST OFFICE BOX 2003
OAK RIDGE TN 37831-7294

7b. ADDRESS *(City, State, and ZIP Code)*
HQ AFCESA/RACO
TYNDALL AFB FL 32403-6001

8a. NAME OF FUNDING / SPONSORING ORGANIZATION
AIR FORCE CIVIL ENGINEERING SUPPORT AGENCY

8b. OFFICE SYMBOL *(If applicable)*
RACO

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
MIPR N88-25

8c. ADDRESS *(City, State, and ZIP Code)*
HQ AFCESA/RACO
TYNDALL AFB FL 32403-6001

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO	WORK UNIT ACCESSION NO.

11. TITLE *(Include Security Classification)*
OPERATION MAINTENANCE, AND SAFETY MANUAL FOR A SHOCK TUBE PRESSURE CALIBRATION FACILITY

12. PERSONAL AUTHOR(S)
SMITH, D.B.; ALLISON, S.W.; MUHS, J.D.; JOHNSON, SR., B.L.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT *(Year, Month, Day)*	15. PAGE COUNT
FINAL	FROM Oct 88 TO May 91	May 1991	24

16. SUPPLEMENTARY NOTATION
AVAILABILITY OF THIS REPORT IS SPECIFIED ON REVERSE OF FRONT COVER.

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
PRESSURE TUBE
SHOCK TUBE
IMPULSE EVALUATION
BLAST TUBE SIMULATION

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

THIS DOCUMENT DESCRIBES OPERATION, MAINTENANCE, AND SAFETY CONSIDERATIONS FOR A SHOCK TUBE FACILITY. THE SHOCK TUBE WAS REQUIRED TO PRODUCE CONTROLLABLE HIGH PRESSURE WAVES WITH SHORT (<1 ms) RISE TIMES IN ORDER TO ASSESS DIFFERENT FIBER PRESSURE-SENSING SCHEMES. THIS METHOD FOR PRODUCING HIGH-PRESSURE IMPULSES WAS CHOSEN BECAUSE IT WAS THE ONLY METHOD FOR RELIABLY PRODUCING REPEATABLE, CONTROLLABLE, AND PREDICTABLE FAST-RISE-TIME, HIGH-PRESSURE IMPULSES. WITHOUT DESTROYING THE SENSOR THE BLAST TUBE CAN SIMULATE BLAST WAVES CREATED BY EXPLOSIONS.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT
☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION
UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL
THOMAS C. HARDY

22b. TELEPHONE *(Include Area Code)*
(904) 283-3732

22c. OFFICE SYMBOL
HQ AFCESA/RACO

DD Form 1473, JUN 86 *Previous editions are obsolete.*

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

EXECUTIVE SUMMARY

A. **OBJECTIVE:** The objective of this effort was to develop and construct a shock tube to test the fiber-optic sensors for measuring rapidly fluctuating pressures.

B. **BACKGROUND:** Instrumentation was required to produce controllable high pressure waves with short (< 1 ms) rise time in order to assess different fiber pressure-sensing schemes.

C. **SCOPE:** The goal was to develop and fabricate a shock tube to produce repeatable and reliable high impulses controllable, and predictable fast-rise-time, high-pressure impulses. It can, for instance, simulate blast waves created by explosions without destroying the sensor.

D. **METHODOLOGY:** State of the art sensor and data system technology was applied.

E. **TEST DESCRIPTION:** The shock tube consists of two cylinders joined together with their interior chambers separated by a diaphragm. One chamber is pressurized while the other is set at a lower pressure (usually atmospheric) until the diaphragm ruptures. The shock wave propagates from the diaphragm into the low-pressure section called the receiver. The fiber-optic sensors are mounted in the chamber from the side and at the end cap of the receiver to measure the pressure profile.

F. **RESULTS:** The strength of the shock wave is determined by the initial pressure ratios; thus, a range of shock pressures may be produced. With the device, pressures as high as 24,500 KPa (3740 psia) may be achieved in a shock wave reflected from the end of the receiver tube.

G. **CONCLUSIONS:** The shock tube was design to operate safely at the designed pressures.

H. **RECOMMENDATIONS:** In a shock tube facility safety provisions must be made to protect operator from any possible cylinder over change.

(The reverse of this page is blank.)

PREFACE

This report was prepared by Applied Technology Division, Oak Ridge National Laboratory, Oak Ridge TN 37831-7294, under MIPRs N88-25 for the Air Force Civil Engineering Support Agency, Air Force Civil Engineering Laboratory, Tyndall Air Force Base, FL 32403-6001.

This report summarizes work done between October 1988 and May 1991. Mr Thomas Hardy was the AFCESA/RACO project officer.

This report has been reviewed by the public affairs office and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

THOMAS C. HARDY Project Officer	EDGAR F. ALEXANDER Chief, Air Base Operabilitv
NEIL H. FRAVEL, Lt Col, USAF Chief, Engineering Research Division	FRANK P. GALLAGHER III, Col, USAF Director, Air Force Civil Engineering Laboratory

(The reverse of this page is blank.)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

(The reverse of this page is blank.)

SECTION I

INTRODUCTION

A. OBJECTIVE

This manual describes operation, maintenance, and safety considerations for a shock tube used for pressure sensor calibration. Dynamic testing of pressure sensors requires a source of short-duration high-pressure waves to simulate shock waves from explosions. Shock tubes can simulate such events with a high degree of control and repeatability.

B. SCOPE/APPROACH

In order to safely operate and maintain the shock tube, a basic understanding of how it works is necessary. A brief description of how a shock tube works is given below to aid the operator in this understanding. The technical report Development and Testing of Fast-Response Fiber-Optic Pressure Sensors, ESL-TR-91-24, describes some results of the initial use of this shock tube and can also be used to acquaint and familiarize the reader with the use of the shock tube. Section II of this report, entitled "System Description" (p. 3), contains an explanation with accompanying photographs of each of the major components of the shock tube apparatus. Section III, "Safety Considerations in Operation" (p. 13), reveals the philosophy of the approach to safety as well as the detailed safety analysis of the system. Section IV, "Setup and Assembly" (p. 16), gives detailed explanation and description of the shock tube, its components, the gas-handling manifold, and accompanying electronics. A step-by-step checklist is given in Section V, "Operations" (p. 18). This is followed by Section VI, "Maintenance" (p. 20). The appendixes provide the operator with the means to control and predict the shock wave amplitude.

C. BRIEF DESCRIPTION OF HOW A SHOCK TUBE WORKS

A shock tube is a simple aerodynamic device that is capable of producing controlled shock waves. In its simplest form as in this case, it consists of two cylinders, closed on each end and joined together by a mating flange. A diaphragm called a burst disk is sandwiched between the opposite faces of the flange and hence separates the enclosed volume into two chambers. A high pressure is established on one side of the diaphragm and a low pressure, usually atmospheric, on the other. The high-pressure side may be termed as either the "driver" or "compression" section and the low-pressure side is usually referred to as the "receiver" or "expansion" section. Under sufficient pressure on the driver side, the burst disk ruptures. As a consequence, a strong shock wave travels along the receiver chamber. Behind the shock front, the gas flow is at a high pressure and temperature. High Mach numbers can be achieved as well as fast rise times. Figure 1 illustrates

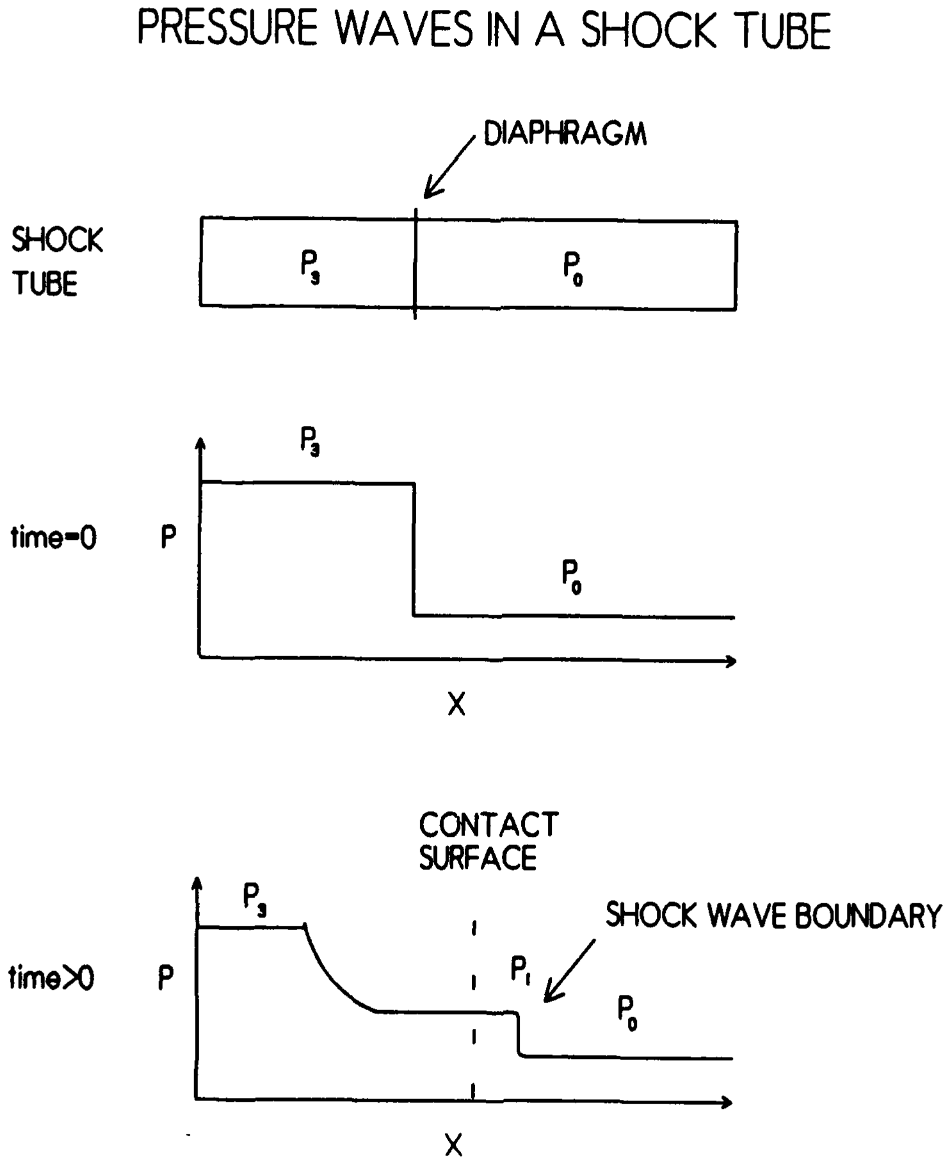

Figure 1. Illustration of Shock Tube Pressure Profiles before (time = 0) and after (time > 0) the Rupture of the Diaphragm.

shock tube pressure profiles at two times, one before diaphragm rupture and the other at some point afterwards, before the shock reflects from the end of the tube.

The theory of shock tube operation is relatively simple. With knowledge of gas properties obtained from standard handbooks and the pressure in the compression and expansion sections, the pressure behind the traveling shock front can be predicted. The validity of the theory calculations may be cross checked by determination of the shock wave velocity. This velocity measurement can be made from measurement of the time-of-arrival of the travelling shock wave at the different sensor locations.

An explanation of the shock tube equations and a sample computer program for calculating values are found in Appendixes A and B.

SECTION II

SYSTEM DESCRIPTION

The complete shock tube system consists of the following units or assemblies:

1. the shock tube assembly,
2. interconnecting hoses, and
3. the gas control panel.

Also needed, but dependent upon the choices made in the facility, is the high-pressure gas supply. This may consist of compressed gas bottles or pumps.

The following is a description of the shock tube. The tube layout is shown in Figure 2. The compression chamber is 1.2 meters long, and the expansion chamber is 3.8 meters long. Both chambers have an inside diameter of 7.6 cm. The diameter of the flange aperture is also 7.6 cm. Figure 3 is a photo of the shock tube with the expansion chamber in the foreground. The rupture disk flange and compression chamber are also depicted. The shock tube rests on a specially designed test stand, shown in Figure 3.

Six instrumentation ports are present on the shock tube and are depicted in Figure 2. These ports allow pressures inside the tube to be monitored by pressure sensors or regulated by pressure relief valves as desired. Port 1 is located on the end wall of the compression chamber, Ports 2 through 5 are located on the top of the expansion chamber, and Port 6 is located on the end wall of the expansion chamber. Table 1 lists the distances of the ports from the plane of the diaphragm.

The flange assembly accepts rupture disks (nickel metal, size 3"H, type SPL B) manufactured by BS&B Safety Systems of Tulsa,

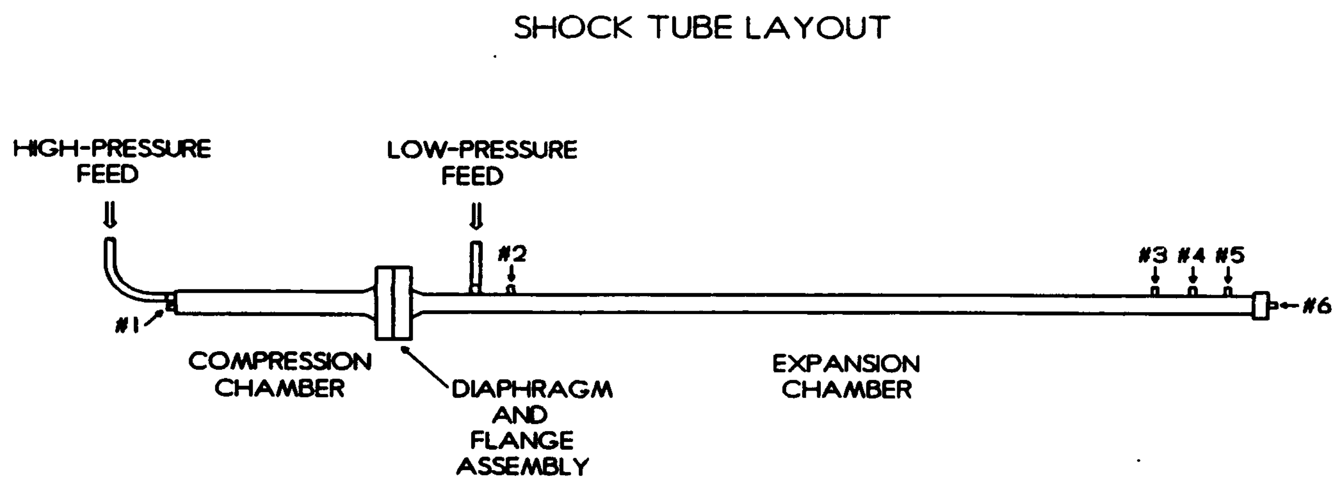

Figure 2. Shock Tube Layout.

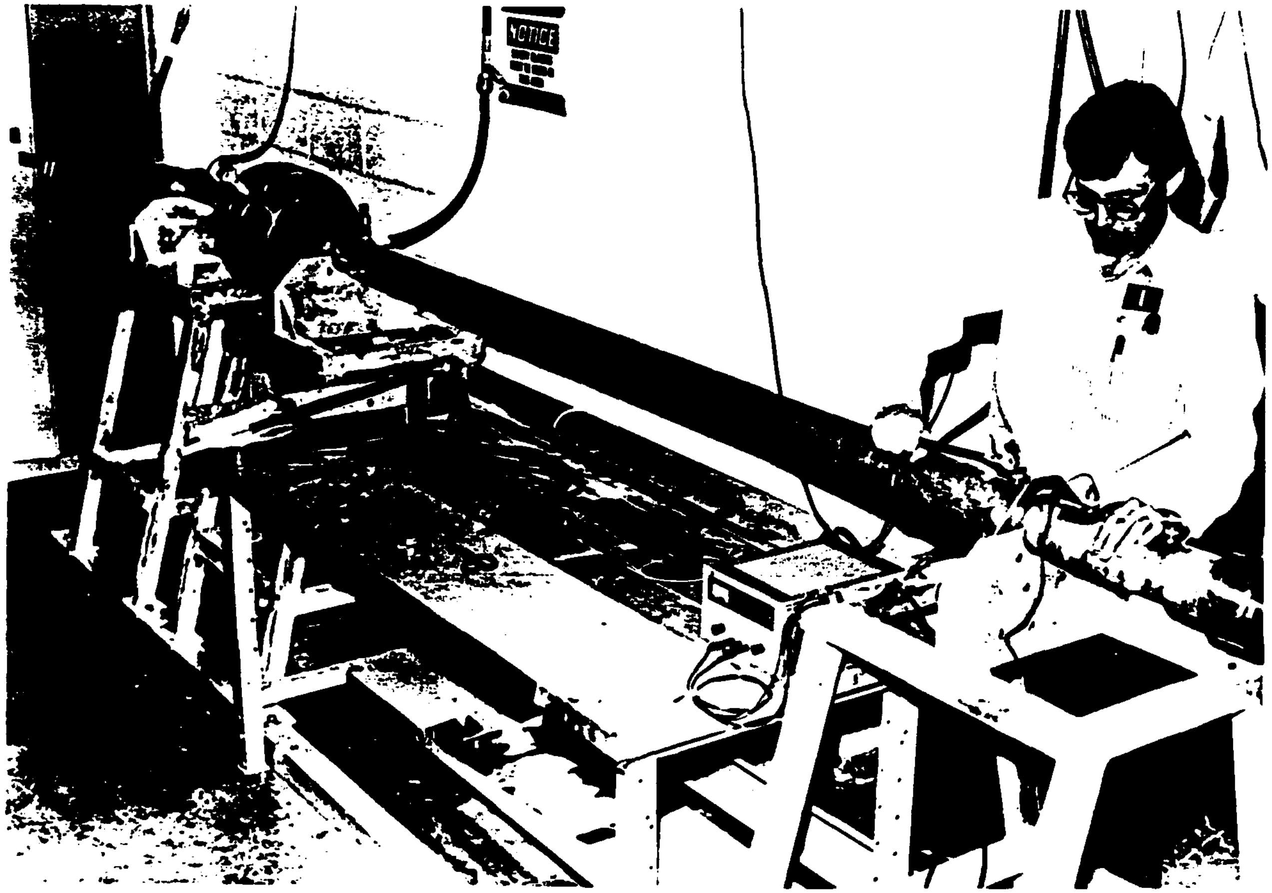

Figure 3. Photograph of Shock Tube.

TABLE 1. SHOCK TUBE DIAPHRAGM-TO-PORT DISTANCES

Port	Distance (cm)
1	120
2	51
3	332
4	347
5	362
6	380

Oklahoma. The disks are designed to rupture at specific pressures and are scored at the center so they "petal open" rather than shatter. The photograph in Figure 4 shows two rupture disks, one before use and the other after use in the shock tube. Either stainless steel or brass shim stock (the latter shown in Figure 5) can provide an inexpensive but less precise alternative. The material in the figure was 5-mils thick and burst at approximately 3150 kPa. Their disadvantage is (1) the uncertainty as to rupture pressure and (2) they do not open cleanly. Because they emit more shrapnel down the tube, the shock wave produced may not be quite as fast and strong as predicted for the ideal case. There is some leakage around the flange when shim stock is used. Nonetheless, they provide a low-cost method for obtaining some useful results.

Two high-pressure hoses connect the shock tube high- and low-pressure sides to the high- and low-pressure sides of the control panel. These hoses are to permit the flow of gas to and from the tube. This is controlled from a gas control panel illustrated in Figure 6, which shows connection to the compression and expansion chambers, along with the control and relief valves. Figure 7 is a photo of the shock tube gas control panel. The high-pressure feed valve allows the delivery of compressed gas from an appropriate cylinder (or pump) to the compression chamber. An additional valve control, the high-pressure throttle, controls the flow rate. Similarly, a low-pressure feed valve for the expansion chamber is used when pressures other than atmospheric are desired in this chamber. A low-pressure vent permits the chamber to be vented after shock tube firing. General-purpose dial pressure gauges (Omega Models PGS-35B-600 and PGS-35B-10000) are mounted on the manifold and monitor pressure in the chambers to 40,000 kPa (5,800 psig) and 69,000 kPa (10,000 psig), respectively. The accuracy of the gauges is specified as ±1 percent of their full-scale reading (±690 kPa for the gauge reading the compression chamber pressure and ±40 kPa for the gauge reading the expansion chamber pressure). A gauge isolation valve is located in front of the lower-range pressure gauge to protect it from the high pressure ensuing from the shot. Figure 8 shows how the high-pressure hoses from the shock tube are

Figure 4. Photograph of Rupture Disks.

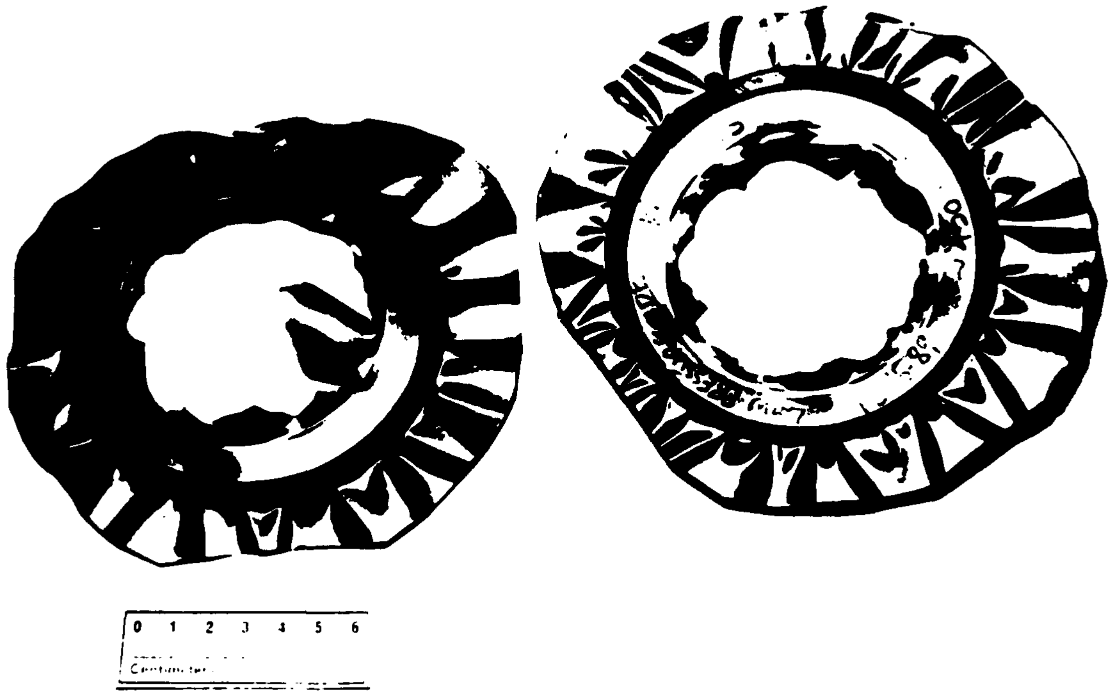

Figure 5. Photograph of Brass Shim Stock.

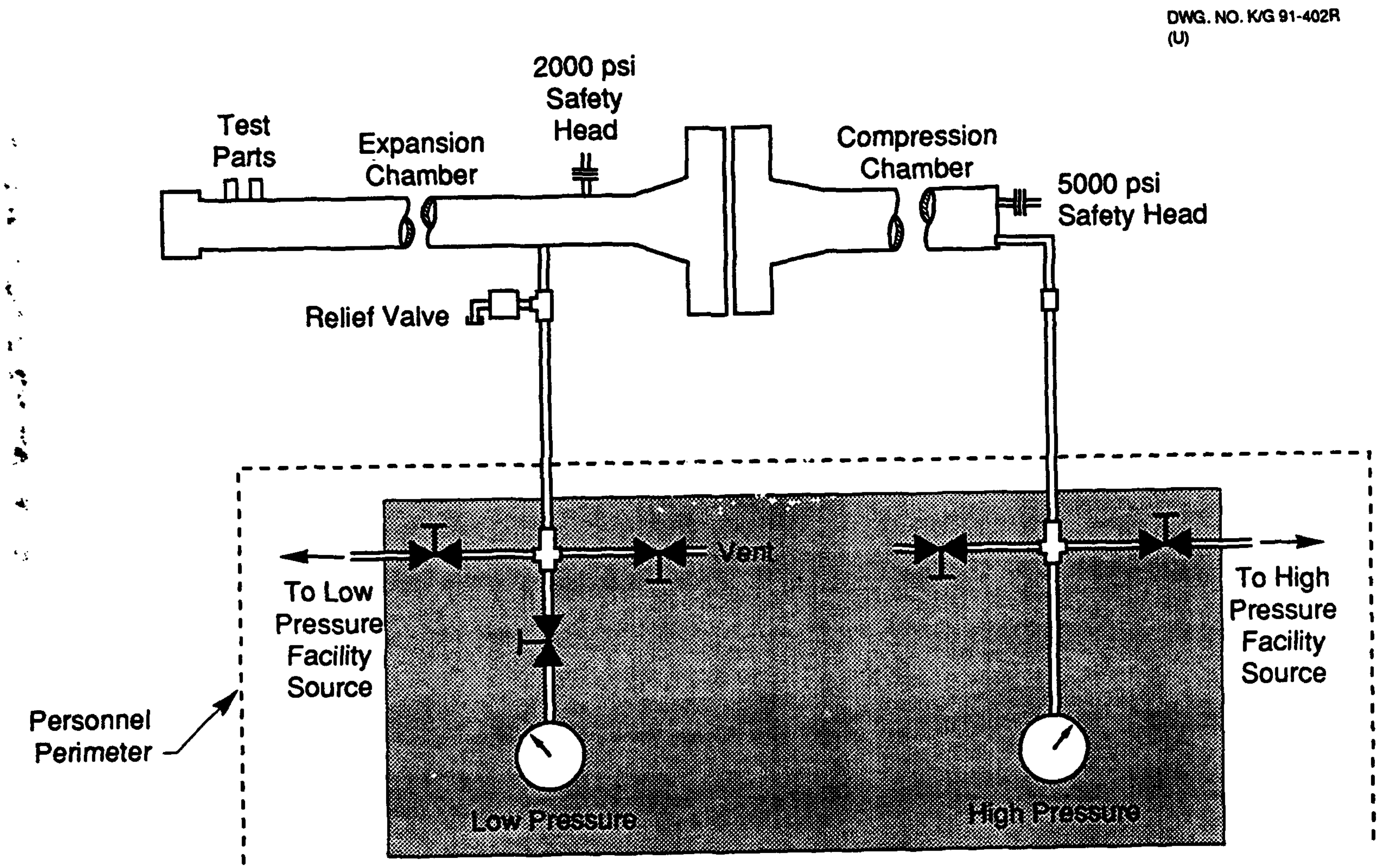

Figure 6. Schematic of Gas Control Panel and Connections.

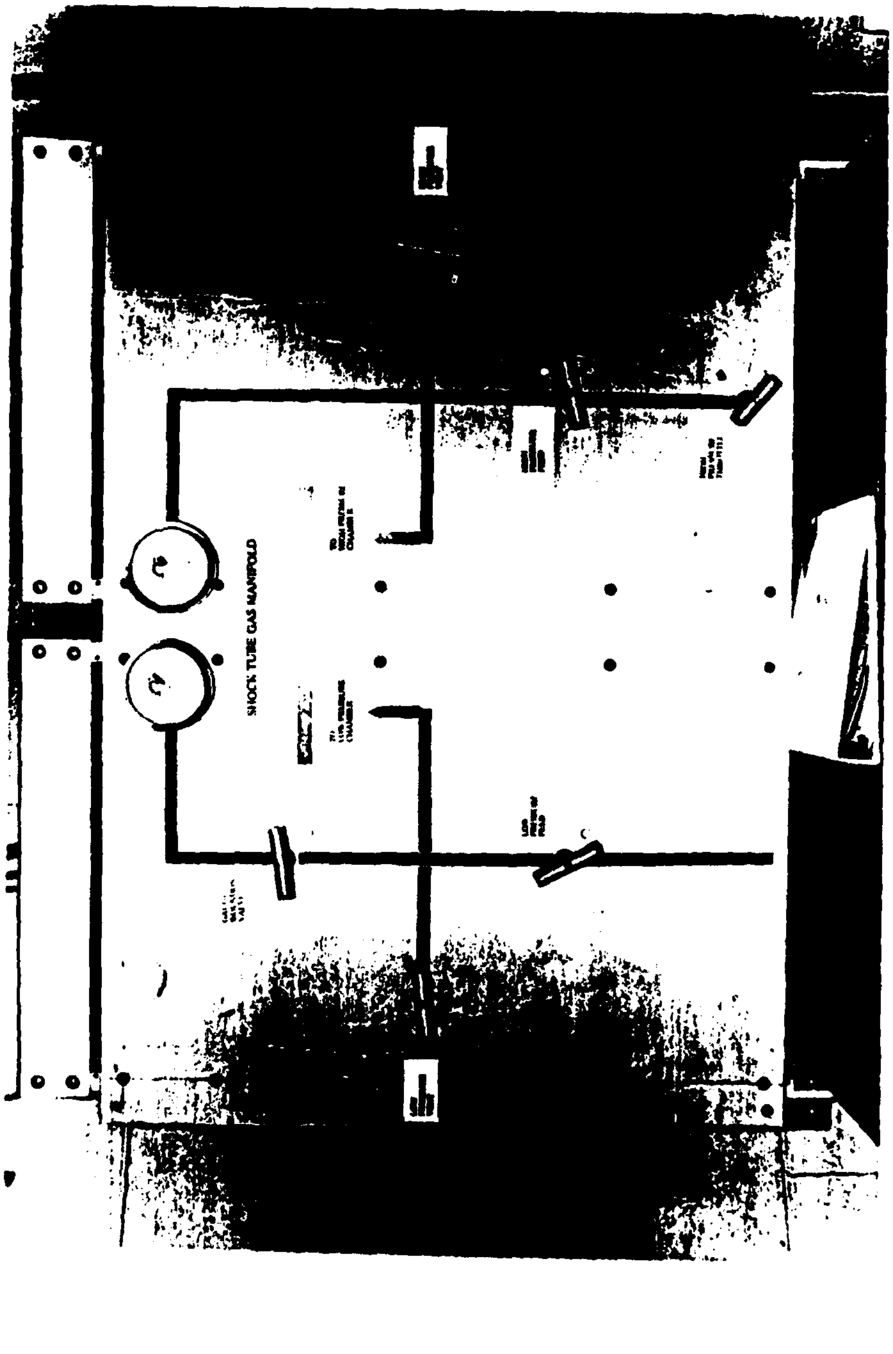

Figure 7. Photograph of Gas Control Panel.

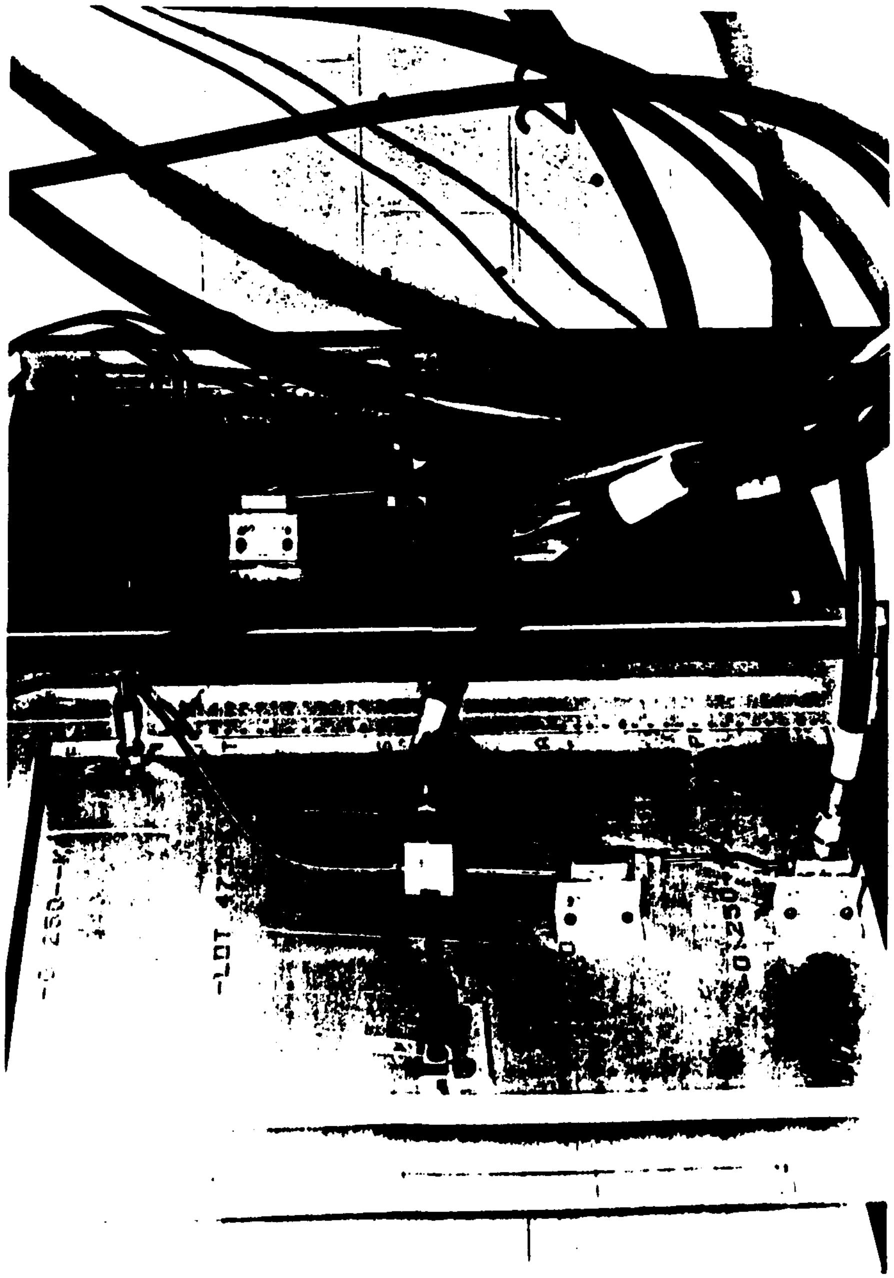

Figure 8. Photograph of Backside of Gas Control Panel.

connected to the backside of the shock tube gas control panel. Standard fittings are used.

Blueprint drawings are listed in Table 2 to facilitate reference to them. In the terminology of these documents, "chamber" designates the compression section of the shock tube, while "test section" refers to the expansion chamber.

TABLE 2. LIST OF DRAWINGS

Drawing Title and Description	Drawing Number
1. Shock Tube Shock Test Assembly; schematic of entire assembly	M1E-MWE-0060001
2. Shock Tube Assembly; schematic for assembly of shock tube	M1E-MWE-0060002
3. Shock Tube Weldment; weldment of rupture flange and test ports	M1E-MWE-0060003
4. Shock Tube Details; expansion chamber details	M1E-MWE-0060004
5. Shock Tube Rupture Disk Assembly; detail of rupture disk assembly	M1E-MWE-0060005
6. Shock Tube Stand (Test Section) Assembly; test stand details (test section)	M1E-MWE-0060006
7. Shock Tube Chamber Stand Assembly; test stand details (compression chamber)	M1E-MWE-0060007
8. Shock Tube Stand (Test Section) Weldment; welding detail for test stand	M1E-MWE-0060008
9. Shock Tube Stand (Chamber End) Weldment; welding detail of compression chamber end of test stand	M1E-MWE-0060009
10. Shock Tube Details; details of threads and holes	M1E-MWE-0060010
11. Shock Tube Details; support saddle and retainer	M1E-MWE-0060011
12. Shock Tube Details; details of test stand rails	M1E-MWE-0060012
13. Shock Tube Installation Schematic; plumbing details for manifold and shock tube connections	M1E-MWE-0060013

SECTION III

SAFETY CONSIDERATIONS IN OPERATION

A. INTRODUCTION

This section discusses the hazards and safety considerations associated with operating the shock tube, based on a review by the Process Engineering Safety Analysis Department at Martin Marietta Energy Systems, Inc., Oak Ridge, Tennessee.

The hazards of shock tube operation are the same as those common to all high-pressure equipment. Persons may be injured when a pressurized vessel (e.g., the shock tube; a compressed gas cylinder; or a high-pressure hose, tube, or valve) ruptures. Rapid rupture may be accompanied by the production of debris that could inflict injuries. The high-velocity gas flow emanating from a ruptured vessel could injure skin tissue or produce noise levels sufficient to damage eardrums. Ruptured hoses or tubing could whip around and strike persons nearby.

B. CONSTRUCTION AND OPERATING PARAMETERS

The shock tube chambers were made from Number 304 stainless steel bar stock. Both chambers have an inside diameter of 7.6 cm. The compression chamber was bored in 11.4-cm-diameter stock, is 1.2 meters long, and has a pressure rating of 34,500 kPa (5,000 psi). The expansion chamber was bored in 8.9-cm-diameter stock, is 3.8 meters long, and has a pressure rating of 13,800 kPa (2,000 psi). The flange assembly (BS&B Safety Systems) was welded to the chambers, and the welds were inspected as required by QA-0-JS-51 (1985). The open end of the expansion chamber is threaded and a cap machined from Number 304 stainless steel functions as the end wall. One instrumentation port was fabricated on the end wall of the compression chamber, four instrumentation ports were fabricated on the side wall of the expansion chamber, and one instrumentation port was fabricated in the expansion chamber end cap.

The shock tube assembly is mounted on stands so it is free to slide axially upon rupture of the diaphragm. The assembly is restrained from vertical motion. The tube recoil, which is canceled by the reflection of the shock wave at the end of the expansion chamber, produces approximately 5 mm of motion in the horizontal direction. Residual motion is damped by rubber shock absorbers.

The compression chamber is pressurized through a flexible hose (Dayco) that is rated at a working pressure of 37,900 kPa. The flow rate is controlled by metering and shutoff valves. Pressure relief for the compression chamber is provided by a burst disk designed to pop open at 34,500 kPa or less. The expansion chamber is also pressurized through a flexible hose, and the flow is controlled by a shutoff valve. All valves are connected with high-pressure-rated steel tubing. Two pressure relief devices are provided for the expansion chamber; one is a burst disk designed to pop open at 13,800 kPa, and the other is a relief valve set at a release pressure of 11,000 kPa. These relief devices prevent operation of the chambers above their rated working pressures.

The pressurization and venting of the shock tube are remote-controlled. Manually operated valves and pressure gauges are located on a gas manifold operated from behind bunkers or in another room.

The shock tube was designed to operate within the safety specifications given in Table 3, and it was hydrostatically tested before its initial use.

TABLE 3. SHOCK TUBE SAFETY SPECIFICATIONS.

Compression chamber gas	Helium
Expansion chamber gas	Air
Initial compression chamber pressure	31,000 kPa, maximum
Initial expansion chamber pressure	700 kPa, nominal
Initial gas temperatures	293 K (20°C)
Final pressure in both chambers	7,700 kPa
Mach number in incident shock wave	3
Pressure behind incident shock wave	5,560 kPa
Pressure behind reflected shock wave	24,500 kPa

While operating the shock tube, the maximum stress occurs in the threads of the end cap on the expansion chamber. The calculated maximum stress is on the order of 70,000 kPa and it occurs for approximately 1 ms. This stress is well below the yield strength for annealed Number 304 stainless steel, and a rupture of the end cap is unlikely. The shock tube is designed for a lifetime of 10^4 cycles; since the tube will probably be used much less than this, fatigue failure is unlikely.

The shock tube design and its operation in the Oak Ridge facilities were approved by the Committee for High Pressure Safety at Martin Marietta Energy Systems, Inc., Oak Ridge, Tennessee.

C. ANALYSIS OF SHOCK TUBE HAZARDS

Shock tubes and high-pressure equipment are in widespread industrial use, and the associated hazards are considered to be standard industrial hazards. Standard safety practices and engineering and administrative controls are sufficient to prevent mishaps and other injuries. Engineering controls include the use of restraints for compressed gas cylinders and lines, fail-safe pressure relief devices, and equipment rated for use at the maximum working pressure. Administrative controls include the implementation of periodic equipment inspections and a requirement that the shock tube be operated from a shielded, remote location.

D. ENERGY CONTENT OF SHOCK TUBE

The analysis of this section is to quantify the maximum amount of energy content in the shock tube. The shock tube built for Tyndall Air Force Base is a test device consisting of a high-pressure section separated from a low-pressure section by a breakable diaphragm. In normal operation, the diaphragm is ruptured after the high-pressure section is pressurized, delivering a shock wave into the gas which fills the low-pressure side of the tube.

Normally, the energy contained within a system dictates the shielding or isolation requirements for personnel operating the system. The energy content of the system must be estimated to provide a basis for determining the precautions needed.

The tube is configured with rupture disk assemblies to limit the pressure which can be reached in each of the sections. The high-pressure rupture disk (located in the high-pressure section) has a 5,000-psi rupture pressure. The low-pressure side of the shock tube has a 2,000-psi disk assembly.

Assuming that the rupture disks are functional, two scenarios are possible: (1) unexpected failure of the high-pressure section at 5,000 psi, or (2) inadvertent pressurization of the whole tube assembly to 2,000 psi accompanied by unexpected failure. The worst case for pressurization would be isentropic compression from room temperature to a failure with no time for loss of energy from cooling. This is assumed in the following calculations. Tabulated values from Reference A-1 are used.

The pressure and, consequently, the total energy which can be placed into the shock tube by mistakes in operation or by malfunction can be limited by a number of means. Limiting the pressure of supply gas bottles or pumping systems permitted in the facility can limit the total energy, irrespective of mistakes or malfunctions. Additional rupture disks or relief valves can also be added to provide more backup relief systems.

1. Scenario 1 - Abrupt Failure

Abrupt failure of high-pressure section at 5,000 psi. Estimate of energy content of high-pressure section at 5,000 psi.

High-pressure section volume = 3 in. diam x 33 in. long
= 233.3 $in.^3$
= 0.1399 ft^3

1 lb mole He = 4 lb

Density of He at 1 atm = 0.0104 lb_m/ft^3

Density of He at 5,000 psi = 0.0104 x (5,000/14.7)
= 3.53 lb_m/ft^3

From Reference A-1: Change in internal energy = 13,404 BTU/lb-mole (from ambient to 5,000 psi)

Energy content = 13,404 x (0.1399 x 3.53)/4 BTU
= 1,645 BTU
= 1,287,497 ft-lb_f
= 1.733 MJ
(approx. 0.41 kg TNT equivalent)

2. Scenario 2 - Inadvertent Pressurization

Inadvertent pressurization of whole tube to 2,000 psi. Estimate of energy content of whole shock tube assembly at 2,000 psi.

Total tube volume = 3 in. diam x 149 in. long
= 1057.5 $in.^3$
= 0.61 ft^3

1 lb mole nitrogen = 28 lb

Density of nitrogen at 1 atm = 0.0732 lb_m/ft^3

Density of nitrogen at 2,000 psi = 9.96 lb_m/ft^3

From Reference A-1: Change in internal energy = 8,110 BTU/lb-mole (from ambient to 2,000 psi)

Energy content = 8,110 x (0.61 x 9.96)/28 BTU
= 1,759 BTU
= 1,369,096 ft-lb_f
= 1.855 MJ
(approx. 0.44 kg TNT equivalent)

SECTION IV

SETUP AND ASSEMBLY

A. SHOCK TUBE AND GAS-HANDLING MANIFOLD

1. Location

The shock tube test stand occupies a space of approximately 5 meter by 1 meter. It is about 1 meter high. The connections for the hose from the gas-handling manifold are at the compression end of the shock tube. As shown in Figure 6, a short length of hose connects from the compression and expansion tubes respectively, to longer hoses. The shock tube should be oriented with the compression end closest to the gas-handling manifold. As stated in Section III, Safety Considerations in Operation (p. 13), the gas manifold and operators should be located with a barrier between them and the shock tube.

2. Test Stand Assembly

The shock tube test stands are bolted onto a pair of rails. The ends of the rails, with two sets of bolts for accommodating two of the test stands, correspond to the compression end. One test stand is located at the far end of the expansion tube. This is seen in Figure 3.

3. Shock Tube Clamps

The tubes are secured to the test stands on which they rest by a set of clamps. The bottom of each clamp bolts to the test stand (foreground of Figure 3).

4. Compression and Expansion Tubes

The compression and expansion tubes are placed on the test stands and the top part of each clamp is attached to secure each tube. The tube sits on roller bearings and can move axially when needed. To insert a burst disk, the tubes can be separated a sufficient length to insert the disk.

5. High-Pressure Hoses

Two short sections of hose connect to the compression and expansion tubes as in the background of the Figure 3. A longer hose connects directly to one of the short hoses at one end and the gas-handling manifold at the other. A pressure relief valve is situated between the long hose and the short hose which is connected to the expansion tube.

6. Pressure Vessel Connections

The gas supply for the compression tube connects directly to the backside of the gas-handling manifold (to the lower left side fitting) as shown in Figure 8. Similarly, the expansion tube is supplied by connection to the backside of the gas-handling manifold fitting on the lower righthand side.

B. ELECTRONICS

Any digital oscilloscope capable of digitizing and following events with a 10-μs rise time should be adequate for recording the output of sensors that measure the shock wave pressure transients produced by this shock tube.

SECTION V

OPERATIONS

A. OVERVIEW

The following is a checklist for operation of the shock tube. The purpose of this list, in addition to enabling successful pressure sensor testing, is to assure the safety of personnel, equipment, and facilities.

NOTE

WHEN THE PRESSURE IS ABOVE ATMOSPHERIC IN THE SHOCK TUBE, ALL PERSONNEL IN THE GENERAL AREA ARE REQUIRED TO BE BEHIND THE PROTECTIVE WALL.

B. PRESHOT PREPARATIONS

1. _____ Ensure vent valves to both sections are open.
2. _____ Ensure low-pressure gauge service isolation valve is open.
3. _____ Ensure that facility gas supplies are valved **OFF**.
4. _____ Clean flange surfaces and assure they are in good condition.
5. _____ Center test diaphragm on flange and make ready for mating of flanges.
6. _____ Inspect, lubricate, and install flange bolts, and then tighten to 150 ft-lb torque. **(Note: Gloves are required for this activity.)**
7. _____ Orient shock tube assembly with ports aligned in the upward direction.
8. _____ Securely fasten the four shock tube assembly clamps.
9. _____ Wrap Teflon® tape on threads of all port fittings and plugs.
10. _____ Check all port fittings for tightness.
11. _____ Hook up all instrumentation cables, fibers, etc., for the specific test correctly and assure they are in working order.
12. _____ Position mobile shielding sections (if they are required) around shock tube assembly.

13. _____ Clean test area for easy access and egress.

14. _____ Visually inspect high-pressure hoses and connectors to assure they are operable. Fittings should be tight and hose restraints placed as required.

C. PRESSURIZATION SEQUENCE

1. _____ Inspect test area. Clear test area of personnel. Post or tag entry.

2. _____ Assure that all valves on gas control panel are in the closed position.

3. _____ Open low-pressure gauge isolation valve.

4. _____ Check to assure that gas cylinder(s) pressure(s) is adequate for conducting proposed test.

5. _____ Open facility gas supply valves and manifold valves between supply and the gas control panel.

6. _____ Throttle the gas supply block valve on the gas control panel to assure pressurization. (Pressurization is done while observing gauges.) Close valve when desired pressure is reached. The low-pressure vent may be used to lower pressure.

7. _____ Close low-pressure gauge isolation valve.

8. _____ Pressurize the high-pressure side gradually by opening the gas supply block valve and throttling the gas supply needle valve located on the control panel. (Pressurization is done while observing gauges.)

9. _____ Record rupture pressures.

10. _____ Immediately after rupture, close high-pressure gas supply block valve.

D. PRESSURE RELIEF SEQUENCE

1. _____ Ensure both supply block valves are closed.

2. _____ Record postrupture equilibrated pressure.

3. _____ Close facility gas cylinder valve(s) and assure regulator adjustment has backed off completely.

4. _____ Slowly release pressure from shock tube using either of the vent block valves located on control panel.

5. _____ Open both vent valves (one previously opened).

6. _____ Reopen test area after venting is completed.

E. POSTSHOT CLEANUP AND MAINTENANCE

1. _____ Ensure facility gas supplies are closed.

2. _____ Close gas supply block valves on control panel.

3. _____ Check/open vents (both high and low pressure).

4. _____ Remove debris from previous shot.

5. _____ Clean and check threaded joints in preparation for next shot.

F. ABORTED SHOT

1. _____ Close both gas supply block valves.

2. _____ Vent **BOTH** sections.

3. _____ Check gauges to certify the pressure is atmospheric and verify cessation of flow from vents.

4. _____ Secure facility gas supply valves.

5. _____ Reopen test area.

G. LONG-TERM SECURING OF SYSTEM FOR STORAGE OR MAINTENANCE

1. _____ Open low-pressure gauge isolation valve.

2. _____ Close facility gas supply system valves.

3. _____ Open both vent valves to ensure shock tube is vented.

4. _____ Open both gas supply block valves to vent volume trapped between facility supply cutoff and shock tube system.

SECTION VI

MAINTENANCE

There are no maintenance requirements for the shock tube beyond what is normal for laboratory equipment.

APPENDIX A

EXPLANATION OF SHOCK PARAMETER RELATIONSHIPS

Properties of shock waves produced in shock tubes are discussed here. References A-2 and A-3 provide a more complete discussion of shock tube dynamics and a derivation of the equations.

The essential shock wave properties can be calculated from a few equations. The basic shock tube parameter is the shock strength, given by

$$y = p_1/p_0 \ , \qquad \text{(A-1)}$$

where p_0 is the initial pressure in the expansion chamber and p_1 is the pressure behind the shock wave. The shock strength is obtained by solving the shock tube equation

$$\frac{c_0}{c_3}\frac{(1-\mu_0)(y-1))}{\sqrt{[(1+\mu_0)(y+\mu_0)]}} = \frac{2}{(\gamma_3-1)}\left[1-\left(\frac{p_0}{p_3}y\right)^{\beta}\right] , \qquad \text{(A-2)}$$

where

p_3 is the initial pressure in the compression chamber,
γ_0 and γ_3 are the heat capacity ratios,
$\mu_0 = (\gamma_0-1)/(\gamma_0+1)$,
$\beta = (\gamma_3-1)/2\gamma_3$, and
c_0 and c_3 are the acoustic velocities.

Acoustic velocities are obtained from the Lagrangian formula

$$c = (\gamma RT/MW)^{1/2} \ , \qquad \text{(A-3)}$$

where R is the universal gas constant ($8314.3\ J \cdot kmole^{-1} \cdot K^{-1}$), T is the absolute temperature, and MW is the molecular weight. Table A-1 lists values of MW and γ for various gases.

TABLE A-1. VALUES OF MW AND γ FOR VARIOUS GASES.

Gas	MW (kg/kmole)	γ
air	28.934	1.40
N_2	28	1.40
He	4	1.66
Ne	20	1.64
Ar	40	1.67

When y has been obtained from the solution of Equation (A-2), the velocity U of the shock front can be calculated from

$$U = c_0 M = c_0 \sqrt{\frac{y+\mu_0}{1+\mu_0}} , \qquad \text{(A-4)}$$

where M is the shock Mach number. The shock wave flow velocity u_1 can be calculated from

$$u_1 = c_0 \frac{(1-\mu_0)(y-1)}{\sqrt{[(1+\mu_0)((y+\mu_0)]}} . \qquad \text{(A-5)}$$

The pressure p_1' of the shock wave after it is reflected by the rigid wall at the end of the expansion chamber is given by

$$p_1' = y p_0 \frac{(2\mu_0+1)y-\mu_0}{\mu_0 y+1} . \qquad \text{(A-6)}$$

Note that for very strong shock waves (y > 1), the pressure in the reflected wave appoaches the asymptotic value $2+1/\mu_0$. For air ($\mu_0 = 1/6$) this value is 8.

Equations (A-1) through (A-6) have been used in the computer program listed in Appendix B to obtain calculated values of the properties of shock waves generated in the shock tube.

REFERENCES

A-1. Keenan, J. H., J. Chao, and J. Kaye, Gas Tables, Table 11, pp. 90-93, John Wiley, New York, New York, 1980.

A-2. Wright, J. K., Shock Tubes, pp. 29-39, John Wiley, New York, New York, 1961.

A-3. Liepmann, H. W. and A. Roshko, Elements of Gas Dynamics, pp. 79-83, John Wiley, New York, New York, 1957.

APPENDIX B

COMPUTER PROGRAM FOR CALCULATING PROPERTIES OF SHOCK WAVES

The following is an annotated listing of a MathCAD® (MathSoft, Inc., Cambridge, Mass.) program that calculates the properties of shock waves generated in the shock tube.

SHOCK.MCD - Calculation of shock wave properties using formulas given in J. K. Wright, Shock Tubes, New York, John Wiley, 1961.
D. B. Smith, ORNL/ATD, November 1990

Define shock tube parameters (0 and 3 designate expansion chamber and compression chamber, respectively)

heat capacity ratios	$g0 := 1.40$ (air)	
	$g3 := 1.66$ (He)	
initial pressures	$p0 := 15 \cdot psia$	$p0 = 103.4 \cdot kPa$
	$p3 := 815 \cdot psia$	$p3 = 5619 \cdot kPa$
initial temperatures	$T0 := 293 \cdot K$	
	$T3 := T0$	
molecular weights of gases	$MW0 := 28.934 \cdot \frac{kg}{kmole}$	$MW3 := 4 \cdot \frac{kg}{kmole}$
universal gas constant	$R := 8314.3 \cdot \frac{J}{kmole \cdot K}$	
acoustic velocities	$c0 := \sqrt{\frac{g0 \cdot R \cdot T0}{MW0}}$	$c3 := \sqrt{\frac{g3 \cdot R \cdot T3}{MW3}}$

Solve for shock strength y (Wright Eq. 3.1)

$$\mu 0 := \frac{g0 - 1}{g0 + 1} \qquad \beta := \frac{g3 - 1}{2 \cdot g3}$$

$$f(y) := root\left[\left[\frac{c0}{c3}\right] \cdot \left[\frac{(1 - \mu 0) \cdot (y - 1)}{\sqrt{(1 + \mu 0) \cdot (y + \mu 0)}}\right] - \left[\frac{2}{g3 - 1}\right] \cdot \left[1 - \left[\left[\frac{p0}{p3}\right] \cdot y\right]^{\beta}\right], y\right]$$

Initial guess for y	$y := 11$
Solution for y	$y := f(y)$
	$y = 11.432$

Calculate pressure behind shock wave

$$p1 := y \cdot p0$$ (Wright, Eq. 2.24)

$p1 = 1.182 \cdot 10^{3} \cdot kPa$ $\quad$ $p1 = 171.485 \cdot psia$

Calculate velocity of shock front

$$M := \sqrt{\frac{y + \mu 0}{1 + \mu 0}}$$ shock Mach number

$$U := c0 \cdot M$$

$$U = 1.083 \cdot 10^{3} \cdot \frac{m}{s}$$

Calculate flow velocity behind shock wave

$$u1 := c0 \cdot \frac{(1 - \mu 0) \cdot (y - 1)}{\sqrt{(1 + \mu 0) \cdot (y + \mu 0)}}$$ (Wright, p. 32)

$$u1 = 811.378 \cdot \frac{m}{s}$$

Calculate pressure behind reflected shock wave

$$p1r := \left[\frac{(2 \cdot \mu 0 + 1) \cdot y - \mu 0}{\mu 0 \cdot y + 1}\right] \cdot p1$$ (Wright, Eq. 6.5)

$p1r = 6.136 \cdot 10^{3} \cdot kPa$ $\quad$ $p1r = 889.86 \cdot psia$

Unit definitions (SI system)

$kg \equiv 1M$ $\quad$ $m \equiv 1L$ $\quad$ $s \equiv 1T$

$N \equiv kg \cdot \frac{m}{s^{2}}$ $\quad$ $kPa \equiv 10^{3} \cdot \frac{N}{m^{2}}$ $\quad$ $psia \equiv 6.895 \cdot kPa$

$K \equiv 1$ $\quad$ $kmole \equiv 1$ $\quad$ $J \equiv N \cdot m$