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14. ABSTRACT

This Test Operations Procedure (TOP) provides guidance for conducting simulated free-field blast overpressure testing using an open-end compressed-gas-driven shock tube. Procedures are provided for instrumentation, test item positioning, estimation of key test parameters, operation of the shock tube, data collection, and reporting. The procedures in this document are based on the use of helium gas and Mylar® film diaphragms.

15. SUBJECT TERMS

ATD, Burst Pressure, Compressed Gas, Diaphragm, Impulse, Incident Pressure, Pressure Transducer, Shock Tube, Shock Wave Velocity

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U.S. ARMY TEST AND EVALUATION COMMAND
TEST OPERATIONS PROCEDURE

*Test Operations Procedure 10-2-400 18 June 2018
DTIC AD No.

OPEN-END COMPRESSED-GAS-DRIVEN SHOCK TUBE

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1. SCOPE.

This Test Operations Procedure (TOP) provides guidance for conducting simulated free-field blast overpressure testing using an open-end compressed-gas-driven shock tube. The procedures in this document are based on the use of helium gas and Mylar®** film diaphragms. Use of other driver gases and diaphragm materials may invalidate the recommendations provided. Due to the likelihood of special test requirements, test setups, item instrumentation and conditioning, an approved test plan should be used in conjunction with this test operations procedure. The primary units of measure in this TOP are generally U.S. Customary, with the exception of units of Impulse, where kilopascal-milliseconds (kPa-ms) is considered primary. International System of Units (SI) are presented parenthetically throughout as an acceptable secondary unit of measure.

2. FACILITIES AND INSTRUMENTATION.

2.1 Facilities.

Item	Requirement
Indoor test facility	Accommodations for the shock tube, compressed gas cylinders, and test area. Sufficient distance from surfaces and walls should be provided to limit unwanted wave reflections during testing.
Shock tube	Appropriately pressure rated tube(s) of circular or rectangular cross-section consisting of driver, expansion (optional), and driven sections. The driver and driven section can be separated at a breech to enable diaphragm insertion.
Compressed helium (He) gas cylinder(s)	Cylinder capacity varies. Driver gas cylinders should be acclimated to facility conditions for a minimum of 24 hours prior to testing.
Pressure gauges, valves, and regulators	For monitoring gas cylinder (bottle) pressure and controlling air and gas flow.
Key-interlock valve control box	Key-controlled box for operating fill and dump stages of the firing procedure from a safe distance.

** The use of brand names does not constitute endorsement by the Army or any other agency of the Federal Government, nor does it imply that it is best suited for its intended application.

Item	Requirement
Diaphragm	Thin polymeric or metallic film such as Mylar® (polyester), aluminum, copper, steel, or similar. Coated woven materials can also be used. Stacked layers of different materials and thicknesses can be employed to vary burst pressure and rupture patterns for tailoring of shock wave characteristics.
Gasket	Breach seal(s) for the diaphragm made from highly compressed cardboard and rubber or similar materials. Inserted on both driver and driven surface ends of the breach.
Compressed air source	For powering the pneumatic valve setup, tools, and devices.
Hydraulic pump (optional)	For powering automated hydraulic breach closure device.
Lifting devices including cranes, hoists, straps, chains, and lift tables	Appropriately load rated devices for moving of large test items, test devices, and for reconfiguration and maintenance of the shock tube.

2.2 Instrumentation.

Data Element	Devices	Permissible Uncertainty
Temperature	Fluke 1620A Thermo-Hygrometer	± 0.5 ° Fahrenheit (°F) ((± 0.25 °Celsius (°C))
Humidity	Fluke 1620A Thermo-Hygrometer	± 2 % Relative Humidity (RH)
Burst pressure (driver section)	Endevco 8530B series pressure transducer	± 1 % Full Scale (FS)
Incident pressure (driven tube)	Endevco 8530C/ PCB 102A series pressure transducer	± 1 % FS
Incident pressure (pencil probe)	PCB 137A series pressure transducer	± 1 % FS
Reflected pressure (plate)	PCB 102A series pressure transducer	± 1 % FS

Data Element	Devices	Permissible Uncertainty
Acceleration (Hybrid III head)	Endevco 7270A-6K accelerometer	± 5 % FS
Angular Rate (Hybrid III head)	DTS ARS-50K angular rate sensor	± 1 % FS
Pressure (Hybrid III head)	Endevco 8530B series pressure transducer	± 1 % FS
Force (Hybrid III head)	Not typically measured. Six axis load cell is available for the Hybrid III neck (Fx, Fy, and Fz (force); Mx, My, and Mz (moment))	± 1 % FS

3. REQUIRED TEST CONDITIONS.

3.1 Environmental Test Conditions.

Testing will be performed at ambient conditions of 68 ± 10 °F (20 ± 5.6 °C) and 50 ± 20 percent RH unless otherwise specified by the customer or by requirements documents. Temperature and humidity conditions will be recorded before the beginning of each subtest. Test items will be acclimated to the required test conditions according to an approved test plan.

3.2 Test Sample Size Considerations.

The number of samples required will be determined based on test requirements, size of the test items, and the allowable number of shots per sample per the requirements documentation. Adequate spare test samples will be provided to allow for retest to account for the occurrence of "no tests" during test execution.

3.3 Test Setup.

An operational schematic for a typical compressed-gas-driven shock tube is shown in Figure 1. The tube consists of high and low pressure sections separated by a frangible diaphragm that is inserted via a breach between the sections. Driver gas, in this case helium, is released from a pressurized gas tank into the driver section in the rear. Pressure increases in the chamber which causes the diaphragm to expand until rupture. This creates a near instantaneous increase in pressure in the driven section of the tube, containing ambient air, causing a shock wave front to propagate down the tube. Test items are placed outside of the tube at the muzzle end of the driven section and are exposed to the shock wave as it exits the tube.

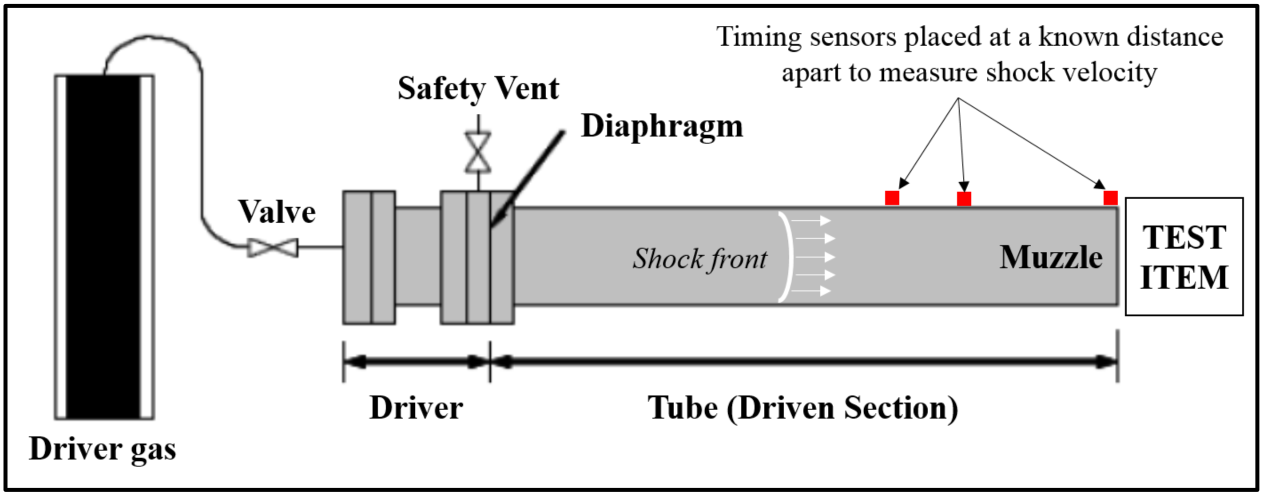


Figure 1. Simplified operational schematic of an open-ended compressed-gas-driven shock tube.

3.3.1 Range Preparation.

Test equipment shall be setup as shown in Figure 1 and in accordance with Section 3.4

3.3.2 Equipment.

3.3.2.1 Shock Tube.

The open-end compressed-gas-driven shock tube at the U.S. Army Aberdeen Test Center (ATC) is shown in Figure 2. Diameters of the driver and tube are both 12 inch (in.) (30.5 centimeters (cm)), and their respective lengths are 12 in. and 120 in. (30.5 cm and 305 cm). The shock tube driver has a maximum operating pressure of 1000 pounds per square inch (psi) (6900 kilopascals (kPa)). The tube can be operated in two breach closure configurations depending on the burst pressure of the test event; hydraulic closure (up to 500 psi (3450 kPa) burst pressure) or, bolted closure (up to 1000 psi (6900 kPa) burst pressure). Ten pressure transducers (pressure sensors) are flush mounted with the inside tube wall at four locations along the length. Sensor 0 is located in the driver for measuring diaphragm burst pressure. Sensors 1-9 are divided into three groups of three located near the muzzle. These sensors measure shock velocity and incident pressure inside the tube. Each group of sensors is evenly spaced around the circumference of the tube on planes perpendicular to the long center axis. Sensors 1-3 (Group M) are located 0.5 in. (1.27 cm) from the end of the muzzle. Sensors 4-6 (Group A) and sensors 7-9 (Group B) are located 24 in. (61 cm) and 36 in. (91.4 cm) respectively from the end of the muzzle.

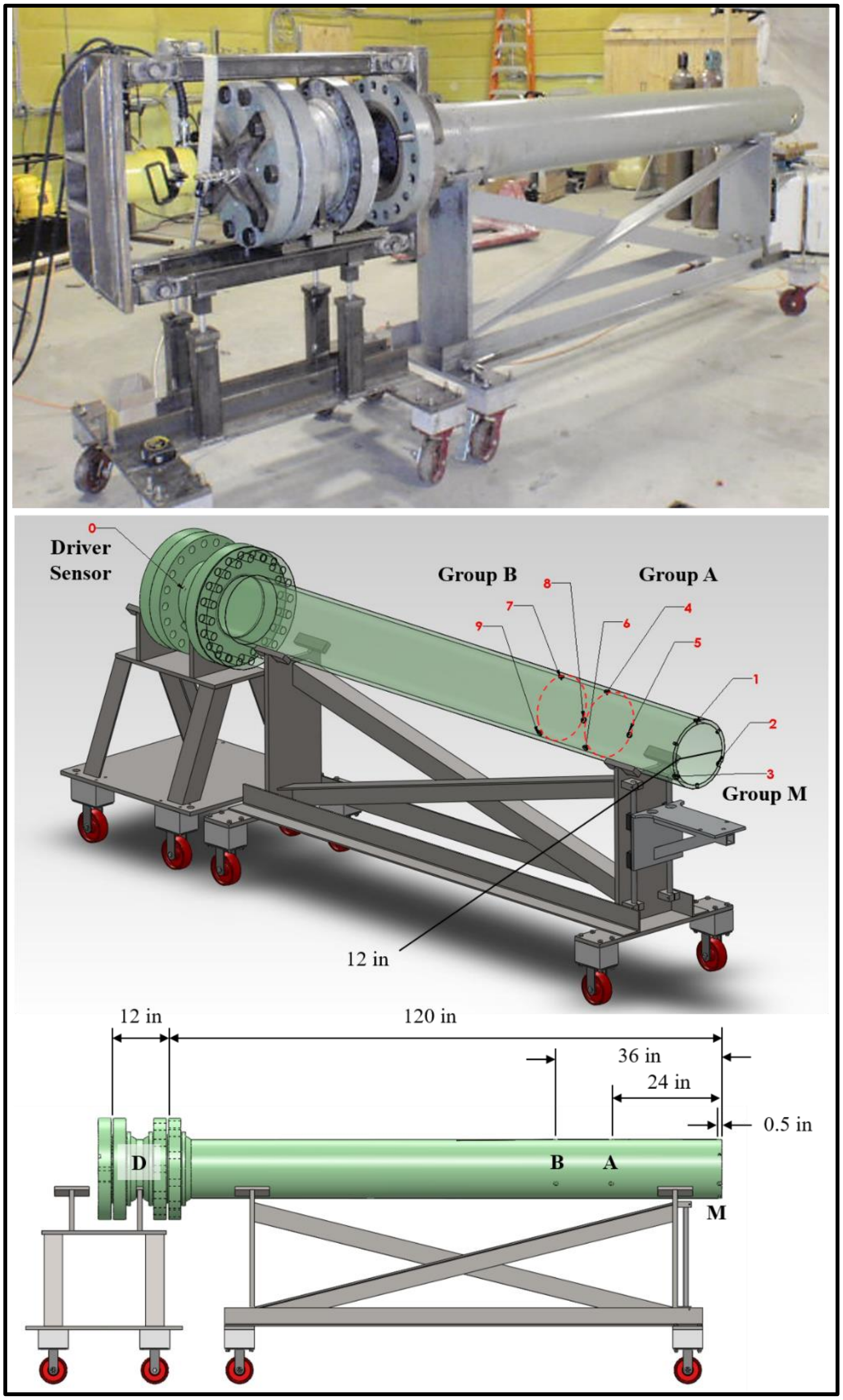


Figure 2. Shock tube at the ATC (top). Computer-Aided-Design (CAD) model renderings of the tube design showing locations of the pressure transducers (center) and the dimensions of the tube (bottom).

3.3.2.2 Gas Management System.

The gas management system, shown in Figure 3 consists of gas tank storage racks, the gas tank manifold, and connecting lines from the manifold to the pneumatic valves which charge the shock tube during the firing procedure. The manifold connects all of the gas tanks in the rack via multiple connecting lines as shown in Figure 3. A single tank is "open" at any given time during operation, the valves on all other tanks are in the closed position. When a tank valve is opened gas flows into the manifold and out to the pneumatic valve setup. The manifold can be easily interchanged to a new tank rack when tank volumes become low.

Figure 3. Gas management system (left) and close up of the gas manifold (right).

3.3.2.3 Pneumatic Valve Setup.

The pneumatic valve setup is shown in Figure 4. The inlet gas line from the gas manifold feeds the valve setup from the gas tank storage rack. Bottle pressure in the gas tank, which is providing driver gas to the system, can be read via the inlet pressure gauge. Dump and fill valves control the flow of gas during the firing procedure and are connected to the key-interlock valve control box by the control wire. In standby (normal) condition, the dump valve is open to the atmosphere allowing gas to vent from the valve system. The fill valve is normally closed. The fill gas line connects the valve setup to the shock tube and carries the gas to the driver section / chamber of the shock tube during the firing procedure. Air supply lines provide compressed air to the pneumatic control valves for the dump and fill stages of the firing procedure. The bleed valve can be opened to depressurize the inlet gas line from the gas manifold.

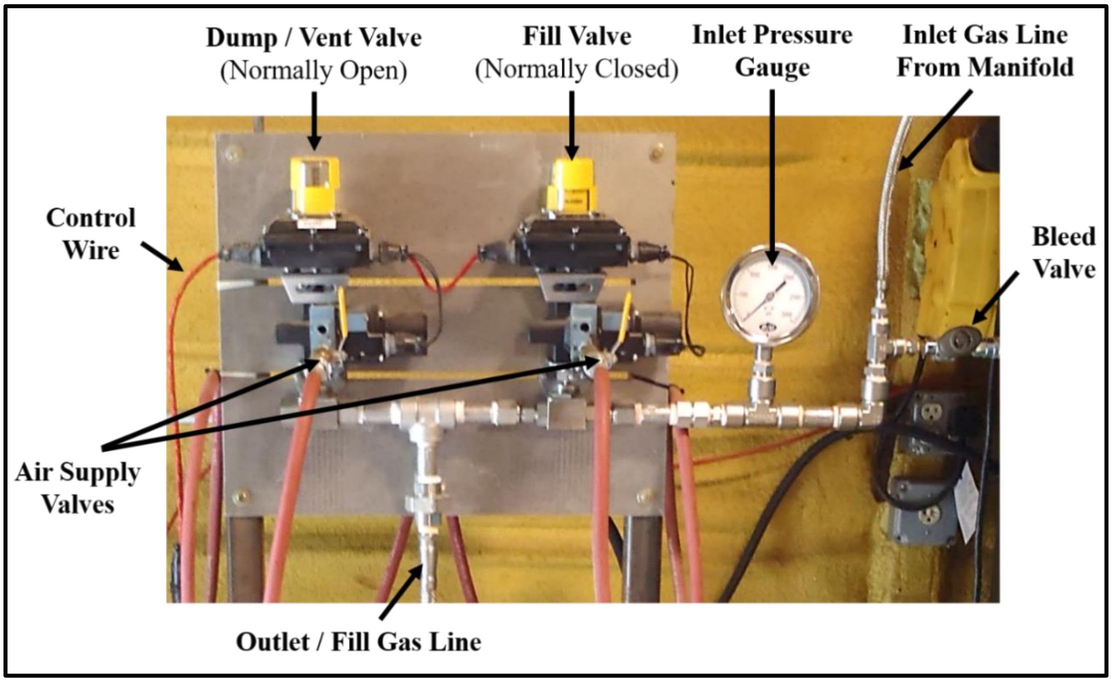


Figure 4. Pneumatic valve setup.

3.3.2.4 Key-Interlock Valve Control Box.

The key-interlock valve control box used for remote operation of the shock tube is shown in Figure 5. The control box is connected to the pneumatic valve setup via the control wire. The key-interlock is located in the upper right corner and can enable or disable the system using the control key. Fill and atmospheric dump buttons are located on the bottom of the panel. Above the fill and dump buttons are green and red lights. The green lights (fill closed and dump open) are the default condition that the box will initiate in when the power switch is turned on, indicating the system is in standby mode. The red lights (fill open and dump closed) will illuminate after the control key is inserted, turned to enable, and the firing buttons (fill and dump) are pressed.

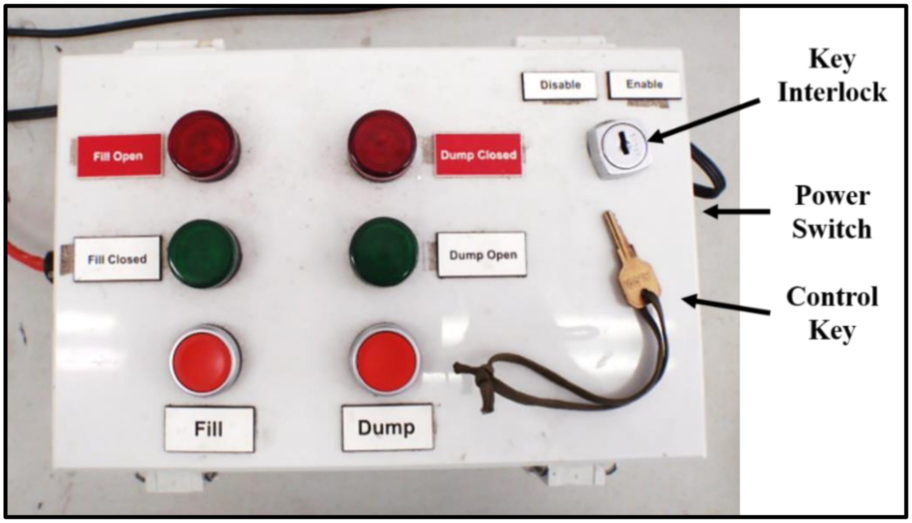


Figure 5. Shock tube key-interlock valve control box.

3.3.2.5 Diaphragms.

Shock tube diaphragms are shown in Figure 6. The diaphragms are thin Mylar® polymer sheets and have a 22 in. (55.9 cm) diameter. Each sheet has 20 precut 1.375 in. (3.49 millimeter (mm)) diameter locating holes spaced uniformly around the perimeter and set in 1.375 in. (3.49 mm) at center from the edge of the sheet. These holes are matched with the size and indexing locations of the locating pins in the breach closure also shown in Figure 6. The diaphragms are placed over the locating pins and when the breach is closed prior to firing, the diaphragm is centered in the breach and sealed between the gaskets on the faces of the driver and driven ends of the breach. Three thicknesses of Mylar® referred to as 1/10, 1/2 and 1 sheet sizes are used corresponding to measured thicknesses of 0.001 in. (0.0254 mm), 0.005 in. (0.127 mm), and 0.010 in. (0.254 mm). Multiple sheets of any combination of thicknesses can be stacked to tune the total diaphragm thickness, allowing the required burst pressure to be achieved. Fractional sheet sizes are converted to decimals to simplify test record keeping. For example 5 (1+1+1+1+1) + 6/10 (1/10+1/2) = 5.6 Mylar® sheets.

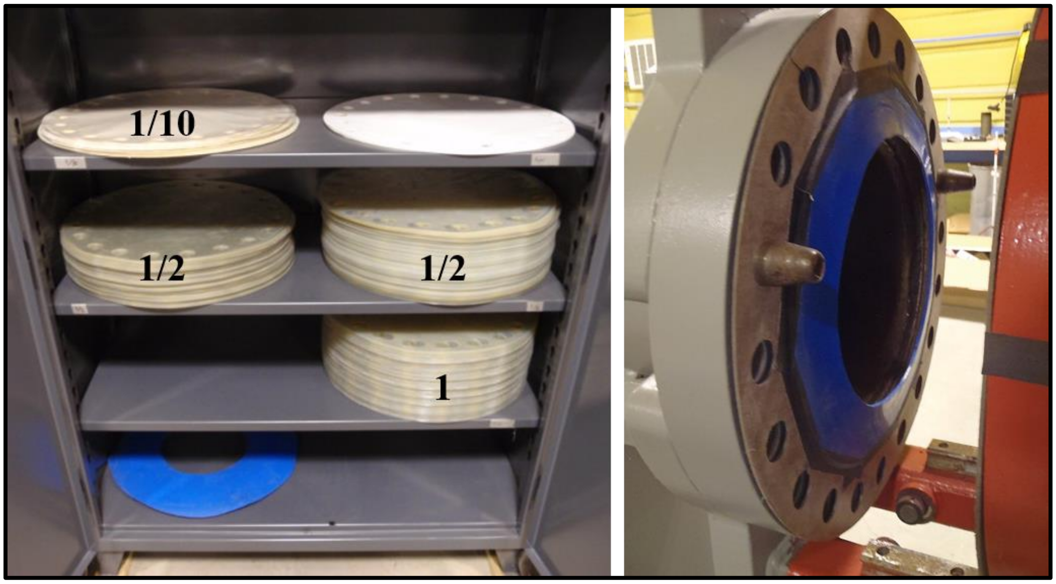


Figure 6. Mylar® diaphragms (left) and the open breach in the shock tube (right).

3.3.2.6 <u>Compressed Air Source / Air Compressor</u>.

Compressed air is required for operation of the pneumatic valve setup during the firing procedure. Compressed air lines are plumbed directly to the valve setup and other various locations in the facility. Compressed air is also used for various other shop tools and for clearing the shock tube barrel of test debris. The air compressor currently used is shown in Figure 7.

Figure 7. Air compressor.

3.3.2.7 Hydraulic Closure.

The shock tube driver can be actuated forward and backward using a hydraulic closure device. This device can be used at burst / driver pressures up to 500 psi (3450 kPa). At higher driver pressures the bolted breach closure configuration must be used. The closure device consists of a hydraulic piston mounted to the end of the driver powered by a hydraulic pump as shown in Figure 8. The driver section rides on a wheel bearing and track system mounted in a rigid frame.

Figure 8. Enerpac hydraulic pump (left) and hydraulic closure on the shock tube (right).

3.3.2.8 Lifting Devices.

Lifting devices such as hoists, straps, chains and lift tables are required for moving of large test items, test devices, and for reconfiguration and maintenance of the shock tube.

3.3.3 Instrumentation

3.3.3.1 Thermo-Hygrometer.

Temperature and humidity conditions in the laboratory are monitored using a thermo-hygrometer as shown in Figure 9.

Figure 9. Fluke thermo-hygrometer.

3.3.3.2 Pressure Transducers.

Pressure Transducers are located on the wall of the driver section for measuring diaphragm burst pressure and at known distances along the length of the driven section for measuring shock velocity as shown in Figure 10.

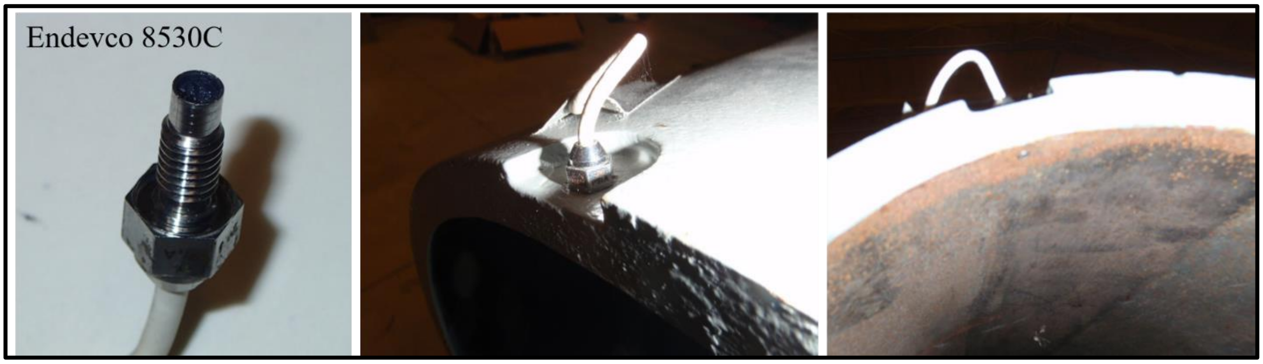


Figure 10. Endevco 8530C-1000 pressure transducer in sensor Group M, flush mounted with the inside wall of the tube 0.5 in. (13 mm) from the end of the muzzle.

3.3.3.3 Hybrid III Headform.

A modified Hybrid III anthropomorphic test device (ATD) headform is shown in Figure 11. Endevco Model 8530B-1000 transducers are threaded into tapped holes of the HIII skull. The gauge face is mounted flush with the outer surface of the skull. Endevco 7270A-6K accelerometers are mounted at the center of the headform. Load transducers for measuring force and moments may also be used when mounted to the Hybrid III neck.

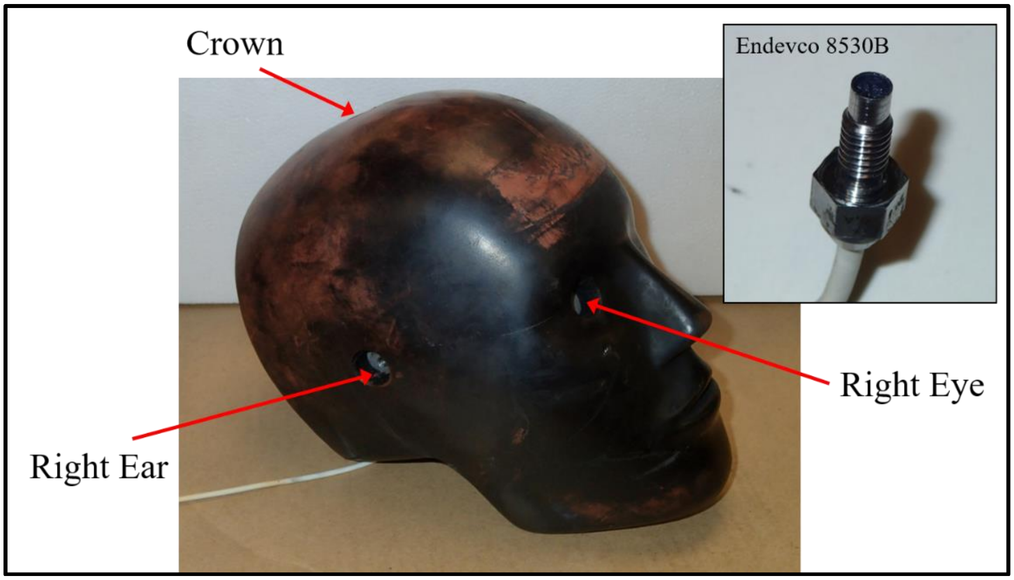


Figure 11. Hybrid III headform instrumented with Endevco 8530B pressure transducers.

3.3.4 High Speed Video.

High speed imaging may be required per the requirements documents.

3.4 Preparation for Test Execution.

3.4.1 Test Item Positioning.

Open-end shock tubes can be suitable for overpressure testing of large test items. The area of the item exposed to the shock wave is limited by the cross-sectional area of the muzzle. In general, the instrumented area of the test item exposed to the shock wave should be centered with the muzzle unless specified otherwise in requirements documents.

3.4.1.1 Friedlander Waveform.

Short duration Friedlander waveforms are considered to be close theoretical approximations of blast waves with a characteristic sharp rise in pressure followed by rapid decay from positive to negative phase. The waveform can be represented as the pressure-time history of a shock event as depicted as a Friedlander waveform in Figure 12.

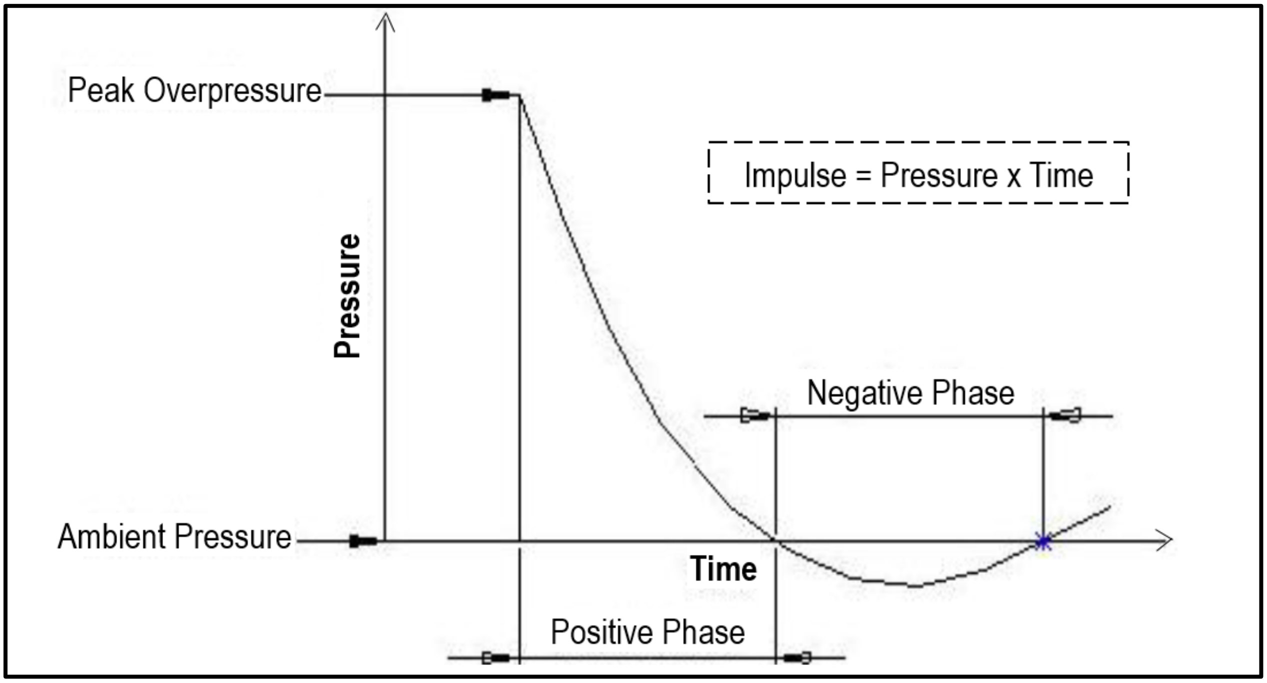


Figure 12. Simplified Friedlander waveform.

3.4.1.2 Standoff Distance.

Standoff distance from the end of the tube is critical when replicating explosive environments. Shock waves decay into sound waves below Mach 1. This occurs rapidly upon exiting the tube as transition occurs from 1-dimensional flow inside the tube, to 3-dimensional flow outside of the tube[1***]. Another important consideration concerns entrainment of near field gas by the shock wave exiting the muzzle, which creates a complex “near-field” shock environment. Entrainment causes shorter duration incident pressure and longer duration reflected pressure in comparison to explosively generated free-field blast waves. Additionally, the ratio between the pressures on the front and back of an object can be higher than witnessed in explosive environments. A secondary pulse can also be produced that increases the duration of the reflected pressure. Pressures generated inside the shock tube are dramatically higher, and not representative of what an object outside the shock tube experiences. Standoff distances used for the 12 in. (30.5 cm) diameter shock tube can vary up to 40 in. (101.6 cm) from the muzzle depending on the required shock conditions. However, optimal distance is commonly between 0 and 9 in. (22.9 cm) from the end of the muzzle. Observations indicate the secondary pulse is negligible at 4 in. (10.2 cm) from the shock tube, is clearly present at 9.5 in. (24.1 cm), and is significant at 14.5 in. (36.8 cm). Figure 13 shows the relationship between peak incident pressure and standoff distance using four diaphragm thicknesses.

*** Superscript numbers correspond to Appendix C, References.

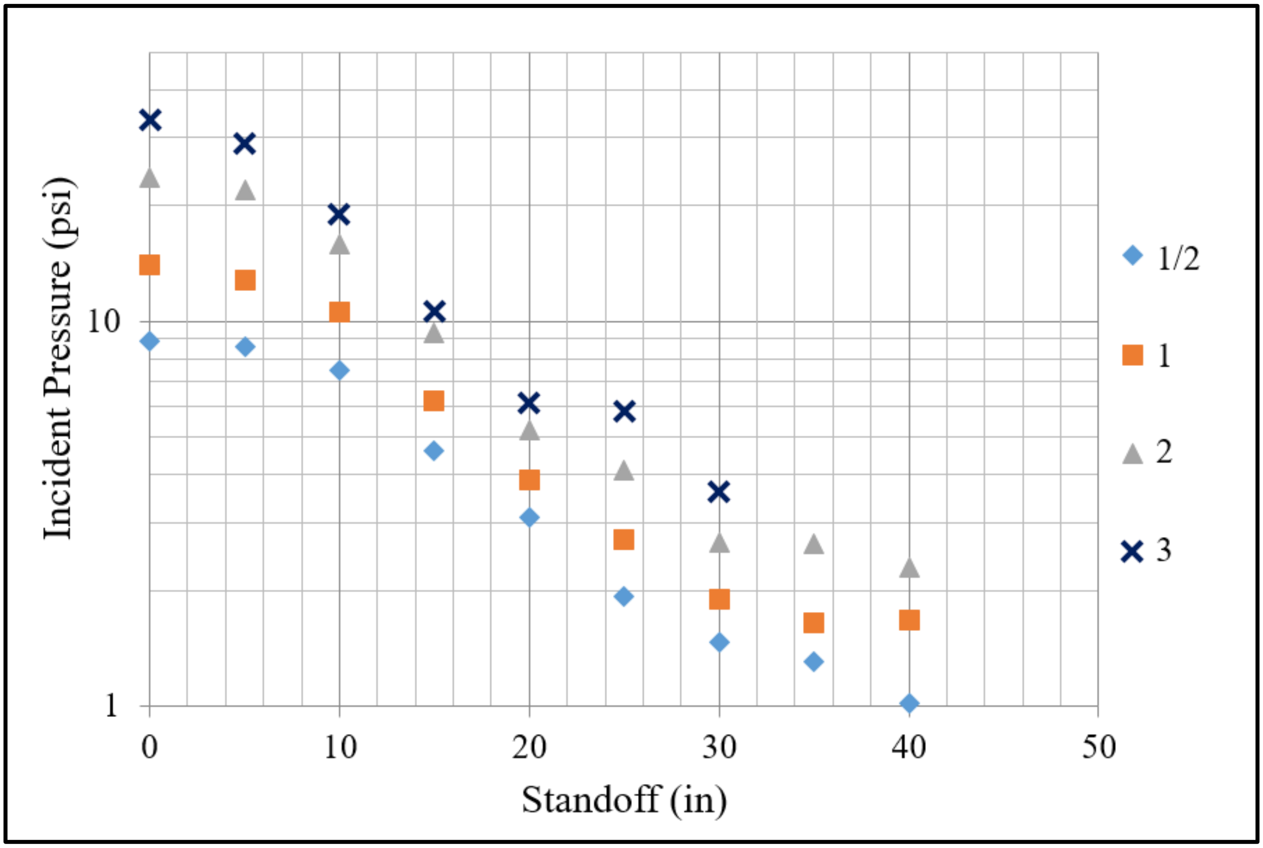


Figure 13. Incident pressure decay between 0 and 40 in. (101.6 cm) from the end of the shock tube using four diaphragm sheet thicknesses.

3.4.1.3 Burst Pressure.

The relationship between incident and burst pressure for the shock tube is shown in Figure 14. The linear curve fit equation can be used to estimate incident pressure for a known driver (burst) pressure, or driver pressure for a known incident pressure. The y axis is the incident pressure at sensor Group M and the x axis is the required driver pressure to burst the diaphragm. This is valid for test events above 45 psi (310 kPa) incident pressure and 225 psi (1550 kPa) burst pressure.

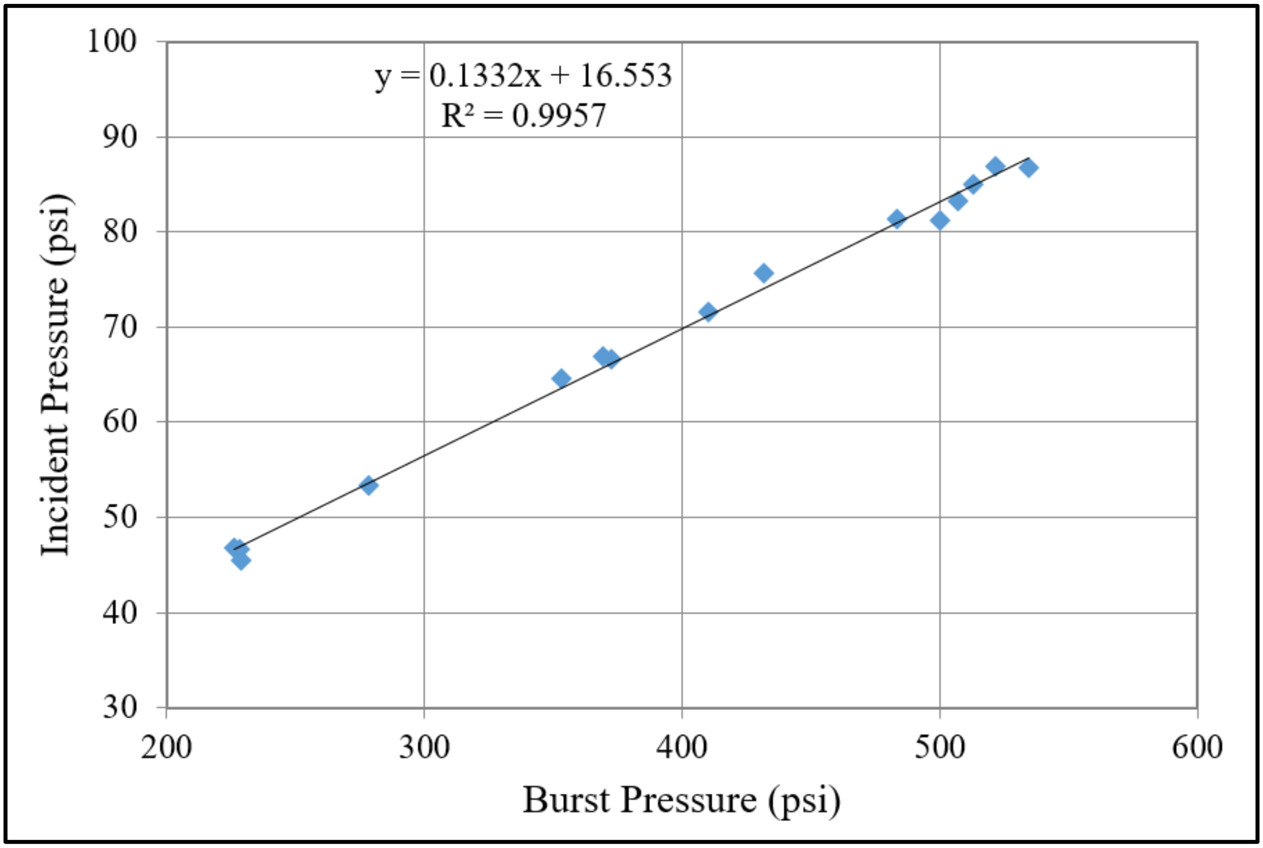


Figure 14. Incident pressure measured at sensor Group M in relation to driver pressure.

3.4.1.4 Incident Pressure and Impulse.

The relationship between impulse and incident pressure for the shock tube is shown in Figure 15. The linear curve fit can be used to estimate impulse based on a known incident pressure, or incident pressure for a known impulse. The y axis is the impulse based on the incident pressure at sensor Group M and the x axis is the incident pressure. This is valid for test events above 285 kPa-ms impulse and 45 psi (310 kPa) incident pressure.

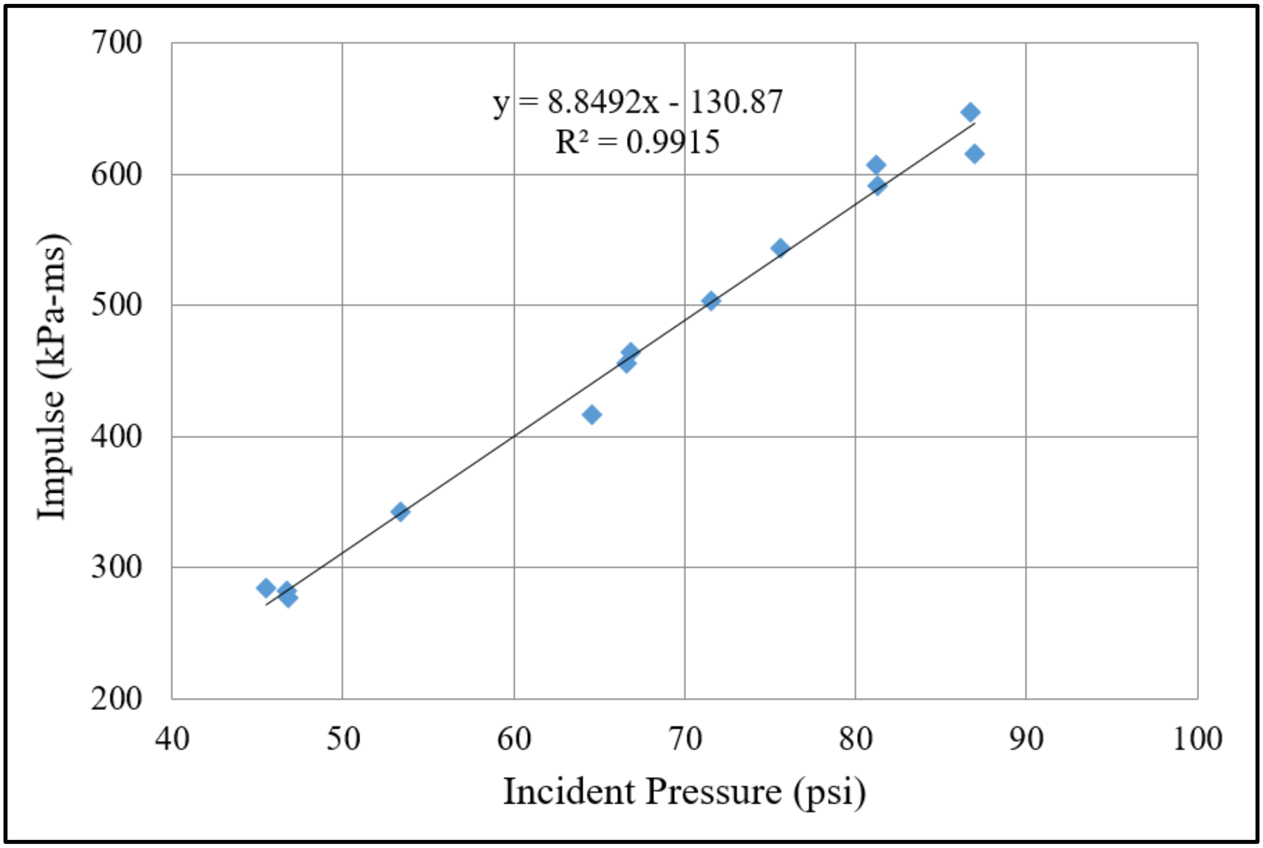


Figure 15. Impulse in relation to incident pressure measured at sensor Group M.

3.4.1.5 <u>Shock Velocity and Impulse</u>.

Sensor Groups M, A, and B measure incident pressure and shock wave velocity. The relationship between impulse and shock velocity for the shock tube is shown in Figure 16. The linear curve fit can be used to estimate impulse based on a shock velocity, or shock velocity for a known impulse. The y axis is the impulse based on the incident pressure at sensor Group M and the x axis is the shock velocity between sensor Groups A and M. This is valid for test events above approximately 200 kPa-ms impulse and shock velocities above 2100 ft/s.

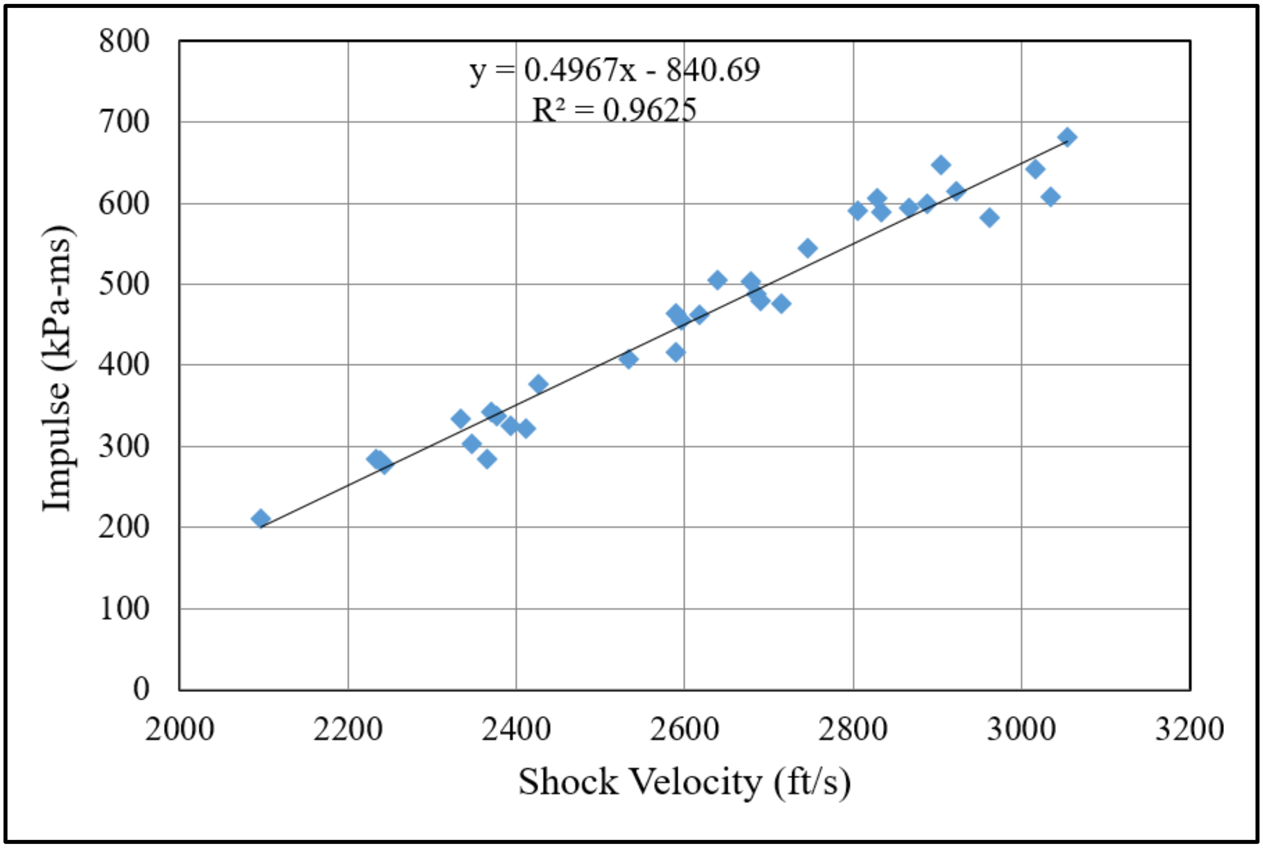


Figure 16. Impulse in relation to shock velocity.

3.4.1.6 Mylar® Thickness and Impulse.

The relationship between impulse and diaphragm thickness for the shock tube is shown in Figure 17. The linear curve fit can be used to estimate impulse based on a diaphragm thickness, or diaphragm thickness for a known impulse. The y axis is the impulse based on the incident pressure at sensor Group M and the x axis is the diaphragm thickness. This is valid for test events above 33 kPa-ms impulse and 1 Mylar® sheet (0.010 in. (0.25 mm)).

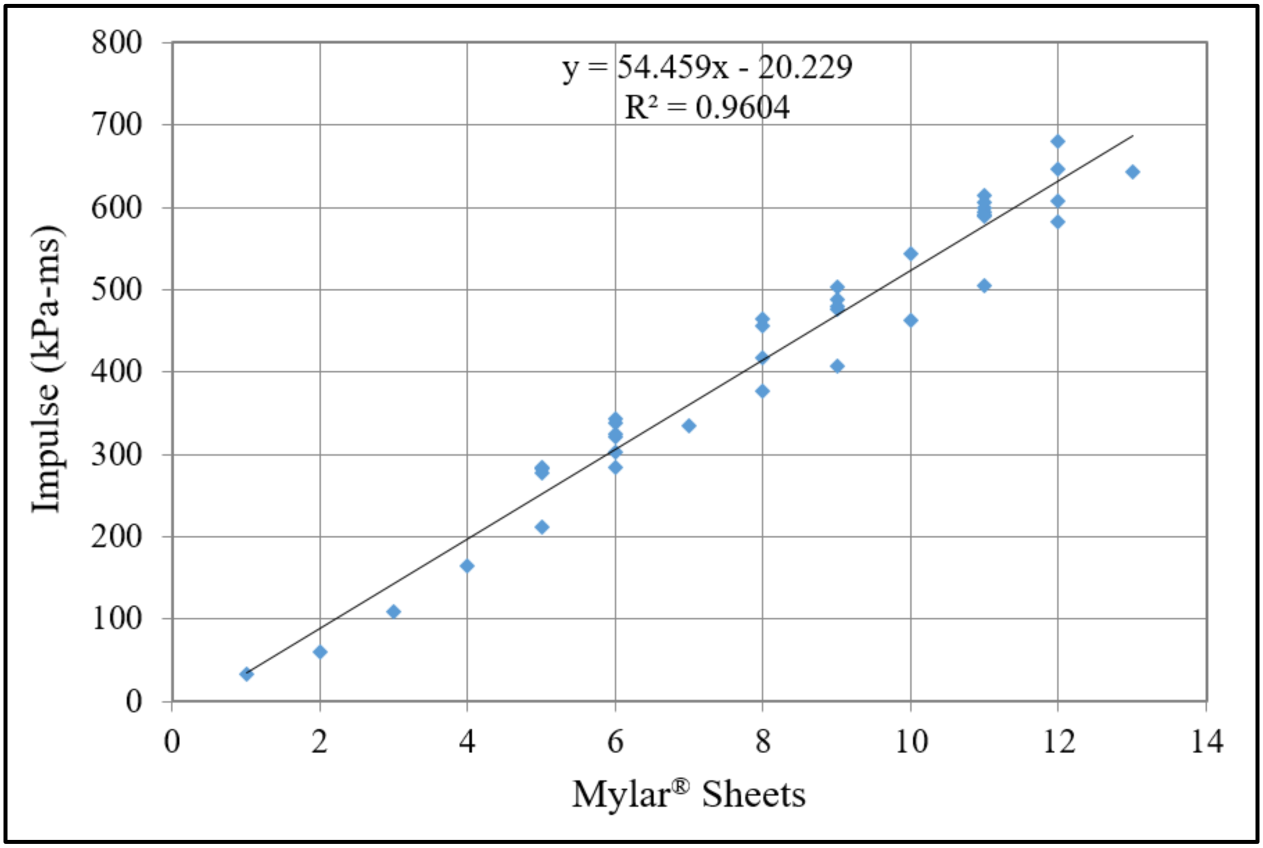


Figure 17. Impulse measured at sensor Group M in relation to the number of Mylar® sheets.

3.4.1.7 Estimation of Test Parameters.

A summary of the linear curve fit equations, their respective test parameters and lower bounds from Figures 14-17, is provided in Table 1. Table 2 shows example estimated values of impulse, incident pressure, shock velocity, and burst pressure for 5.6, 6, 9 and 12 diaphragm sheets. These estimates are calculated using the linear curve fit equations from Figures 15-17 shown in Table 1. Note that estimates based on the equations in Table 1 must be made (calculated) using the same unit system as the corresponding figure for each equation and are not valid for calculations in other unit systems. In addition, Figures 16 and 17 allow for estimation of impulse at values which are smaller than the lower bound of the equation used in Figure 15 (285 kPa·ms). For example, smaller value estimations for impulse may be made using the equations used in Figures 16 and 17 based on shock velocity or the number of Mylar® sheets. However, an impulse estimate that has been calculated using the equations in Figures 16 and 17 can only be used to estimate incident pressure or burst pressure using the equations in Figures 14 and 15 if the impulse estimate is greater than or equal to the lower bound of the equation in Figure 15. With the above limitation considered, the lower recommended range for these equations to estimate all of the parameters was calculated to be approximately 5.6 Mylar® sheets. The estimated shock parameters for 5.6 Mylar® sheets are shown in row 1, Table 2.

TABLE 1. SUMMARY OF THE LINEAR CURVE FIT EQUATIONS IN FIGURES 14 - 17

FIGURE	EQUATION	PARAMETER	LOWER BOUND
14	Incident = 0.1332 * Burst + 16.553	Burst Pressure	225 psi
		Incident Pressure	45 psi
15	Impulse = 8.8492 * Incident - 130.87	Incident Pressure	45 psi
		Impulse	285 kPa·ms
16	Impulse = 0.4967 * Velocity - 840.69	Shock Velocity	2100 ft/s
		Impulse	200 kPa·ms
17	Impulse = 54.459 * Sheets - 20.229	Mylar® Thickness	1 sheet (0.001 inch)
		Impulse	33 kPa·ms

TABLE 2. ESTIMATED DRIVER IMPULSE, INCIDENT PRESSURE, SHOCK VELOCITY, AND BURST PRESSURE USING FOUR THICKNESSES OF MYLAR®

DIAPHRAGM	THICKNESS	[a] IMPULSE	[b] INCIDENT PRESSURE	[c] SHOCK VELOCITY	[d] DRIVER (BURST) PRESSURE
Sheets	inch (mm)	kPa·ms	psi (kPa)	ft/s	psi (kPa)
5.6	0.056 (1.422)	285	47 (324)	2266	228 (1574)
6	0.060 (1.524)	307	49 (341)	2310	247 (1702)
9	0.090 (2.286)	470	68 (468)	2639	385 (2657)
12	0.120 (3.048)	633	86 (595)	2968	524 (3613)

[a, b, c, d] = calculated using the linear curve fit from Figures 17, 15, 16, 14 respectively.

3.4.2 Test Fixtures.

3.4.2.1 Test Item Fixtures and Mounts.

Appropriate fixtures for rigid and non-rigid positioning of the test item and instrumentation are typically needed based on the test requirements. These may include but are not limited to stands, mounts, and suspension fixtures. An example helmet test setup using the head and neck components of an instrumented Hybrid III ATD is shown in Figure 18. The stands and fixtures used allow the sensors located at the center of the headform to be positioned 5 in. (10.2 cm) from the muzzle.

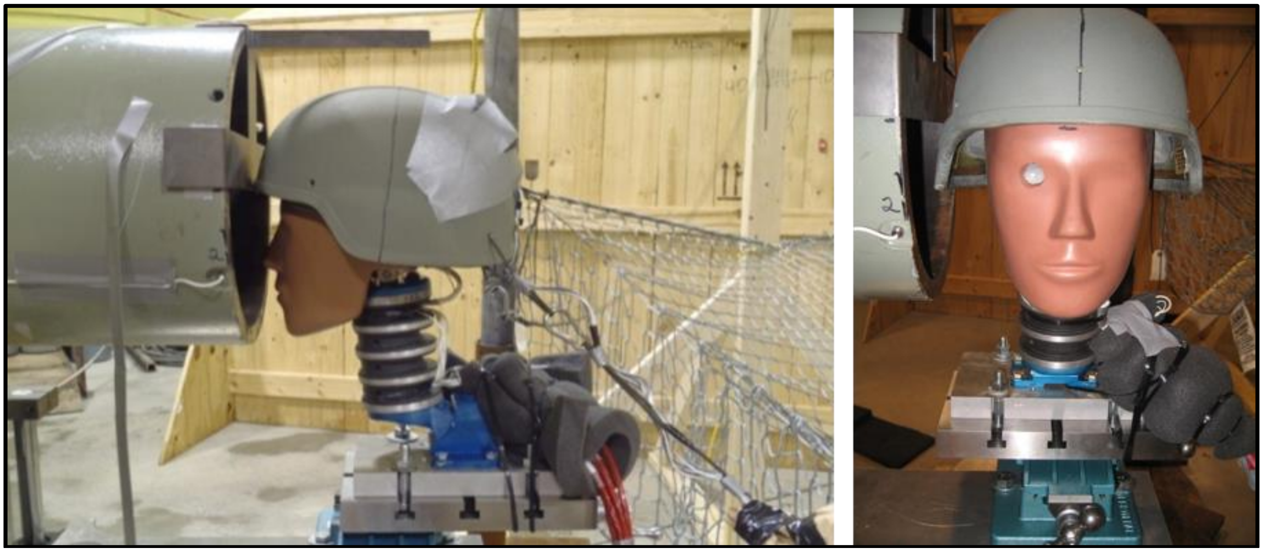


Figure 18. Instrumented Hybrid III ATD head and neck used during shock tube helmet testing.

3.4.2.2 Test Item Backstop.

Backstops or catch devices may be required depending on the test requirements. Figure 19 shows a netted fixture used as a catch for testing of suspended test items.

Figure 19. Catch net placed behind the test item position.

3.4.3 High Speed Video Setup.

Setup of the camera(s) and any supplemental lighting should be arranged appropriately to capture the test item response to the shock event and avoid damage to the imaging equipment. Typical setups capture close-up peripheral (side) views at frame rates above 250,000 frames/s.

3.4.4 Test Sample Accountability.

When applicable, such as for source selection or some types of blind testing, test grouping and randomization concepts shall be followed to eliminate any bias in test conditions.

3.4.5 Sampling, Grouping, and Randomization.

Any environmental conditioning shall be conducted in accordance with the Performance Specification, or as specified by the customer or test plan.

4. TEST PROCEDURES.

4.1 Shock Test Requirements.

Test requirements including, but not limited to test setup, test item configuration, orientation, and shock test performance criteria will be specified by the customer, requirements documents, or an approved test plan. Blast test requirements may serve as the basis for shock tube to blast comparative testing.

4.2 Test Item Mounting.

Immediately before testing the test sample shall be visually inspected. Positioning of the test item is verified to meet the test requirements. When multiple tests are conducted on a test item a visual inspection shall be made between tests to check for any degradation of the test item. Any observed degradations shall be documented. The visual inspection shall also check for safety hazards.

4.3 Data.

4.3.1 Capture.

Time = 0 of the test event occurs when the shock wave front passes sensor Group M located 0.5 in. (1.27 cm) from the end of the muzzle. The data acquisition system is set to trigger all sensors when a threshold pressure value has been crossed at this position. Setting the trigger at the muzzle position greatly reduces post-shot data alignment procedures of all data sources in the test. It is recommended that the data acquisition system be set to record at least 20 ms of pre-trigger data to ensure data from the Driver, Group B, and Group A sensors are captured. Trigger and sensor checks shall be performed including warmer tests prior to beginning record testing.

4.3.2 Sampling Rates and Filtering.

Data generators should be mindful of data alignment in certain tests when sampling rates are not identical across all instrumentation data channels. Efforts should be made to select appropriate data sampling rates which adhere to specification requirements and allow the data to be easily aligned post-test (by common time-steps) for data reduction and analysis.

4.3.2.1 Pressure.

Recommended sampling rate of 400,000 samples / second using a Low-Pass 40,000 Hertz 6-pole Bessell filter type.

4.3.2.2 Acceleration, Force, and Moment - Hybid III Mannequin Head.

Recommended that the sampling rates and filter setting adhere to the Society of Automotive Engineers (SAE) International J211-1[2] Specification.

4.4 Pre-Firing Checks.

a. Inspection of the shock tube barrel and area surrounding the muzzle shall be performed prior to initiating the firing procedure to ensure the area is free of debris and foreign objects that could cause a safety hazard or detrimental effect to the test item.

b. Shock tube firing events require a minimum bottle pressure, depending upon the required burst pressure of the diaphragm. Refer to Section 3.4.1.7 to estimate the burst pressure (driver) required for the test requirements. Verify there is sufficient bottle pressure in the helium tank to operate the test at the desired driver pressure by visual reading of the inlet pressure gauge. A minimum bottle pressure of 500 psi (3450 kPa) is recommended for tests requiring less than 500 psi (3450 kPa).

c. Gaskets in the driver breach shall be inspected for damage prior to each test event. Damaged gaskets will be replaced prior to the next test event.

4.5 Pressure Determination.

4.5.1 Driver (Burst) Pressure.

Peak pressure measured by the driver pressure transducer (sensor 0) will be a direct measurement recorded as pre-trigger data and output by the data acquisition software.

4.5.2 Incident and Reflected Pressure.

Peak pressure measured by the driven pressure transducers (sensors 1-9), reference plate(s) or pencil probe(s), and instrumented test items will be direct measurements. Pressure inside the tube (sensors 1-9) will be recorded as pre-trigger data. All data will be output by the data acquisition software.

4.6 Time and Duration Determination.

4.6.1 Time-To-Peak Pressure.

Time measurement from t=0 to the point of peak incident pressure will be recorded and output by the data acquisition software.

4.6.2 Phase-Time Duration.

Time measurement from t=0 to point where incident pressure transitions from positive to negative values will be recorded and output by the data acquisition software.

4.7 Velocity Determination.

Shock velocity can be measured between any two pressure transducers which are located at different distances in the test setup along the shot line. Shock exit velocity from the end of the muzzle should generally be used as the standard for reporting. However, when possible the shock velocity at the surrogate or test item may also be reported. Exit velocity is calculated as the distance per unit time that the shock wave travels between sensor Groups A (sensors 4-6) and M (sensors 1-3). Refer to Section 3.3.2.1 and Figure 2 for distances between sensor locations.

4.8 Impulse Determination.

4.8.1 Calculation.

Impulse can be calculated theoretically via the incident pressure and shock velocity measurements based on the correlations established in Figures 15 and 16, and shown in Table 1. Impulse can also be calculated as the area under the pressure-time curve at positive values, or the integral of the pressure-time curve.

4.8.2 Estimation.

A direct impulse measurement often cannot be made for the test item in situ. A series of baseline tests were conducted which correlate shock velocity to open tube (unobstructed impulse) and are shown in Figure 16. During actual test events, shock velocity is recorded and may be used to determine an estimated impulse based on standoff of the test item from the tube. Peak pressure and shock velocity are generally used to determine if a test is valid when estimated impulse is used as a test criteria.

4.9 Fair Hit Requirements.

a. A test is considered valid if the following criteria are met:

(1) Diaphragm burst pressure is within the expected range for the test.

(2) Peak incident pressure measured inside the tube is within the expected range for the test.

(3) Shock wave velocity measured inside the tube is within the expected range for the test.

(4) Impulse measured at the test item (when possible) is within the expected range for the test.

b. In the event a test result is unfair, any test results for preceding shots that have been determined to be fair shall stand. Any unfair tests shall be marked as misfires. Any test with unfair results shall be labeled “no-test” to indicate that additional testing may occur. Should additional tests cause the item to fail, the test shall not be valid.

4.10 Misfire Procedure.

In the event the diaphragm does not burst and pressure in the driver section does not exceed 1000 psi (6900 kPa), release of both the dump and fill buttons will re-open the atmospheric venting solenoid in the dump valve and depressurize the driver section. Reinitiating the test is acceptable for a misfire event that has not impacted the test item with a shock wave and if the test item continues to meet any environmental conditioning requirements after inspection of the tube and determination that the shock tube is in proper functioning condition.

5. DATA REQUIREMENTS.

5.1 Test Information.

Data requirements will be coordinated and agreed upon between the test agency and test sponsor. Typical test information for reporting include, but are not limited to the information shown in Table 3. Test notes including any test abnormalities observed and information related to warm-up, calibration, or prerecorded test events, may be reported per the requirements documents.

TABLE 3. TEST DATA

DATA ELEMENT	INFORMATION
Test Operator	First and last name
Test Facility	Building and lab numbers
Test Description	Brief description of the type of test and device used
Test Date	Day/month/year (01/01/0000)
Test Time	Local military time (24:00)
Test Center Information	Program number
	Subtest number
Vendor Information	Company name
	Contract number
Test Item Information	System
	Component (if applicable)
	Test item identification number
	Test Director Alias (if applicable)
	Size information (if applicable)
	Mass / weight (if applicable)
	Serial number
	Lot number
	Cage number
	National stock number
	Part number
Shock Tube Instrumentation	Serial number
	Calibration date
Reference Instrumentation	Serial number
	Calibration date
Test Item Instrumentation	Serial number
	Calibration date
Test Data Sampling Rate	Samples / second
Test Data Filter Settings	Filter type and frequency

5.2 Data Requirements.

Typical test data requirements for reporting may include, but are not limited to, the information shown in Table 4. The most commonly reported data values from shock tube testing are peak overpressure (typically incident), positive phase-time duration, and impulse. Photos of the test setup, pre- and post-test item images are generally required. High speed video is also commonly required for data analysis purposes or qualitative analysis. Presentation of calculations based on test surrogate injury criteria, integrated response curves, and estimated test values may also be required. Test item response measurements for instrumented test surrogates are not provided as there is no standard surrogate device, however data often includes, but is not limited to pressure, acceleration, and force profiles.

TABLE 4. SHOCK TUBE DATA

DATA ELEMENT	MEASUREMENT UNIT	
	Primary	Secondary
Temperature in test facility	°F	°C
Humidity in test facility	%	%
Gas cylinder bottle pressure	psi	kPa
Driver chamber burst pressure	psi	kPa
Peak incident pressure	psi	kPa
Time to peak incident pressure	ms	ms
Phase-time duration	ms	ms
Incident pressure vs. time curve	psi vs. ms	kPa vs. ms
Impulse	kPa·ms	kPa·ms
Shock velocity	ft/s	Mach number
Peak reflected pressure	psi	kPa
Time to peak reflected pressure	ms	ms

6. PRESENTATION OF DATA.

6.1 Shock Tube Pressure Profile.

Figure 20 shows an example incident pressure versus time plot.

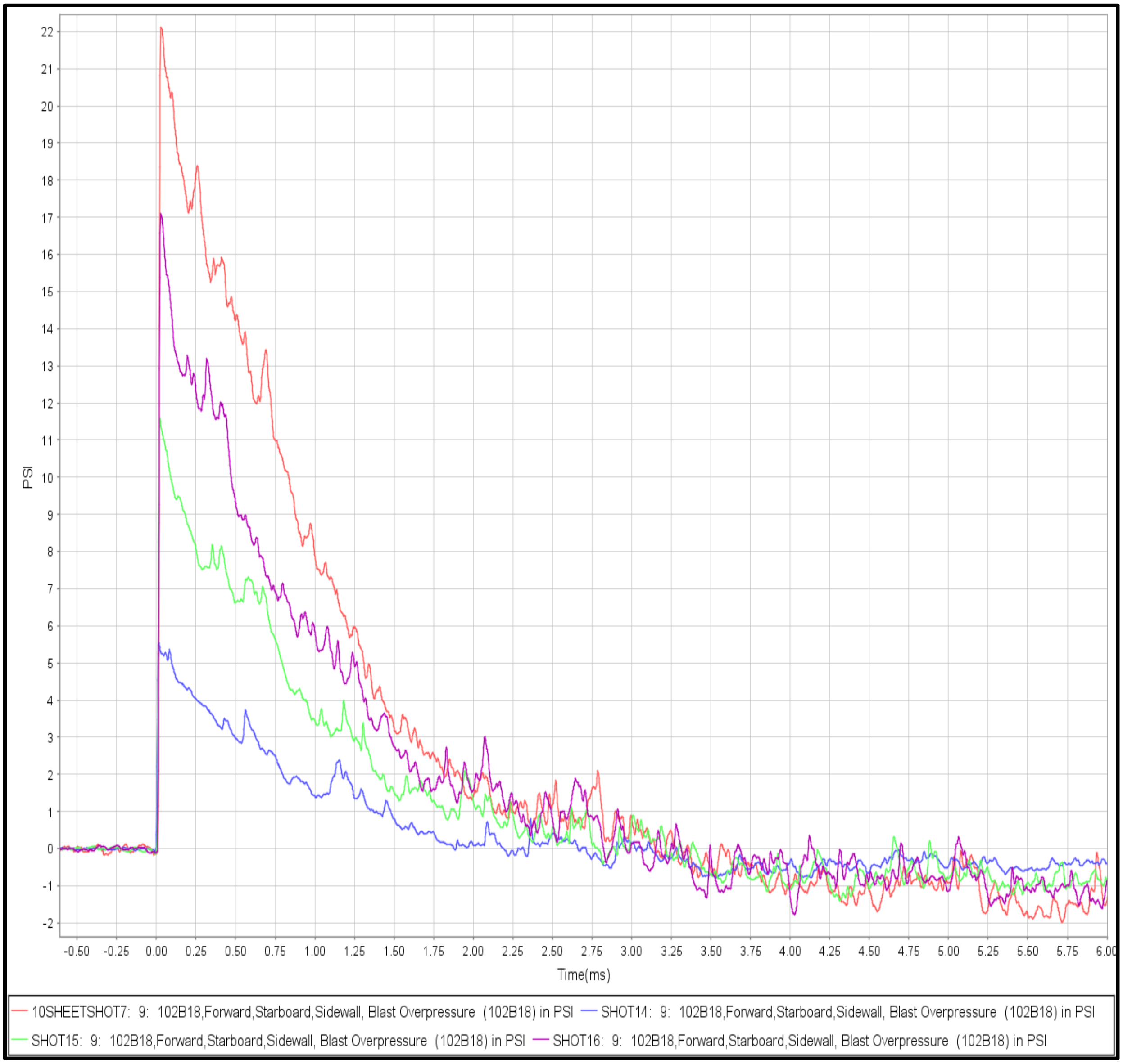
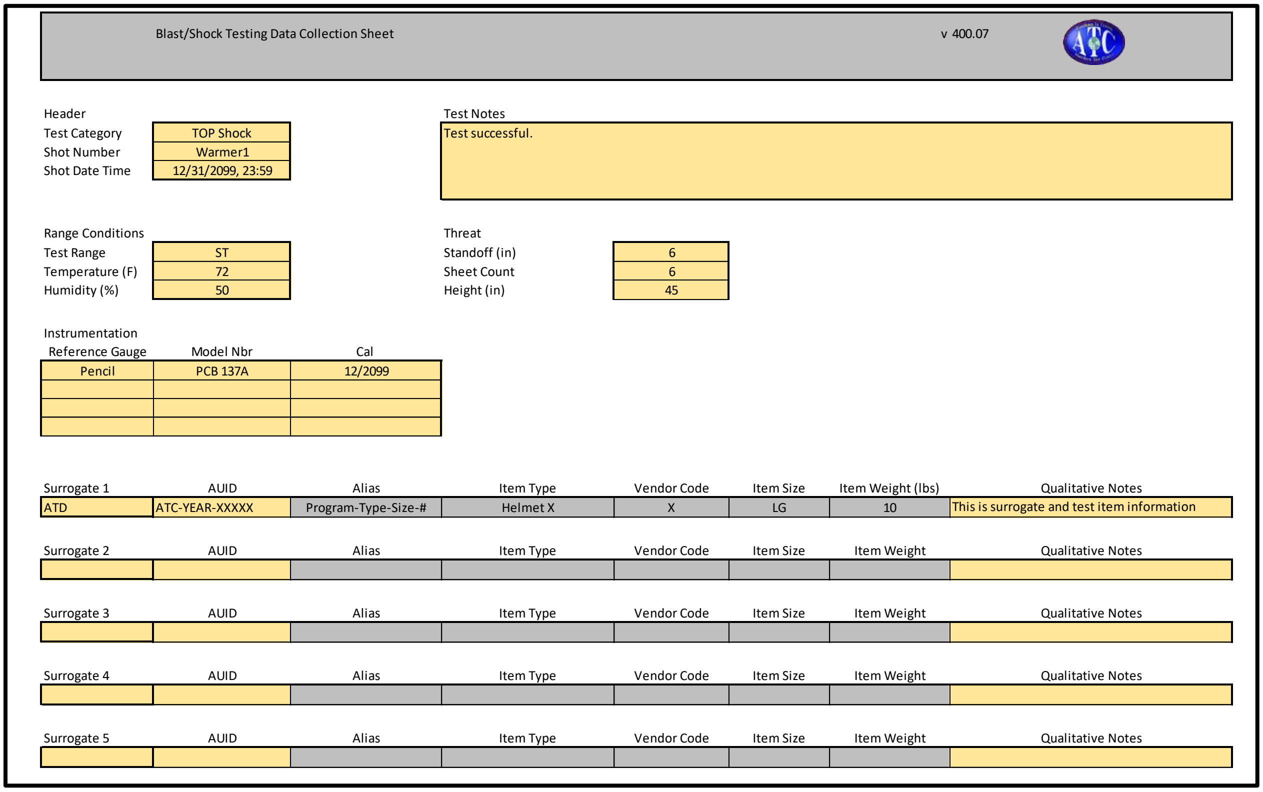


Figure 20. Example incident pressure versus time plots as measured inside the driven section of the shock tube.

6.2 Data Collection Sheet.

Figure 21 shows an example data collection sheet.



Blast/Shock Testing Data Collection Sheet

v 400.07

Header

Test Category	TOP Shock
Shot Number	Warmer1
Shot Date Time	12/31/2099, 23:59

Test Notes

Test successful.

Range Conditions

Test Range	ST
Temperature (F)	72
Humidity (%)	50

Threat

Standoff (in)	6
Sheet Count	6
Height (in)	45

Instrumentation

Reference Gauge	Model Nbr	Cal
Pencil	PCB 137A	12/2099

Surrogate 1	AUID	Alias	Item Type	Vendor Code	Item Size	Item Weight (lbs)	Qualitative Notes
ATD	ATC-YEAR-XXXXX	Program-Type-Size-#	Helmet X	X	LG	10	This is surrogate and test item information

Surrogate 2	AUID	Alias	Item Type	Vendor Code	Item Size	Item Weight	Qualitative Notes

Surrogate 3	AUID	Alias	Item Type	Vendor Code	Item Size	Item Weight	Qualitative Notes

Surrogate 4	AUID	Alias	Item Type	Vendor Code	Item Size	Item Weight	Qualitative Notes

Surrogate 5	AUID	Alias	Item Type	Vendor Code	Item Size	Item Weight	Qualitative Notes

Figure 21. Example data collection sheet.

6.3 Data Table.

Figure 22 shows an example data table.

DATE (Day-Month-Yr)	TIME	VENDOR ID	ITEM ID	SHOT NUMBER	SHOT LOCATION	SHEET COUNT	BURST VALID (Y/N)	SHOCK VALID (Y/N)	BOTTLE PRESSURE (psi)	BURST PRESSURE (psi)	Shock Velocity (ft/s)	INCIDENT PRESSURE (psi)	TARGET IMPULSE (kPa·ms)
12/31/2099	23:59	A	atc-xx-xx	Warmer1	Front	6	Y	Y	1500	245.999	2242.999	47.999	300

Figure 22. Example data table.

APPENDIX A. GLOSSARY.

Term	Definition
Anthropomorphic test device	Test device that simulates the dimensions, weight, and articulation of the human body.
Burst pressure	Pressure required to explosively perforate the diaphragm in the shock tube.
Diaphragm	Material separating the driver and driven sections of the shock tube.
Driven tube	Shock tube barrel.
Driver tube	Shock tube pressure chamber.
Entrainment	Incorporate in a fluid and sweep or carry along in its flow.
Friedlander Wave	Simplified depiction of a blast wave approximated as a lead shock wave in a graphical curve.
Hygro-meter	Instrument for measuring atmospheric moisture content.
Impulse	The integral of force over the time interval for which it acts.
Incident pressure	Near instantaneous rise from ambient pressure due to transient conditions caused by a blast wave.
Muzzle	Open end of the shock tube barrel.
Pencil Probe	Long, narrow, circular rod of generally aerodynamic shape but with one flat surface for mounting a transducer.
Phase-time duration	Time interval of either positive or negative (relative to ambient) pressure measurement.
Pressure transducer	Sensor for measuring pressure, typically of a gas or fluid by generating a signal as a function of pressure applied.
Reflected pressure	Pressure which is reflected from a solid object or surface.
Shock Tube	Enclosed tube in which experimental shock waves are produced as a result of the rupturing of a diaphragm separating two chambers containing a gas or gases at different pressures.
Standoff	Separation distance between two objects or between an object and the initiation site of an energetic event.

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APPENDIX B. ABBREVIATIONS.

°C	Degrees Celsius
°F	Degrees Fahrenheit
ATC	U.S. Army Aberdeen Test Center
ATD	Anthropomorphic Test Device
CAD	Computer Aided Design
cm	centimeter
FS	full scale
Fx, Fy, Fz	force
He	helium
in.	inch
kPa	kilopascal
mm	millimeter
ms	millisecond
Mx, My, Mz	moment
psi	pounds per square inch
RH	relative humidity
SAE	Society of Automotive Engineers
SI	International System of Units
TOP	Test Operations Procedure
U.S.	United States

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APPENDIX C. REFERENCES.

1. Sundaramurthy A, Chandra N. A parametric approach to shape field-relevant blast wave profiles in compressed-gas-driven shock tube. *Front. Neurol*. 2014; 253(5): 1-10.

2. SAE J211-1 (2014): Instrumentation for Impact Test, Part 1, Electronic Instrumentation.

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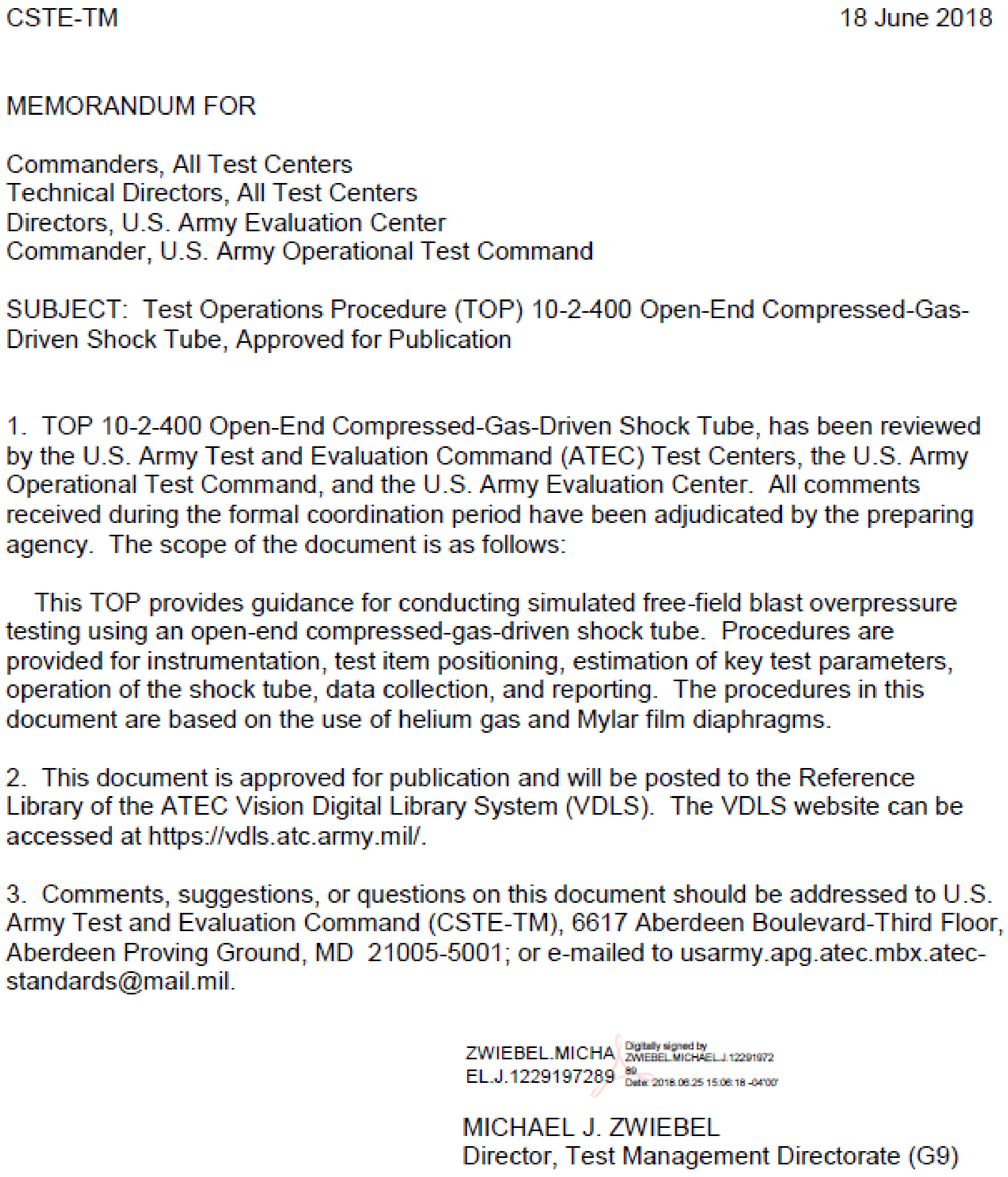
APPENDIX D. APPROVAL AUTHORITY.



CSTE-TM 18 June 2018

MEMORANDUM FOR

Commanders, All Test Centers
Technical Directors, All Test Centers
Directors, U.S. Army Evaluation Center
Commander, U.S. Army Operational Test Command

SUBJECT: Test Operations Procedure (TOP) 10-2-400 Open-End Compressed-Gas-Driven Shock Tube, Approved for Publication

1. TOP 10-2-400 Open-End Compressed-Gas-Driven Shock Tube, has been reviewed by the U.S. Army Test and Evaluation Command (ATEC) Test Centers, the U.S. Army Operational Test Command, and the U.S. Army Evaluation Center. All comments received during the formal coordination period have been adjudicated by the preparing agency. The scope of the document is as follows:

This TOP provides guidance for conducting simulated free-field blast overpressure testing using an open-end compressed-gas-driven shock tube. Procedures are provided for instrumentation, test item positioning, estimation of key test parameters, operation of the shock tube, data collection, and reporting. The procedures in this document are based on the use of helium gas and Mylar film diaphragms.

2. This document is approved for publication and will be posted to the Reference Library of the ATEC Vision Digital Library System (VDLS). The VDLS website can be accessed at https://vdls.atc.army.mil/.

3. Comments, suggestions, or questions on this document should be addressed to U.S. Army Test and Evaluation Command (CSTE-TM), 6617 Aberdeen Boulevard-Third Floor, Aberdeen Proving Ground, MD 21005-5001; or e-mailed to usarmy.apg.atec.mbx.atec-standards@mail.mil.

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MICHAEL J. ZWIEBEL
Director, Test Management Directorate (G9)

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Forward comments, recommended changes, or any pertinent data which may be of use in improving this publication to the following address: Policy and Standardization Division (CSTE-TM), U.S. Army Test and Evaluation Command, 6617 Aberdeen Boulevard, Aberdeen Proving Ground, Maryland 21005-5001. Technical information may be obtained from the preparing activity: Firepower Directorate (TEDT-AT-FPP), U.S. Army Aberdeen Test Center, Aberdeen Proving Ground, Maryland, 21005-5001. Additional copies can be requested through the following website: http://www.atec.army.mil/publications/topsindex.aspx, or through the Defense Technical Information Center, 8725 John J. Kingman Rd., STE 0944, Fort Belvoir, VA 22060-6218. This document is identified by the accession number (AD No.) printed on the first page.