In-Depth Survey Report

DESIGN AND CONSTRUCTION OF AN ACOUSTIC SHOCK TUBE FOR GENERATING HIGH-LEVEL IMPULSES TO TEST HEARING PROTECTION DEVICES

Amir Khan, William J. Murphy, Ph.D. and Edward L. Zechmann

Division of Applied Research and Technology
Engineering and Physical Hazards Branch
EPHB Report No. 350-12a

May 2012

DEPARTMENT OF HEALTH AND HUMAN SERVICES
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health

Site Surveyed: Not Applicable

NAICS Code: 423450 for Hearing Protection Manufacturers

Survey Dates: Not Applicable

Surveys Conducted By: Amir Khan, William Murphy and Edward Zechmann

Employer Representatives Contacted: Not Applicable

Contractor Representatives: Not Applicable

Disclaimer

Mention of any company or product does not constitute endorsement by NIOSH. In addition, citations to websites external to NIOSH do not constitute NIOSH endorsement of the sponsoring organizations or their programs or products. Furthermore, NIOSH is not responsible for the content of these websites. All web addresses referenced in this document were accessible as of the publication date.

Acknowledgements

The National Institute for Occupational Safety and Health (NIOSH) developed the acoustic shock tube between 2006 and 2011. The shock tube located at the U.S. Army Aeromedical Research Laboratories (Fort Rucker, AL) provided inspiration. Edward L. Zechmann (NIOSH), William J. Murphy (NIOSH), and Dr. Jay Kim in the Mechanical Engineering Department at the University of Cincinnati were the principal designers of the prototype shock tube. Mark Cauble (B/C Precision Tool Inc.) built the second shock tube. Amir Khan (NIOSH) and the dedicated workers of Four Seasons Engineering at NIOSH iteratively improved the design. Amir Khan and student interns Brian Kim and Joseph Echt conducted substantial testing of the shock tube's performance.

Without the impetus to revise the U.S. Environmental Protection Agency's (EPA) regulation for labeling hearing protection devices, none of this work would have been pursued. The U.S. EPA sponsored portions of this work through an interagency agreement DW 75-92197301-4 with NIOSH. The U.S. Army Medical Research and Materiel Command partially funded the procurement of data acquisition equipment through the Army MIPR 08-19-09M1 / MIPR9J07586218. NIOSH funded improvements to the shock tube design, the development of the exponential and catenoidal horns and the development of the Impulse Noise Testing Laboratory.

Table of Contents

List of Figures

Abstract

Background: The noise reduction performances of Hearing Protection Devices (HPDs) have normally been evaluated at or near the threshold of hearing because the performance of the device was assumed to be constant across the typical range of occupational noise exposure levels. With the advent of new technologies in hearing protection and associated electronics, the noise reduction performance for some HPDs was found to increase with the increase in the sound levels (Parmentier et al. 2002; Zera and Mlynski, 2007; Berger and Hamery 2008; Murphy et al., 2012). These devices are typically described as amplitude-sensitive, non-linear, sound-restoration or level-limiting hearing protectors. The electronic level-limiting or sound restoration HPDs detect the external exposure level and then adjust the gain of the amplification circuit to limit the level of sound played back underneath the protector. Passive HPDs with a non-linear valve or orifice rely on increased acoustic impedance with an increased pressure differential across the two sides of the orifice or valve.

In order to accurately assess the performance of these types of protectors, the American National Standards Institute revised the ANSI/ASA S12.42 (ANSI, 2010) standard to include a method to measure the impulse peak insertion loss of all hearing protectors over a wide range of impulse levels using a dual-ear acoustic test fixture and a field microphone. The ANSI/ASA S12.42-2010 requires that impulse tests be performed at three ranges of impulse peak sound pressure levels. The low-level impulse range is between 130 and 134 dB peak SPL; the mid-level range is between 148 and 152 dB peak SPL; the high-level range is between 166 and 170 dB peak SPL. For all impulses, the duration of the initial positive pressure phase of the waveform (A-duration) is required to be between 0.5 and 2.0 milliseconds. The standard recommends generating the required impulse sound events using explosive charges or an acoustic shock tube.

Description: This report describes the design and construction of the NIOSH acoustic shock tube. The first prototype shock tube was built under a contract to the University of Cincinnati, but suffered from design flaws that prevented it from achieving the specified impulse ranges. A second prototype shock tube was designed and constructed by Cauble Precision Machine Inc. of Lawrenceburg, IN. The second prototype could generate the specified impulse ranges, but because

the manual clamping system to hold the membrane and pressurizing the shock tube chamber was unwieldy to use for a sustained period. NIOSH modified the shock tube and improved the pressure control and installed a pneumatic clamping system on the third prototype shock tube. Safety features were integrated into the pneumatic clamping system to prevent inadvertent crushing of hands or fingers between the flanges. An acoustic horn was designed and manufactured to provide impedance matching between the shock tube and the room. The horn provided a small amount of gain necessary to generate impulses at the highest peak pressure levels 166 to 170 dB SPL. In summary, the operational performance and safety of the third shock tube was significantly improved relative to the second prototype. The modifications to the acoustic shock tube have been incorporated into subsequent versions of the shock tube manufactured and sold by B/C Precision Tool (formerly Cauble Precision Machine Inc.).

Conclusions: The NIOSH acoustic shock tube has demonstrated that impulses can be successfully produced using a polyester membrane of thicknesses of 0.001 or 0.002 inch thickness. In addition, this system, developed in support of the Environmental Protection Agency hearing protector labeling requirements (40CFR Part 211 Subpart B), fulfills the operational requirements specified in the ANSI S12.42-2010 standard. This report describes the design, construction and basic operation of shock tube.

[Portions of this work were supported by the U.S. EPA Interagency Agreement DW75921973-01-4.]

Introduction

Background

In 2003, the US Environmental Protection Agency held a public meeting to gather input from representatives of hearing protector manufacturers, testing laboratories, academic researchers and government officials regarding the need to revise the Noise Reduction Rating (NRR) according to the EPA labeling regulation for hearing protection devices at 40 CFR Part 211 Subpart B (EPA, 1979, 2003). One major outcome of this meeting was the identification of a need to provide a rating for hearing protection devices that are designed to provide increasing noise reduction as the sound exposure level increases. The noise reduction of Hearing Protection Devices (HPDs) has typically been evaluated at or near the threshold of hearing because the performance of the device was not believed to change significantly over the range of occupational exposure levels for noise. With the advent of new technologies in hearing protection and associated electronics, some HPDs provide small amounts of noise reduction at low sound pressure levels and yield increasing noise reduction as the exposure level increases. These devices can be amplitude-sensitive, non-linear, sound-restoration or level-limiting hearing protectors.

Electronic level-limiting or sound restoration HPDs sense the external exposure level and then adjust the gain of the amplification circuit to limit the level of sound played back underneath the protector. Passive nonlinear HPDs use a valve or orifice to provide increased acoustic resistance as the pressure differential across the valve increases. In order to assess the performance of these types of protectors, the American National Standards Institute has revised the ANSI/ASA S12.42-2010 (ANSI/ASA, 2010) standard which defines a method for measuring the impulse peak insertion loss of a hearing protector over a range of impulse sound events using an acoustic test fixture and a field microphone. ANSI/ASA S12.42-2010 stipulates that the ranges of levels shall be 130 to 134, 148 to 152, and 166 to 170 dB peak SPL. The duration of the initial blast overpressure (A-duration) is required to be between 0.5 and 2.0 milliseconds. The standard describes creating the requisite impulse events by using either explosive charges or an acoustic shock tube (ANSI, 2010).

Explosive charges require a dedicated firing range sufficiently remote from surrounding communities to minimize annoyance. The charges range anywhere from blasting caps to a few hundred grams of explosive material such as C4 or Semtex. Handling of these explosives requires extensive training and precautions that are impractical for most hearing protector testing laboratories outside of the military. Small-caliber weapons can generate the required impulse levels, but the A-durations tend to be shorter than 0.5 milliseconds, which is outside the allowable range of durations. Small caliber weapons pose hazards for ventilation of combustion gases, remediation of toxic dusts as well as safety associated with firing a weapon indoors.

Acoustic shock tubes are cited in the standard as having greater operational flexibility in generating impulses at different levels. The major component of the shock tube design presented in this report consists of a pressure chamber sealed on one end by a membrane. Manually opening up the compressed airflow valve pressurize the chamber. The pressure in the chamber is monitored with a pressure gauge. Once the desired pressure is reached, the membrane is punctured to produce the impulse. If the pressure in the chamber is too low relative to the thickness of the membrane, the cylinder depressurizes with a hiss rather than an explosive release of the gas. Generally, as the peak pressure is increased, the impulse peak sound pressure level increases.

Two acoustic shock tubes are commercially available: one developed by NIOSH and another was developed by Professor Jan Zera in Poland (Zera and Mlynski, 2007). The design, operation and the performances of these shock tubes differ from each other. The Polish shock tube is vertically oriented and does not utilize a horn or an extension of the shock tube. The lack of an exit tube and a horn on the Polish shock tube inhibits the development of a shock wave for impulses below about 150 dB peak SPL. The NIOSH acoustic shock tube is horizontally oriented and can accommodate extensions and a horn to adjust characteristics of the impulse. The extension of the exhaust tube facilitates the formation of a shock wave in the duct and the horn provides impedance matching between the duct and the open space. The NIOSH shock tube can be fitted with a catenoidal, exponential, or linear horn. A linear horn provides finite transmission across all frequencies; an exponential horn has a sharp lower cutoff frequency for energy transmission; and a catenoidal horn has better high-frequency transmission than a linear horn but has a cutoff frequency that is similar to an exponential horn (Blackstock, 2000).

This report describes the design, construction and operation of the NIOSH acoustic shock tube. Early versions of the NIOSH shock tube and subsequent improvements are described. The manufacturer, part number and normal operating parameters for the shock tube components are provided.

Shock Tube Design

Prototype Development

The first prototype of the NIOSH shock tube was developed under a $24,000 contract with the University of Cincinnati. Due to significant design and operational deficiencies, a second shock tube was developed building on the experience with the first prototype. Bids for the design and fabrication of the second shock tube were obtained from local Cincinnati-area machine shops. Cauble Precision Machine Inc. was awarded a contract for $5,000 to construct the second prototype of the NIOSH shock tube (see Figure 1).

During extensive use of the second prototype of the shock tube, several operational deficiencies were identified. The manual clamping system for sealing the plastic membrane between the flanges was not ergonomic and impractical to use for more than an hour or two. The pressure controls were imprecise and failed after several months of use. The flat gaskets used to seal the membrane with the flanges would leak at pressures above about 45 pounds per square inch (psi). Positioning the shock tube in the laboratory was cumbersome because the shock tube lacked wheels.

The second prototype was modified to include pneumatic clamping, improved air controls, a mobile base for accommodating the shock tube assembly and an acoustic horn to provide gain to the impulse (see Figure 2). Four pneumatic air cylinders (100 psi) capable of delivering over 3000 pounds of force were used to clamp the membrane between the flanges. The airflow controls were upgraded to provide better control of the pressure in the shock tube chamber. The gasket material was changed to a softer material that provided the ability to reach higher pressures before leaks would develop between the plastic membrane and the flanges. The shock tube assembly was mounted on a mobile cart base that allowed the shock tube to be easily maneuvered from one position to another. Finally the airflow circuit was modified to be more serviceable and to improve the safety of the operation of the pneumatically operated clamping system. The modifications to the shock tube included several thousand dollars of parts, including the acoustic horns and upgrades to the air supply for the laboratory (Murphy, 2010).

Theory

The NIOSH acoustic shock tube consists of three major components:

1. The compressed airflow system pressurizes the shock tube to the desired level.
2. The shock tube pressure chamber contains the pressurized air and generates an impulse when the membrane is burst.

3. The acoustic horn provides impedance matching between the exhaust tube and the open air.

The essential design of the shock tube clamps a membrane material (foil, paper, plastic film) between flanges with sufficient force to create an airtight seal in the pressure chamber. The chamber is pressurized with air and a trigger activates a lance to burst the membrane. The sudden release of the compressed air forms a shock wave as it propagates along the exhaust tube and into the acoustic horn. The horn reduces the reflection of energy at the interface between the horn and the room (open air). The horn minimizes a downstream flow-induced turbulent vortex for chamber pressures above about 20 psi when the horn is absent.

Design Description

The description of the equipment, their operational performance and ranges associated with the compressed airflow system, the shock tube and the horn are briefly described below.

Compressed Airflow System

The Impulse Noise Laboratory has a dedicated compressed airflow system housed in a mechanical room located in the High Bay Area of the Robert A. Taft Laboratories. The laboratory is about 60 feet by 20 feet and an 8 foot suspended ceiling. Conditioned room air is filtered and compressed to supply 100 psi airflow for operating the shock tube. The compressed airflow system has a large compressor with a three-stage-filtration system and is piped into the Impulse Noise Laboratory.

The main compressor is an Ingersoll Rand, Model 2475N, 7.5 horsepower premium reciprocating air compressor with an 80 gallon vertical tank. The compressor is housed in a mechanical room outside the Impulse Noise Laboratory that reduces the noise of the compressor in the high bay area, in the adjacent office spaces and in the Impulse Noise lab (See Figure 6). The compressor does not need to be in an isolated space, but the sound levels when the compressor is active can easily exceed 90 dB SPL.

When air is compressed, moisture condenses in the reservoir and the air lines and lubricating oil from the compressor can also accumulate. Figure 7 shows a three-stage filter panel located inside the mechanical room that cleans and conditions the compressed airflow prior to exiting the mechanical room. The compressed airflow is filtered in the first stage by a coalescing standard oil removal SPEEDAIRE filter (Model 4ZL45, ½ inch National Pipe Thread (NPT), 35 cubic feet per minute (CFM) maximum airflow, 250 psi maximum pressure, 150°F maximum temperature). The second stage regulates the pressure with a SPEEDAIRE airline regulator (Model 4ZL49, ½ inch NPT, 80 CFM, 150 psi, 125°F). The pressure can be adjusted between 5 and 150 psi. The third stage lubricates the air via a SPEEDAIRE mist intermediate lubricator (Model 4ZL77, ½ inch NPT, 95 CFM, 150 psi 125°F).

In Figure 8, the clean and conditioned compressed airflow is supplied at 100 psi to the airflow panel in the Impulse Noise Laboratory using ½ inch black pipe coupled to A53A S40 iron pipe. Once the airflow enters the Impulse Noise Laboratory, the flow is regulated with an FNW 410 shutoff valve. The air pressure supplied to the shock tube is indicated on an Ashcroft pressure gauge (Model 50-1008S-02L-XFF-160#, ¼" NPT, stainless steel case, 0-160 psi, lower connection, flush panel flange, 50 mm dial). The gauge is installed upstream of the shut-off valve FNW 410. The airflow panel is connected to the shock tube with HITACHI ¼" inner diameter (ID) flexible rubber tubing rated at 300 psi. The rubber tubing connects the shock tube inlet and the airflow panel outlet with quick-disconnect couplers.

In Figure 9, a DeWalt D55146 portable air compressor serves as the backup for the large compressor. The DeWalt compressor has a 4.5-gallon reservoir and a 1.6 horsepower motor capable of providing 200 psi.

Three pneumatic systems of the shock-tube clamp the membrane material, pressurize the shock-tube chamber, and trigger the pneumatic lance. These systems together with other additional parts of the shock tube (e.g. such as flanges, linear bearings, extruded aluminum frame, mounting plates, extension pipe and the mobile base) are briefly described below.

Pneumatic clamping system

The membrane must be securely clamped to create a seal and pressurize the shock tube pressure chamber before bursting the membrane. In Figure 14, four SPEEDAIRE air cylinders (model 6D886) are installed on the four corners of the moveable plate which is bolted to the moveable flange and mounted on to the open end of the shock tube chamber. The actuators' arms pass through the mounting plate affixed to the shock tube pressure chamber and are bolted to a fixed plate. The Wilkerson regulator (model R12-02-F000, Figure 14) provides a constant pressure level airflow to the Ingersoll Rand 4-way 2-position valve (model M212LS-G, Figure 12) for the operation of the four air cylinders. When the valve is activated, the air cylinders retract the actuator arms and clamp the membrane material in between the fixed flange and the gasket of the moveable flange. When the valve is deactivated, the actuator arms will extend and open the space between the flanges. An inherent safety feature forces the cylinders open when the pressure is not applied by operating the hand lever. Furthermore, the hand lever is located near the flanges so that the operator's free hand is less likely to be caught in between the flanges when the pressure chamber is in the act of closing.

The valve has a maximum operating pressure of 150 psi, maximum operating temperature of 122°F and maximum airflow of 26 CFM. The Wilkerson Regulator has a range of 0-125 psi and ¼ inch ports. The airflow exhaust noise is reduced by an Arrow 1EJW1 silencer. The SPEEDAIRE cylinders are 10.69 inches long, have a diameter of 2 inches and a 6-inch stroke. Each cylinder is double acting and can provide a maximum load of 785 pounds. The operating temperature for the air cylinder ranges from 20 to 200°F with the maximum operating pressure of 250 psi. The nose of the cylinder is threaded (12 threads per inch) and screwed into the plate affixed to the second movable flange. The air cylinder's actuator arm has a 5/8 inch diameter and is threaded (20 threads per inch) and is screwed into the fixed plate at the front of the shock tube.

The airflow circuit for the unpressurized shock tube and unclamped membrane are illustrated in Figure 15. When the Ingersoll Rand valve (Figure 12) is in the OFF position, compressed air exits the valve and opens all four air-cylinders. Figure 16 illustrates the pressurized shock tube with the clamping system closed. When the Ingersoll Rand valve is in the ON position, compressed air exits the valve and retracts the actuators to seal the membrane between the moveable flange and the fixed flange. The shock tube chamber is now ready for pressurization.

<u>WARNING: The SPEEDAIRE actuator arms default to the extended position to prevent accidental crushing of fingers or hands in between the moveable and fixed flanges.</u>

Pressurization system

Once the clamping system is activated and the shock tube chamber is sealed, the chamber can be pressurized (see Figure 17). The airflow is controlled by the Deltrol (model EF-30-B) needle valve and the chamber pressure is regulated by a Norgren R72G-2AT-RMG regulator (see Figure 10). A dust and moisture filter conditions the compressed air before entering the chamber. The Deltrol valve responsible for adjusting the flow rate to the pressure chamber is installed in between the regulator and the chamber. When the regulator is opened, the pressure inside the chamber will increase rapidly and then slow as it reaches the regulator's setting. Pressure can be increased or decreased by adjusting the regulator in small increments. All of the components of the pressurization system are connected using ¼" brass fittings, ¼" brass tubing and ¼" nylon tubing. The regulator has ¼" port size, pressure range of 5-125 psi, maximum inlet pressure rating of 300 psi, maximum outlet pressure rating of 150 psi with a maximum temperature rating of 150°F.

Pneumatic lance system

The MAC palm button (model 180001-112-0038, Figure 11) manually activates the pneumatic lance system consisting of the MAC button assembly and the Clippard Minimatic actuator. The MAC palm button has a 3-way, 2-position valve, spring return and button guard with five, ¼ inch NPT threaded ports. One port is connected to the compressed air and two ports are connected to the actuator. The remaining two ports are exhausted into the room via a muffler. Once the palm button is depressed, compressed air enters the Clippard Minimatic piston shown in Figure 11 and extends the actuator to make contact with the membrane material. The original lance design used a razor knife to pierce the membrane; however, the razor knife was not sufficiently robust for sustained use. A stainless steel bolt was ground to produce a sharp tip and was threaded into the socket that held the razor knife; this lance has operated flawlessly. The stainless steel Clippard Minimatic actuator has a 4-inch stroke, operating pressure of 250 psi and temperature range of 32 to 230°F. The pneumatic circuit is illustrated in Figure 18.

Other membrane materials were evaluated in the shock tube. The paper and foil membranes produced impulses below 150 dB. The low tensile strength of the materials yielded inconsistent peak pressure levels. Consistent peak impulse sound pressure levels have been achieved with 1-mil (0.001”) and 2-mil (0.002”) thick polyester films. The 1-mil polyester film pressurized to 8 psi produced 130-134 dB peak levels when burst. The 2-mil polyester film yielded about 150 dB peak levels when burst at 10 psi and yielded the 168 dB peak levels when burst at 40 psi. The 3-mil (0.003”) polyester film tended to burst with a slit and produced impulses that lacked a single wave-front. Polyester or acrylic films thicker than 5 mils (0.005”) tended to produce a hissy leak due to a lack of pressure to catastrophically rupture the membrane. Piedmont Plastics Inc. (Wheeling, IL) has supplied plastic films cut to size (7 x 9 inches) to use with the shock tube. While this report is not intended to detail the acoustic performance of the shock tube, the most consistent levels and uniform waveforms were achieved with the 1-mil and 2-mil polyester films.

Shock Tube Pressure Chamber

The shock tube pressure chamber is constructed of steel pipe with an inside diameter (ID) of 4” and outside diameter (OD) of 4½” with an overall length of approximately 34”. The chamber is open on one end and closed on the other end. A 4” pipe flange is welded flush to the open end of the chamber and a second 4” pipe flange is welded to the chamber approximately 10 ½” from the closed end. The bottom two bolt holes of the movable flanges are aligned to receive linear bearings for the turned ground polished (TGP) rods. The shock tube chamber is equipped with a safety relief valve, a digital pressure indicator and a handle. The Steuby safety valve (model AS250M) will vent when the pressure exceeds 100 psi (Figure 13). The Omega digital pressure gauge (model DPG8000-200) can measure pressures up to 200 psi and has settings which change what is displayed on to the pressure gauge (Figure 13). The instantaneous chamber pressure is the most commonly used setting and displays the pressure with a precision of 0.1 psi. The Omega gauge is battery operated, requires several seconds to turn on and automatically shuts off after about 15 minutes. In order to facilitate testing, the operator should occasionally press a button on the Omega gauge to prevent automatic shutoff.

Three 4-inch cast iron pipe flanges (U.V. International, LLC) were used in the sliding mechanism of the shock tube pressure chamber. The first fixed flange is bolted to the larger mounting plate by three ½″ x 1 ½″ long socket head cap screws. The second moveable flange is welded flush to the open end of the pressure chamber and bolted to the air cylinder support plate using six ½″ bolts. The third moveable flange is welded to the pressure chamber, approximately 10.5 inches away from the closed end with its bolt holes aligned with the second flange. The two bottom bolt holes of the fixed flange support the two sliding TGP rods which pass through the linear bearings inserted into the corresponding bolt holes of the second and third moveable flanges. The flanges are carefully aligned along with the actuator arms of the air cylinders to make the surfaces of the first and second flanges parallel.

In order to seal the membrane between the fixed flange and the flange at the open end of the pressure chamber, a ⅜ inch thick flat gasket (approximately 5⅛ inch outer diameter and 4 inch inner diameter) is affixed to the face of the second flange using Permatex-2 gasket sealer. In subsequent versions of the shock tube built by B/C Precision Tools, an O-ring groove was machined into the flange and a ¼″ O-ring was used in place of the flat gasket material. The O-ring provides a better seal allowing higher pressure in the shock tube chamber and therefore a higher peak impulse pressure.

The supporting frame of the shock tube is built from T-slotted extruded aluminum manufactured by 80/20 Inc. (model 1515). The framing material is 1.5″ x 1.5″ and has T-slots on all four sides that are compatible with the 15-Series fasteners and accessories. The supporting frame consists of two 56″ front vertical legs and two 37″ rear vertical legs. These legs are connected together by four horizontal side bars and two end bars. The bottom shelf of the cart is supported by two horizontal side bars, approximately 33.5″ long and two horizontal end bars, approximately 13″ long. The top shelf is supported by two side bars; approximately 36.5″ long which accommodates the air flow controls of the shock tube (see Figures 2, 3, 4, and 5 for dimensions and connectors).

Three different sized mounting plates are incorporated in the overall design of the shock tube. Two of the plates surround the open end of the pressure chamber and the fixed flange/exhaust tube (see Figure 3 and Figure 5). The third plate supports the TGP rods on which the pressure chambers moves laterally. The largest mounting plate has a 4″ hole in the center of this plate and dimensions of 16″ x 16″ x ½″. The fixed flange is bolted to the mounting plate and is welded to the 4″ ID exhaust pipe, approximately 24″ long. Four ½″ holes were drilled and tapped to accommodate the tangs from the four air cylinders. The open end of the shock tube is bolted to the second mounting plate and has dimensions of 12″ x 12″ x ¼″. Each of the air cylinders is mounted in a corner of this plate and aligned with the respective holes of the first mounting plate. The plate is divided into two halves and the corners rounded to allow it to be mounted on the second flange using six ¾″ bolts. The heads of these bolts were machined down to provide adequate clearance for the flanges to appropriately seal with the plastic membrane when they are in the closed position. Parts of the bottom section of both halves have been removed to eliminate any obstruction associated with the movement of the pressurized chamber. The third mounting plate supports the chamber sliding system on the other end and has dimensions of 16″ x 5.25″ x 1″.

The 24″ long extension pipe is a 4″ ID steel pipe welded to the fixed flange (see Figure 2). The extension pipe provides a connection for the acoustic horn and serves as a one-dimensional duct in which the shock wave can fully develop.

The NIOSH acoustic shock tube was built without any integral wheels to facilitate moving it around the laboratory space. An HTC Products mobile base (model HTC-2000) was purchased and adjusted to fit the shock tube frame. Subsequent versions of the shock tube built by B/C Precision Tool have a pair of wheels installed on the front legs of the shock tube stand that touch the ground when the rear of the shock tube is elevated by about 3 inches.

Acoustic Horn

The propagation of the shock wave from a cylindrical duct into an open room presents two problems. First, the abrupt change in cross-sectional area from the cylindrical duct of the exhaust tube to the open room is a step function that results in a large impedance mismatch and causes a significant amount of acoustic energy to be reflected back into the tube. Second, the wave front exiting the exhaust tube generates a vortex that creates a significant flow noise downstream from the exhaust tube. Consequently, a solution to both the impedance mismatch and the vortex was to design a horn that could be attached to the exhaust tube. In this section, the mathematical formulae are detailed and measurement tables used to construct the NIOSH exponential and catenoidal horns are provided.

Design

Two different profile rectangular horns were developed for the acoustic shock-tube: exponential and catenoidal. The exponential horn has more discontinuity at the juncture of the exhaust pipe and the horn than the catenoidal horn. The catenoidal horn has a more gradual increase in cross-sectional area than the exponential horn and is longer than the exponential horn. The cross sectional profiles of the two horns are shown in Figure 19. The blue outline is the exponential cross section through the centerline. The red outline is the catenoidal cross section through the centerline of the horn's axis. The horn amplifies the acoustic impulse allowing the generation of higher-level impulses. The highest levels produced by the NIOSH acoustic shock tube are around 166 to 170 dB peak SPL.

The exponential and catenoidal horns were designed using the Webster horn equation (Blackstock, 2000). The horns had four identical sides and the flat sheet projection drawing of one side was made using Matlab program (Zechmann, 2011). The flat-sheet projections for both horns are shown in Figure 20. The three-dimensional renderings of the "assembled" horns are shown in Figure 21 and Figure 22 for the exponential and catenoidal horns, respectively.

Exponential Horn

The distance from the centerline of the horn to the wall increases exponentially as one moves from the throat to the end of the horn,

$$y = r_0 e^{\frac{mx}{2}}, \qquad (1)$$

where x is the distance along the centerline of the horn, m is the flare constant of the horn and r_0=2.25" is the throat radius. For the exponential horn the cutoff frequency, f_c, was chosen to be 100 Hz, below the lowest octave band for real ear attenuation at threshold testing. The cutoff frequency is related to the flare constant,

$$m = \frac{4\pi f_c}{c_0}, \qquad (2)$$

where c_0 is the speed of sound. Solving for the flare constant yields m = 3.6637 when the cutoff frequency is 100 Hz and the speed of sound is 343 m/s.

The distance from the centerline describes the cross section of the horn, but does not provide sufficient information to construct the actual sides of the horn to form the rectangular cross section. The distance along the surface of the side of the horn must be integrated to yield the arc length. Then a second arc length must be integrated to find the distance between the centerline of the surface to the edge of the horn.

The general arc length integral is

$$s_{center}(x) = \int_0^x \sqrt{d\hat{x}^2 + dy^2} = \int_0^x \sqrt{1 + \left(\frac{dy(\hat{x})}{d\hat{x}}\right)^2}\, d\hat{x} = \int_0^x \sqrt{1 + y'(\hat{x})^2}\, d\hat{x} \tag{3}$$

where *s(x)* is the arc length as a function of *x* and *y'(x)* is the derivative of the horn's cross sectional profile, in this case the exponential function. Next the arc of the edge is defined in terms of the arc length, *s(x)*, of the profile,

$$y_{EDGE} = y(s_{CENTER}(x)). \tag{4}$$

The arc length along the edge can be computed using the arc length of the centerline,

$$s_{EDGE}(x) = \int_0^x \sqrt{1 + y'(s_{CENTER}(\hat{x}))^2}\, ds_{EDGE}(\hat{x}) \tag{5}$$

where $s_{EDGE}(x)$ is the arc length along the edge. The integral in Equation 3 can be determined analytically. The arc length integral in Equation 5 is numerically integrated to yield the final profile. The coordinates for the exponential horn calculated in increments of 1 inch along the center axis are provided in Table 1. The x coordinates should be plotted along the centerline of the sheet metal material and the y coordinates are the positive and negative distance from the centerline. The outline describes the sides for an exponential horn with a throat of 2.25" radius to be coupled to the exhaust of the acoustic shock tube or an extension. Nominally a 4-inch diameter cast iron pipe is assumed to be the size of the shock tube's exit.

Catenoidal Horn

The cross sectional area of the catenoidal horn increases as a hyperbolic cosine from the throat to the end of the horn,

$$y = r_0 \cosh\left(\frac{mx}{2}\right) \tag{6}$$

where r_0 is the radius of the throat and *m* is the flare constant calculated from Equation 2. Using the theory and a cutoff frequency of 100 Hz described for the exponential profile horn, the arc-length of the catenoidal horn can be determined. The x and y coordinates for the horn profiles are given in Table 2.

According to Blackstock (2000), the amount of energy transmitted (transmission factor) by an exponential horn will be 0 below the cutoff frequency, f_c. For the catenoidal horn, the transmission factor is finite below f_c and grows asymptotically to 1 above f_c. The catenoidal horn has been used more frequently than the exponential horn in the NIOSH Impulse Noise Laboratory.

Horn Construction

Four identical catenoidal flat-projection profiles were cut from 16-gauge steel. The four profiles were welded together at the corners to create a square cross-section for the catenoidal horn. A rotary grinder was used to remove sharp edges at the seams and along the edges of the horn's opening. Using the coordinates provided in Table 1 or Table 2, the sides in Figure 20 can be laid out. The programs used to calculate the horn shapes are provided in the archive available on Matlab Central File Exchange (Zechmann, 2011). If Matlab is not available, numerical analysis software such as Octave could run a modified version of the programs developed for the horn.

The coordinates pairs for [s(x)], y_2(x)] were calculated and saved in a *.dxf file. A computer numerical control (CNC) machine can read the .dxf file and cut the sheet metal within a tolerance of 0.0001 inch. Alternatively, the profiles were imported into Microsoft Visio software, printed with a large-format printer and then transferred to the metal for cutting the sides.

The throat of the horn was joined to the exhaust tube of the shock tube. A square cap was constructed to fit over the end of the horn and was welded to the horn. A 4½ inch diameter was cut in the cap to join the square cap to a 4 3/8 inch long pipe. These pieces were welded together. The horn and the exhaust tube for the shock tube were connected by a PVC 4½ inch coupler.

The horn is mounted on a wheeled frame of 2-inch angle iron to support the horn and allow it to be mobile. The overall dimensions of the base of the cart are approximately 26 ½ inches by 46 ¼ inches. The front side of the horn is welded to the base of the cart using two 2-inch angle irons approximately 31 ½ inches long and installed 22 inches apart. The bottoms of the angle iron frames are welded to the front two corners of the base of the cart while the upper ends are vertically welded to the two sides of the horn, approximately 24 ½ inches away from the outlet of the horn. The rear of the horn is welded to the cart using two 2-inch angle iron approximately 38 ¼ inches long and installed 5 ¾ inches apart. The bottoms of the angle iron frames are welded to the back of the base of the cart, approximately 10 inches away from the two back corners of the base of the cart while the upper ends are vertically welded to the two sides of the horn, approximately 11 inches away from the inlet of the horn. The base of the cart is equipped with four 2” castors with lock-in mechanism, which increases the mobility of the horn.

Figure 21 and Figure 22 illustrate a three-dimensional rendering of the catenoidal and exponential horns. The NIOSH horns were manufactured by D & D Metal Supply Inc., located in Cincinnati, Ohio. The external surface of the horn should be covered with an extensional damping material to reduce the ringing and vibration of the horn when the shock tube is fired. While the NIOSH horn is covered with a material purchased from McMaster Carr, the damping material is somewhat brittle and has cracked at the edges and seams of the material. B/C Precision Tool has manufactured three shock tubes and catenoidal horns using the NIOSH design and at least one of the horns used the E-A-R C2003 extensional damping material to cover the external surfaces of the horn. The increased flexibility of the E-A-R material seems to reduce the cracking observed with the NIOSH horn.

Shock Tube Operation

Activation (Start-up)

Step-by-step instructions for the activation of the shock tube are listed below:

1. Turn the FNW 410 valve to the “ON” position to allow flow of compressed air to the shock tube.
2. Adjust the compressed airflow pressure to 100 psi at the airflow panel.
3. Turn on the OMEGA pressure indicator by pressing the first button on top of the digital readout screen to “ON” setting.
4. Press the first button on the bottom of the digital readout screen to “Max” setting which will set the pressure indicator to read the maximum chamber pressure at any time during operation of the shock tube.
5. Press the third button on the bottom of the digital readout screen to “PSI” setting that will set the pressure indicator to read the pressure inside the shock tube chamber in psi.

Operation (Firing)

Step-by-step instructions for firing the shock tube are listed below:

1. Insert a membrane (plastic, foil or paper) between the flanges.
2. Close the shock tube with the Ingersoll Rand red handled lever.
3. Pressurize the shock tube with the Norgren R72G regulator.
4. Watch the OMEGA pressure gauge until the desired pressure is reached.

5. Press the MAC palm button to activate the pneumatic lance.
6. If the pressure is sufficient, the membrane will be catastrophically ruptured resulting in a shock wave propagating out of the tube and horn assembly. If the membrane is too thick or the pressure too low, the membrane will only be punctured and air will be released slowly with a hissing sound.

Termination (Shut-Down)

Step-by-step instructions for shutting-down the shock tube operation are listed below:

1. The operation of the shock tube is shutdown by turning the FNW 410 valve to the "OFF" position.
2. Completely "OPEN" the Norgren 2" pressure regulator to allow for the compressed airflow to completely bleed out of the shock tube chamber and the clamping system air lines.

Environment and Periodic Maintenance

The laboratory space should be maintained at a temperature of 75°F ± 5°F and a relative humidity of 50% ± 10% to minimize operational variability.

Compressed Air System Maintenance

The oil level in the compressor frame should be checked on a monthly interval. If oil level is below manufacturer's recommended level, add lubricant to restore the level to the proper level. In Figure 7, the stage 1 filter (Speedaire 4ZL45) needs to be bled on a weekly basis to remove coalescing oil residue collected from the compressor airflow. The stage 3 filter (Speedaire 4ZL77) should be bled on a weekly basis to remove oil mist produced in the stage 2 filter (Speedaire 4ZL49).

Prior to daily use of the shock tube, purge the water from the shock tube system by bleeding off the Wilkerson regulator located on the bottom of the top shelf of the shock tube cart. On a monthly basis clean the viewing glass bowl installed on the shock tube pressure regulator with soap and water. Daily inspect the rubber gasket installed on the moveable flange of the shock tube chamber to ensure proper sealing of the shock tube with the plastic membrane. If the gasket is lose then re-glue the gasket appropriately on to the moveable flange using Permatex 2 gasket sealer. If the shock tube cannot be sealed because of the degradation of the rubber gasket, then it should be replaced with a new gasket.

Horn Maintenance

Periodically inspect the exterior surface of the horn to make sure the dampening material has not peeled off from the horn due to the vibration of the horn. Replace the damage dampening material with a new material. 3M manufactures the E-A-R C2003 extensional damping material that can be applied to the exterior surface of the horn to reduce ringing.

Safety

The NIOSH acoustic shock tube has the potential to cause immediate and permanent damage to hearing if it is operated in a careless, unsafe manner. At levels of 140 dB peak sound pressure level and above, one risks hearing damage if no protection is worn. The NIOSH recommended exposure limits include a suggested ceiling of 140 dB. Clearly, the shock tube is capable of delivering significantly higher peak levels. Therefore, personnel that are operating the shock tube should always wear double protection. NIOSH personnel are enrolled in the hearing conservation program administered by the NIOSH Safety Office.

Several safety precautions have been implemented in the Impulse Noise Testing Laboratory. Outside the laboratory, a red-flashing light is activated to indicate that testing is being conducted. Warning signs are posted on the two doors leading into the laboratory area. Earmuffs and safety glasses are available in a bin just outside the door. When the shock tube is being operated, the room is locked from the outside to prevent an observer from entering during a test. The far end of the room has a glass window that allows the operator to see when someone is waiting to enter the laboratory. Inside the laboratory, more than a dozen different pairs of earmuffs are available along with a range of disposable earplugs for operators and observers to wear during testing. Operators and observers wear safety glasses. Because the shock tube is designed to rupture a membrane clamped between the flanges, the risk of the tube exploding is minimal and probably nonexistent. The shock tube pressure chamber has a safety relief valve that will open at 100 psi. However, the flat gaskets of the shock tube in its present design will begin to leak at about 40 to 50 psi. In subsequent designs the use of O-rings has increased the pressure that the chamber can hold before leaks occur. Thus, the risk of the tube exploding and having debris flying about the room is quite minimal. Furthermore, when the membrane ruptures, the material (plastic film, paper, foil) has never been observed to exit the horn or the exhaust tube. Regardless, safety is still paramount and operators and observers should always wear hearing and eye protection while the tube is in operation.

Trip hazards pose a significant risk that can easily be avoided. During our initial work with the shock tube, as many as a dozen microphones and cables were laid out across the length of the laboratory to different positions in the room. The NIOSH Safety Office recommended that hangars for the wire be installed near the ceiling to get the cables off the floor. Thus, the microphone cables and the air hose from the airflow panel are suspended from the ceiling to reduce clutter and trip hazards.

Good laboratory safety practices will prevent inadvertent impulse noise exposures and minimize the risk of incurring hearing loss for operators and observers. The operator should always check with others in the laboratory to ensure that they are wearing the safety equipment properly before firing the shock tube. Lastly, high-level impulses will elicit a startle response from most persons. When demonstrating the shock tube, the operator should provide a countdown to the uninitiated observers.

References

ANSI S12.42. [2010]. American National Standard Methods for the Measurement of Insertion Loss of Hearing Protection Devices in Continuous or Impulsive Noise Using Microphone-in-Real-Ear or Acoustic Test Fixture Procedures. American National Standards Institute: New York.

Berger EH and Hamery P [2008]. Empirical evaluation using impulse noise of level-dependency of passive earplug designs. In Acoustics `08, Paris, July 2008. Acoustical Society of America.

Blackstock DT [2000]. Fundamentals of Physical Acoustics, John Wiley and Sons, New York NY, pp. 252-267.

EPA [1979]. 40 CFR 211B Hearing Protective Devices Product Noise Labeling Hearing Protection Devices; Final Rule. U.S. Environmental Protection Agency, Washington D.C., September 28, 1979.

EPA [2003] Workshop Report for Labeling Regulation, Docket Number EPA–HQ–OAR–2003–0024, U.S. Environmental Protection Agency, Washington D.C., March 27-28, 2003.

EPA [2009]. 40 CFR 211B Hearing Protective Devices Product Noise Labeling Hearing Protection Devices; Proposed Rule. U.S. Environmental Protection Agency, Washington D.C., August 5, 2009.

Holland RK [2001]. Principles of sound radiation, In Borwick J. ed. Loudspeaker and Headphone Handbook 3rd edition, Focal Press, Oxford UK, pp. 30-40.

Kinsler LE, Frey AR, Coppens AB, Sanders JV [1999]. Fundamentals of Acoustics 4th edition, John Wiley and Sons, New York NY, pp. 414-416.

Long M [2006]. Architectural Acoustics, Elsevier Academic Press, Burlington MA, pp. 228–234.

Murphy WJ [2010]. Cost Estimate for the Impulse Acoustic Testing Laboratory, Letter to Senior Policy Analyst, U.S. Environmental Protection Agency, Dec. 20, 2010.

Murphy WJ, Flamme GA, Meinke DK, Sondergaard J, Finan DS, Lankford JE, Khan A, Vernon JA, and Stewart M [2012]. Measurement of impulse peak insertion loss for four hearing protection devices in field conditions. Int J Aud, 51: S31–S42.

Partmentier G, Dancer A, Buck K, Kronenberger G, and Beck C [2000]. Artificial Head (ATF) for Evaluation of Hearing Protectors. Acustica, 86:847-852.

Pierce AD [1989]. Acoustics: An Introduction to Its Physical Principles and Applications, Acoustical Society of America, Melville NY, pp. 362-365.

Zechmann, EL [2011]. Horn Design.m - Simple Acoustic Horn Design for Amplification, Matlab Central File Exchange http://www.mathworks.com/matlabcentral/fileexchange/26457-simple-acoustic-horn-design-for-amplification, Accessed Jan 19, 2012.

Zera J and Mlynski R [2007]. Attenuation of high-level impulses by earmuffs. J Acoust Soc Am, 122:2082-2096

Tables

Table 1. Exponential horn dimensions. The following table provides the coordinates for laying out the sides of the exponential horn on a flat sheet of material. Four identical sheets of material should be cut from 14 gauge sheet metal to be welded together at the corner seams. The x values are the distance along the center line of the 48 x 96 inch sheet metal. The ±y values describe the layout line above and below centerline.

X	+Y	-Y
0.0	2.25	-2.25
1.0	2.35	-2.35
2.0	2.45	-2.45
3.0	2.55	-2.55
4.0	2.66	-2.66
5.0	2.77	-2.77
6.0	2.89	-2.89
7.0	3.01	-3.01
8.0	3.13	-3.13
9.0	3.26	-3.26
10.0	3.40	-3.40
11.0	3.54	-3.54
12.0	3.68	-3.68
13.0	3.83	-3.83
14.0	3.98	-3.98
15.0	4.14	-4.14
16.0	4.30	-4.30
17.0	4.47	-4.47
18.0	4.65	-4.65
19.0	4.83	-4.83
20.0	5.02	-5.02
21.0	5.21	-5.21
22.0	5.41	-5.41
23.0	5.61	-5.61
24.0	5.82	-5.82
25.0	6.04	-6.04
26.0	6.26	-6.26
27.0	6.49	-6.49
28.0	6.72	-6.72
29.0	6.96	-6.96
30.0	7.21	-7.21
31.0	7.47	-7.47
32.0	7.73	-7.73
33.0	8.00	-8.00
34.0	8.27	-8.27

X	+Y	-Y
35.0	8.55	-8.55
36.0	8.84	-8.84
37.0	9.13	-9.13
38.0	9.43	-9.43
39.0	9.74	-9.74
40.0	10.06	-10.06
41.0	10.38	-10.38
42.0	10.71	-10.71
43.0	11.05	-11.05
44.0	11.39	-11.39
45.0	11.74	-11.74
46.0	12.09	-12.09
47.0	12.46	-12.46
48.0	12.83	-12.83
49.0	13.20	-13.20
50.0	13.59	-13.59
51.0	13.98	-13.98
52.0	14.38	-14.38
53.0	14.78	-14.78
54.0	15.19	-15.19
55.0	15.61	-15.61
56.0	16.03	-16.03
57.0	16.46	-16.46
58.0	16.90	-16.90
59.0	17.34	-17.34
60.0	17.79	-17.79
61.0	18.25	-18.25
62.0	18.71	-18.71
63.0	19.18	-19.18
64.0	19.65	-19.65
65.0	20.13	-20.13
66.0	20.62	-20.62
67.0	21.11	-21.11
67.6	21.41	-21.41

Table 2. Catenoidal horn dimensions.The following table provides the coordinates for laying out the sides of the catenoidal horn on a flat sheet of material. Four identical sheets of material should be cut from 14 gauge sheet metal to be welded together at the corner seams. The x values are the distance along the center line of the 48 x 96 inch sheet metal. The ±y values describe the layout line above and below centerline.

X	+Y	-Y
0.0	2.25	-2.25
1.0	2.25	-2.25
2.0	2.26	-2.26
3.0	2.27	-2.27
4.0	2.29	-2.29
5.0	2.31	-2.31
6.0	2.34	-2.34
7.0	2.37	-2.37
8.0	2.40	-2.40
9.0	2.44	-2.44
10.0	2.49	-2.49
11.0	2.54	-2.54
12.0	2.59	-2.59
13.0	2.65	-2.65
14.0	2.71	-2.71
15.0	2.78	-2.78
16.0	2.85	-2.85
17.0	2.93	-2.93
18.0	3.01	-3.01
19.0	3.10	-3.10
20.0	3.19	-3.19
21.0	3.29	-3.29
22.0	3.39	-3.39
23.0	3.50	-3.50
24.0	3.62	-3.62
25.0	3.74	-3.74
26.0	3.86	-3.86
27.0	3.99	-3.99
28.0	4.13	-4.13
29.0	4.27	-4.27
30.0	4.42	-4.42
31.0	4.57	-4.57
32.0	4.73	-4.73
33.0	4.89	-4.89
34.0	5.06	-5.06
35.0	5.24	-5.24
36.0	5.42	-5.42
37.0	5.61	-5.61
38.0	5.81	-5.81
39.0	6.01	-6.01
40.0	6.22	-6.22
41.0	6.44	-6.44

X	+Y	-Y
42.0	6.66	-6.66
43.0	6.89	-6.89
44.0	7.13	-7.13
45.0	7.37	-7.37
46.0	7.62	-7.62
47.0	7.87	-7.87
48.0	8.14	-8.14
49.0	8.41	-8.41
50.0	8.68	-8.68
51.0	8.97	-8.97
52.0	9.26	-9.26
53.0	9.56	-9.56
54.0	9.86	-9.86
55.0	10.17	-10.17
56.0	10.49	-10.49
57.0	10.82	-10.82
58.0	11.15	-11.15
59.0	11.49	-11.49
60.0	11.84	-11.84
61.0	12.20	-12.20
62.0	12.56	-12.56
63.0	12.93	-12.93
64.0	13.30	-13.30
65.0	13.68	-13.68
66.0	14.07	-14.07
67.0	14.47	-14.47
68.0	14.87	-14.87
69.0	15.28	-15.28
70.0	15.69	-15.69
71.0	16.12	-16.12
72.0	16.55	-16.55
73.0	16.98	-16.98
74.0	17.42	-17.42
75.0	17.87	-17.87
76.0	18.33	-18.33
77.0	18.79	-18.79
78.0	19.26	-19.26
79.0	19.73	-19.73
80.0	20.21	-20.21
81.0	20.70	-20.70
82.0	21.19	-21.19
82.5	21.43	-21.43

Figures

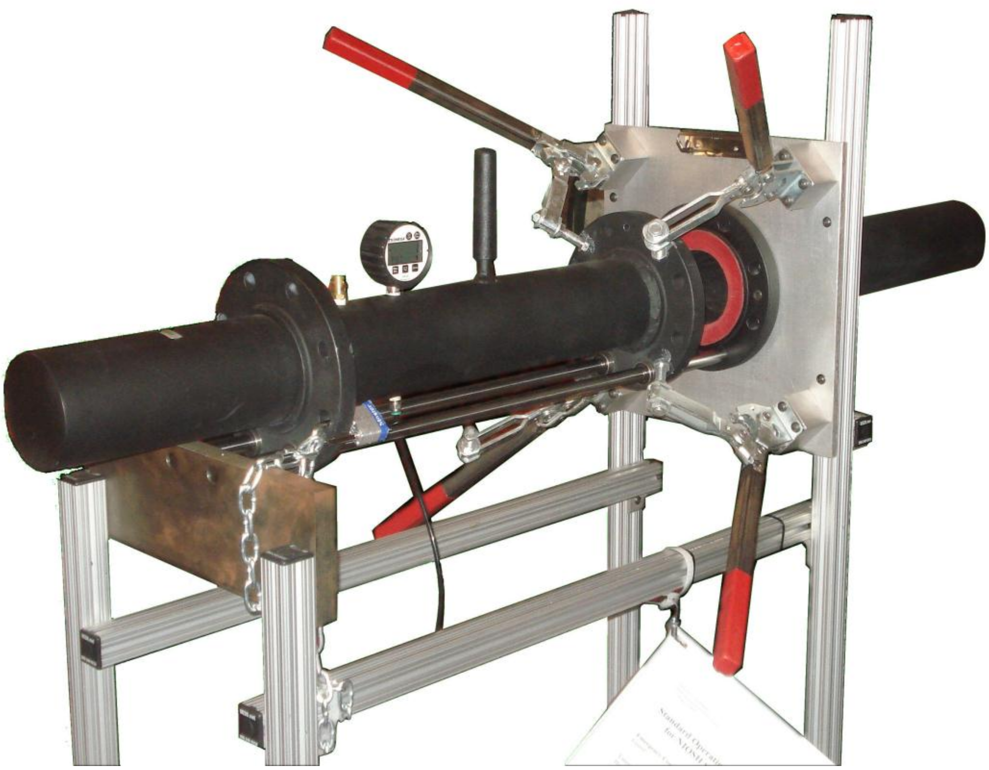

Figure 1: Second prototype acoustic shock tube

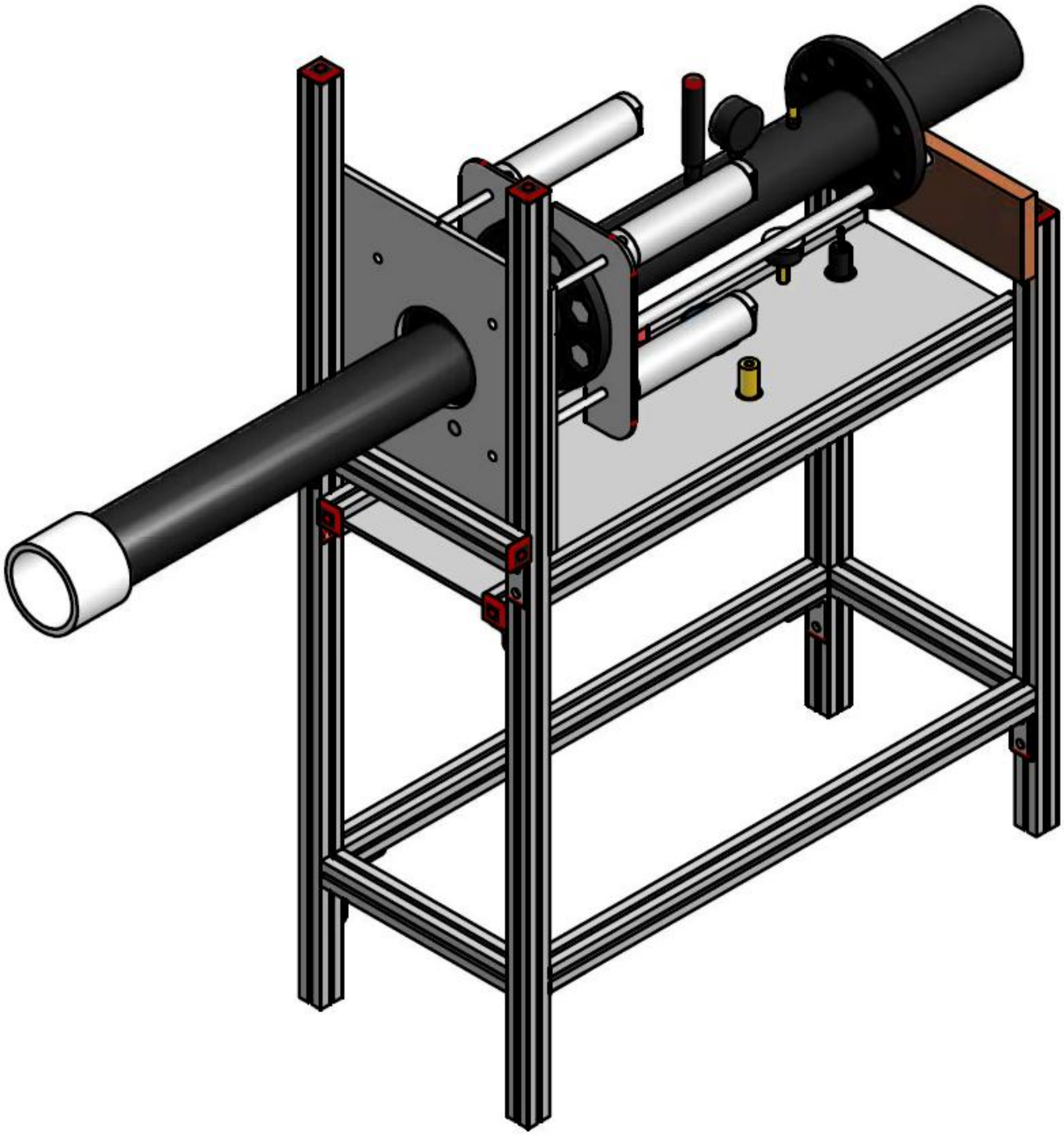

Figure 2: Three-dimensional mechanical rendering of the acoustic shock tube

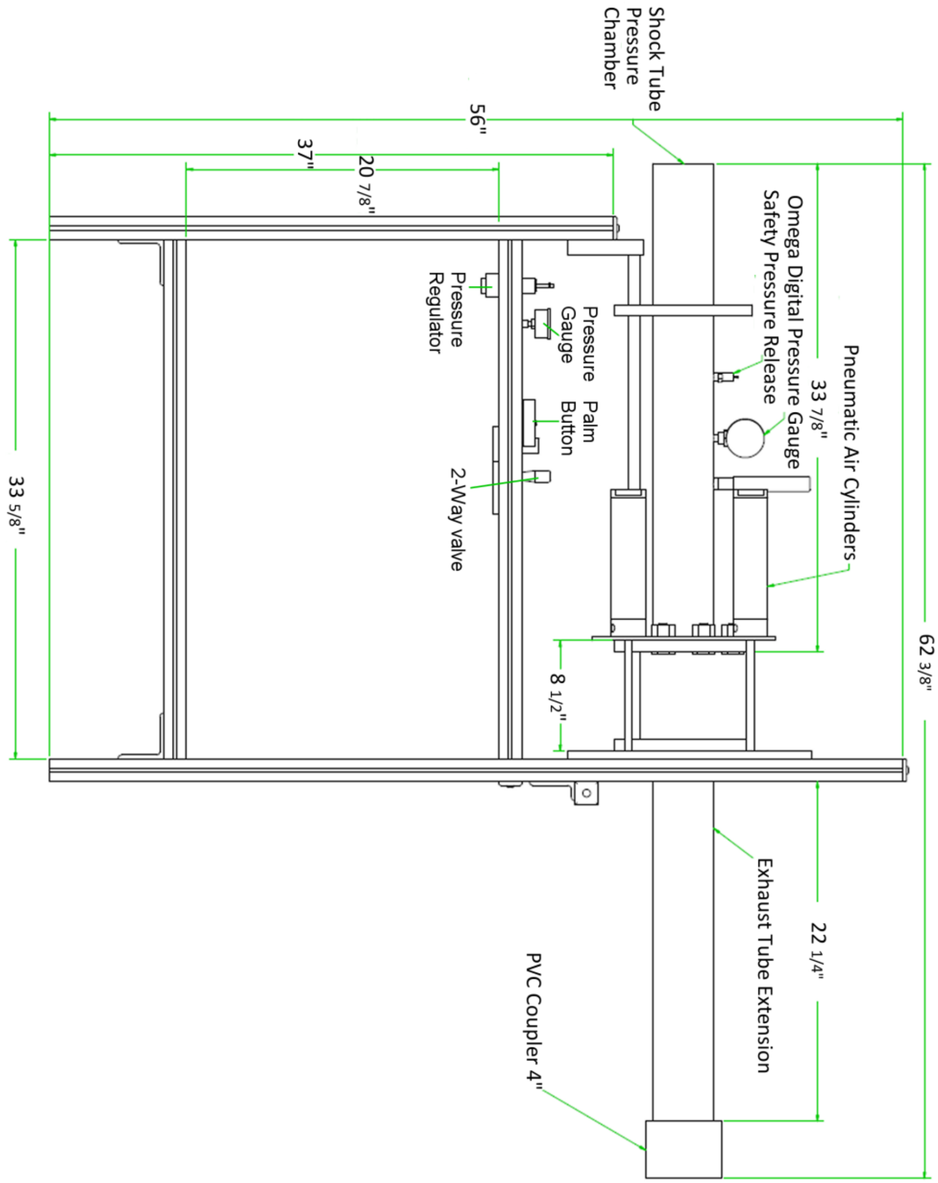

Figure 3: Side view of the acoustic shock tube

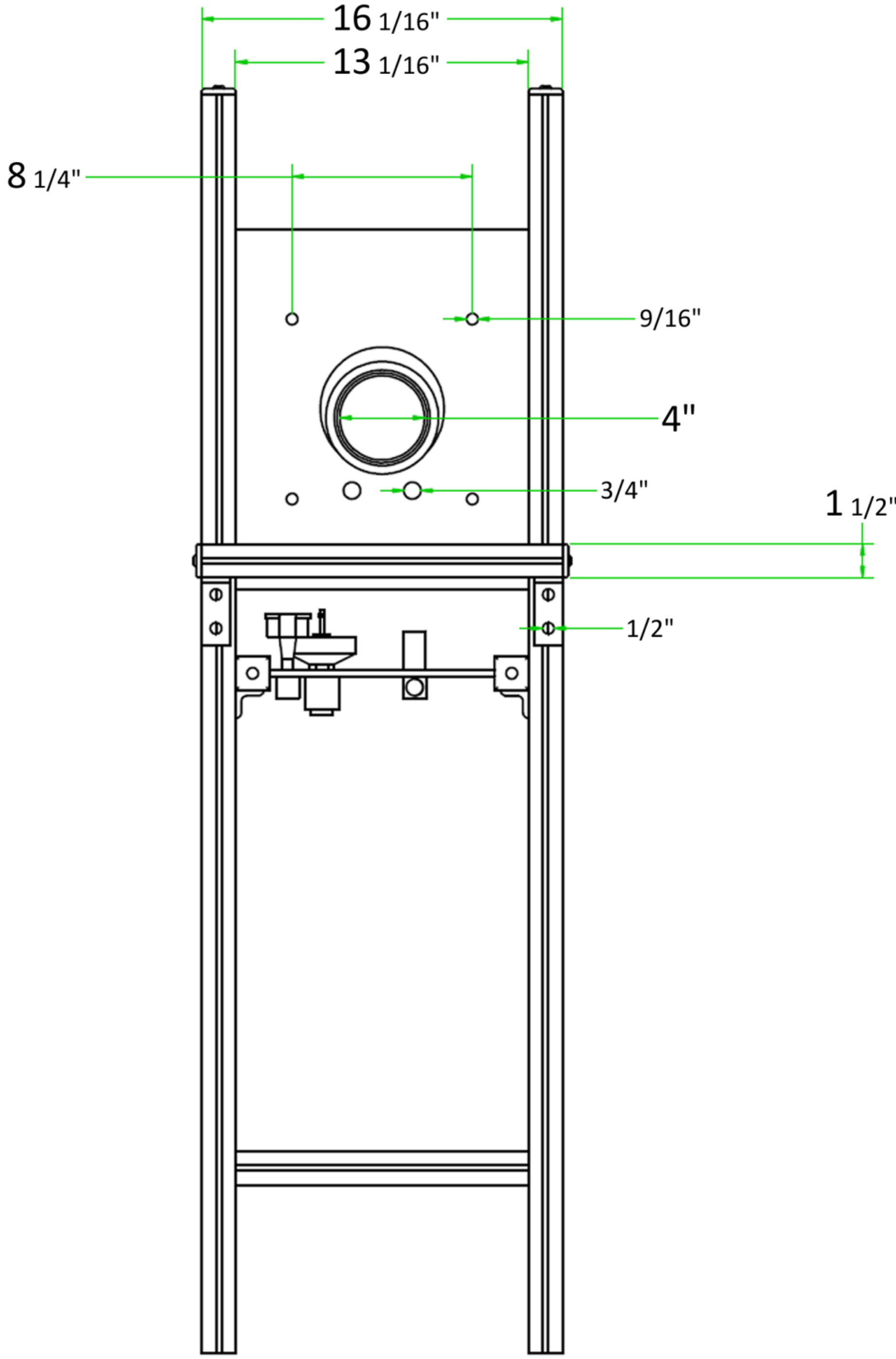

Figure 4: Front view of acoustic shock tube

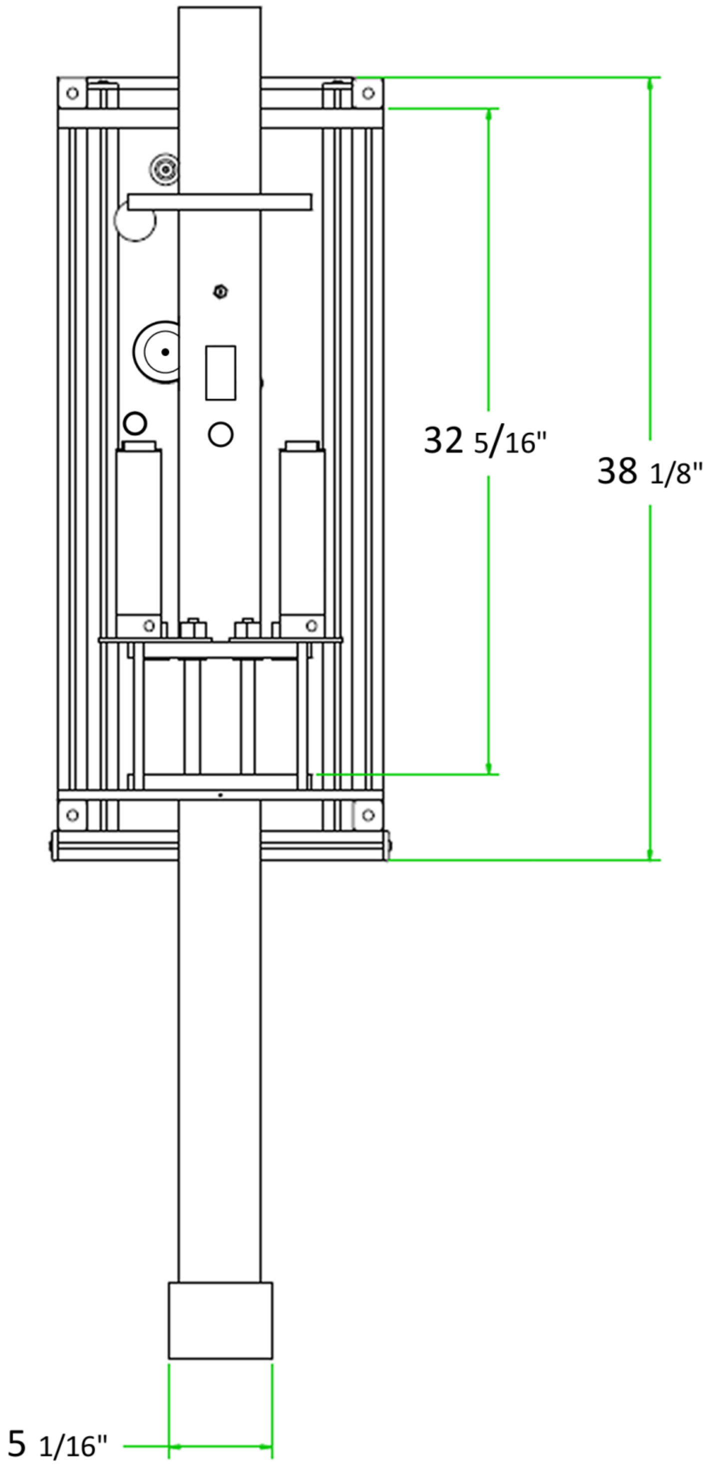

Figure 5: Top view of acoustic shock tube

Figure 6: Ingersoll Rand, Model 2475N, 7 ½ horsepower air compressor

Figure 7: Three-stage filter for the compressed airflow

Figure 8: The FNW 410 valve and the Ashcroft analog pressure gauge

Figure 9: DeWalt model D55146 portable air compressor

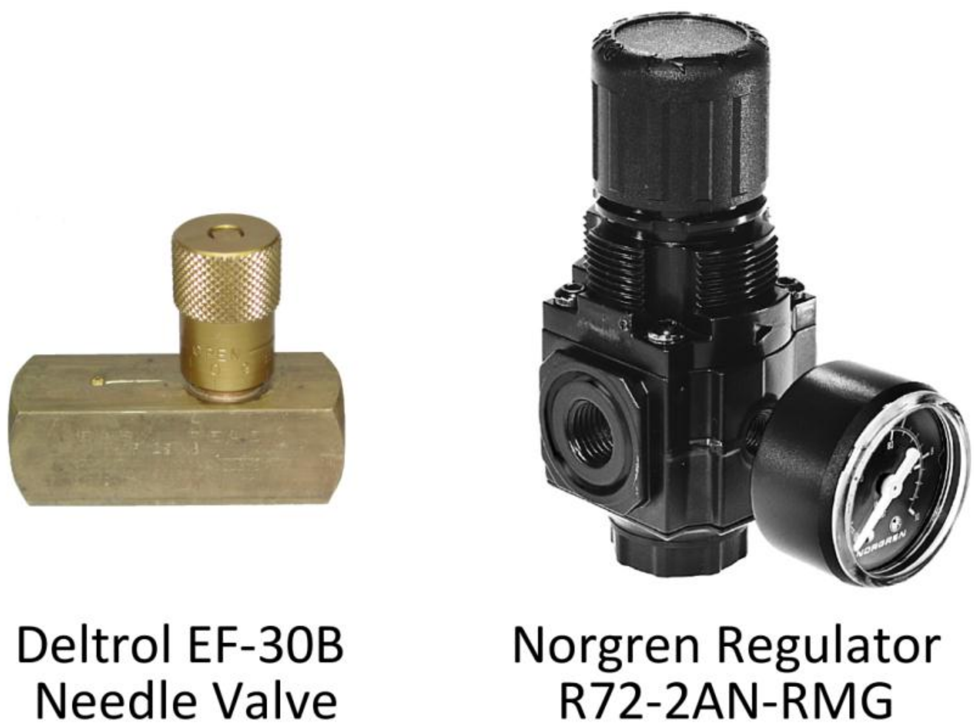

Figure 10: Needle flow-control valve and pressure regulator

Figure 11: Button and actuator to lance the membrane

Figure 12: Ingersoll Rand 2-way valve (model M212LS-G) and Arrow silencer (model 1008) for the pneumatic clamping system

Figure 13: Safety relief valve and digital pressure gauge mounted on pressure chamber

SPEEDAIRE cylinder
Model 6D886

Wilkerson Regulator
Model R12-02-F000

Figure 14: Pneumatic clamping system air cylinder and regulator

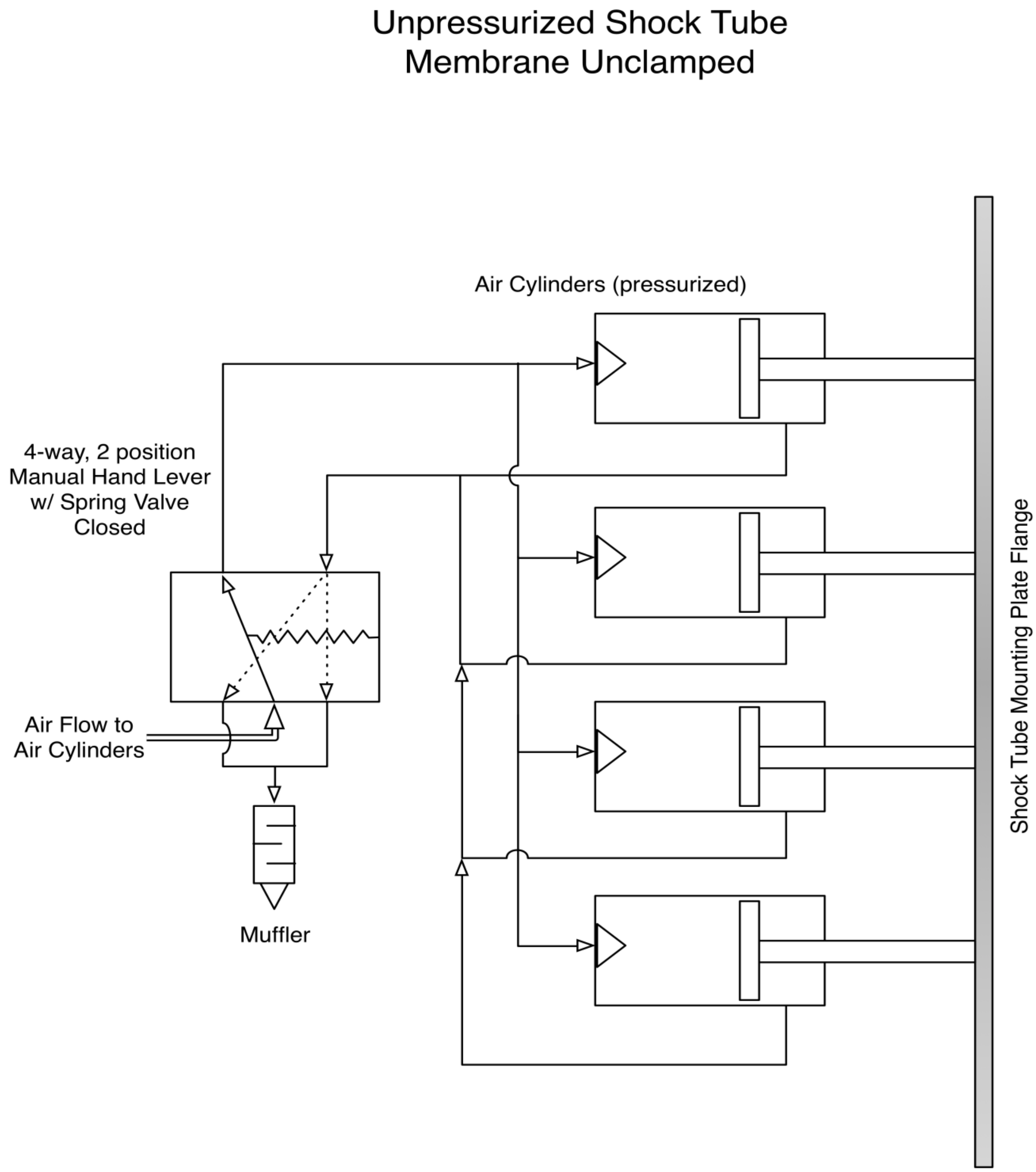

Figure 15: Unpressurized shock tube with unclamped membrane airflow diagram

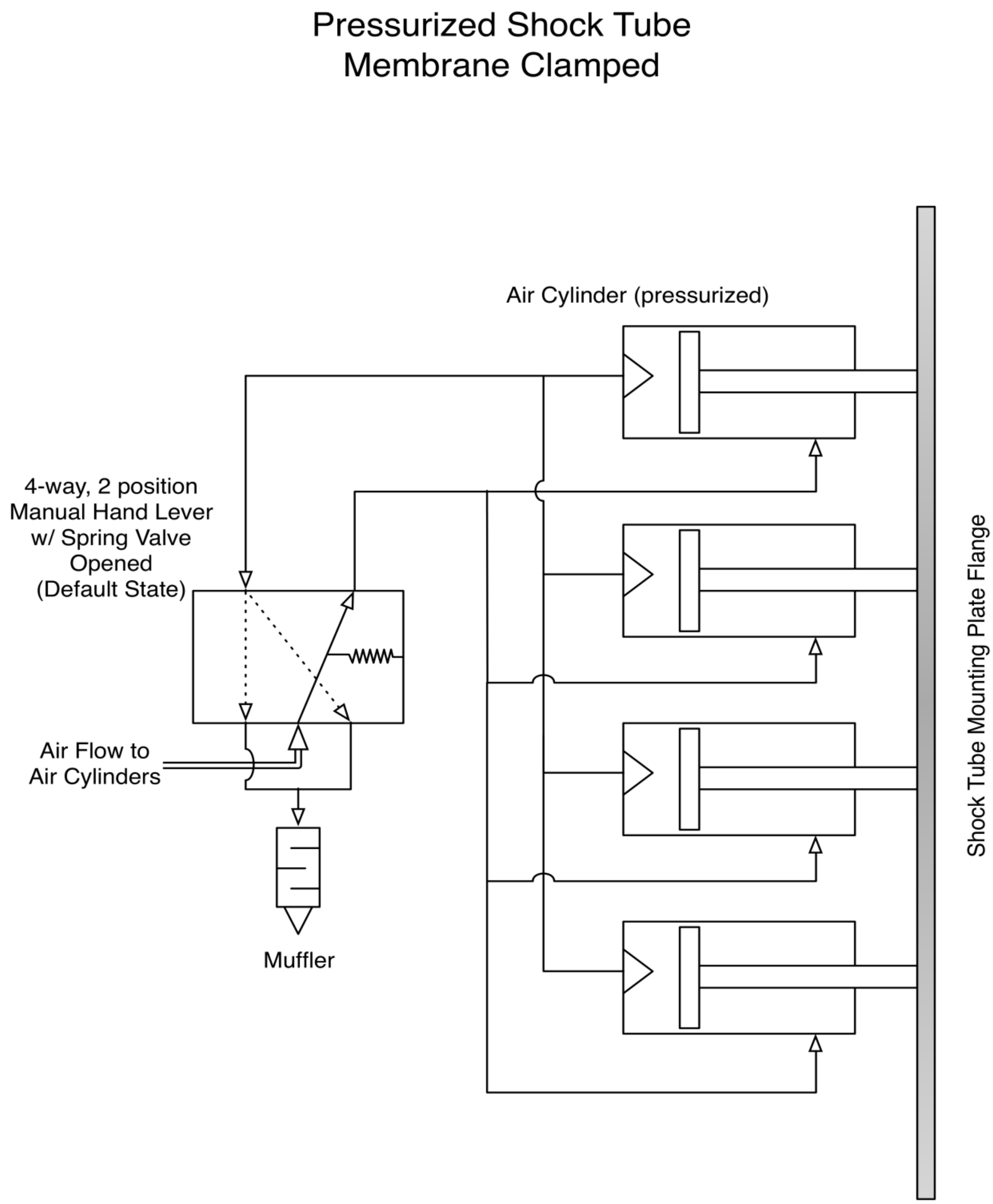

Figure 16: Pressurized shock tube with clamped membrane airflow diagram

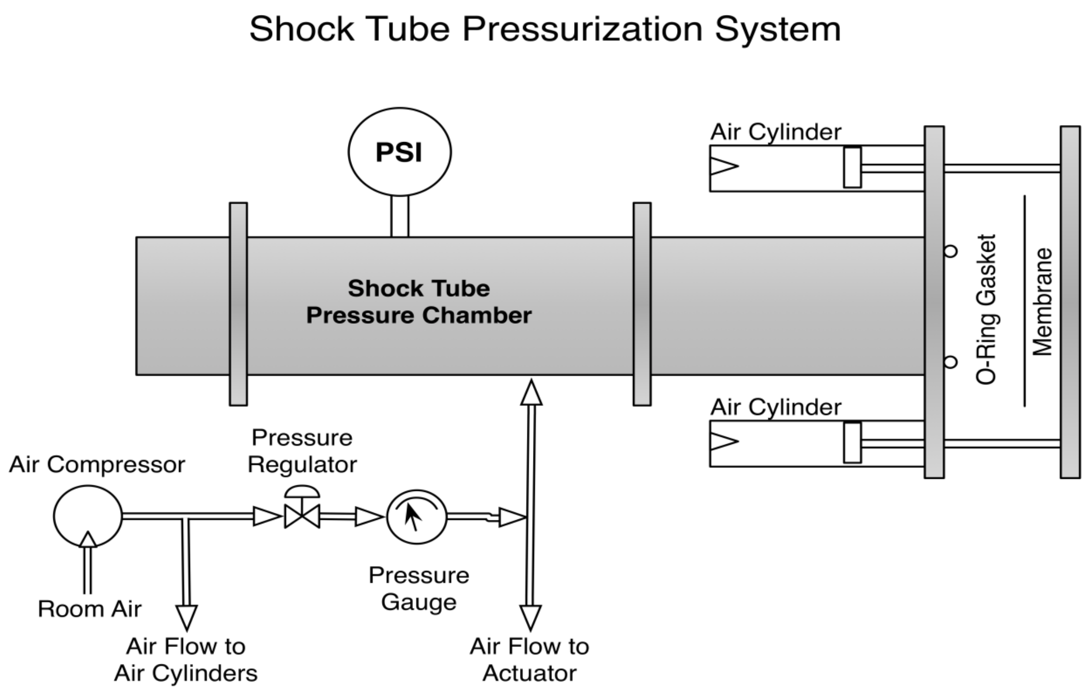

Figure 17: Shock tube pressurization system

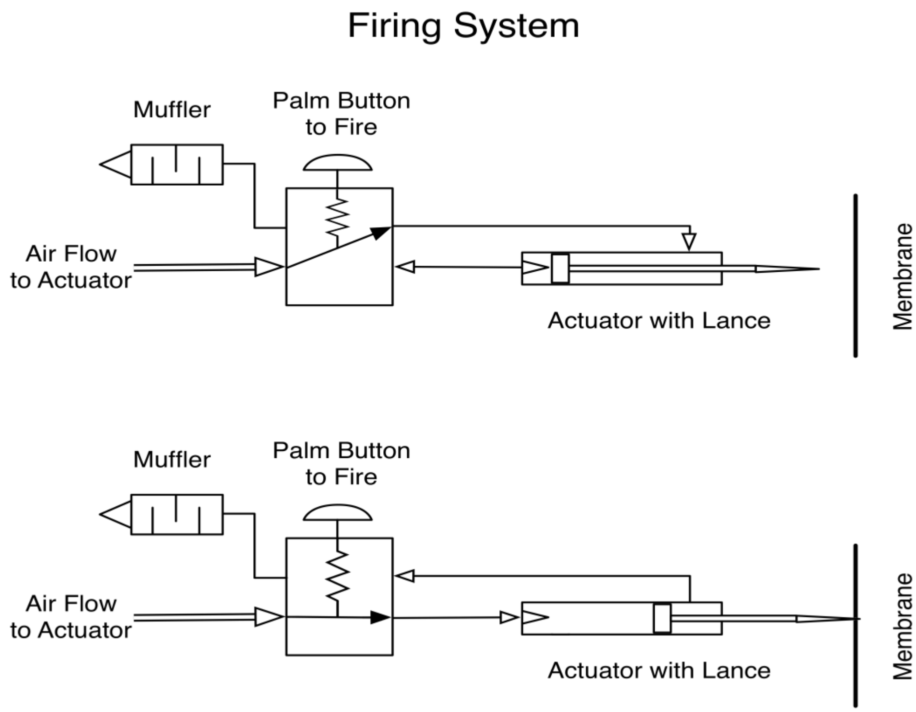

Figure 18: Pneumatic lance system for puncturing the membrane

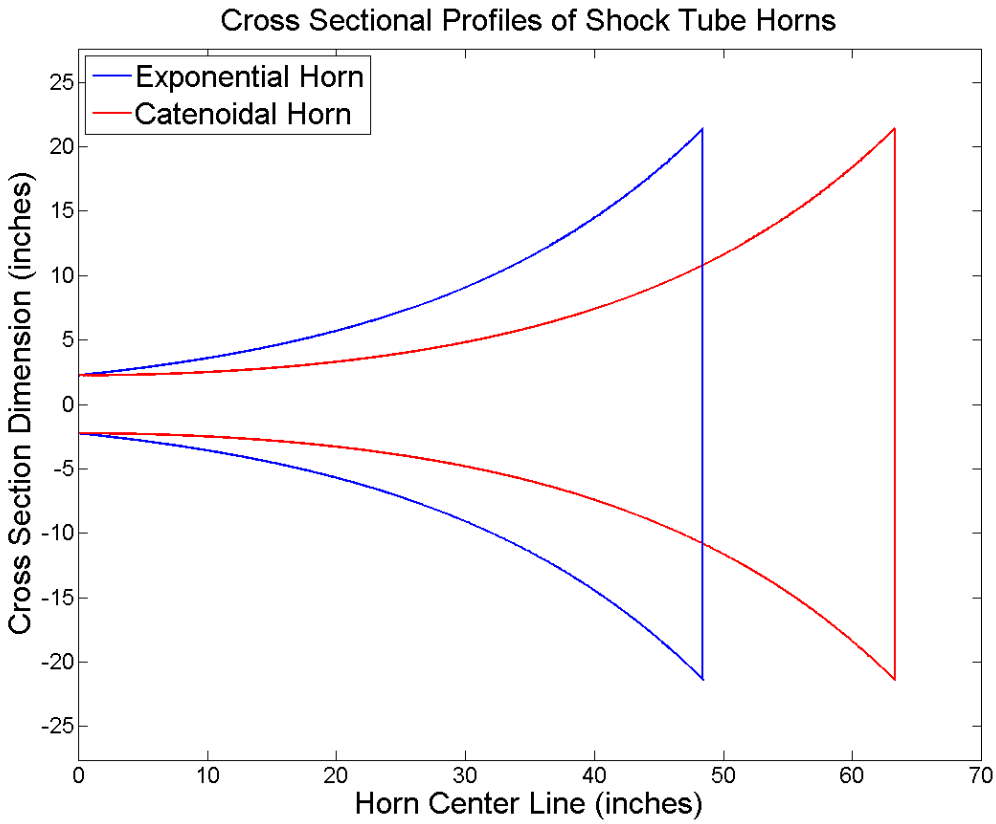

Figure 19: Catenoidal and exponential center-line cross-section profile of the horn

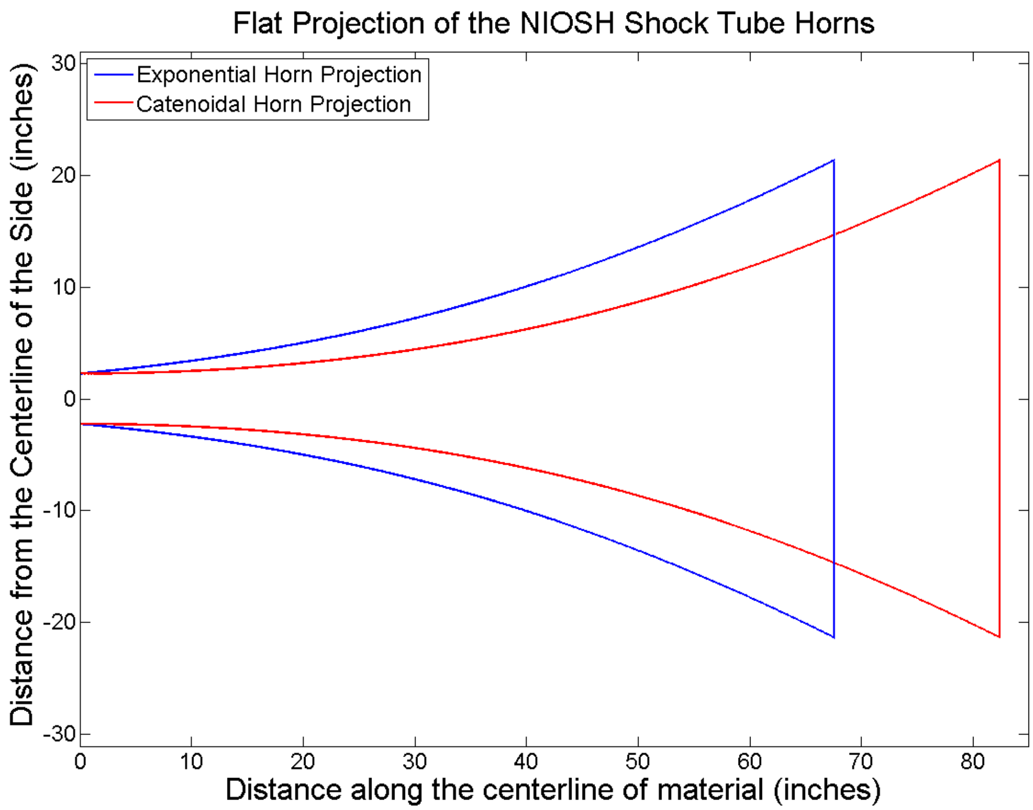

Figure 20: Catenoidal and exponential sides of the horn projected onto a flat surface

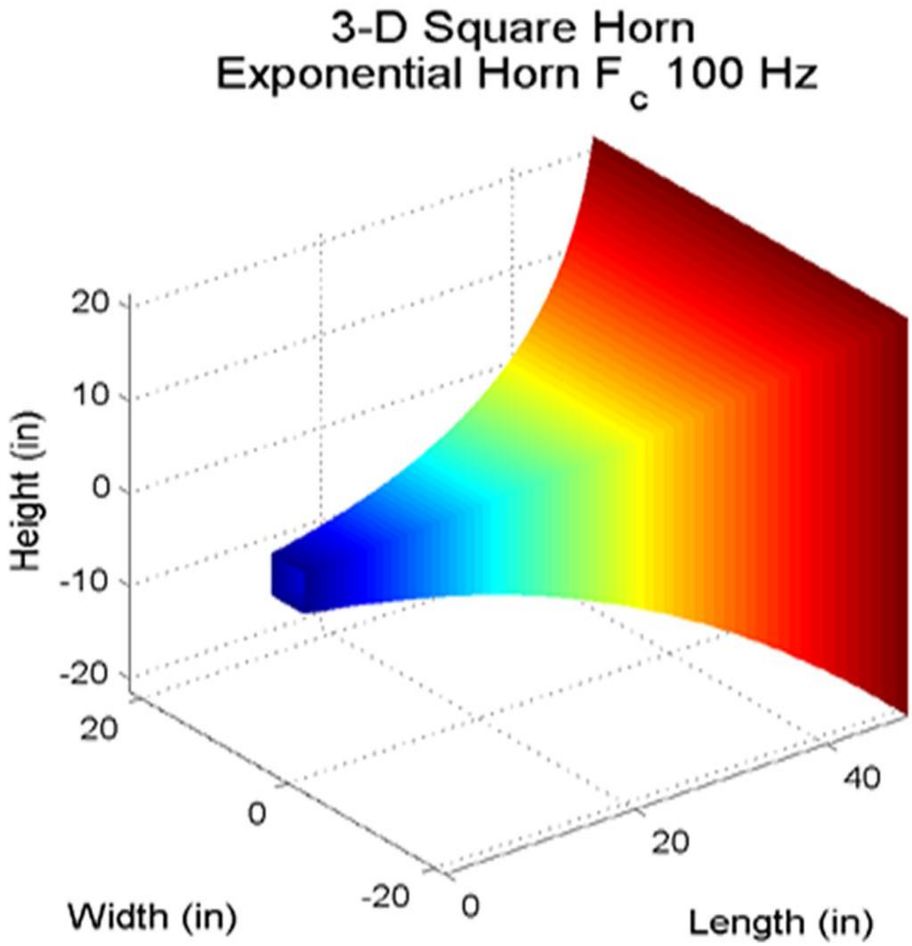

Figure 21: Three-dimensional rendering of the exponential horn

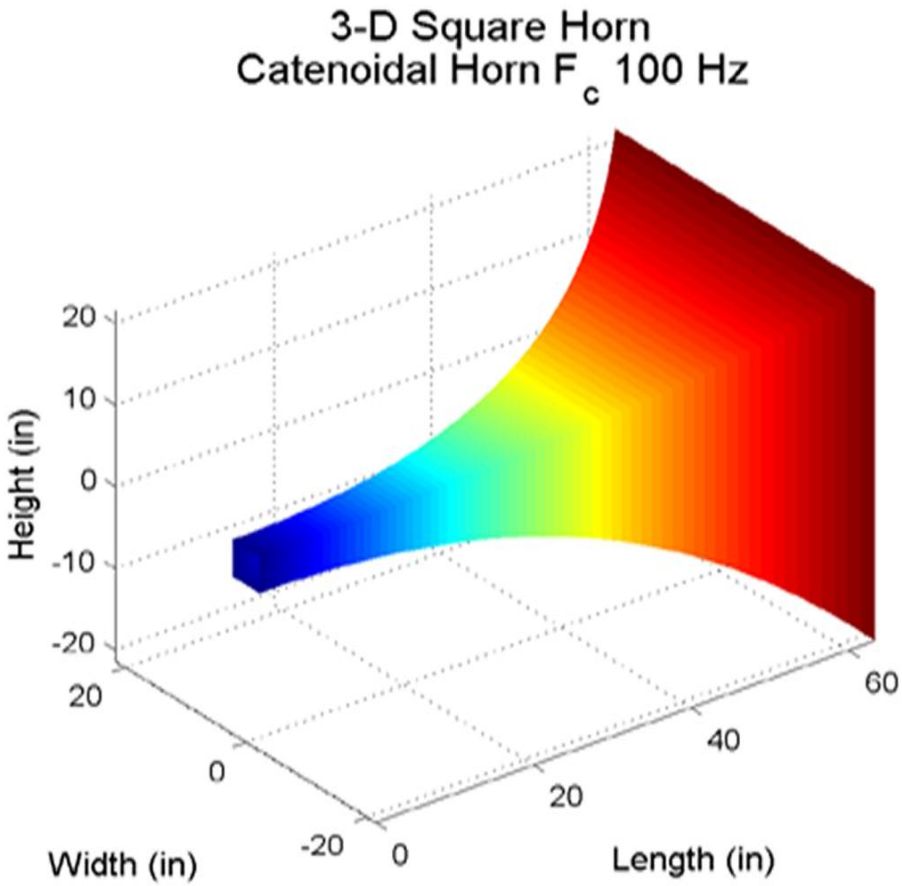

Figure 22: Three-dimensional rendering of the catenoidal horn

Delivering on the Nation's promise: Safety and health at work for all people through research and prevention.

To receive NIOSH documents or other information about occupational safety and health topics, contact NIOSH at

1-800-CDC-INFO (1-800-232-4636)

TTY: 1-888-232-6348

E-mail: cdcinfo@cdc.gov

or visit the NIOSH Web site at www.cdc.gov/niosh

For a monthly update on news at NIOSH, subscribe to NIOSH eNews by visiting www.cdc.gov/niosh/eNews

SAFER • HEALTHIER • PEOPLE