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Ventilation System Pressure Transients

Proposed Experiments and Shock Tube

Conceptual Design

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LOS ALAMOS SCIENTIFIC LABORATORY
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W. S. Gregory
P. R. Smith*

*Department of Mechanical Engineering, New Mexico State University, P.O. Box 3450, University Park, NM 88003.

VENTILATION SYSTEM PRESSURE TRANSIENTS

Proposed Experiments and Shock Tube Conceptual Design

by

W. S. Gregory and P. R. Smith

ABSTRACT

This report describes a proposed experimental program to evaluate ventilation system component responses to natural and man-caused pressure transients. Initial program emphasis is on tornado- and explosive-generated pressure loadings on filtration devices. A review of other investigations revealed that only standard high-efficiency particulate air (HEPA) filters have been considered for experimental analysis. We propose to test new types of HEPA filters that will be capable of handling larger flow rates. Larger flow rates mean increased filter life with a subsequent reduction in the quantity of contaminated filters. Following these experiments we propose to perform shock pressure loadings on other ventilation system components such as duct work, blowers, and dampers. Also, the effect of these components on shock wave characteristics will be determined. A conceptual shock tube design shows how the current tornado simulation apparatus can be modified to generate shock pressure pulses. Equipment to vary the magnitude and shape of the shock transient is also described.

I. INTRODUCTION

Nuclear facilities require ventilation for occupant health and safety. Ideally, the ventilation systems in these facilities collect any radioactive particulate released from reprocessing and fabrication operations or as a result of abnormal conditions. Safety considerations for these systems go beyond the plant occupants and must extend to the protection of the population in the surrounding area. Air that is circulated through contaminated areas must have the particulate material removed before being discharged into the environment. Filtration devices such as high-efficiency particulate air (HEPA) filters are located within the ventilation system to assure removal of such material from the exhaust air. These devices require a narrow range of flow conditions for optimum performance. A drop in efficiency or complete loss of filtration capability can occur under the abnormal flow conditions caused by pressure transients.

Pressure transients can result from both natural and man-caused phenomena.[1] An atmospheric pressure drop caused by a tornado can initiate undesirable flows and pressures within a ventilation system. Man-caused pressure transients can result from sonic booms, internal explosions, or nuclear excursions. The characteristics of such transients are extremely varied. The tornado depressurization results in a relatively slow pressure pulse that originates outside the facility and can create a large air flow. Internal explosions or nuclear excursions create high-pressure, short-duration transients (shock conditions) and generally occur inside the plant near the most contaminated filters. Figure 1 illustrates the pressure-time profiles for these types of transients.

As shown in Fig. 1, an internal explosion would cause a sudden impulse loading on the filters; however, a tornado depressurization is relatively slow and can generate a large air flow through the filter from either direction. This long-duration oscillatory flow through the filter represents a unique loading condition that has not been experienced in shock testing. The Tornado (B) plot (Fig. 1) is extrapolated from criteria for the United States Nuclear Regulatory Commission (NRC) Region I tornado.[2] However, considerable uncertainty exists concerning the shape and size of a tornado-generated pressure transient, so this plot is an idealized curve. T. Fujita suggests that some tornados may consist of smaller "suction spots" rotating around the center of the tornado system.[3] If these smaller vortices exist, the Tornado (C) plot may be a better representation of an actual tornado-induced pressure transient.

Investigations of transient or pulse loadings on filtration components, particularly HEPA filters, are reviewed in the following sections. The results of these experimental investigations are presented, and gaps in the literature are highlighted. We intend that this study go beyond investigation of filtration device transients to include transients through all components in facility ventilation systems.

II. REVIEW OF PAST INVESTIGATIONS

A. Shock Transients

C. E. Billings has reported his results of shock overpressures on filtration devices.[4] Apparently, he was concerned primarily with external explosions because the shock overpressures were imposed in a direction opposite to normal flow. His experimental apparatus was a pressurized tank connected to a shock tube. Paper disks were used to seal the pressure tank from the shock tube containing the filter to be tested. Sudden rupture of the paper disks created a shock wave that was allowed to propagate down the shock tube and impinge upon the test filter. No attempt was made to shape the pressure pulse or control the duration. Measurement of filter resistance after a test was used as an indicator of the shock wave effect. A drop in filter resistance caused Billings to conclude that some degree of damage had been sustained. An attempt was made to evaluate the amount of dust reentrained by the shock transient. The following results were reported.

- Moderate damage to 610- by 610- by 152-mm filters by 17.2-kPa pressure transients was found.
- Re-entrainment studies using artifically loaded filters indicated that a large amount of particulate was dislodged.

W. L. Anderson and T. Anderson also performed a series of shock transient tests on high-efficiency filters.[5] Their study was concerned principally with determining the shock overpressures necessary for failure of several sizes of filters. As in Billing's investigation, simulation of external explosions was a prime requirement for these tests. The experimental apparatus consisted of a firing chamber connected to a shock tube. The explosive charges detonated in the firing chamber generated a pressure transient of 50-ms duration. Failure was defined as filter penetration greater than or equal to 0.03% using a smoke test rig and DOP (dioctylphthalate). New filters were pulsed repeatedly until the failure point was found. Quantitative determination of particulate re-entrainment or loading loss was not made. The following results were reported.

- The 203- by 203- by 152-mm and 610- by 610- by 152-mm filters failed at pressures of 31 kPa and 15.2 kPa, respectively.
- An increase in failure resistance was found for thicker filters.
- An increase in filter width resulted in lower resistance to shock damage.
- Dust loading resulted in a 15% drop in shock wave resistance capability.

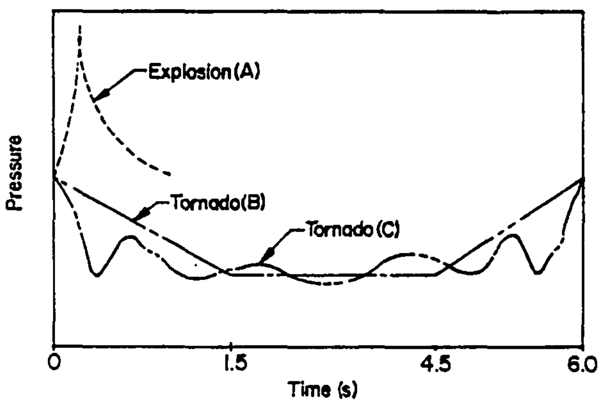


Fig. 1. Pressure transients.

Shock transient information has been obtained from industry, government, and European countries. Communication with Hans Ruegg at the LUWA company in Switzerland indicates that he is confident of the shock resilience of the LUWA V-type HEPA filters. However, he does not have information for filter response under high flow rate conditions produced by slow tornado-generated transients.[6] Ruegg expressed interest in this program and emphasized important variables to be measured. He is willing to cooperate in a testing program and placed particular emphasis on the importance of impulse duration in shock testing. He also recommended impulse control (varying the duration or dwell time of the shock wave).

W. Eckstein (Dragerwerk, West Germany) has sent a list of reports concerning blast effects on ventilation system components.[7] These reports have been added to the list we are compiling on pressure transient effects. Although the literature review is continuing, it indicates that only standard HEPA filters have been subjected to shock conditions. New types of HEPA filters have been developed since this earlier work, and testing of the new types is needed. In these future tests, careful control of the pressure wave total impulse should be emphasized.

B. Tornado Transients

Investigations into tornado transients have been performed by Los Alamos Scientific Laboratory (LASL) and New Mexico State University (NMSU).[8,9] An experimental program has been established to evaluate HEPA filter response to simulated tornado pressure pulses. The test facility, which is located at NMSU, uses a pressurized air tank in a blowdown system to impose transient pressure differentials across test specimens. Further description of this facility is given in Sec. III.

Initial results from the structural testing of standard HEPA filters were reported as follows.[9]

- The 152-mm-thick 610- by 610-mm HEPA filters failed catastrophically when exposed to a simulated NRC Region I tornado pulse.
- The 305-mm-thick 610- by 610-mm HEPA filters failed randomly when exposed to a simulated NRC Region I tornado pulse.
- Failure of the 305-mm-thick filters occurred at the downstream face where the fiber mat folds around the separator.
- Flow-resistance data indicate a change in resistance mechanism at higher flow rates.
- Preliminary testing of 203- by 203-mm filters artificially loaded with particulate indicates significant material release downstream.

III. SHOCK TUBE CONCEPTUAL DESIGN

A. Present Test Facility

The filter test facility contains two large high pressure tanks, each 1.67 m in diameter and 19.81 m long. Compressed air is supplied by a 0.566-m^3/s, 1724-kPa diesel-powered air compressor. Air from the tanks is discharged through sonic nozzles into a large prefilter room. Here HEPA filters operating at their design flow rates clean the air before it is discharged through a 0.61- by 0.61-m duct. The HEPA filter under test is at the end of the duct. The pressure pulse rise, dwell, and fall times are varied by electronically controlling the opening rate of the sonic nozzles. Figure 2 is a schematic of the NMSU facility, and Fig. 3 is a current photograph of the facility.

We believe that the filter test facility can be modified easily to create shock waves equivalent to those expected from explosions. A facility capable of simulating detonation waves is commonly referred to as a shock tube. Figure 2 shows the location of the proposed shock tube.

B. Preliminary Shock Tube Design

A shock tube with a maximum driving pressure of 1724 kPa can simulate the desired peak pressures needed to simulate gas, vapor, or dust explosions within facilities. Consider the shock tube shown in the schematic in Fig. 4. If p_4, the driving pressure, is 1724 kPa and the atmospheric pressure is 86.9 kPa (for Las Cruces, New Mexico), then $p_4/p_1 = 20.84$. From shock tube equations (A-1) and (A-2)[10] in the Appendix, we find $p_2/p_1 = 3.787$. Therefore, p_2 = 328.8 kPa = 242 kPa is the overpressure directly behind the generated shock wave. Most buildings are designed to withstand small pressure difference across their walls, so 242 kPa is a very severe pressure pulse within a building. Standard HEPA filters have failed at shock wave overpressures of 20.68 kPa, so a capability of 242 kPa overpressure should be sufficient for testing purposes.[5]

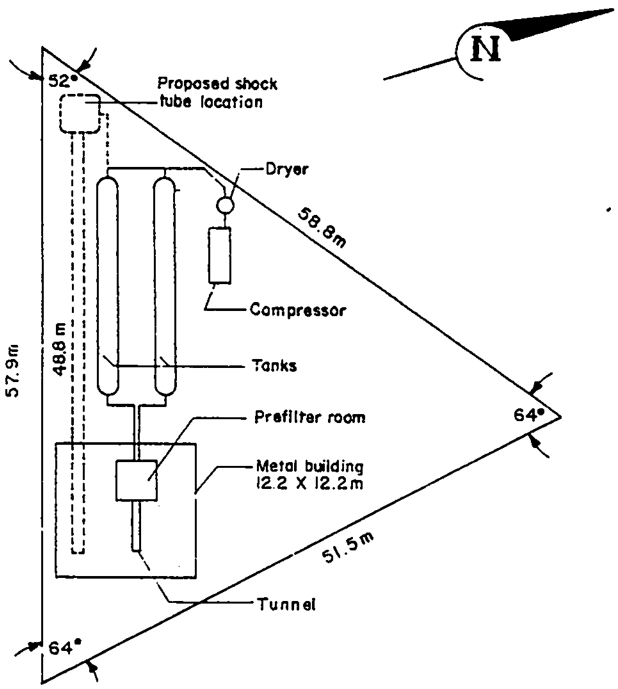


Fig. 2. Schematic of filter test facility on NMSU campus.

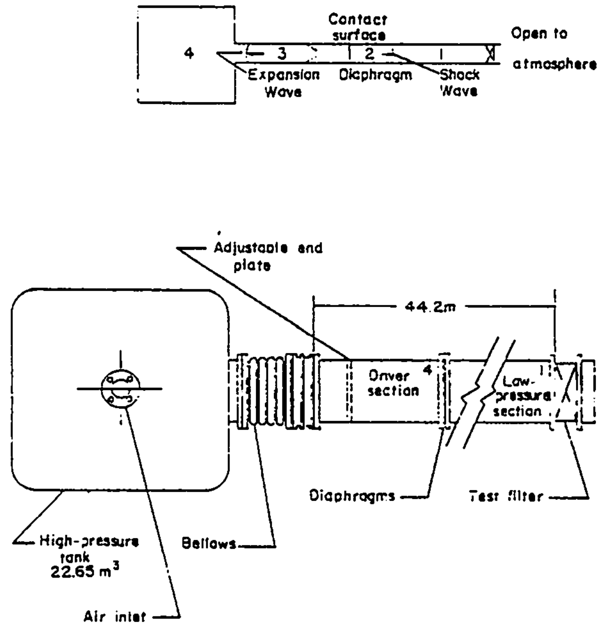


Fig. 4. Schematic of shock tube.

Because the total pressure wave impulse depends upon the time the pressure (p_2) behind the wave is sustained, a shock tube must control the dwell time of p_2 to produce a desired impulse. A wide range of dwell times can result from internal explosions. Diverse systems within facilities and their geometrical configurations are responsible for part of the variability in dwell times, but other conditions may be even more influential. These conditions result from the character of the material causing an internal explosion. Fuel cycle operations typically involve gases, vapors, and dust or fine granular material. These materials often have explosive potential and vary widely in their deflagration or detonation characteristics.

Our investigations of gas and dust explosions indicate that a single representative dwell time for a detonation wave is impossible to select.[11,12] Based on these investigations, we believe that a method to produce variable dwell times will be necessary to simulate the wide range of impulse loading expected from facility internal explosions.

A method to produce the variable dwell times is suggested by the physics of the phenomenon occurring in the shock tube. Consider Fig. 4. When the diaphragm is ruptured between the high-pressure side (region 4) and the low-pressure side (region 1), a shock wave proceeds to the right and an expansion wave to the left. If region 4 is short enough, the expansion wave reflects from the far left wall and races back down the shock tube, tending to overtake the shock wave. We take the dwell time to p_2 to be the difference between the time at which the shock wave reaches the filter and the time at which the expansion wave reaches the filter. Assume the entire shock tube is of constant diameter. Then from the shock tube equations (Appendix), assuming $T_1 = T_4 = 298$ K, we obtain the results shown in Table I for the dwell time, Δt.

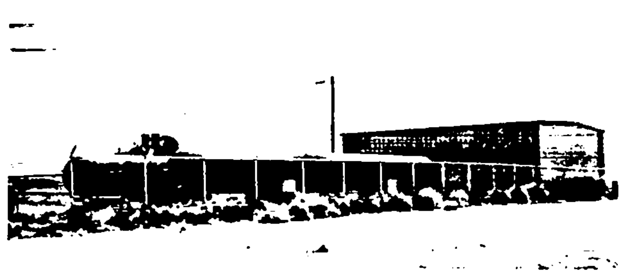
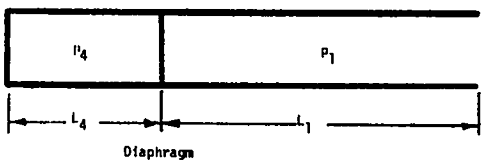


Fig. 3. Present filter test facility, showing tanks and building housing wind tunnel.

TABLE 1

P_2 DWELL TIMES



L_4, m	L_1, m	Δt, ms
3.04	38.1	10.5
1.52	38.1	3.8
1.22	38.1	2.5
0.91	38.1	1.2
0.76	38.1	0.51
0.70	38.1	0.24

p_1 = 86.87 kPa

p_4 = 1810 kPa

p_2 = 242 kPa

Apparently, if the length of the driver section of the shock tube, L_4, is variable, the dwell time can be controlled. For our purposes, a length from about 0.61 m to 4.57 m would probably be sufficient.

Figure 3 is the preliminary design now under consideration, a shock tube fabricated from 864-mm-i.d. pipe. The driver section is 4.57 m long with an adjustable end plate that can reduce its effective length to 0.61 m. The large high-pressure tank, 22.63 m^3 in volume, is pressurized to the same pressure as region 4 to minimize the effects of leaks around the adjustable end plate. Furthermore, by removal of the end plate, the shock tube could be used as a conventional shock tube. The low-pressure region, region 1, will be 38.1 m long. pressures at which the aluminum diaphragms rupture will be controlled by the use of a double diaphragm. Both diaphragms will be designed to rupture at a pressure ratio intermediate to p_4/p_1. However, pressure will be maintained between the diaphragms such that neither is subjected to a bursting pressure ratio until the space between the diaphragms is suddenly evacuated.

C. Instrumentation

Piezoelectric pressure transducers will be used to measure the pressure behind the shock wave. These gauges are capable of the fast response necessary for shock work. Transducers with ranges from about 0 to 344.7 kPa or 0 to 689.5 kPa are needed.

Because the piezoelectric pressure transducers will register only transient pressure pulses, the pressure in the driver section and the low-pressure region before diaphragm rupture will be measured by precision dial gauges.

Although the dwell time of the pressure behind the shock wave can be measured by the piezoelectric pressure transducers, a secondary timing system will be constructed of a thin platinum film. Such films are very sensitive to temperature changes; therefore, the arrival of the shock wave and the expansion waves can be detected easily.[13,14]

An additional parameter behind the pressure wave must be measured to describe completely the thermodynamic state downstream of the shock wave. This parameter could be temperature, density, shock velocity, or flow velocity. The density changes in the shock tube can be measured using interferometry. Further, the optical system can be made flexible enough so that either schlieren or shadowgraph photographs of the interaction of the shock wave with the filter face can be obtained.

IV. INITIAL PROPOSED EXPERIMENTS

Using both the filter test apparatus and the shock tube, several experiments are proposed. Pulse testing of new HEPA filter types, such as standard separatorless, European, 50-mm flat pack, and American V-type, is needed for both shock and tornado flow regimes.

Knowledge of shock effects on the geometrical configuration of ducts (area reduction, orifice plates, tees, elbows) and ventilation system components is needed. The effect of these components on the shock wave characteristics is unknown and will also be evaluated.

A. HEPA Filter Tests

New HEPA filters that allow higher flow rates without increase in pressure differentials are under development. Higher flow rates imply possible increased filter life or reduction in quantity of filter media used. In any case, these developments would reduce the waste management problem associated with filter disposal. We believe that some of the filter configurations will respond differently depending upon whether the pulse loading generates shock impingement or large air flow rates. For example, the European or American V-type filter may show good resistance to shock loadings but low resistance to tornado loadings. The face plates shown in Fig. 5 could improve performance under

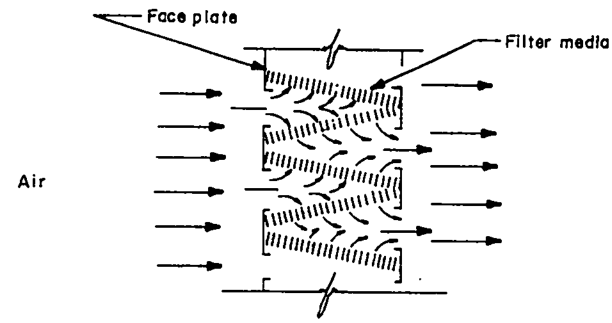


Fig. 5. Experimental impulse vs distance curves (on ground) for various sources.

shock loading, but tornado loading could cause the air flow distribution shown in Fig. 6. The air flow configuration in Fig. 6 could place undesirable stress at points A and B.

HEPA filter tests would be performed to determine the following for tornado and shock transients.

- Threshold for structural failure,
- Mechanisms of structural failure,
- Flow path through the filters at high flow rates,
- Structural effect of filter orientation with respect to flow direction,
- Effect of duration time at peak pressure,
- Filter effectiveness after exposure to the transient,
- Effect of loading on structural strength, and
- Amount of particulate release from loaded filters.

In the shock tests, emphasis will be placed on total impulse loading as well as peak shock wave pressure.

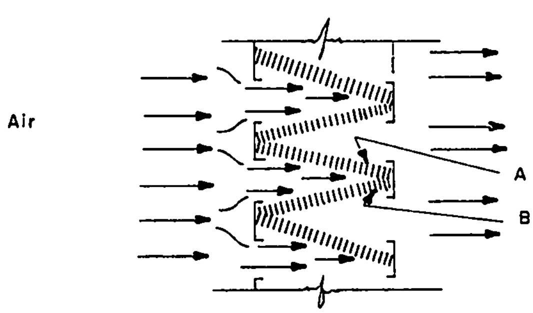


Fig. 6. V-type filter pleat arrangement with possible high flow rate pattern (top view).

B. Component Shock Testing

Although determination of shock effects on the components, such as HEPA filters, is of prime importance, the effect of ventilation system components on the shock wave itself is unknown and needs to be determined. Shock wave characteristics under full or partial failure of these components will be determined.

License applicants, designers, and reviewers should be able to ascertain the effect of shock propagation through duct systems. LASL is developing a digital computer code that will aid analysts in estimating location and magnitude of explosion-generated shock waves in a ventilation system. The Oak Ridge National Laboratory has also developed an analytical method for estimating the propagation of shock waves down a single duct. These and other programs need experimental verification and data to determine the effect of the following on the shock wave.

- Varying duct geometrical configurations for area change, elbows, tees, orifice plates, etc., and
- Blowers, dampers, and HEPA filters.

V. SUMMARY

An experimental program to evaluate pressure transient effects in nuclear facility ventilation systems has been described. Both slow (tornado-generated) and fast (explosion-generated) transients will be considered. Initial program focus will be upon those components most crucial for containment of airborne particulate release. Therefore, filtration devices such as HEPA filters will be examined for their response to large pressure pulses.

Review of past and present investigations revealed that standard HEPA filters have been or are being evaluated for tornado or shock conditions. However, new types of HEPA filters are under development, and this program will evaluate these devices for several pressure transients.

The literature review and our communications with industry and government laboratories indicate a need for experimental shock wave data concerning duct work configuration and component response. Component effect on shock wave characteristics is needed in addition to shock wave effect on components. These data are required for analysts to predict magnitude and location of shock waves within ventilation systems resulting from internal explosions.

A shock tube conceptual design shows how the existing tornado simulation apparatus can be modified for shock transients. A capability to vary the magnitude and shape of the pressure wave is also described.

VI. FUTURE WORK

The method for controlling dwell time, outlined in previous sections, will require some preliminary work. A small 76.2-mm shock tube will be used to prove the concept. This method will require modification of the 76.2-mm shock tube to accommodate a new driver section with a variable position endwall. Installation of a double diaphragm shock initiation system and instrumentation will be required.

While the small-scale experimental work is being done, we will start procurement of the test HEPA filters. The procurement lead time could be quite long, particularly for the European filters.

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APPENDIX

SHOCK TUBE EQUATIONS

An expression relating driving pressure and the Mach number of the shock wave is

$$\frac{p_4}{p_1} = \frac{k_1 - 1}{k_1 + 1}\left[\frac{2k_1}{k_1 - 1} M_s^2 - 1\right] \qquad \text{(A-1)}$$

$$\left[1 - \frac{\frac{k_4 - 1}{k_1 + 1}\frac{C_1}{C_4}\left(M_s^2 - 1\right)}{M_s}\right]^{\frac{-2k_4}{k_4 - 1}},$$

where

p_4 = shock tube driving pressure,
p_1 = low-pressure gas (atmospheric),
k_1, k_4 = ratio of gas specific heats on regions 1 and 4,
C_1, C_4 = velocity of sound at regions 1 and 4,
M_s = W/C_1 = shock Mach number, and
W = shock velocity.

Solving this implicit equation for M_s and substituting M_s into

$$\frac{p_2}{p_1} = \frac{k_1 - 1}{k_1 + 1}\left(\frac{2k_1}{k_1 - 1} M_s^2 - 1\right), \qquad \text{(A-2)}$$

where

p_2 = pressure upstream of shock wave, allows the shock pressure ratio to be calculated. Using p_1, the magnitude of the shock wave can then be obtained.

The temperature change across a shock wave is calculated using

$$\frac{T_2}{T_1} = \frac{\left(1 + \frac{k - 1}{2} M_s^2\right)\left(\frac{2k}{k - 1} M_s^2 - 1\right)}{\frac{(k + 1)^2}{2\,(k - 1)} M_s^2}, \qquad \text{(A-3)}$$

where

T_2, T_1 = temperature at regions 2 and 1, respectively.

This results in a temperature ratio of 1.56, thereby allowing T_2 to be calculated assuming T_1 = T_4 = 298 K. If T_2 is known, the speed of sound in region 3 can be calculated using

$$C_3 = \sqrt{k\, T_2\, R}\ , \qquad \text{(A-4)}$$

where

C_3 = sound speed in region 3, and
R = universal gas constant for air.

The Mach number for region 3 is calculated using

$$M_3 = \frac{2}{k_4 - 1}\left[\left(\frac{p_4}{p_3}\right)^{(k_4 - 1)/2k_4} - 1\right], \qquad \text{(A-5)}$$

where

M_3 = Mach number in region 3, and
p_3 = pressure in region 3.

Using the condition that p_3 = p_2 and evaluating Eq. (A-5) gives M_3 = 1.38. Noting that

$$M_3 = \frac{V_3}{C_3} \qquad \text{(A-6)}$$

or

$$V_3 = M_3 C_3\ , \qquad \text{(A-7)}$$

the velocity of the expansion wave V_3 can be calculated.[10] Similarly, the velocity of the shock wave can also be calculated. Knowing the velocities of both expansion and shock wave, we can obtain the results shown in Table I (in text) for the dwell time, Δt.

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