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AIAA, Aerospace Sciences Meeting & Exhibit, 35th, Reno, NV, Jan. 6-9, 1997

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Experimental Investigation of an Annular Multi-Cycle Pulsed Detonation Wave Engine

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ABSTRACT

The Detonation Wave Facility at the University of Texas at Arlington has been operated at low to moderate frequencies in a multi-cycle mode as a Pulse Detonation Engine simulator. A fuel, oxidizer, and air injection system and an ignition system which can operate repetitively are used. A description of the facility and results of operation with a centerbody and nozzle are presented for hydrogen and oxygen operation. Comparison with previous results and the effects of a nozzle and centerbody are presented.

INTRODUCTION

Pulsating engines have been around for quite some time and found use in World War II in the German V-1. These engines took in fuel and oxidizer, burnt then and expelled the products at higher pressure out the back for thrust. The combustion process in these engines took place at subsonic speeds as a deflagration. The pulse detonation wave engine operates in a cyclic fashion like a pulse jet but operates at a higher pressure level. The detonation wave creates higher pressure due to the higher energy release from the fuel and oxidizer. The pulse detonation engine also has the potential to operate at higher frequencies since the detonation wave traverses the chamber at high supersonic speeds. Frequencies on the order of 100 Hz appear feasible. These concepts of a pulsating propulsion device have not found wide spread

use, but have received attention of researchers.^{1,2}

The use of detonation waves for propulsive applications show great promise. Detonation waves can be used in a propulsion system for aerospace applications as a Pulse Detonation Engine (PDE) and in other industrial applications. The airbreathing propulsion system use of the PDE would use the detonation wave process to release the energy, generate high pressure, produce thrust, and have substantially higher efficiency than conventional propulsion systems.³ The detonation wave engine would be less complex than a conventional turbo jet as the high pressure is generated by the detonation process and the need for the compressor is eliminated. Without the compressor, the turbine is also not required. Without the rotating machinery the engine becomes much less complicated and the weight is reduced.

Detonation waves can also be used in rocket applications⁴ to increase performance and eliminate many of the heavy and complex rotating components such as the high pressure turbo pumps, since the fuel and oxidizer is injected at lower pressure instead of the current high operating pressure.

THEORY OF OPERATION

A Pulse Detonation Engine operates by filling a chamber with a fuel and oxidizer combination, then detonating the mixture for combustion. The detonation wave and combustion products are allowed to exit the chamber to provide thrust. The high pressure wave exits the chamber and then the pressure equilibrates to the surrounding pressure through several expansion and compression waves. The chamber can then be refilled with fuel and oxidizer and the cycle repeated. The fuel and oxidizer are injected at low pressure and then detonated to obtain the

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high pressure to produce the thrust, in a constant volume mode of operation. The process is modeled thermodynamically as a Humphrey cycle. The injection pressure is much lower than required for conventional propulsion systems which operate at constant pressure and are modeled thermodynamically as a Brayton cycle. The fuel and oxidizer are injected during the low pressure portion of the cycle. Air must be injected into the combustion chamber between cycles. The residual combustion products quickly drop in pressure to the ambient pressure but the temperature remains very hot for an extended period of time. The temperature is hot enough to cause auto ignition of the hydrogen and oxygen of the next cycle immediately up injection. This auto ignition is of a deflagration nature. A buffer of cold air separates the hot gas from the new charge of hydrogen and oxygen.

The detonation wave is a coupled shock wave and combustion process as Figure 1 illustrates. The shock front increases the pressure and temperature similar to a normal shock wave. Immediately following the shock the combustion process adds heat at constant volume after a short ignition delay time. The Zeldovich-Von Neumann-Doring (ZND) spike seen in Figure 1 is generated by the initial shock wave and the combustion process takes a finite amount of time so it follows behind the initial wave. This significantly increases the temperature and reduces the pressure. The combustion region is followed by an expansion region which brings the supersonic flow behind the detonation wave to rest at the closed end wall.

Combustion waves traveling at supersonic velocity tend to approach the Chapman-Jouguet detonation velocity. Even a subsonic deflagration will transition to a supersonic C-J detonation in a tube given sufficient length and diameter. The confined space contains the heat until it builds to a level sufficient for a detonation.

A detonation wave can also be created by adding sufficient energy in a sufficiently short period of time, such as with an arc discharge. The transition length can be shortened considerably by using a high energy arc discharge. Generating an immediate detonation wave requires a very large amount of energy and is not easily done.

The addition of turbulence generators can also speed the process of generating a deto-

nation wave by increasing the mixing of the fuel and oxidizer and releasing more energy. Turbulence generators increase the velocity of the detonation wave to Chapman-Jouguet velocity but the pressure is decreased due to losses associated with blockage in the chamber. The detonation must be generated in a relatively short distance in order to make a pulse detonation engine feasible as the size must be kept as small as possible.

FACILITY

A facility specifically designed to study detonation waves at the University of Texas at Arlington is being utilized to study repetitive detonation waves as a propulsion device after previously being used for single shot detonation wave research^{5,6} and preliminary low frequency multi-cycle operation⁷. The injection system of the facility has been designed for repetitive use. The ignition system has also been upgraded for repetitive use. A control circuit in Figure 2 was also designed and built to sense the injection of fuel and oxidizer, provide a short time delay, trigger the ignition source, recharge the ignition capacitor bank, and provide a synchronized signal to the data acquisition if required or desired.

TEST CHAMBER

The cylindrical facility has a fixed internal diameter of 7.62 cm (3 inch) and sections of 7.62 cm (3 inch), 15.24 cm (6 inch), and 30.48 cm (12 inch) in length for a total length of up to 91.44 cm (36 inch). The sections can be utilized in different combinations to provide various length to diameter (L/D) ratios of between 3 and 12. The diameter is not changed. Each section of the facility has provisions for mounting pressure transducers, thermocouples, thin film gauges, and heat flux gauges every 7.62 cm (3 inch). Figure 3 shows the various sections. Two 15.24 cm (6 inch) sections are available which simulate a nozzle of 4.76° and 7.12° half angles. A center body can also be installed throughout the length of the chamber to create an annular configuration. The centerbody is 2.54 cm (1 inch) in diameter and is the same length as the combustion chamber.

The ignition plug is mounted in a 7.62 cm (3 inch) section of its own and can be inserted any

where along the length of the tube between other sections.

One end of the chamber is sealed with a blind flange. The fuel and oxidizer is injected through this plate. The various sections of the chamber are flanged and bolted together at each joint. The open end of the chamber is bolted to a thrust stand to hold the chamber in place. Figure 4 shows the overall schematic.

INJECTION SYSTEM

The pneumatic gas control system used in the single shot experiments was also used in the multi-cycle tests with minimal modifications. The fuel, oxidizer, and air lines were used as before while the others lines were not required. The remote control valves were retained as a measure of positive control over fuel and oxidizer flow through the rotary valves for safety reasons. The injection system has been designed for hydrogen, propane, or methane as the fuel and oxygen or air as the oxidizer. Other fuels or oxidizers could be used if they were compatible with the valve materials and seals.

The fuel and oxidizer are injected through an endplate which closes one end of the tube. The fuel and oxidizer is measured by setting the valve supply pressure according to regulator flow rate charts and injected using rotary valves. Buffer air is also injected between cycles to provide a buffer between the hot products of one cycle and the unburnt reactants of the next cycle. The buffer air is injected similarly as the fuel and oxidizer using a third rotary valve that is timed to inject air between cycles. An air line is also installed for purging of the explosive gases for safety purposes. The opposite end is open for the exhaust of the detonation wave and combustion products.

The rotary injection valves are connected together by pulleys and a timing belt turned by a variable speed electric motor controlled remotely from the control room for frequency control. A magnetic pickup is located nearby to sense the closure of the valves and initiate the ignition process.

The fuel and oxidizer are injected perpendicular to the axis of the detonation chamber and in such a way to impinge upon each other during the injection process but not into the supply line of the other. This is in an effort to mix the fuel with the oxidizer

IGNITION SYSTEM

The ignition source is one high voltage, high current arc plug driven by a discharge capacitor bank and initiated by a high frequency arc welding source. The arc plug is mounted in a 7.62 cm (3 inch) section of the facility which allows placement at nearly any location along the length of the facility. The arc welder ionizes a path between the two electrodes of the arc plug using high frequency, high voltage, low current energy. When the path is ionized sufficiently the discharge capacitors discharge through this path in the form of a high current arc. An electrical schematic of the ignition system is shown in Figure 5.

The discharge capacitor bank consists of two 11000 microfarad 75 VDC capacitors connected in series and charged to about 135 VDC. A second charge capacitor bank, identical to the discharge capacitor bank, is used to recharge the discharge capacitor bank between cycles and is kept at 135 VDC by a 1.2 kVA variable transformer and a rectifying diode bridge. The two capacitor banks are isolated by means of a thyristor. The thyristor turns on just long enough to recharge the discharge capacitor bank and then turns off. If the two capacitor banks are not isolated during the arc discharge both capacitor banks will discharge and then the variable transformer will begin driving the arc in a welding mode. This draws large amounts of current and leads to rapid heating and destruction of certain components. Minimizing the discharge time results in more energy transferred to the gas and less to the structure of the arc plug for the same energy discharge from the capacitor. The charge capacitor bank is used to even out the current flow through the variable transformer and allow the discharge capacitor bank to be recharged more quickly. The outputs of the discharge capacitor bank were connected together with a diode to eliminate ringing of the discharge current. This eliminates reverse voltage on the capacitor bank and reduces the maximum voltage differential seen by the thyristor.

The thyristor is controlled by a timer circuit (Figure 2) that also initiates the high frequency welding unit, provides a delay for recharging the discharge capacitor bank, and the signal to the thyristor.

The energy from the discharge capacitor bank is discharged through an arc plug which is constructed from two tungsten electrodes mounted in ceramic and the assembly mounted in a threaded steel housing. The end of the electrodes are flush with the surface of the ceramic. The threaded housing assembly is then installed into the ignition section of the facility so the ceramic and ends of the electrodes are nearly flush with the inner wall of the chamber. The energy discharges in an arc between the two electrodes.

INSTRUMENTATION

The instrumentation used to obtain the experimental data are seven pressure transducers which are water cooled for continuous multi-cycle operation. The instrumentation sensors can be mounted in the sidewall at 7.62 cm (3 inch) increments with the capability for all types of sensors to be mounted at the same axial locations. The pressure transducers are PCB model 111A24 dynamic pressure transducers with a full scale range of 6.89 MPa (1000 psi), rise time of 2 microseconds, and a time constant of 100 seconds.

The initial reference pressure is atmospheric pressure and is measured by a Baratron Pressure Transducer from MKS, model number 127A. This transducer has a maximum pressure range of 1333 kPa (10000 Torr). This transducer is used for enclosed single detonation tests and it provides a very accurate measure of atmospheric pressure.

The pressure transducers are connected to a DSP Technology data acquisition system which has 48 channels capable of 100 kHz sampling rate, 12 bits of accuracy. Each channel has a dedicated amplifier and analog to digital converter to allow for simultaneous sampling of all channels. The system has 512 Kilobytes of memory available for distribution to the channels being utilized. Eight channels are also available with the capability of 1 MHz sampling rate, 12 bits of accuracy, and also with separate analog to digital converters for each channel. Two Megasamples of memory are available for these eight channels. The data acquisition system is controlled by a PC which retrieves the data through an IEEE-488 interface. The data is then stored on a harddrive for later analysis.

CONFIGURATION

The facility was configured using a 30.48 cm (12 inch) section, a 15.24 cm (6 inch) section, and the 7.62 cm (3 inch) ignition section. The ignition section was located nearest the closed end of the chamber. This length was chosen as it contained 6 instrumentation locations which was all the pressure sensors available and it provided the approximate length required to contain the expected fuel and oxidizer charge. Three configurations were tested. The first was a cylindrical geometry 53.34 cm (21 inch) long and 7.62 cm (3 inch) in diameter. The second was the same cylindrical geometry with a 2.54 cm (1 inch) diameter centerbody installed which extended the full length of the combustion chamber. The third configuration was to replace the 15.24 cm (6 inch) section closest the exit with a section of the same length but with a diverging conical shape with a half angle of 4.76° to simulate a nozzle. The centerbody used with the nozzle was the same as used in the cylindrical case.

DATA ANALYSIS

Voltage readings from the pressure transducers are converted into pressure readings and plotted against time. The pressure plots were used to obtain an experimental wave diagram. The time interval between the observed abrupt rise in pressure from adjacent transducers was used to calculate wave propagation speed of the detonation wave. The second peak 40-60 μ s behind the initial peak is caused by the wave reflected from the closed end and follows the initial detonation wave to the exit.

The effect of the expansion wave generated behind the detonation wave was analyzed to determine how long it takes to die out and how it affects the next detonation wave in particular.

Pressure data were analyzed to determine basic system operating parameters such as pressure level, detonation velocity, expansion wave velocity, and cycle time in general.

All data presented in this paper is sampled at 100 kHz, although the pressure transducers have a 2 μ s response time. Previous tests have indicated that due to the lag associated with the transducer mounting arrangement, higher sampling speeds do not provide any additional information. Previous tests also indicate that the

lag also prevents the pressure measured from rising to its true value.

RESULTS & DISCUSSION

Figures 6, 7, and 8 are wave diagrams for the cylindrical chamber, the cylindrical chamber with the centerbody, and the chamber with centerbody and nozzle, respectively. Figure 8 is obtained from the pressure traces in Figures 9 and 10. Figures 6 and 7 are obtained from similar pressure traces for their respective cases but those pressure plots are not shown. Plotting the time of arrival of the detonation wave, the reflected detonation wave from the closed end, the reflected compression wave, expansion wave, and compression wave from ambient conditions produce the experimental wave diagram in Figure 6 and is obtained from Figures 7 and 8 for the nozzle with the centerbody case. Figure 7 is used to locate the maximum peak for each transducer and that is used for the initial detonation arrival. The second slight increase is used to locate the passage of the reflected detonation wave of the end wall. Figure 8 is used to locate the point of minimum pressure for the expansion wave and the very next rise in pressure for the recompression wave on the wave diagram.

The path of the detonation wave is clearly evident but not straight forward to plot. Before a true detonation wave is created the pressure begins to rise well ahead of the combustion wave. The combustion process is still supersonic in the core flow but the boundary layer behind the combustion wave causes enhanced mixing and combustion and accelerates the process ahead of the boundary layer near the wall. The less well mixed core flow lags behind in the combustion process but creates the larger pressure rise. The precompression phenomena has also been observed in experiments reported by Helman.⁸

The precompression is present to a large extent even when the detonation wave velocity approaches C-J velocity. Previous single shot experiments clearly illustrated the total elimination of precompression at near C-J velocities. The operation of the combustion chamber at these frequencies heats up the wall and after several cycles the chamber is no longer operating with cold walls. The wall temperature is much greater than the cold gas injection temperature. The hot walls cause a thermal gradient in the fresh gas. The warmer

region near the wall has a higher speed of sound. The combustion process therefore propagates faster in the warmer region. This results in a larger precompression region than would occur with a cold wall and a constant temperature gas.

The time passage of the detonation wave is approximated by ignoring the precompression and locating the location of the steep pressure jump which is associated with the peak pressure. The detonation wave proceeds from the ignition source towards the open end of the chamber. A wave is also started which travels in the opposite direction towards the closed end of the chamber. This wave travels only 3.81 cm (1.5 inch) before it reflects off the solid wall and proceeds towards the open end of the chamber behind the initial detonation wave. After reflecting off of the end wall this wave is traveling in burnt products of combustion. The wave would produce no additional combustion if the detonation wave it follows were a C-J detonation wave in a perfectly mixed stoichiometric mixture of hydrogen and oxygen. The pressure traces illustrate a more gradual rise in pressure than one would expect from a shock wave. In some cases it appears to create a plateau in the pressure trace due to the expansion wave following the initial detonation. The 3.81 cm distance from the ignition source to the end wall is not of sufficient length to obtain a C-J detonation wave and after reflection there is not enough fuel available to continue combustion so the wave continues as a compression wave with combustion occurring in the pockets of unreacted mixtures. This wave travels 7.62 cm (3 inches) further than the initial detonation wave when it is picked up by each sensor. This second wave travels faster than one would expect since it is in a hot gas environment and the speed of sound is greater. An expansion wave follows the detonation wave down the tube in order to bring the high velocity flow behind the detonation wave to rest at the end plate. An expansion wave enters the exit of the chamber once the detonation wave passes in order to reduce the high pressure to a level closer to ambient. A compression wave is generated once the expansion wave has reduced the pressure to a level below ambient at the exit of the chamber. Expansion waves and compression waves continue to traverse up the chamber, reflect off the end wall and return the exit until the pressure in the combustion chamber reaches ambient.

After the detonation wave exits the chamber the high pressure generated by the detonation wave expands to match the atmosphere pressure. This generates a series of expansion waves which enter the chamber and progress towards the closed end. The pressure transducer nearest the open end sense the greatest effect of this series of expansion waves.

The second transducer from the open end senses the expansion wave as well but the reflected compression waves from the closed end reaches this location at about the same time. The two waves interact and the result is a plateau in the pressure trace and very little rise in pressure.

The transducer closest to the closed end does not pick up the reflected compression wave as the expansion wave more than overwhelms the compression waves. This results in a significantly lower pressure at this location relative to the others for approximately 0.5 milliseconds.

The series of expansion waves continue to propagate up the chamber, reflect off the solid wall opposite end, and return to the open end. During the downstream motion towards the open end the pressure drops to a sub-atmospheric level. After the returning expansion waves reach the exit of the tube the pressure is below the ambient atmospheric pressure so a compression wave enters the chamber to correct this. This compression wave increases the pressure to a slightly positive gage pressure at the first sensor from the exit of the chamber. Sensors further from the exit record lower pressures before the compression wave pass as they experience the expansion waves for longer periods of time before the compression wave arrives at the closed end of the chamber. The compression wave then returns to the exit of the chamber. This process of expansion and compression waves is repeated until the pressure in the tube matches the ambient pressure. The low frequency covered in this paper allows plenty of time for this series of expansion and compression waves to play out and the pressure to return to ambient. At higher frequencies these waves will have an effect on the injection of fuel and oxidizer for the next cycle.

The velocity of the initial combustion wave initially starts out at between 300 and 700 m/s (980 and 2300 ft/s) then accelerates supersonically throughout the length of the chamber. The velocity obtained from time of

flight measurements from the pressure sensors is shown in Figure 11. All three cases tested are plotted on one graph. The nozzle case has the greatest velocity. The velocity approaches the C-J velocity in the nozzle as the acceleration is much more noticeable. Before reaching the nozzle the acceleration is fairly linear in its increase. Both the cylindrical geometry with and without the centerbody exhibit consistent acceleration of the detonation process throughout the length of the chamber. The geometry without the centerbody produced higher velocities than with the centerbody. This is contrary to what was expected and is attributed to the fact that the mixture of hydrogen and oxygen was nearer stoichiometric for the non-centerbody test than the test with the centerbody. The amount and pressure of the buffer air was also less for the centerbody test. All the velocities observed were below the C-J detonation velocity calculated with the TEP⁹ computer code, a Windows™ version of the NASA CEC76¹⁰ code but accelerating.

A comparison of pressure traces for the three cases and a single shot case of the nozzle without the centerbody is made in Figures 12-15. Figures 12-14 contain a pressure trace at a single location (the same for all three) for the cases of the cylindrical geometry, the cylindrical with the centerbody geometry, and the nozzle with centerbody geometry, respectively. Figure 15 is a pressure trace at the same location for a single shot test of the same nozzle without the centerbody. All are similar in wave pattern. All figures are taken from the same location in the combustion tube, which is 19.05 cm (7.50 inch) from the closed end. Figure 16 is a pressure trace from the same location of the chamber and extends for three complete cycles for the nozzle with the centerbody.

UNCERTAINTIES

The pressure plots show no definitive shock or detonation wave near the open end of the chamber. The fuel and oxidizer here was the first injected during the cycle and has mixed with the buffer air and diluted. The way the air and the combustible reactants are injected has a significant influence on their mixing. Different techniques of injecting the buffer air could reduce the amount required, reduce the turbulence created and reduce the mixing with the combustible reactants. The mixture ratio of

hydrogen to oxygen is not precisely controlled so it may not consistently be stoichiometric and full C-J pressure not generated. The timing belt also slips and skips a few teeth on occasion so the timing maybe off for some of the cycles and the results different from what is expected.

CONCLUSIONS & RECOMMENDATIONS

The operation at the 10-12 Hz frequencies range described here appear to be nearly identical to the operation in single shot mode and at 2-5 Hz range⁷. The chamber pressure has equalized out to ambient conditions in approximately 50 milliseconds. Frequencies of 20 Hz appear possible but injection of an air buffer will require some time. At the point where one cycle's waves interact with the buffer air injection and the next cycle's fuel and oxidizer injection, the frequency may be governed by the wave location during purge air, fuel, or oxidizer injection and ignition.

The length of the chamber will affect the interaction of the detonation waves and expansion waves, so the length will have to be considered to understand how it affects the performance at various frequencies. This length requires a finite amount of time for either the detonation or expansion wave to traverse it. The effect of these waves on the previous or following cycle must be known to optimize performance.

The time of flight velocity indicates a full C-J detonation wave was not generated. The detonation wave approaches C-J velocity but exits the tube before obtaining C-J velocity. Methods to create a near C-J detonation wave in a shorter distance without introducing a large pressure loss must be developed. Improving the mixing during injection using swirl or other techniques, measurement of fuel and oxidizer flow rates, and creating turbulent flow including the possible use of a tubulator are issues which must be addressed.

The most immediate and easiest problem to correct is the timing of the fuel, oxidizer, and buffer air. The current timing belt will be replaced with one with more positive interaction between the pulleys and the belt or with a chain to prevent the timing from changing undesirably.

Increasing the operating frequency will be done in the future in incremental steps to understand the wave interaction phenomenon. A 100+ Hz ignition system has already been

developed and will be incorporated. The present fuel injection system will be enlarged and improved for high flow rates as the frequency increases.

Measurement of heat transfer and force must also be obtained. The thrust produced must be measured to provide a real indication of the usefulness of a PDE device. The heat transfer measurement are required for designing the combustion chamber of a flight engine. Such measurements are extremely difficult for a single cycle but an average measurement could be obtained during multi-cycle operation. The higher the frequency the more accurate the average measurements will be. Wall temperature measurements will also be of interest.

ACKNOWLEDGMENT

This material is based in part upon work supported by the Texas Advanced Technology Program under Grant No. 003656-031.

REFERENCES

1. Smith, D.E., "The Synchronous Injection Ignition Valveless Pulsejet," Ph.D. Dissertation, University of Texas at Arlington, TX, May 1987.
2. Nicholls, J. A., Wilkinson, H. R., Morrison, R. B., "Intermittent Detonation as a Thrust-Producing Mechanism," *Jet Propulsion*, May 1957, pp 534-541.
3. Bussing, T. R. and Pappas, G., "An Introduction to Pulse Detonation Engines," AIAA Paper 94-0263, Jan., 1994.
4. Kim, K., Varsi, G., and Back, L. H., "Blast Wave Analysis for Detonation Propulsion," *AIAA Journal*, Vol. 15, #10, 1977, P. 1500-1502.
5. Stanley, S. B., "Experimental Investigation of Factors Influencing the Evolution of a Detonation Wave," M. S. Thesis, University of Texas at Arlington, 1995.
6. Stanley, S. B., Stuessy, W. S. and Wilson, D. R., "Experimental Investigation of Pulse Detonation Wave Phenomenon," AIAA Paper 95-2197, 1995.

7. Stuessy, W. S. and Wilson, D. R., "Experimental Investigation of a Multi-Cycle Pulsed Detonation Wave Engine," AIAA Paper 96-0346, January, 1996.
8. Helman, D., Shreeve, R. P., and Eidelman, S., "Detonation Pulse Engine," AIAA Paper 86-1683, 1986.
9. "Thermal Equilibrium Program for Windows User's Manual," Software and Engineering Associates, Inc., 1992.
10. Gordon, S., and McBride, B. J., "Computer Program for Calculation of Complex Chemical Equilibrium Compositions, Rocket Performance, Incident and Reflected Shocks, and Chapman-Jouguet Detonations," NASA SP 273, 1971.

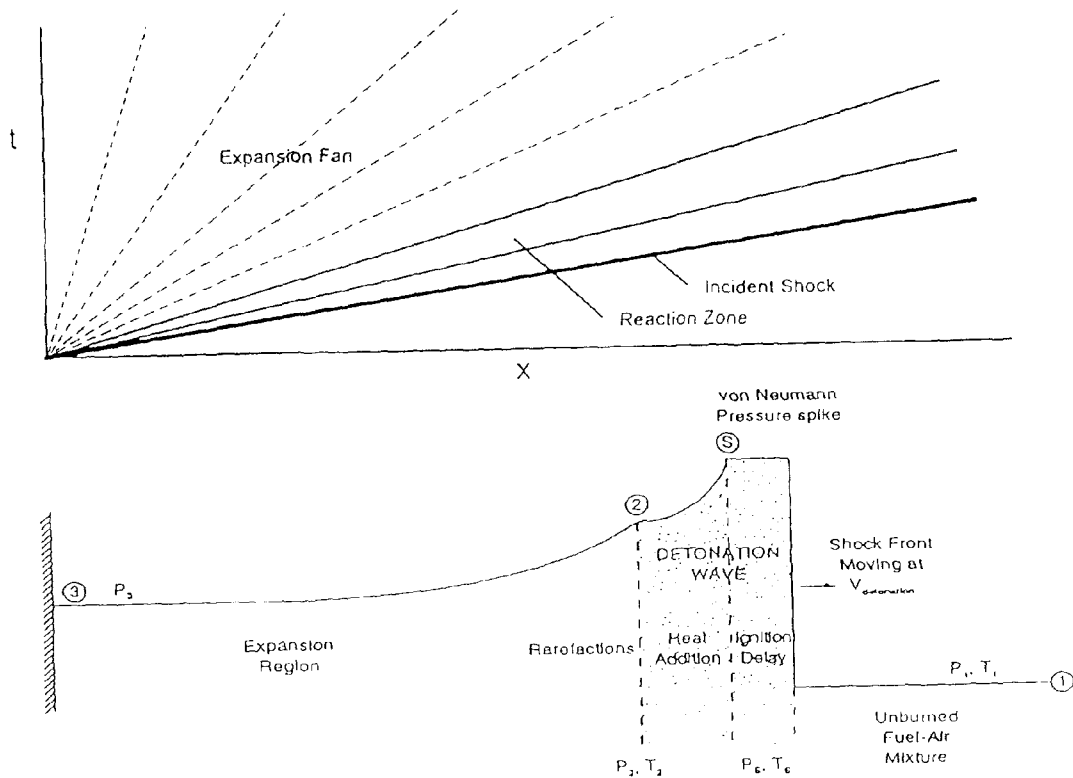


Figure 1 ZND detonation wave model

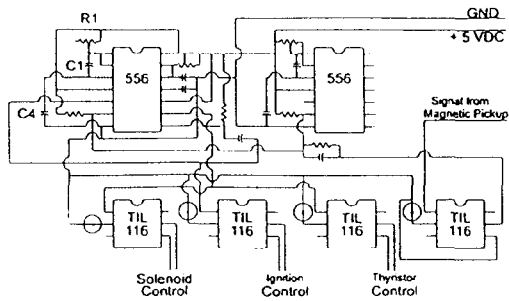


Figure 2 Electronic control circuit

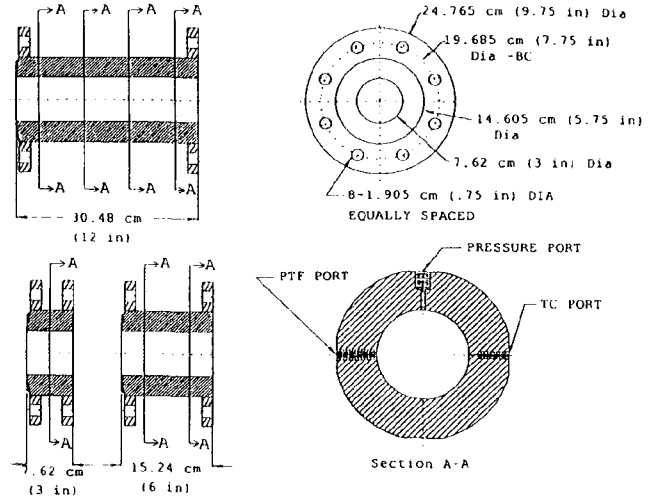


Figure 3 Test chamber sections

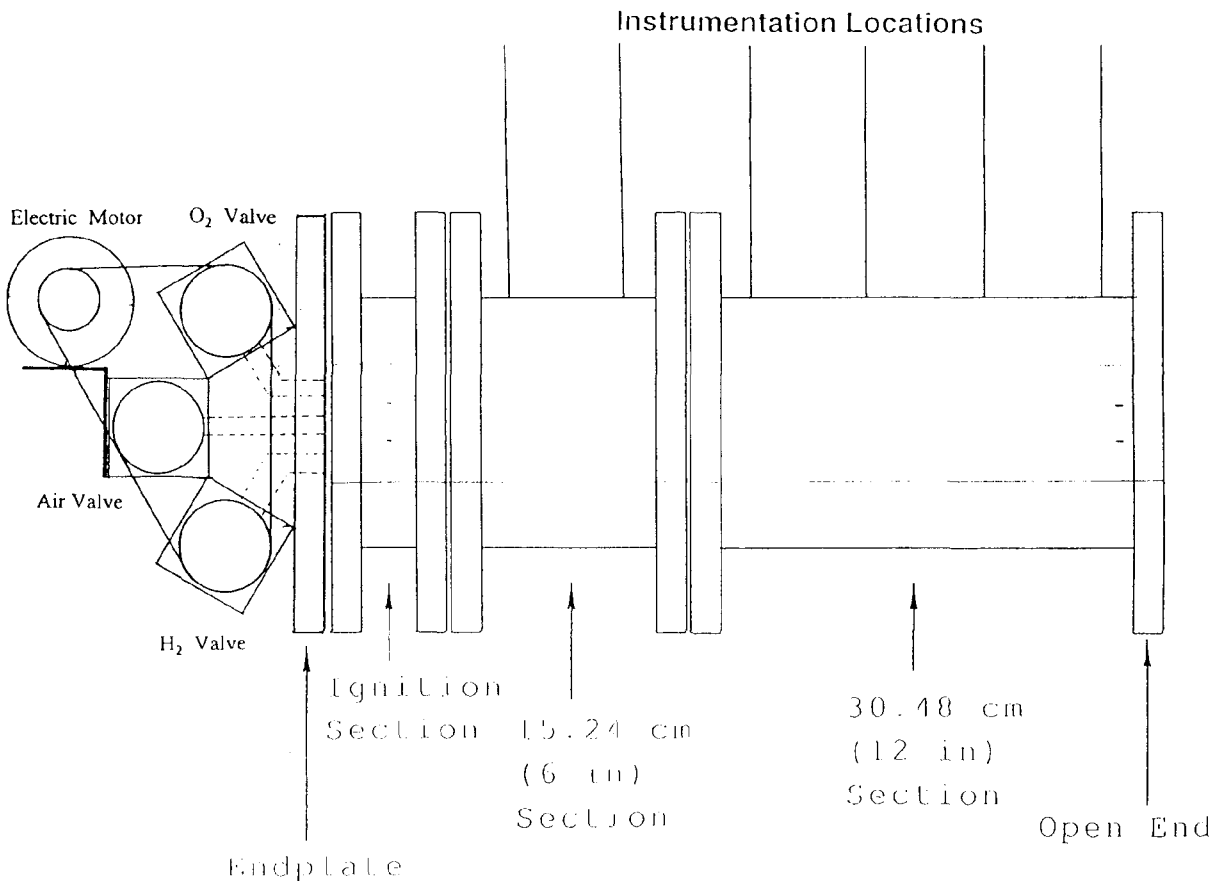


Figure 4 Test chamber Schematic

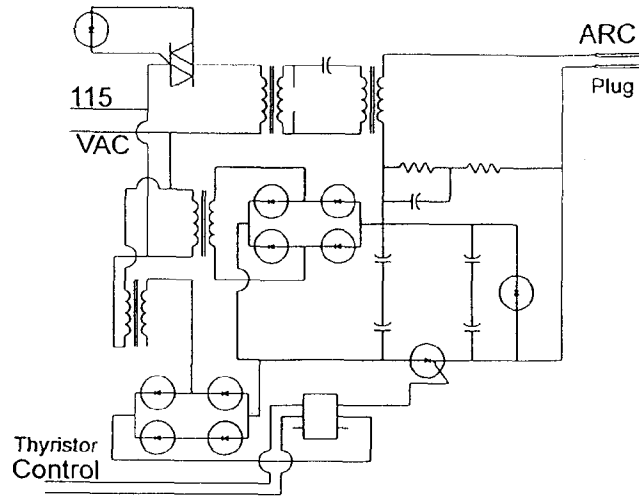


Figure 5 Ignition system schematic

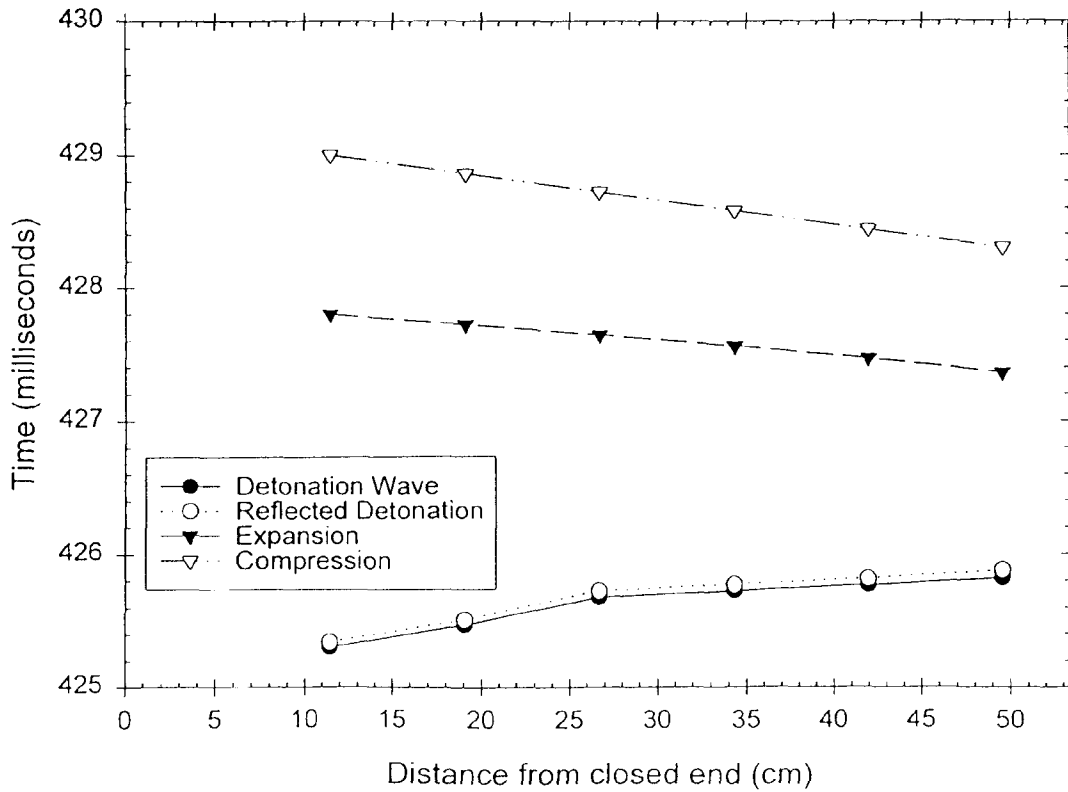


Figure 6 Wave diagram cylindrical case

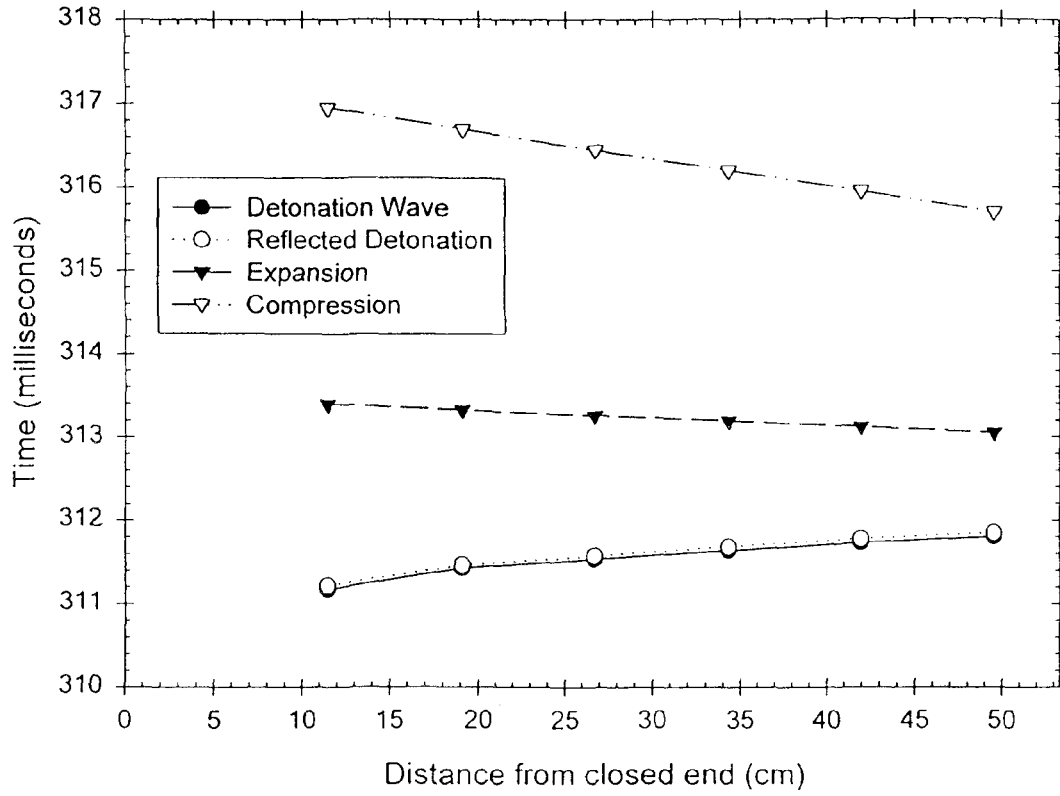


Figure 7 Wave diagram centerbody case

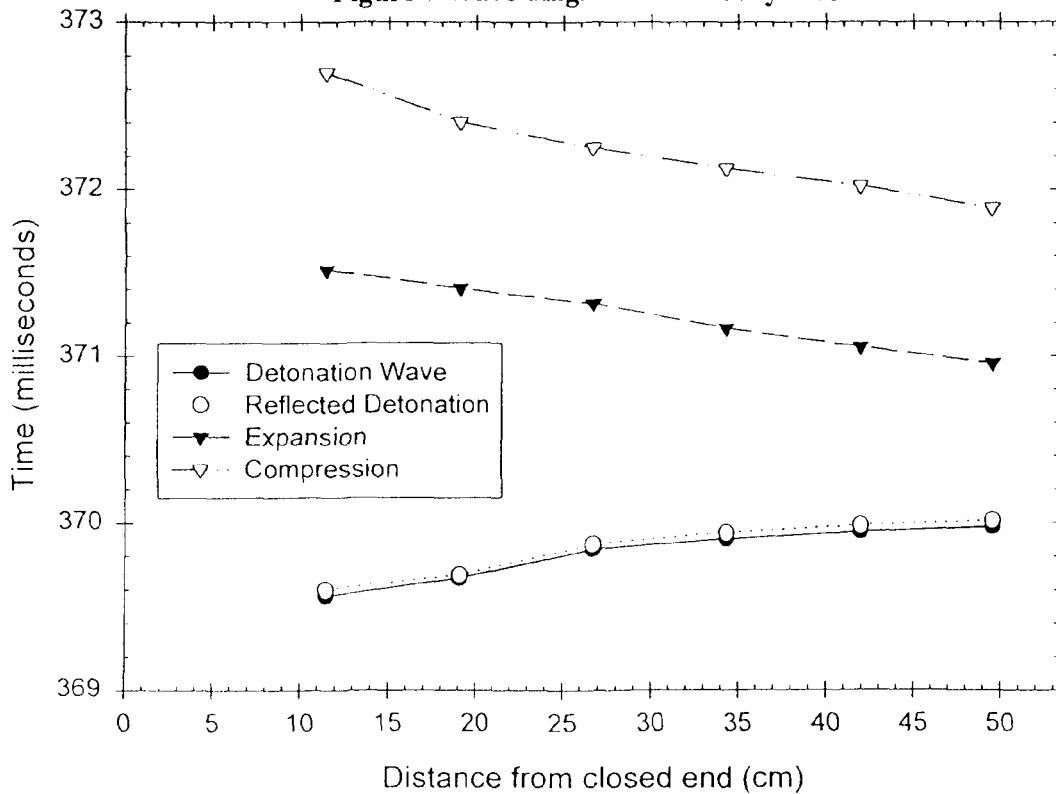


Figure 8 Wave diagram nozzle with centerbody case

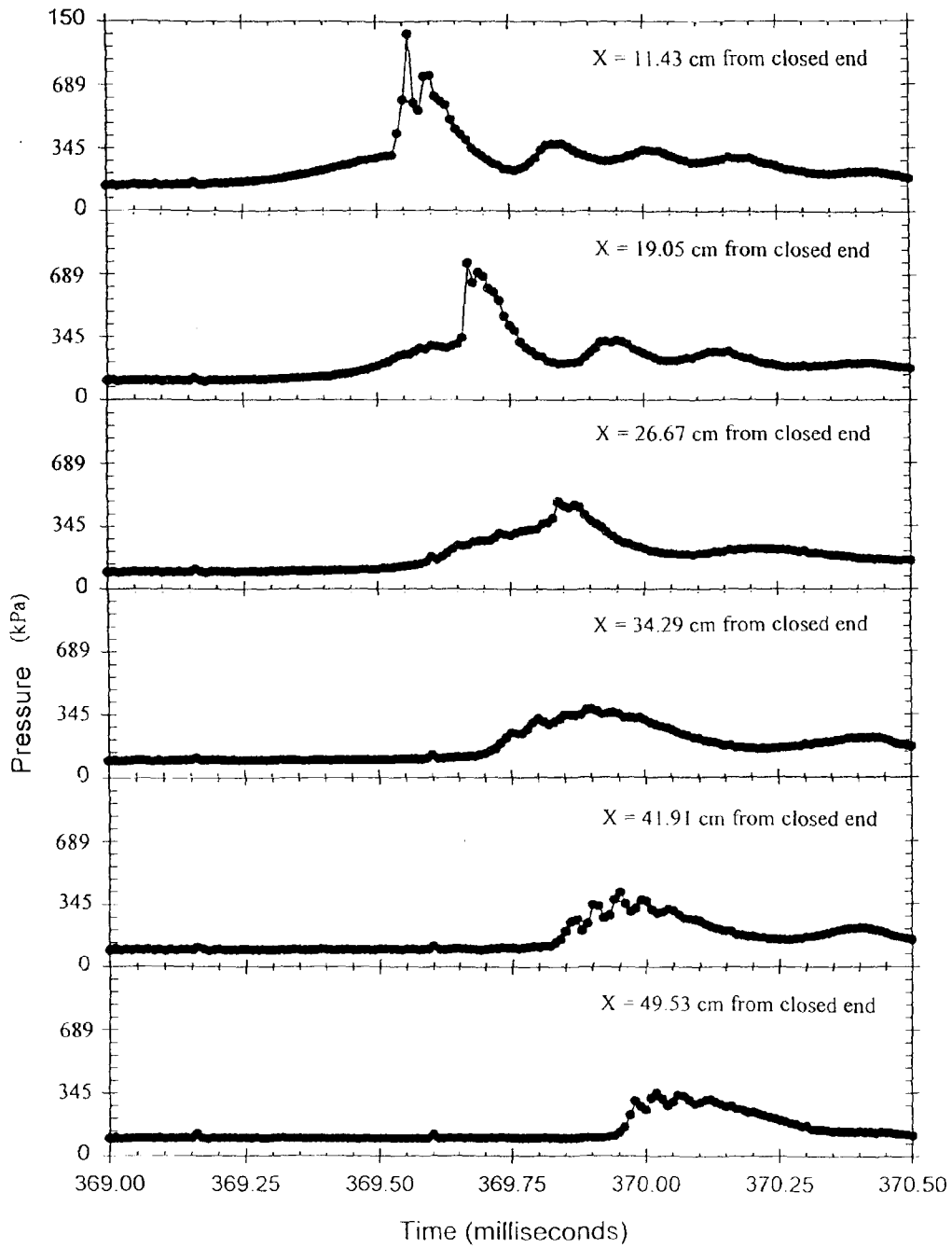


Figure 9 Detonation wave pressure traces

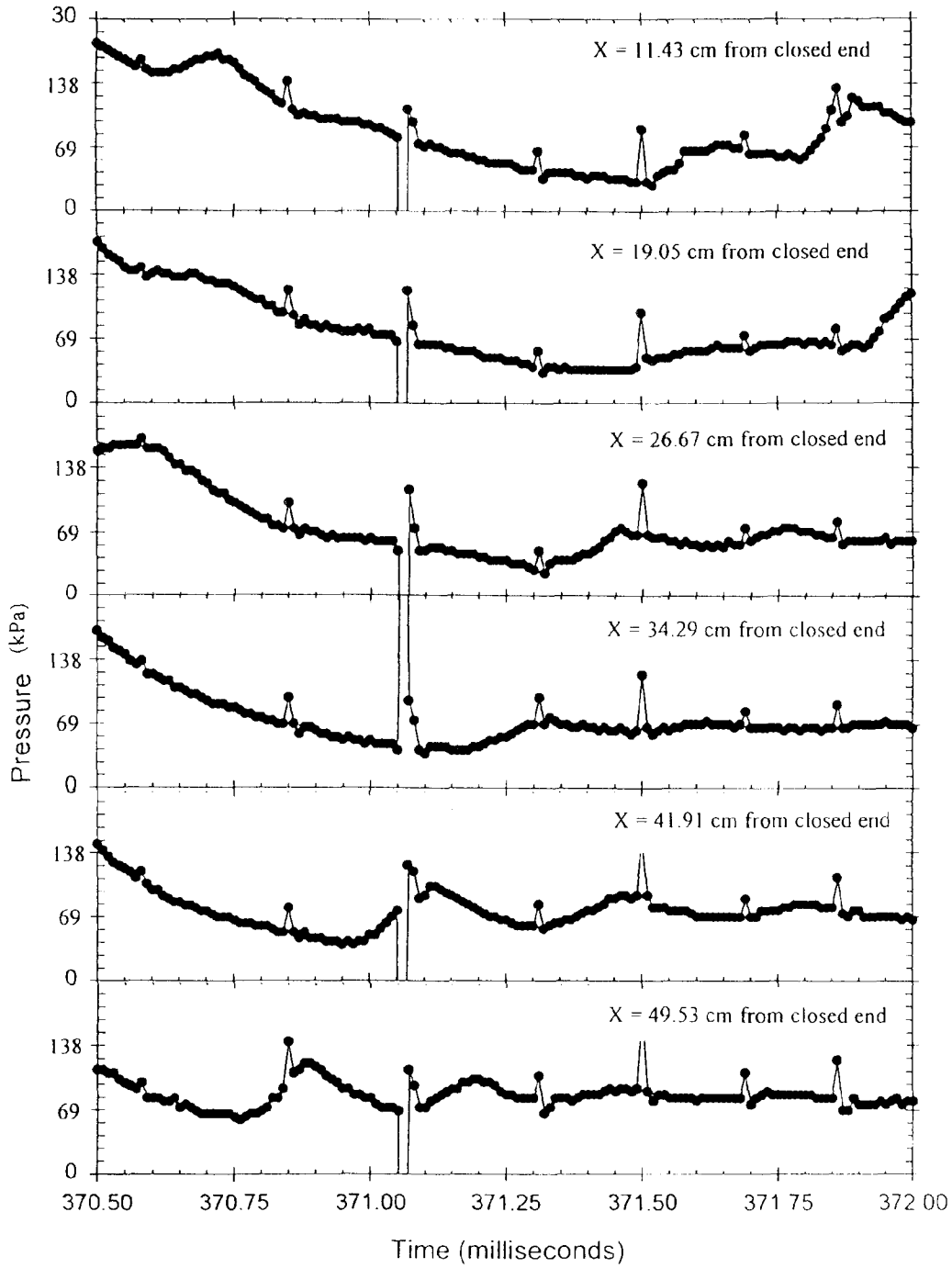


Figure 10 Expansion wave pressure traces

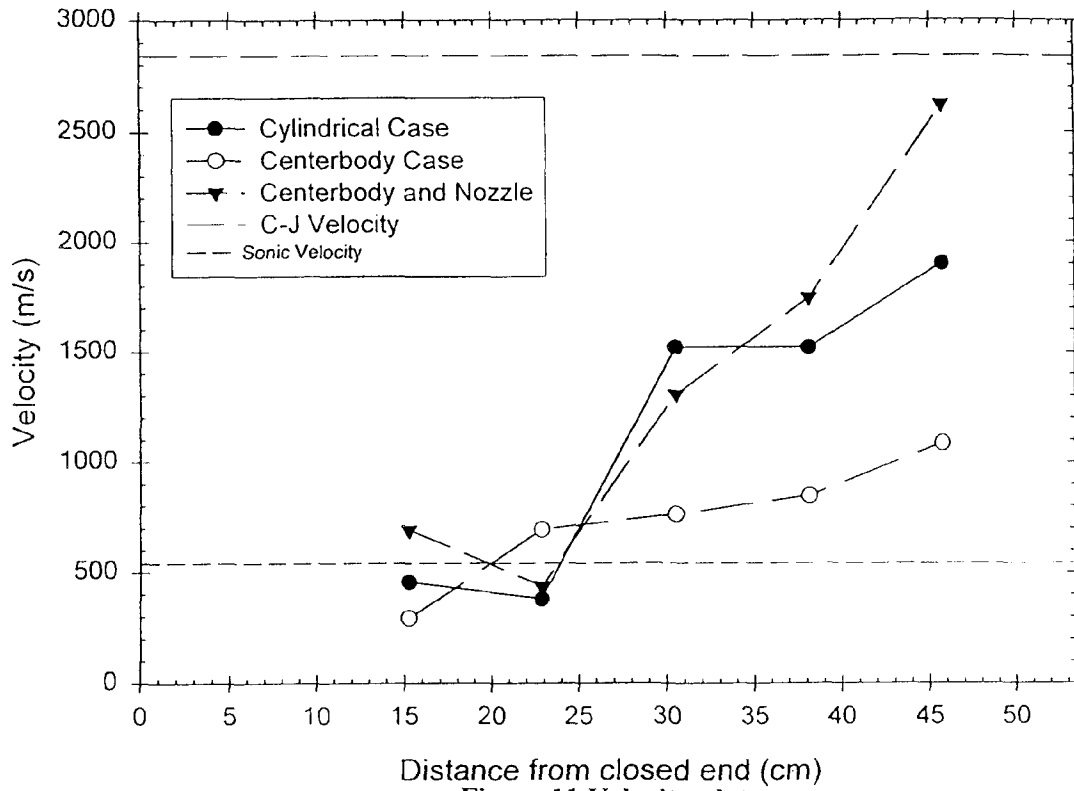


Figure 11 Velocity plot

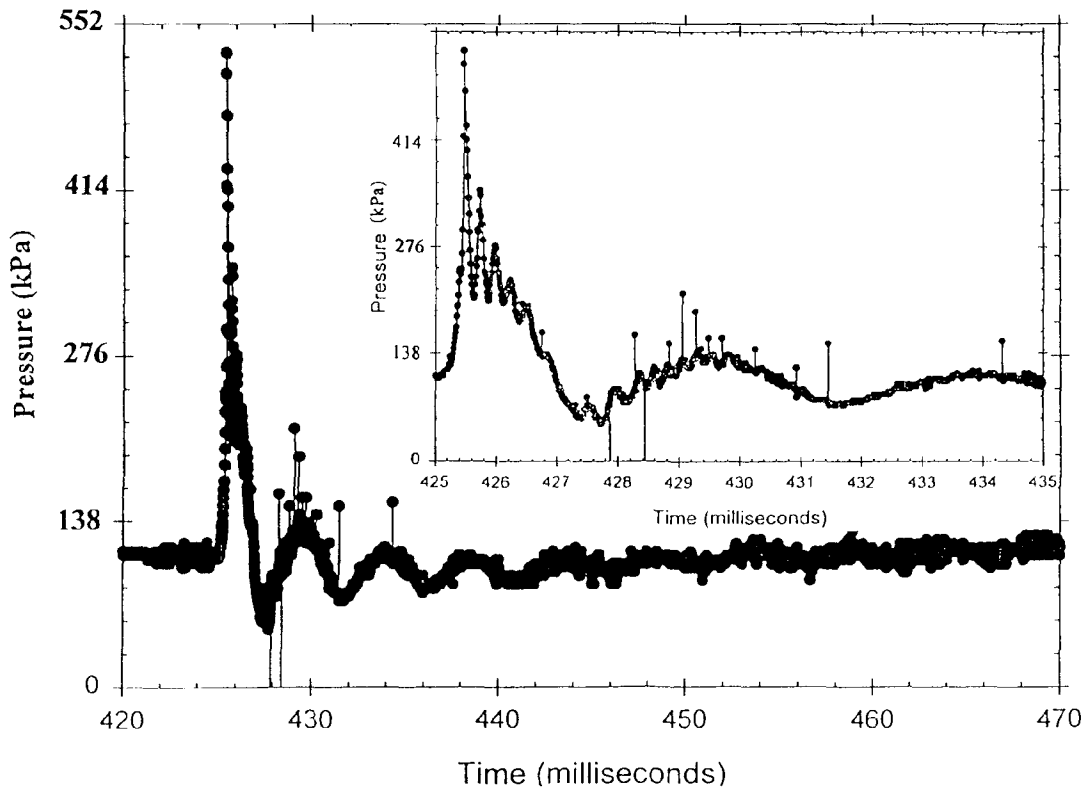


Figure 12 Pressure trace cylindrical case

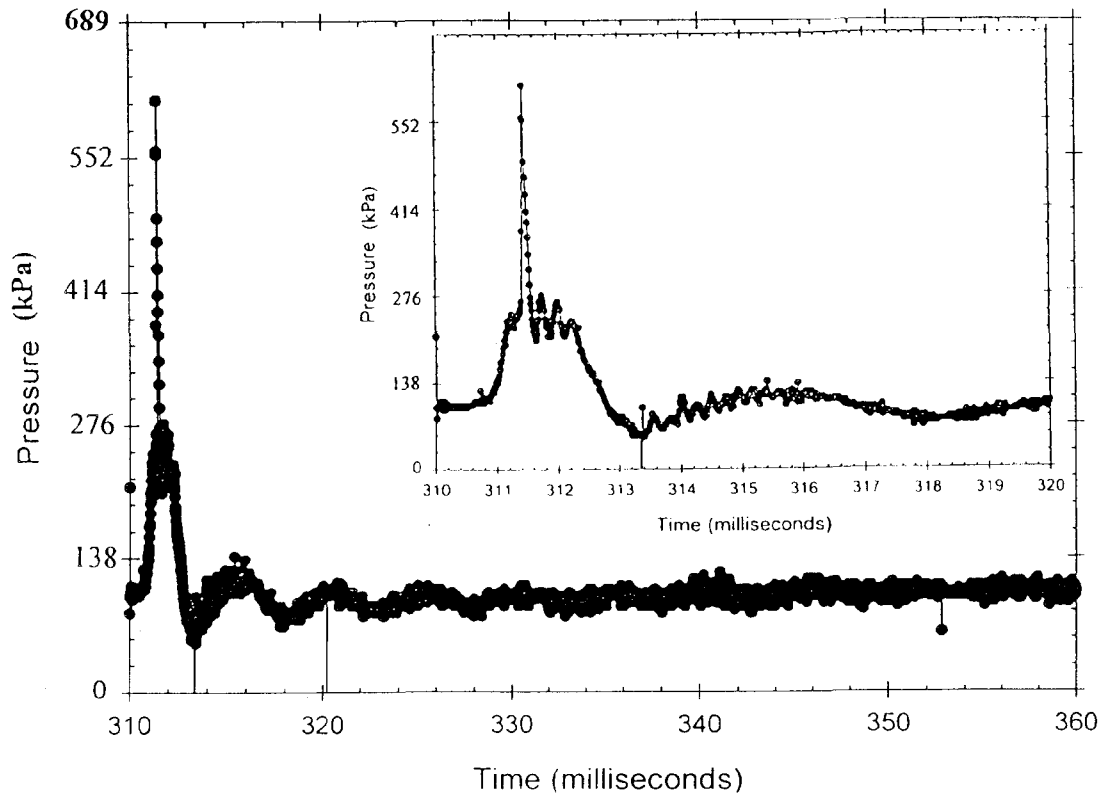


Figure 13 Pressure trace centerbody case

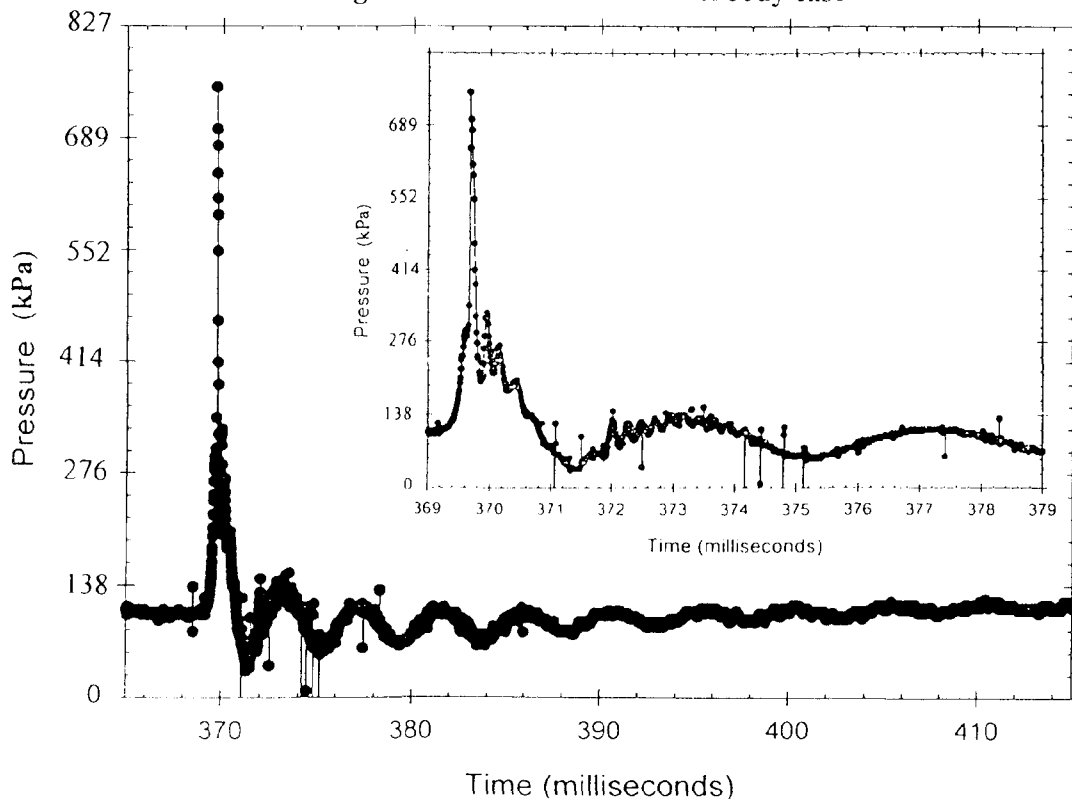


Figure 14 Pressure trace nozzle with centerbody case

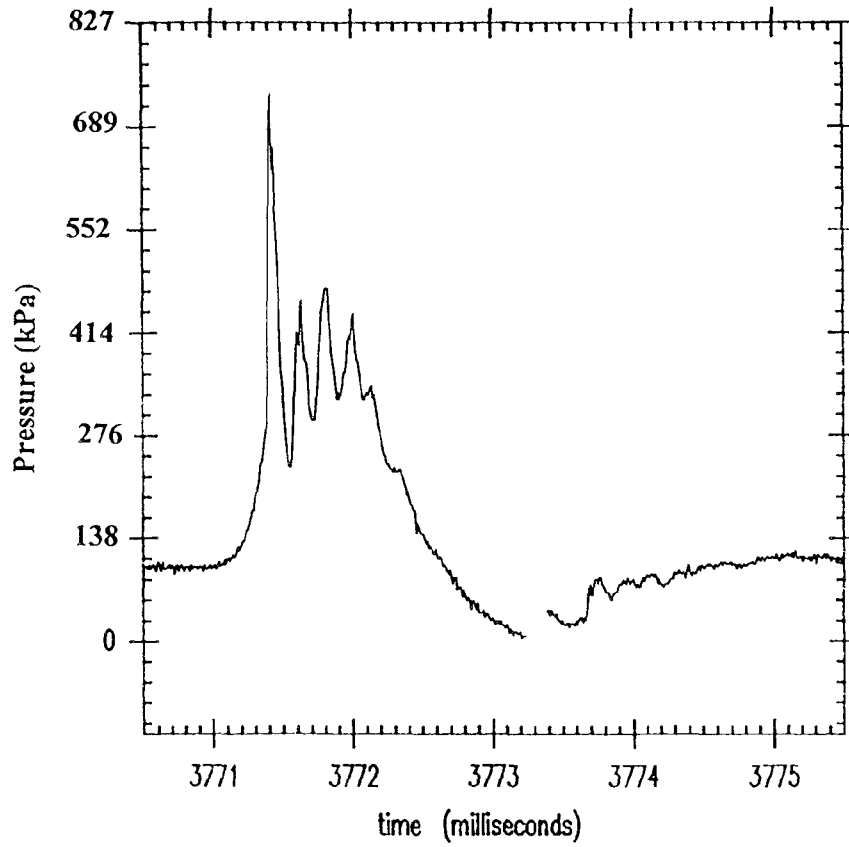


Figure 15 Pressure trace nozzle without centerbody single shot test

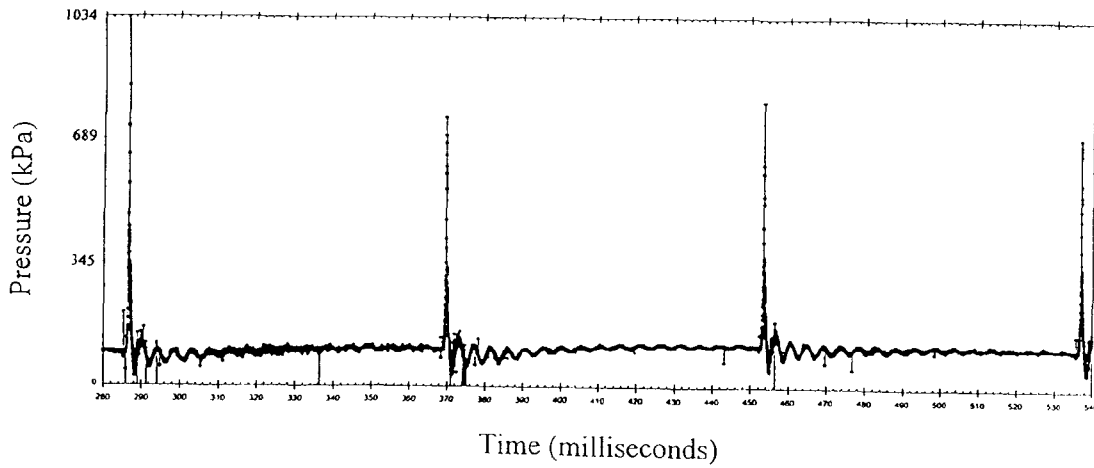


Figure 16 Multiple cycle pressure trace