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Experimental Investigation of a Multi-cycle Pulsed Detonation Wave Engine

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ABSTRACT

The Detonation Wave Facility at the University of Texas at Arlington has been modified to run in a multi-cycle mode as a Pulse Detonation Engine simulator. A fuel injection system to inject repetitively was incorporated as well as an ignition system which could be used repetitively to ignite the combustible mixture. A description of the facility and results from pressure measurements from initial multi-cycle operation are presented for hydrogen/oxygen mixtures at low frequencies. Comparison with results from the facility operated in the single shot mode of operation are also made.

INTRODUCTION

Pulsating engines have been around for quite some time and found us in World War II in the German V-1. These engines took in fuel and oxidizer, burnt then and expelled the product 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 utilizes combustion at supersonic velocities by detonation waves. The engine operates in a cyclic fashion like a pulse jet but operates at a higher pressure level due to the detonation waves and potentially at higher frequency. 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 is thought to have applications from static conditions to around Mach 10 conditions, perhaps more, and have substantially higher efficiency than conventional propulsion systems.[3] The complexity of the engine could be reduced. The detonation wave would generate the high pressure so the compressor would no longer be required. Without the compressor, the turbine is also not required. With out the rotating machinery the engine becomes much less complicated.

Detonation waves can also be used in rocket engines[4] to increase performance and eliminate many of the heavy and complex 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 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 high pressure to produce the thrust, in a constant volume mode of operation. The injection pressure is much lower than required for conventional propulsion systems which operate at constant pressure. The fuel and oxidizer can be injected during the low pressure portion of the cycle.

The detonation wave is a coupled shock wave and combustion process as Figure 1 illustrates. The shock front increases the pressure and

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temperature similar to a normal shock wave. Immediately following the shock the combustion process adds heat at constant volume. The Zeldovich-Von Neumann-Doring (ZND) spike seen in Figure 1 is 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 significantly. The combustion region is followed by an expansion region which brings the supersonic flow behind the detonation wave to rest at the 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. 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. This results in an almost immediate detonation wave but requires a very large amount of energy.

The addition of turbulence generator can also speed the process of generating a detonation wave by increasing the mixing of the fuel and oxidizer. The detonation must be generated in a relatively short distance in order to make a pulse detonation engine feasible.

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.[5,6,7] The injection portion of the facility has been replaced with one 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, fire 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.

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 test 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 synchronized 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 through an unused port in the ignition section, perpendicular to the axis of the chamber and against the opposite wall by means of a solenoid valve. 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. 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 show in Figure 5.

The discharge capacitor bank consists of two 11000 micro farad 75 VDC capacitors connected in series and charged to about 100 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 100 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 that also initiates the high frequency welding unit, provides a delay for recharging the discharge capacitor bank, and the signal to the thyristor. The timer circuit also provides a signal to a solenoid valve for purge air.

The energy from the discharge capacitor bank is discharged through a 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 transduces are PCB model 111A24 dynamic pressure transducers with a full scale range of 6.89 MPa (1000 psi), rise time of 1 microsecond, 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 1333.22 kPa (10000 Torr). This transducer is used as it was part of the facility when it was used for enclosed single detonation test and it provides a very accurate measure of atmospheric pressure.

The pressure transducers are connected to a DSP Technology data acquisition system which has the capability of 100 kHz sampling rate, 12 bits of accuracy, and 48 channels each with its own 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. The data acquisition system is controlled by a PC which retrieves the data, stores it on a harddrive, and analyzes the data.

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 as 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.

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.

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

RESULTS & DISCUSSION

Initially only fuel and oxidizer was injected during each cycle. The fuel and oxidizer in the chamber burned almost continuously and produced a very low pressure after the first supersonic combustion wave. There was no noticeable increase during or following the injection, ignition, or combustion periods. Purge air was then introduced between cycles and supersonic combustion was sucessful. A solenoid valve was used to introduce compressed air to provide a this buffer air between the combustion products of one cycle and the fresh charge of hydrogen and oxygen of the following cycle. A solenoid valve was used to expedite the test program and will be replaced by a rotary valve. The solenoid valve was controlled by the control system and was set to open for approximately 100 ms each cycle. At this opening time it was found the supply air pressure required to provide a sufficient air buffer was approximately 2.76 MPa (400 psi). Pressures below 2.41 MPa (350 psi) resulted in a continuous burning process and no detonation wave as if no air at all were added. Pressure above up to 3.45 MPa (500 psi) produced no significant improvement in the detonation process. The air was injected through the ignition section using an unused ignition plug port. The air was injected against the opposite wall.

Plotting the time of arrival of each detonation wave, 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.

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 time passage of the detonation wave is approximated by ignoring the precompression and locating the location of the steep pressure jump. 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 so it is suggested that it is a series of compression waves. The 3.81 cm distance from the ignition source to the end wall is probably not of sufficient length to obtain supersonic combustion and after reflection there is not enough fuel available to continue combustion so the wave continues as a compression wave. This wave travels 7.62 cm (3 inches) further than the initial detonation wave when it is picked up by each sensor. An expansion wave follows the detonation wave down the tube and is created in order to bring the high velocity flow behind the detonation wave to rest at the end plate. The compression wave follows the expansion wave to generate the secondary pressure increase but then the pressure again begins to drop due to additional expansion waves. The first combustion wave is continuously producing expansion waves behind it and these interact with the trailing compression wave to produce several smaller rises and decreases in pressure as they travel down the length of the chamber.

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 save 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 open end doesn't 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 supersonic combustion wave initially starts out at over 670 m/s (2200 ft/s) then drops but remains supersonic before beginning to accelerate again throughout the length of the chamber. The velocity obtained from time of flight measurements from the pressure sensors is shown in Figure 9. The flat lines between symbols represent average velocity between pressure transducer locations. All the velocities observed were well below the C-J detonation velocity calculated with the TEP[8] computer code, a Windows™ version of the NASA CEC76[9] code.

A comparison of pressure traces from single shot and multi-cycle operation is made in Figures 10 and 11. Both figures are taken from the same location in the tube, which is midway between the open and closed ends. Figure 10 is from the multi-cycle operation and shows the initial combustion wave and extends for fifty milliseconds and includes several cycles of expansion and compression waves. Figure 11 shows the same portion of the waves for operation in the single shot mode. The two are very similar in wave pattern and peak pressure. Figure 12 illustrates a complete cycle with two pressure pulses that are at the same chamber location as Figures 10 and 11.

UNCERTAINTIES

The pressure plots show no definitive shock or detonation wave for the last two instrumentation locations 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 detonation wave has basically died out. 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 and reduce the turbulence created and reduce the mixing with the combustible reactants. The mixture ratio of hydrogen to oxygen is not precisely known so it may not be very near stoichiometric.

CONCLUSIONS & RECOMMENDATIONS

The operation at the low frequencies described here appear to be nearly identical to the operation in single shot mode. 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. Frequencies of at least 10 Hz should be obtained before the interaction of one cycle's wave with the injection of the next cycle's fuel becomes a problem. At this point when the interactions begin 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 pressure level measured and time of flight velocity indicate a C-J detonation wave was not generated. Methods to create a near C-J detonation wave must be developed. Improving the mixing and measurement of fuel and oxidizer, creating turbulent flow including the use of a tubulator spiral, and increasing wall area must be addressed.

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.

ACKNOWLEDGMENT

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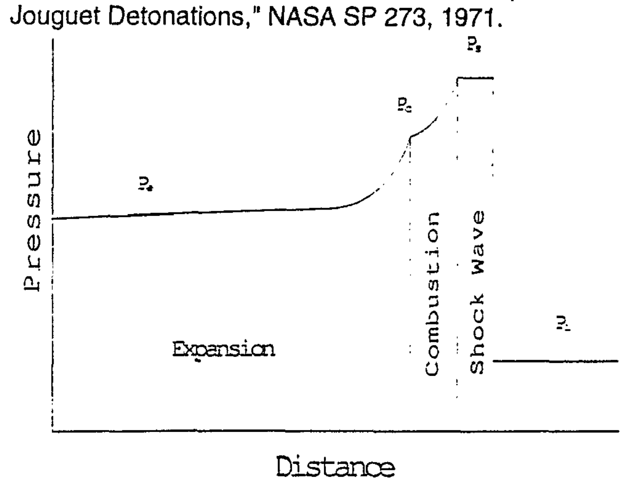

Figure 1 ZND detonation wave model

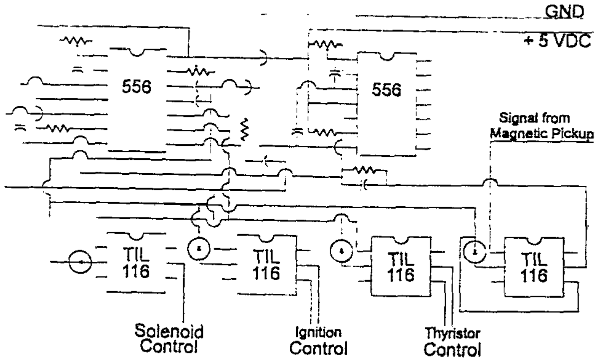

Figure 2 Control circuit

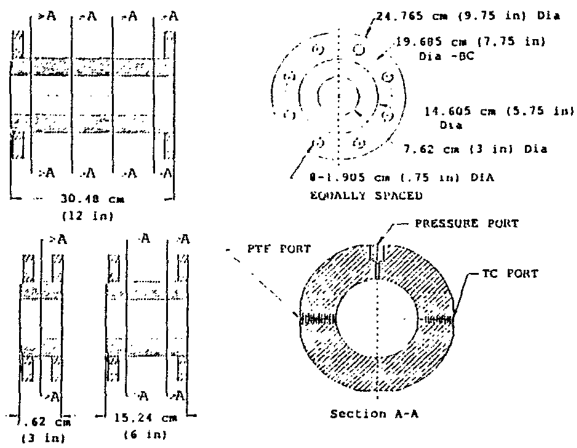

Figure 3 Test chamber sections

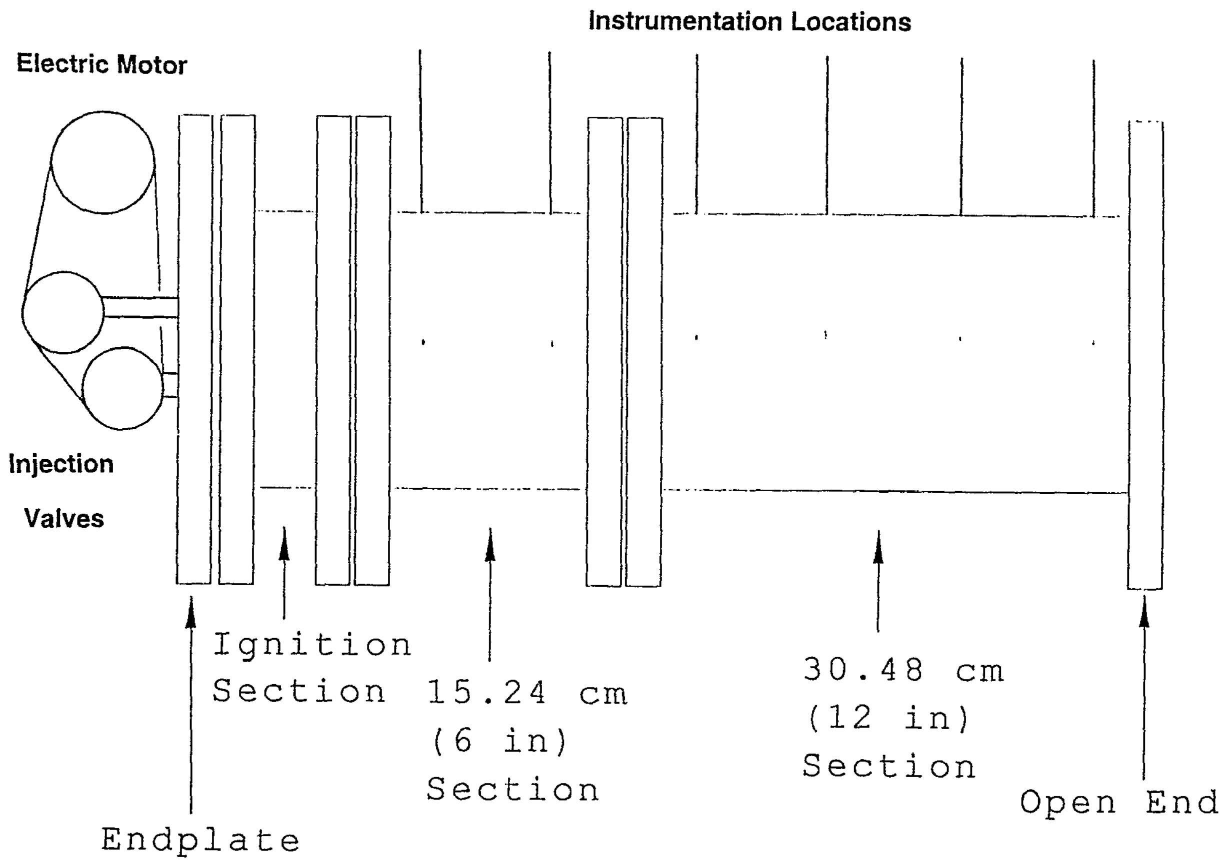

Figure 4 Test chamber schematic

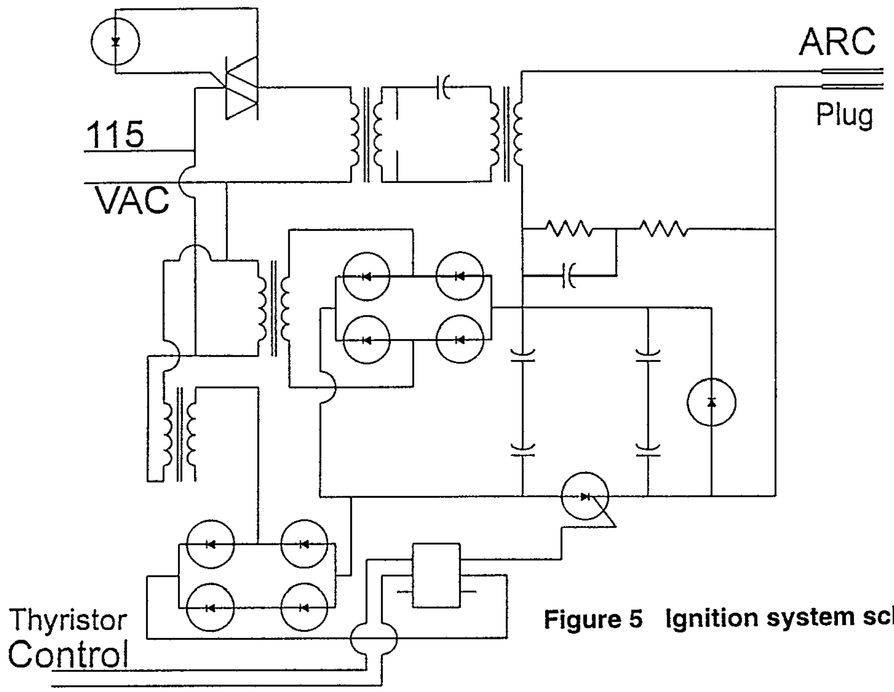

Figure 5 Ignition system schematic

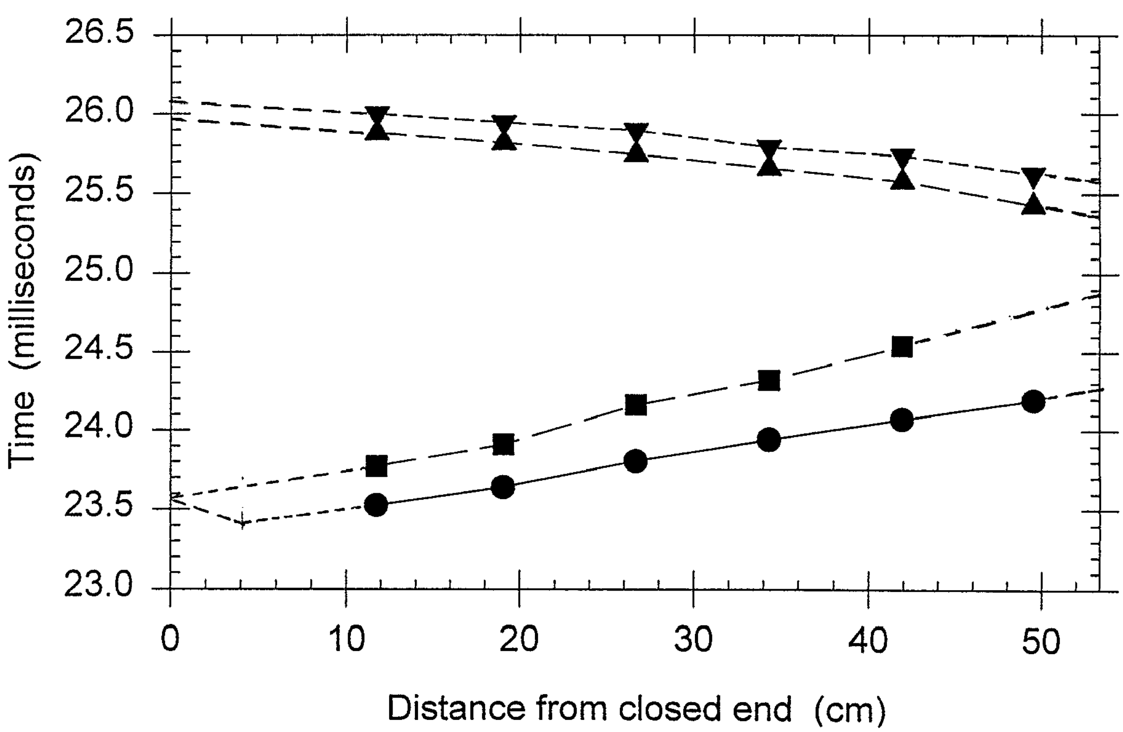

Figure 6 Experimental Wave Diagram

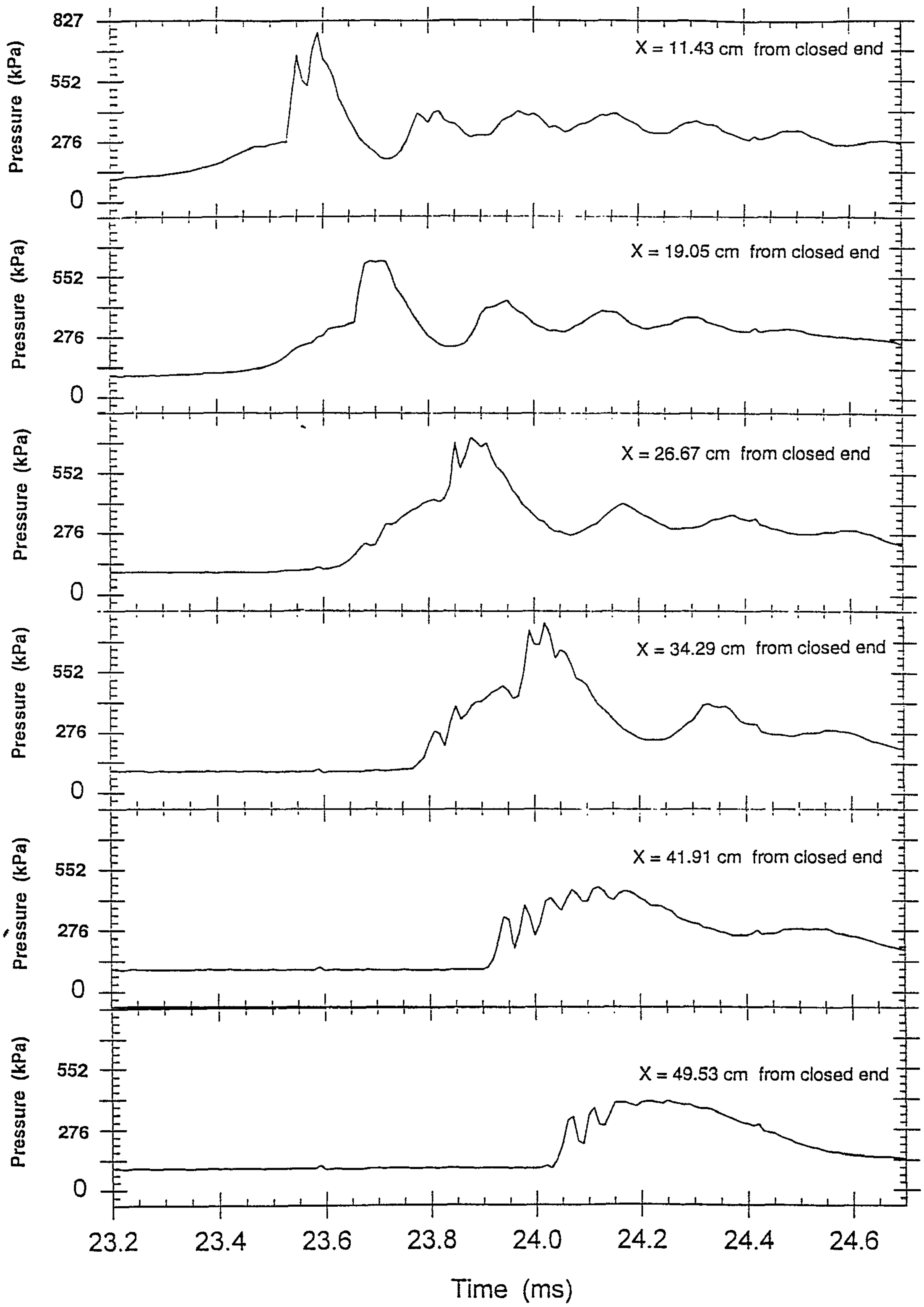

Figure 7 Detonation wave pressure trace

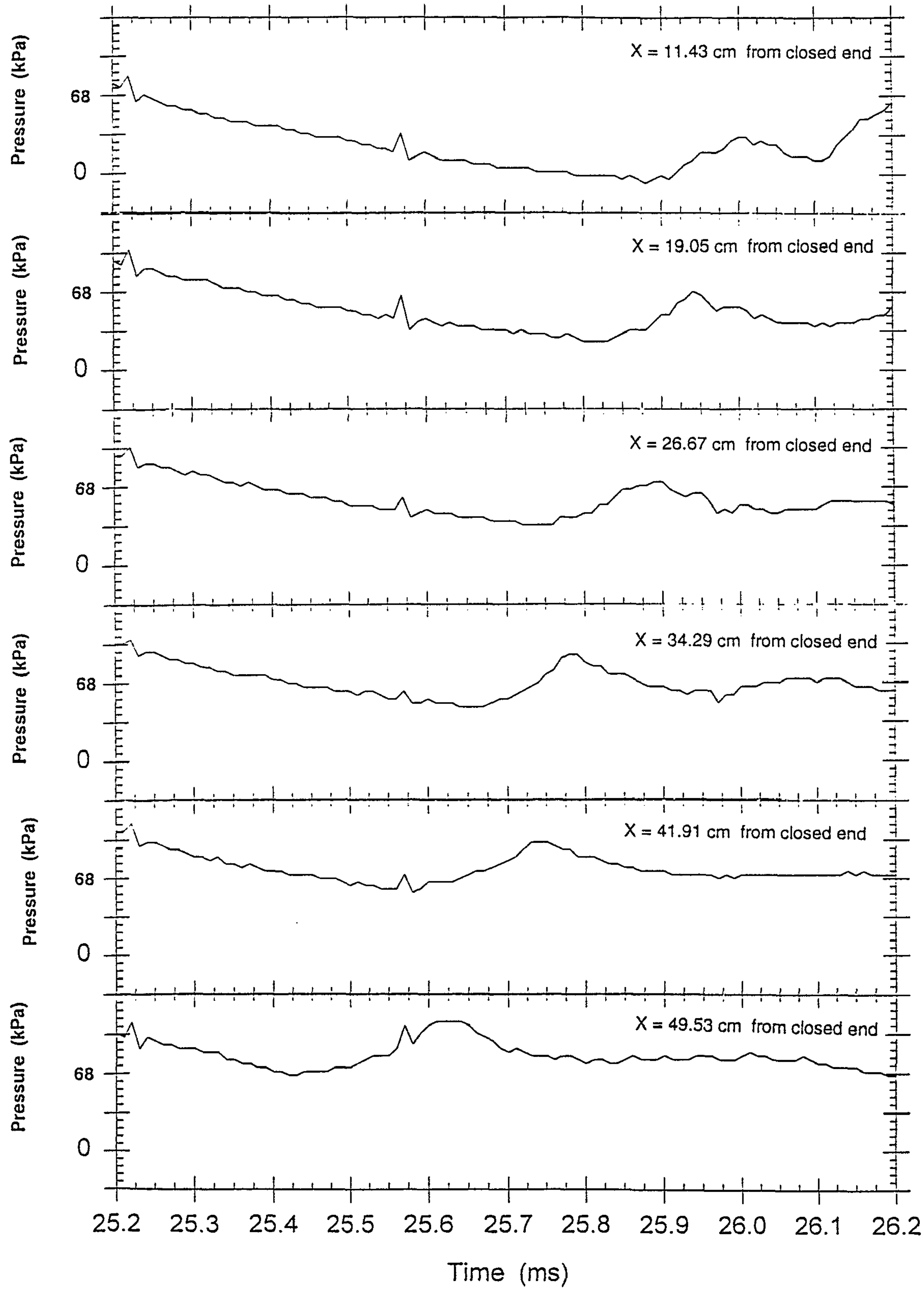

Figure 8 Expansion wave pressure trace

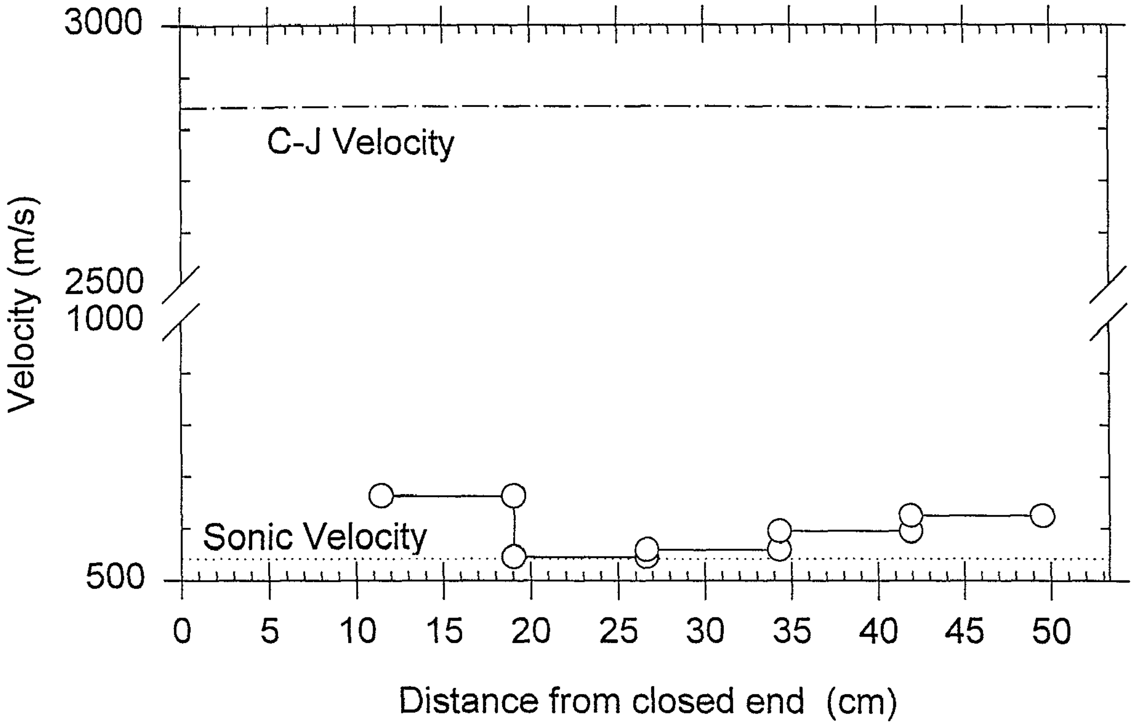

Figure 9 Velocity Plot

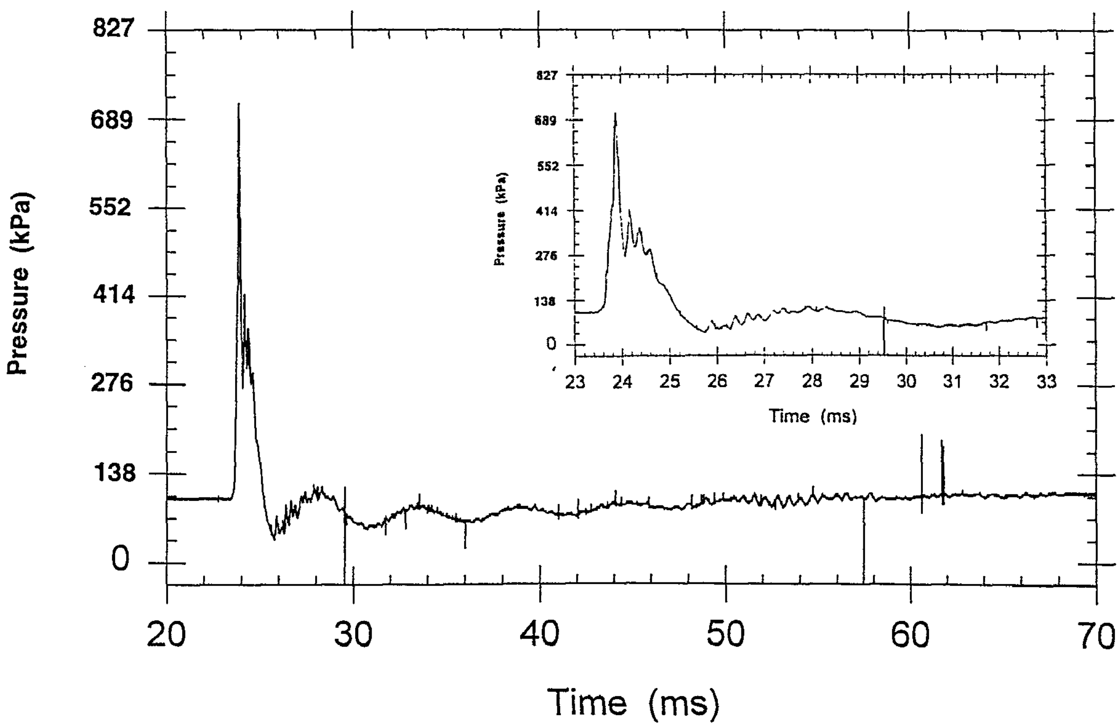

Figure 10 Multi-cycle pressure trace

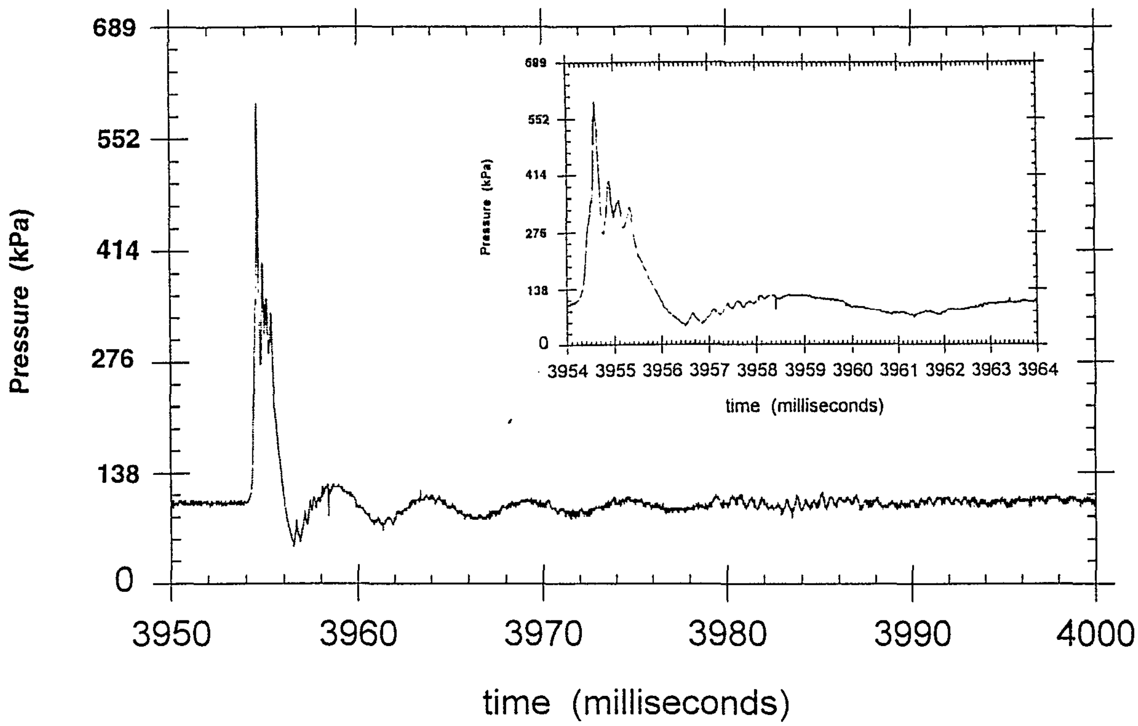

Figure 11 Single shot pressure trace

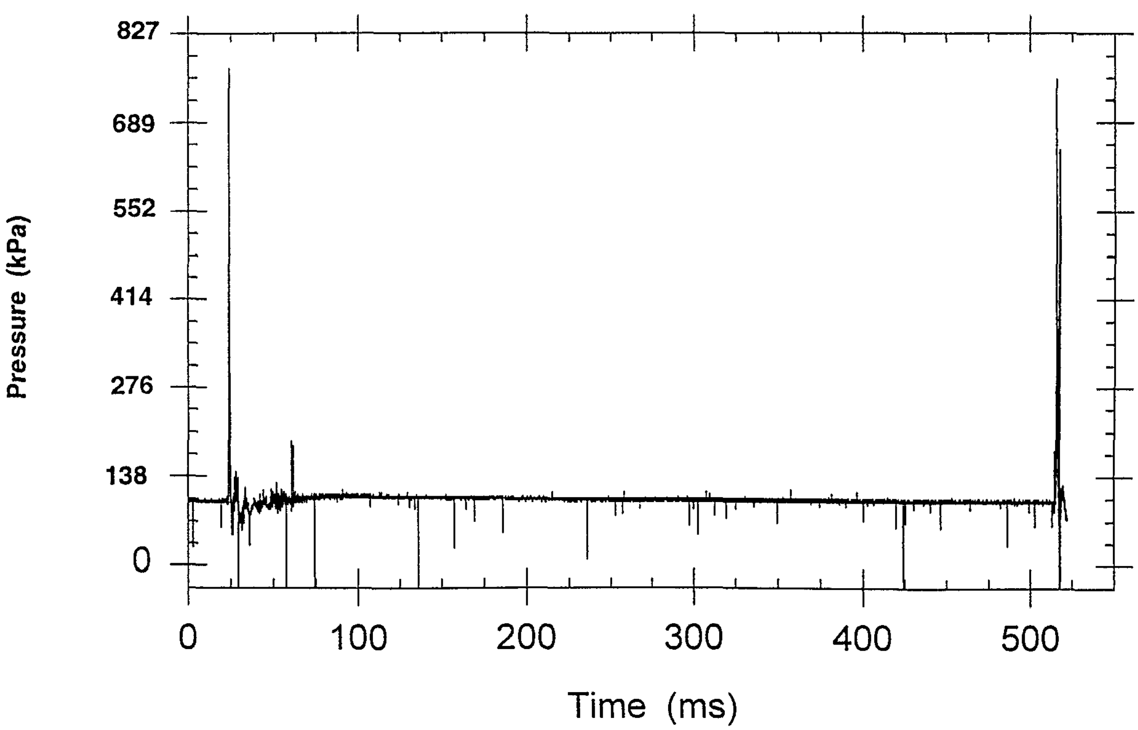

Figure 12 Complete cycle pressure trace