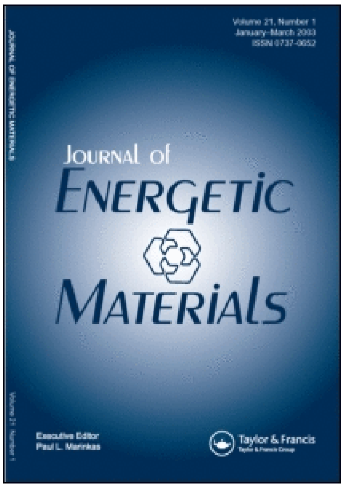

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A NEW CLOSED VESSEL FOR DETERMINING THE BALLISTIC PERFORMANCE OF HIGH ENERGY SOLID AND LIQUID GUN PROPELLANTS

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ABSTRACT

A new closed vessel, designed and build by Cranfield University under contract to the UK Defence Evaluation and Research Agency (DERA), is described. The jacketed vessel, which can be operated at high pressure (500 MPa) and has the capability of firing liquid monopropellants, is fitted with a single instrumented head and a detachable liner. The internal surface profile of the combustion chamber is shaped so as to prevent the build up of shock waves which can occur between parallel surfaces and this feature leads to improved output signal quality. Vessel venting following a firing is carried out by remote control via a proprietary air-actuated high pressure valve. The vessel can be fitted with optical windows or converted to a vented device for gas erosion studies.

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INTRODUCTION

Closed vessel testing provides a valuable and dependable means of evaluating the ballistic performance of a gun propellant. The test consists of igniting a known mass of propellant in a fixed volume combustion chamber and recording the pressure/time history via a pressure transducer. The signal is processed electronically and the rate of change of pressure and maximum pressure are recorded. Future gun systems are likely to require higher energy propellants which are capable of developing greater gas pressure than those currently in service. Test equipment such as closed vessels, designed to characterise the ballistic performance of these propellants, must therefore be able to withstand increasingly higher pressures. A new closed vessel capable of meeting these demands has therefore been developed which is of improved ergonomic design, is versatile, easy to use and can provide reliable ballistic data. The design and manufacture of the new vessel is described in this paper. A preliminary report of the work has been published(1).

It was intended that the new vessel would be suitable for the ballistic assessment of a wide range of solid and liquid propellants. In accordance with a general user requirement, it is of monobloc steel construction with a single head to provide access for ignition devices and instrumentation. The vessel has a single cylindrical cavity with a length/diameter ratio of approximately 1:1 and internal volume of some 250 cm^3. An inner cell or combustion chamber of internal volume approximately 100 cm^3 and length/diameter ratio of approximately 1:1 could then be inserted into the main body of the vessel. This facilitates alteration of combustion chamber shape. The vessel was designed to have a maximum pressure capability of 500 MPa and has provision for initiating combustion at a closely controlled temperature, over a temperature range likely to be experienced in the field. Consideration was given at the design stage to the possible later use of the vessel as a vented device for gas erosion studies. Provision was also made for the fitting of optical windows.

In most closed vessels, the propellant charge weight and the vessel weight are proportional. This parallels the situation in gun systems where the charge weight increases with the size of the gun. In the current UK standard closed vessel[2], CV21, a compromise is reached whereby the charge is large enough to reduce sampling errors without making the overall system too heavy. Design constraints therefore lead to a cylindrical chamber with a length twice that of the diameter. However, a long narrow chamber encourages the build up of pressure pulses and excessive cooling. It follows that, since the charge density is approximately 25 times greater than the resultant gas density, the fluctuations in burning rate (due to heat loss) will cause a fluctuation in the gas pressure which is about 25 times greater in magnitude. In order to minimise heat loss a spherical chamber is preferred for the following reasons:

a. The internal surface area is minimised.

b. A continuous thermally insulating boundary layer is formed.

c. The possible build-up of shockwaves between parallel surfaces is eliminated (no reinforcement). Hence chamber resonant frequencies are less likely to be encountered or will, at least, be of lower amplitude.

It is the penetration of the boundary layer by shock waves that is thought to cause excessive cooling. This leads to a reduction in pressure, which in turn causes a drop in the propellant burning rate. Such a retardation of burning rate near to the grain surface causes a momentary reduction in the rate of mass flow and leads to pressure pulses which exacerbate the situation. By incorporating into the closed vessel design a combustion chamber of profiled internal geometry, heat losses should be reduced and pressure pulses minimised.

VESSEL DESIGN CONCEPT

Several design schemes were produced and evaluated with the aim of selecting those features having the development potential worthy of inclusion in the prototype design. A ring of bolts, female threaded clamping nut and a deep, screwed bezel closure were all considered as means of clamping the closure head. These were rejected in favour of an integral male threaded cap (head) as shown in Figure 1. The final scheme was considered to offer the following benefits:

a. Inherently strong.

b. Reliable sealing, using a standard proprietary seal.

c. Excellent access to the top of the cap.

d. Mechanical ejection of the liner, using a proprietary self-contained hydraulic ram.

e. Possibility of replacing the ejection plug by a plug containing an additional instrumentation orifice or a hollow plug which would permit operation as a vented vessel.

f. Flexibility for alternative instrumentation configuration within the cap.

The more important areas to be subjected to detailed study for the final design were:

a. Determination of stress distribution in the body in relation to fatigue strength of available materials.

b. Design of screw thread for cap and extractor plug retention.

c. Choice of sealing elements for cap and extractor plug.

d. Method of assembly and removal of cap.

The complete vessel is mounted in a cylindrical heating/cooling jacket, through which fluid at a controlled temperature can be circulated in order to achieve a desired vessel temperature prior to firing. This enables the effect of temperature on combustion kinetics to be studied. The vessel/jacket assembly is mounted in trunions, enabling it to be tilted about a horizontal axis and locked at any angle –

principally to assist charging, assembly, dismantling and cleaning. This feature may also be useful in investigating the effect of attitude on combustion. The trunions are hollow and serve as feed and efflux ports for the temperature control fluid, so that connecting pipework does not need to be disturbed when the vessel is tilted.

STRESS/STRENGTH ANALYSIS

Conventional stress analysis techniques were used to evolve a design in which the general stress levels in the vessel were acceptable in relation to the fatigue strength of available materials. However, since the vessel is designed to operate at very high pressures, and is of complex geometrical shape, such analyses do not give an accurate indication of maximum stress at critical points. A more detailed analysis was therefore carried out using the finite element technique. The model used comprised the assembly of the body, cap and extractor plug, considered as axi-symmetrical components, with the threaded interfaces treated as elastic connections.

Calculation of the Von Mises equivalent stress throughout the vessel wall confirmed that the stress distributions in the main body, cap and plug were satisfactory, with only localised areas of plasticity resulting from geometric stress raisers. This is commensurate with the stress patterns typically found in gun breeches and is considered acceptable. The results of the finite element analysis also suggested that the stresses in the threaded interface were likely to be high and indicated that further detailed analysis should be carried out in this area.

DESIGN OF SCREW THREADS

Detailed calculations showed that the threaded interfaces between the body/head and body/extractor plug required further optimisation to ensure adequate safety margins. The following modifications were made:

a. Threaded form truncated to reduce bending loads and root radius of female thread increased to alleviate geometrical stress concentration.

b. Thread pitch increased to improve strength and reduce tolerance sensitivity whilst maintaining adequate friction to ensure self-locking.

c. Length of thread engagement increased.

d. Axial clearance reduced to ensure adequate axial load sharing, yet avoiding interference due to plastic load redistribution.

This resulted in a satisfactory design margin for both threads. It was assumed for calculation purposes that the vessel will have a life of 1000 firings at maximum pressure. It was statically proof-tested before firing to a pressure of 1.2 times the maximum service pressure (ie 600 MPa). This is in line with the over-pressures used for proofing guns.

SEALING ELEMENT

There is little definitive experience of sealing elements working at the specified design pressure of 500 MPa. The choice of seal was made on the basis of a number of factors, including unit cost, re-usability, reliability, availability, size and geometry. Three types of seal were selected for detailed consideration, following an exhaustive investigation of both proprietary and purpose-designed seals. These were a tubular metal 'O' ring, a spring energised elastomer and a metal chevron section. The final decision to employ metal 'O' ring seals was based principally on the greater experience and proven reliability of this type of seal when working at the pressure specified for the closed vessel. It also has the advantage of being smaller in cross-section than the other contenders. This reduces the load on the cap and extractor plug threads, thereby increasing the safety margin. It also means that a seal cavity machined to suit an 'O' ring seal could later be enlarged to permit evaluation of alternative seals, if required. At very high pressure, some plastic deformation is likely to occur, rendering the seal unsuitable for a second firing. However, it is considered that re-use of the 'O' ring may be feasible when firing at lower pressures. The selected seal (Advanced Products (Seals and Gaskets) Ltd, Consett, UK) is a pressure energised, hollow stainless steel 'O' ring, silver plated to increase surface conformability. A diagram showing the position of the seal in the vessel is presented in Figure 2.

ASSEMBLY AND REMOVAL OF CAP

The threaded cap is assembled and removed using a special ring spanner locating over castellations machined onto the periphery of the cap. The tightening torque is not particularly critical, but must be sufficient to bottom the cap on its seating in the vessel body, thereby automatically achieving the prescribed compression of the metal 'O'ring seal. Final tightening to achieve this condition is by means of the same small proprietory hydraulic ram used for extraction of the combustion chamber. The ram is easily operated by hand pressure and, via an attachment to the cap ring spanner, provides the design tightening torque. By inverting the spanner, the cap is easily unseated after a firing, enabling the cap then to be unscrewed by hand.

PROVISION FOR INSTRUMENTATION

The vessel can be provided with a total of six access ports; five are for instrumentation and control and are located in the head. A large, adaptable service port is located at the base of the body. The five instrumentation and control ports are in two groups. The two fluid control ports are designed for direct connection to valves which control venting and purging of the combustion space. The three instrumentation ports are positioned across the diameter of the head. All port axes converge at the centre of the combustion space. The large service port at the base of the body is designed to accept a proprietary hydraulic ram to enable liner removal. The plug for this port could also be adapted for other instrumentation, if required, or substituted with a hollow plug for vented-vessel work. The three instrumentation ports can be fitted with a pressure transducer, an electrical lead through or an optical emission/absorption window. All three ports are identical and compatible with the Kistler type 6215 piezo-electric pressure transducer. The fitting and sealing detail of this instrument form the basis for mounting all other instrumentation by means of a modification to a dummy transducer body. An electrode design was identified and developed for use as an electrical lead through.

PRESSURE TRANSDUCERS

After reviewing suitable ballistic pressure transducers, a Kistler type 6215 front sealing transducer was chosen. This transducer will survive under extreme conditions of temperature and mechanical load without losing sensitivity through Dauphiné twinning and shockloading. By incorporating a thermal protective shield onto the end of a transducer, spurious signals due to flame impingement are avoided. The small measuring duct in the cap of the vessel, required for a front sealing transducer, enables a grease cushion to be inserted, if necessary. Front sealing transducers are much less susceptible to fouling than the shoulder sealing type and have the best anti-strain capability; consequently the 6215 transducer is unaffected by differing tightening torques and installation conditions. The 6215 transducer has good linearity and was calibrated before use by the manufacturer at both the upper and lower ends of its range of 0-500 MPa, with a calibrated partial range of 0-50 MPa. As a result, it is very good at determining both low and high pressures with equal precision. The functional fit to the calibration is linear.

ELECTRICAL LEADTHROUGH/OPTICAL WINDOW

A number of concepts were examined, including high/low tension electrical lead through devices and optical window laser ignition. All designs would be required to survive flame temperatures up to 3000 K and function at pressures in excess of 500 MPa. Tompkins[3] has described a design based on a shoulder sealing Kistler transducer blank/dummy. Therefore, in order to maintain uniformity, the electrical lead through was based upon the face sealing Kistler type 6215 transducer (see Figure 3). The conducting centre electrode (a modified taper pin) could be insulated by, for example, PTFE tape, engineering adhesive or shrink fit (film) tube.

PYROTECHNIC INITIATORS

Black powder puffer bags fitted with a nichrome hot wire initiator have traditionally been used in the UK for igniting the propellant charge inside the CV21 closed vessel. Experience has shown that this method of initiation is unsuitable for igniting liquid monopropellants. It was decided that the squib/igniter for the new closed vessel had to be made from a well-defined combustible material, manufactured to a close tolerance. Each igniter would then behave in a known and reproducible manner. Suitable materials of construction could include paper, celluloid or gelatin of known calorific values. A two part gelatin capsule, as used in the pharmaceutical industry, was chosen. Capsule size 00 (vol. 0.95 cm^3) was found to be the most suitable. Two holes to take the fusehead wires were drilled in the base of the smaller half capsule. The igniter consisted of a Vulcan or Type E fuzehead (Orica Europe Ltd, Wigan, UK) and the capsule was filled with 0.75-0.80 g of G12 black powder (packing density 1.01 gcm^{-3}). The complete assembly is shown in Figure 4.

This design was found to be very successful in igniting solid propellants. A different filling was used for igniting liquid propellants, consisting 0.5 g of G12 black powder and 0.25 g of pelleted SR252 (a pyrotechnic igniter composition based on black powder [SMP], silicon and potassium nitrate). On firing this igniter down onto the liquid propellant the G12 caused its atomisation into very small droplets, raising the internal pressure. The burning, hot, sparky pyrotechnic igniter granules then successfully ignited the liquid propellant mist.

ULTRA HIGH PRESSURE VALVES

A number of valve manufacturers of both foreign and UK origin were identified. Many of the products examined were either bulky or difficult to automate. However Sno-Trik, part of the Swagelok group of companies of Ohio USA, manufacture high pressure air actuated needle valves which will operate remotely (from the open position) at 30,000 lbf/in^2 (200 MPa) by a compressed air actuator driven by gas supplied at pressures up to 105 lbf/in^2 (and will function up to 150 lbf/in^2). If the valve is kept in a closed position prior to and during ignition of the propellant charge, as is usual with closed vessel operation, then it should withstand pressures well in excess of 300 MPa. This is a consequence of the gas pressure working on the smaller area of the valve seat rather than the much larger diameter of the valve bore. In fact a pressure of 500 MPa has been demonstrated in some of in the firings conducted to date with no damage to the valves.

An additional feature of an air actuated valve system is its ability to act as a pressure relief valve, as any excessive internal pressure will defeat the air actuator. Some damage may occur as a result of flame wash, although the damaged parts may be replaced at low cost. The double-acting air actuated valve

SS-445-FPAR-D was chosen as being the most suitable. The maximum operating temperature of this valve is 230°C but only the needle tip is exposed to a high gas temperature which is anyway very transient. The gas from the closed vessel is cold when it is exhausted through the valve. There is no evidence of damage to the valves as a result of high temperatures from the firings that have been made. It was decided to incorporate a second high pressure valve into the closed vessel design. This was the manual type (SS-445-FPAR) and is manufactured to the same standard as the double-acting high pressure valve already specified. Its purpose is to act as a back-up valve or inert gas purging valve.

SUPPLEMENTARY SEAL FOR FIRING LIQUID PROPELLANTS

During initial liquid propellant trials, a small quantity of unburnt propellant had been found to seep between the liner and the internal face of the closed vessel body. Although this volume was small compared to the total propellant burnt, it was considered that recorded pressure might have been lower than expected and that a potential toxic hazard existed. A number of different seal options for the liner were considered and tried experimentally. Subsequently, a groove to take a rubber 'O' ring was machined into the top face of the liner. Although the rubber 'O' ring will fail at very high pressures, it would remain intact long enough for all liquid propellant to be consumed. There is no definitive indication of the upper pressure limit for this seal. However, it has proved satisfactory in the limited number of liquid propellant firings conducted to date. The dead volume between the external liner face and the internal walls of the closed vessel is very small compared to the full internal volume of the vessel and would, as a matter of course, be determined as part of the total free space inside the closed vessel.

FIRING PROGRAMME

In an initial programme, the prototype closed vessel was fired 23 times, using four different propellants, three solid and one liquid. The pressure/time curves and their derivatives are given in Figures 5 to 8. The signal quality is high, with very little noise compared to the results from similar propellants in a CV21 vessel[4]. Little further signal processing or curve fitting was required, indicating that noisy interferences from shockwaves, propellant burning instabilities and acoustic anomalies may have been reduced by the internal features incorporated into the closed vessel design. Further extensive firings have proved that the vessel is reliable, durable and easy to operate, provided the correct operating procedures are followed.

CONCLUSIONS

The vessel is a versatile research instrument for the internal ballistic measurement of high energy solid and liquid gun propellants. It includes a number of design features which allow for the provision of modern instrumentation and remote operation and venting. It also has a unique internally profiled detachable liner, whose shape can be readily varied. By using different liners, it would be possible to determine how differing internal profiles and materials of construction affected the output signal from the transducer and the pressure/time curves. (The closed vessel can be adapted without further machining to add an optical window or vented vessel adaptor).

ACKNOWLEDGEMENTS

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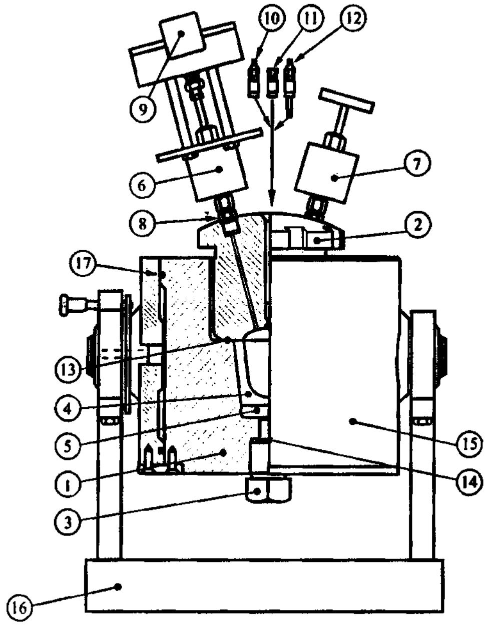


ITEM	DESCRIPTION	QTY
1	Body	1
2	Cap	1
3	Plug	1
4	Liner	1
5	Pad	1
6	Vent valve	1
7	Purge valve	1
8	Adaptor	2
9	Solenoid valve	1
10	Transducer	1
11	Blank transducer	1
12	Leadthrough	1
13	Large seal	1
14	Small seal	1
15	Cooling jacket	1
16	Support frame	1
17	O - seal	2

Figure 1 RMCS Designed Closed Vessel – General Assembly

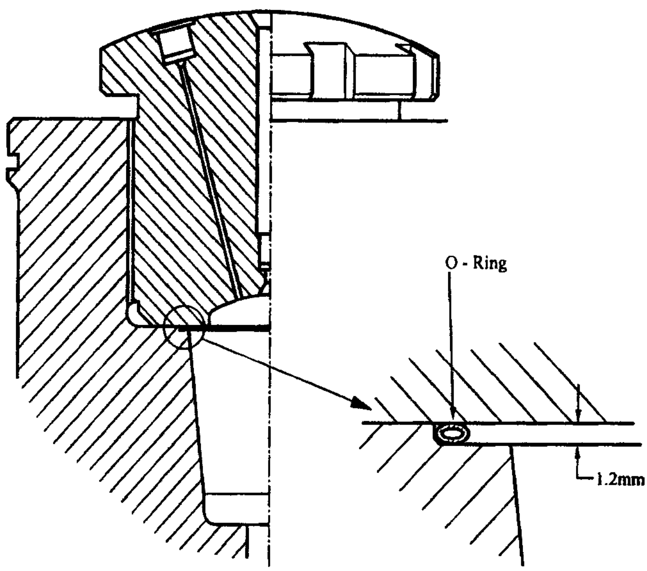


Figure 2 Detail of Hollow Metal O-Ring Seal

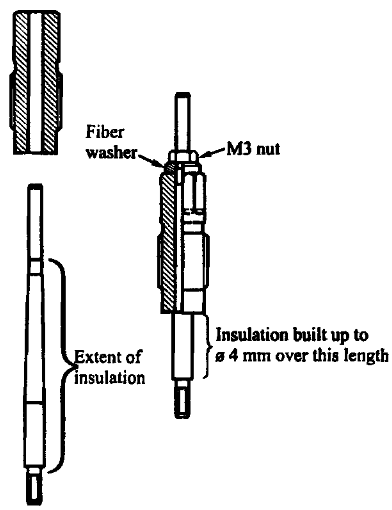


Figure 3 Electrical Lead Through Based on a Kistler Blank Transducer Body and a Modified Taper Pin

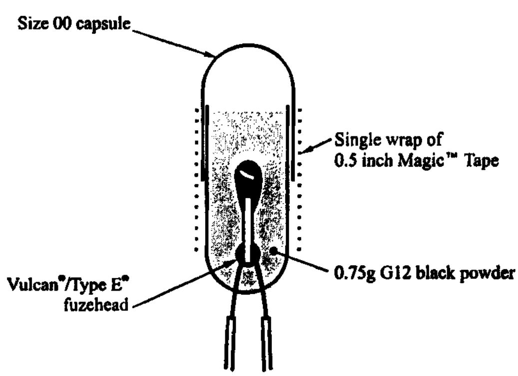


Figure 4 Closed Vessel Igniter Capsule

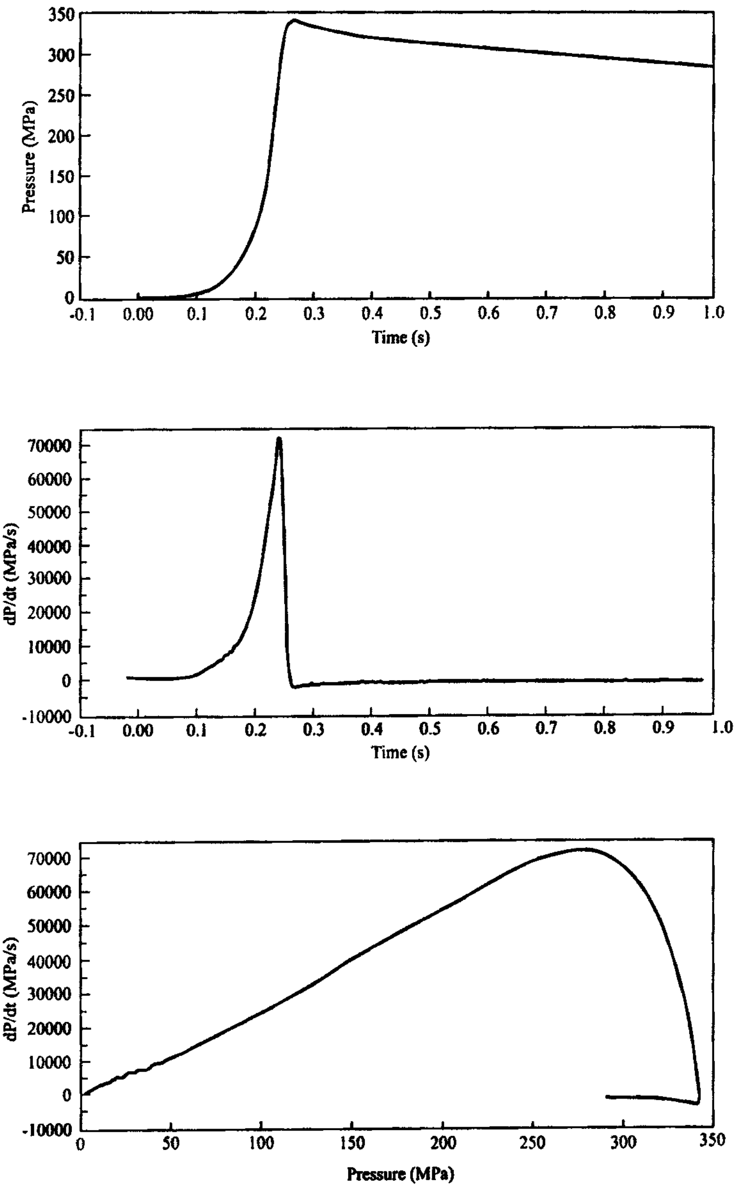


Figure 5 Multi Tubular Triple-Base Propellant 30.0g (0.30 g/cm^3 loading density)

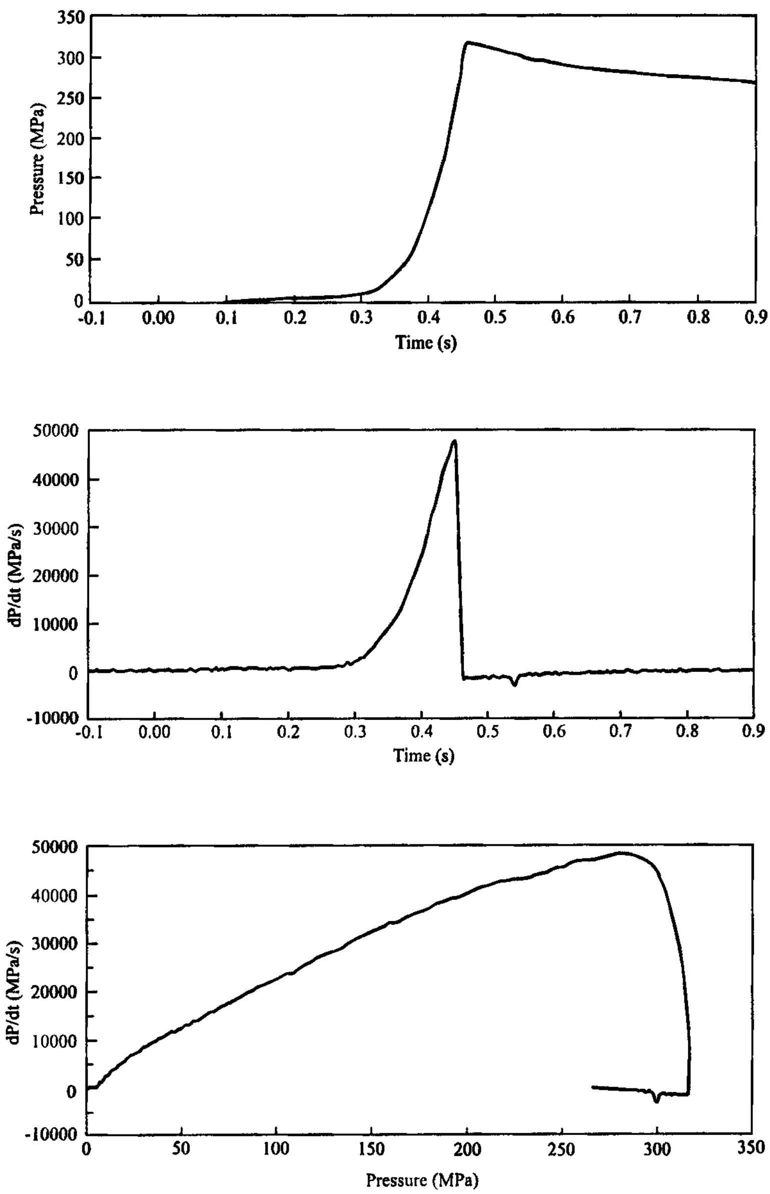


Figure 6 Slotted Tube High Energy Propellant 20.0g (0.20 g/cm^3 loading density)

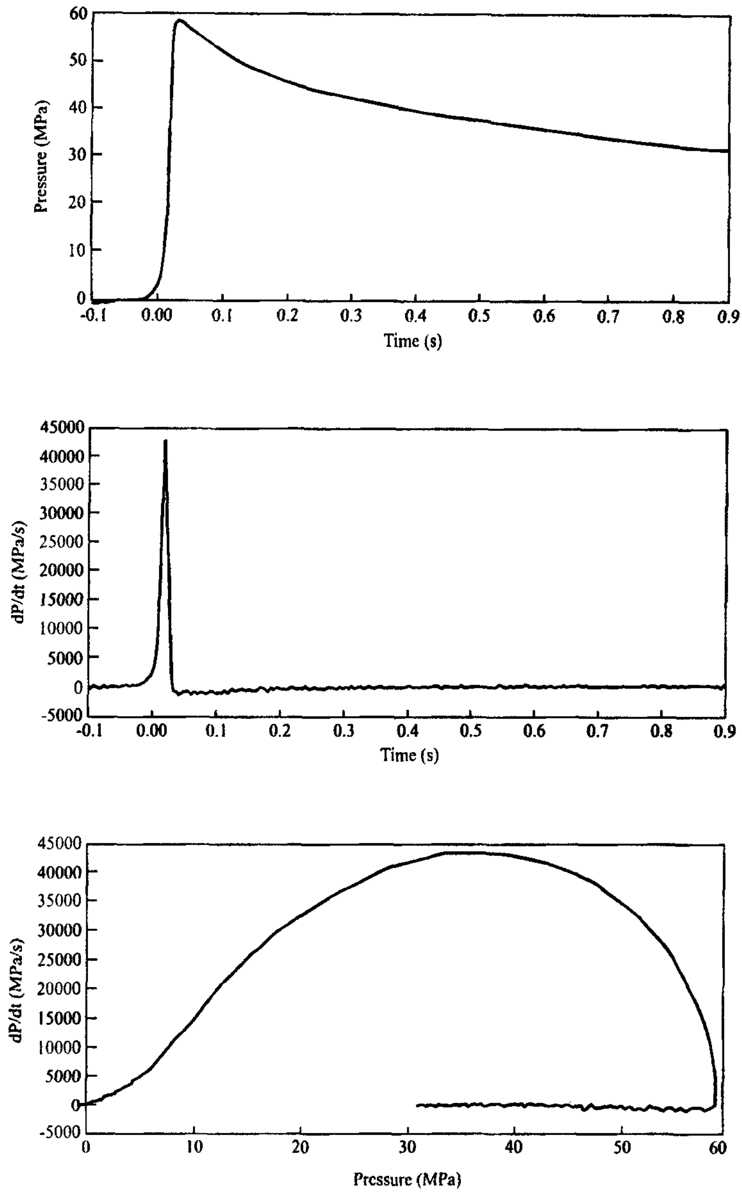
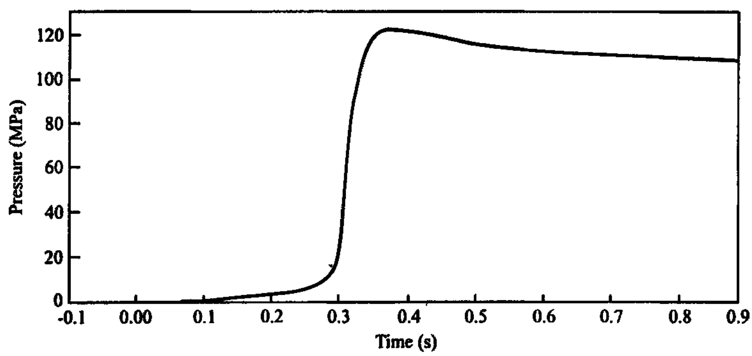
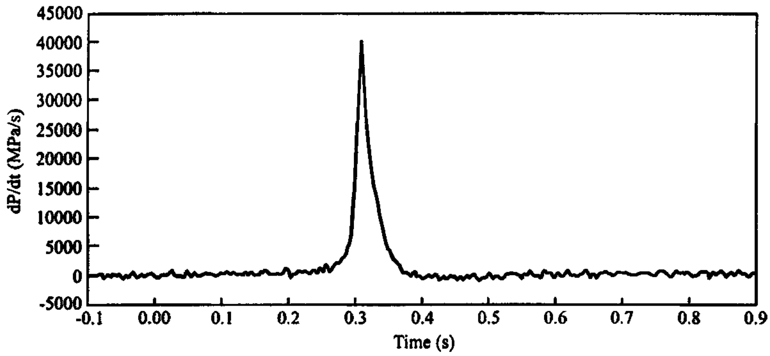


Figure 7 Porous Disc Single-Base Propellant 5.0g (0.5 g/cm^3 loading density)





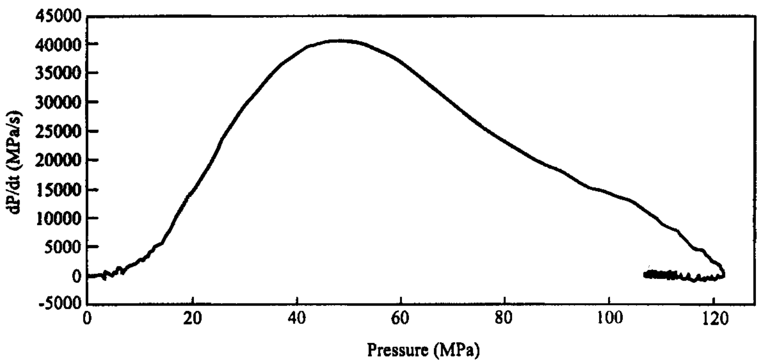


Figure 8 Liquid Monopropellant 12.5g (0.125 g/cm^3 loading density)