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SHORT COMMUNICATION

Application of Ultrasonic Technique for Measurement of Instantaneous Burn Rate of Solid Propellants

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ABSTRACT

The ultrasonic pulse-echo technique has been applied for the measurement of instantaneous burn rate of aluminised composite solid propellants. The tests have been carried out on end-burning 30 mm thick propellant specimens at nearly constant pressure of about 1.9 MPa. Necessary software for post-test data processing and instantaneous burn rate computations have been developed. The burn rates measured by the ultrasonic technique have been compared with those obtained from ballistic evaluation motor tests on propellant from the same mix. An accuracy of about ± 1 per cent in instantaneous burn rate measurements and reproducibility of results have been demonstrated by applying ultrasonic technique.

NOMENCLATURE

C	Acoustic velocity
K	Constant
n	Burn rate index
P	Pressure
Δt	Time lapse
T	Temperature
V	Voltage
X	Thickness
α, β, γ	Constants
ε	Calibration constant

Subscripts

b	Burning surface
i	Interface
p	Pressure
r	Reference
T	Temperature

1. INTRODUCTION

In the conventional methods for the measurement of burn rate of solid propellants (e.g. the strand burner, ballistic evaluation motor, etc.), the burn rate is obtained by monitoring the burn time of an initially known thickness of the propellant. These methods give the average burn rate of the propellant over the web at an average test pressure, but do not give the local burn rates inside the propellant web. Hence, abnormalities in the burn rate within the grain are not brought out quantitatively by these methods. Further, since each test gives burn rate at only one pressure (test average pressure), determination of pressure dependence of burn rate necessitates conduct of several tests, each of them at a different pressure.

These drawbacks of the conventional methods can be overcome if a measurement technique is used, wherein the instantaneous burn rate is determined as the propellant web burns. In this context, visualisation techniques, such as high

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speed photography require experimental motors with windows. X-radiography and gamma radiography may also be considered as extensions of the visualisation technique, but these require cumbersome setups. Moreover, these techniques have limitations in terms of spatial resolution and accuracy. γ absorptiometry also lacks accuracy in view of statistical fluctuations of the source radiation (*Cs:* 137, *Ir:* 192). Also, introduction of radioactive source raises safety and supply problems that restrict its use for routine tests. Use of electromagnetic waves of about 10 GHz (microwave) has been successfully tried in the laboratory[1,2]. However, the complexity of the microwave setup and the required high quality of associated instrumentation severely limit its use in actual motors.

The ultrasonic pulse-echo technique is the potential technique to non-intrusively measure the instantaneous burn rate of propellants[3]. It also has the advantage of simple and portable instrumentation for application on solid motors[4,5]. This technique was used in the study to measure the instantaneous burn rate of aluminised composite solid propellant specimens at nearly constant pressure in a laboratory setup. The objectives of this study were to optimise the measurement procedure and to establish the accuracy and reproducibility of the measurements, which are essential before the technique is adopted for instantaneous burn rate measurements in actual motors.

2. BURN RATE MEASUREMENT SYSTEM

The ultrasonic technique for burn rate measurement is based on the property of ultrasound that an acoustic wave reflects (partly) on encountering an interface where the local acoustic impedance changes. Using this property, ultrasound is employed to determine the instantaneous thickness , x of the propellant using the 'ultrasonic pulse-echo technique', in which the same probe (transducer) acts alternatively as an emitter and a receiver of sound waves. The thickness of the propellant at any instant of time during combustion is determined as:

$$x = C \Delta t / 2 \tag{1}$$

The instantaneous burn rate can be calculated by taking the time-derivative of the propellant thickness. The important elements of the measurement system are discussed here.

2.1 Choice of Transducer

An ultrasonic transducer is characterised by the natural frequency and damping ratio of its ceramic. For burn rate measurement, the damping ratio should be chosen to be as high as possible, so that the return echo does not interfere with the end of the emission pulse. In the present study, a heavily damped broadband ultrasonic transducer (Videoscan from Panametrics, USA) with peak frequency of 2.25 MHz and of diameter 12.5 mm was used.

2.2 Mounting of Transducer

To obtain linear operation down-to-zero propellant thickness, an intermediary coupling material between transducer and propellant is introduced. This also brings into the measurement a slight delay that reduces the transducer damping problems, limits the near-field effects of the transducer, and isolates the transducer from the severe pressure and temperature conditions in the combustion chamber. In the present work, polymethyl methacrylate (PMMA) was used as the coupling material.

2.3 Pulse-Echo Interface Measurement System

The pulse-echo interface measurement (PIM) system, developed by Prins Maurits Lab-TNO, The Netherlands, was used[6] to measure the instantaneous burn rate of the solid propellant. The system has an ultrasonic transmitter and receiver which measures the time lapse between the emitted and the received echoes from the propellant. From the output of the PIM system, which is in the form of voltage corresponding to the time lapse, web thickness of the burning propellant at any instant of time can be calculated by:

$$x = C \varepsilon (V_b - V_i / 2 \tag{2}$$

where

$$C = C_r\,[1+K_P\,(P-P_r)]\,[1+K_T\,(T-T_r)] \qquad (3)$$

and ε is the calibration constant of the PIM system, which is determined using a calibrator simulating the time lapses ranging from 0 to 90 μs. The instantaneous burn rate of the propellant can be obtained by differentiating the instantaneous web thickness (Eqn 2) with respect to time.

3. EXPERIMENTAL DETAILS

The instantaneous burn rates of aluminised composite solid propellant specimens at nearly constant pressure were measured by ultrasonic technique using the experimental setup described here. For this, the acoustic velocity in the propellant was also measured (Eqns 2 and 3) to experimently determine K_p and K_T.

To determine K_p, the acoustic velocity in the propellant specimen (Fig. 1) was measured at an ambient temperature of 30 °C for different pressures. K_p for test propellant was 3.3 x 10^{-3}/MPa. To determine K_T, the propellant specimen cast in PMMA cup was soaked for 4 hr at a constant temperature in an oven. Thermocouples (chromel-alumel) fixed at three different locations on the propellant specimen confirmed homogeneity of temperature in the specimen. The acoustic velocity in the propellant specimen at different temperatures (at atmospheric pressure) was obtained. K_T for the test propellant was -2.76 x 10^{-3}/ °C.

The burn rates of the propellant obtained by the ultrasonic technique were compared with the burn rates from ballistic evaluation motor test for the same batch mix of the propellant.

3.1 Propellant Specimens

The specimens (Fig. 1) were prepared using aluminised composite propellant (AP-HTPB-*Al*) with 18 per cent metal and 86 per cent solid loading). Since PMMA was used as the coupling material, PMMA cups were fabricated and the propellant was cast directly in these cups. The propellant thickness was ~ 35 mm with diameter ~30 mm.

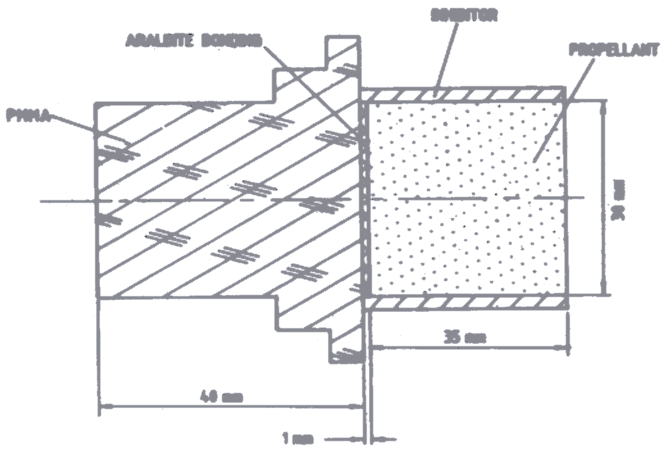

Figure 1. Propellant specimen

3.2 Experimental Setup

The schematic of the experimental set-up is shown in Fig. 2. It consists of a combustion chamber (inner diameter 70 mm, length 170 mm) connected to a N_2 gas reservoir of 100 l^3 to maintain nearly constant pressure during propellant burning. An end-burning propellant specimen (Fig.1) with PMMA as the coupling material, was mounted in the combustion chamber. The ultrasonic transducer was attached to the propellant specimen on the outer face of PMMA. The pressure transducer was connected to the combustion chamber. For propellant ignition, a pyrotechnic charge was fixed on the propellant surface.

3.3 Instantaneous Burn Rate Measurements

Before the test, the PIM system and the pressure transducer were calibrated. The ultrasonic transducer was connected to the PIM system through a cable. The entire experimental setup was pressurised by N_2 gas at a pressure of ~ 1.8 MPa. Ignition of the propellant specimen in the chamber was initiated from remote by a pyrotechnic charge attached to the propellant surface. The output of the PIM system and the pressure transducer were recorded at the rate of 200 data/s for the entire burn time of the propellant specimen (~8s) in a computer.

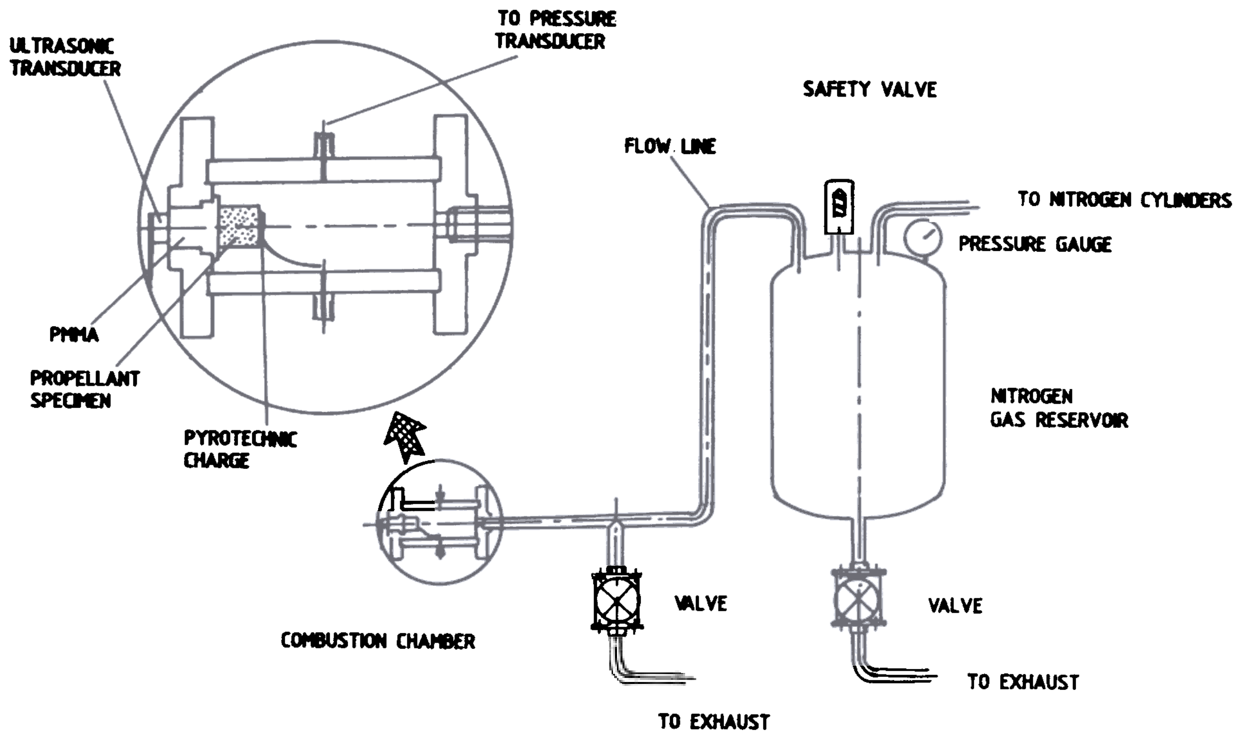

Figure 2. Experimental setup for burn rate measurement by PIM system

4. DATA PROCESSING SOFTWARE

PIM output (voltage) can be converted into time lapse for the ultrasonic pulse by using the calibration constant of the equipment. Since the acoustic velocity of the propellant is predetermined, the data for the measured propellant web thickness *vs* time can be obtained (Eqn 2). However, before evaluating the instantaneous burn rate from the slope of this curve, the data needs filtering and smoothening due to scatter of data points, noise and base line shift, if any. The required software was developed by this team for data processing involving filtering, base line shifting, smoothening, and instantaneous burn rate evaluation. The details of this software are given in the flow chart (Fig. 3). First of all, raw data for web thickness *vs* time was processed to identify various regions of base line shift. To each of these regions, a second-order curve ($x = \alpha t^2 + \beta t + \gamma$) was fitted by keeping α and β same for all the regions. Data points most deviated from the fitted curves were removed one by one and the curves were refitted till all the remaining points got fitted in the curve with a scatter in data points less than an acceptable value. From the fitted equation of web thickness against time, the instantaneous burn rate was evaluated by taking the time derivative.

5. RESULTS

Instantaneous burn rates of end-burning aluminised composite solid propellant specimens of the same batch mix were measured by ultrasonic technique in an experimental setup for the burn time of ~8 s and the corresponding pressure in the chamber was also monitored. In spite of the large volume reservoir connected to the combustion chamber, chamber pressure varied from 1.8-2.0 MPa; the average pressure being 1.9 MPa due to combustion. Hence, to compare the instantaneous burn rate results in the tests, the burn rate values were normalised to a reference pressure of 3.24 MPa, (33 kgf/cm^2). For normalising the burn rates, the value of n for the propellant (n = 0.3334) obtained earlier from several ballistic evaluation motor tests was used.

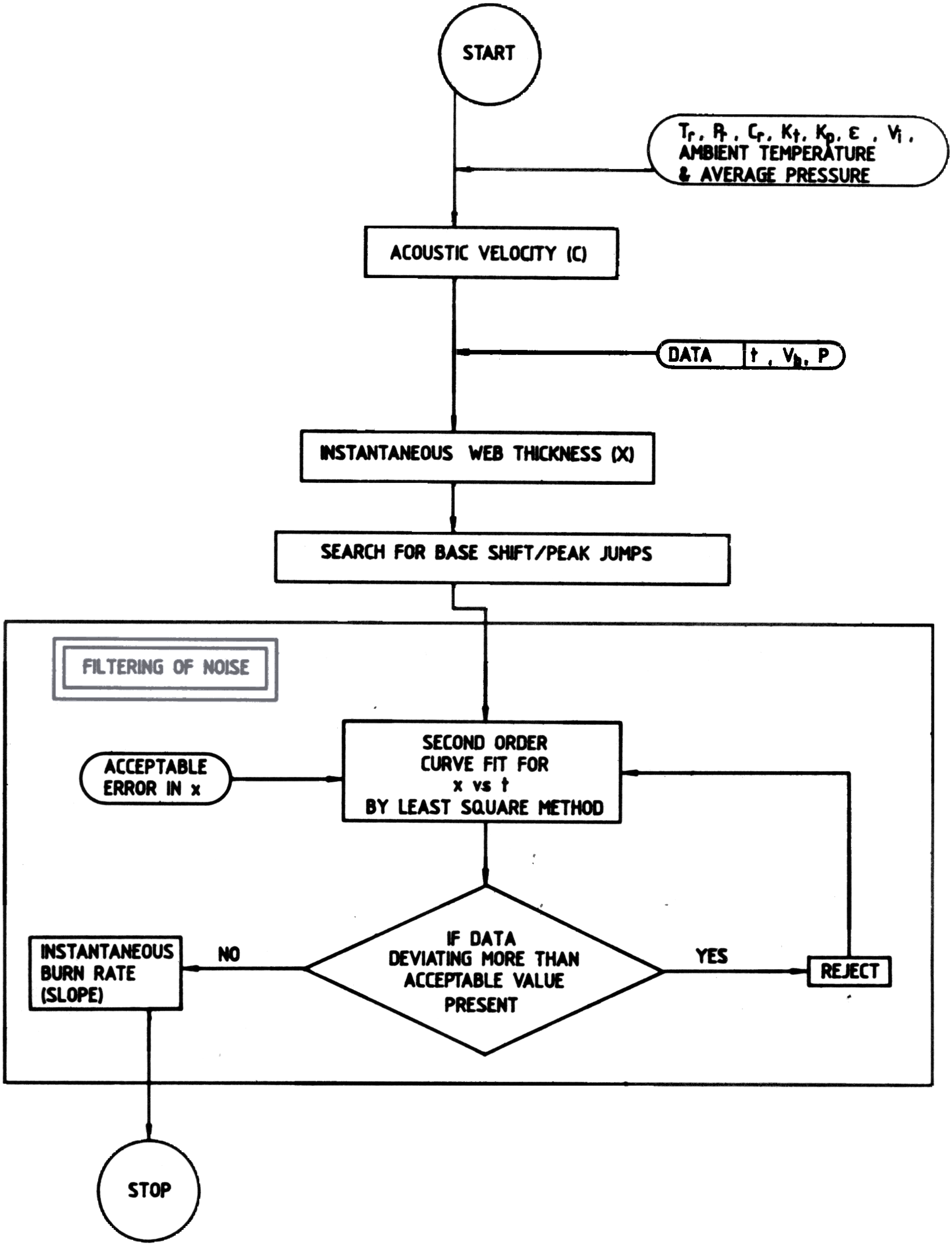

Figure 3. Flow chart of software for burn rate evaluation

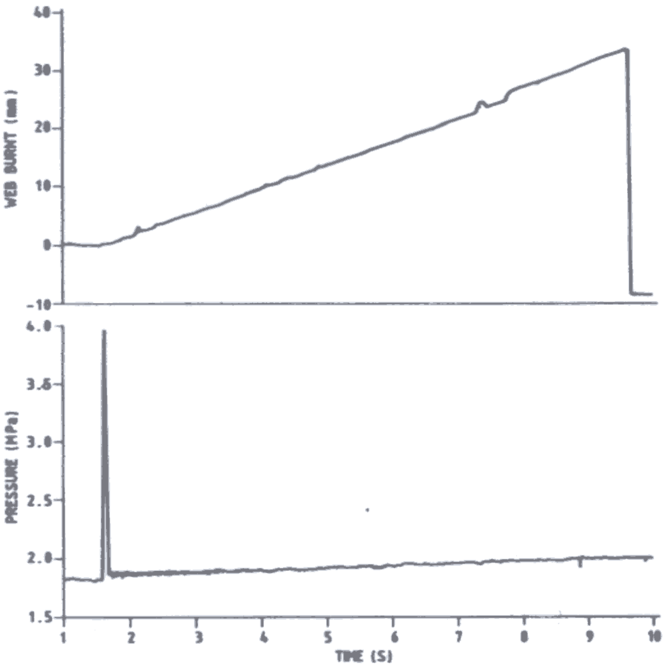

Figure 4. Thicknesss of web burnt measured by the PIM system and the chamber pressure.

The thickness of web burnt *vs* time measured by ultrasonic technique in a typical test (No. US-1) is shown in Fig. 4. The instantaneous burn rates measured in this test and normalised burn rate values are plotted in Fig. 5. Figures 4 and 5 also give pressure variation during the tests. Since the pressure change during the test is quite small, the measured instantaneous burn rates do not show much variation. The burn rates at each instant, normalised to 3.24 MPa , are also shown in Fig. 5. The average of these normalised burn rates in this test is 4.92 mm/s, with maximum variation of ± 0.04 per cent (Table 1). Results from the other tests using ultrasonic technique are given in Table 1 along with the burn rates obtained from ballistic evaluation motor tests with propellant of the same batch mix.

The averages of the normalised burn rates for the propellant in the four tests are 4.92, 4.94 , 4.96, and 4.95 mm/s (Table 1), which are measured with an accuracy of about ± 1 per cent. The average burn rate of the propellant of this batch evaluated using the conventional method in two ballistic evaluation motor tests were 4.96 and 4.97 mm/s. This confirmed the accuracy and reproducibility of

Table 1. Results of burn rate measurements obtained using ultrasonic technique

Propellant*	AP-HTPB-*Al* (18% metal & 86% solid loading)
Propellant web thickness	~35 mm
Burn time	~ 8s
Pressure range in test	1.8-2.0 MPa

Test No.	Average of instantaneous burn rates measured by ultrasonic technique (normalised to 3.24 MPa) (mm/s)	Maximum variation (±) of normalised burn rate in a test (%)
US-1	4.92	0.04
US-2	4.94	0.90
US-3	4.96	1.06
US-4	4.95	0.66

* For this batch mix of propellant, burn rate values obtained by the conventional method using ballistic evaluation motor tests gave the following burn rates:

(i) 4.96 mm/s at 3.24 MPa (motor 1)

(ii) 4.97 mm/s at 3.24 MPa (motor 2)

the instantaneous burn rate results obtained by ultrasonic technique.

6. CONCLUSIONS

Measurements of instantaneous burn rates of the solid propellant using ultrasonic pulse-echo technique at specimen level have given consistent results with an accuracy of about ± 1 per cent. The technique offers simple and portable instrumentation, which is advantageous for its application to measure instantaneous burn rate in ballistic evaluation motor tests. Towards this end, measurement procedures have been optimised and necessary software for post-test data processing and instantaneous burn rate computations have been developed.

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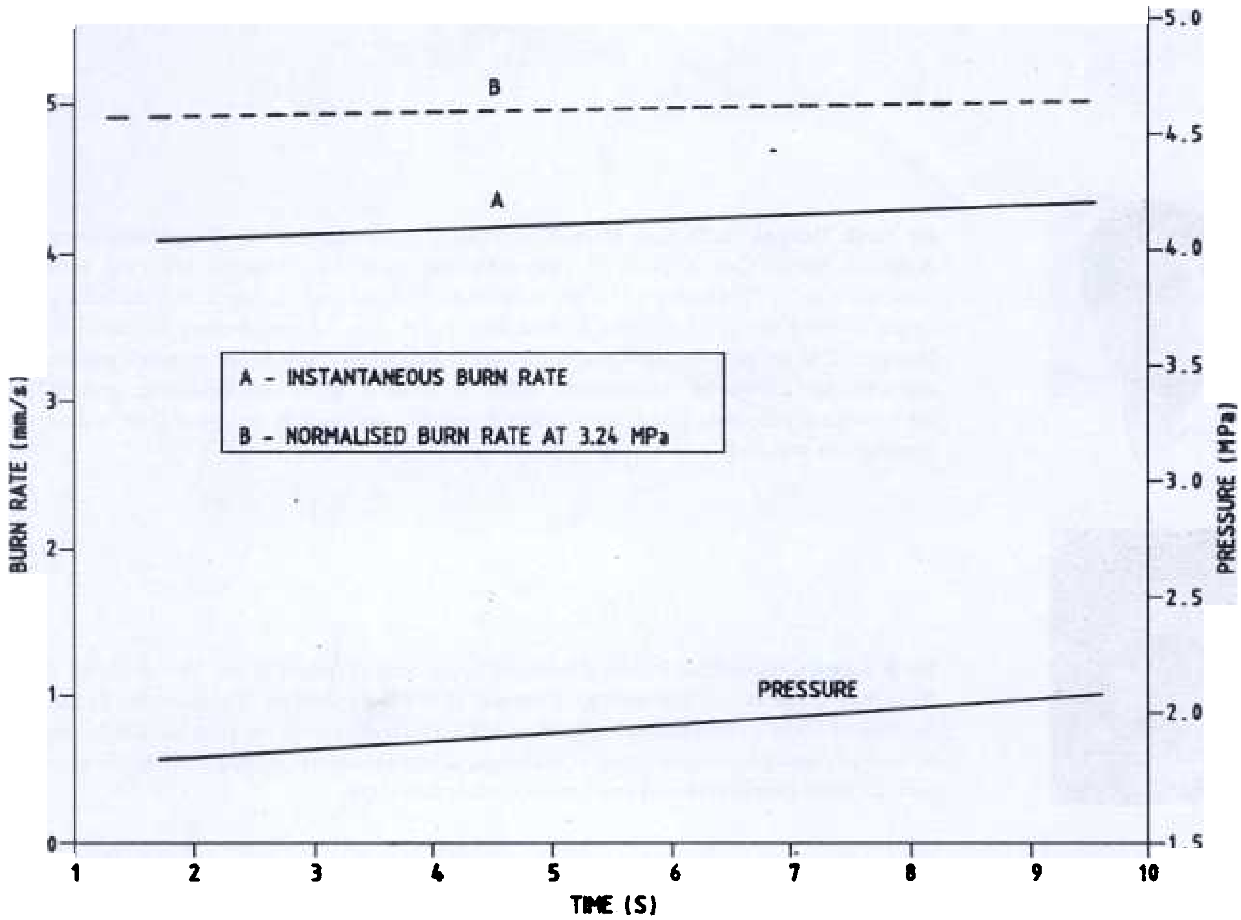

Figure 5. Instantaneous and normalised burn rates of propellant

authorities of the Rocket Propellant Plant for providing propellant specimens for all the tests and to Igniter and Pyrotechnic Division for supplying igniters.

REFERENCES

1. Strand, L.D.; Schultz, A.L. & Reedy, G.K. Microwave doppler shift technique for determining solid propellant transient regression rates. *J. Spacecraft Rockets*, 1974, **11**(2), 75-83.

2. Strand, L.D. & McNamara, R.P. A variable-frequency driver-microwave transient regression rate measurement system. AIAA 14th Aerospace Sciences Meeting, American Institute of Aeronautics and Astronautics, Washington, 1976. Paper No. AIAA-76-105.

3. Kuentzman, P.; Demaris, J.C. & Cauty, F. Ultrasonic measurement of solid propellant burning rate. *La Recherche Aerospatiale*, 1979, **1**, 71-90.

4. Traineau, J.cl. & Kuentzman, P. Some measurements of solid propellant burning rates in nozzleless motors. AIAA/SAE/ASME 20th Joint Propulsion Conference/American Institute of Aeronautics and Astronautics, Cincinnati, Ohio, 1984. Paper No. AIAA-84-1469.

5. Traineau, J.cl. & Kuentzman, P. Ultrasonic measurement of solid propellant burning rates in nozzleless rocket motors. *J. Propul. Power*, 1986, **2**(3), 215-22.

6. Dijkstra, F.; Korting, P. & van den Berg, R. Ultrasonic regression rate measurement in solid fuel ramjets. AIAA/SAE/ASME/ASEE 26th Joint Propulsion Conference, American Institute of Aeronautics and Astronautics, Orlando, Florida 1990. Paper No. AIAA -90-1963.

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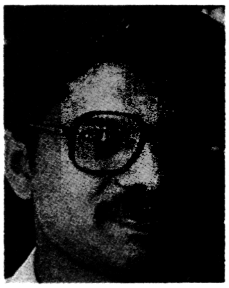

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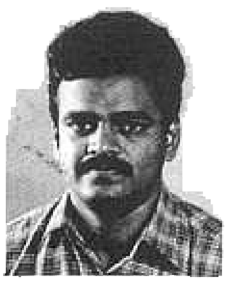

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