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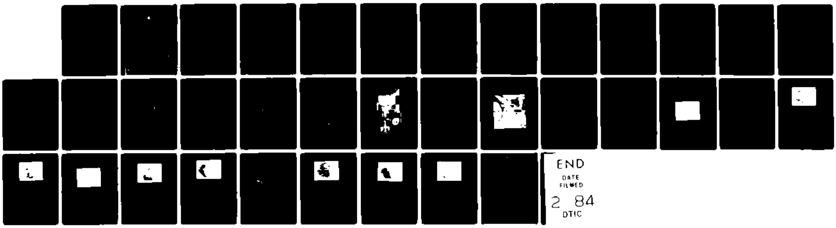

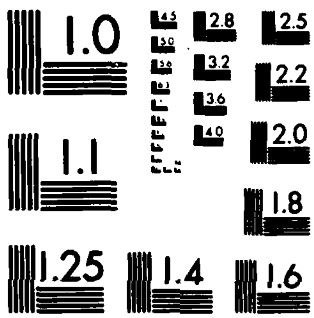
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INVESTIGATION OF PULSED PERFORMANCE OF AN ELECTROTHERMAL HYDRAZINE THRUSTER, USING A SPECIAL SEE-THROUGH THRUSTER

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SUMMARY

A special see-through thruster was developed to investigate the pulsed performance of a prototype 0.2N electrothermal hydrazine thruster (EHT), designed for spacecraft attitude control applications. Results from tests were recorded by high-speed cine photography, synchronised with analogue data records. These showed that the poor response of a prototype EHT was related mainly to the injection and vaporization characteristics of the propellant in the thrust chamber. Various phenomena are described and an indication is given of the interaction between these events during repeated pulsed operation. Conclusions are reached regarding design changes necessary to improve performance.

Departmental Reference: Space 625

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1 INTRODUCTION

Hydrazine thrusters are used in many spacecraft propulsion systems to provide small impulses for attitude control. During the development of an electrothermal hydrazine thruster (EHT) some problems were experienced with its pulsed performance[1]. On investigation, comparable performance anomalies were recorded during pulsed operation of a similar 0.2N RAE prototype EHT (Fig 1). A projection of the plenum pressure profiles from twenty consecutive thrust pulses is shown in Fig 2, recorded during an experimental test of the prototype EHT. The performance was typified by poor transient response and the occurrence of apparently random plenum pressure spikes, especially during the first few seconds of operation.

An indication of possible propellant injection and vaporization phenomena was gained from a preliminary study[2] using water in a simulation of the prototype EHT. This was confined to the first pulse transient behaviour, and provided visible evidence of the Leidenfrost phenomenon[3] as a cause of inhibition of vaporization. Confirmation was required that these film boiling effects occurred with hydrazine. Since water was used, the study could not show any effects of exothermic decomposition of the propellant, which were expected to vary with pulsed operation, and since the simulation of the model was open-sided, the build-up of plenum pressure was precluded. To study fully the pulsed operation of the prototype EHT it was necessary to develop a special 'see-through' thruster. This would enable high speed cine photography to be used to record the internal events for subsequent correlation with simultaneously recorded analogue data.

This Report describes the design, experimental testing and the results obtained with the special thruster. Conclusions are drawn regarding possible design changes to overcome the performance anomalies of the prototype thruster.

2 THRUSTER DESIGN

A special see-through thruster was designed in which the physical phenomena could be observed and recorded. The choice of a 'sandwich' type construction combined with a plane walled interior as shown in Fig 3 allowed observation of the entire head and tail spaces of the decomposition chamber. To provide adequate lighting for high-speed cine photography, back illumination was to be employed. Two windows were therefore required and for minimum distortion of the image and uniform illumination, these were optically flat quartz (fused silica) plates.

To reproduce the behaviour of the prototype the following parameters had to be kept as close as possible to those of the prototype EHT:

(i) the thruster internal cross-section in the plane of view,

(ii) the injector dimensions,

(iii) the nozzle throat diameter,

(iv) the volume of the head space,

(v) the volume and packing density of the gauze pack,

(vi) the volume of the tail space,

(vii) the thermal mass of the thruster body,

(viii) the thermal mass of the injector/body joint and the thermal conduction path from thruster body to injector,

(ix) the thermal conduction between head-end and flow control valve mounting.

In the region of the injector entry to the thrust chamber, the end of the body was slotted as shown in Fig 4 to make the thermal mass and conduction between body and injector similar to those of the prototype EHT. The internal contour was machined by spark erosion, giving a rectangular cross-section perpendicular to the flow axis.

Initially sealing was to be achieved between the quartz windows and the body by means of annealed nickel shims, the faces of the body being ground flat. Nickel was chosen as a high temperature material which offered chemical resistance to hydrazine and its decomposition products. During development the shims were eliminated and reliance for sealing was placed on accurate mating between the thruster body and the quartz plates. This was achieved by lapping the sealing faces of the body to an optical flatness within 1.5 wavelengths of sodium light, to match that of the quartz windows.

The thruster was mounted, as shown in Fig 5, between point contact screws to minimise thermal conduction losses. The clamps were spring loaded as indicated in the diagram. The use of springs of known rate and preload ensured that overstressing of the quartz, due to differential thermal effects, did not occur. This also gave some protection against pressure spiking in the thruster, since the windows could act as pressure relief seals in the event of large pressure excursions in excess of the preload.

The sheathed heater of the prototype EHT was replaced by two specially manufactured flat heater elements positioned above and below the body of the thruster as shown in Fig 6. Some radiative thermal loss from the windows was inevitable. However, it was minimised as far as practical by positioning of insulation such that viewing was through a 'tunnel' of similar internal contour, and only slightly larger than the windows. This required an accurate alignment of the optics for illumination and filming of the experiment. The insulation used was a commercially available mineral wool.

The thruster body was mounted from the flow control valve on a bipedal tubular structure shown in Figs 3 and 4. This was designed to approximate the thermal conduction path of the prototype thruster support tube. The flow control valve was identical to that employed on the prototype EHT evaluation and was representative of valves qualified for space applications[4]. A cross-section of the valve is included in Fig 1.

3 THRUSTER TESTS

The see-through thruster and flow control valve assembly is shown in Fig 7 and the instrumentation is indicated in Fig 8. A specially developed orifice flowmeter[6] was incorporated to record the transient flow characteristics during pulsed operation. Plenum pressure was recorded using a fast response transducer, thermally isolated from the thruster by means of a small bore tube.

The thruster assembly was installed in a vacuum test facility (Fig 9) with back illumination as shown in Fig 10. The light source and high-speed cine camera were located outside the vacuum chamber. A schlieren photographic technique[7] was employed for the main series of tests to obtain information on the variation of gas density within the thrust chamber.

Prior to testing with hydrazine the thermal balance of the thruster assembly was checked at a holding temperature of 550°C (measured on thermocouple No.1, Fig 8). A check that the quartz windows were not overstressed during heating was made at the same time using polarised light and the photoelastic effect of quartz[5].

Synchronisation of the cine film with the analogue record was achieved by generating event marks on both media, triggered from the flow control valve drive amplifier. Time-base signals of 100 Hz were also recorded on both media.

A preliminary test was carried out to validate the use of the see-through thruster. Details are recorded in Table 1. The results were encouraging and showed typical plenum pressure profiles (Fig 11) similar to those of the prototype EHT (Fig 2). This was considered adequately representative of the prototype device. Comparison of the analogue recordings with the cine film record further supported the use of the thruster as a means of investigating prototype thruster performance.

The main programme of tests is shown in Table 2. The effects of changes in thermal distribution as a result of repetitive pulsed operation were to be observed. For the range of duty cycles to be investigated camera speeds between 100 and 500 frames per second were selected. This enabled complete trains of pulses to be recorded on one uninterrupted film, but still provided adequate time resolution for comparison with the analogue records.

4 TEST RESULTS

The tests resulted in the accumulation of over 1500 m of 16mm cine films with corresponding analogue records, depicting the pulsed operation of the prototype thruster. In the following presentation major physical events or states are identified from the films and examples are related by means of figures to their particular pressure and flow characteristics. The durations of the events are indicated on the figures. It should be borne in mind that although discussed in isolation, during the tests more than one of these events were often seen at any one time. Thruster operation is divided for convenience of treatment into several broad areas, with most of the phenomena largely dependent on temperature. Both the thruster body and the injector/body interface temperatures were found to be particularly significant. The variation of these temperatures was influenced by the pulsed duty cycle of the thruster. Firstly, the energy from the exothermic decomposition reaction caused the thruster body temperature to increase. The rate of increase was dependent on the pulse interval, longer intervals resulting in slower increases of the mean body temperature. Secondly, the local injector/body interface temperature was close to that of the thruster body immediately preceding a pulse train, but was subsequently reduced by the flow of propellant through the injector tube during the pulse. The interface temperature then increased during the pulse interval as a result of heat flow from the thruster body, with longer pulse intervals resulting in a greater increase of the interface temperature.

4.1 Initial transient effects

4.1.1 Propellant vaporization/atomisation in the injector

The effect which was most evident at the start of first pulses is illustrated in Fig 12. A spray consisting of a mixture of vaporized and atomised propellant can be seen emerging into the head space of the thruster. The effect usually decreased in duration with subsequent pulses in a train. Examples for first and second pulses are given for comparison in Fig 13a&b. The flow of propellant through the injector was inhibited during this phase, with a resultant low plenum pressure, even though the initial rate of pressure rise was high.

When the end of the injector tube in contact with the thruster was well above the boiling point of the liquid, propellant flow extracted heat from the tube wall causing complete or partial vaporization of the propellant. When vaporization was incomplete, turbulence caused atomisation of the remaining liquid in the flow stream and the increased surface area resulted in initially high vaporization and decomposition rates. The inhibition of propellant mass flow resulted from the change of phase within the confines of the injector tube. The duration of this 'thermal choking' increased when the supply pressure was reduced.

4.1.2 The change from spray to steady liquid flow

This flow condition, illustrated in Fig 14a, followed the initial vaporization/atomisation phase described above. Fig 14b shows that over the duration of the effect the propellant flow rate increased to the stage where full injector flow was achieved. Vaporization inside the tube ceased, marking the end of thermal choking.

Since the propellant entered the chamber as a liquid stream of relatively low surface area compared with the previous spray phase, vaporization and consequently decomposition of the propellant was not as rapid. During this phase of increasing propellant flow, the pressure in the thrust chamber levelled off or even decayed slightly from the initial peak produced by the sprayed flow, Fig 14b. The chamber pressure did not rise until the vaporization rate of propellant exceeded the rate prevailing during the initial vaporization phase.

4.1.3 Formation of a quenched zone in the gauze matrix

When the incoming liquid stream first became incident on the gauze matrix the liquid was rejected from a small quenched zone at the surface of the gauze, as seen in Fig 15a. The elevated temperature of the gauze caused partial vaporization at the zone of impact and consequent breaking up of the stream. This continued until the liquid stream reduced the temperature at the zone of impact below some critical but indeterminate value. During this phase the vaporization rate of the propellant was low and generally less than the incoming flow rate. The plenum pressure was below the steady state level (Fig 15b), although the inlet flow rate was generally fully established. Also, the pressure record exhibited some small fluctuations due to the sporadic nature of vaporization and decomposition of the propellant droplets. The higher the thruster temperature at the start of a pulse, the longer the state could prevail, and as a train of pulses progressed the effect could become more pronounced.

4.1.4 Accumulation of liquid propellant at a quenched zone

When rejection of the liquid stream ceased, the propellant remained in contact with the gauze surface and gradually accumulated at a quenched zone (Fig 16a), showing the vaporization rate was below the incoming flow rate. As cooling continued the accumulating liquid spread across the surface of the gauze. From Fig 16b it can be seen that during this phase the plenum pressure was below the steady level as a result of the reduced vaporization rate. The pressure rose towards the steady level as the vaporization rate increased due to the increase of surface area of the accumulating liquid.

4.2 Operating modes after the initial transients

During the transient conditions just described some liquid propellant may have accumulated in the thrust chamber. If the vaporization rate of the accumulated propellant became greater than the incoming flow rate, then the chamber pressure rose above its nominal steady state level. This resulted in a reduction of both the incoming flow rate and the rate of accumulation of propellant in the thrust chamber. Operation of the thruster with an accumulated mass of propellant appeared to depend mainly on the temperature of the gauze matrix.

4.2.1 Lower gauze temperatures

At lower mean gauze pack temperatures the accumulating propellant mass at the quenched zone locally cooled the matrix surrounding the zone and was totally absorbed into the gauze pack. Fig 17a shows the propellant stream being absorbed into the quenched zone. It is demonstrated by Fig 17b that the quenched zone expanded within the matrix until the vaporization rate, and hence the decomposition rate, equalled the incoming flow rate, when a steady plenum pressure was achieved.

4.2.2 Intermediate gauze temperatures

The mode of operation shown in Fig 18a occurred at higher mean gauze pack temperatures than the previous case. Expansion of the quenched zone within the matrix had ceased but accumulation of propellant mass continued into the head space until the vaporization and decomposition rates equalled the incoming mass flow rate. However, without the stabilising influence of the surrounding gauze matrix (which led to the smooth steady pressure shown in Fig 17b for the previous case) fluctuations in the vaporization rate led to the fairly rough pressure characteristic shown in Fig 18b, and led in some cases to pressure spikes. In the extreme the head space filled with liquid which decomposed very rapidly as its surface was forced into contact with the thruster walls. This resulted in a large pressure spike which caused the thruster body/quartz seal to vent the pressure in excess of the spring preload.

4.2.3 Higher gauze temperatures

After several previous pulses in a train had raised the mean thruster temperature, a further mode of operation was observed (Fig 19, pulses 7 to 20). The liquid stream incident on the gauze matrix did not form a quenched zone and was rejected as a spray of small droplets into the head space of the thruster, as shown in Fig 20a. This figure bears a superficial resemblance to Fig 15a. However, comparison of the plenum pressure records for the two pulses (Figs 15b and 20b) shows that when this effect was present during the first of the pulses, the chamber pressure was low. As a result of the low vaporization rate, propellant was accumulating in the thruster. The increased vaporization and decomposition rate of the droplets in the second pulse resulted in very little accumulation of liquid, and consequently good response times for both rise and decay of chamber pressure.

4.3 Pressure decay at the end of a pulse

When the inlet flow of propellant ceased following closure of the flow control valve, the decay of plenum pressure was dependent on the amount and location of unvaporized propellant within the thrust chamber.

4.3.1 With very little residual propellant

Following the mode described in section 4.2.3 and illustrated by Fig 20, with little residual propellant and a high vaporization rate the pressure decay was extremely rapid.

4.3.2 Following the accumulation of propellant in the matrix

When the inlet flow had been absorbed into the gauze matrix, as for example in Fig 17a, at the end of the pulse the liquid still present within the matrix slowly vaporized and decomposed to produce the relatively long pressure decay shown in Fig 17b.

4.3.3 Residual propellant in head space, attached to matrix

With an accumulation of liquid in the head space of the thruster on cessation of flow (Fig 21a), vaporization usually continued at a rate similar to that prevailing during the pulse. This resulted in the prolonged maintenance of plenum pressure after valve closure (Fig 21b), followed by a shorter decay than in the previous case. However, the vaporization rate of the accumulated propellant could increase when the cooling effect of the incoming stream ceased. This could result in a pressure spike prior to a more rapid decay of pressure, which was observed on some of the pulses shown in Figs 2, 11 and 19.

4.3.4 Residual propellant film boiling in head space

Fig 22a shows a large propellant droplet in the head space of the thruster. The droplet was formed at the end of the pulse when the accumulated liquid was prevented from contact with the gauze by film boiling. Under these conditions the droplet had a very low vaporization rate. Although the initial pressure decay was rapid, the very low vaporization rate resulted in an extremely prolonged low plenum pressure which was sometimes close to the limit of resolution of measurement. For the particular pulse shown in Fig 22b the droplet was observed for the entire pulse interval of 1 s with little reduction in size.

5 CONCLUSIONS

The see-through thruster was shown to be a valid means of investigating the performance of the prototype EHTs, and the anomalous behaviour was successfully reproduced. A greater understanding of the prototype thruster response to pulsed operation was gained from comparison of the analogue data with the cine film record.

The major causes of the anomalous behaviour were related primarily to the temperature and heat flow in the thruster and the effects varied, to a lesser or greater extent, during pulsed operation as the decomposition reaction raised the thruster temperature. *The causes may be summarized as:*

(a) thermal choking of propellant flow due to vaporization of propellant in the injector,

(b) low vaporization rates caused by propellant film boiling effects, and as a consequence

(c) the accumulation of liquid propellant in the thrust chamber.

With the particular design of the injector/thruster body interface thermal choking was inevitable, especially for first pulses, as the injector temperature would then be close to that of the body. To minimise this effect the injector/body interface would need to be redesigned to reduce the temperature of the injector tube.

The matrix design of the prototype thruster was inadequate to produce rapid vaporization of the propellant over the range of conditions tested. Low vaporization rates led to the accumulation of liquid propellant which film boiled in the thruster. Modifications would be needed to the matrix to increase the heat transfer rates to the liquid and prevent the accumulation of propellant.

Acknowledgments

We would like to express our gratitude to the members of the Photo-instrumentation Services Section of Instrumentation and Trials Department, RAE, who provided and operated the high-speed cine equipment during the experimental tests.

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Table 1

Pulse train No.	Supply pressure (bar)	Initial thruster body temperature (C)	Pulse duration (s)	Pulse interval (s)	Number of pulses
1	18	550	0.5	1.0	1
2	18	550	0.5	5.0	5
3	18	550	1.0	5.0	5
4	18	550	1.0	5.0	20
5	18	550	1.0	1.0	20
6	18	550	1.0	1.0	10
7	24	550	1.0	5.0	20

Table 2

Pulse train No.	Supply pressure (bar)	Initial thruster body temperature (C)	Pulse duration (s)	Pulse interval (s)	Number of pulses
1	12	550	0.5	5.0	20
2	12	550	0.5	3.0	20
3	12	550	0.5	1.0	20
4	24	550	0.5	5.0	20
5	24	550	0.5	3.0	20
6	24	550	0.5	1.0	20
7	24	550	10.0	1.0	4
8	18	550	0.5	5.0	20
9	18	550	10.0	3.0	1
10	18	550	0.5	3.0	20
11	18	550	0.5	1.0	20
12	5	550	0.5	5.0	20
13	5	550	0.5	1.0	20
14	12	550	0.5	3.0	20
15	12	550	10.0	1.0	12

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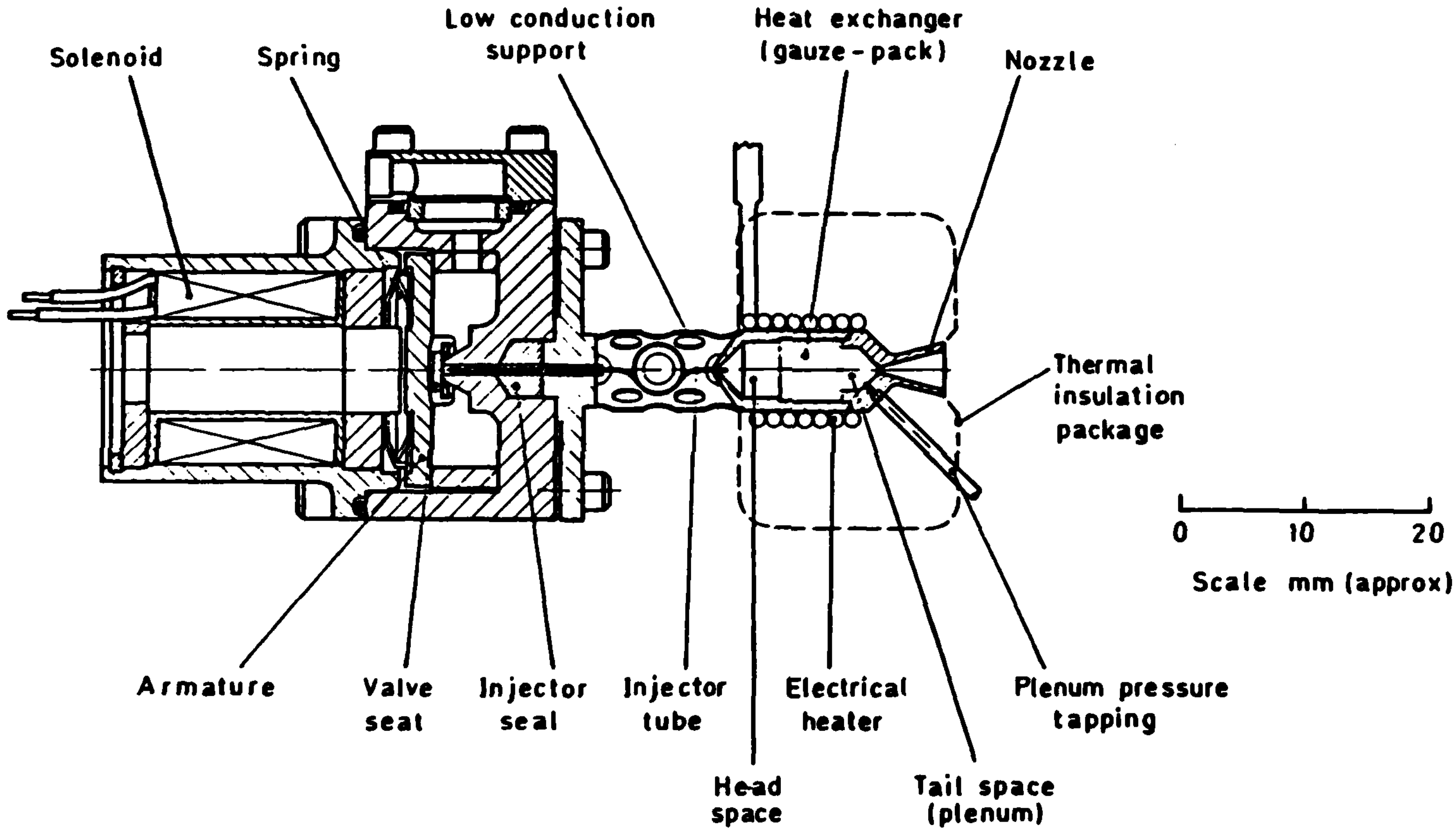


Fig 1 RAE prototype EHT design (EF1) coupled to RAE fast response flow control valve

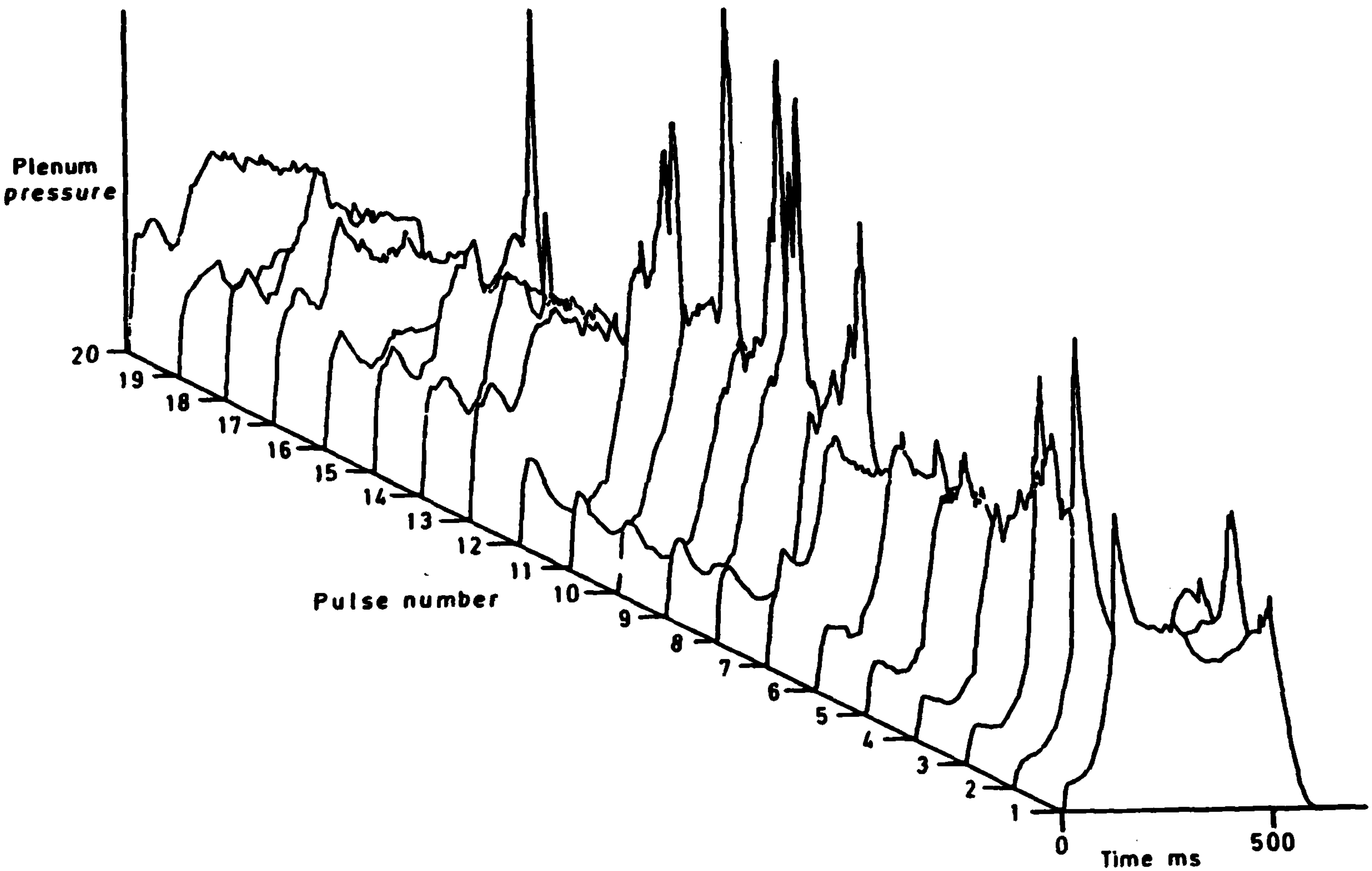


Fig 2 Train of typical prototype thruster pulses

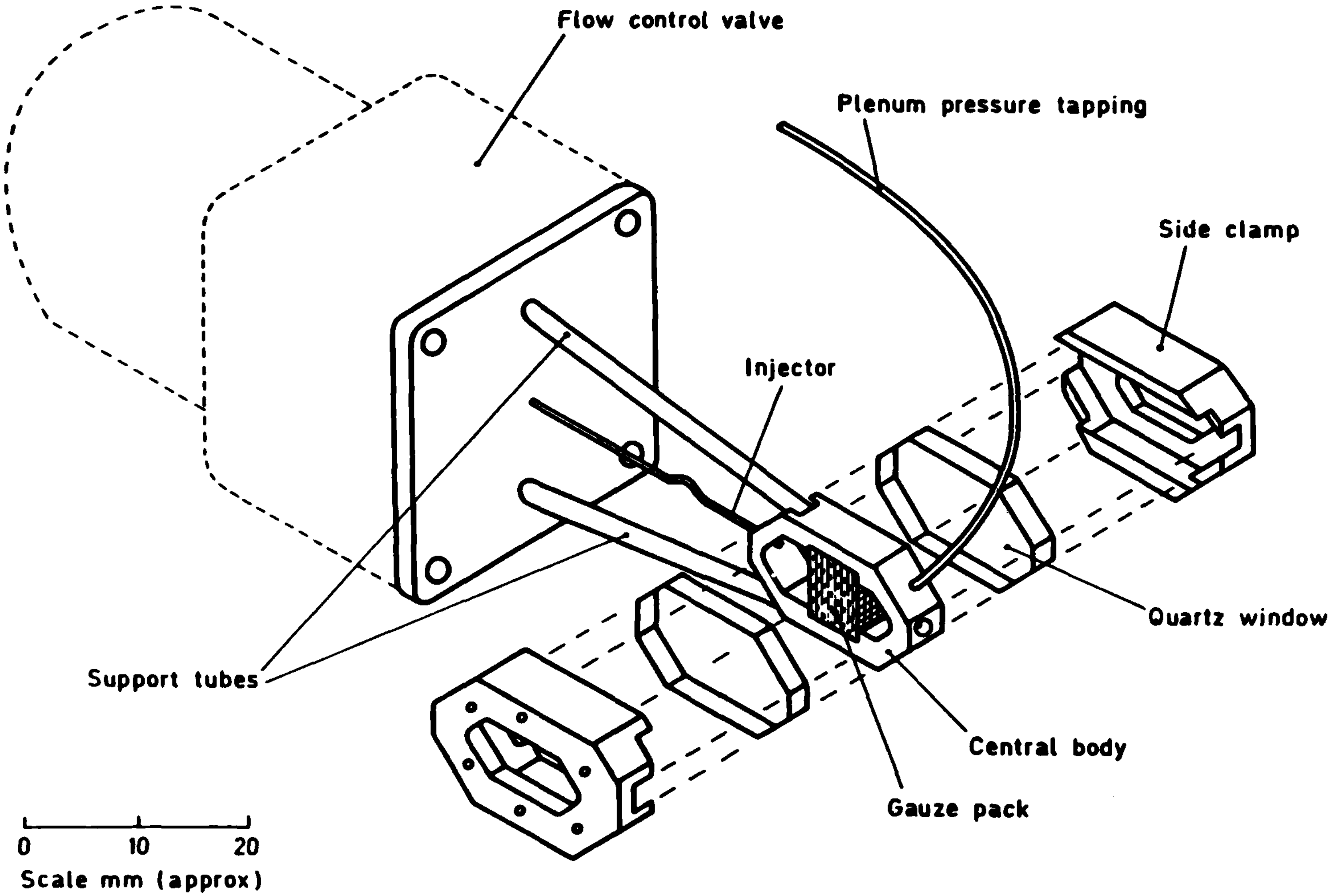


Fig 3 Main components of see-through EHT

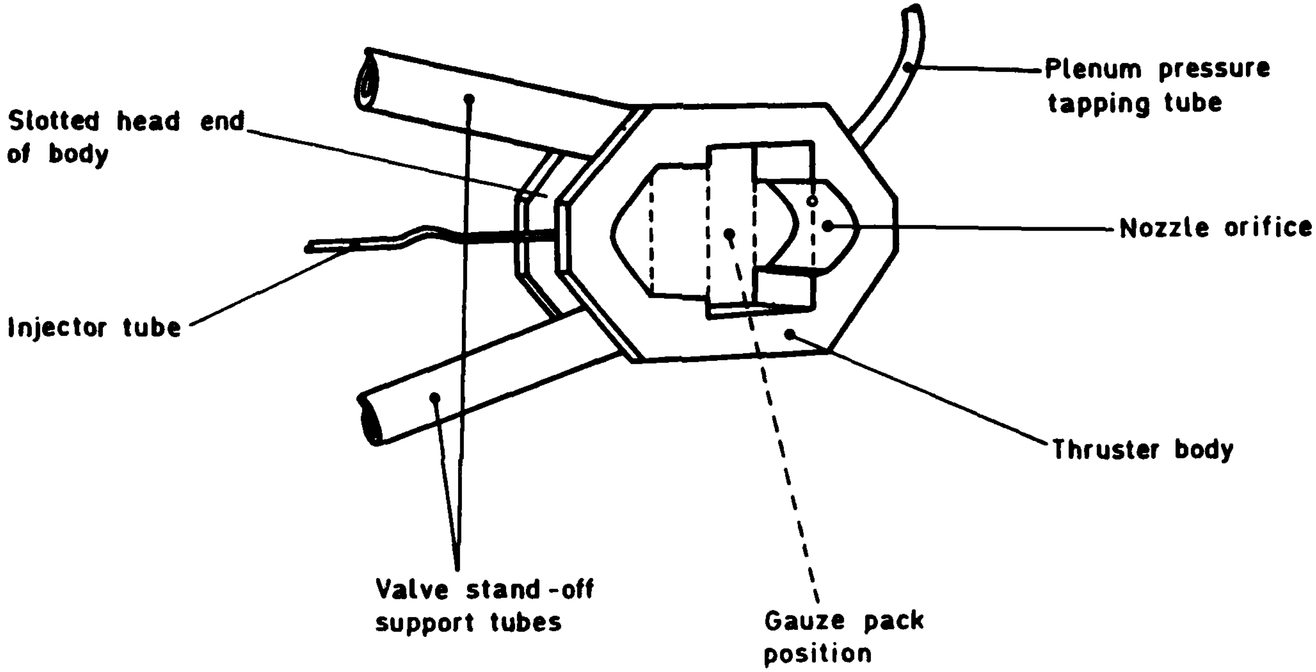


Fig 4 Thruster body detail

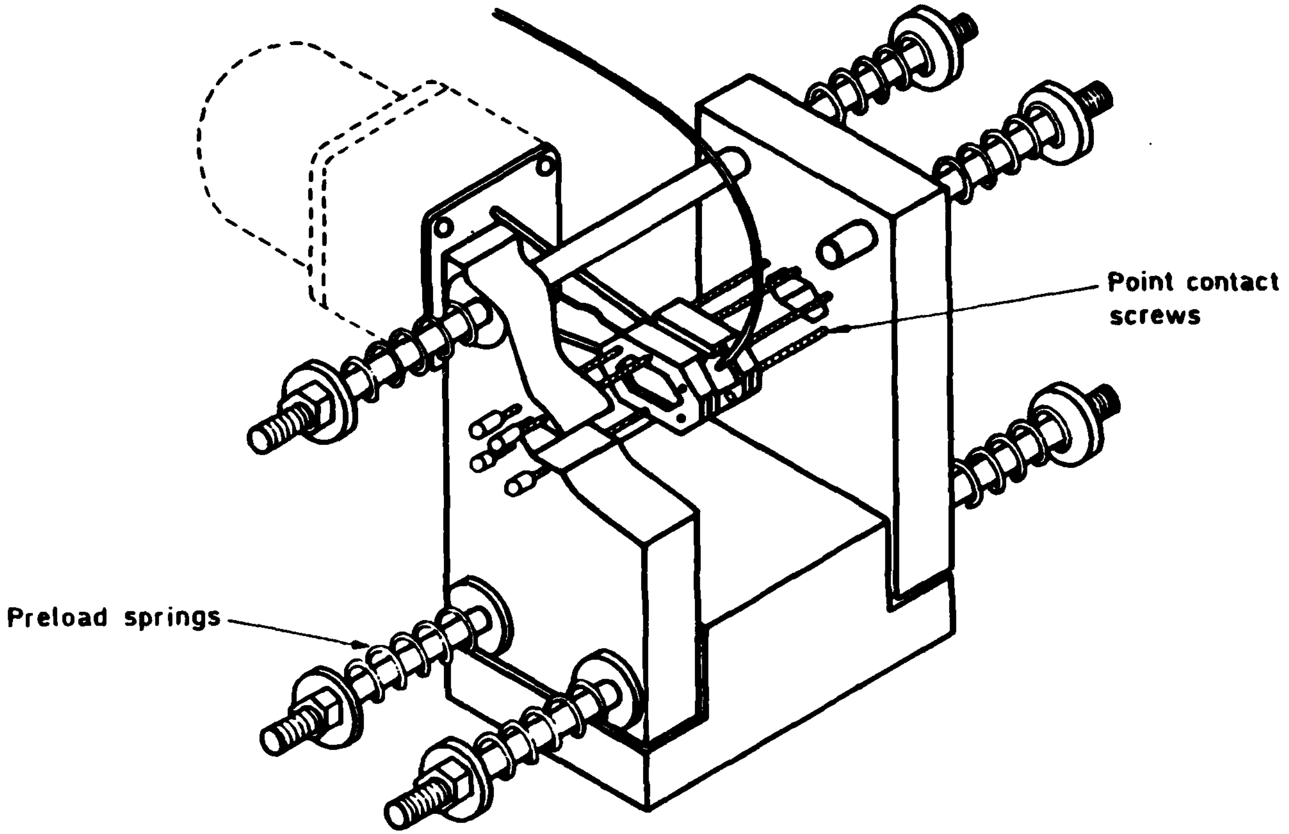


Fig 5 See-through thruster mounting

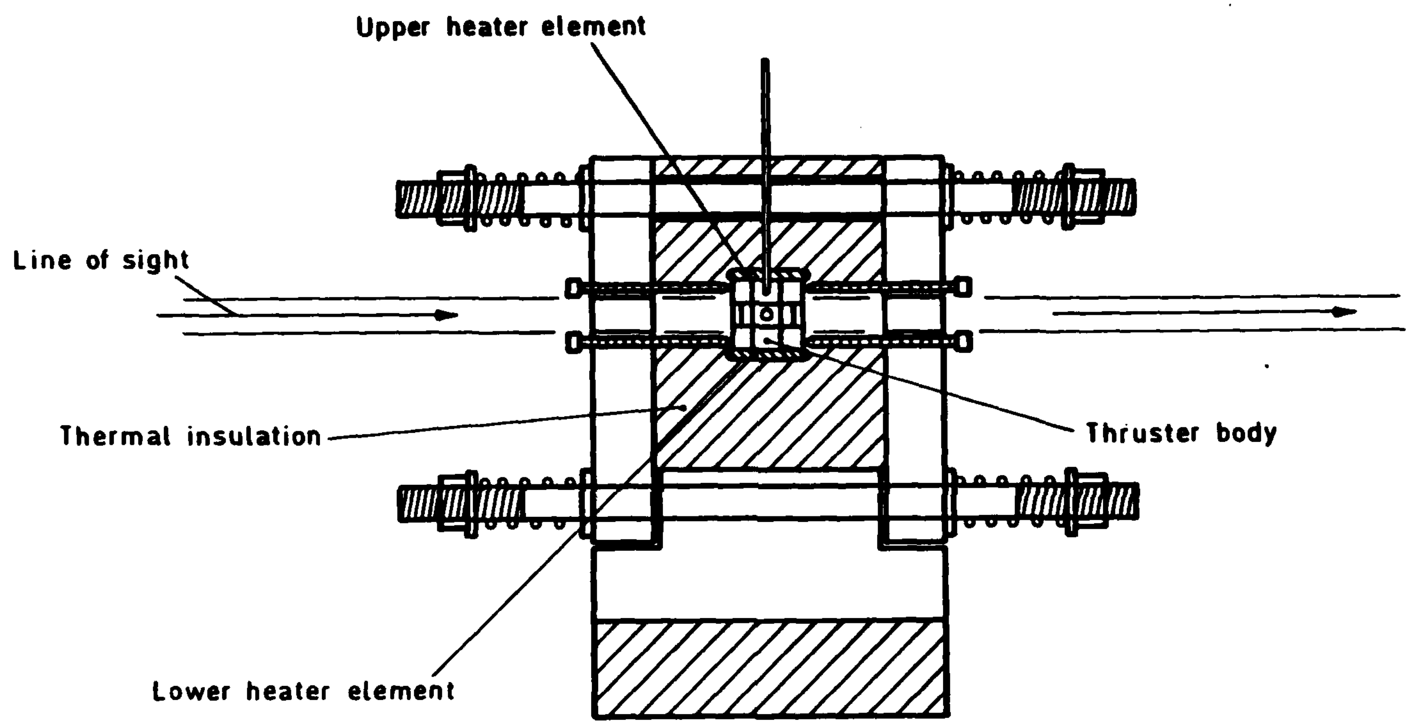


Fig 6 See-through EHT — heaters and insulation

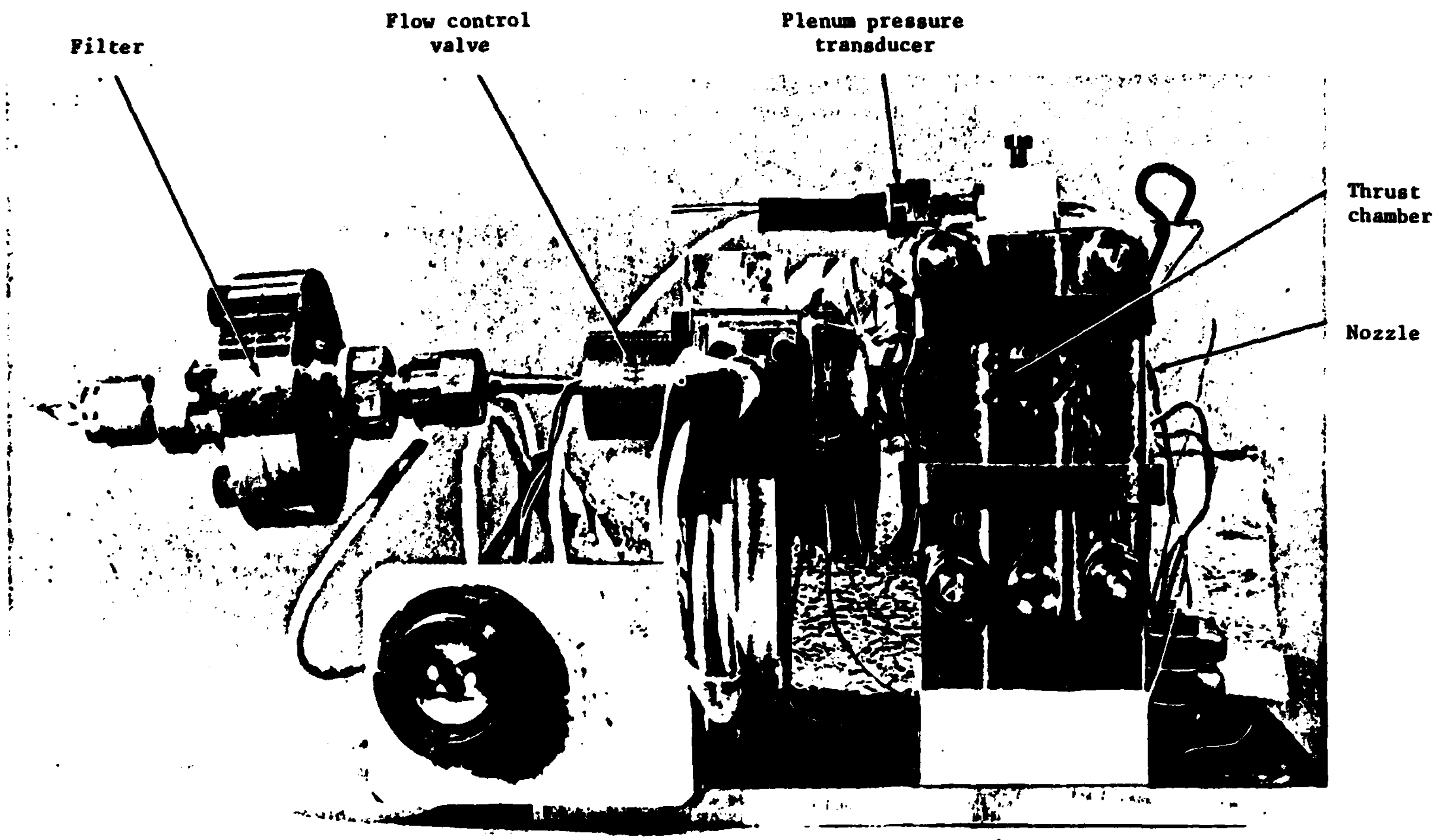


Fig 7 See-through thruster assembled

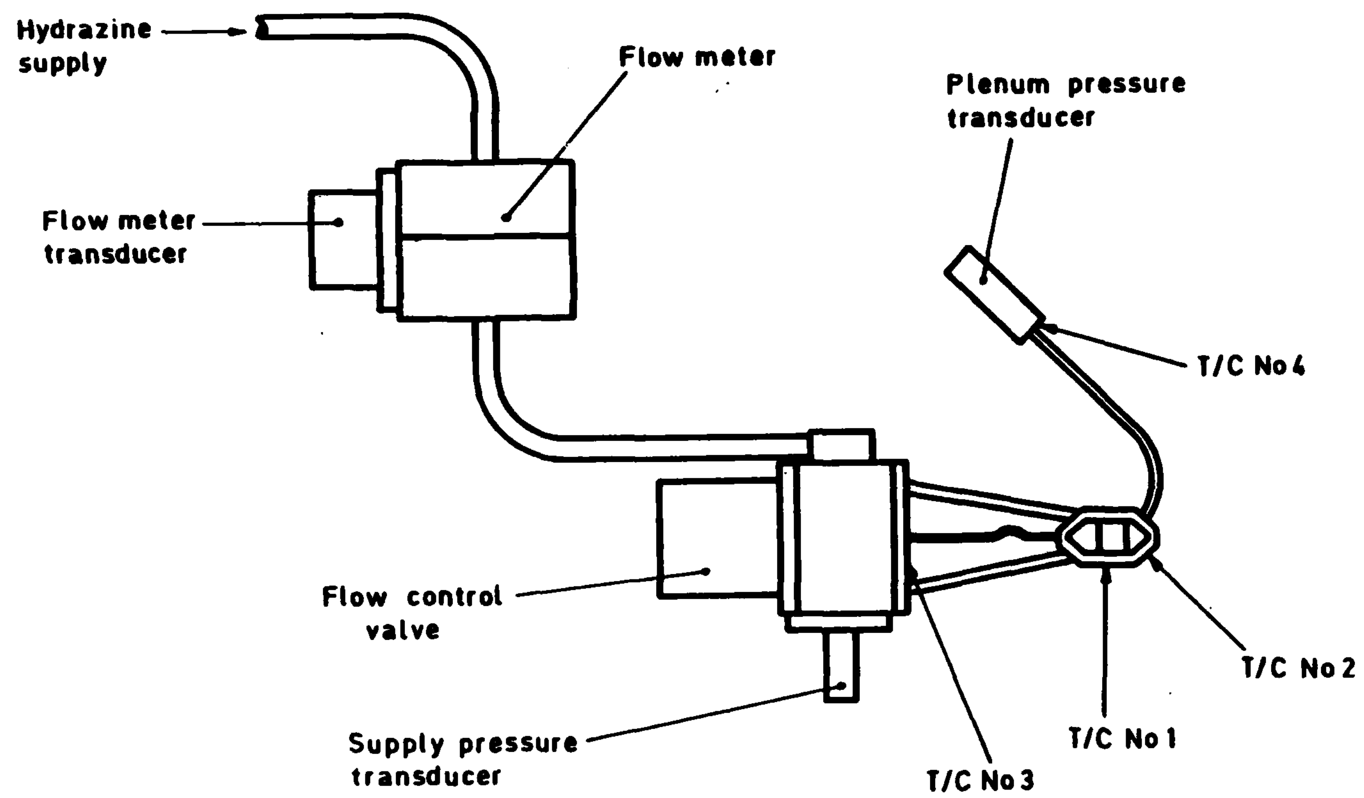


Fig 8 Thruster instrumentation (schematic)

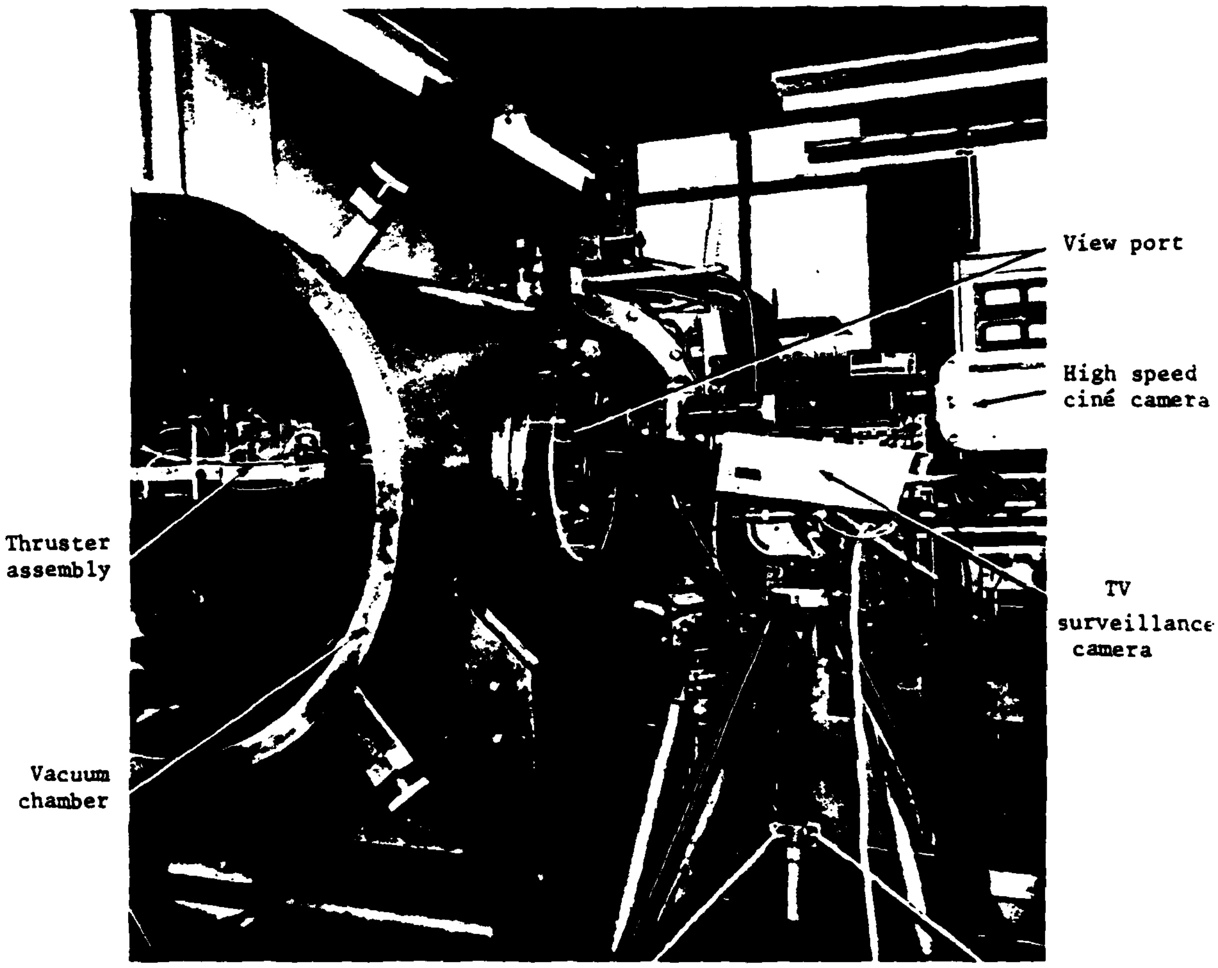


Fig 9 Thruster installed in vacuum chamber

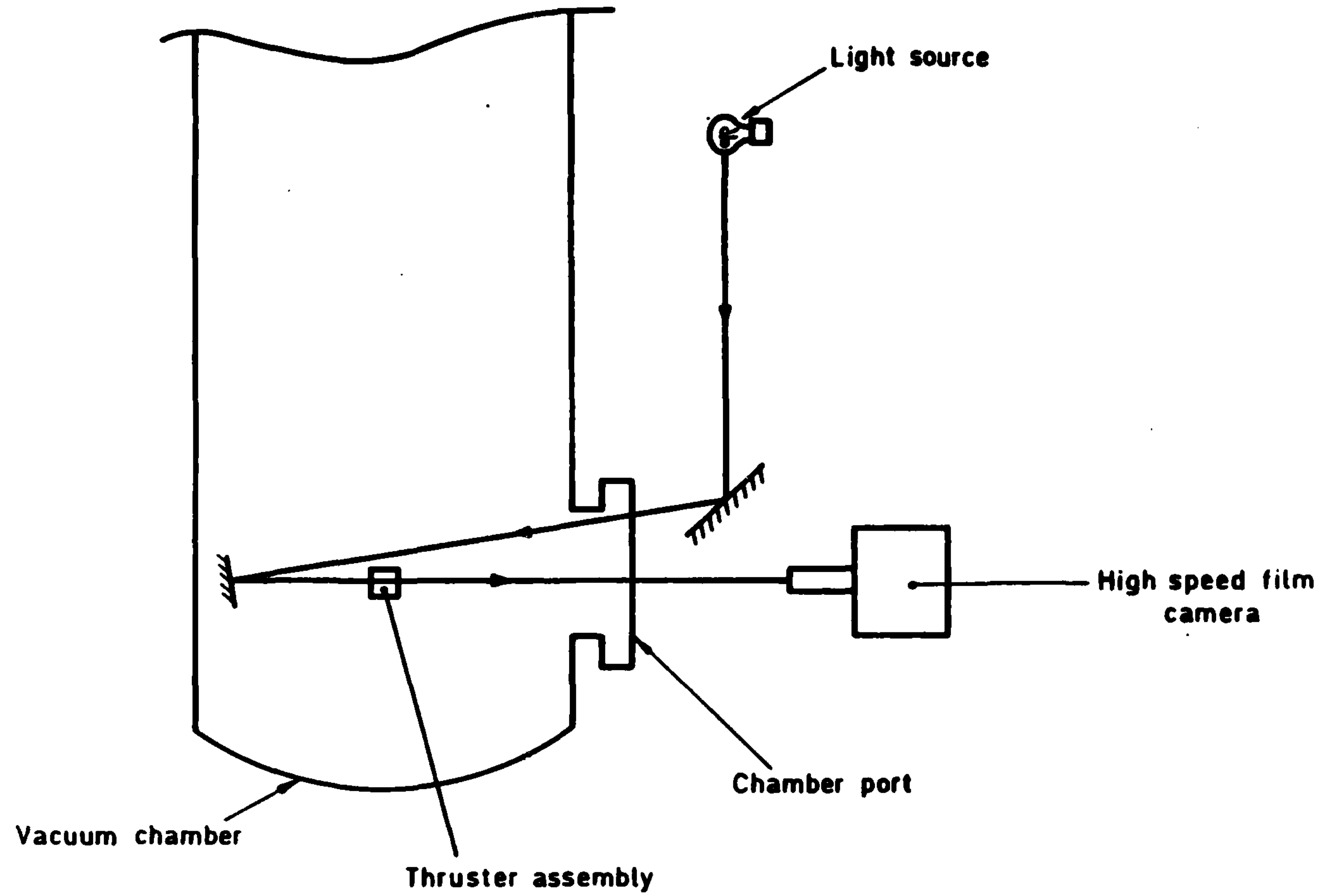


Fig 10 Arrangement of optics

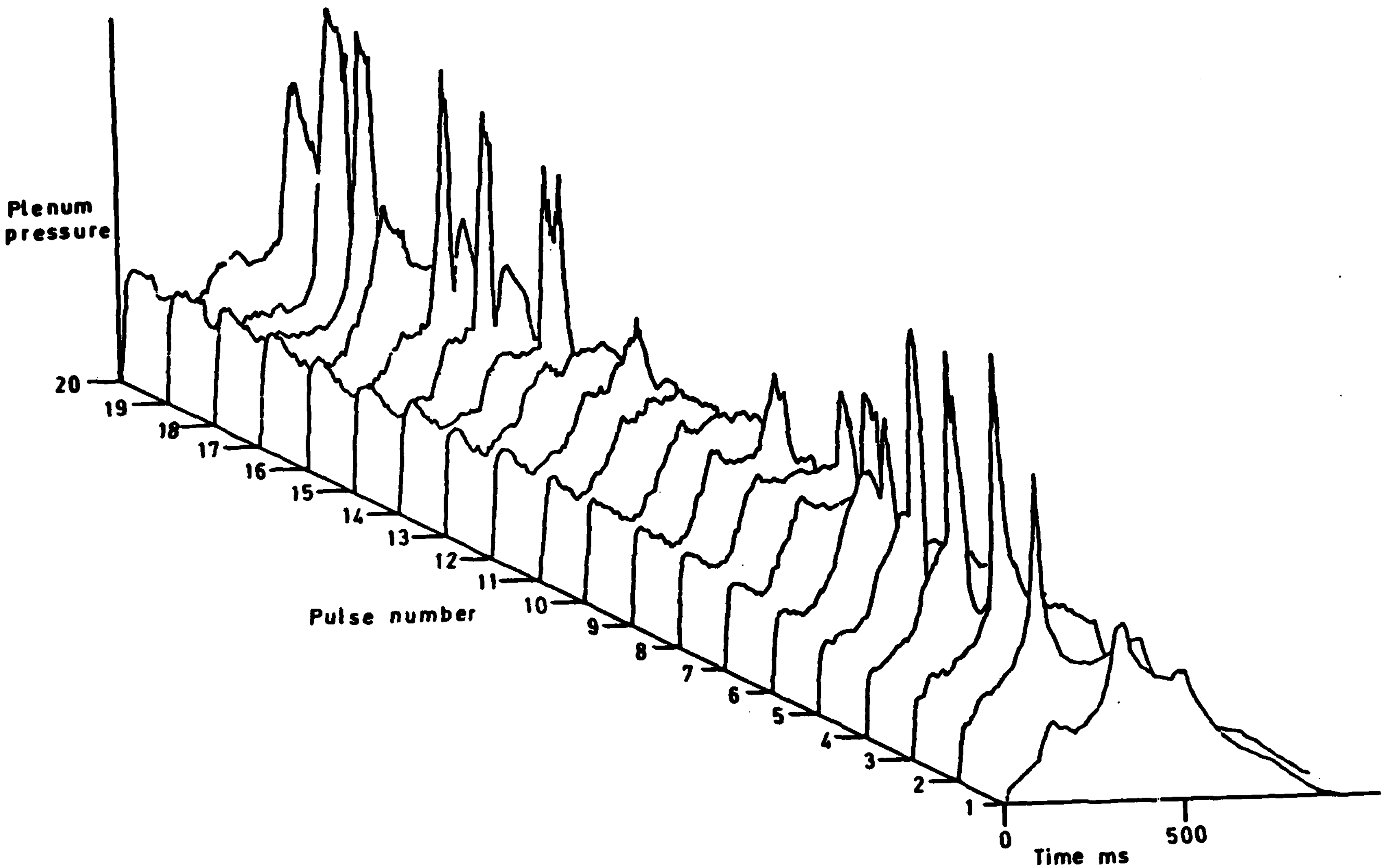


Fig 11 Train of typical see-through thruster pulses

Fig 12

Fig 12 Vaporization/atomisation of propellant flow in the injector tube

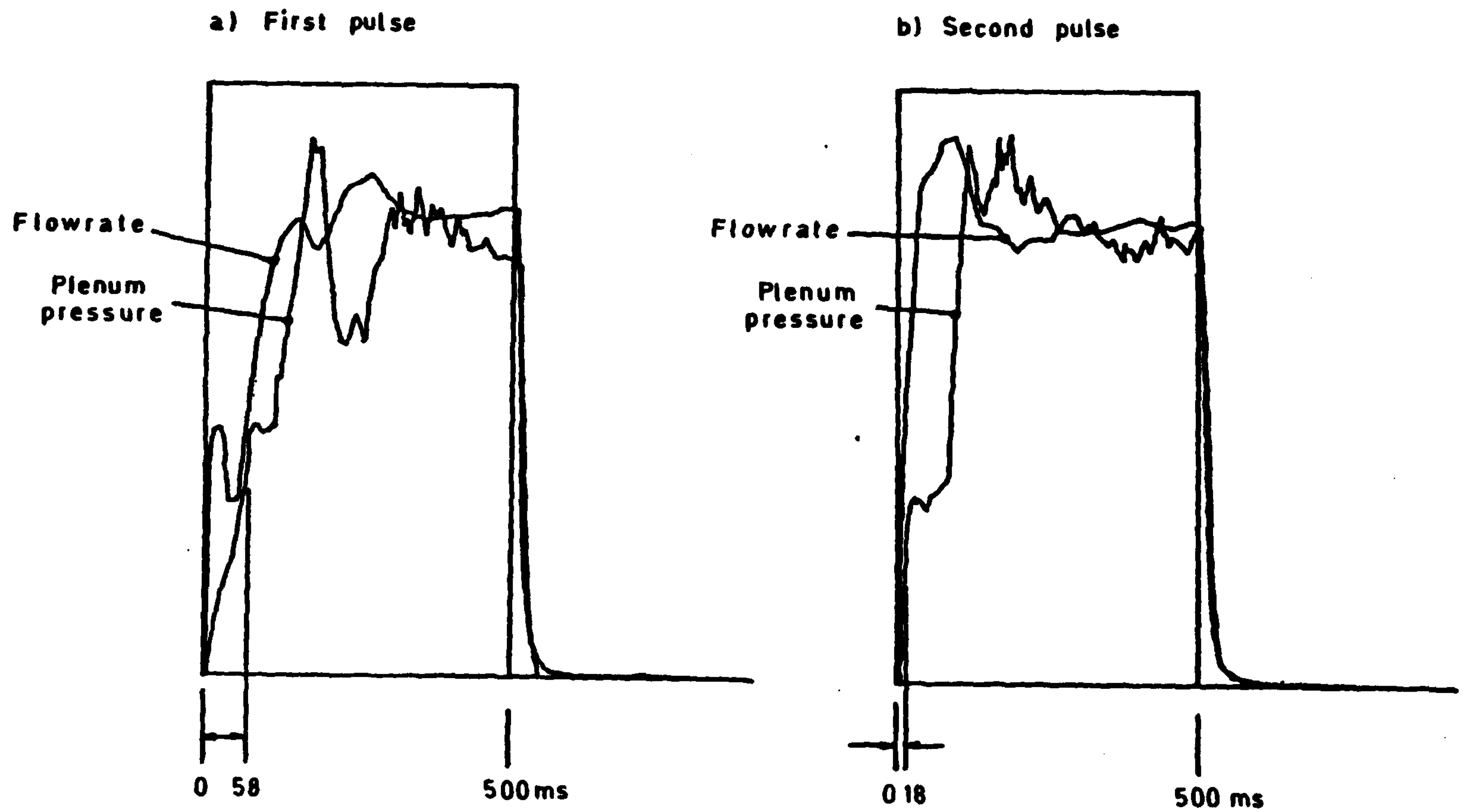
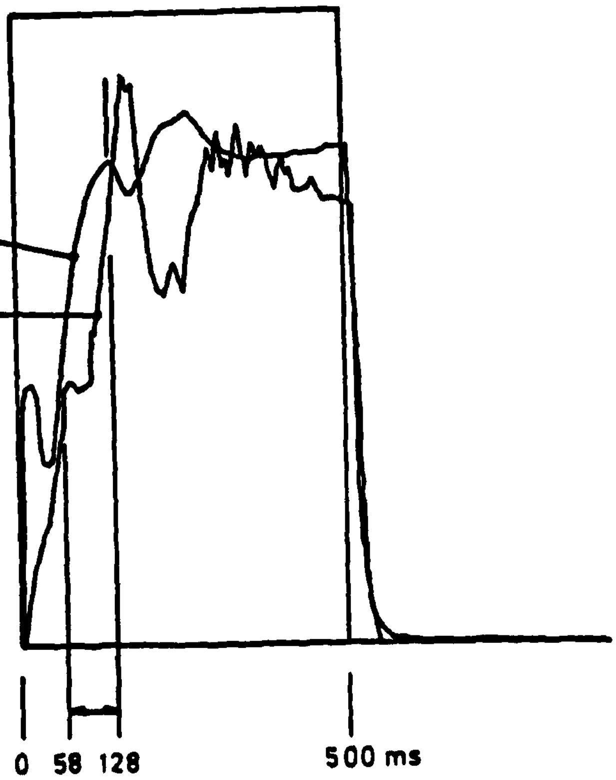


Fig 13a&b First and second pulse characteristics

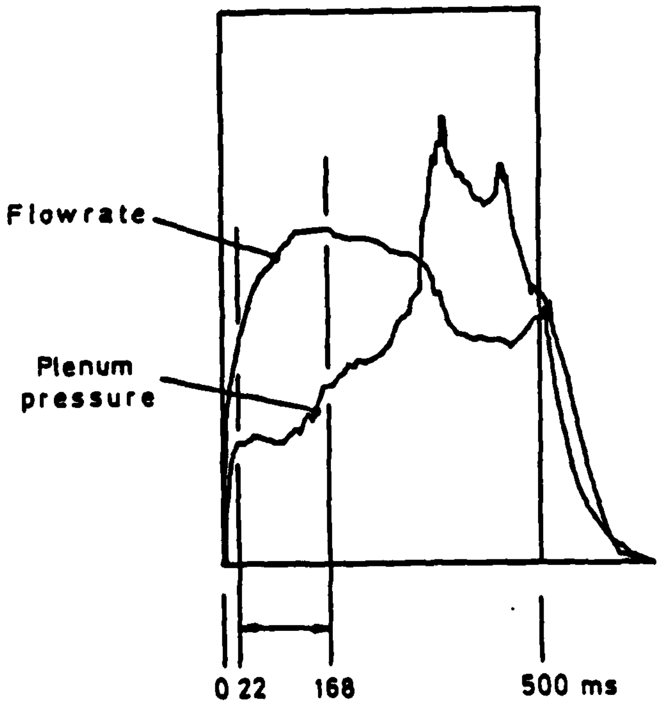
a)



b)

Fig 14a&b Turbulent propellant inlet flow

a)



b)

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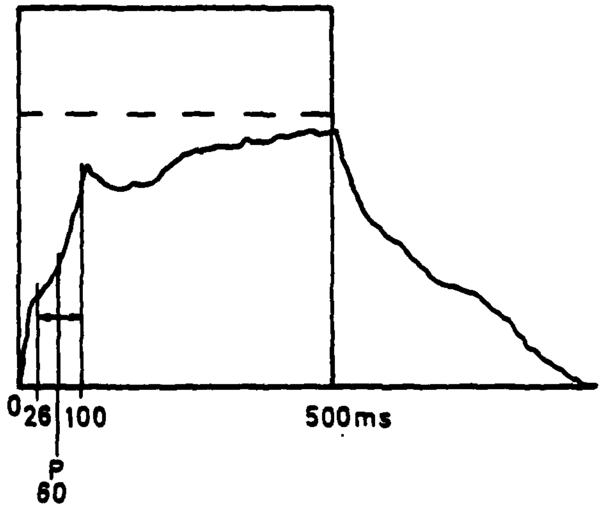
Fig 15a&b Propellant droplets film-boiling in thruster

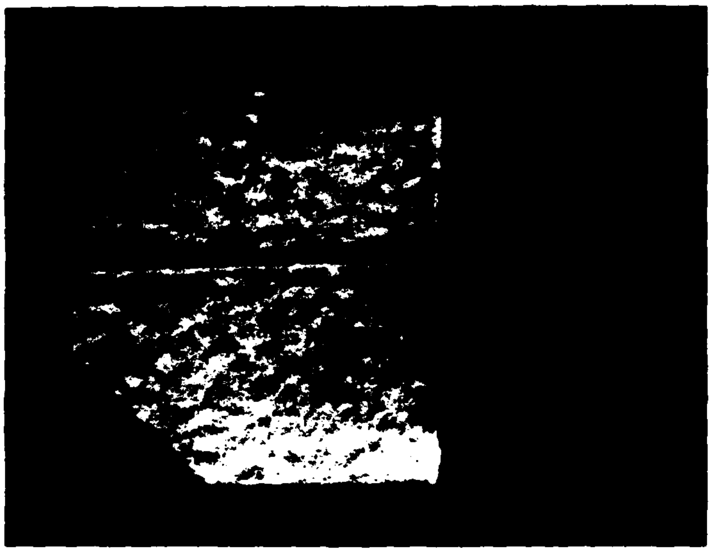
Fig 16a&b

a)

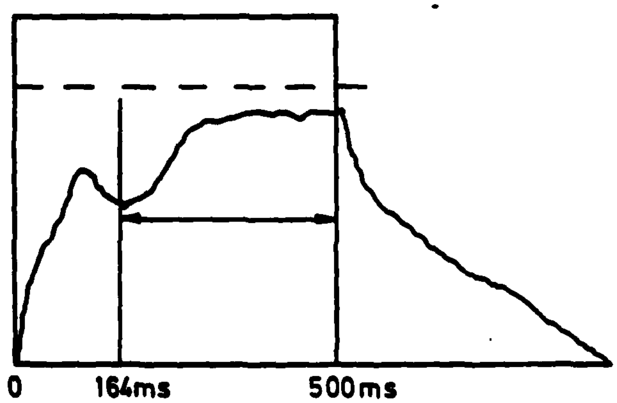


b)

Fig 16a&b Accumulation of propellant on the thruster gauze pack (photographed at point 'P')



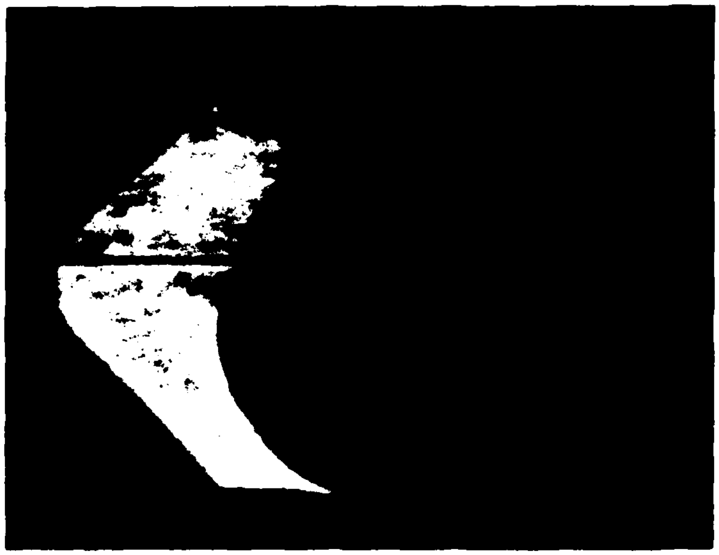
a)



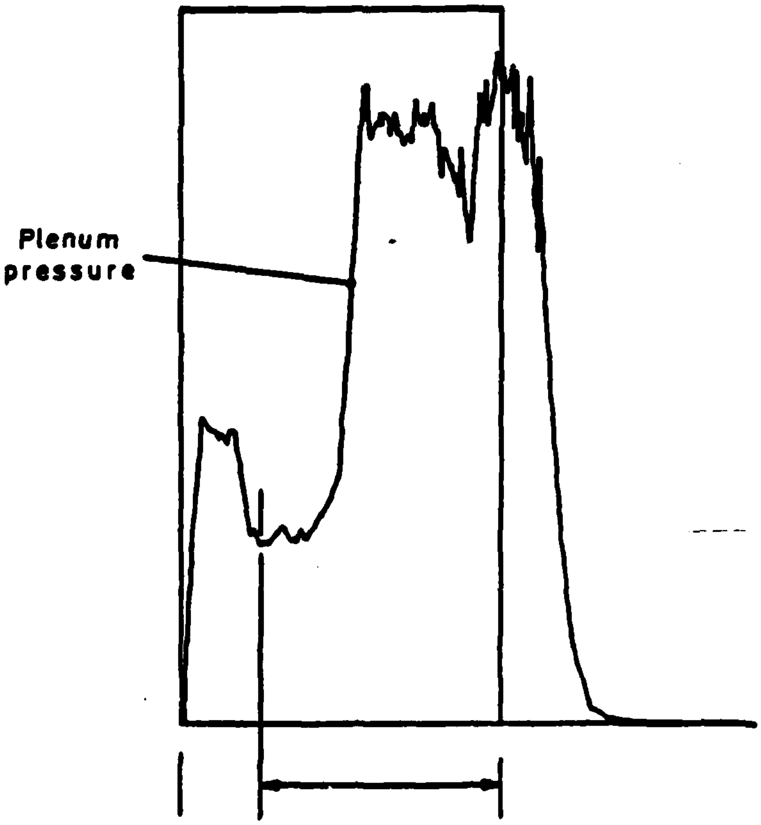
b)

Fig 17a&b First mode of steady state thruster operation

Fig 18a&b



a)



b)

Fig 18a&b Propellant accumulation

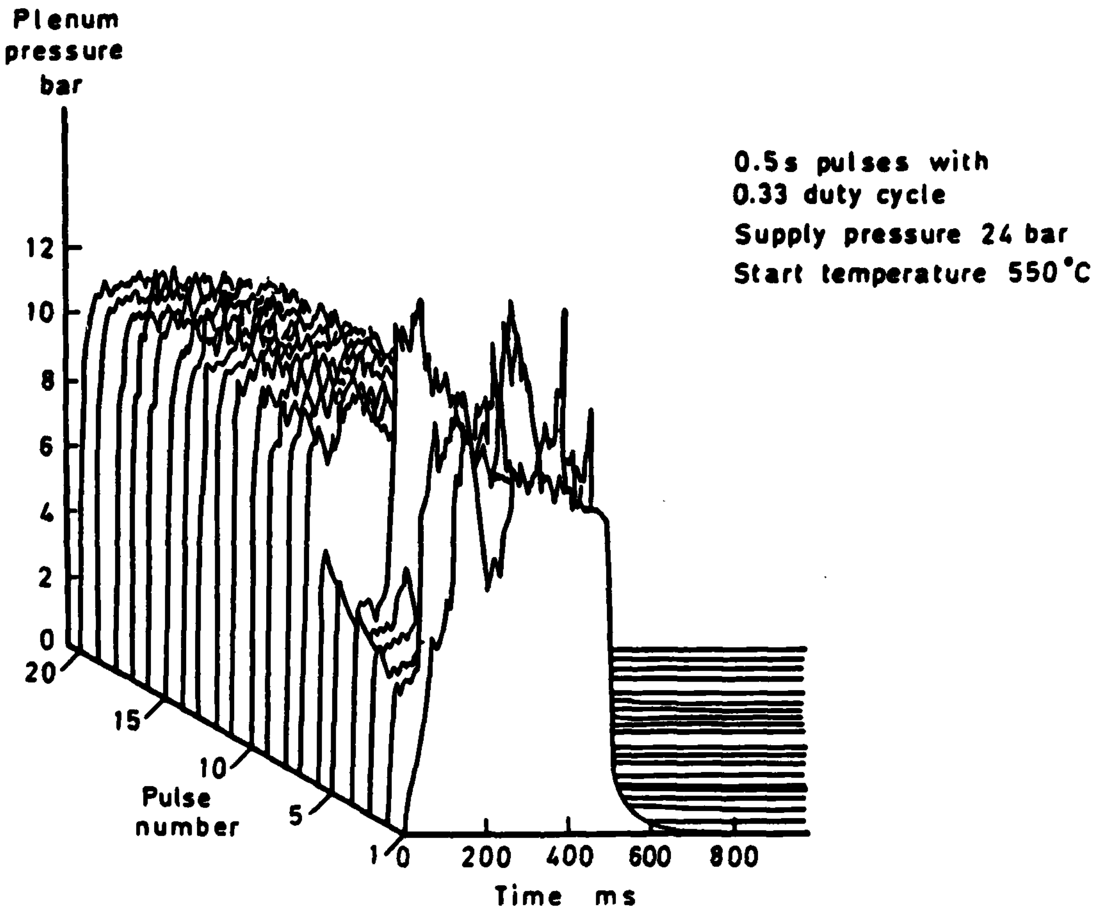
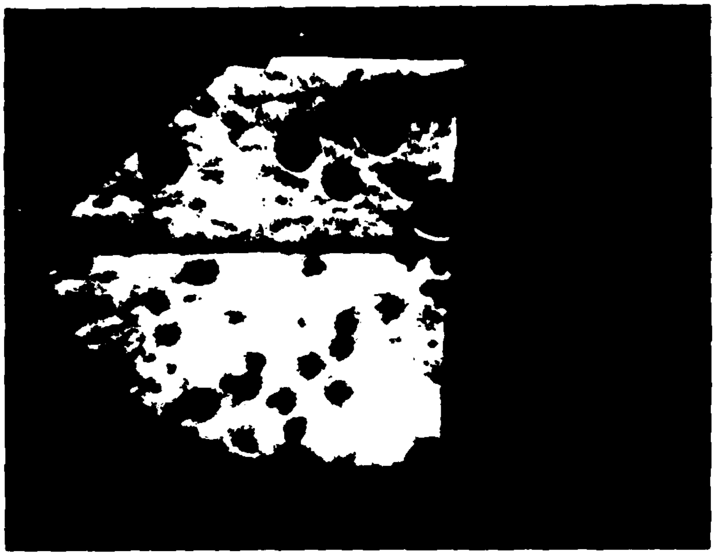
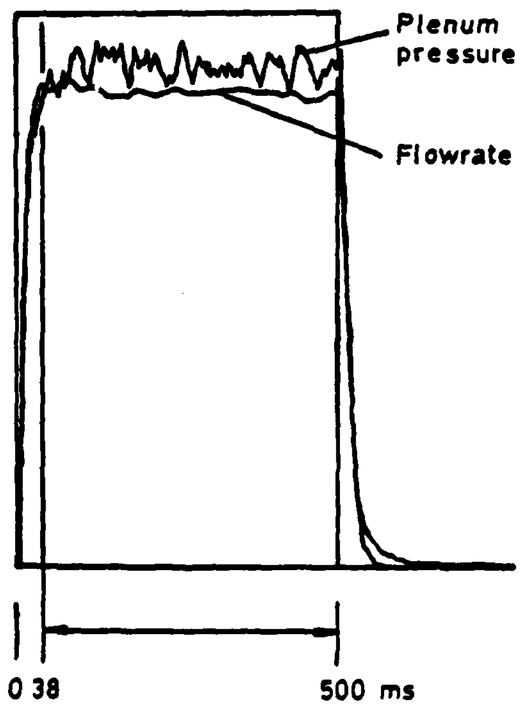


Fig 19 Particular pulsed performance of see-through thruster



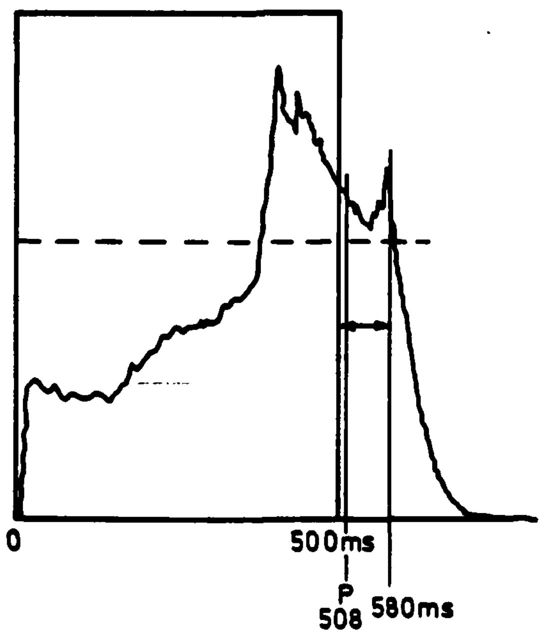
a)



b)

Fig 20a&b Droplet spray mode

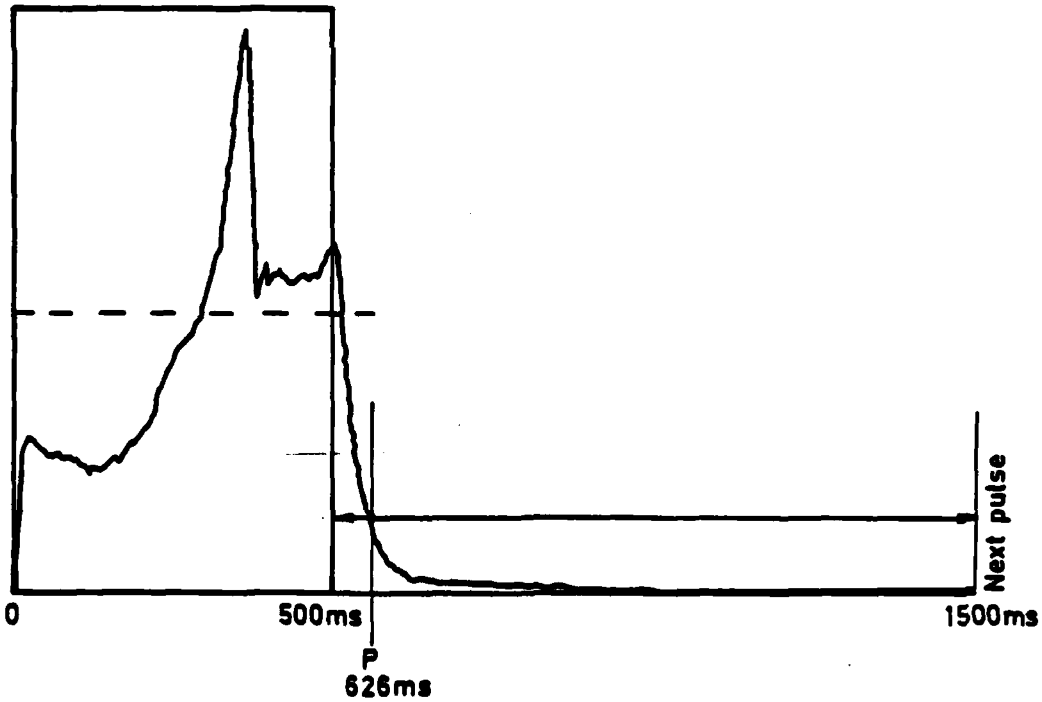
a)



b)

Fig 21a&b Large volume of propellant in thruster after the end of a pulse (photographed at point 'P')

a)



b)

Fig 22a&b Single film boiling droplet of propellant in thruster after the end of a thrust pulse (photographed at point 'P')

REPORT DOCUMENTATION PAGE

Overall security classification of this page

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Electrothermal hydrazine thruster. EHT. Satellite attitude control. Spacecraft propulsion. Vaporization. Leidenfrost effect. Film boiling. Propellant. High speed cine photography. Flow visualization.

17. Abstract

A special see-through thruster was developed to investigate the pulsed performance of a prototype 0.2N electrothermal hydrazine thruster (EHT), designed for spacecraft attitude control applications. Results from tests were recorded by high-speed cine photography, synchronised with analogue data records. These showed that the poor response of a prototype EHT was related mainly to the injection and vaporization characteristics of the propellant in the thrust chamber. Various phenomena are described and an indication is given of the interaction between these events during repeated pulsed operation. Conclusions are reached regarding design changes necessary to improve performance.

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