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AF397279

ROYAL AIRCRAFT ESTABLISHMENT
FARNBOROUGH, HANTS

REPORT No: R.P.D.10

UNCLASSIFIED

DEVELOPMENT OF THE BETA I ROCKET MOTOR

by

L.W.BROUGHTON and W.KRETSCHMER,
ROCKET PROPULSION DEPARTMENT,
WESTCOTT

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U.D.C. No. 621.455 Beta I

10 Report No. R.P.D.10

September, 1951
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2 ROYAL AIRCRAFT ESTABLISHMENT, FARNBOROUGH

Development of the Beta I Rocket Motor
4

by

L.W. Broughton
5 and
W. Kretschmer

SUMMARY

This report describes the development of the Beta I rocket motor, designed primarily as a power unit for a model aircraft. It is of the liquid bi-propellant type using the self-igniting combination hydrogen peroxide (80%) and C-fuel, and gives a thrust of 1800 lb for 45 seconds (the duration being governed by the tank capacity of the aircraft.) The motor incorporates regenerative cooling of the two combustion chambers with hydrogen peroxide, a turbo-pump pressurization system and a steam generator using silver plated gauze as the catalyst.

The overall specific thrust per lb of propellant is 177 lb/lb/sec (86% of the theoretical value) that of the combustion chambers being 190 lb/lb/sec (92% of the theoretical value). The weight of the motor complete with tanks and propellants (but excluding wings, rudder, etc) is 744 lb giving a specific thrust 109 lb per lb total weight per second.

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1. Liquid propellant rockets
2. Hydrazine hydrate

I Broughton, L.W.
II Beta I Rocket Motor
III C fuel

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1 Introduction

The Beta I rocket motor was designed primarily as a power unit for a model aircraft built by the Fairey Aviation Co. for vertical take-off experiments. It is of the liquid bi-propellant type using the self-igniting combination hydrogen peroxide (80%) and C-fuel and gives a total thrust of 1800 lb for 45 seconds, (the duration being governed by the tank capacity of the aircraft). Whilst the general design of the motor follows well established principles it also incorporates a few interesting features such as the regenerative cooling of the combustion chambers with hydrogen peroxide, a turbo pump propellant feed unit and a steam generator using silver plated gauze as the catalyst.

Two combustion chambers are fitted each swivelling through a small arc in planes at 90° to each other to enable control of the aircraft in pitch and yaw to be obtained at low flying speeds before the aerodynamic controls become operative.

It was originally intended that the turbo-pump unit should also drive an electrical alternator for supplying the aircraft electrical requirements, but because the development of a suitable control system took longer than was anticipated this was abandoned and batteries were used instead. A satisfactory control system has, however, since been developed and will be described in a separate report[1].

R.A.E./R.P.D. were responsible for the basic design and development of the motor whilst the Fairey Aviation Co. undertook the manufacture and design of the motor as a power plant. The design of the tanks and tank pressurization system was also the responsibility of the Fairey Aviation Co. and consequently is not described in detail in this report.

2 Propellants

The oxidant is hydrogen peroxide (H.T.P.) and consists of 80% by weight pure hydrogen peroxide and 20% water.

The fuel is a mixture of methyl alcohol, hydrazine hydrate and water (called C-fuel) in the following proportions.

Methyl alcohol	(CH_3OH)	-	57% (Wt)
Hydrazine hydrate	($N_2H_4H_2O$)	-	30% "
Water		-	13% "

The great advantage of this fuel is that it reacts spontaneously with hydrogen peroxide, thus obviating the need for any special igniting device. There is, however, an ignition delay and in order to speed up the reaction a small amount of copper catalyst in the form of potassium cuprocyanide is added to the fuel. Fuller details of this and the propellant combination are given elsewhere[2].

The stoichiometric mixture ratio of H.T.P./C-fuel is 2.78/1 (by weight) and the motor has been designed to run at this ratio.

3 Description of motor

Fig.1 shows a diagrammatic layout of the propellant system whilst Fig.2 and 3 show photographs of the complete motor mounted in its test frame. Fig.4 is a view of the motor complete with tanks fitted to the launcher ready for a static firing test in the vertical position.

As shown in Fig.1 the H.T.P. and C-fuel are contained in P.V.C. bags inside the main tanks in order to provide a positive feed to the pumps under all conditions of flight acceleration. The low pressure air acting on the outside of these bags forces the propellants to the turbo-pump unit via the tank supply valves. These valves are spring loaded to the closed position and isolate the tanks from the turbo-pump unit when the motor is shut down. A tapping from the H.T.P. supply to the steam generator allows both valves to be opened as soon as H.T.P. is supplied to the steam generator for operation of the turbo-pump unit.

From the turbo-pump unit the propellants are fed to the H.T.P. and C-fuel main valves. The C-fuel main valve is kept closed by the pressure of the C-fuel acting on the back of the valve via a solenoid valve. When the solenoid is closed the pressure on the back of the valve is released and the valve opens allowing C-fuel to flow directly to the injector of each combustion chamber. The H.T.P. valve is kept closed by a spring and the pressure of H.T.P., and is opened by C-fuel pressure tapped downstream from the main C-fuel valve. From the H.T.P. main valve the H.T.P. goes to a collection ring at the throat of the venturi of each combustion chamber, passes through the coolant jacket and then into the injectors. Tapped into the coolant space of each combustion chamber is a dump or vent valve, spring loaded so that it is open to the atmosphere when the motor is not operating thus H.T.P. is emptied from the coolant jacket when firing is finished. When the main propellant valves are opened the rise in H.T.P. pressure acting on the back of the valve closes it.

The H.T.P. supply to the steam generator for starting the turbo-pump unit and running it at "no delivery" conditions (i.e. no delivery from the pumps) is obtained from an external pressurized tank, and is fed into the motor through a pull-off coupling having self-sealing connections. The flow of H.T.P. to the generator is controlled by two fixed throttle orifices, the "no delivery" throttle (about 0.150 in. diameter) which limits the power output of the turbine before the motor is fired, and the "full delivery" throttle (about 0.20 in. diameter) which, being larger is only effective when the motor is fired and a greater quantity of H.T.P. is being supplied to the generator. H.T.P. from the external tank is the only supply to the turbine until the motor is fired, when a tapping downstream from the main H.T.P. valve feeds H.T.P. to the steam generator through a non-return valve and the "full delivery" throttle. The non-return valve prevents H.T.P. feeding into the combustion chamber when starting the turbine and running it under conditions of "no delivery".

In the H.T.P. line to the steam generator is a P.V.C. burster disc which bursts at a minimum pressure of about 110 lb/sq in. The purpose of this burster disc is to prevent H.T.P. from the external supply being fed to the steam generator whilst the H.T.P. is pressurized to 80 lb/sq in. for the purpose of opening the tank supply valves so that bleeding of the propellant system can take place both during filling and also immediately before operation of the motor. This bleeding is essential for successful starting of the motor and must ensure the removal of all air right up to the main H.T.P. and C-fuel valves. A total of four manually operated bleed connections are provided, two before and two after the pump unit.

Upstream from the main H.T.P. and C-fuel valves are pressure switches which operate remote indicating lights on the firing panel, thus ensuring that the correct pressures are obtained before the motor is fired. A tapping from the steam generator to each combustion chamber allows steam to be fed through the injectors just before the motor is fired and thus assists the ignition.

4 Operation of motor

The H.T.P. and C-fuel tanks and the propellant feed system up to the main valves are filled with liquid, care being taken to ensure the removal of all trapped air. The high pressure air bottle is then charged, which automatically pressurizes the propellant tanks. The C-fuel solenoid valve is now energized, and thus ensures that when the C-fuel pressure rises the main C-fuel valve remains closed.

To start the turbine, H.T.P. at 250 lb/sq in. is fed from the external tank to the steam generator through the fixed throttles and burster disc, and to the tank supply valves which are thus opened. Steam at a pressure of about 120 lb/sq in. then passes to the turbine which starts the pumps. At the same time a small quantity of steam is fed to each combustion chamber injector, thus it pre-heats the injector and provides a small quantity of free oxygen to assist ignition. When the correct propellant pressures are obtained, as shown by the extinction of the indicating lights on the firing panel, the C-fuel solenoid valve is manually de-energized, thus the C-fuel main valve is opened and allows H.T.P. and C-fuel to be fed to the injectors and the motor to be fired. As soon as H.T.P. starts feeding to the injectors it also feeds a small quantity directly to the steam generator through the "full delivery" throttle and thus by-passes the "no-delivery" throttle. As this feed is at a higher pressure than the external supply, the pressure in the steam generator is built up and supplies the extra steam required by the turbine under "full delivery" conditions. Also, because of these higher pressures the flow from the external supply is automatically stopped and the motor is now self-sustaining. As soon as the motor has built up its full thrust, the aircraft starts moving up the launching ramp, and thus breaks the external supply connection to the aircraft, the self-sealing connections in the latter preventing any loss of H.T.P.

To stop the motor the C-fuel solenoid valve is energized by means of a programme switch and closes the main C-fuel valve and therefore, the main H.T.P. valve. When the main H.T.P. valve is closed the feed to the steam generator stops and hence stops the turbine. This fall in pressure also allows the dump valves to open and release the H.T.P. from the coolant jacket of the combustion chambers.

A summary of the main operating details of the motor is given in Appendix I. A description of the motor is also given in the handbook[3] together with details of the tests required on the individual components and on the complete motor. Instructions for firing the motor are also given together with a list of possible failures and suggested remedies. A section on the filling rigs is included.

5 Development of motor components

Each component was made and tested for correct functioning as an individual item before being assembled into the motor which was then tested as a complete unit. The following paragraphs describe the purpose and development of each component. A summary of the weights is given in Appendix II.

5.1 Injector

Previous experience in the use of H.T.P. and C-fuel indicate that the essentials of a good injector are:-

(1) good atomization of the propellants

(2) good mixing of the propellants

(3) good distribution of the propellants in the combustion chamber

(4) large contact area between the two propellants

(5) preheating of the burner with superheated H.T.P. steam

(6) simple design for low cost and ease of production

Points 1, 3 and 6 apply of course to any bi-fuel rocket motor and 4 to any motor in which the mixing takes place in the combustion chamber. Point 5 presents a new idea applicable especially to motors where H.T.P. is available to produce H.T.P. steam, i.e. superheated steam and free oxygen. This steam can serve three purposes.

(1) to provide free oxygen to assist ignition

(2) to preheat the injector and to some extent the combustion chamber; this favours ignition

(3) to provide in a suitably designed rocket motor a barrier to prevent the propellants from dribbling into each other's metering holes during starting and shutting down, this is a very useful safety precaution, especially with self igniting propellants.

The Beta I injector (Fig.5) was designed with the above points kept in view as far as possible.

5.1.1 Description of injector

Good atomization of the C-fuel was achieved by injecting it through twenty swirl nozzles arranged on a pitch circle diameter of 3.8 in. The H.T.P. was injected radially inwards through fifteen pairs of radially drilled holes, the resulting jets impinging on a target ring whose face was set at 15°, to the path of the jets. This ring served to spread each separate jet into a fan shaped spray, and thus form a continuous sheet of H.T.P. spread across the combustion chamber immediately in the path of the spray from the C-fuel swirl jets. The C-fuel jets are arranged so that they overlap each other before meeting the sheet of H.T.P., the mean angle of contact of the propellants being about 90°. A point to be noted is that the H.T.P. is metered by the 15 pairs of drilled holes and not by the slot between the target ring and the face of the injector, so that the width of the slot is not critical and can be between 0.040 and 0.080 in. This avoids the necessity for setting the slot accurately which is always a difficult matter for such large diameters; for instance if the slot was used for metering it would have to be about 0.004 in. wide. The pressure drop across the injection system for both H.T.P. and C-fuel is 145 lb/sq in.

The H.T.P. steam is fed to the chamber through the same slot as the H.T.P. The motor is so designed that when it is started, C-fuel is fed into the combustion chamber slightly ahead of the H.T.P. Because of this there is the possibility of C-fuel leaking into the H.T.P. system; this is prevented however, by feeding steam to the combustion chamber before either of the two propellants, so that steam flowing through the slot provides an effective barrier to the entrance of C-fuel. At the same time the steam preheats the target ring and to a smaller extent the injector plate and combustion chamber.

The material of the injector is mild steel (BSS.S1); to prevent corrosion during storage the surfaces in contact with the C-fuel are chromium plated.

It can be seen that the design is relatively simple and would appear to incorporate in a reasonably balanced manner the points set out earlier.

5.1.2 Development of injector

As the method of injecting H.T.P. was unusual, preliminary water flow tests were made to determine the arrangement of holes which gave the best spray pattern. This was found to be thirty holes of about 0.060 in. diameter, the holes being arranged in pairs, with the holes in each pair 0.10 in. apart and the pairs 1.25 in. apart. The C-fuel swirl nozzles were of a well proved type incorporating a "swirl plug" with a helical groove to give the necessary swirl to the liquid.

Firing tests were made on a rig using pressurized propellant tanks instead of the turbo-pump unit which was used in the final motor. A diagrammatic layout of this rig used for both injector and chamber development is shown in Fig.6. The entry of the propellants into the injector was controlled by valves (5) and (9); these were arranged so that the H.T.P. valve (9) could not be opened until the C-fuel valve (5) had opened and a slight pressure built up in the C-fuel line to the injector. This ensured that C-fuel was injected into the chamber slightly ahead of the H.T.P., previous experience having shown that by avoiding an excess of H.T.P. at ignition, "hard" starts were minimized. The flow of H.T.P. steam to the injector took place as soon as the H.T.P. tank was pressurized, the flow of peroxide to the steam generator (7) being controlled by the hand operated throttle valve (8).

The flow rate of steam before ignition takes place was between 0.025 to 0.030 lb/sec for a pressure drop across the injector of 120 lb/sq in. During combustion the flow rate is about 0.025 lb/sec for a pressure difference of between 30 and 40 lb/sq in , the actual steam pressure being 290 lb/sq in. The pressure drop across the H T.P. and C-fuel injector was 145 lb/sq in. In the final motor the C-fuel pump gave a pressure 30 lb/sq in. higher than the H.T.P. pump, so the difference across the C-fuel injector was increased to 175 lb/sq in.

The first firing tests were "open" burning tests, i.e. no combustion chamber was fitted and burning took place in the open atmosphere; this is a very useful method of testing as it enables a qualitative assessment of the ignition and burning to be made. These tests showed that the ignition and burning were quite good. The ignition delay (measured by photographing the injector at a camera speed of 48 frames per second) was between 0.020 and 0.040 sec, and burning appeared to take place close to the injector face.

Tests with a water cooled combustion chamber were then made with a chamber of volume 280 cu in. and an L* of 117 in. In the first tests the thrust was reduced to about 70% of the designed value, but in subsequent tests it was increased to the maximum of 900 lb. In all cases ignition was quite smooth and there was no sign of any "peaking" of the combustion chamber pressure; the igntiion delay obtained from electronic recordings of propellant and chamber pressures was between 0.080 and 0.12 sec. The combustion as judged from visual observation of the exhaust flame appeared very good; the measured values of the specific thrust were between 190 and 195 lb/lb/sec (92 to 94% of the theoretical value).

5.2 Combustion Chamber

For an expendible motor an uncooled combustion chamber with a heat resisting lining would probably be simplest and cheapest. Experience so far, however, has shown that whilst a carbon lined chamber would easily last for a 60 second run[4], erosion of the throat is very rapid and there is a consequent fall in efficiency, but as a better heat resisting material was not readily available it was decided to cool the chamber regeneratively.

The coolant may be either the oxidant (hydrogen peroxide) or the fuel (C-fuel). Hitherto with this combination the C-fuel has been quite successfully used as the coolant and the natural choice was to use it again. Hydrogen peroxide has also been used as a coolant but only in a few limited cases and never in this country. In view, therefore, of the possibility of having to cool with hydrogen peroxide in motors where the fuel is not suitable, it was decided to use the hydrogen peroxide as the coolant and so obtain experience with it as soon as possible. Calculations showed that the temperature rise of the hydrogen peroxide after passing round the Beta I chamber should be about 60°C, the temperature reached is thus well below the boiling point of hydrogen peroxide which at 400 lb/sq in. is about 210°C.

The use of hydrogen peroxide entails the precaution that normally the materials with which it comes into contact should be either stainless steel or a copper free light alloy. Because of the expendible nature of this motor it was decided to make the combustion chambers of mild steel (BSS.S1) in view of the relative cheapness, availability and ease of machining of this material, and to plate the coolant channels that come into contact with hydrogen peroxide with some protective material. The primary object of this plating was to prevent rust forming in the coolant channels during storage as it was feared that this rust would cause trouble by acting as a catalyst to the hydrogen peroxide and also tend to block the metering jets. In actual fact most of the experimental chambers were run with no protective plating, and although considerable rusting of the coolant channels took place it never gave rise to any difficulty. This was due to the fact that the peroxide was not allowed to remain static in the coolant channels, but was either flowing (as during a run) or else released to atmosphere through the dump valve at the end of a run. Nevertheless it was deemed desirable to give some protection to production chambers.

The first intention was to hot tin plate the whole chamber by immersing it in a tin bath, but there was some doubt as to whether the tin would give a satisfactory coating in the cooling channels, especially on the helical thread which was fitted around the exhaust nozzle. Some test specimens were, therefore, made of the coolant channel, incorporating a helical thread of the desired dimensions and sent to the Tin Research Institute to enable them to determine whether tin plating of the coolant channel was feasible. Their plating tests showed a uniformly thin and consistent tin coating over the whole of the internal cooling channel including the helical thread. (See Appendix III for details of their plating method.) In view of these good results a complete chamber was tin plated at R.P.D. using rather crude facilities, but subsequent sectioning of this chamber showed very poor tinning, certain areas having little or no tin whilst in others the plating had piled up in blobs. Because of the lack of proper tinning facilities and the difficulty in finding a firm to do it in a reasonable time it was decided to abandon tinning and to chromium plate the coolant passage before assembling and welding the chamber together. The whole of the coolant passage in the chamber therefore, with the exception of a small area adjacent to each weld is chromium plated to a depth of 0.001 in. Although rust can form adjacent to each weld the amount is very small and can be neglected; no trouble whatever has been experienced from about 20 chambers protected in this manner.

5.2.1 Development of combustion chamber

Fig.7 shows the first type of chamber to be tested. This chamber had an L* of 116 in., an inner jacket thickness of 0.128 in., and a uniform coolant annulus width of 0.120 in. with a 4 start helix in the converging and diverging sections of the nozzle. The coolant velocities were 46 ft/sec along the diverging section of the nozzle to the throat, 17 ft/sec from the throat to the chamber and 2½ ft/sec along the chamber. The expansion nozzle together with the helixes were machined from the solid, whilst the chamber and complete coolant jacket were fabricated from sheet. The metering holes for the H.T.P. injector were drilled circumferentially around the inner jacket of the combustion chamber so that H.T.P. after cooling the nozzle and chamber passed directly into the chamber. Two firings with this chamber gave smooth ignition and a normal exhaust jet, but the pressure records showed violent fluctuations of the H.T.P. pressure and to a smaller extent of the C-fuel and combustion chamber pressures, whilst later examination of the chamber revealed a number of hot spots where local boiling of H.T.P. had occurred.

Concurrently with the first chamber a second chamber had been manufactured similar in all respects except that it had no helixes in the cooling space and was completely fabricated from sheet. The coolant velocities were 8½ ft/sec around the throat and 2½ ft/sec along the chamber. In view of the results from the first chamber it did not appear that the second chamber with its lower coolant velocities would be any more successful. Tests, however, were carried out, but it was not found possible to run them longer than 2 to 3 seconds before the motor stopped due to local boiling of the H.T.P. in the coolant channels and consequent blockage of the H.T.P. metering holes with vapour. Examination of the chamber revealed hot spots in both the inner and outer jackets where they had touched owing to manufacturing errors. These errors were rectified and a run of 45 seconds was obtained, but fluctuations of the H.T.P. pressure were still apparent, though to a smaller extent than on the first chamber.

The results from these first two chambers with widely differing coolant velocities seemed to indicate that the coolant velocity was not critical and that the trouble was possibly poor distribution of the H.T.P. in the coolant space. The third chamber, therefore, was made similar to the second except that it had a single start helically wound wire running round the coolant space the whole length of the nozzle and chamber; this gave a constant coolant velocity of 20 ft/sec. The fourth chamber was also similar to the second but had six wires running axially along the coolant space, coolant velocities being 8½ ft/sec around the throat and 2½ ft/sec along the chamber. Both chambers were unsuccessful and stoppage of the motor owing to local boiling of the H.T.P. occurred within 2 to 3 seconds of starting. The fifth chamber was similar to the second but had a 4 start helix in the converging section of the nozzle, the coolant velocities being 8½ ft/sec around the throat, 19 ft/sec between the throat and the chamber and 2½ ft/sec along the chamber. This chamber ran reasonably well and two runs of 45 seconds were obtained although with a fluctuating H.T.P. pressure. A further run of 75 seconds was obtained with no pressure fluctuations whatever by increasing the H.T.P./C-fuel ratio from the stoichiometric value (2.78/1) to 3.0/1. A sixth chamber similar to the fifth also ran reasonably well but still gave a fluctuating H.T.P. pressure; after 45 seconds a hole burnt through the chamber near to the injector and the inner jacket partially collapsed owing to local boiling of the H.T.P.

All the cooling failures experienced so far had made themselves evident in the combustion chamber either as an overheating of the wall or an actual burn out. Fig.8(a) and 8(b) show photographs of two typical failures. Fig.8(a) shows the combustion chamber with the cooling jacket removed and illustrates that the failure is due to overheating and burn out with a partial inward collapse of the wall owing to local boiling of H.T.P. with consequent high pressure. Fig.8(b) shows the combustion chamber with the coolant jacket partially removed and illustrates that the wall has collapsed inward with no burn out or obvious sign of overheating. In some cases the overheating of the wall extended the whole length of the chamber as far as the converging section of the nozzle, but in tests on chambers of identical construction there was no consistency in the relative position of the overheated areas, which appears to indicate that the injector is not the cause of the overheating. Although in no case was there any sign of overheating at the nozzle, even with a cooling velocity as low as 8½ ft/sec in the throat of the nozzle, it was thought that the trouble originated there, and the next chamber, therefore, included a number of modifications to improve the cooling conditions around the nozzle. The modifications were:-

(a) reduction in the area of the nozzle to be cooled by leaving the expansion section uncooled

(b) reduction of the depth of coolant annulus around the nozzle and the chamber from 0.120 in. to 0.060 in. and consequent increase in the velocity of the H.T.P. uniformally over chamber and nozzle

(c) feeding the H.T.P. tangentially into the throat of the nozzle to give it an initial swirl and thus improve the distribution

(d) reduction of the L^* from 116 in. to 89 in. and consequent reduction of the area of chamber to be cooled (Preliminary tests on a water cooled chamber had shown that this involved no reduction in efficiency.)

An 8 start helix, formed by spot welding flat strip, was fitted to the converging section of the chamber. The coolant velocities were 16 ft/sec in the throat, 22 ft/sec between the throat and the chamber, and 5 ft/sec along the chamber. A diagram of this chamber is shown in Fig.9. Owing to the use of an uncooled expansion nozzle the construction is simplified, the inner and outer jackets between the nozzle throat and injector being each made in a single piece thus obviating the need for longitudinal welds. Because of the small depth of coolant annulus (0.060 in.) both jackets were machined.

Tests carried out on this chamber showed the cooling to be quite satisfactory, there being no sign of any fluctuations in the flow of H.T.P. The temperature rise of the H.T.P. through the coolant jacket was 40°C compared with a calculated figure of 44°C. Fig.10 shows curves calculated by Mr. Walder for the coolant temperature, inner wall temperature and heat transfer rate at various sections along the chamber (including in this case a cooled expansion nozzle). The coolant temperature rise for the chamber with a cooled nozzle is shown to be 60°C, the temperature rise with an uncooled nozzle being 44°C as already mentioned. The calculated mean heat transfer rate (uncooled nozzle) is 0.63 CHU/sq in/sec, compared with a measured value of about 0.57 CHU/sq in/sec. Details of the heat transfer calculation for hydrogen peroxide as the coolant will be given in a later report. The pressure drop through the coolant jacket was 25 lb/sq in.

For the first tests the uncooled expansion nozzle was made of mild steel, but this burnt through in a short time of the order of 15 to 20 seconds. In later tests a mild steel expansion nozzle chromium plated on the gas side to a depth of 0.004 in. was tried and proved successful, continuous runs up to 70 seconds being obtained with no signs of serious erosion; a stainless steel expansion nozzle gave similar results. The chromium plated mild steel nozzle was adopted as standard for the motor. To prevent radiation of heat to components situated near the chamber when mounted in the aircraft a shield was fitted around the expansion nozzle with holes drilled through it at the end near the throat to allow air to circulate between the shield and expansion nozzle. The temperature of this shield on the outer surface was between 200°C and 240°C after a run of 60 seconds.

A few tests were made to determine the lowest thrust at which the chamber would operate. With a water cooled chamber it was possible to get down to a thrust of 345 lb (corresponding chamber pressure 90 lb/sq in. gauge) before combustion commenced to become unstable, but with the H.T.P. cooled chamber it was only possible to get down to a thrust of 570 lb (corresponding chamber pressure 150 lb/sq in. gauge). The higher minimum thrust with H.T.P. cooling is of course due to the inadequate cooling at the lower flow rates, which causes local boiling of the H.T.P. The combustion chamber pressure is 250 lb/sq in. for a thrust of 900 lb.

Some tests were made to determine the minimum volume of combustion chamber. With a water cooled combustion chamber the volume was progressively reduced from 275 cu in. to 214, 183, 152 and 122 cu in., the values of L* being 116, 89, 76, 63 and 51 in respectively. No reduction in performance was noticed down to an L* of 76 in., but at 63 in. and 51 in. the performance fell by about 4% and 7% respectively. In all cases the ignition was smooth. As the motor had at that time been designed to take a chamber with an L* of 89 in. (vol. 214 cu in.) and chambers of this size were already being made it was decided to adopt this size, although a value of 70 in. would have been possible.

The following table summarizes the principle combustion chamber particulars:-

TABLE I

Principle particulars of combustion chamber

Inside diameter of chamber	6.0 in
Thickness of inner wall	0.128 in
Length of chamber	10.3 in
Chamber length/diameter	1.7/1
Volume of chamber	214 cu in
Diameter of nozzle throat	1.75 in
Area of nozzle throat	2.405 sq in
Chamber vol./nozzle throat area (L*)	89 in
Chamber diam./nozzle throat diam.	3.4/1
Diameter of nozzle exit	3.3 in
Area of nozzle exit	8.55 sq in
Designed pressure expansion ratio	19/1
Coolant (H.T.P.) velocities:-	
Throat	16 ft/sec
Throat to chamber	22 ft/sec
Chamber	5 ft/sec
Weight of chamber including injector	25.36 lb

As mentioned in section 1, two combustion chambers are fitted to each motor. The two chambers are fitted into a framework to form a combustion chamber unit which is slid into the monocoque type fuselage from the rear, the fixing points and all propellant and pressure connections being accessible from the outside. Because the two chambers swivel, all pipe connections to it (H.T.P., C-fuel and steam) are made from flexible tubing. Two views of the combustion chamber unit are shown in Fig.11.

5.3 Turbo-pump unit

An external view of the turbo-pump unit is shown in Fig.12(A), a view of the turbine casing ready for assembly in Fig.12(B) and a cross sectional drawing of the complete unit in Fig.13. As the development of this turbo-pump has been described fully elsewhere[5], only a brief description of the unit is given here.

It consists of a central turbine wheel running in unlubricated carbon bearings and driving a centrifugal pump on each side; the impellers and the turbine wheel are on a common shaft. The H.T.P. pump has the largest entry and two outlet diffusers, whereas the C-fuel pump has only one outlet diffuser. There are four steam inlets to the turbine and four exhausts. The bucket type turbine wheel is rotated at about 24,000 r.p.m. by means of H.T.P. steam (290 lb/sq in., 470°C) which is directed from nineteen nozzles round the periphery of the turbine wheel on to the buckets. The nozzles are formed by tapered slots milled in the mating face of one half of the turbine casing, so that when this is bolted to the other half, which has a flat mating face, a series of nozzles are formed. Between each pump and the turbine is a fluid seal consisting of an impeller which prevents the flow of fluid out of the pump when the pump is running, and a loose silicone rubber/glass fabric diaphragm which seals against a washer on the shaft when the turbine is stationary. All rotating components are secured to the turbine shaft by means of a nut and locking washer on the C-fuel side and a screw and locking washer on the H.T.P. side.

The material of the turbine casing, pump casings and impellers is light alloy (BSS.TA/7/AW.10 B). The turbine rotor is stainless steel (BSS.S 62 or S 80), the bearing surface of the shaft being chromium plated.

The weight of the complete unit is $14\frac{1}{2}$ lb.

5.4 Main H.T.P. valve

This valve acts as the shut off valve for the H.T.P. supply to the combustion chambers. A view of the general arrangement of the valve is shown in Fig.14. It is a poppet type of valve which is kept on its seating by the pressure of a spring and, when the pumps are operating, by the pressure of the H.T.P. To open the valve, C-fuel is fed to the diaphragm chamber on top of the valve, the chamber being sealed from the H.T.P. side of the valve by two P.V.C. diaphragms. Since the two liquids are self-igniting two diaphragms are used as an extra precaution in case one of them should rupture. The space between the diaphragms is vented to atmosphere so that should one of the diaphragms rupture the leakage can quickly be detected; and also the accumulation of liquid prevented. The likelihood of both diaphragms rupturing simultaneously and allowing mixing of the self-igniting liquids is very remote. The design of the valve is such that a minimum C-fuel pressure of 280 lb/sq in is required to open the valve against an H.T.P. pressure of 600 lb/sq in. This type of valve ensures that the C-fuel arrives at the injector slightly ahead of the H.T.P. as it has been found by experience that this gives smooth ignition, whereas if H.T.P. arrives first it invariably gives rise to a "hard" start.

The valve body is a light alloy silican casting (D.T.D.240), the valve seat being a stainless steel insert with all moving parts (except the distance piece between the diaphragms which is light alloy) also of stainless steel (BSS.S 61). The spring is normal spring steel and the diaphragms and sealing washers are of P.V.C.

Little trouble was experienced in making the valve work satisfactorily, the main points requiring attention were the operation of the diaphragms and sealing of the joints. Rupturing of the diaphragms by overstretching was prevented by limiting the valve movement to 0.20 in. and by suitably shaping the distance piece and upper and lower discs of the pressure transmitter. Trapping of the diaphragms between the distance piece and the spacing ring was avoided by keeping the clearance small, about 0.004 in. To prevent the diaphragms pulling inwards when under tension and also to make a better seal, mating ridges and grooves were turned on the metal faces. To give a good seal it is essential for the P.C.D. of these ridges and grooves to be less than that of the inner edge of the bolt holes, otherwise leakage takes place past the bolts. It was also found necessary to put a lip on the outside of the spacing ring to prevent the P.V.C. from being squeezed outwards. The P.V.C. sealing ring on the bottom cover was prevented from being squeezed out by housing it in a groove.

The valve as designed required a minimum C-fuel pressure of 280 lb/sq in. to open against an H.T.P. pressure of 600 lb/sq in; this worked quite satisfactorily on the first five motors but on the sixth motor considerable trouble was experienced in making the valve open, owing apparently to too big a difference between the H.T.P. and C-fuel pressures during the change over from no delivery to full delivery conditions. There appeared to be no reason for this change in behaviour compared with that of previous motors especially as the pumps were giving the correct pressures under full flow conditions. As it was not possible, therefore, to adjust the pump pressures the diaphragm chamber on the H.T.P. valve was increased in diameter by 1 inch and thus the minimum C-fuel pressure necessary to open the valve was reduced from 280 lb/sq in. to 120 lb/sq in. at an H.T.P. pressure of 600 lb/sq in. This modification was made quite simply by putting a larger diaphragm chamber on the existing valve body (see Fig.15) and as it worked quite satisfactorily all subsequent valves were modified in a similar manner.

Fig.16 is a view of the valve showing the position and purpose of the various connections.

5.5 Main C-fuel valve

This valve acts as the shut off valve for the C-fuel supply to the combustion chambers. A sectioned view of the valve is shown on Fig.17. It consists of a poppet type valve (1) which is kept closed by means of a spring acting upon the piston (2). When the turbo pump unit is running C-fuel from the pump acts against the head of the valve (1) through connection (3) and also on the back of the piston (2) through connection (4), the difference in loading upon the valve being such as to keep it closed. The C-fuel is fed to connection (4) through the C-fuel solenoid valve. When it is desired to fire the combustion chambers this solenoid valve is de-energized and this releases through its vent valve the C-fuel pressure acting upon the back of piston (2). The C-fuel acting on the face of valve (1) is now capable of forcing the valve open and flow takes place to the combustion chamber.

The material of the valve body is light alloy (AW.10B), the valve seat being a pressed in stainless steel insert (DTD.176). The valve head and piston are both of brass (BSS.B 251).

The main trouble experienced with this valve was to obtain a good seal at the valve seat and across the piston. The first valve had the valve head and piston integral with each other and no piston rings, but due to the close clearance between the piston and cylinder (0.0005 in.) it was difficult to obtain a good seal at the valve seat. By making the valve head separate from the piston, increasing the clearance of the piston to 0.003 - 0.007 in. and fitting P.V.C. piston rings a satisfactory seal was obtained at the valve seat and across the piston.

5.6 C-fuel solenoid valve

Views of this valve are shown in Fig.18. When the valve is opened (energized) and the pumps are running it allows C-fuel to be fed to the operating piston of the main C-fuel valve and ensures that the C-fuel valve remains closed. When the solenoid valve is closed (by de-energizing) the pressure on the operating piston of the main C-fuel valve is released through a vent (3) in the solenoid valve and thus allows the main C-fuel valve to open and feed to the combustion chambers.

The working of the valve is shown by the sectioned view in Fig.18. When the valve is opened (as shown) C-fuel from (1) goes past the lower piston up through the lower orifice and out through (2). When the valve is closed, the lower piston makes contact with its seat and the upper piston opens and thus allows the C-fuel downstream from the valve to be released through the upper orifice and out through the vent (3). The solenoid is operated by a 24 volt supply and takes a current of about 1 ampere.

This solenoid valve is of German manufacture and is of the type used in the air system of the V.2 rocket motor. To enable the valve to function satisfactorily in the Beta motor the following four modifications were found necessary:-

(1) replacement of the rubber seats in the upper and lower pistons by tin ones; the original seats rapidly became soft and disintegrated under the action of the C-fuel, but the tin seats performed very well,

(2) insertion of a plug in the lower orifice so as to reduce its area and thus enable the solenoid to open the valve against pressures up to about 1000 lb/sq in

(3) blanking off the original vent holes (situated between the intermediate nut and the solenoid) by fitting a rubber insert in the solenoid body and

(4) drilling and tapping the valve body to take a new vent connection (3). This was necessary in order to get rapid venting and also because it was impossible to fit a drain pipe to the original vent holes.

5.7 Steam generator

A sectioned view of the steam generator is shown in Fig.19. H.T.P. enters the generator at (1) and passes through the fixed "full delivery" orifice throttle which meters the correct quantity of H.T.P. required by the turbine when the motor is firing. The H.T.P. passes through a distributor plate and then through layers of silver plated gauze catalyst which decomposes the H.T.P. into superheated steam at a temperature and pressure of about 470°C and 290 lb/sq in. (gauge) respectively. The steam is then fed to the turbo-pump unit through connections (2), (3), (4) and (5) and to the combustion chambers through (6).

The body, coverplate, gauze support plate, and steam connections of the generator are of mild steel, but the H.T.P. inlet connection is of stainless steel. The gauzes are copper of 32 s.w.g. and 24 mesh/inch, the copper being silver plated to a thickness of 0.003 in. The gauze discs are 0.050 in. larger in diameter than the inside of the generator to ensure a good fit and so prevent leakage of liquid H.T.P. along the walls of the generator. The depth of catalyst bed is 4 in., the number of gauzes being 145 ± 2.

The steam consumption of the turbine at full delivery conditions is 0.63 lb/sec which with that supplied to the combustion chambers makes a total of 0.66 lb/sec; this produces a loading on the generator of 30 lb/sec/sq ft. The life of the gauze under these conditions is at least 10 minutes, but at the end of this period the silver tends to strip from the gauzes nearest to the injector which causes a fall in decomposition temperature. The total pressure drop across the generator is approximately 100 lb/sq in. which consists of 50 lb/sq in. across the injector and 50 lb/sq in. across the gauze filling. The generator can cope with flow rates up to 1.0 lb/sec (corresponding to a loading of 40 lb/sec/sq ft), but only at the expense of a shorter catalyst life and higher pressure drop. The relatively short catalyst life experienced on this motor is due to the poisoning of the silver gauze by the stabilizer (phosphoric acid) in the hydrogen peroxide. A very much longer life could be obtained if a different stabilizer were used such as sodium stannate.

Although the generator in its present form is quite satisfactory for its purpose, it has the disadvantage of giving a slow start, especially in cold weather. This is overcome by giving a burst of H.T.P. of about 1 second duration to the generator a few seconds before starting. This preheats the generator and starting thereafter is quite satisfactory.

The development of the generator consisted mainly of getting a satisfactory injector system. The injector system as originally designed is shown in Fig.20. With this injector rapid steam pressure fluctuations were apparent (± 50 lb/sq in. at 250 lb/sq in. mean), and starting was slow even at low (0.25 lb/sec) flow rates. The pressure fluctuations were apparently due to the formation of vapour in the free space between the full delivery throttle and the first gauze which caused intermittent flow. These fluctuations were eliminated by reducing the free volume between the full delivery orifice and the first gauze to an absolute minimum, and by putting the distributor plate as close as possible (within 0.010 in.) to the first gauze and increasing slightly the pressure drop across it. These modifications are incorporated in the final design shown in Fig.19 from which it can be seen that the distributor plate now takes the place of the upper support plate. The ratio of the area of the holes in the distributor plate to that of the full delivery throttle is 2.7/1, whereas in the original design it was 4/1. These modifications besides eliminating the pressure fluctuations also improve the starting considerably, but as mentioned earlier starting is still somewhat slow in cold weather.

5.8 Tank supply valve unit

A sectioned drawing of this unit is shown in Fig.21. It consists of two poppet type shut off valves – one for H.T.P. and the other for C-fuel – and is fitted in the low pressure H.T.P. and C-fuel pipe lines between the tanks and the turbo-pump unit (as indicated in Fig.1); the purpose of this unit is to isolate the tanks from the motor except when the motor is operating.

As shown in Fig.21 C-fuel enters the unit at (1) passes through the valve and comes out at (2). Similarly H.T.P. enters the other end at (3) and comes out at (4). The valves are opened by H.T.P. pressure in chamber (9) which is supplied from the feed line to the steam generator through connections (5) and (6). The H.T.P. valve is opened by pressure acting on its stem and the C-fuel valve is opened by pressure acting on a sealing diaphragm; since the liquids are self-igniting two diaphragms are used as a precaution in case one should rupture. In the H.T.P. valve the only seal is that provided by a P.V.C. washer which is attached to the valve stem and seats against a lip on the valve guide. The valve seatings are formed by a lip on the face of each valve which makes contact with the inner diameter of the P.V.C. sealing washers (12) and (13). Connections (7) and (8) are used for bleeding trapped air from the system before the motor is fired. The minimum pressures necessary to open the H.T.P. and C-fuel valves are about 40 lb/sq in. and 60 lb/sq in. respectively with atmospheric pressure in the tanks, and 155 lb/sq in. and 230 lb/sq in. respectively with a pressure of 17 lb/sq in. in the tanks.

The valve body is a light alloy silicon casting (DTD.240) and all the moving parts are of stainless steel (BSS.S80) with the exception of the distance piece between the diaphragms which is of light alloy. The springs are of normal spring steel and the tubular spring retainers of stainless steel (BSS.S80). As a protection against corrosion the valve body is anodized.

Little difficulty was experienced in getting the valve unit to work satisfactorily, the two main difficulties being the operation of the diaphragms and H.T.P. leakage from chamber (9) along the stem of the H.T.P. valve. The former was cured in the same manner as already described for the main H.T.P. valve. The leakage along the stem of the H.T.P. valve was prevented by fitting a P.V.C. washer to the stem of the valve which is seated against a lip on the valve guide when the valve opened. However, a slight leakage along the stem of the valve is permissible, but unless the seal is fitted, this leakage becomes excessive; the maximum leakage was set at 30 drops per minute with a pressure of 100 lb/sq in. in chamber (9).

5.9 Dump valve

This valve (Fig.22) is a shut off valve which is spring loaded in the open position, so that when the main H.T.P. valve is closed, the H.T.P. system downstream from the main H.T.P. valve is vented to atmosphere through outlet (2). As soon as the main H.T.P. valve is opened to fire the combustion chambers, the H.T.P. pressure reaches the back of piston (4) through connection (3); this causes a differential pressure across the valve and closes it. When the valve is closed the pressure differential across the piston is quite small (about 25 lb/sq in.) so that the leakage is not very great; in any case a small leakage here is not important.

The body and piston of the valve are of stainless steel (DTD.176A and BSS.S80 respectively), the spring being of normal spring steel.

5.10 Non-return valve

A drawing of this valve is shown in Fig.23. It is a simple valve lightly spring loaded in the closed position, and is used to prevent H.T.P. from the external supply to the steam generator being fed into the main H.T.P. feed line to the combustion chambers whilst the turbo-pump unit is being run up to speed. When the main H.T.P. valve is opened the H.T.P. supply to the steam generator is taken through this valve.

The material of the body and valve are both stainless steel (DTD.176A and BSS.62 respectively). The spring is normal spring steel and the sealing washer is of pure aluminium.

5.11 Burster disc unit

A drawing of this unit is shown on Fig.24. The purpose of this burster disc is to prevent H.T.P. being fed to the steam generator when the external H.T.P. supply, at a pressure of 80 lb/sq in., opens the tank supply valve to bleed the air from the propellant system before the motor is started.

As shown in Fig.24 H.T.P. from the external supply enters at (1) and after the P.V.C. disc has burst emerges at (2) and goes to the steam generator. Removal of the skin cover (3) and sealing cap (4) allows the bursting disc assembly (5) to be taken out in order to replace the P.V.C. bursting disc. The whole unit is fitted into the motor so that the skin cover (3) is flush with the fuselage to enable the disc to be easily replaced.

The burster disc is required to hold a pressure of 80 lb/sq in. indefinately without rupturing and to burst at a pressure of 250 lb/sq in. Unfortunately P.V.C. tends to "flow" under a sustained pressure so that for a given thickness of disc its maximum "non-bursting" pressure is well below its minimum instantaneous bursting pressure. For instance a P.V.C. disc with a thickness of 0.011 in. bursting at an instantaneous (i.e. less than 1 sec) pressure of 250 lb/sq in. will burst at 135 lb/sq in. after 6 seconds, and hold a pressure of 120 lb/sq in. indefinately. The P.V.C. is also adversely affected by a rise in temperature, a rise in temperature from 10 to 25°C and from 10 to 40°C causing a reduction in bursting pressure of about 33% and 55% respectively. Because of this temperature characteristic two thicknesses of burster disc are necessary, one of 0.011 in. for ambient temperatures up to 25°C and one of 0.018 in. for ambient temperatures above 25°C. The 0.011 in. disc will have at 10°C an instantaneous bursting pressure of about 300 lb/sq in. and a minimum bursting pressure of about 160 lb/sq in., whilst at 25°C these pressures are about 200 lb/sq in. and 110 lb/sq in. respectively. The fact that the instantaneous bursting pressure of 300 lb/sq in. is 50 lb/sq in. higher than the bursting pressure applied (i.e. the external H.T.P. tank pressure) means that the disc will not burst instantaneously but after an interval of a few seconds; this is, however, of no consequence. The 0.018 in. disc will have at 25°C an instantaneous bursting pressure of about 250 lb/sq in. and a minimum bursting pressure of about 130 lb/sq in., whilst at 40°C these pressures are about 200 lb/sq in. and 110 lb/sq in. respectively. The physical characteristics of P.V.C. also change from batch to batch so that tests have to be made to determine the bursting pressure of each new batch. This difficulty was overcome in the Beta I motor by obtaining sufficient material of one batch to cover all needs.

Also included in the burster disc unit is the "no-delivery" throttle (8) which controls the flow of H.T.P. to the steam generator when the pumps are running but not delivering any propellants to the combustion chamber.

The material of the body is light alloy (AW.10B) and the burster disc assembly is of stainless steel (BSS.S80).

5.12 Pressure switches

Two of these pressure switches are fitted to the motor, one each in the H.T.P. and C-fuel lines immediately before the main valves; their function is to indicate to the operator that the pumps are giving the correct pressures before he fires the combustion chambers. Each switch consists of a pair of contacts kept closed by a spring and connected to a lamp on the firing panel. As the propellant pressures rise the contacts are forced apart and the lamps are, therefore, extinguished. These switches are a proprietary article made by the Thermal Control Co., Hove.

6 Development of propellant system

The two main considerations which led to the adoption of a turbo-pump pressurization system were its low overall weight and the possibility of using it to drive an electrical alternator to supply power for the various aircraft requirements. This entailed running the alternator at a constant speed (within ± 5%) for three distinct periods:-

(a) about 30 seconds immediately before firing the chambers; during this period the pumps are only pumping sufficient H.T.P. to drive the turbine, and the pump loading on the turbine, therefore, is low.

(b) about 50 seconds, whilst the chambers are being fired; during this period the pumps are delivering their full quantity and the pump loading on the turbine is, therefore, high.

(c) about 60 seconds immediately after the chambers have stopped firing; during this period the pumps are only delivering sufficient H.T.P. to drive the turbine and the pump loading on the turbine is, therefore, low.

A turbine speed control system had to be devised which catered for a sudden change in loading on the turbine of approximately 50% whilst changing between periods (a), (b) and (c), and for a load variation on the turbine of about 15% due to electrical load variations on the alternator.

As already described[5] control valves, based upon a spring datum with the H.T.P. pressure as the signal operating the valves were tried in the H.T.P. feed line to the steam generator; these were not very successful because of the fundamental fact that for a certain position of the metering device the spring datum has one compression load whilst for another position of the metering device the spring alters so that it is no longer a datum. Tests with the valve in the complete motor showed that while it could cope with small changes in load, it certainly could not cope with the large change during the transition from period (a) to (b). This change was made more difficult by the fall in H.T.P. pump pressure which occurred at this instant. The transition from period (b) to (c) gave no trouble. To overcome these difficulties a booster solenoid valve was fitted in the system to deliver an extra supply of H.T.P. to the steam generator during the change over, and this worked successfully. A layout of this arrangement is shown in Fig.25. With the pumps running and the main H.T.P. valve closed the H.T.P. is fed to the generator through the turbine control valve and the steam generator shut off valve, the booster solenoid valve being closed. At the instant the main H.T.P. valve is opened, the booster solenoid valve is also opened thus an extra quantity of H.T.P. is fed to the steam generator; this quantity is limited by a throttle orifice immediately downstream from the turbine control valve. As soon as the turbine speed has stabilized at the higher load conditions (a matter of 2 - 3 seconds) the booster solenoid valve is closed and a supplementary feed of H.T.P. taken to the steam generator from a tapping downstream from the main H.T.P. valve; this feed supplements that passing through the turbine control valve so that the movement of the latter from its datum point is a minimum. The shut off valve included in the circuit was intended to enable the turbine to be stopped if required.

This system worked reasonably well, but because of the limitations of this control valve, a new type of valve was designed in which a constant air pressure was the datum, the need for either the booster solenoid valve or the supplementary feed thus being eliminated. This valve has been successfully used on a turbo-pump test rig and is described elsewhere[1].

Due to the delays, however, in achieving the satisfactory operation of a control valve it had previously been decided to dispense with the alternator on the Beta I motor and to use storage batteries instead for the aircraft electrical requirements. This made possible a considerable simplification of the H.T.P. feed system to the steam generator, the system finally adopted being as shown in Fig.1. With this system the H.T.P. is fed to the steam generator, during the period when the pumps are being run up to speed with no delivery taking place, from a tank external to the aircraft and supplied to the motor through a pull-off coupling. When the pumps are delivering to the combustion chambers the H.T.P. supply to the steam generator is taken off downstream from the main H.T.P. valve and, as this is at a higher pressure than the external H.T.P. tank, the flow from the latter is automatically stopped, a non-return valve in the external supply line preventing back-feeding of H.T.P. into the external tank. The constant pressure of the external H.T.P. supply prevents an excessive fall in turbine speed during the transition from no delivery to full delivery and thus helps to give a quick take-over. This change-over has of necessity to be rapid otherwise, if the aircraft moves up the launcher and disconnects the pull-off coupling before the turbine has stabilized, the motor is liable to stop. This possibility is minimized because (a) the aircraft is launched almost vertically upward and, as its weight is not very much less than the thrust of the motor, the motor has to develop almost full thrust before the aircraft will move; (b) the boost rockets are only fired when the aircraft has moved a definite distance (about 2 in) along the launcher; and (c) the aircraft has to move about 2 in. along the launcher before the pull-off coupling is disconnected.

As already shown[5], to obtain a given thrust the pressure drop of the H.T.P. supply to and through the steam generator must be kept constant. Due to the straightforward nature of the feed system to the generator little variation can take place there, and the drop through the generator is kept reasonably constant by controlling the number and uniformity of packing of the gauze discs. Any variation in pressure drop here or through the rest of the system is controlled by adjusting the size of the fixed "full delivery" throttle (Fig.1) to give the desired thrust.

7 Performance of motor

The motor gives a nominal thrust of 1800 lb at a combustion chamber pressure of 250 lb/sq in. The limits of thrust are set at ± 5% (i.e. between 1710 and 1890 lb), but the maximum variation in thrust between each combustion chamber of a given motor is 5%. A curve giving the relationship between combustion chamber pressure and thrust is shown in Fig.26.

Fig.27 shows representative curves of propellant and chamber pressures and thrust. The reason for the fall off in propellant pressures (and therefore thrust) as the run proceeds is that the H.T.P. pump is sensitive to inlet pressure; with the present tank pressurizing system the pump inlet pressures fall from 17 lb/sq in. at the start to about 3 lb/sq in. at the end of a run.

The specific thrust of the chambers is 190 lb/lb/sec and the overall specific thrust (including the turbine) is 177 lb/lb/sec giving an overall specific consumption of 0.565 lb propellant/lb thrust/sec. The total propellant consumption is 10.15 lb/sec which at a chamber mixture ratio of 2.78/1 and a turbine steam consumption of 0.63 lb/sec gives H.T.P. and C-fuel consumptions of 7.63 lb/sec and 2.52 lb/sec respectively.

The total weight of the complete motor including the monocoque type fuselage but excluding the tanks is 159 lb (see Appendix II for details). The weight of the tanks including the P.V.C. bags and air pressurizing system is 100 lb giving a total dry weight for the motor and tanks of 259 lb. The weight of propellants contained in the tanks is 485 lb giving a total charged weight of 744 lb. Due to the impossibility of completely emptying the tanks the weight of propellant used is 465 lb, the duration being 45 seconds. The specific thrust/lb total weight/second is therefore, 109.

8 Conclusions

The Beta I motor has been successfully developed to give a thrust of 1,800 lb for a duration of at least one minute (the actual duration when the motor is installed in the aircraft depends on the size of the tanks). The overall specific thrust/lb of propellant is 177 lb/lb/sec (86% of the theoretical value), that of the combustion chambers alone being 190 lb/lb/sec (92% of the theoretical value).

The weight of the motor complete with tanks and propellants (but excluding wings, rudder etc) is 744 lb giving a specific thrust of 109 lb/lb total weight per sec. With the existing tanks the duration is 45 seconds.

Regenerative cooling of the combustion chambers with 80% hydrogen peroxide has been quite successful. Although during the development period some burning through of the chamber wall was experienced no trouble whatever has been encountered due to the unstable nature of the hydrogen peroxide.

A slightly larger motor than the Beta I is now under development to meet a separate requirement. This motor, known as the Beta II is similar in most respects to the Beta I, the main difference being that it has a single combustion chamber of 2500 lb thrust instead of two separate chambers each of 900 lb thrust.

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Attached: Drawings RP.650 - 654, 656 - 673

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APPENDIX I

Summary of Main Details of Motor

1 Performance

Thrust	1800 lb total ± 5%

On each motor the difference in thrust between each combustion chamber does not exceed 5%

Duration	45 seconds (Dependant upon size of tanks)
Total Impulse	81,000 lb - sec
Specific thrust (chamber only)	190 lb thrust/lb/sec
" " (overall)	177 " " "
" consumption (overall)	0.565 lb propellant/lb/sec
Propellant consumption (overall):-	
H.T.P.	7.63 lb/sec
C-fuel	2.52 lb/sec
Total	10.15 lb/sec

2 Propellants

Oxidant - Hydrogen peroxide (H.T.P. (80%)

Fuel - C-fuel (methyl alcohol 57% hydrazine hydrate 30%, water 13% plus copper catalyst)

H.T.P./C-fuel mixture ratio for combustion - 2.78/1 (wt)

3 Pressures

High pressure air	2300 lb/sq in
Propellant tanks:-	
Static	17 lb/sq in
Flow	3 lb/sq in
H.T.P. pump	
No delivery	550 - 600 lb/sq in
Full "	390 - 420 "
C-fuel pump	
No delivery	450 - 500 lb/sq in
Full "	420 - 450 lb/sq in

Pressure warning lights set to extinguish at:-	
H T P.	460 lb/sq in
C-fuel	400 lb/sq in
Steam pressure	290 lb/sq in
Combustion chamber pressure	250 lb/sq in ± 20 lb/sq in
External H.T.P. supply:-	
For bleeding system	80 lb/sq in
For starting turbine	250 lb/sq in
Pressure to operate bursting disc	110 lb/sq in (minimum)

4 Propellant feed

H.T.P. steam driven turbo-pump unit

5 Combustion chamber

Two chambers each of 900 lb constant thrust

Chamber regeneratively cooled with H.T.P.

6 Temperatures

Combustion	1900°C (approx)
H.T.P. steam	470°C

7 Burster disc

The thickness of the P.V.C. diaphragm is:-

for ambient temperatures up to 25°C	0.011 in
for ambient temperatures between 25°C and 40°C	0.018 in

APPENDIX II

Summary of component weights

Main H.T.P. valve		3.30 lb
Main C-fuel valve		0.74 "
C-fuel solenoid valve		1.30 "
Steam generator		4.70 "
Tank supply valve unit		5.98 "
Dump valves (2 off)		2.39 "
Burster disc unit		1.28 "
Combustion chambers and injectors (2 off)		50.72 "
Turbo-pump unit		14.50 "
Non-return valve		0.25 "
H.T.P. pipes		10.00 "
C-fuel pipes		8.00 "
Steam feed and exhaust pipes, bleed and distributor blocks		5.00 "
Automatic pull-off connection		1.12 "
Mounting for chambers		15.00 "
Mounting for valves (with attachments including pressure switches)		3.50 "
Mounting for turbo-pump unit		1.50 "
Monocoque type fuselage around motor		29.50 "
Total weight of motor		158.78 "
H.T.P. and C-fuel tanks (including P.V.C. bags, feed pipes to tank supply valve, air bottle and piping, etc.)		100 "
Total weight of motor plus tanks (empty)		259 "
H.T.P.	349 lb	
C-fuel	136 "	
Total propellants		485 "
Total weight of motor and propellants		744 "

APPENDIX III

Hot Tinning of Rocket Combustion Chambers as Recommended by the Tin Research Institute

CLEANING

(1) Degrease in trichlorethylene vapour.

(2) Pickle for 10 minutes in cold dilute hydrochloric acid.
(3 parts commercial acid to 1 part water)

(3) Etch for 1 minute in cold dilute nitric acid.
(1 part concentrated nitric acid to 3 parts water)

(4) Pickle for 1 minute in cold hydrochloric acid as in (2).

(5) Dip in flux (I).

The pieces should be well rinsed between these acid dips.

TINNING

1st tinpot at 280°C T.R.I. flux (II) cover.

2nd tinpot at 250°C Palm oil cover.

Drain in grease pot at 240/245°C containing palm oil.

Paraffin oil quench.

COMPOSITION OF FLUX

FLUX (I)

Zinc chloride	25%
Sodium "	5%
Ammonium "	3%
Hydrochloric acid	½%
Water - remainder	

T.R.I. FLUX (II)

Zinc chloride	82%
Sodium "	18%

In view of the narrow clearance between the helix and the casing, care must be taken when immersing the wet article into the tinpot. When the body is being drained it must be held vertically for about 50 seconds and twisted sharply to clear the threads from tin.

FIG. 1

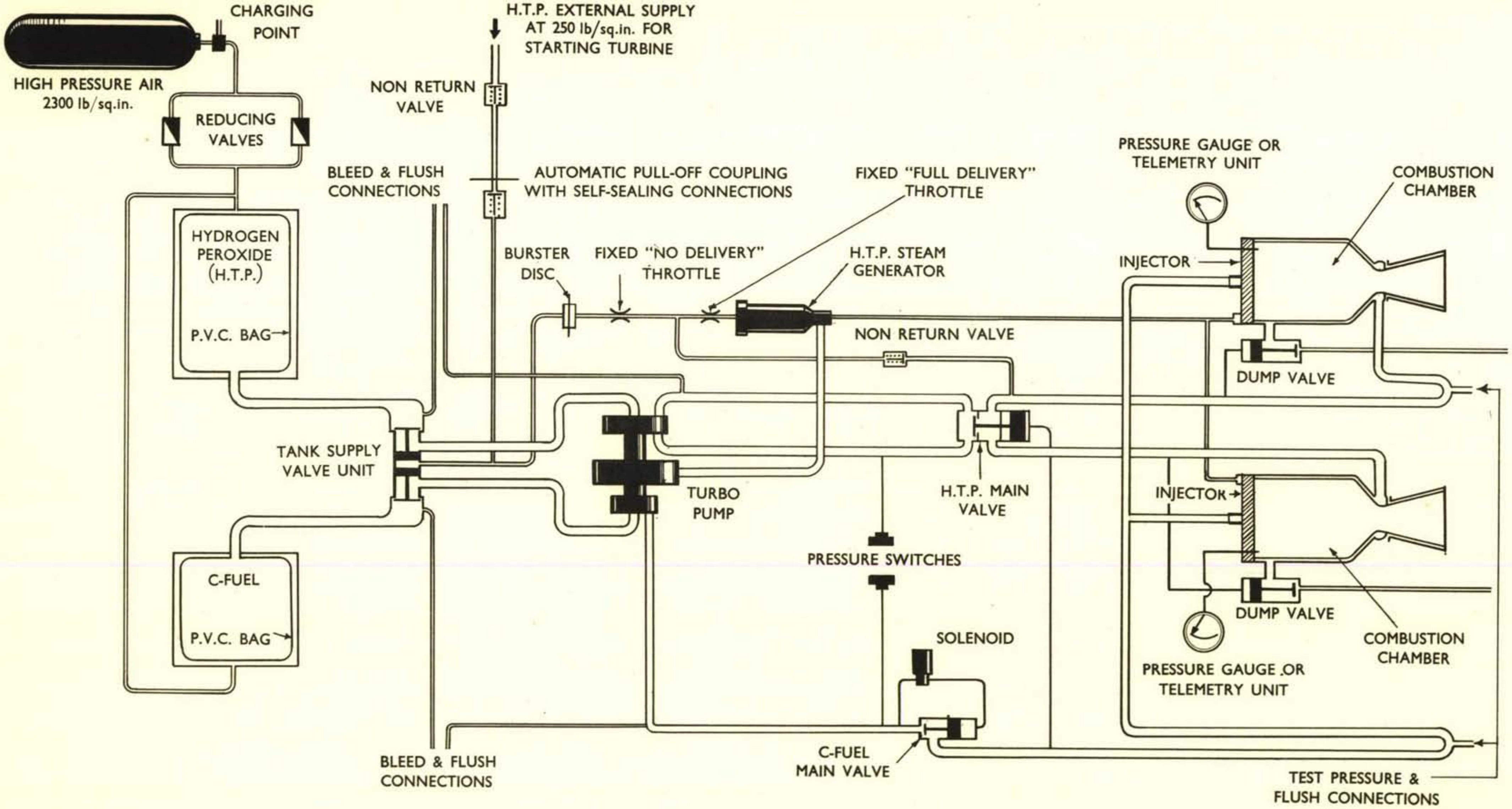
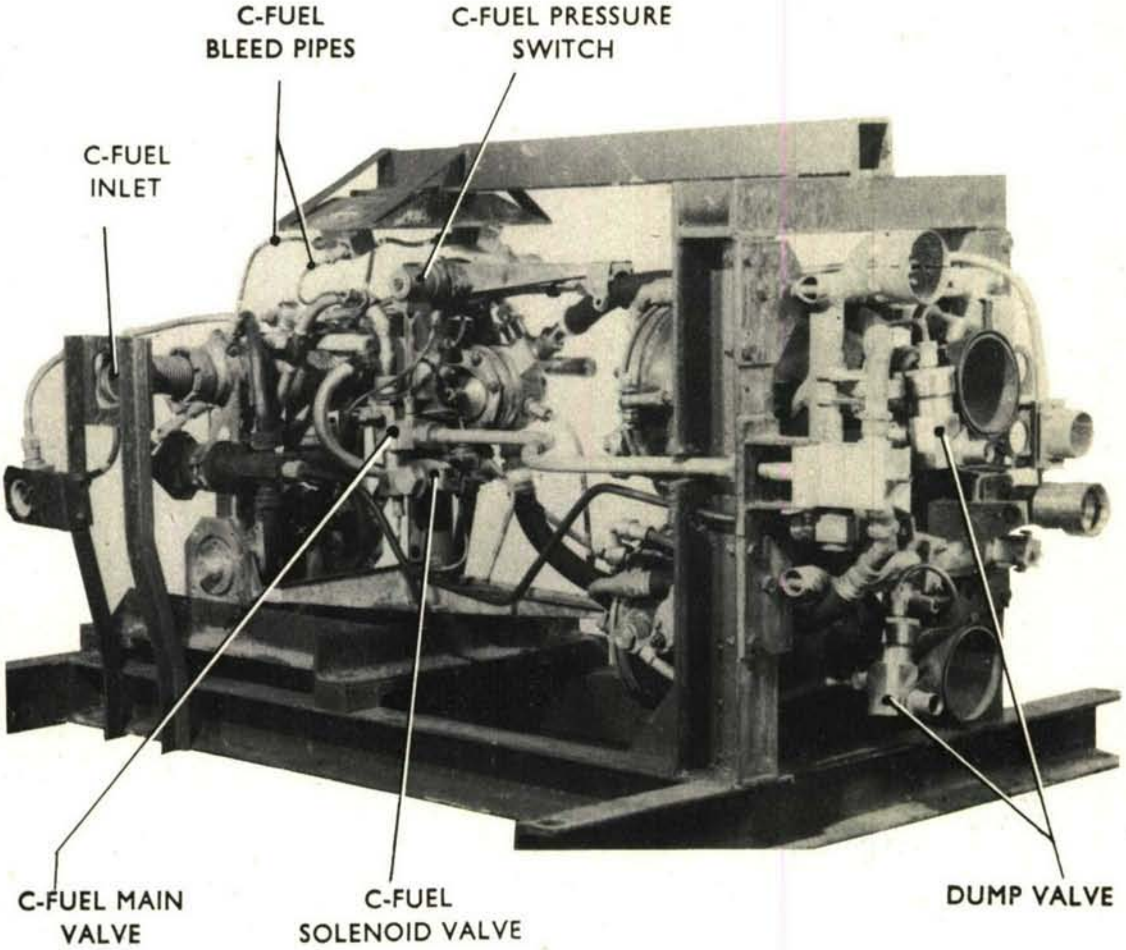


FIG.1. BETA 1 - PROPELLANT SYSTEM

FIG.2



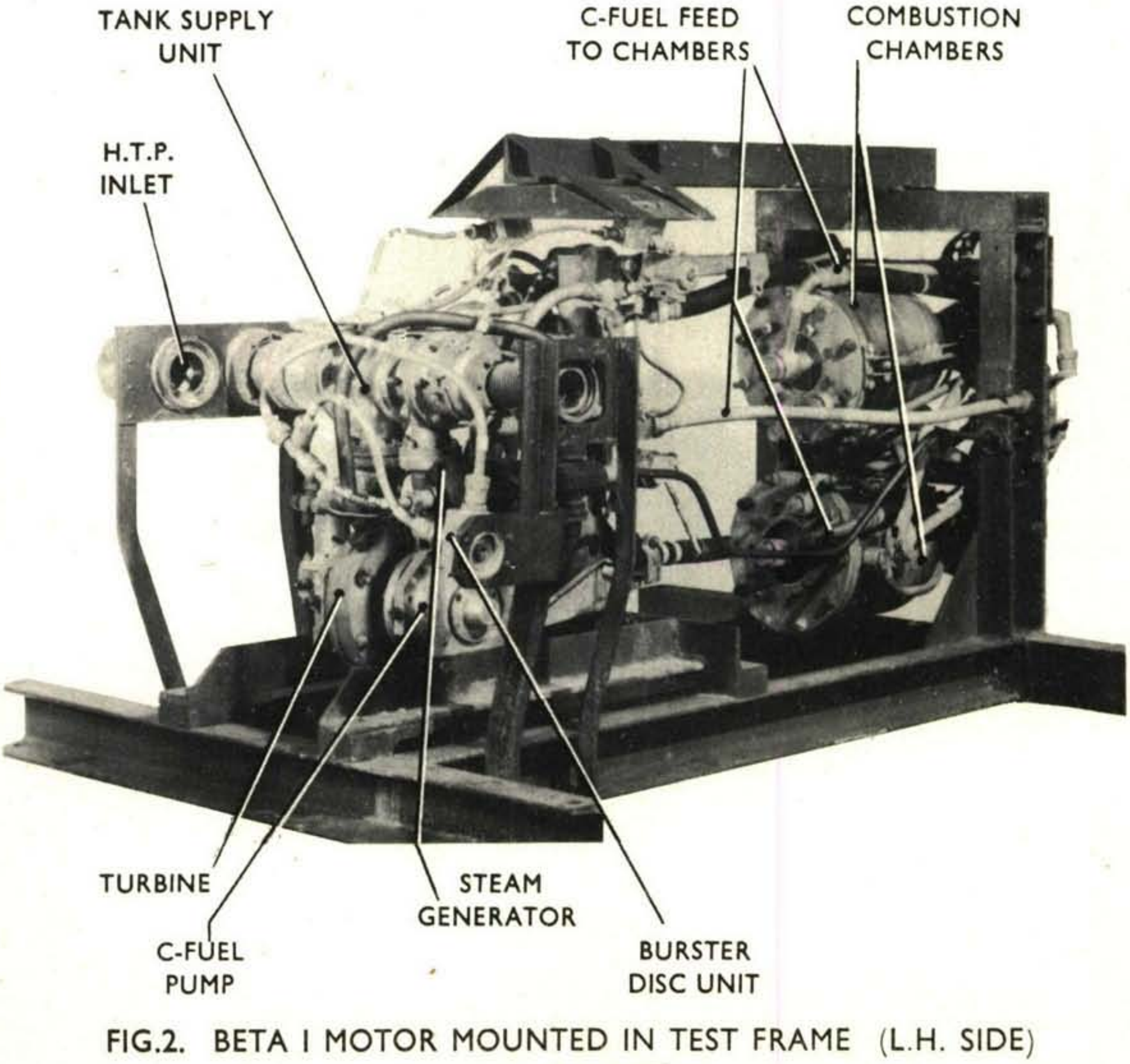


FIG.2. BETA I MOTOR MOUNTED IN TEST FRAME (L.H. SIDE)

FIG.3

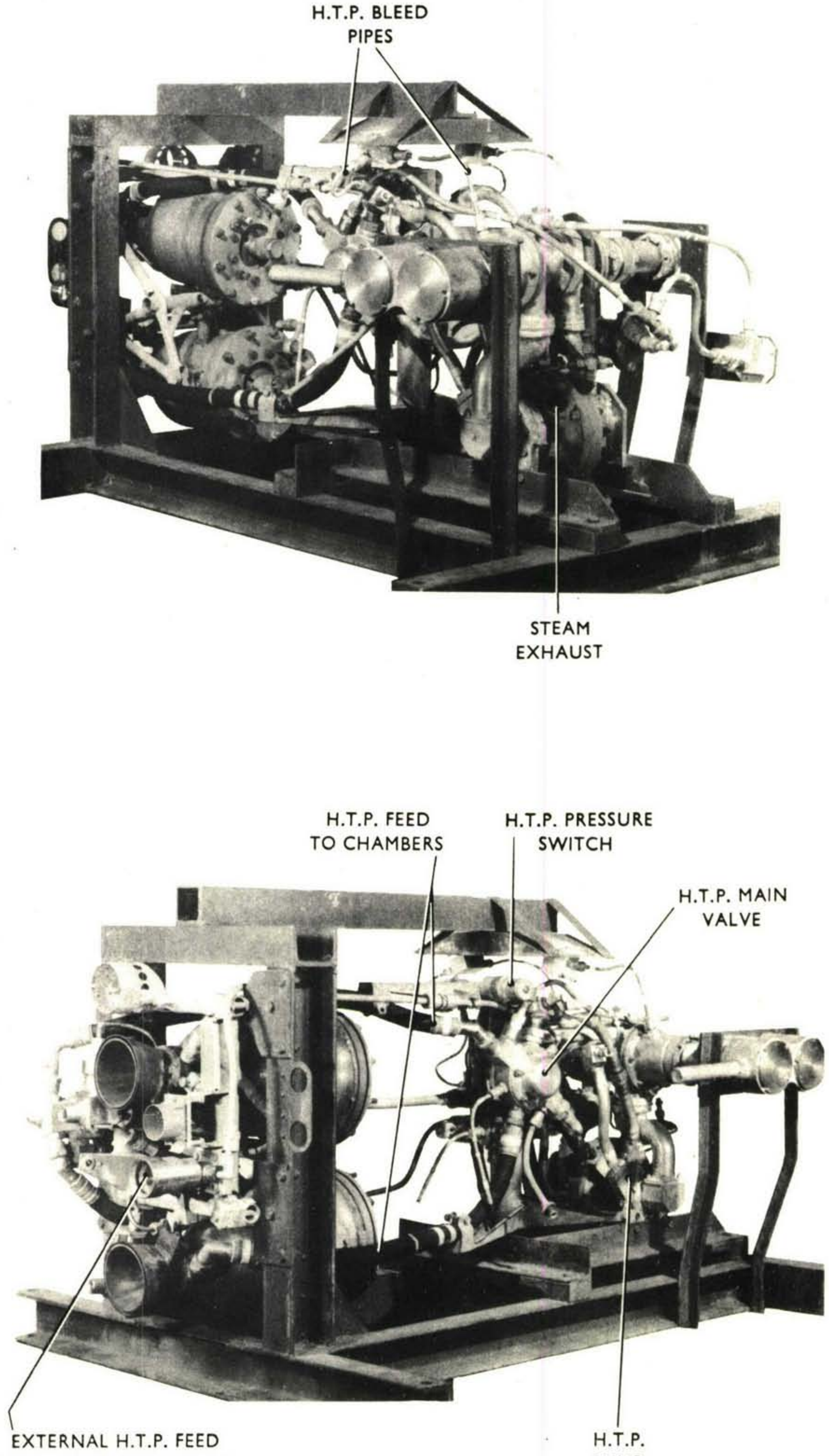


FIG.3. BETA I MOTOR MOUNTED IN TEST FRAME (R.H. SIDE)

FIG.4

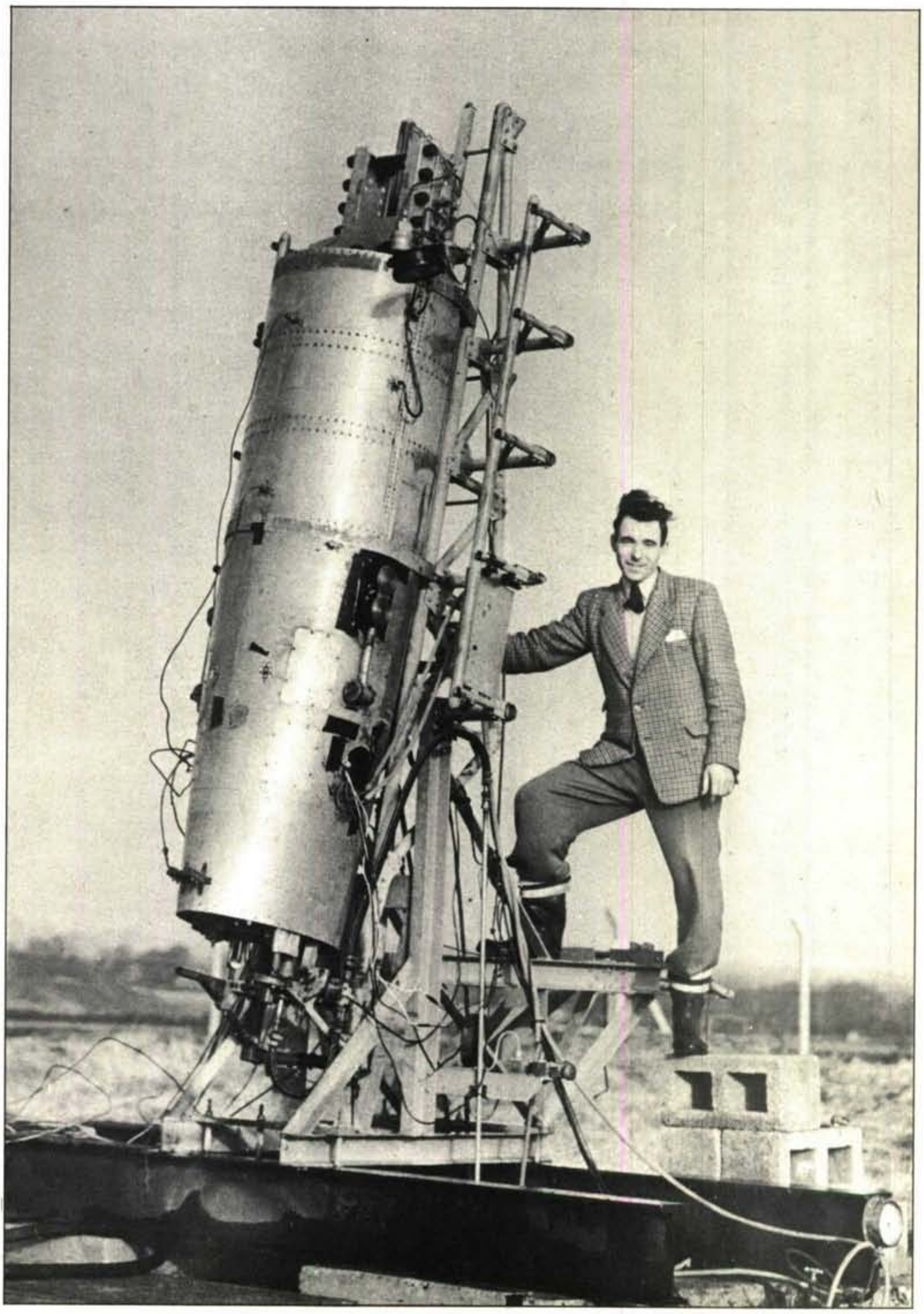


FIG.4. BETA I MOTOR COMPLETE WITH TANKS FITTED TO LAUNCHER FOR VERTICAL STATIC FIRING

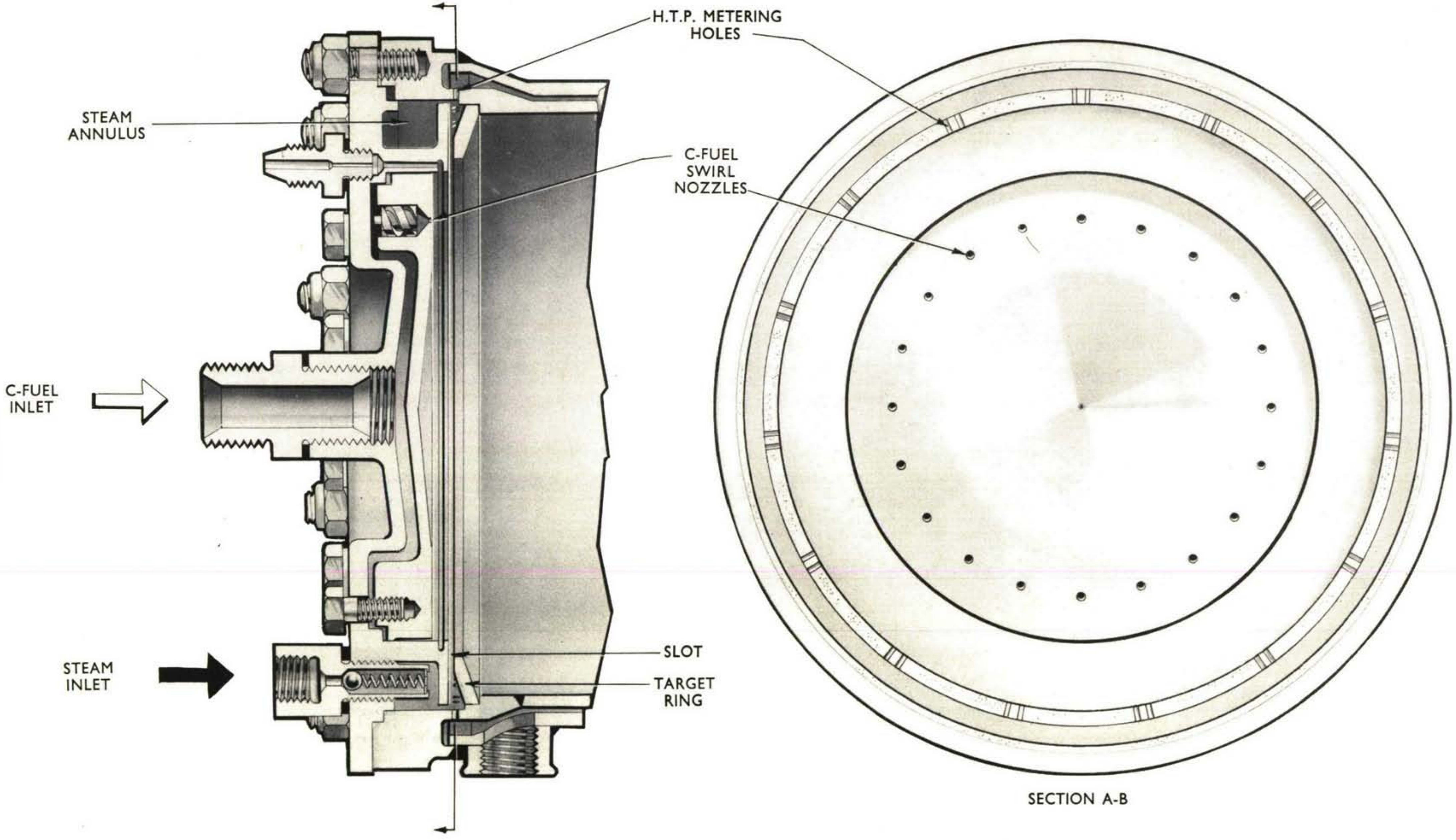
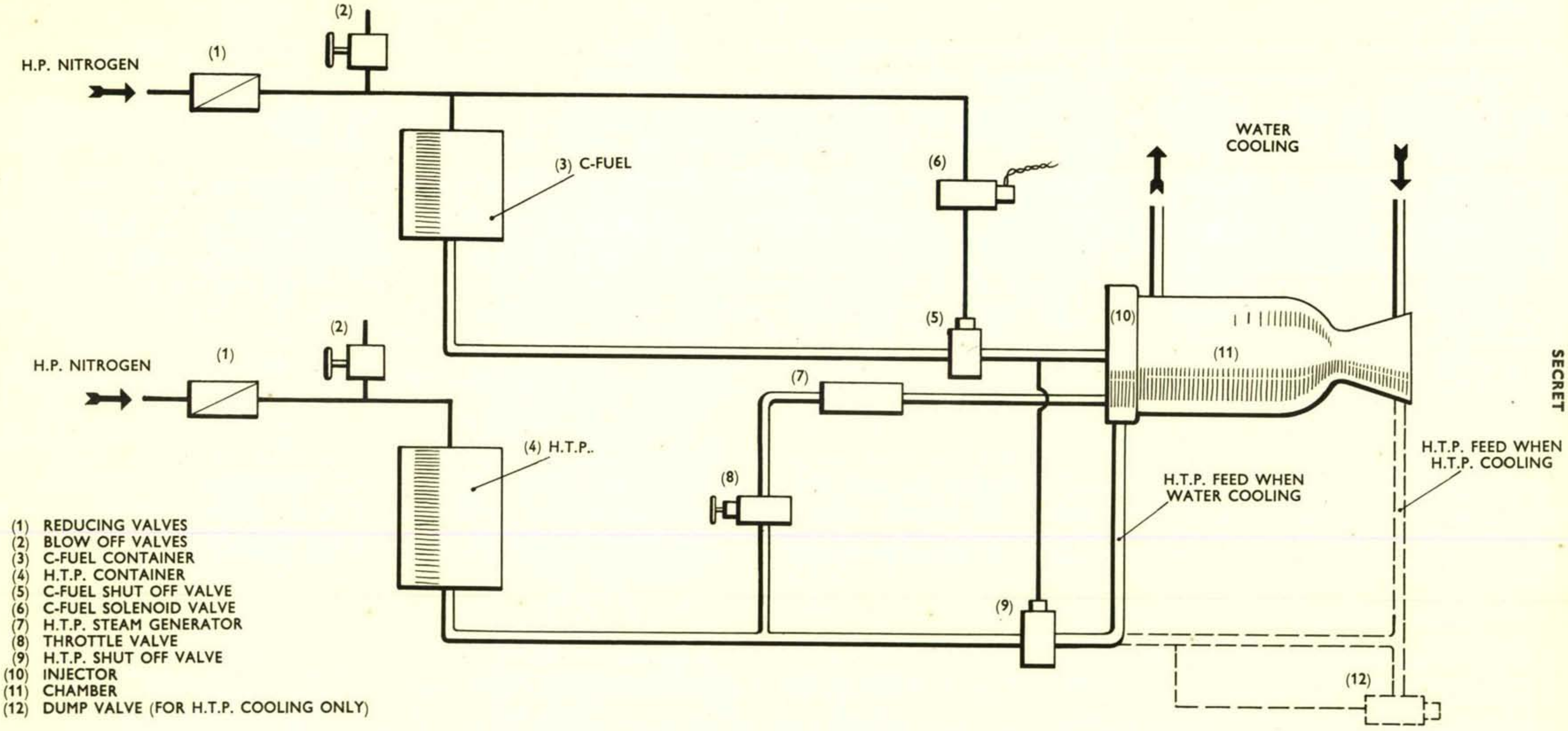
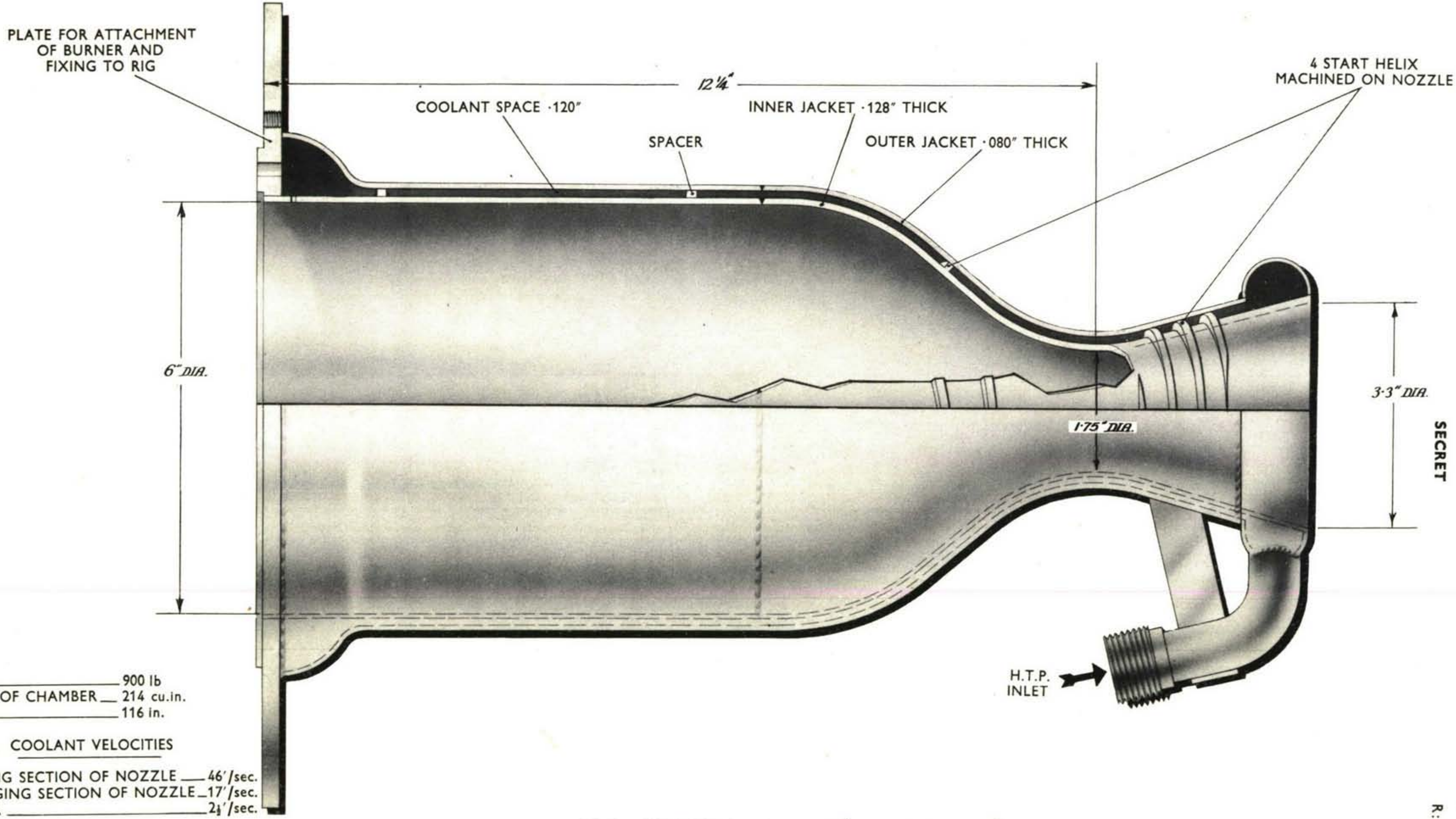


FIG.5. BETA I INJECTOR



(1) REDUCING VALVES
(2) BLOW OFF VALVES
(3) C-FUEL CONTAINER
(4) H.T.P. CONTAINER
(5) C-FUEL SHUT OFF VALVE
(6) C-FUEL SOLENOID VALVE
(7) H.T.P. STEAM GENERATOR
(8) THROTTLE VALVE
(9) H.T.P. SHUT OFF VALVE
(10) INJECTOR
(11) CHAMBER
(12) DUMP VALVE (FOR H.T.P. COOLING ONLY)

FIG.6. LAY-OUT OF TEST RIG FOR INJECTOR AND CHAMBER DEVELOPMENT



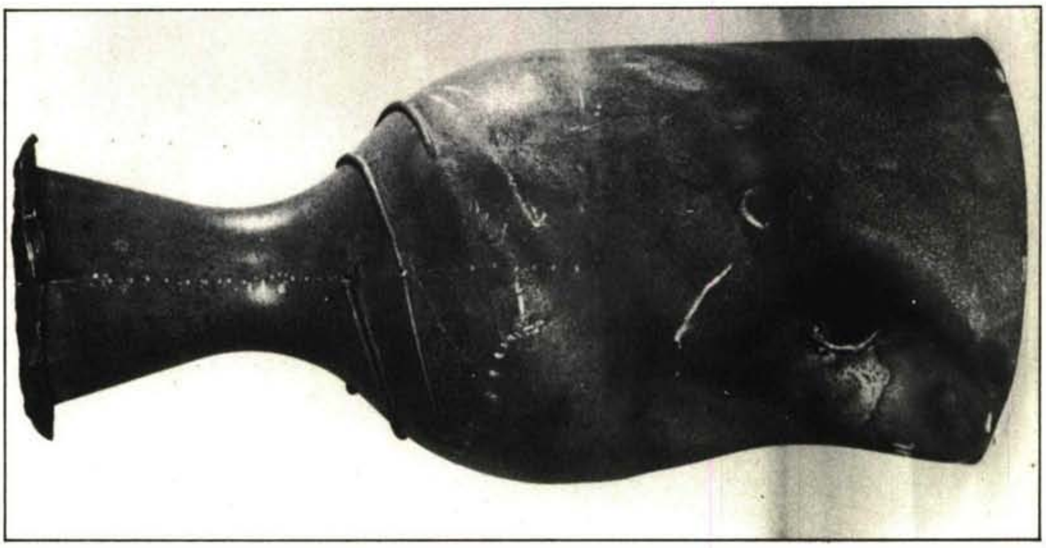
THRUST ____ 900 lb
VOLUME OF CHAMBER __ 214 cu.in.
L* ____ 116 in.

COOLANT VELOCITIES

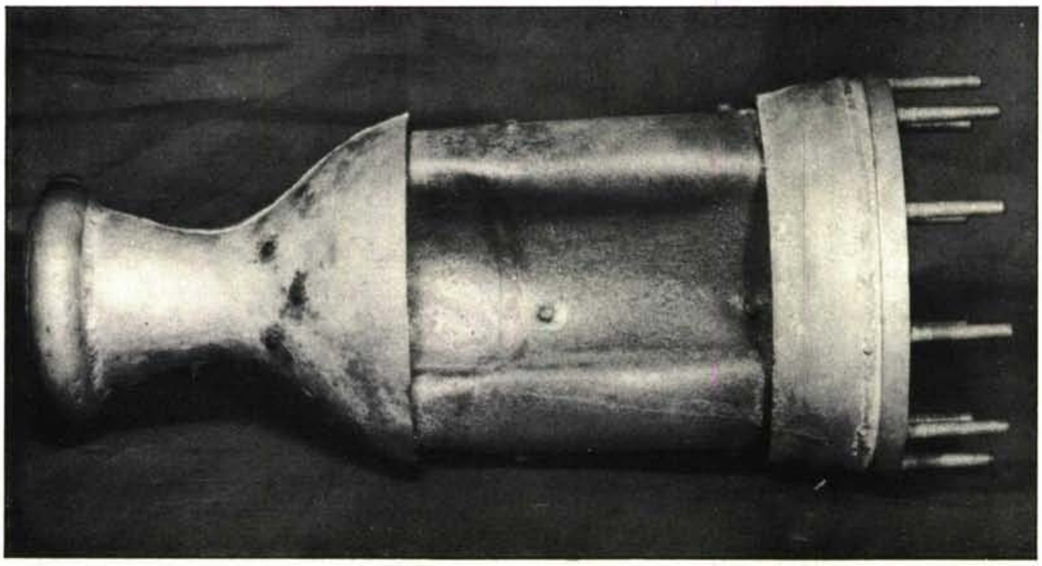
DIVERGING SECTION OF NOZZLE ___ 46′/sec.
CONVERGING SECTION OF NOZZLE _ 17′/sec.
CHAMBER ____ 2¼′/sec.

FIG.7. COMBUSTION CHAMBER (ORIGINAL DESIGN)

FIG.8



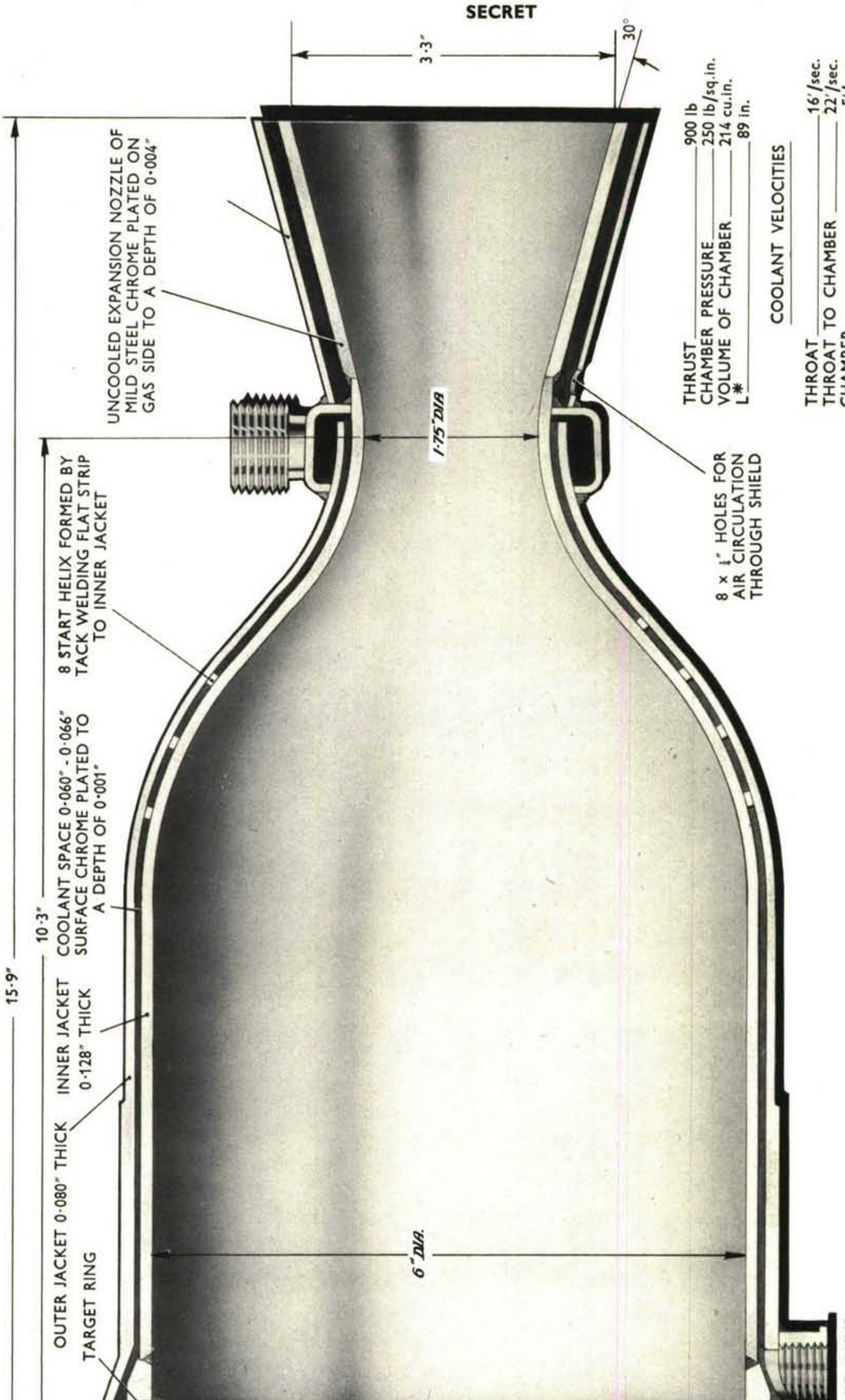
a



b

FIG.8. COOLANT FAILURE DUE TO BOILING OF H.T.P.

FIG.9.



THRUST	900 lb
CHAMBER PRESSURE	250 lb/sq.in.
VOLUME OF CHAMBER	214 cu.in.
L*	89 in.

COOLANT VELOCITIES

THROAT	16′/sec.
THROAT TO CHAMBER	22′/sec.
CHAMBER	5′/sec.
MATERIAL OF CHAMBER AND INJECTOR	MILD STEEL

FIG.9. COMBUSTION CHAMBER (FINAL DESIGN)

FIG.10

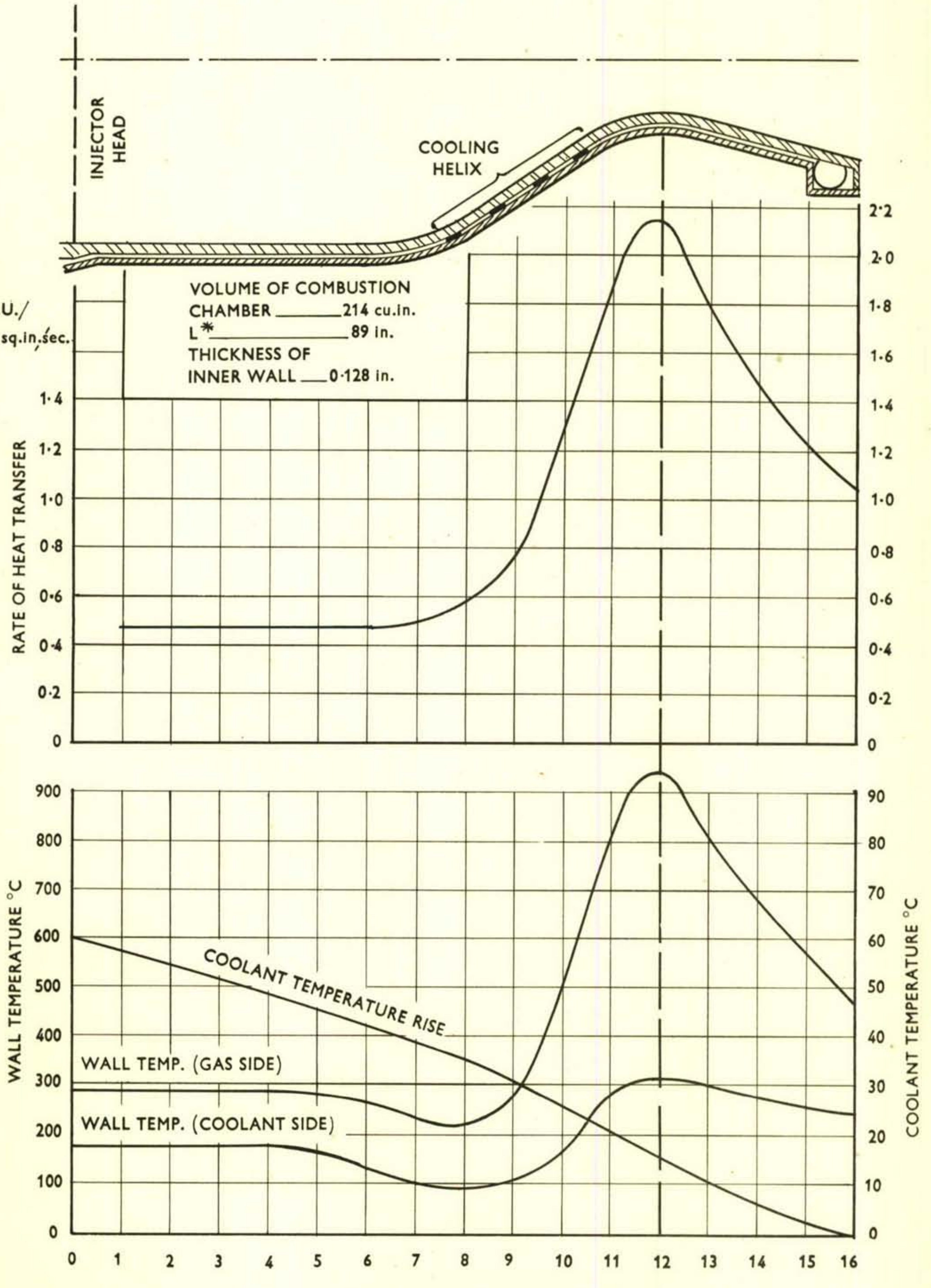
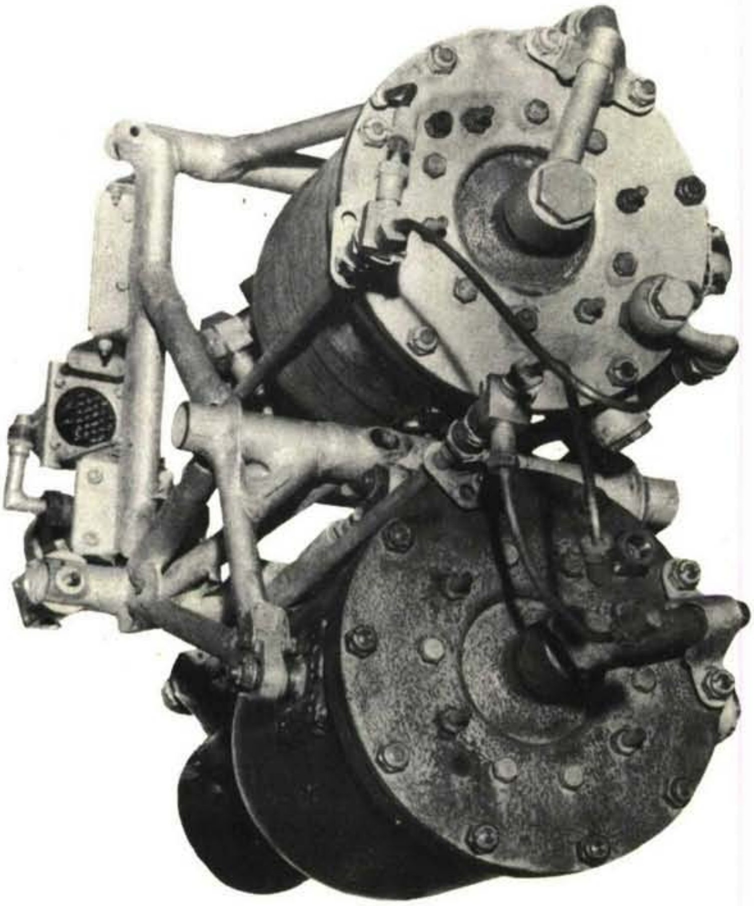
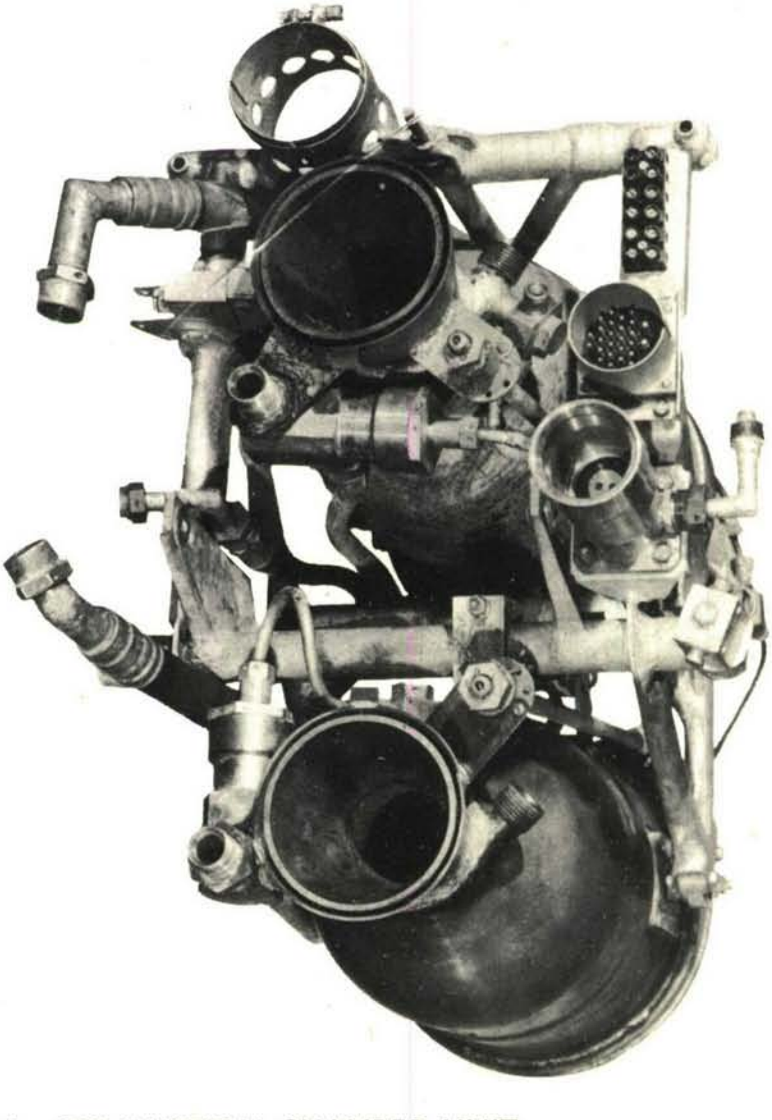


FIG.10. CALCULATED HEAT TRANSFER CURVES FOR FULLY COOLED COMBUSTION CHAMBER

FIG.11



FRONT
VIEW



REAR
VIEW

FIG.11. COMBUSTION CHAMBER UNIT

FIG.12

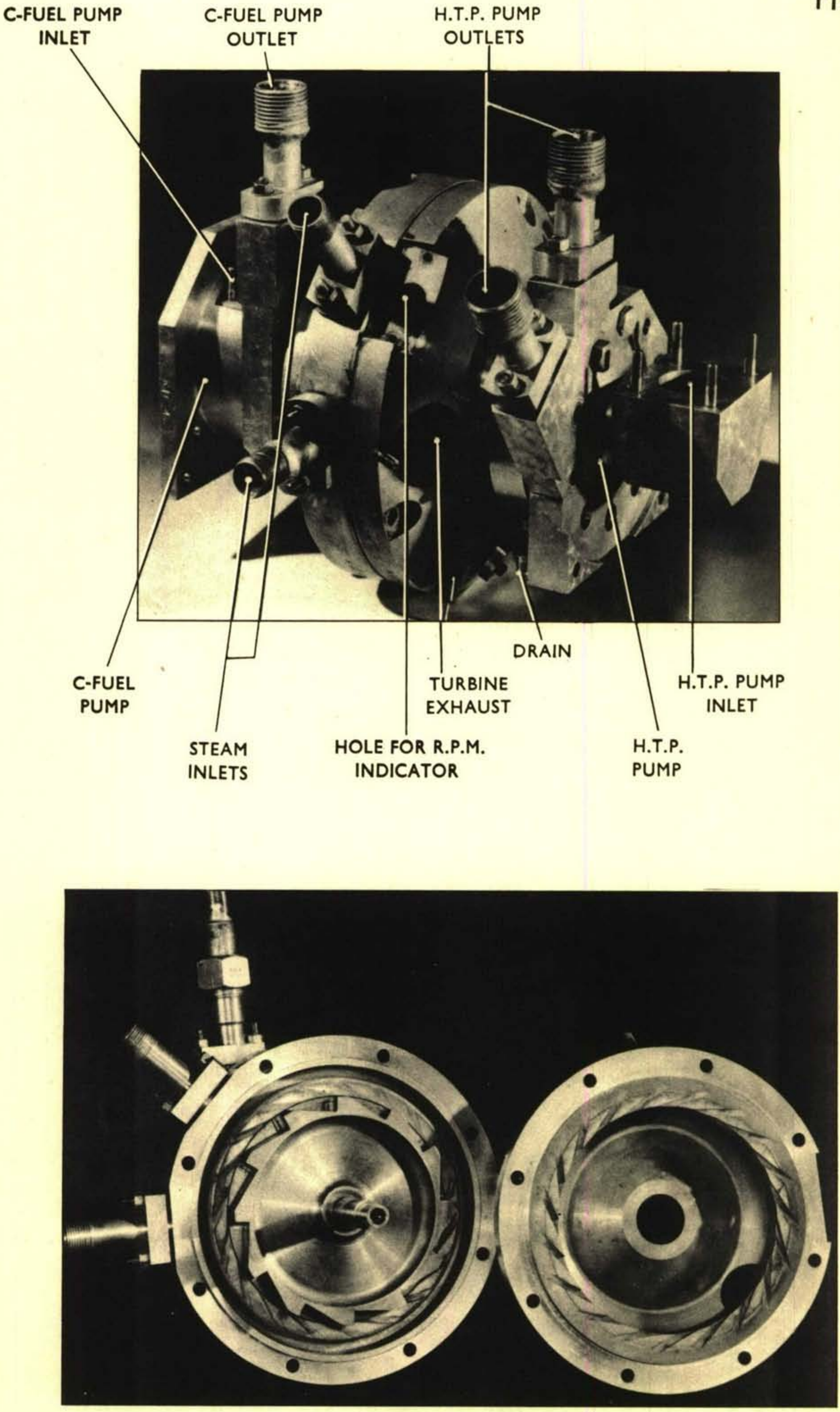


FIG.12. BETA I TURBO-PUMP UNIT

FIG. 13

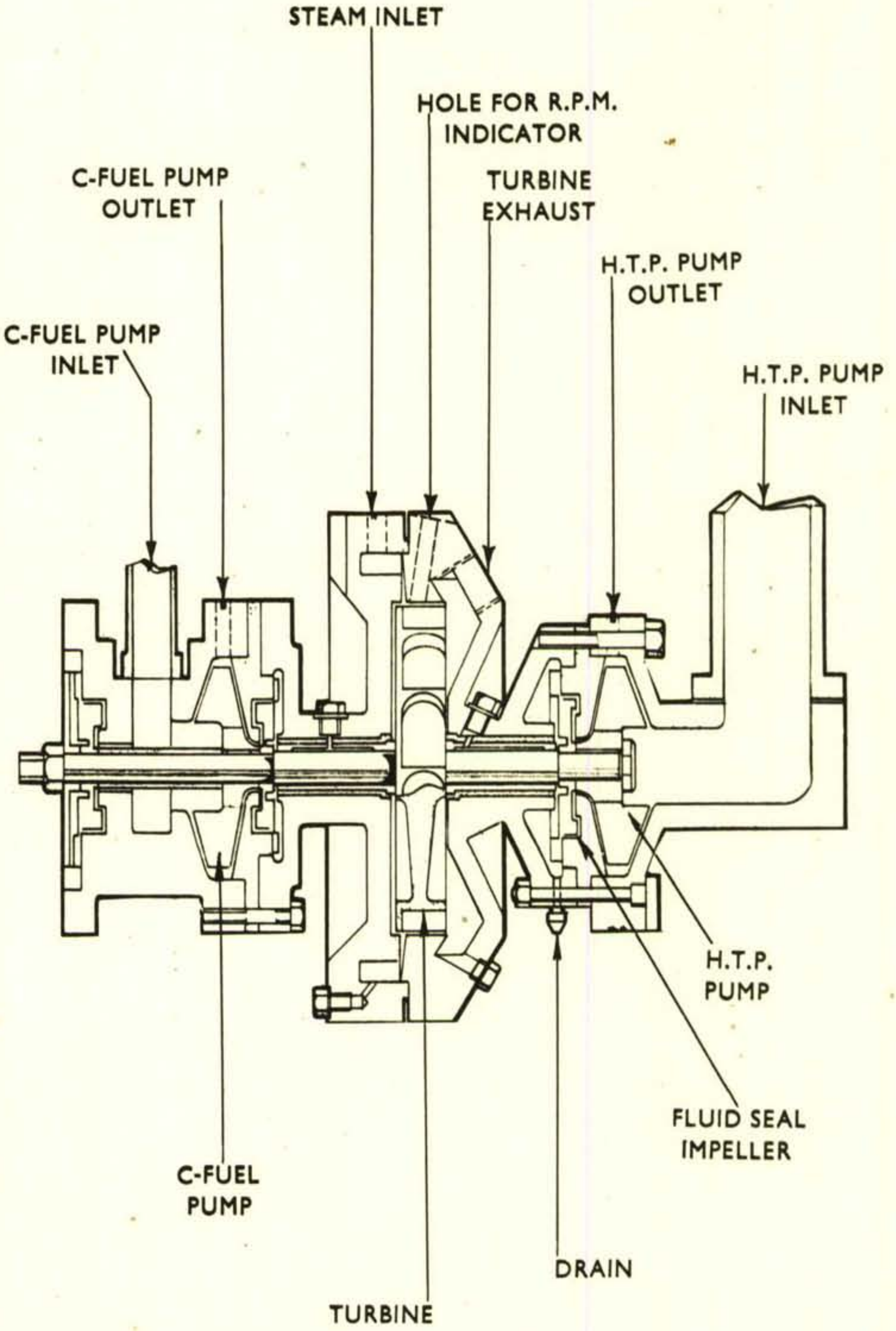


FIG.13. BETA I TURBO-PUMP UNIT (SECTIONED)

FIG.14, & 15

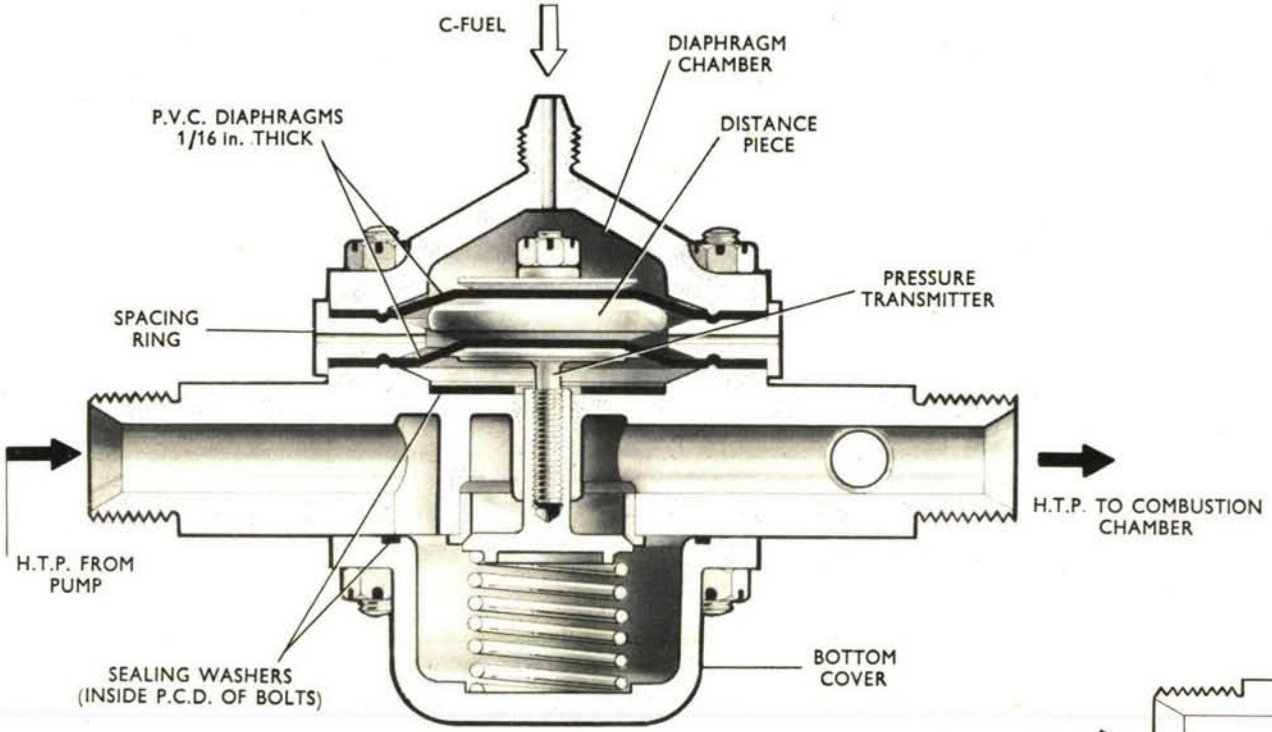


FIG.14. H.T.P. MAIN VALVE

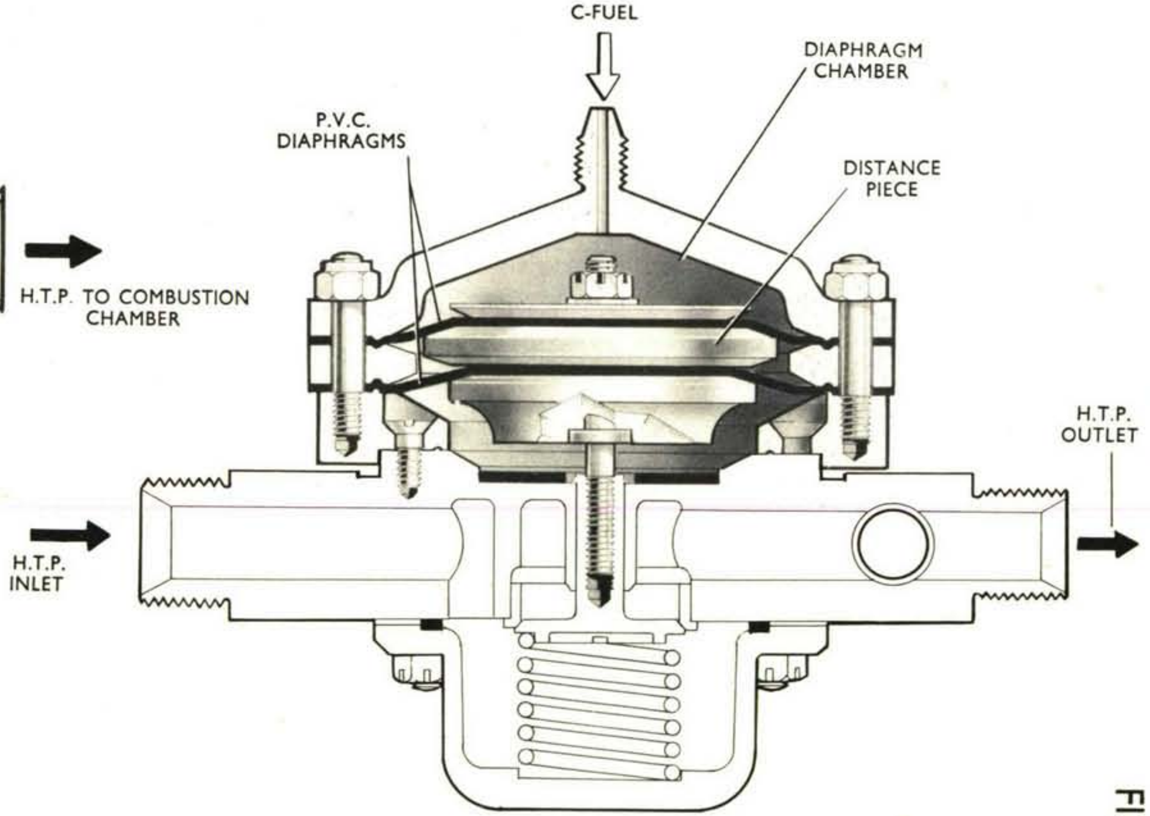
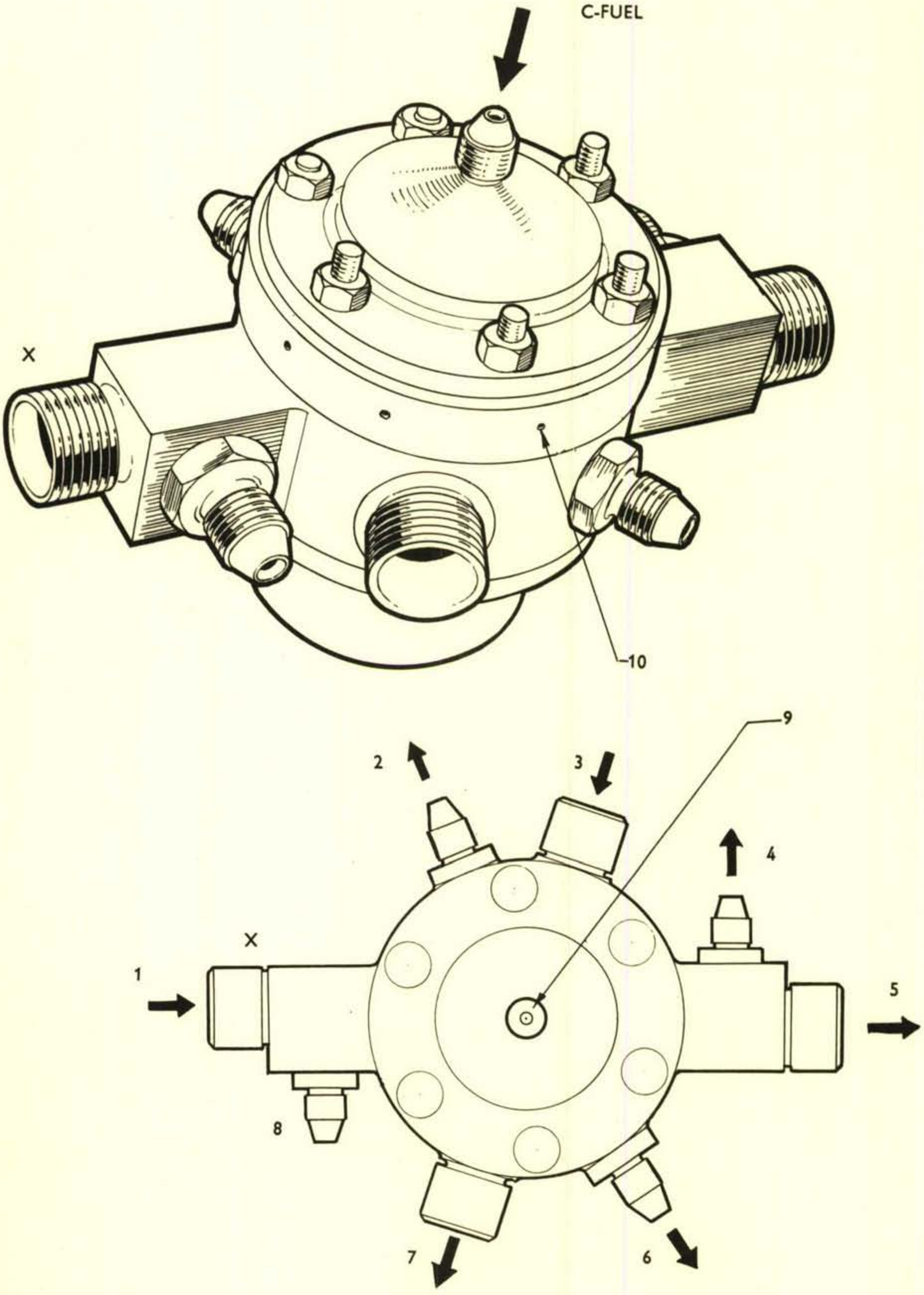
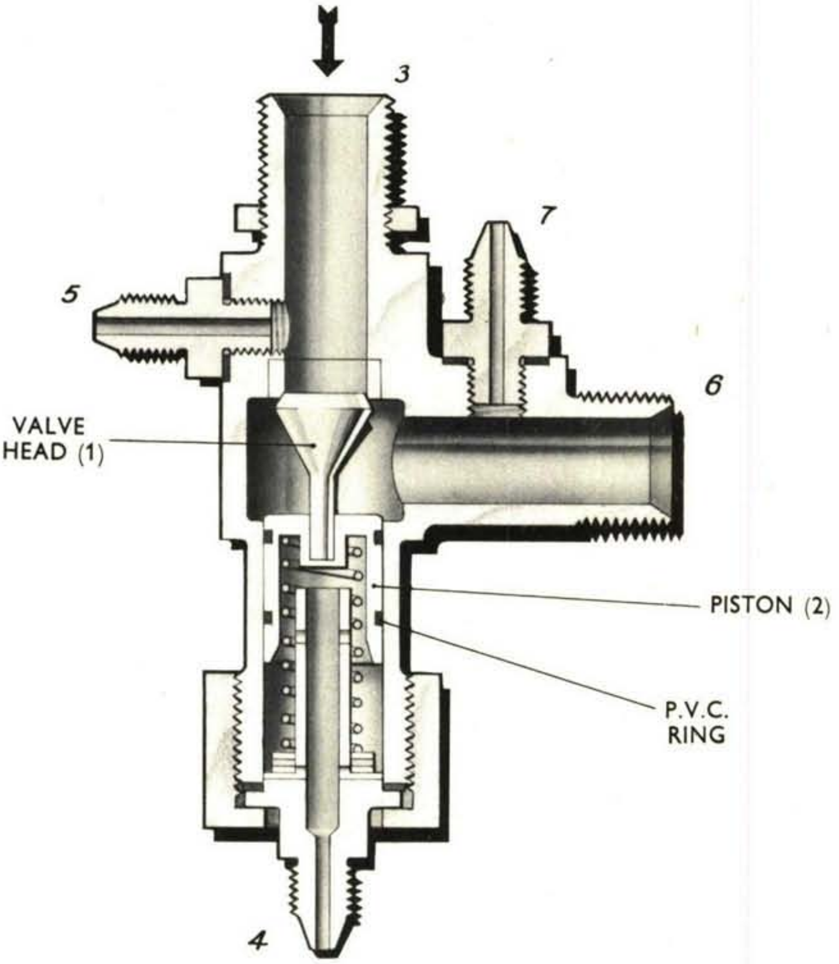


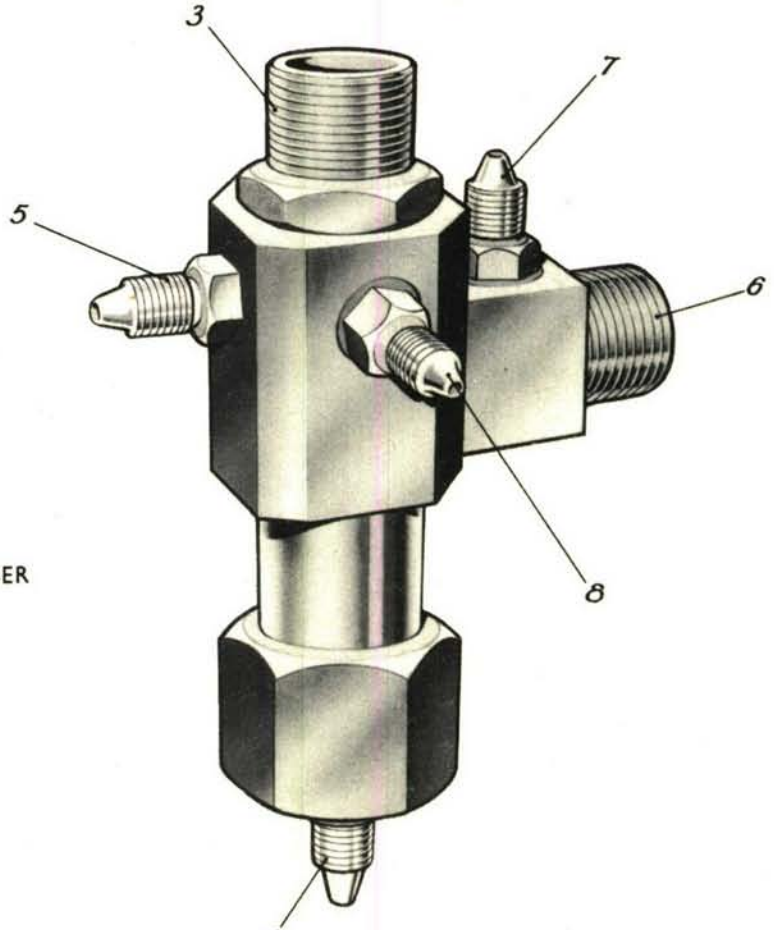
FIG.15. H.T.P. MAIN VALVE WITH ENLARGED DIAPHRAGM CHAMBER



(1) FROM TURBO-PUMP
(2) TO PRESSURE SWITCH
(3) FROM TURBO-PUMP
(4) TO STEAM GENERATOR
(5) TO UPPER COMBUSTION CHAMBER
(6) DRAIN
(7) TO LOWER COMBUSTION CHAMBER
(8) NOT USED
(9) IMPULSE LINE FROM C-FUEL VALVE
(10) DRAIN FROM BETWEEN THE TWO DIAPHRAGMS

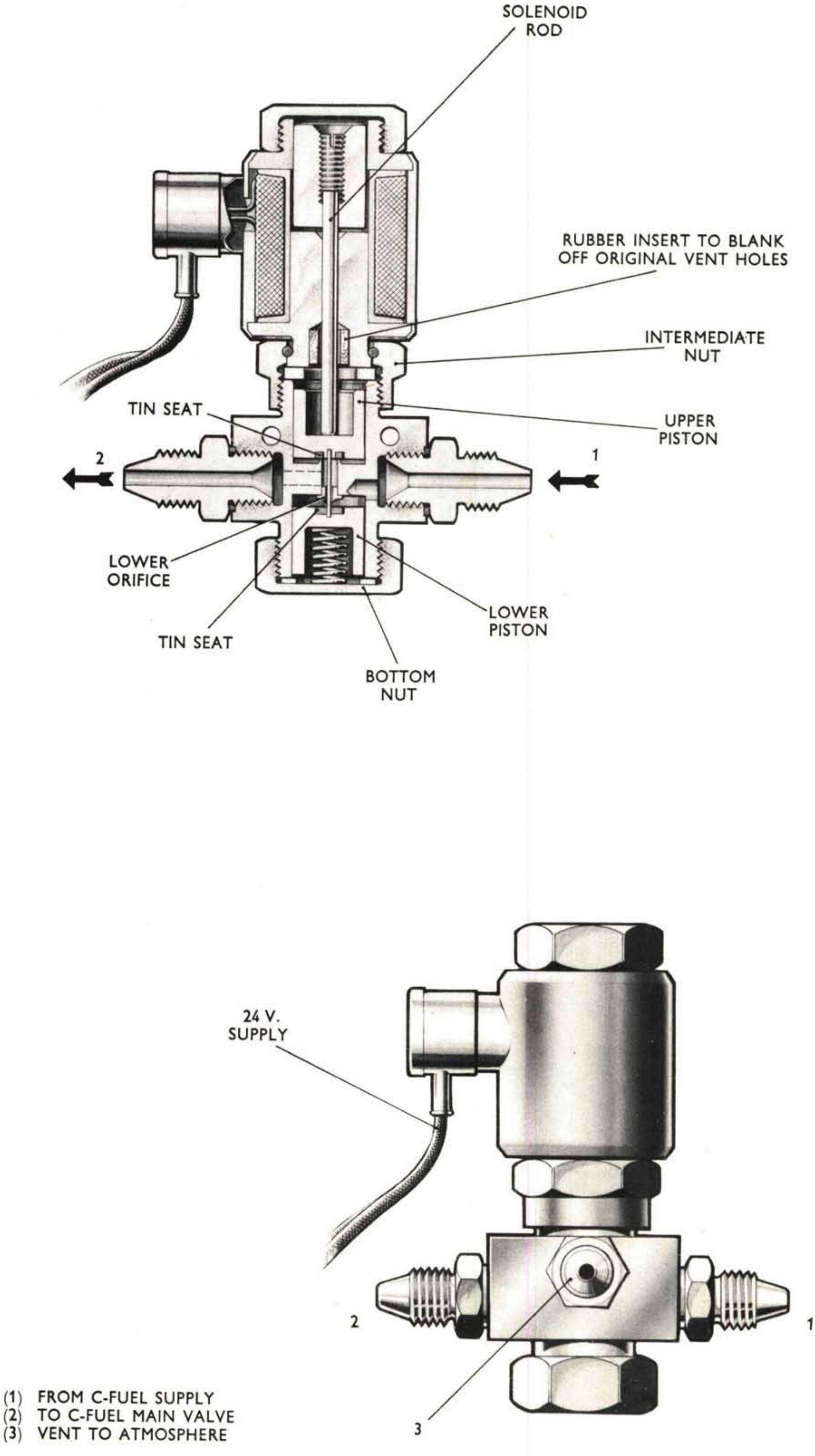
FIG.16. VIEW OF MAIN H.T.P. VALVE SHOWING CONNECTIONS





(3) FROM TURBO-PUMP
(4) FROM SOLENOID VALVE
(5) TO SOLENOID VALVE
(6) TO COMBUSTION CHAMBER
(7) TO MAIN H.T.P. VALVE
(8) TO PRESSURE SWITCH

FIG.17. C-FUEL MAIN VALVE



(1) FROM C-FUEL SUPPLY
(2) TO C-FUEL MAIN VALVE
(3) VENT TO ATMOSPHERE

FIG. 18. C-FUEL SOLENOID VALVE

FIG.19 & 20

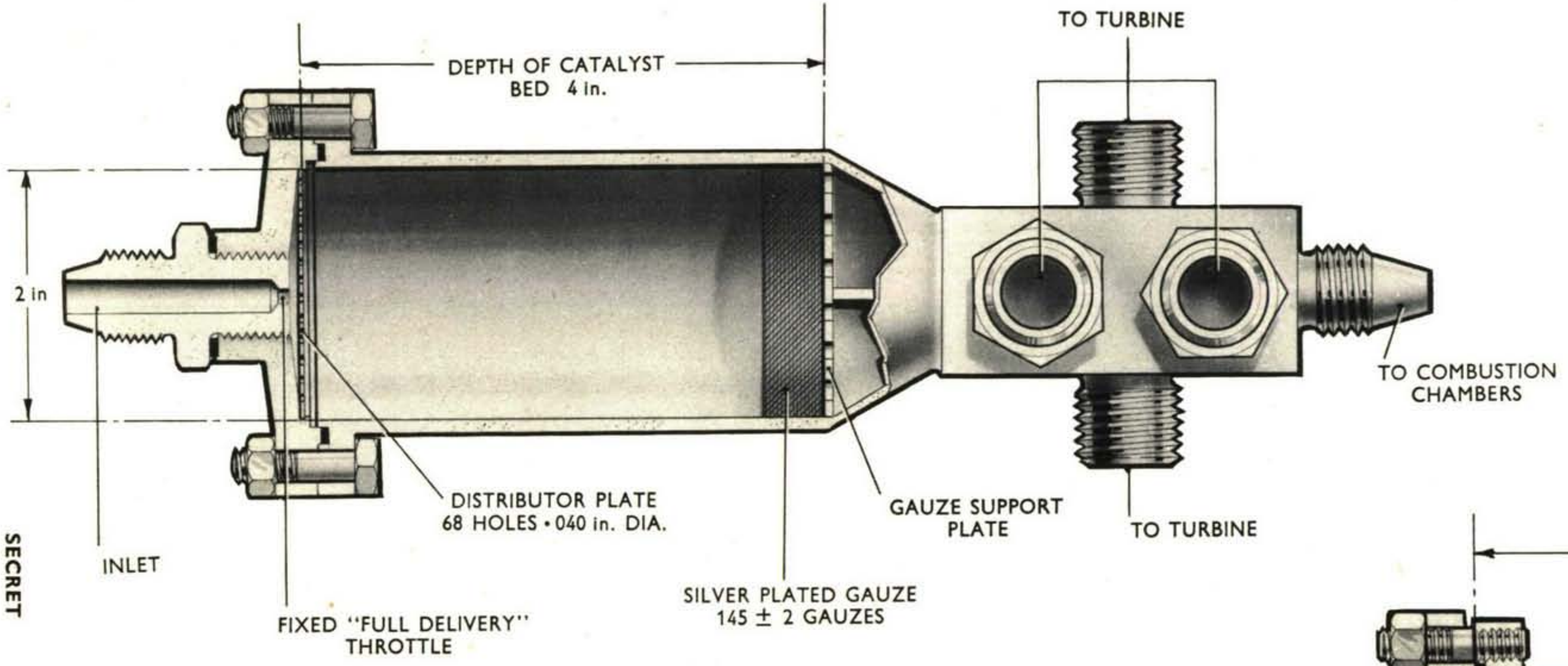


FIG.19. H.T.P. STEAM GENERATOR

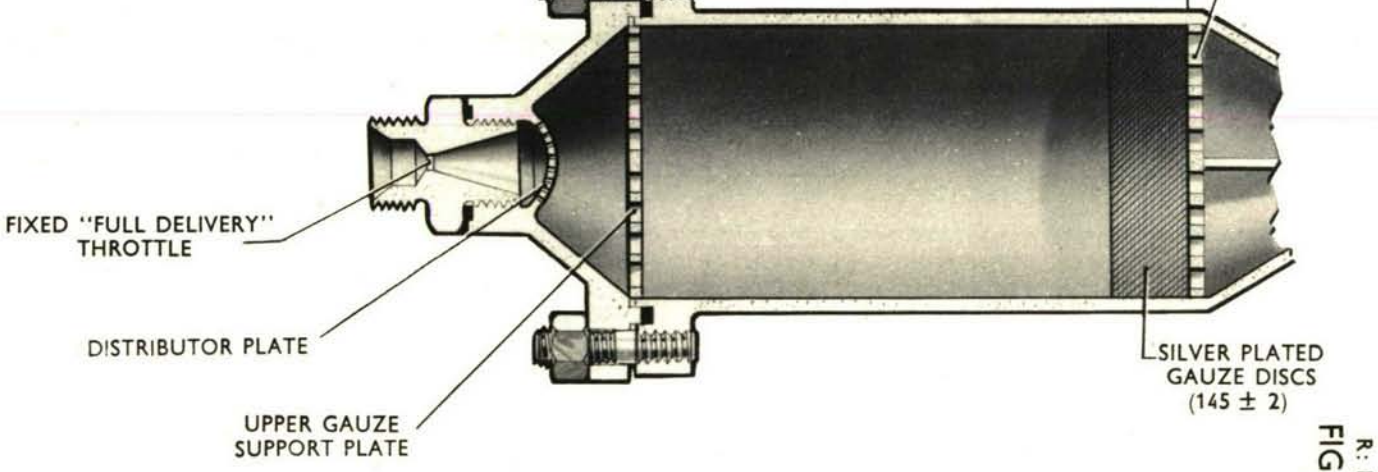


FIG.20. ORIGINAL INJECTOR SYSTEM FOR STEAM GENERATOR

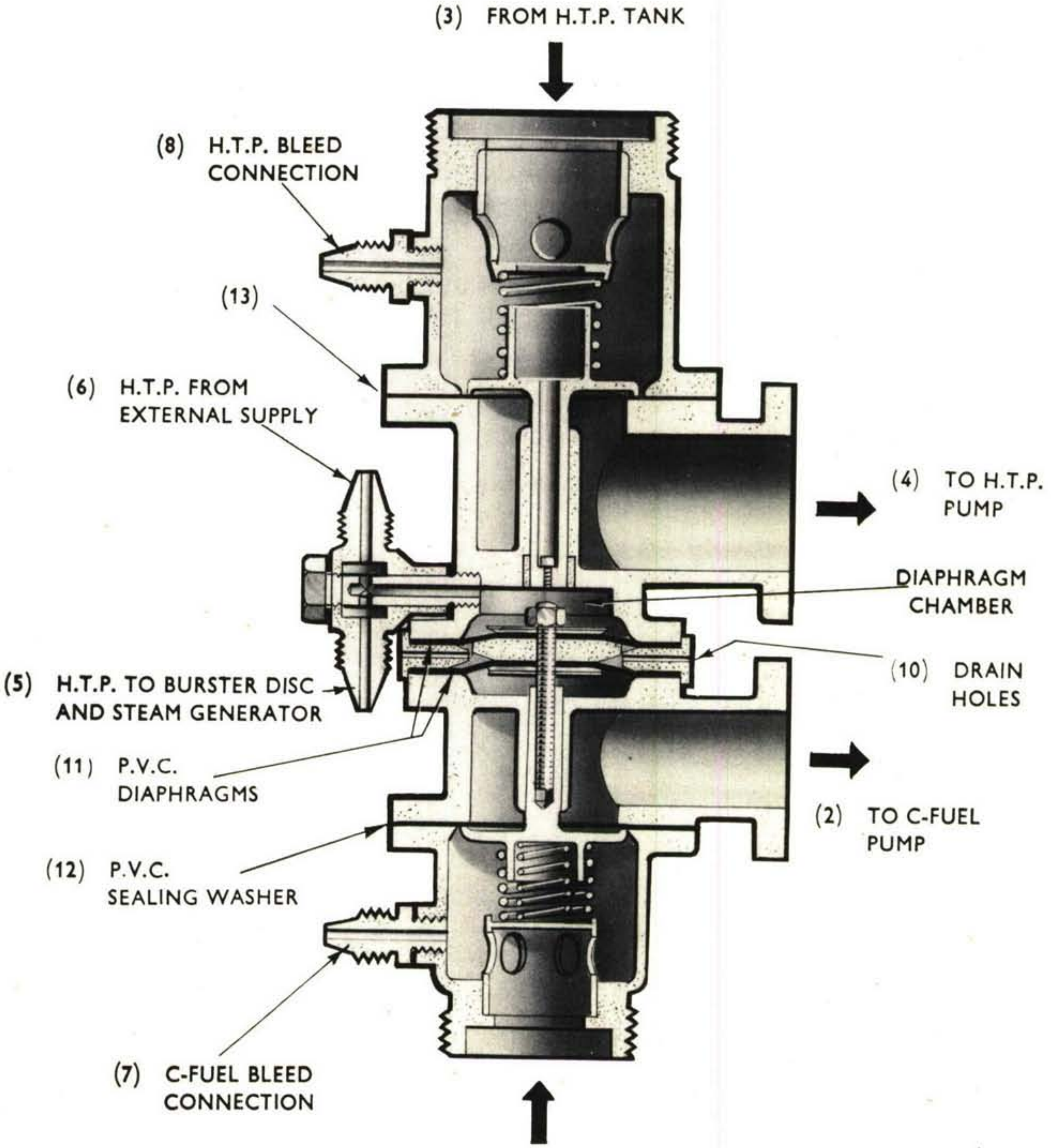


FIG.21. TANK SUPPLY VALVE UNIT

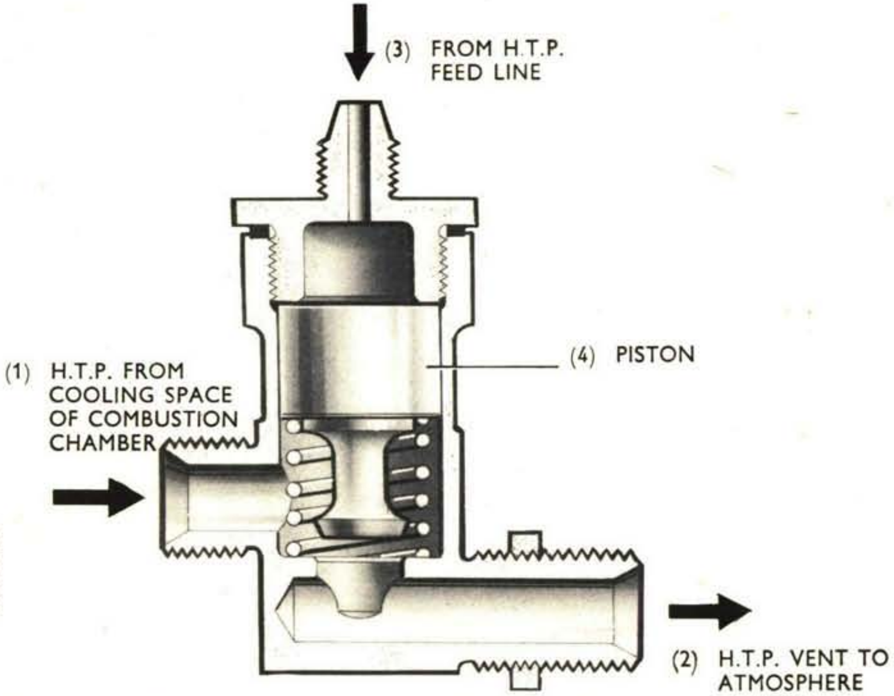


FIG.22. DUMP VALVE

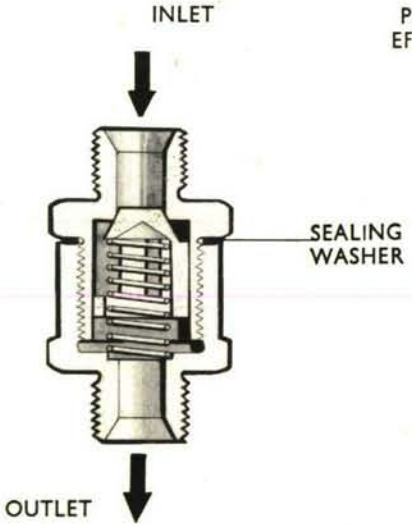


FIG.23. NON-RETURN VALVE

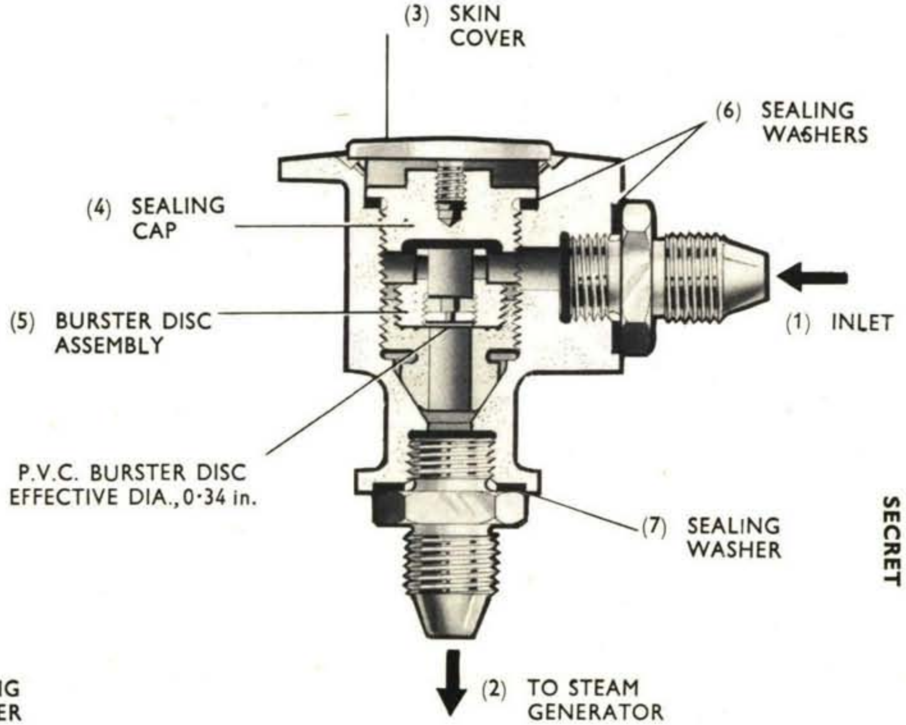


FIG.24. BURSTER DISC UNIT

FIG.25

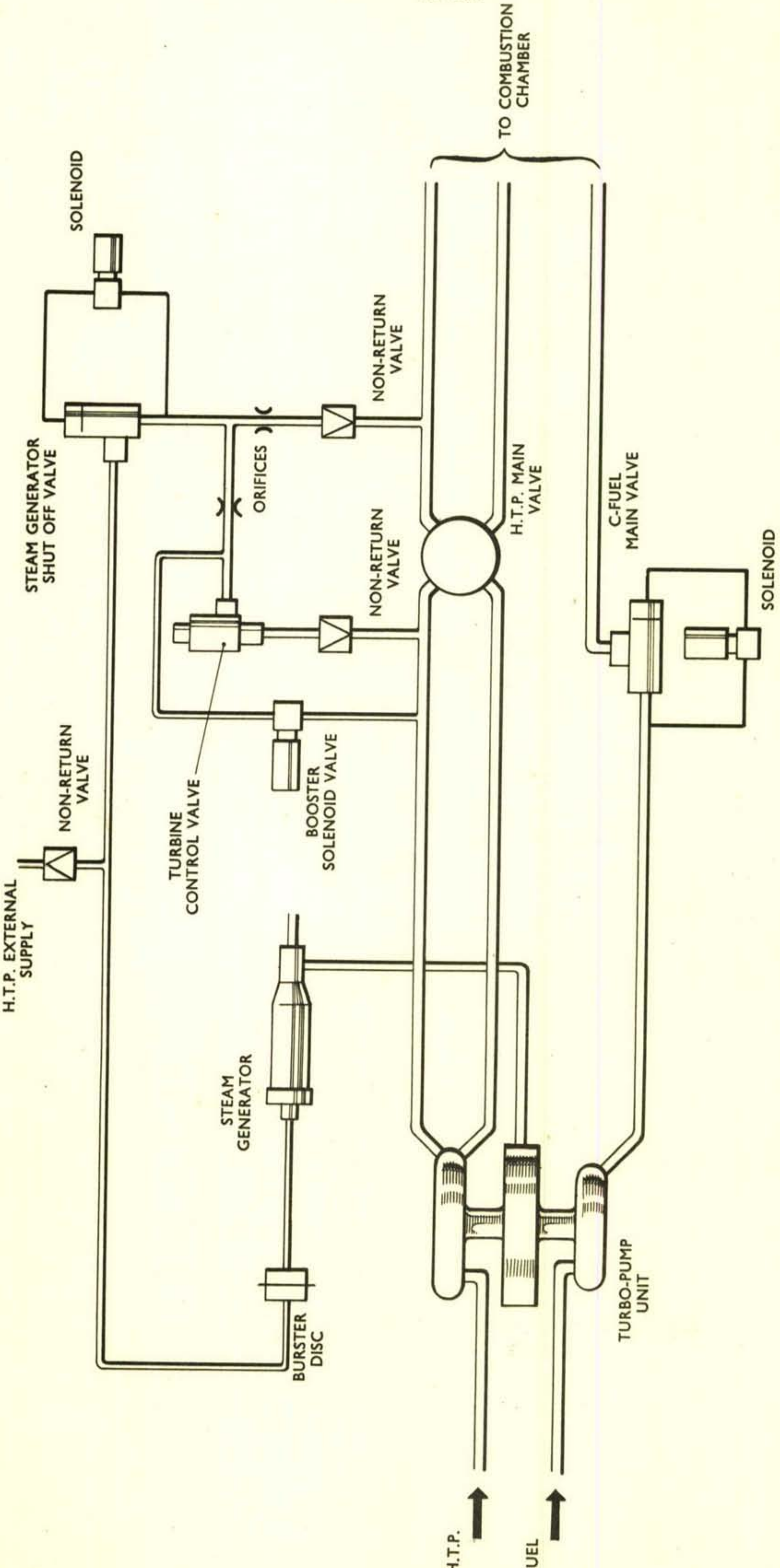


FIG.25. ORIGINAL H.T.P. FEED SYSTEM TO STEAM GENERATOR

UNCLASSIFIED

~~SECRET~~

FIG.26

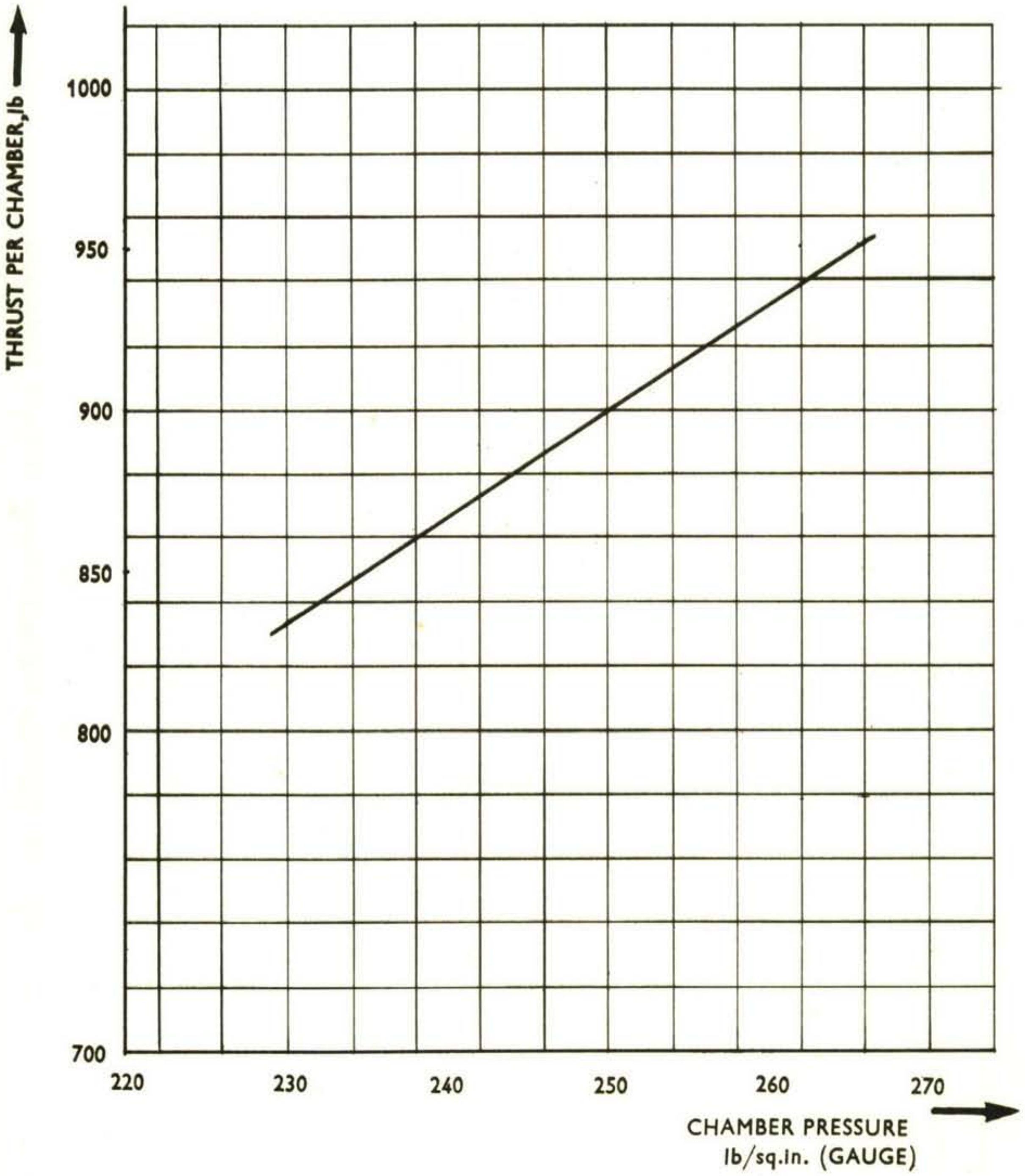


FIG.26. RELATION BETWEEN COMBUSTION CHAMBER PRESSURE & THRUST

UNCLASSIFIED

~~SECRET~~

FIG.27

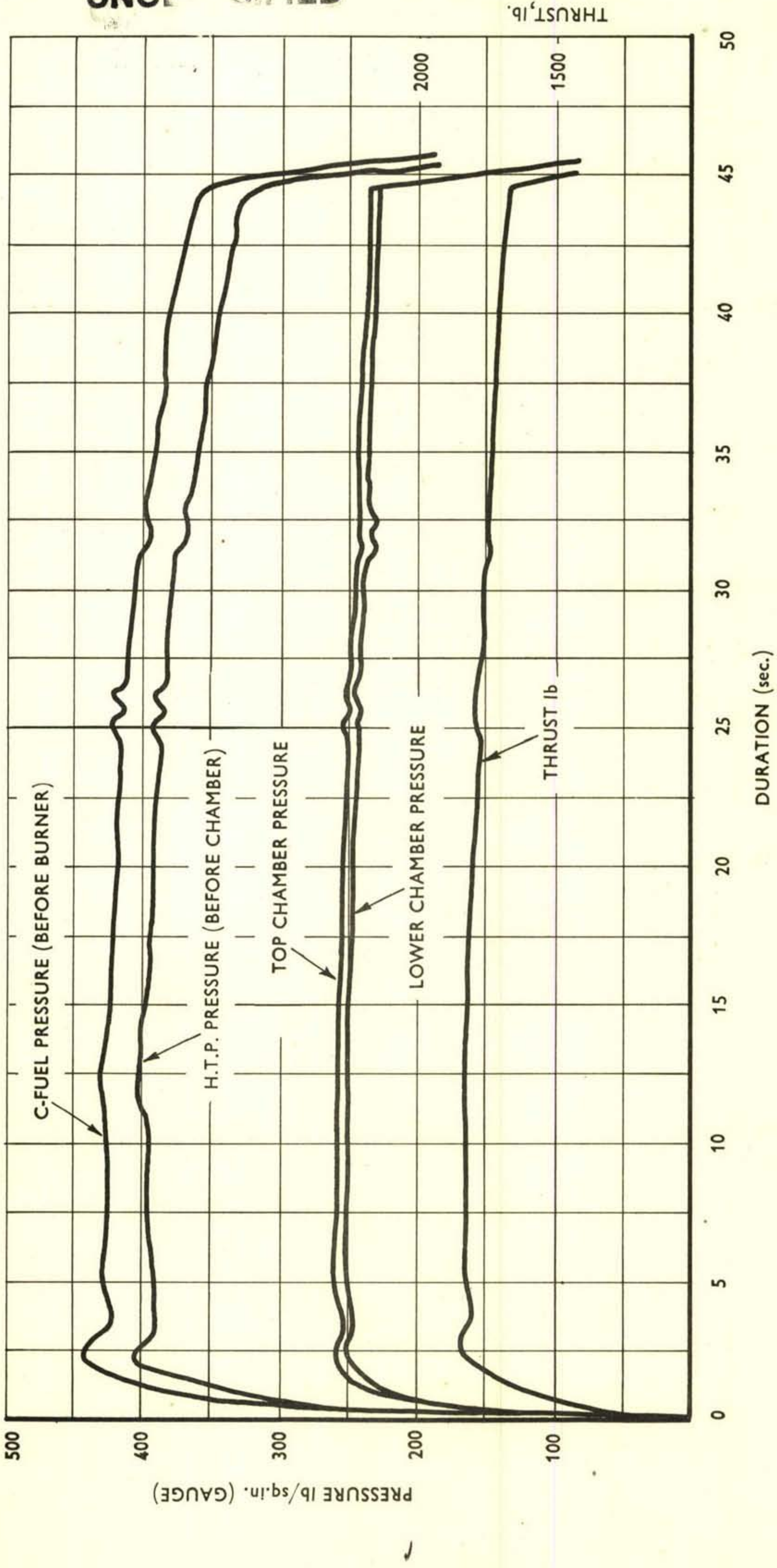


FIG.27. TYPICAL PRESSURE AND THRUST RECORDS