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IGNITION CHARACTERISTICS AT LOW AMBIENT PRESSURES OF A FULL-SCALE INJECTOR USING H.T.P. AND C-FUEL

by

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SUMMARY

The "altitude effect" on the ignition of self-igniting bi-propellants, first reported by Murray and Hall was further investigated using a Walter 109-509 stage 1 injector. Tests without combustion chamber show that the effect is pronounced at altitudes below 30,000 ft. This is at variance with the results of tests on impinging jets obtained by Murray and Hall. The results of the tests described in this note were widely scattered and this is considered to be chiefly due to the design of the injector.

During tests with a combustion chamber at ground level pressure, many explosions occurred and it is concluded that these were due to detonation of the mixture rather than normal burning of an accumulation of propellant.

I Humphries, J.

1. Injectors
2. Nitric acid
3. Kerosene

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1 Introduction

After the failure of the "Alpha" rocket motor to ignite correctly at 34,000 ft,[1] laboratory experiments were conducted at R.A.E.[2,3] to investigate the effect of reduced pressure on the ignition delay of bi-liquid propellants. The experiments were carried out in an 8 ft-diameter decompression chamber using a "twin-jet" apparatus[4]. A range of expulsion pressures from 4 to 13 lb/sq.in. was used and orifice diameters were chosen so that the total propellant flow was about 75 cc/min (0.003 lb/sec) and the linear jet speeds were about 200 cm/sec. The oxidant in all cases was H.T.P. (80%) and the fuels were C1, (30.2% hydrazine hydrate, 56.7% methyl alcohol, 13.1% water) C2 (30% hydrazine hydrate, 35.6% propyl alcohol, 34.4% water) and hydrazine hydrate. Other variables were the altitude (0 to 61,000 ft), ambient temperature (-22° to +15°C) and propellant temperatures (0° to 25°C). The main result from these tests was that there was a marked "altitude effect" for all the propellant combinations tested, the ignition delay increasing with altitude. There appeared to be a certain altitude above which ignition could not be achieved.

All these tests were carried out under conditions vastly different from those obtaining in practice. The present note describes a series of tests which were carried out during 1949 on a full-scale burner and were intended for comparison with the laboratory results. The Walter 109-509 stage 1 (Fig. 1) injector was used since this was the burner used in the "Alpha" motor. The injection differential pressure under normal running conditions was 142 lb/sq.in. and gave a total propellant flow of about 1.37 lb/sec. The work was divided into two main sections, open-burning tests and tests with a combustion chamber. The present note describes the former series and the first few tests with a combustion chamber. C-fuel (30% hydrazine hydrate, 57% methyl alcohol, 13% water) and 80% H.T.P. were used throughout.

2 Test Rig and Methods of Measurement

The test equipment was installed in a Mobile Decompression Chamber Mk.I (Fig. 2). The seats and the original equipments for the oxygen supply and inter-communication were stripped out and the windows replaced by steel plates fixed in place by means of Bostik and anchored by chains. These plates were designed to blow off at a pressure of 4 to 5 lb/sq.in. gauge and were intended to act as safety links.

Fig. 3 is a schematic layout of the test rig. This was divided into two main sections; (1) the propellant tanks and pressurizing equipment outside the decompression chamber, and (2) the firing valves and injector head inside the chamber. The method of operation was as follows. The propellant tanks were first pressurized from the nitrogen bottle through the reducing valves 1 and 2 and stop valves 3 and 4. The firing valves 5 and 6 were then operated. The solenoid valves supplying the operating nitrogen for the firing valves were connected to a bomb-switch and energized for one second only, thus limiting the amount of propellant accumulating in the decompression chamber in case of a very long ignition delay. As a further safety measure a tray of water was placed beneath the injector to dilute unburnt propellants and only a limited quantity of each propellant was put into the tanks for each firing.

For this work it was essential that the firing valves should give a perfect seal, but great difficulty was experienced in achieving this. In the first instance German solenoid valves[5] were used as shown in Fig. 4, but it was found that these opened momentarily when the propellant tanks were pressurized and before the actuating solenoids were energized; these values were also slow and the time of opening was variable and indeterminate. Several modifications were tried, but none of these was satisfactory. Next pneumatic valves designed at R.P.D. were tried, but after exhaustive tests it was found that the polythene seats used would not stand up to the high impact loads obtained during rapid opening and closing. Finally V.2 H.T.P. pneumatic valves[6] were tried; these were found to be quite successful and were used in the majority of the tests; although even these valves develop slight leaks after a period of use.

The injection time of the propellants was measured by means of pressure pick-ups in the propellant lines, close to the injector head. Indications from the pick-ups were recorded on a Miller recording equipment. The time of ignition was indicated by means of a photocell facing the injector head and was also recorded with the same time-base as the pressures. A typical record is shown in Fig. 5. Preliminary water tests were made to determine whether the pressure pick-ups gave an accurate indication of the time of injection of the propellants. A pair of very light contacts were placed immediately below the injector in the path of each propellant stream in turn. The contacts were set with a small gap, and connected to one channel of the Miller recorder in such a way as to produce a kick on the trace when the contacts closed. For both propellant lines the pressure pick-ups lagged behind the contacts by 0 to 3 m.sec. This was considered satisfactory and so for all tests the pick-up pressures were used to give an indication of the injection times.

As time was wasted both in waiting for records and in duplicating tests where, for one reason or another, the Miller record was unsatisfactory, an attempt was made to develop a direct-reading instrument. As a first step a number of tests were made using a light-beam shining across the propellant spray on to a photocell. As the propellant spray starts the photocell output diminishes and when ignition occurs, it increases thus giving two datum points; the time interval between these two points could then be measured by means of suitably developed electronic circuits. Unfortunately, the spray-indication was indeterminate and the device would only indicate the time of entry of the first spray and not that of the second. It was hoped to make both propellant valves open at the same time or to obtain a constant delay between the two, but as neither of these objectives was achieved the work was stopped.

As an alternative, pressure-operated switches were attached to the propellant lines at the same point as the pressure-pickups to indicate the time of entry of the spray, and a separate photocell was used to indicate ignition. The time elapsing between the injection of the second propellant and ignition was measured directly using a modified version of the electronic timer devised for the drop-tests used in ignition delay measurements[7]. The ignition delays thus obtained were 35 to 115 m.sec. longer than those obtained from the Miller records. The discrepancy between the two sets of measurements was considered to be due to two effects: (i) The pressure switch was very sensitive and opened before the Miller recorder indicated a rise in pressure, (ii) The photocell used with the electronic timer was less sensitive than that used with the Miller recorder. This meant that a higher light intensity would be required for the electronic timer than for the Miller recorder and thus any variation in the place where ignition commenced or in the spread of the flame would cause an indeterminate increase in the measured ignition delay. In order to make the pressure switch less sensitive it was re-set to open at about 35 lb/sq.in. (original setting 20 lb/sq.in.). In this way better agreement was obtained between the two sets of figures, but the results obtained by the electronic timer still differed from those obtained by the Miller recorder by -12 to +38 m.sec. This discrepancy was not eliminated and the electronic timer was used mainly as a check in case the Miller recorder failed, which in fact did occur on several occasions.

High-speed photographic records were made for some of the tests with a combustion chamber and for one open burning test in order to obtain a comparison with the results obtained by the Miller recorder; good agreement was found between the results.

3 Tests without combustion chamber

Calibrations of the Walter 109-509 injector with water at a pressure drop of 142 lb/sq. in. (the normal working pressure drop of the injector) gave the following rates of flow with water:-

C-fuel side	0.368 lb/sec.
H.T.P. side	0.86 "

This is equivalent to 0.35 lb/sec C-fuel, 1.00 lb/sec H.T.P. and a total propellant flow of 1.35 lb/sec giving a mixture ratio, C-fuel/H.T.P., of 0.35. For the majority of the tests injection pressures of about 330 lb/sq. in. were used giving a total propellant flow of 2.05 lb/sec.

Using the injector and head only, without combustion chamber, a series of tests were carried out at pressures equivalent to altitudes from ground level to 30,000 ft in steps of 5,000 ft. The results are given in Table I and plotted in Fig. 6, 7 and 8. The results obtained by Murray and Hall are also plotted for comparison. It will be noted from Fig. 6 that the present results are very widely scattered, whereas the results of Murray and Hall over the same pressure range (0 to 30,000 ft) are consistent and show little variation with pressure. Reference to Fig. 7, however in which Murray and Hall's results for lower pressures (corresponding to altitudes up to 60,000 ft) have also been included, shows that, when the altitude effect becomes noticeable their results are also considerably scattered.

It has been shown that for diesel engines[8] and for rocket motors[9] there is a relationship between the pressure and ignition delay of the form $\log_{10}(Zp^n) = \frac{A}{T} + B$, where Z is the ignition delay in seconds, p the ambient pressure in atmospheres absolute, T the ambient temperature in degrees absolute, and n, A, B are constants. This work related to experiments at pressures above one atmosphere and it is obvious from the form of the equation that if a certain pressure exists below which ignition will not take place, then the equation cannot be applied down to zero pressure. It seems feasible, however, that the present results with measurable ignition delays could be made to fit this form of equation and so they have been plotted on a log - log basis in Fig. 8. The points do tend to lie in a band, but again there is a great deal of scatter. The only other ignition delay measurements made on this type of injector have been made at ground level pressure and agree well with the present results, the values obtained ranging from 86 to 230 m.sec.[8] In one or two instances at high altitude the electronic delay indicator tripped long before actual ignition took place as indicated by the Miller recorder. This suggests that non-propagating flashes occur before the main ignition, as reported by Murray and Hall.

The scatter of the results is large. This may be due to the random nature of the ignition process in a droplet cloud, combined with the poor mixing obtained with this type of injector. However, other factors may have influenced the ignition delay and various possibilities are reviewed here. The independent variable in the tests was the ambient pressure and all other conditions were held as constant as was deemed necessary, but it is obvious that a further independent variable exists. This variable must be a function of the equipment, the experimental conditions or the methods of measurement. Throughout this work the test rig remained unaltered, but, as an injector seized in the head and had to be turned out, a second injector was used. There is, however, no significant difference between the results obtained with the two injectors. On the other hand this design of injector had previously been found to give an unreliable ignition delay. This defect was thought to be caused by the small angle at which the propellant sheets met and the consequent poor mixing. From the photographs taken it can be seen that ignition is initiated at varying distances from the injector and it is, therefore, considered that this poor initial mixing is a major cause of the scattered results.

The following additional factors may have affected the ignition delay:

(1) The air temperature was not kept constant. According to Murray and Hall, a decrease in the air temperature raises the ignition delay at ground level, but has much less effect on it at 30,000 ft. Only a few results were obtained, but they are sufficient to show that in the present series of tests, in which the air temperature varied from 0 to 20°C for various runs, the results should not be appreciably affected.

(2) The temperature of the injector head and associated pipework was not controlled and the temperature of the propellants and tanks was only held within certain limits. As thermostatically controlled baths were not available at the time, the temperature of the storage vessels was kept as near as possible at 20°C by means of water-baths over an open fire. The propellant tank temperatures were similarly regulated. By these means the propellant temperatures were kept within a few degrees of 20°C, although in a few cases the difference may have amounted to as much as 5°C. The fact that the temperature of the head and associated pipework was allowed to vary may have meant that there was a slight change in the propellant temperature before the propellant passed through the injector, but as the pipe lines were short ($\sim$ 2 ft) and the flow velocities low ($\sim$ 6 ft/sec.) the change in propellant temperature was probably not appreciable and the maximum variation probably not more than $\pm$ 5°C. According to Broatch[4], this would be equivalent to a variation of $\pm$ 25% in the ignition delay at ground level; no comparable figures are available for low ambient pressures. It should be noted that this deviation would in any case apply to only a few of the results and Fig. 6 shows that the results at any given pressure are fairly evenly scattered over the range. This would appear to indicate that the variation of propellant temperature was not the main reason for the scatter of the results, although its effect may have been appreciable in some cases and closer control should be exercised in any future work of this kind.

(3) The exact ambient pressure at the moment of ignition was not known. The method of determining the pressure was to evacuate the decompression chamber to a predetermined value, switch off the vacuum pump and carry out the test, the predetermined pressure being taken as the test figure. In practice this was not quite accurate as the vapour produced by the boiling and partial reaction of the propellants before ignition caused a rise in ambient pressure. Thus the ignition delay figures obtained correspond more nearly with the actual pressure at ignition than with the nominal pressure. To reduce this error attempts were made to operate the pump throughout the test, but it was not found possible to do this without the pump seizing up owing to the fumes; this method was, therefore, abandoned. To observe the rise in pressure, a visual reading pressure gauge was connected to the decompression chamber. On all but the longest delays it was impossible to differentiate between the rise before and after ignition. On the longest delays a rise was noted, but it was not sufficient to have any serious effect on the results. It was intended

to record the actual ambient pressure on the Miller recorder by using an aneroid with a strain-gauge, but this was not available before the tests were finished. The overall effect of any correction due to this error would be a reduction of the pressure at ignition which would be a function of the ignition delay and ambient pressure, but it would have a negligible effect on the scatter of the results.

(4) Broatch[4] ascribes some of the irreproducibility of ignition delay measurements by the falling drop method to the inability of the photocell to detect immediately the light emitted on the ignition of the propellants. This may also have been the case in these tests as it was found from cine-records that ignition did not always take place at the same distance from the injector or along the same radius. However, since the flame spreads rapidly the error involved should not be appreciable and could be obviated by using several photocells in different positions. Another minor source of error could be introduced by the varying sensitivity of photocells. In the present tests two photocells of unknown sensitivity were used at different times, but as no variation in the scatter of the results of tests using different cells is noticeable, the effect must, in the present case, be negligible.

(5) The compositions and performance under laboratory conditions of H.T.P. and C-fuel were not accurately checked each day. Ignition delay tests by the usual drop test with the propellants were carried out, but only in a few isolated instances were any measurements made. As the stored propellants are checked regularly there seems to be little chance of any serious error arising in this way, but it is suggested that in future work of this nature the ignition delay of each propellant batch should be measured in the laboratory to obviate any possible error due to accidental contamination or dilution.

4 Tests with combustion chamber

The injection head and combustion chamber used are shown in Fig. 9. Tests were made at ground level pressures only, the results being given in Table II. It was intended to use quartz glass windows for the photocell, but on the first test heat resistance glass was used instead. Test No. 1 was intended simply as a functioning trial and no measurements were made; an explosion occurred which shattered the glass and blew the venturi plate off, although no damage was done to the chamber. Test No. 3 took place immediately after test No. 2. The result was obviously spurious and was thought to have been caused by a slight propellant leak which initiated ignition when the main valves were opened. In test No. 5 the chamber was torn from the rig and considerable damage was done to the rig. In subsequent tests blanks were used instead of glass or quartz and only four bolts were used in the venturi plate so that they would act as a weak link in case of further explosions. Up to this time the chamber had been oriented at a small angle, about 20°, to the vertical and it was thought that this may have allowed a certain accumulation of propellants at the venturi plate and thus caused an explosion. The chamber was, therefore, put into a vertical position. The other places where the propellants might accumulate were the window bosses and these were blanked from the inner end. In all further tests the photocell was placed just outside the venturi.

Test No. 6 gave a very hard start, but no damage was done. The rise in combustion chamber pressure corresponded exactly with the photocell indication and thus showed that the photocell outside the venturi could be used for indicating the ignition. In test No. 7 the venturi plate was again blown off and approximate calculations from the deformation of the copper blanking discs gave a chamber pressure of about 6,000 lb/sq. in. As earlier work had shown that ignition occurred at a considerable distance from the injector and that a given minimum chamber length as well as minimum L* were needed for ignition, it was decided to increase the chamber length. The chamber length was, therefore, doubled (giving an L* of about 130 in) and all further chamber tests were carried out in this condition. In test No. 8 and 9 the venturi plate was blown off. No ignition delay measurements were obtained since in test No. 8 the photocell failed to function and in test No. 9 the record was useless due to electrical interference. A photographic record was obtained in test No. 9 which appeared to indicate that ignition occurred inside the chamber only, but this was not completely conclusive as the camera speed was not sufficiently high (about 100 frames/sec). In test No. 10 the lower section of the chamber was split, but no damage was done to the rest of the chamber.

In the Alpha motor three injectors of the type shown in Fig. 1 were used and smooth ignition was accomplished by allowing C-fuel to be injected through all three injectors and H.T.P. through one only and thus a fuel-rich mixture was produced. As a high percentage of explosions was being obtained, it was decided to simulate the Alpha chamber conditions by injecting extra C-fuel. Since there was insufficient room in the head for two more Walter 109-509 injectors, two hollow-cone swirl-type injectors were designed and built to fit into the side of the chamber (Fig. 10). The approximate mixture ratio of C-fuel to H.T.P. on starting the Alpha motor was 1.08/1 and that achieved in the test chamber with two extra swirlers was 0.83/1. In the first test (No. 11) with extra C-fuel an explosion resulted and the venturi plate was blown off. The subsidiary C-fuel was tapped off from the main line just before the main injector. As the pipe-lines to the subsidiary injectors were somewhat tortuous it was considered that the C-fuel might be reaching them at the time of ignition, or even later. The original pipe-lines were replaced by more direct lines and pressure pick-ups were placed in the lines just before the subsidiary injectors. In test No. 12 the times were as follows: C-fuel main 0 m.sec; H.T.P. 33 m.sec; C-fuel subsidiary 49 and 53 m.sec; ignition 174 m.sec; chamber pressure rise 176 m.sec. It can be seen that although the subsidiary C-fuel followed the main C-fuel by about 50 m.sec, it followed the H.T.P. by 20 m.sec. at the most and considerably preceded ignition. From 'open burning' tests it has been seen that, within reasonable limits, the order of entry of the propellants appears to have no appreciable effect on ignition delay. It would appear, therefore, that this lag is not the reason for the explosion in test No.12 which shattered the lower half of the chamber and left the upper half intact (Fig. 11). However, it was considered advisable to introduce the propellants at predetermined times and so work was commenced in an attempt to use a coupled valve. This work was suspended at the end of 1949 and has not yet been recommenced.

5 Conclusions

5.1 Tests without combustion chamber

Although the results are widely scattered it can be clearly seen that small scale impinging jet tests are not satisfactory for deducing the behaviour of full-scale injectors. The ignition delay increases rapidly with increase in altitude, whereas the results of Murray and Hall show no appreciable increase up to an altitude of 30,000 ft. The Walter 109-509 injector is shown to be unreliable for ignition purposes unless a pre-heating system, such as is used in the 109-509 motor, is used. There are indications that at low ambient pressures ignition can occur without the propagation of combustion.

5.2 Tests with combustion chamber

Owing to the number of explosions occurring at ground level ambient pressure it was not found possible to carry out a series of tests over an altitude range and so no comparison can be given of the altitude characteristics of the Walter 109-509 injector with and without combustion chamber.

It appears that these explosions are not just due to the burning of an accumulation of propellants in the chamber but are, at least in part, due to the detonation of the mixture. As the chamber was arranged vertically a large amount of propellant could not accumulate in the chamber and in fact the amount in each test should be the same, if the time of stay of the propellants in the chamber is assumed to be less than the ignition delay. Measurements of time required for the liquid jet to traverse the chamber from injector to exit were made; these times varied between 25 and 40 m.sec. In 40 m.sec sufficient propellant mixture could accumulate to cause a chamber pressure of about 7,000 lb/sq.in.; this would be sufficient to explain the failure of the bolts holding the venturi plate which would fail at 6,000 lb/sq.in. chamber pressure, but for the fact that the chamber also would fail at about the same pressure. Some bulging of the chamber might be expected with the normal burning of an accumulation of propellant. This was not the case, although in one instance copper discs were inserted as blanks in place of the quartz windows and an approximate calculation from the amount of dishing gave a peak pressure of about 6,000 lb/sq.in. In the tests with a double length chamber evidence of detonation was more conclusive. In test No. 10 the lower half of the chamber was split, and in test No. 12 it was completely shattered (see Fig. 11). In neither case was the upper half of the chamber damaged which suggests that the mixture ignited and detonated near the exit of the chamber probably because the propellants had had time to mix intimately by the time they reached the end of the chamber and were in a sensitive state.

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No.	Author	Title, etc.
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TABLE I

Tests without Combustion Chamber

Altitude ft	Ignition delay from Miller Record (milliseconds)	Ignition delay from electronic timer (milliseconds)	Remarks
0	47		High-speed cine record gave 50 m.sec.
	100		
	87		
	105		Drop-tests in the laboratory gave 53 m.sec.
	247		
	156		
	61		
	209		
	193		
	154		
	55		
5,000	302		
	232		
	165		
	334		
	174		
	143		
10,000	75		
	154		
	507		
	396		
	82		
	495	530	
15,000	170		
	411		Ignition after propellants were shut off
	176		
	426		
	506		
	740	841	
	361	475	
	774	870	
	810	893	
		645) 813)	Miller recorder failed.
20,000	533		
	500		
		173) 287) 860) 205)	Miller recorder failed.
	167		
	190	178	
	793	823	

TABLE I (continued)

Altitude ft	Ignition delay from Miller Record (milliseconds)	Ignition delay from electronic timer (milliseconds)	Remarks
25,000	918		
	737	778	
	775	813	
	No ignition	1000	
	1307	1000	Ignition some 300 m.sec. after propellants switched off
	1104	1000	Ignition some 100 m.sec. after propellants switched off
	No ignition	1000	
30,000	No ignition		
	No ignition		
	1239		Ignition some 240 m.sec. after propellants switched off
	1268		Ignition some 250 m.sec. after propellants switched off
	1420	1000	Ignition some 300 m.sec. after propellants switched off
	1358	1000	Ignition almost 400 m.sec. after propellants switched off
	No ignition	1000	
	1578	1000	Ignition some 600 m.sec. after propellants switched off
	1419	1000	Ignition some 450 m.sec. after propellants switched off

TABLE II

Tests with Combustion Chamber

Test No.	Ignition delay (m. sec)	Time of entry of C-fuel	Remarks
Single Chamber			
1	-	-	Explosion caused venturi plate to be blown off. No instrumentation.
2	51	-15	
3	6	-3	Firing took place immediately after test No. 2. Short ignition time thought to be due to drops remaining from previous test.
4	87	?	
5	92 (approx.)	?	Ignition delay only approx. as one pickup unserviceable. Explosive start and chamber torn from head.
6	254	10	'Hard' start but no damage to chamber. Combustion chamber pressure indicated simultaneously with photocell.
7	141 (approx.)	?	Ignition delay only approx. as one pickup unserviceable. Explosive start and venturi plate blown off. Combustion chamber pressure indication simultaneous with photocell. Copper discs indicated 6,000 lb/sq. in. combustion chamber pressure.
Double Chamber			
8	-	-	Explosion and venturi plate blown off. No record, photocell unserviceable.
9	-	-	Explostion and venturi plate blown off. Record useless owing to interference. Photographic record inconclusive.
10	164	?	Explosion, lower chamber split. Combustion chamber pressure indication simultaneous with trace.
11	125	-43	Explosion, venturi plate blown off. Extra C-fuel injectors used, mixture ratio changed to 0.83/1.
12	141	-33	Explosion and lower chamber shattered. Extra C-fuel used. Recorded combustion chamber pressure rose to 1440 lb/sq. in. in 7 m.sec.

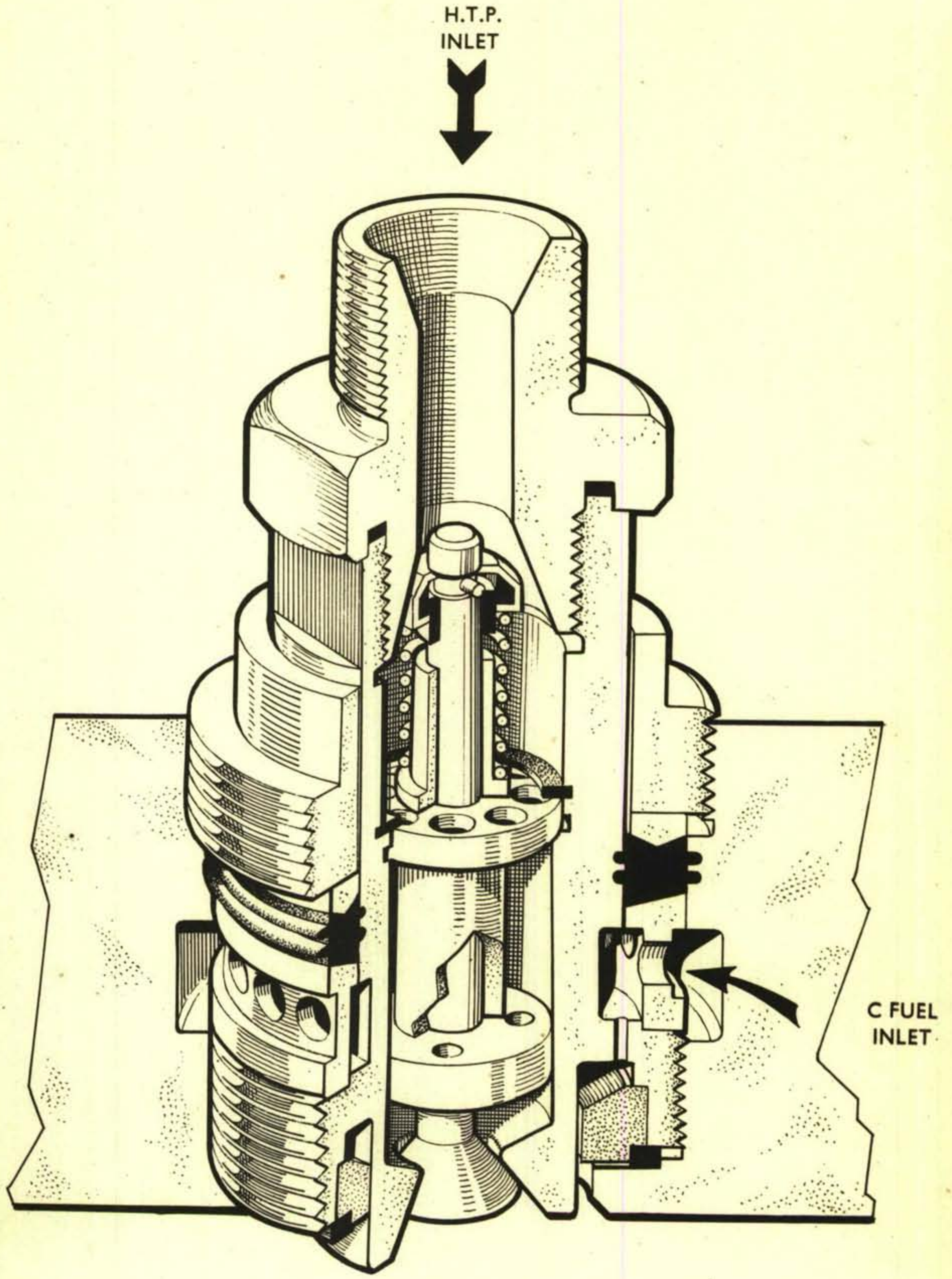


FIG. 1. WALTER 109 - 509 STAGE I INJECTOR

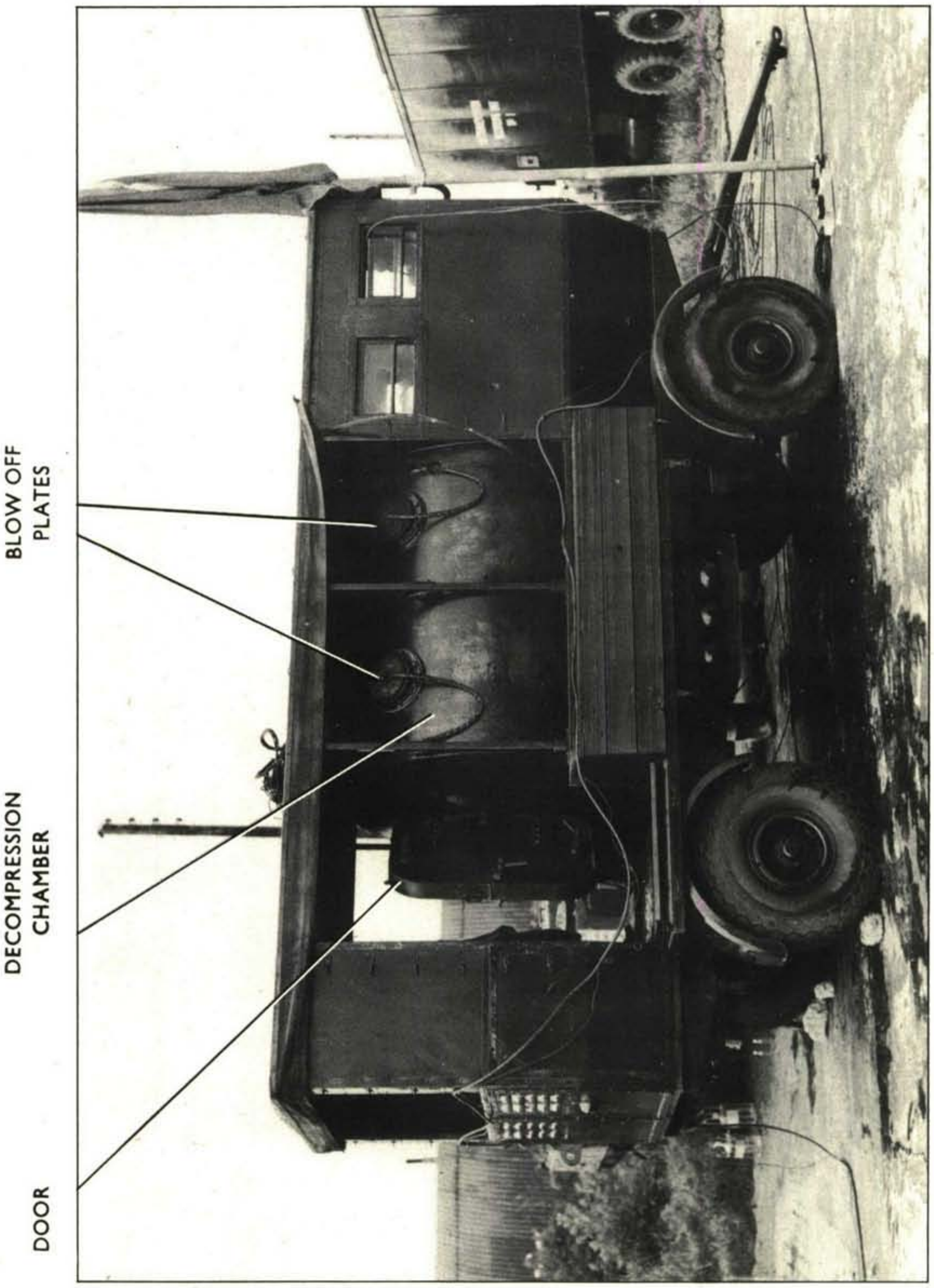


FIG.2. MOBILE DECOMPRESSION CHAMBER

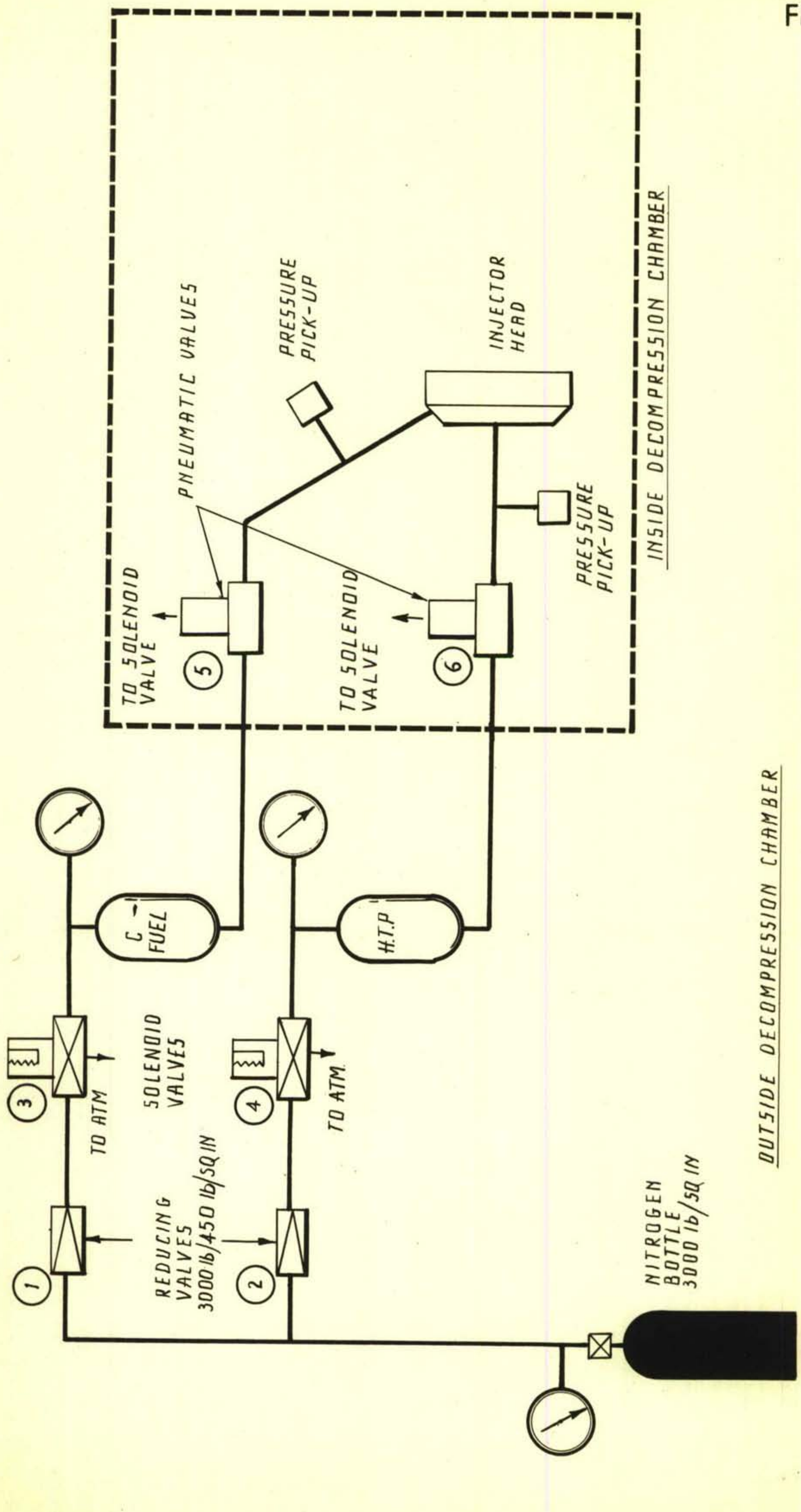


FIG.3. DIAGRAM OF TEST RIG

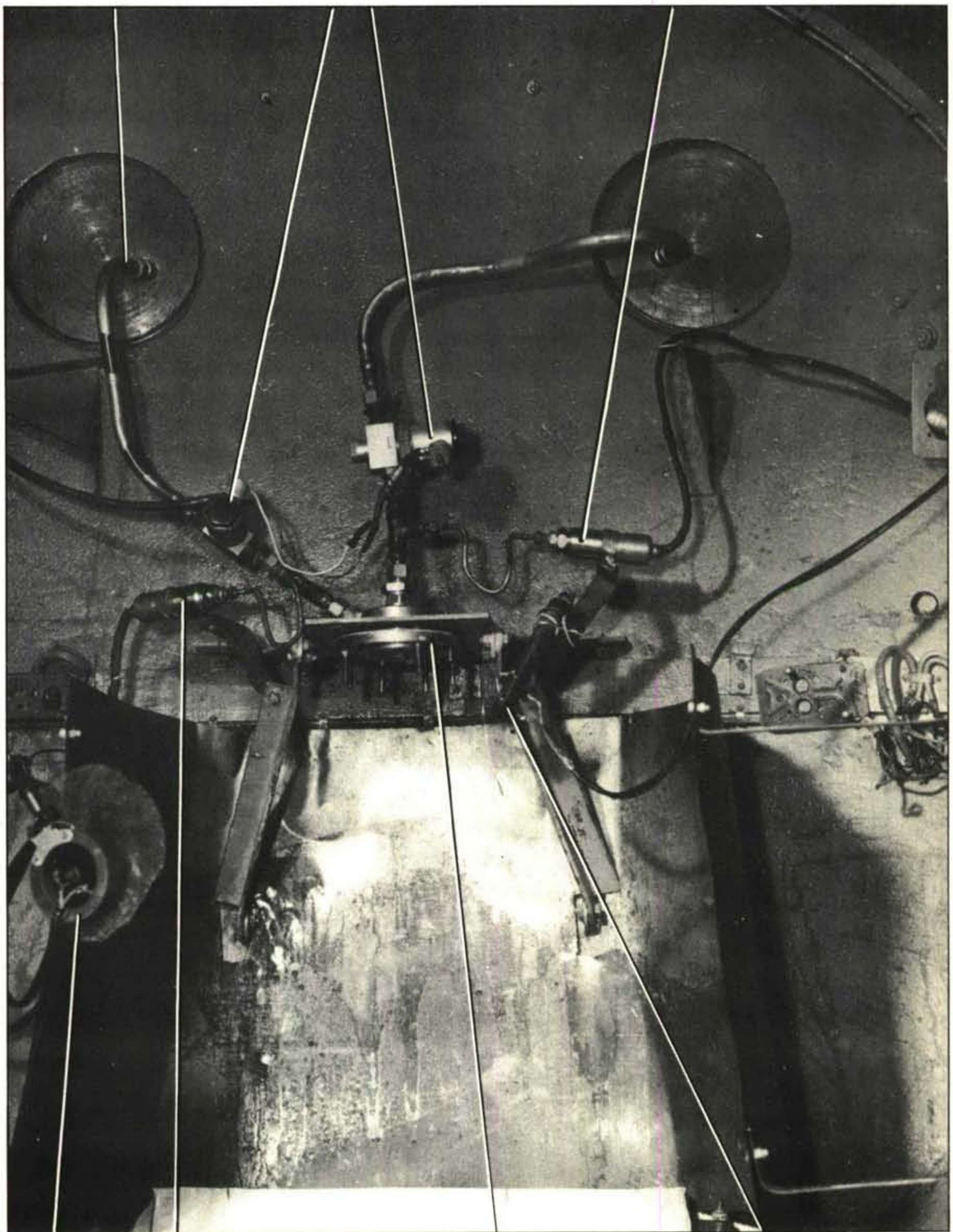


FIG.4. TEST RIG INSIDE DECOMPRESSION CHAMBER

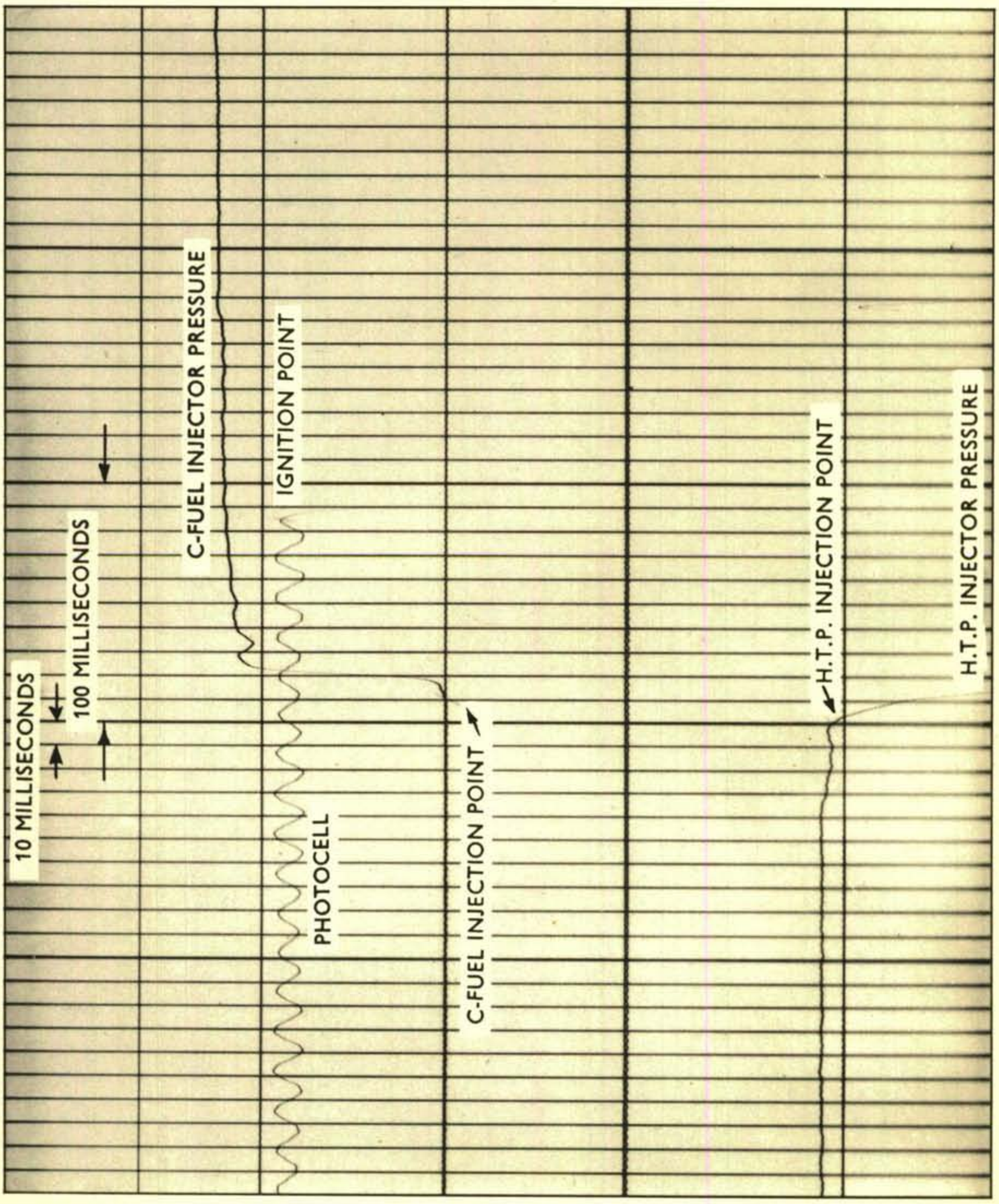


FIG.5. TYPICAL MILLER RECORD

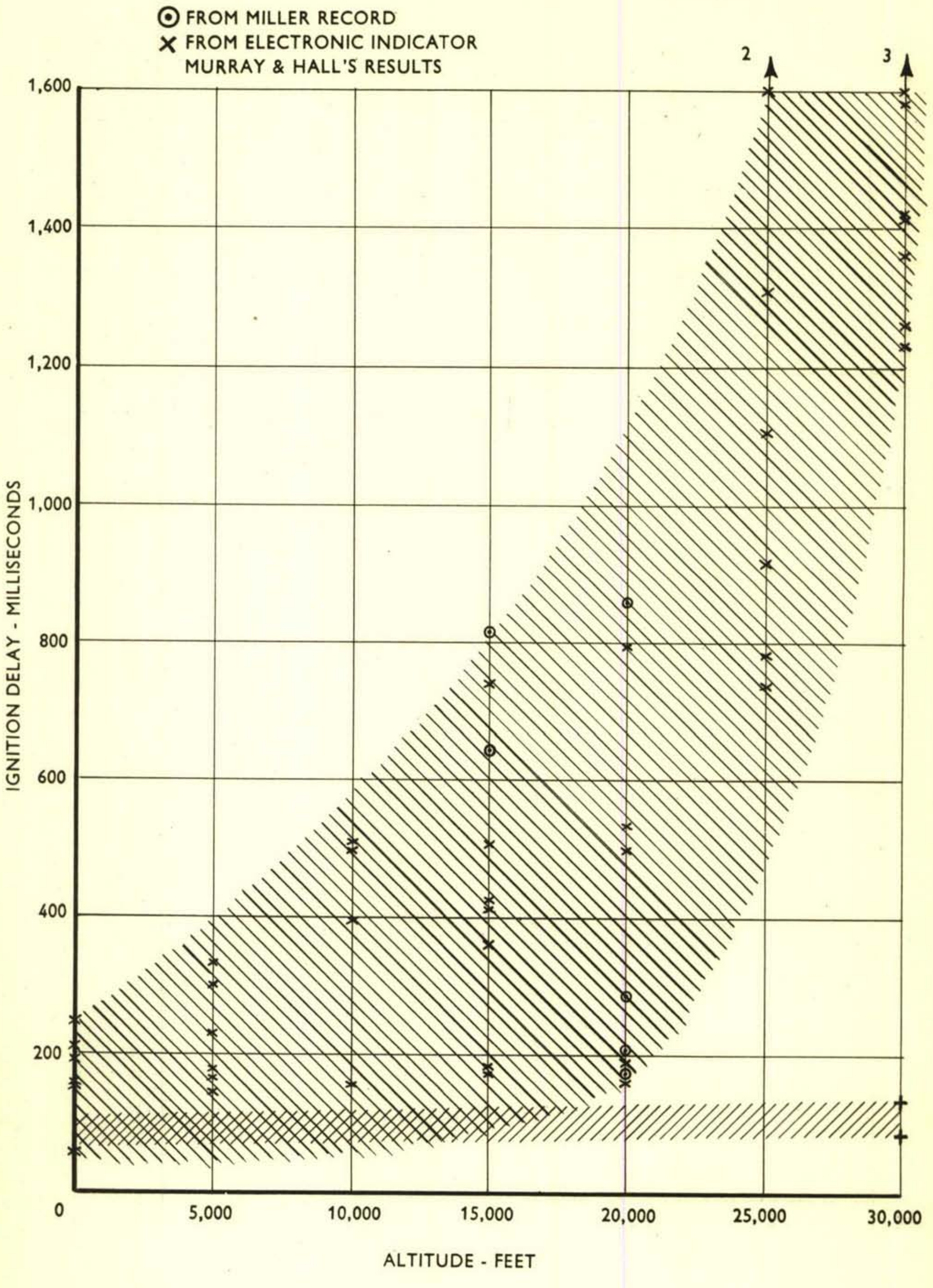


FIG.6. IGNITION DELAYS (0 - 30,000 FT)

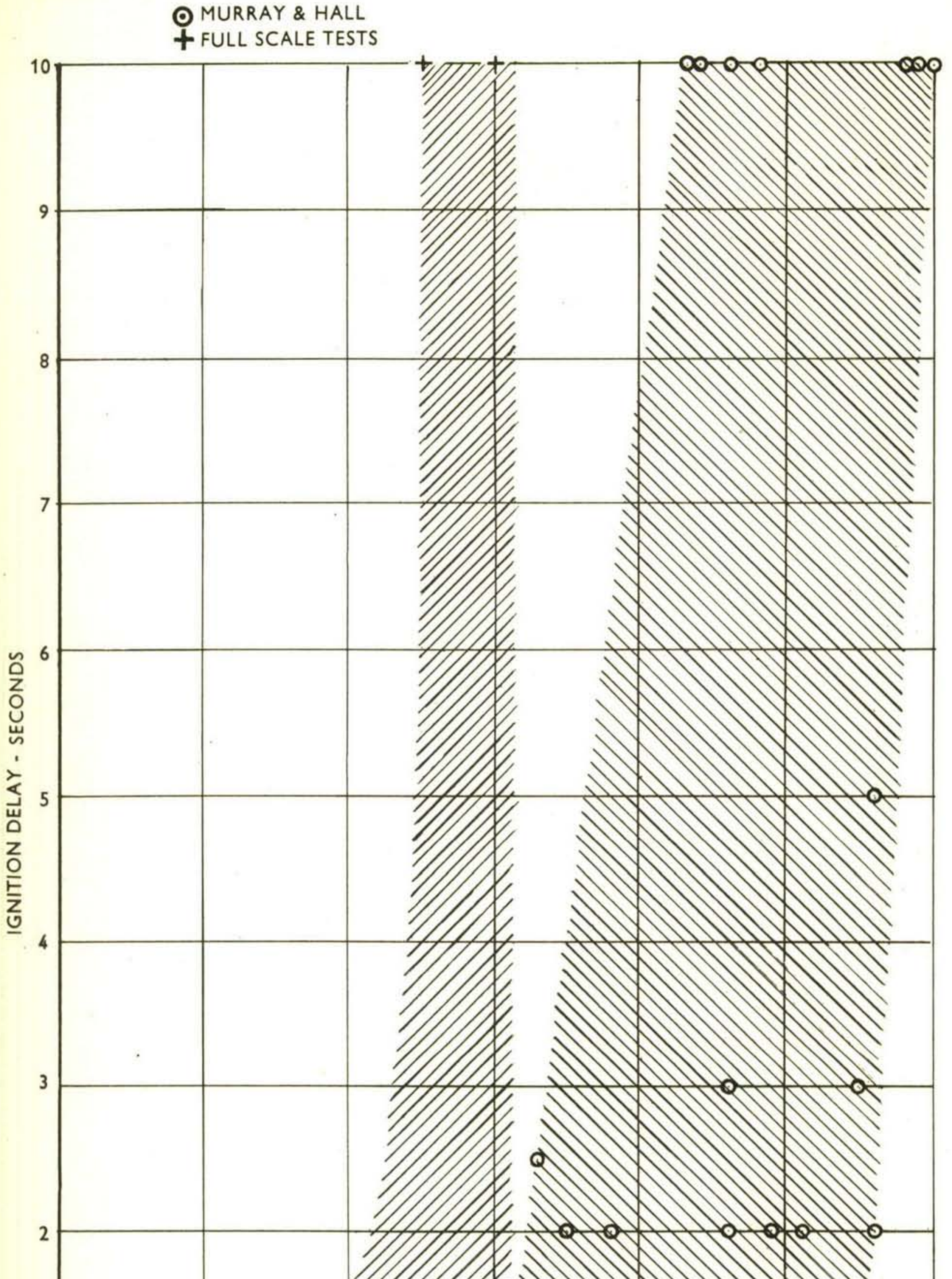


FIG.7. IGNITION DELAYS (0 - 60,000 FT)

FIG.8

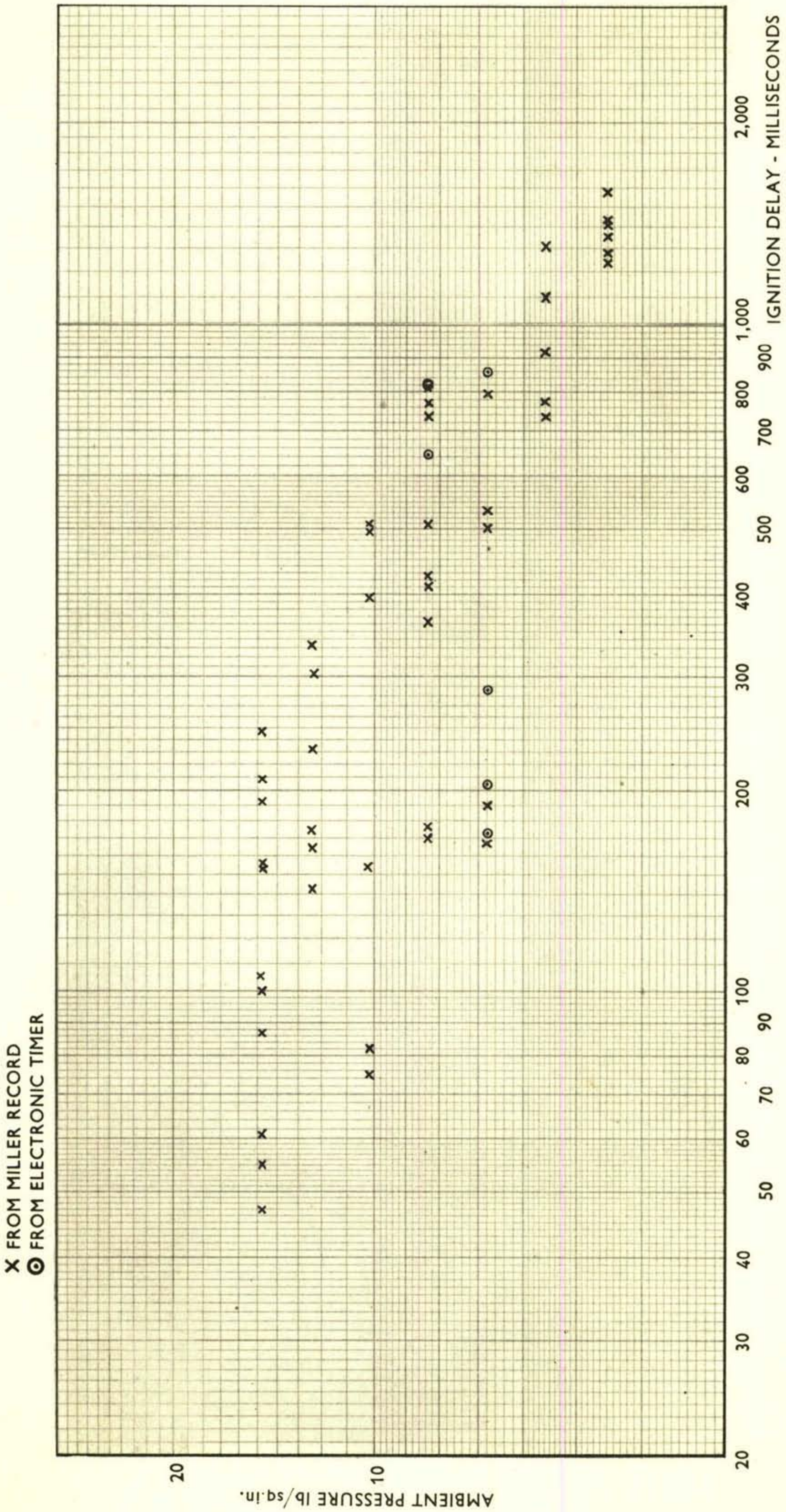


FIG.8. IGNITION DELAY, (REPLOTTED FROM FIG.6.)

FIG.9

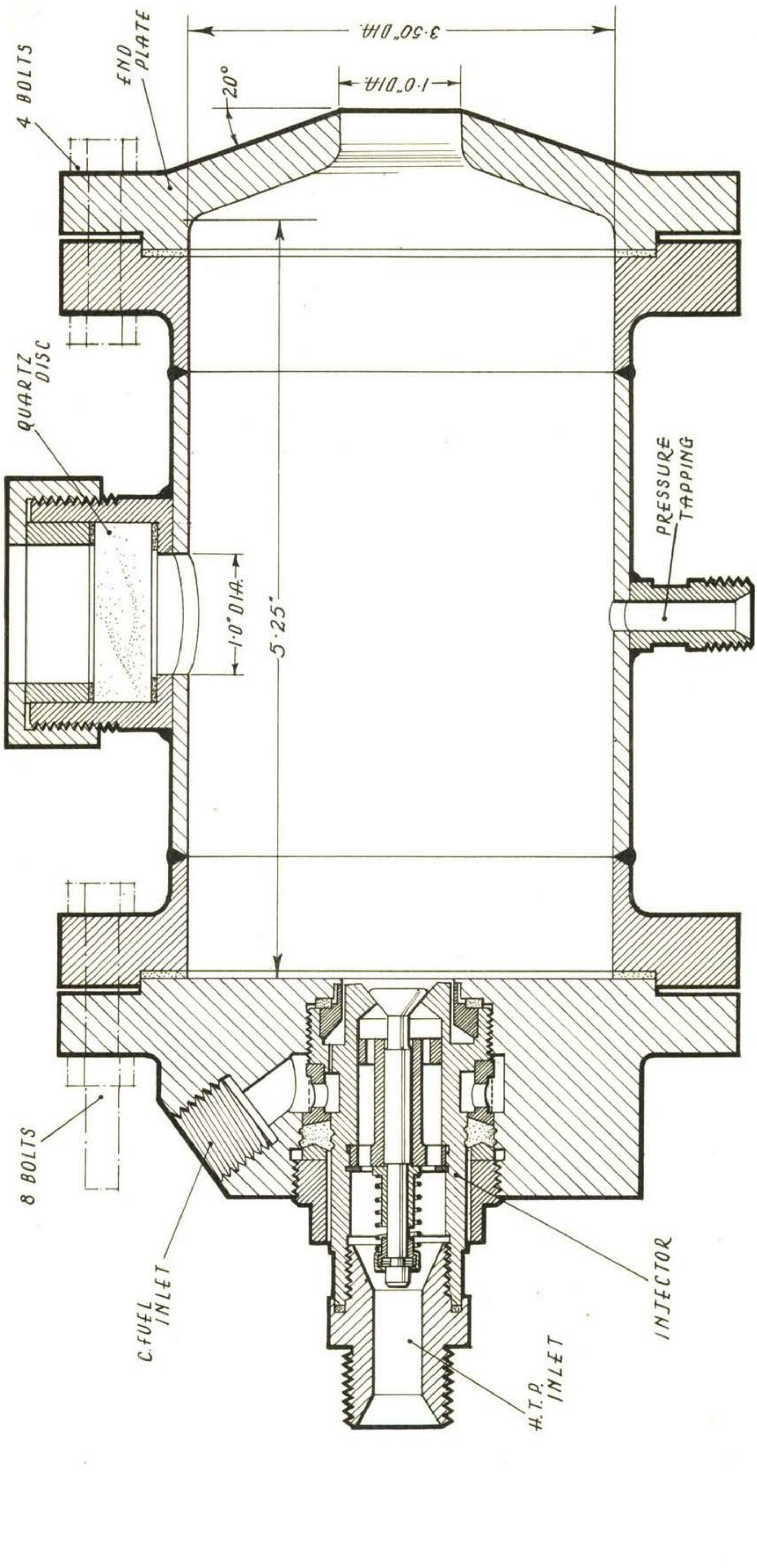


FIG.9. INJECTION HEAD AND COMBUSTION CHAMBER. L* 65" APPROX.

FIG. 10

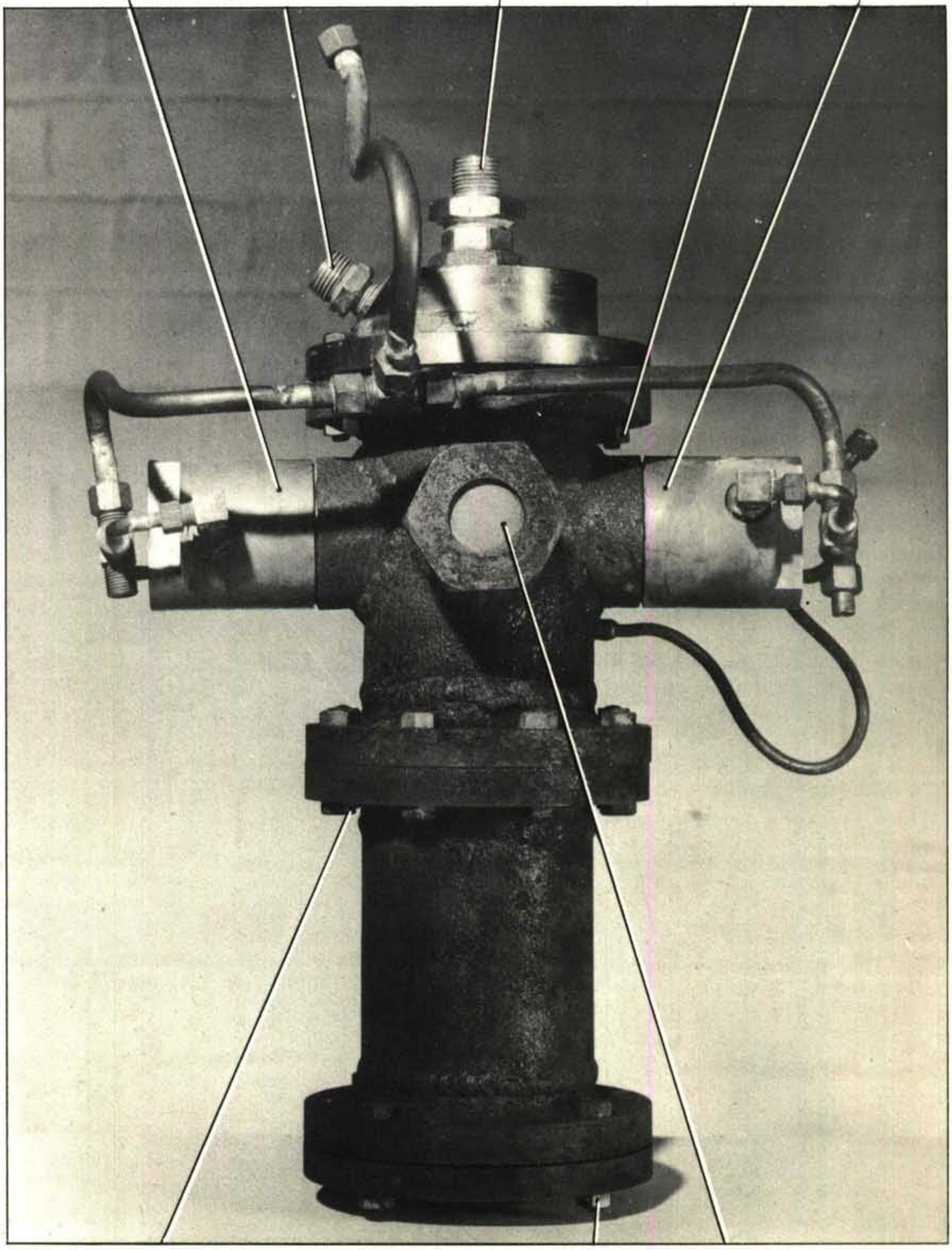
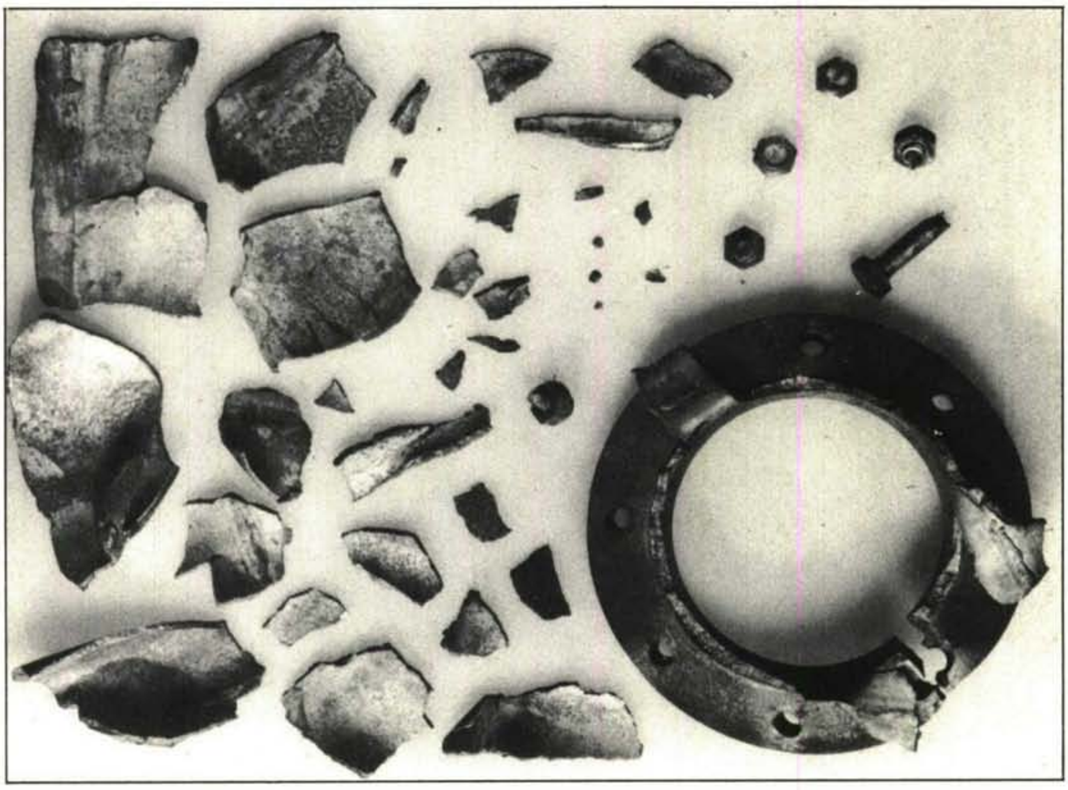
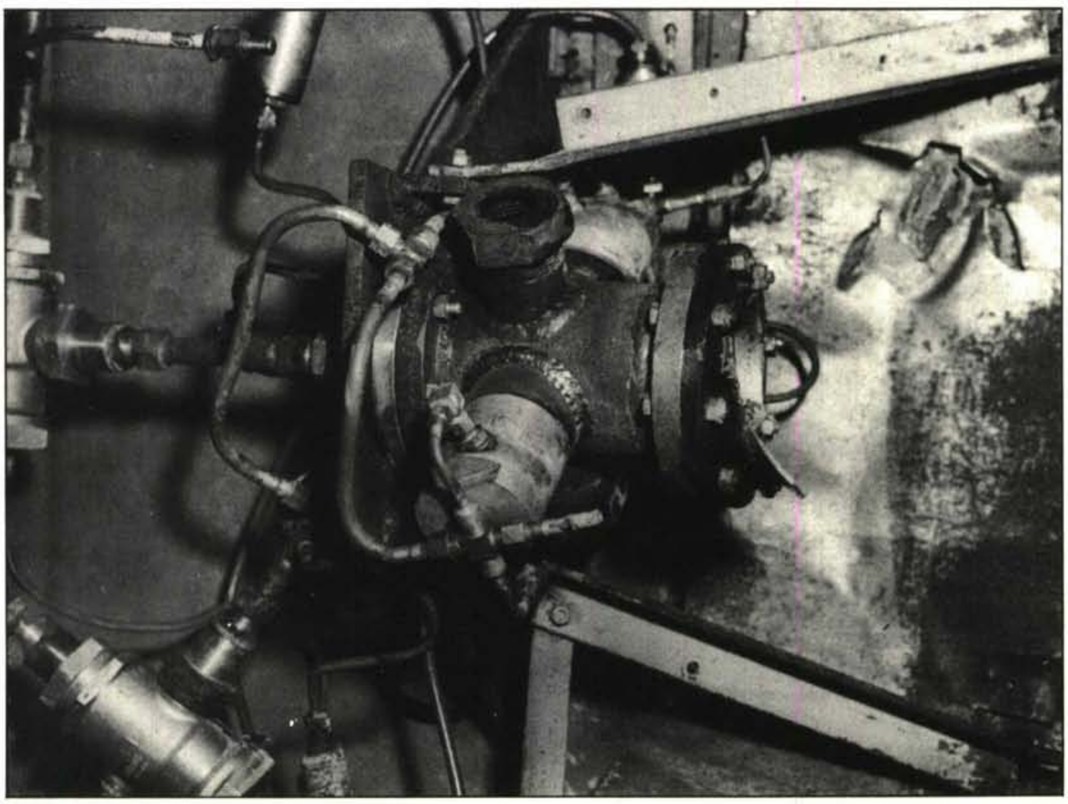


FIG.10. COMBUSTION CHAMBER WITH EXTRA C-FUEL INJECTORS



LOWER SECTION



UPPER SECTION

FIG.11. COMBUSTION CHAMBER AFTER EXPLOSION