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ARMAMENTS DESIGN DEPARTMENT

Technical Report No. 4/46.

(MONOFUEL ROCKET MOTORS)

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Armaments Design Department,
Ministry of Supply,
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Abstract

Various motors have been made, and tested statically at rates of fuel flow up to 1. lb./sec., using chiefly nitroglycerine (desensitised) and myrol as fuels.

Conclusions are drawn on the essentials for safe and efficient design, and theories relating to fuel combustion and motor design are put forward.

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MONOFUEL ROCKET MOTORS

Contents

Introduction

The Armament Design Department and Armament Research Department have worked together since the end of 1944, investigating the properties of monofuels, for the purpose of finding one suitable for rocket propulsion, and if possible, develop a rocket motor suitable for propelling the guided anti-aircraft projectile (G.A.P.), then being considered.

This report is based chiefly on work done by the Design Department, and describes the problem, the experimental methods used, and the results obtained. A certain amount of theory (see Appendix) has been developed during these experiments, some of which has been tried, but some is as yet unproved.

2. Requirement

Early in 1945, it was decided to proceed with a design of liquid fuelled guided A.A. rocket projectile, to meet Navy and Army requirements. C.E.A.D. was delegated by the GAP Working Committee, to design the structure of the projectile and propulsion unit. Since the chief requirement was to get a projectile into the air for tests of the radio control apparatus, it was decided initially to use the relatively well tried liquid oxygen - petrol fuel combination; the motor using these fuels to be designed by The Asiatic Petroleum Company. At the same time, C.E.A.D. and C.S.A.R. were to carry out research on combustion of monofuels, with a view to developing a suitable monofuel rocket motor in time for use with the Gap projectile, when the control side was satisfactory.

The requirement for this was a motor with a thrust of 1,000 lb., a specific impulse of 200 lb./sec./lb. or over, and duration of 25 seconds.

3. Fuels

3.1 Advantages and disadvantages of monofuels

Monofuels are ultimately unstable liquids, containing oxygen for their own combustion, desensitisers, and possibly catalysts. An example, is liquid nitroglycerine, with the addition of 30% nitrobenzene as a desensitiser. It is evident, that their properties are very different from those of bifuels, and must be used in different ways, and with different precautions. Compared with bifuels, they have many advantages and disadvantages, the most important of which are tabulated below:-

Advantages	Disadvantages
Simplicity of tankage, burner design etc.	Lack of safety. Fuels can be exploded or even detonated by impact or local detonation.
Simplification of piping etc. in fuel expulsion methods.	Difficulty of using pumps, cordite gas, for expulsion.
Ease of storage. Tanks can be sealed, hence readiness for immediate use.	Reduction of specific impulse if fuels are fully desensitised.
Ultimate possibility of better combustion owing to molecular association between atoms of carbon, hydrogen, etc. and the oxygen.	Not self igniting.
	Difficulty of providing cooling for combustion chamber.

3.2 Availability of fuels

At the start of the experiments in October, 1944, only four types of fuel were available, and little was known of their properties, though some measurements had been made of the sensitivity, the flash point, (temperature below which the vapour will not ignite on sparking) and the self-ignition point, (temperature at which liquid automatically ignites on heating), etc. Later, fuller data became available through the work of C.S.A.R. at both Fort Halstead and Woolwich.

The fuels available were as follows:-

(a) Nitromethane — in small quantities
(b) 70% Nitroglycerine, 30% Nitrobenzene — in unlimited quantities
(c) 90% D.E.G.N. (Diethyleneglycol dinitrate) 10% Nitrobenzene
(d) Myrol (Methylnitrate plus methyl alcohol) in various ratios, at first 80/20 and later 75/25.

The mixture ratios given could of course be varied, but at that time, the above were considered to give an adequate margin of safety from burning to detonation. The possibility of detonation on impact was for the time, being ignored, as impact risk during experimental work was negligible..

3.3 Choice of fuel

The first test run was carried out using nitromethane, which failed to ignite in a hot cordite igniter flame. Due to this, its cost (6/- per lb.), and its limited availability, no further runs were made with this fuel. Then D.E.G.N. and N.G. mixtures were used as these fuels were available in large quantities, but N.G. was decided upon as it has a higher theoretical specific impulse value than D.E.G.N., and in order to fix attention on one fuel.

Meanwhile, arrangements were made for the production of Myrol at Woolwich Arsenal, as it was hoped that this would show an improvement over N.G. Compared with N.G., Myrol is very much less viscous and more volatile, and has a higher self-ignition point and considerably lower combustion temperature (2400°K compared with 2750°K), for a given specific impulse. Its rate of burning was expected to be high. When Myrol became available in December, 1944, it was used at once, and became the standard fuel. Some tests were still made using N.G. fuel when supplies of Myrol ran out.

During all these early stages, no very great importance was attached to the type of fuel used, as it was expected that much of the information gained from experiments with one type, could be related to others. This has since been more or less borne out in practice. It is however necessary, when the design of a specific motor is to be undertaken, for a definite fuel to be decided upon as different fuels require minor differences in motor design, such as, for instance, the sizes of the spray jet.

4. Design of experimental test rig

4.1 Initial data

It was decided, to make a start with a combustion chamber and test rig to handle fuel flows up to 1 lb./per sec, and hence thrusts of about 200 lbs. A combustion pressure of about 300 lb./per sq.in. was decided on, partly by analogy with known bifuel systems, and partly from consideration of tank strength, gas expulsion system weight, etc. There are many considerations involved in fixing an optimum working pressure and is discussed further in section 6.

4.2 Description of test rig

On this data, a static test rig was designed in which a combustion chamber firing horizontally, and supported by two guide plates, could slide along two horizontal rails, the thrust being taken by a measuring head. (see Fig.1). The slide contact was metal giving dynamic frictional reaction up to 5 lb. The combustion chamber, of internal diameter 3 inches and length 4 inches, and built up of 4 detachable sections bolted together was uncooled; the parts being machined from solid mild steel bar (Fig.2A).

The fuel was fed under nitrogen pressure (see Fig.3), from a vertical fuel tank 3" diameter and 3 feet long, through an electrically operated valve and a flexible pipeline, and injected into the combustion chamber through a single swirl type cone spray similar to the usual commercial type. The pressure drop across this nozzle was initially about 50-100 lb./sq.inch. In the first test, a cordite igniter having a burning time of one second, was used, but in all subsequent tests, an igniter with a "cigarette" burning plastic charge of some 200 gm. was used, which had a burning time of about 5 seconds, and a rate of heat input of 44,000 calories per second.

4.3 Method of operation

The method of operation was as follows:-

First, the fuel tank was pressurised by openeing the cock on the nitrogen bottle. The igniter was then switched on and, after a delay period, sufficient to ensure that the igniter was burning correctly, the electrically operated valve was opened, allowing the fuel into the chamber. These operations were carried out by remote control, the apparatus being in an earth covered tunnel.

4.4 Recording

During the functioning of the combustion chamber, readings were taken of the pressure, and the pressure in a cylinder of oil between the thrust head and thrust piston. This latter pressure gave the thrust of the motor. Pressure gauges were of the electrical condenser type loading directly to a local oscillator box, and from which two variable frequency currents, corresponding to thrust and pressure were transmitted to the recording amplifiers. There they were transformed to variable voltages after amplification, and used to produce movement of two spots on a cathode ray tube. These were photographed on a revolving drum camera. An accuracy of ± 1% was claimed by the operators for this method of recording.

A screwed inlet was also provided near the venturi throat of the combustion chamber, permitting the insertion of a thermo couple, but this was not initially used. By the use of an electrically operated tuning fork, time intervals of 1/25 of a second were recorded by marks on the films. This method gave considerable accuracy for estimating the length of runs. The whole recording gear was that already in use for the development of plastic propellant by Dr. Runicles of C.S.A.R.

5. Detailed design and early modifications for safe and satisfactory operation.

It is not proposed here to describe tests in detail, but rather to describe the initial difficulties encountered, and the methods used to overcome them. These difficulties fall chiefly into sections and are related to the design of various parts of the apparatus with regard to their satisfactory operation and their safety, and the conclusions in para. 5.13 should be helpful in further work.

Later tests dealt more with changes in flow rates, pressures, type of injector etc., and less with detailed modification of apparatus. These are described in section 6.

5.1 D.E.G.N. Tests

In all the five tests using D.E.G.N. fuel, the results were negative. The first of these was highly oscillatory; in the next three there were igniter failures, and in the fifth a blowout disc failed. There seems no reason why D.E.G.N. could not be made, if desired, to give a performance approaching that of N.G., as these failures had little or no connection with the fuel used.

5.2 Channelling

The second of the N.G. tests, was satisfactory for a short time, ending in an explosion. This was assumed to be due to channelling of the fuel in the tank and feed pipe lines by nitrogen gas at the end of the run, and the consequent injection into the combustion chamber of a mixture of fuel vapour and nitrogen, with possibly some of the air which initially filled the ullage space in the fuel tank. The rate of flame propagation through the vapour being higher than the velocity of the flow of vapour through the nozzles, it was possible for the flame to carry back along the fuel line, blowing this up and igniting the remaining fuel.

To prevent this in subsequent runs, a relatively inert fluid (water in the case of N.G., and paraffin in the case of Myrol), was floated on top of the fuel in the tank, and found satisfactory.

5.3 Igniter failures

While the "cigarette burning" plastic propellant filled igniters (see Fig.4), proved fairly reliable, there were at first (runs 7a, 7b, 7c, 31a, 51 and 52) a number of failures to ignite, or cases of unduly fast burning. These were finally cleared up in March, 1945, by carrying out tests on igniters fired in the open. It was found that when the propellant was pressed with a flat ended punch, giving a flat end surface to the propellant, erratic burning times were obtained. Modifying the punch so as to produce a concave propellant surface, overcame this, and consistent burning times resulted. It was found essential to use the 'hot' propellant R.D. 2633 - one or twofailures to ignite being due to using a low energy propellant with perspex binder.

It was also found, that if the cavity containing the electric puffer at the choke end of the igniter pot were too great, ignition was liable to fail. Hence when a short burning igniter was required, it was necessary, first to fill the pot partially with inert propellant, and then to press on top of this the required amount of live propellant, so as to leave a constant small ullage space.

5.4 Positioning of igniters

Up to December, 1944, (run 23), the igniter had always been placed so as to fire across the chamber towards the spray injector, at an angle of 20° to a diameter. This caused a certain amount of preheating of the injector and in some cases resulted in its melting, and may have filled up the space behind it with hot gas.

It is very likely that this arrangement was the cause of some blow ups, the fuel being ignited behind the nozzle due to its high temperature or by the gas. In subsequent runs, the igniter was placed nearer to the venturi and pointing away from the spray injector, when satisfactory ignition was still obtained, and a possible cause of mishaps eliminated.

When using thin walled combustion chambers, it was necessary to keep the delay before the entry of fuel down to reasonable limits of approximately 1 sec. as the igniter had a tendency to overheat the chamber wall which would bulge out on combustion of the fuel at higher pressures.

5.5 Other methods of ignition

A few runs were carried out early on (runs 34, 39) using a sparking plug, giving a repeated spark, and also using a pyrotechnic igniter firing through the same hole in the side of the combustion chamber.

With the sparking plug arrangement, no ignition occurred, though in one case a 'pop' (very mild explosion) was produced, which broke the flexible fuel line.

With pyrotechnic ignition, N.G. fuel was ignited, but the run was unstable; with Myrol fuel an immediate explosion occurred.

It is possible, that ignition is considerably assisted by the existence of the moderate pressure which the plastic igniter creates (about 40 lb./sq.in. observed, 80 lb./sq.in. calculated, ignoring losses), but which is absent in the case of the other two methods. Since ignition tests were not of primary importance at this stage, and satisfactory ignition could be obtained using the original plastic igniter, all further tests were carried out using this type which, though less simple and rather bulky, was reliable.

5.6 Filters

Initially, no filters were used in the fuel line, but it very soon became evident from water tests etc. that, without a filter, there was every possibility for the jets being choked. This was especially important when using impinging jet nozzles (Figs. 5, 6A, 6B and 7) as in the early tests but rather less so in later tests when using swirl types (Figs. 8 and 9). It was therefore absolutely essential to incorporate a filter immediately before the spray nozzle, and this was done in all runs after run 12.

The exact positioning was varied. Filters soldered directly on to the impinging jet nozzles proved unsatisfactory (See section 5.11), and eventually a filter in a special filter holder was fitted in the pipe line just before the inlet flange (Fig. 2B).

Later, when using solenoid as opposed to motor operated valves, some valve failures occurred, and it was found essential to interpose a filter to protect the valve from small particles of grit.

In each case, a flat circular disc of fine gauze of 80 or 100 mesh and about 1½ inches diameter was used (though other shapes might be equally suitable), held clamped between leather washers which were frequently replaced. The importance of using filters in these two positions cannot be over emphasised.

5.7 Blow out discs

Many safety devices were tried, consisting of blow out discs fitted at various points in the system, to give immediate release of pressure in the event of an explosion at the combustion chamber. These were fitted to the inlet flange, to the pipe line and next to the fuel tank, and used both with and without an accompanying non return valve.

Their intended function was to release the pressure during any explosion so as to hinder burning down the pipe line and the transmission of detonation. Opinions differ as to their value, as it is not certain whether they can produce a large enough release aperture in a short enough time. They are probably of little value once a detonation has set in, and blow-ups have occurred in spite of their presence, though they may have limited the extent of the damage.

Those used, consisted of silver foil clamped between hardened and ground washers of internal diameter 0.55 in, the foil being in 3 layers, each .005 in. thick. It was found, that thicknesses calculated to withstand two or three times the working pressure were necessary to withstand the initial pressure surge due to ram effect on switching on. Discs were changed every two or three runs, as failures occurred, thought due to pulsation, and consequent weakening of the disc during runs which were not completely steady.

5.8 Non return valves

Non return valves used in conjunction with a blow-out disc, were intended to close the fuel line between the combustion chamber and fuel tank (see Fig.3), while the disc would release the pressure. This was in order to prevent the entire fuel tank from bursting on every minor explosion, and to prevent burning back along the pipe line.

Simple flap type valves (from Buck and Hickman) were used, but it is dubious whether their response was sufficiently rapid to be of value. Some explosions (not detonations) were stopped at the valve, while in other cases the valve was retrieved from the floor in small pieces.

As the value of this piece of apparatus has not been proved, it is thought that some form of detonation trap consisting of constructions or enlargements of special shape in the pipe line might be the solution.

5.9 Detonation stopper

A detonator stopper, consisting of nine small diameter pipes in the form of a U, connected in parallel with each other and in series with the fuel line, was tried experimentally. Due to its doubtful value and the constriction to flow, its use was not continued.

5.10 Main Fuel control valves

The main fuel valve being one of the key pieces of the apparatus had to be protected from solid particles in the fuel by a filter.

It was found after tests with different types of valves that there are certain features which are essential for efficient operation. The requirements are broadly as follows:-

(a) The valve must be able to pass the required flow with a reasonably low pressure drop across it, and also to produce a minimum of turbulence, in order to prevent mixing of the fuel and follow-through liquid, and to prevent the possibility of initiation of the fuel due to viscous shearing.

(b) Leakage across the valve to the combustion chamber must be small, as this may cuase premature ignition of the fuel and an explosion, or the production of vapour, the ignition of which would also cause an explosion. Some leakage to atmosphere can be tolerated if it can be collected and measured. These conditions can be met by using a two way valve, the feed to the combustion chamber being offset and above the feed line from the fuel tank, and the vent line below it.

(c) A metal to metal valve should be unable to impact back on its seating in the event of a pressure rise in the combustion chamber. If, as once happened, this occurs, it may produce detonation at the valve itself.

(d) It should preferably be fairly resistant to corrosion by the fuels used, for though the fuel is largely cleared by the follow through liquid, some trace may remain after firing.

(e) It may well be found necessary in future experiments, to design valves having a rate of opening which is variable, in order to prevent the initially high fuel flow which occurs when there is no back pressure in the combustion chamber. With the rig used, however, the time of operation was not found to be important. Delays from off to fully open varying from almost zero to about 1/2 or 1 second were used satisfactorily. Naturally such delays could not be tolerated when actually studying ignition intervals, which has yet to be done.

(f) It must be capable of being remotely controlled and operated by electrical apparatus with ease. This means that some type of solenoid or electric motor driven valve must be incorporated, either as main or pilot valve. The valves actually used are given in the following, but it is hoped finally to use some form of piston valve with a straight and clear passage when open, and possibly operated by an electric jack (Rotax - A/C type) with varying delay times.

5.10.1 <u>The valves actually used</u>

The valves actually used were:-

(a) A three turn stop valve operated through worm gearing and rubber coupling by a small electric motor. This had conical brass seats and operated fairly satisfactorily, though with slight leaking and occasionally sticking.

(b) A solenoid valve made by Thorpe and Co. (Manchester) utilising a very large mains operated solenoid, and having a self locating steel ball in ring seat. This valve eventually impinged on the sealing and detonated the fuel.

(c) A German valve, operated by nitrogen pressure after passing through a small German solenoid valve. The particular valve used had a steel conical valve which seated on a small conical area of steel, but it was prone to jam.

(d) A German solenoid valve used direct, with seating similar to the above. This valve has been quite satisfactory, but is somewhat small and produces a high pressure drop.

5.11 Fuel sprays (burner or nozzles)

The design of these sprays, together with their associated mountings (the inlet flange or burner plate) and the lead in to it is crucial for safety and performance.

The latter aspect, together with the use of a combination of different sprays and use of new principles for producing good combustion, is dealt with in section 6.

The safety and mechanical design of the two main types of spray which have been used are described below:-

(a) Impinging jet sprays. Three main types have been made and tried as shown in figures 5, 6A, 6B and 7. Nearly all of these consist of 8 holes drilled in pairs to meet at right angles, the sizes of the holes being varied to give the correct flow with different fuels. With holes made by a No.52 drill (.0635 in.dia.) and 150 lb./sq. in. pressure drop, the medium mass drop diameter was about 600μ. With a No.68 drill (.031 in.dia.) this decreases to about 300μ. Neither of these is very good.

Trouble was discovered with the first type, Fig.5, due to the large dead space behind the nozzle in which fuel could remain fairly static and 'self ignite'.

In the second type, Fig.6A difficulty was found in seating the nozzle without getting slow leaks past the threads, in which case 'self ignition' occurred in the threads. The use of leather seating washers was also unsatisfactory (though essential when a gauze filter was soldered to the nozzle direct) as these became impregnated with static fuel, which could again ignite. The nozzles were finally used with washers and pulled up very tight, but it was felt that this was not very satisfactory.

The seating of the third type, Fig.7 in which asbestos string was used, was satisfactory.

(b) Swirl sprays. Two main types of burner utilising these were tried; one with a single large central spray nozzle, Fig.8 and one with six small nozzles arranged symmetrically around a seventh, Fig.9.

For safety reasons, the first type was fabricated in various ways, but gave only moderately fine atomisation (300μ) and bad spray distribution, inherent in the use of a single cone of spray. Results with these nozzles were steady but poor.

The second type consisted of seven Monarch nozzles made by Watsons (Widnes - Lancs) screwed into a plate and seated on asbestos string. These have been satisfactory from the safety aspect, and from the point of view of good distribution of spray and good atomisation (200μ) they have proved the best so far tried.

5.12 Materials

Up to the present date, all the main components of the motor have beem made of mild steel. The later combustion chambers, Fig.2B were fabricated from drawn mild steel tube, and the venturis turned from solid bar. With the rather low S.I's obtained for times of under 30 seconds, these have each lasted for several runs, though the chambers, which frequently attained a deep red heat, eventually tended to bulge.

The spray nozzles were made of mild steel or brass and show no sign of melting. Others made of aluminium have not yet been tested.

Tanks and pipe lines which to some extent have to withstand corrosion, were initially made of mild steel to speed delivery, but have recently been replaced by stainless steel tanks and copper piping. Tanks made of aluminium have also proved satisfactory.

It was anticipated that the uncooled venturi would burn out, but this has as yet not occurred. As a result of enquiries for production of the venturi in heat resisting materials, the following have been made and are undergoing tests.

M.S. venturi with graphite insert
" " " tungsten carbide insert
" " " molybdenum coating (by gaseous diffusion method)
" " " tungsten coating
" " " chromium coating
" " " chromium carburised coating
" " " zircon insert (varieties by Smith and Shaw Ltd.).

5.13 Conclusions

For the safe operation of an experimental monofuel rocket motor, the following points were found essential:-

1. Provision should be made for the protection of personnel and at the same time means for observing the experiments.

2. A non explosive follow-through fluid, which is relatively non miscible with the fuel used and lighter than it, should be floated on the fuel in the fuel tank, to prevent channelling of the fuel by the expelling gas.

3. Igniters filled with "cigarette burning" plastic propellant should be pressed to give a concave initial burning surface, to obtain constant burning time. The ullage space containing the electric puffer should be kept constant and small, to ensure certain ignition.

4. The igniter should be placed so as to direct its flame away from the burner and towards the venturi. The time between initiation of the igniter and entry of the fuel should not be excessive. (say = 1 sec.).

5. From the experiments so far carried out, no conclusions can be made as to the ultimate possibility of using pyrotechnic or spark ignition with success.

6. Filters must be placed immediately before the fuel sprays, and also immediately before the main fuel control valve.

7. No conclusion can be made on the efficiency of non-return valves (flap type), blowout discs or the one type of detonation stopper, in preventing the transmission of explosion or detonation down a line full of a monofuel.

8. Main fuel control valves should be electrically operated, directly is possible, vent the combustion chamber line when in the off position and allow no leaks to this line. A three-way valve suitably orientated will satisfy the requirements.

9. In the design of spray burners, the greatest care must be taken to eliminate static pockets of fuel in places where the temperature may rise to the ignition point of the fuel. This can be arranged by seating the nozzles at the 'fuel inlet' end of their screw threads, the avoidance of sharp corners and fuel absorbing washers, and by the use of welding where possible.

6. Principles of motor design

In order to understand the varieties of motor designs (especially of spray injection) used, and be able to develop future designs, it is first necessary to understand a number of basic principles. These are given in the following three groups, the first being well known standard principles true for all liquid fuel rocket motors. The second group are less well known but are more or less rigid. The third group give the assumptions made essentially for monofuels, and the deductions, the validity of which depends on their ability to explain the facts. This they have done to some extent, resulting in the development of theories which have helped in understanding (perhaps only approximately) the mechanism of the motor, and in designing improvements. The theory which is linked with these deductions and principles is given in the appendix.

6.1.1 Well known standard principles

(a) The rate of fuel consumption in lb./sec. is proportional to the total area of the spray injection orifices and the square root of the pressure drop across them (i.e. the feed pressure less the c.c. pressure).

(b) The mass flow of gas out of the chamber via the venturi, which must be equal to (a), is proportional to the venturi throat area and the combustion chamber pressure.

(c) The velocity of the ejected exhaust gas is roughly constant for all rates of fuel flow and all combustion pressures, being equal to the product of the specific impulse produced, and g

(d) With increasing combustion chamber pressure the gas density and hence the mass flow increases in proportion.

6.1.2 Less well known principles

(a) The mean axial gas velocity at any cross section of the chamber, is approximately proportional to:-

$$\frac{\text{Fuel flow rate}}{\text{c.c. pressure x cross section area}}$$

(b) Hence the average time which any particle of gas spends in the chamber, is proportional to:-

$$\frac{\text{c.c. pressure x c.c. volume}}{\text{fuel flow rate}}$$

(c) And in 'scaling up a motor, if one is to retain the same conditions (i.e. the same velocities in the combustion chamber), one must retain the same length of combustion chamber, and increase the cross section proportional to the increase in fuel flow rate.

6.1.3 Assumptions and derived principles

(a) Drops of fuel sprayed into the combustion chamber burn on the surface radially inward at a constant rate.

(b) Drops rapidly achieve the velocity of the surrounding gas (see appendix).

(c) The time each drop spends in the combustion chamber is therefore much the same as for each particle of gas and proportional to:-

$$\frac{\text{c.c. pressure x c.c. volume}}{\text{fuel flow rate}}$$

(d) The linear rate of burning of the fuel increases with pressure, probably in the relation p^m, where m is constant.

6.2 Application to the problem - conflicting consideration

Since the whole problem is fundamentally one of burning a given quantity of fuel as efficiently as possible, we have on the basis of these principles a number of conflicting requirements. For complete combustion, each drop must be so small that, in the time available and with the prevailing rate of burning, it will be completely burnt before leaving the combustion chamber. This can be obtained -

(a) by fine atomisation,

(b) by the use of a large chamber to increase the time available in it,

(c) by use of high pressures to increase the time available and the rate of burning. This may also improve atomisation (see below), and

(d) by the use of catalysts etc. to increase the rate of burning.

Another and distinct consideration is that of efficient burning of the drops as opposed to their complete burning. This requires that the exhaust gas produced by burning the fuel should have a certain composition and that it should not contain, for instance, a large percentage of formaldehyde and N.O. This efficiency, which is a chemical consideration, depends largely on the combustion pressure and slightly on the time available for the reaction. There is thus fixed a minimum combustion pressure below which it is uneconomical to run, even though combustion of fuel may be complete in the mechanical sense.

6.3 Trend of design

In the first instance, combustion pressures of approximately 300 lb./sq.in. were used, as it was considered that the design of the fuel tankage would be unduly heavy if it had to withstand pressures of over 450 lb./sq.in. (the approximate required expulsion pressure). Later tests carried out with combustion pressures up to 450 lb./sq.in. have shown improvement in Specific Impulse, but the acceptance of this increase depends on the design and strength of the projectile. There is obviously much to be gained by the use of high combustion pressures if it is at all possible, though the minimum for efficiency may be reduced by catalysts.

In the experimental rig, the combustion chamber volumes have always been high for the flow rates used; L^*, the ratio of c.c volume to venturi throat area, being variously 50, 100, 240 and 480 inches. Values of under 100 are normally used on bifuel systems, and there is a great disadvantage in having to use very large combustion chambers with corresponding increase in weight, heat loss, air drag of projectile, and cost of manufacture. Consequently the solution does not lie in an increase of combustion chamber size, but rather in its decrease combined with some other approach.

Until it becomes possible to increase considerably the rates of burning of monofuels by the use of dopes and catalysts, without making them unduly sensitive - and it is by no means sure that this can be achieved - the only solution lies in some form of fine atomisation.

6.4 Spray injectors - limits to fine atomisation with usual type

As explained previously, a series of different type sprays have been tried with increasingly good atomising characteristics and improved spray distribution. These all depended on breaking up the fuel by energy obtained from the pressure drop across the nozzle, though at first impinging jets were used and later swirl sprays.

Mean mass drop diameter, for a flow of 1 lb./sec. and a pressure drop of about 150 lb./sq. in. was reduced as progress was made along this series from about 600μ to 180μ or 200μ. Although drop size decreases slowly with decreasing nozzle diameter, it is considered that much further improvement cannot be obtained by using an increased number of smaller nozzles. The mechanical limit in this field has been more or less reached. Furthermore, although drop size decreases with increasing pressure drop, this decrease becomes progressively less and less (see curve in appendix) at high pressure drops, again giving a practical limit. It is considered, therefore, that a mean drop diameter of approximately 180μ can be obtained, but it cannot be greatly improved, using the principle of break up by pressure drop through a nozzle, for the applications envisaged.

6.5 Pre-combustion Principle for very fine atomisation

It was found in experiment that only about 85% of the theoretical Specific Impulse was being obtained, even using the best sprays of the above type available, and including the large combustion chambers mentioned. A number of types of spray were therefore designed on a different principle. This consisted mainly of devices similar to a flit spray, Fig.10, whereby most of the fuel was injected into a high velocity stream of gas, produced either by combustion of a small percentage of the fuel sprayed in the orthodox way or from an igniter burning throughout the whole run. By this means it was hoped to produce a new order of fineness in atomisation, since the drop radius is in theory inversely proportional to the square of the velocity of the breaking up gas stream, and far greater energy is available for atomising from the heat energy of the fuel itself. A long conical burner forming a constriction in a long combustion chamber has been the main basis for this design, but this still suffers from other detailed practical troubles and so far results have been inconclusive.

It seems, however, that only by the use in some way of some new principle such as this will atomisation, and hence performance of a new high order, be obtained.

6.6 <u>Contraflow spraying</u>

Another question which at one period assumed importance was that of drop penetration. Consider for instance, a motor in which the gas has a mean velocity down the chamber to say 30 ft./sec., and into which a spray of fuel is injected with a forward velocity of 150 ft./sec. If this spray penetrates the gas and retains to a large extent its velocity, it would leave the chamber in approximately one fifth of the time, were it at once to take up a velocity of 30 ft./sec. This would allow far less time for combustion, and nullify the effect of lowering the gas velocity by the use of high pressure and large c.c. volumes.

Obviously something between the two extremes of, either continuing with unchanged velocity or slowing at once to the gas velocity, must hold. On the basis of calculation it is now thought that the latter is a near approximation (see appendix).

Some tests were carried out with sprays mounted on a ring around the body of the combustion chamber and pointing backwards at the igniter which screwed into the end - Fig.11. This resulted in the sprays having to enter the gas and then reverse their direction before they could reach the venturi. Only one of these tests was successful, giving results almost identical with those normally obtained with the usual spray burner and thus adding weight to the above approximate theory.

6.7 <u>Drop break-up after spraying</u>

Further thought, based on the same principle as the pre-combustion device for atomising, suggested that the drops may break up still more after spraying due to their own velocity relative to the gas into which they are sprayed. This may have accounted for the smallness of the improvement in performance when changing from bad sprays (600μ), to good sprays (200μ), but cannot be a very large effect due to the low value of this relative velocity, and the impossibility of increasing it. (It is proportional to the square root of the pressure drop across the nozzle). The effect should increase with increasing gas density, and decrease with decreasing drop diameter, thus it may break up all drops above a certain size while leaving those below this size unaffected.

6.8 <u>Surface tension effects</u>

All drop break-up problems are essentially surface tension problems. In practice, however, no improvement has been obtained by lowering surface tension artifically (a difficult procedure), and no great difference has been found when fuels of very different surface tension have been sprayed. This part of the subject is not yet clear.

6.9 Other methods of injection and combustion

Some consideration was given to two other methods, whereby the fuel could be burnt completely and efficiently in a reasonable volume at a reasonable pressure, but neither has been attempted.

In the first of these, the fuel was to be saturated with a soluble gas at 400-500 lb./sq.in. pressure, and held in this condition in the fuel tank. This combination would then be forced into the combustion chamber in the usual way through spray nozzles, and on the reduction in pressure, the gas would tend to come out of solution. It seems probable, that this would break up still further the drops of fuel, and assist rapid combustion. A gas, whose critical pressure at atmospheric temperature is about 400-500 lb./sq.in. would probably be most suitable.

The second method was that involving preheating the fuel, either a small amount to assist combustion, or enough to provide vapourisation on drop in pressure across the injector. The heat could be provided by combustion of the fuel itself, as it passes through some form of preheating coil inside the chamber. The heat transferred to the fuel in a cooling jacket would be insufficient. The design of the coil would have to provide for the transfer of a large quantity of heat, and ensure that at no point did the fuel reach a temperature above its ignition point; this being of the order of 200-300°C, depending on the length of time that the fuel would be subjected to it. It was thought, however, that the requirements here were far too critical, and the idea was dropped for the time being.

7. Stability of methods of fuel injection

Several possible methods of injecting the fuel into the combustion chamber have been suggested. A rough idea of the stability of operation to be expected from them is given in this section.

Basic facts

(a) Rate of fuel flow through burner $Q \propto$ (pressure drop across it)$^{\frac{1}{2}}$

(b) Rate of discharge of gas through venturi $Q_e \propto$ (combustion pressure)

7.1 Constant fuel injection rate

Such as from a constant speed driven piston moving down a cylinder containing fuel.

$$Q = \text{constant}$$

$$Q_e \propto P_c$$

As the combustion chamber pressure Pc rises, the outflow of gas rises and stable conditions are arrived at. This system is stable over an infinite range of combustion pressures, providing the motor driving the piston has adequate power, which is several Horse Power for 1 lb./sec. at 300 lb./sq.in. This system is however, less stable than system 7.3.

7.2 <u>Fuel tank pressurised through a differential piston device from the combustion pressure</u>

In this case the feed pressure P rises proportionately with the combustion pressure Pc.

$$Q \propto (P - Pc)^{\frac{1}{2}}$$

$$Q_e \propto Pc$$

This is a stable system over an infinite range, but less stable than (7.1), since an increase in Pc increases the inflow of fuel as well as the outflow of gas, though to a lesser extent.

7.3 <u>Fuel pressurised by a constant gas Pressure P</u>

$$Q \propto (P - Pc)^{\frac{1}{2}}$$

$$Q_e \propto Pc^{\frac{1}{2}}$$

As the combustion pressure increases, the gas outflow increases and the fuel inflow decreases, finally very rapidly. Barring oscillations therefore, the system is very stable until Pc = P when fuel is forced back along the pipe and burning along it may take place.

This system would be expected to give the most even running.

7.4 <u>Contrifugal pump feed</u>

Any feed producing a constant head is in principle the same as 7.3.

APPENDIX

8. Calculations of gas and drop velocity and drop volume at cross sections of a combustion chamber - Factors affecting combustion.

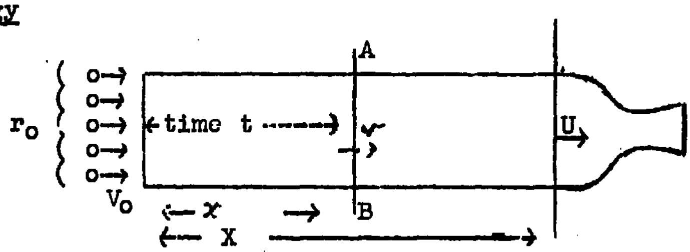
8.1 General

Consideration is given here to the effects produced by varying the conditions of burning, theories being produced which to some extent explain these effects. These theories are intended only as a preliminary guide and their application is approximate.

It is assumed that fuel is sprayed into the combustion chamber in the form of small spherical drops of the order of 200μ in diameter, ('μ' being one thousanth of a millimetre), and that these burn on the surface so that each drop decreases in size at a constant radial rate. For the purpose of calculation it is assumed that these drops are all of one size and enter the cylindrical chamber uniformly over one plane and with a certain initial velocity.

Two extreme alternative cases are then considered, between which the actual case must lie. In one, we assume that the initial velocity of the drop remains constant, and in the other that it is at once reduced to the local velocity of the surrounding gas. For both cases, the gas and drop velocities and drop volume at any point down the chamber are worked out, and also the effect of the chamber size, the initial drop size and gas pressure on the completeness of burning.

8.2 Terminology



Distance travelled by drop	x ft.
" " to all-burnt	X ft.
Time taken to position AB (see sketch)	t secs.
" " " all-burnt	T secs.
Linear rate of burning	b ft./sec. ($\propto p^m$)
Initial drop radius	r_o ft.
Drop radius at time t	$r_o - bt$ ft.
Velocity of drop at position AB	V ft./sec.
Velocity of gas at position AB	u ft./sec.
Uniform velocity of gas after all-burnt	U ft./sec.
Rate of flow of fuel	Q cu.ft./sec.
Combustion chamber pressure	P lb./sq.ft.
Volume of gas made per cu.ft. of fuel at the temperature and pressure of combustion	K/P (K is a constant)
Area of cross section	A sq.ft.

Completeness of burning specified by:

$$\frac{\text{linear rate of burning x time of burning}}{\text{initial drop radius}} = bt/r_o = t/T$$

Number of drops produced per sec. $3Q/4\pi r_o^3$

Surface area of all drops of radius $(r_o - bt)$ passing a cross section at time t $= (3Q/4\pi r_o^3)4\pi(r_o-bt)^2$

$$= (3Q/bT)(1-t/T)^2$$

8.3 Drop velocity = gas velocity - Both initially zero

Consider the element AB

The total area of surface of all drops to the left side of AB at any time

$$= \int_0^t \frac{3Q}{bT}(1-t/T)^2 dt = F(t) \text{ say}$$

∴ The rate of fuel comsumption by volume to the left side of AB

$$= b\,F(t) \text{ cuft/sec.}$$

∴ The rate of production of gas by volume to the left side of AB

$$= Kb(F(t))/P \text{ cuft/sec.}$$

∴ The velocity of flow of gas across AB, u, = dx/dt

$$= KbF(t)/AP$$

i.e. $u = dx/dt = (KQ/AP)\left[3t/T - 3t^2/T^2 + t^3/T^3\right].$ (1)

Putting $t = T$ we get $U = KQ/AP$,

so that $u/U = 3t/T - 3t^2/T^2 + t^3/T^3.$ (2)

Integrating (1) and remembering that

$x = 0$ when $t = 0$

we get

$$x = \int_0^x \frac{dx}{dt}\,dt = (KQT/AP)\left[3t^2/2T^2 - t^3/T^3 + t^4/4T^4\right] \quad (3)$$

Putting $t = T$ we get $X = 3KQT/4AP$ (3a)

So that equation (3) becomes

$$x/X = (4/3)\left[3t^2/2T^2 - t^3/T^3 + t^4/4T^4\right] \quad (4)$$

and from (3a) $T = 4PAX/3KQ$, which is four thirds the time taken to pass through the chamber by each particle of gas on the assumption that the fuel burns instantaneously at $t = 0$.

From the above equations can be obtained the velocity of the gas and distance travelled in terms of the time taken. The volume of a drop, assumed travelling with the gas, is $4\pi(r_0-bt)^3/3$, which is also dependent on t/T. These can all be plotted on a base of distance travelled using the above equations.

8.31 Burning condition relations

These relations can now be obtained by transposing equation (3)

$$xA \propto \left[3t^2/2T^2 - t^3/T^3 + t^4/4T^4\right].KQr_0/P.P^m.$$

It is seen, that the volume (xA) of the combustion chamber, necessary for burning fuel to a specified completeness given by t/T is

(1) Proportional to the initial drop radius

(2) Proportional to the rate of fuel injection

(3) Inversely proportional to the (m+1)th power of the combustion chamber pressure.

From the shape of the graph of drop volume, it is evident that we can use a chamber far too small and still get reasonable results. See Fig. 12 or the following table:-

t/T	u/U	x/X	Fraction of initial drop volume $(1 - t/T)^3$
0	0	0	
.1	.271	.019	.729
.2	.488	.077	.512
.3	.657	.147	.343
.4	.784	.242	.216
.5	.875	.355	.125
.6	.936	.475	.064
.7	.973	.603	.027
.8	.992	.733	.008
.9	.999	.867	.001
1.0	1.0	1.00	0

8.4 <u>Drop velocity constant = V_c</u>

As before, the velocity is given by

$$u/U = 3t/T - 3t^2/T^2 + t^3/T^3$$

Here dx/dt is constant and again x = o when t = o

$$\text{so } \frac{x}{X} = t/T \qquad (5)$$

and $u/U = 3x/X - 3x^2/X^2 + x^3/X^3$ gives the gas velocity. (6)

The drop volume is $4\pi r_0^3\left[1 - t/T\right]^3 = 4\pi r_0^3\left[1 - x/X\right]^3$. (7)

These can also be plotted on a base of distance travelled.

<u>Burning condition relations</u>

These now come from equation (5), which becomes $x = Xt/T = r_0 V_c t/bT$

$$\propto r_0 V_c t/P^m T$$

So in this case, for burning to a completeness specified by t/T, the length of combustion chamber necessary is :-
(1) Proportional to the initial drop radius
(2) Proportional to the (constant) drop velocity
(3) Inversely proportional to the m^{th} power of the combustion chamber pressure.

As before, a chamber too small will give reasonable results, but the effect is less marked. See Fig.13.

9. Calculation of the retardation of small drops of decreasing size injected into a static gas.

9.1 General

Some idea of the amount by which the velocity of the drops sprayed into a combustion chamber is reduced by the resistance of the gas to their motion, can be obtained as follows.

Consider a drop of initial radius r_0 (decreasing at a uniform rate b units/sec.), and sprayed into a static gas with initial velocity V_0.

Reynolds Number can be calculated for the initial case, and hence the constant K in the resistance formula $W = \frac{1}{2}K\rho v^2 \pi r^2$ found from the table (Appdx.p5). This enables us to find the initial retardation.

To calculate the drop velocity at subsequent stages, a step by step method must be used, as the coefficient K does not remain sufficiently constant over the range of Reynolds Numbers which occur. It is probably sufficient to divide the combustion time into ten stages, and assume ten values for K (also found step by step), each of which is constant over its own stage.

Given the initial velocity (v_0) and the initial acceleration (f_0), and assuming as constant a mean value of (K_{01}) for the first 1/10 of the total time taken by the drop to burn (T), an integration can be carried out to find the velocity (v_1) and acceleration (f_1) at the end of this stage.

The process is then repeated for the next stage, remembering that the new 'initial' drop radius r_1 is now equal to $.9r_0$, and proceeding step by step through each stage.

Validity. The results given by this process should give some idea of the order of magnitude of the retardation of the drops sprayed into a rocket motor combustion chamber, but it would be futile to expect any great accuracy for the following reasons.

(1) The drop sizes vary and are not accurately known.

(2) Large drops may break up.

(3) Gas flow down the chamber is not uniform.

(4) The gas is not static, but has a velocity which increases from zero to a value comparable with the drop injection velocity along the chamber.

(5) In accelerating the spray, the gas in the chamber must be accelerated towards the venturi, altering its velocity distribution; so that the velocity at any point is slightly higher than it would otherwise have been.

(6) The drops will not be spherical.

(7) The force on a drop depends not only on the velocity but also on the relative acceleration.

In spite of the above, it is instructive to make the calculations for an ideal case in which the relative velocity is 150 ft./sec. (equal to the injection velocity which corresponds to a pressure drop of 150 lb./sq.in. across a spray nozzle with axial injection).

9.2 Resistance formula

The following table is built up from a graph, given by Barr in a monograph of viscometry, and attributed initially to Liebster and Schmiedel. Its approximate accuracy appears to be agreed on, though others give slightly different curves. An R.K. graph can be plotted, to avoid the necessity of interpolating for values of K, required in calculation.

Log K	Log $\frac{vd\rho}{\eta}$	R	K
+ 1.40	0	1	25.1
+ 1.25	.2	1.58	17.8
+ 1.1	.4	2.51	12.6
+ .95	.6	3.98	8.9
+ .87	.8	6.3	5.89
+ .6	1.0	10.0	3.98
+ .5	1.2	15.8	3.16
+ .40	1.4	25.1	2.5
+ .25	1.6	39.8	1.78
+ .15	1.8	63	1.41
.00	2.0	100	1.02
- .02	2.2	158	.95
- .1	2.4	251	.79
- .2	2.6	398	.63
- .25	2.8	630	.56
- .30	3	1000	.50

9.3 Additional terminology

Reynold's number	=	R	
drop radius	=	r	1/1000 ths. of a mm.
drop retardation	=	f	ft./sec./sec.
density of drop	=	σ	gm/cc.
density of gas	=	ρ	gm/cc.
viscosity of gas	=	η	c.g.s. units
velocity	=	V	ft./sec.
linear rate of burning	=	b	$\frac{1}{1000}$ths. of mm./sec.

9.4 Calculation of Reynold's Number R = $2vr\rho/\eta$ in uniform c.g.s. units.

Using the above units $R = (2.54 \times 12V)(2r/10^4)\rho/\eta$

i.e. $R = 6 \times 10^{-3}\ \rho rv/\eta$

9.5 Calculation of retardation

Resistance to motion of drop $= \frac{1}{2}K\rho v^2 \pi r^2$

From the laws of motion, this equals $(\frac{4}{3}\pi r^3 \sigma)f$
giving $f = \frac{3}{8}K\rho v^2/r\sigma$

Using the above units $f = \frac{1}{(12 \times 2.54)}\ \frac{3}{8}\ \frac{k\rho}{\sigma}\left(\frac{12 \times 2.54v}{r/10^4}\right)^2$

$= 114{,}000\ K\rho v^2/r\sigma$ ft./sec./sec.

9.6 Calculation of drop velocity at subsequent stages

Using the above retardation formula $f = \frac{3}{8} K\rho v^2/r\sigma$

and assuming that the drop radius decreases at a constant radial rate b 1/1000 mm. per sec., then for the first stage.-

Retardation at time t, $f = f_o(v/v_o)^2(r_o/r)$

$$= f_o r_o v^2/v_o^2(r_o - bt)$$

where f_o is calculated using the mean value K for the first stage K_{01}, which is assumed constant for the stage.

Writing $f = \dot{V}$ and transposing we have

$$-\dot{v}/v^2 = f_o r_o/b v_o^2(r_o/b - t)$$

Integrating with respect to t between zero and T/10, we have (the corresponding limits for v being v_o and v_1)

$$1/v_o - 1/v_1 = - f_o r_o/b v_o^2 \log\left(\frac{r_o/b}{r_o/b - T/10}\right)$$

from which $v_1 = \dfrac{v_o}{1 + (f_o r_o/b v_o) \log\left(\dfrac{r_o}{r_o - bT/10}\right)}$

Thus, knowing the radius, velocity and retardation at the start of the first stage and assuming the resistance co-efficient is constant over this stage, we can calculate the velocity at the end of the stage. The equation above, applies to the subsequent stages by change of suffixes, and can in each case be simplified by putting,

$$r_1 = .9r_o \quad r_2 = .8r_o \quad \text{etc.}$$

Thus $V_1 = \dfrac{V_o}{1 + (f_o T/v_o) \log(1/0.9)}$

$V_2 = \dfrac{V_1}{1 + (.9f_1 T/v_2) \log(.9/.8)}$

In each case the new 'initial' retardation can be worked out from the formulae.-

$$f_1 = f_o(v_1/v_o)^2(r_o/r_1)K_{12}/K_{01}$$

$$f_2 = f_1(v_2/v_1)^2(r_1/r_2)K_{23}/K_{12} \quad \text{etc.}$$

in which K_{01} is the mean value for the first stage and therefore applies to f_o and K_{12} applies to f_1, and similarly for the following stages.

Reynold's Number must also be calculated at each stage, to enable an estimate of these K values to be worked out from the table given.

9.7 Calculation of approximate viscosity η of gas at 300 lb./sq. in. and 2400°K.

Assume $\eta \propto T^n$
Take n = .8 (see 'High Press Plant' by Newitt)
Assume η independent of pressure
Take η at 25°C = 1.7×10^{-4} c.g.s. units.
Then η at 2400°C = $1.7 \times 10^{-4} \times (2400/300)^{.8} = 9 \times 10^{-4}$ c.g.s. units.

9.8 Example. Approximate stage by stage calculation of drop velocity

Assume.

Initial drop radius r_0 = 100 μ.
Initial drop velocity = 150 ft./sec. (corresponding to pressure drop of 152 lb./sq.in.).
Density of drop σ = 1.1 c.g.s. units.
Viscosity of gas η = 9×10^{-4} c.g.s. units.
Density of gas ρ = $\frac{1}{700}$ gm/c.c. (corresponding to a press of 300 lb./sq.in.).
Linear rate of burning of fuel b = 0.5 in./sec.
= 13000μ/sec.
Hence time for complete combustion T = 100/13,000 = .0077 secs.
(compare value estimated from size of combustion chamber actually required for complete combustion of .0095 secs.).

a Then Reynolds Number $R = 6 \times 10^{-3} \frac{1}{700} rv \frac{1}{9 \times 10^{-4}}$

$= 9.55 \times 10^{-3} rv$

and initially $R_0 = 9.55 \times 10^{-3} \times 100 \times 150 = 144$

So that the initial value of K, K_0 is about .96, which is near enough for K_{01}.

Hence the initial retardation

$$f_0 = 114{,}000 \; \frac{.96(1/700)(150)^2}{100 \qquad 1.1}$$

$= 32{,}000$ ft./sec./sec.

Example:-

Table showing method of approximate stage by stage calculation -

$T = .0077$ example $f_1 = f_0 \left\{\frac{v_1}{v_0}\right\}^2 \left\{\frac{r_0}{r_1}\right\} \frac{(K_{12})}{(K_{01})}$

$R = 9.55 \times 10^{-3} rv$

Note: the ratio in last bracket of above equation is given in the following table as K ratio.

	v ft./sec.	r in μ	R	K	K ratio	$f/10^3$	log. (etc.)	$\frac{fT}{V}$	$\frac{ft}{V}$ log (etc.)	$\frac{1}{1+ETc}$
0	150	100	144	.96 .96	1	32.	.105	1.64	.172	.853
1	128	90	110	1.01 1.07	1.11	28.7	.118	1.73	.204	.830
2	106	80	81	1.20 1.30	1.22	27.0	.134	1.96	.262	.792
3	84	70	56	1.50 1.70	1.31	25.5	.155	2.34	.362	.735
4	62	60	35.4	1.95 2.3	1.35	22	.183	2.73	.50	.667
5	41.5	50	19.7	2.85 3.4	1.48	17.5	.224	3.26	.73	.578
6	24	40	9.2	4.2 6.0	1.75	12.8	.288	4.1	1.18	.46
7	11	30	3.15 2.0	10.5 15.0	2.5	9.0	.405	6.3	2.55	.28
8	3+	20	.8	-	-	-	.694	-	-	-
9	-	10	-	-	-	-	∞	-	-	-
10	-	0	-	-	-	-	-	-	-	-

See Fig. 14 of drop velocity against fraction of time t/T to all-burnt.

10. Break up of drops sprayed into a gas

It has been suggested, that the distortion and consequent break up of a liquid drop projected into a gas, depends on the ratio of the kinetic pressure of the gas ($= \frac{1}{2}\rho . v^2$) on the drop at its forward stagnation point, and the pressure inside the drop due to its surface tension ($= 2T/r$).

As the ratio approaches unity, the drop will distort and may break up as the ratio approaches 2 or 3, though how rapidly is not known.

The following applies to Myrol 80/20

Surface tension at 20°C	T =	25 dynes/cm.
Radius	r =	100μ
Velocity	V =	150 ft./sec.
Gas pressure		300 lb./sq.in.
" temperature		2,400°K.
" density		1/700 gm/cc.

$\frac{1}{2}\rho . v^2$ = 14,900 dynes/Sq.cm.
$\frac{2T}{r}$ = 5,000 " "
} Ratio = 3 approx.

This suggests that drops with a radius of over 100μ will probably break up at this spray injection velocity, and that smaller drops will not.

11. Estimate of time each particle of gas spends in combustion chamber and of maximum permissible drop size, assuming rate of burning known.

First calculate the mass of gas in the combustion chamber any instant

Assuming	Gas pressure	300 lb./sq.inch.
	Gas temperature	2,400°K
	Gas constant	8.32×10^7 ergs/gm.
	mean molecular weight	14 (assumed). This value is lower than that at N.T.P. due to dissociation.

Then gas density is 1/700 gm/cc.

Assuming	Combustion chamber	length	=	7 in.
"	"	"	diameter	=	5 in.
Then	"	"	volume	=	138 cu.in.
				=	2,250 c.c.

Then mass of gas in chamber at any instant $= \frac{2250}{700} = \underline{3.2 \text{ gm}}$.

It is then obvious, that if 1 lb. (454 gm) of gas passes through the chamber every second, each particle of gas must on the average remain in the chamber for 3.2/454 = .0071 second, if we assume instantaneous combustion of the fuel. Assuming that drop velocity = gas velocity (see 8.3) the time is $\frac{4}{3} \times .0071 = .0095$ secs.

If we assume that each drop spends the same length of time in the chamber, and that the radial rate of burning of the drops is 1/2 in./sec. (13,000μ/sec.), then the max. permissible drop radius is 13,000 x .0071 = 92μ or 13,000 x .0095 = 120μ.

Alternatively, this can be considered as a check on the assumed rate of burning, since in fact, drops with a radius of 100μ, do more or less, completely burn in this size of chamber, and with this through-put of fuel (Specific impulses of over 85% of the theoretical are obtained).

12. Analysis of test results

A specimen test result sheet is appended, with the data filled in for two specimen runs. This indicates the quantities measured and calculated for every run. Notes are appended on two of these quantities.

12.1 Nozzle factor

This is equal to $\dfrac{\text{actual thrust}}{\text{combustion pressure x venturi throat area}}$

and should have a value in the neighbourhood of 1.2 to 1.5, depending on the fuel used. For each fuel, there is a theoretical nozzle factor almost independent of combustion pressure, and the actual value obtained, which is lower than the theoretical value, gives a measure of the quality of the run. When combustion is bad, the value of the factor falls.

12.2 The quantity L^*

This is equal to $\dfrac{\text{combustion chamber volume}}{\text{venturi throat area}}$

and has the dimension of a length, and gives a measure of the volume of combustion space available per pound of fuel. Comparison of two or more combustion chambers by means of the quantity L^*, is only strictly legitimate if they are used at the same pressure.

12.3 MONOFUEL TEST RESULT

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
			NOZZLES												
DATE	FUEL TYPE AND WEIGHT	L* INS	No.	CAPY. GAL/MIN.	SPRAY ANGLE	IGNITER	IGNITER DELAY	N2 PRESS lb./sq.in.	THRUST lb.	C.C. PRESS lb./sq. in.	BURNING TIME SECS.	FLOW RATE lb./sec.	S.I. lb sec./lb.	NOZZLE FACTOR	TEST NO.
	N.G. 70% N.B. 30% 1 litre	240	Impinging jet 8 holes x No. 56 drill			5 sec. cigarette burning		500	160	220	3.54	.920	174		32
	Myrol 75/25 2 litres	480	7	48	-	Ditto		600	103	291	8.5	0.56	184		71

13. Performance of Various Spray Nozzles

The nozzles were functioned spraying vertically downwards. The liquid employed was dyed water, and the pressure applied was 150 lb./sq.in. in each case. No rates of consumption were determined.

Snap samples of the sprays were caught on sheets of white absorbent paper, which were placed inside a mechanically operated shutter device, situated about 6 feet below the actual nozzle. Employing a predetermined calibration curve, the size of the stain produced by the droplets gave the drop size. The percentage distribution of the drops in their various size ranges were plotted on two-cycle logarithmic probability paper, and from this, the median mass diameter for each spray nozzle was obtained. (The median mass diameter is the drop size, above and below which 50% of the mass of spray is distributed).

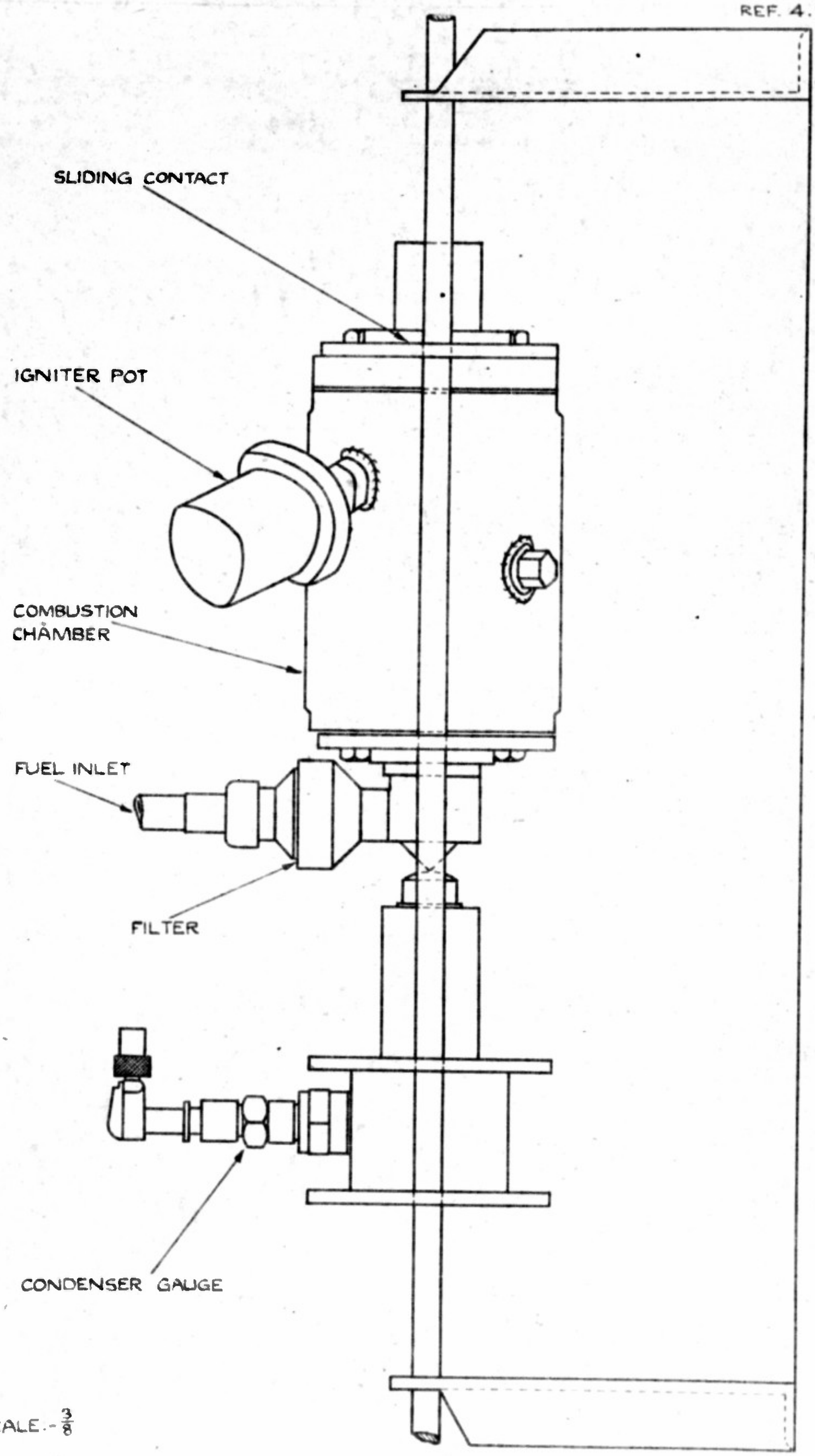
Results

Type of Spray	Performance		
	Median mass diameter $\frac{1}{1000}$ mm	Smallest drop diameter $\frac{1}{1000}$ mm	Largest drop diameter $\frac{1}{1000}$ mm
1. Monarch swirl spray .06 lb./sec.	150	40	240
2. " " " .067 "	170	40	280
3. Wallsend swirl spray. similar (F.22).	180	40	280
4. Monarch swirl spray 1 lb./sec.	300	40	510
5. Impinging jet spray No.60 drill.	320	40	560
6. " " " No.53 "	600	80	1000

It is evident, that the F.22 gives a similar performance to the Monarch sprays 1 and 2, but the remaining three sprays are much coarser. These tests were carried out by Dr. Bannerman, H.P.S. Porton, in April, 1945.

FIG. 1.

REF. 4.2

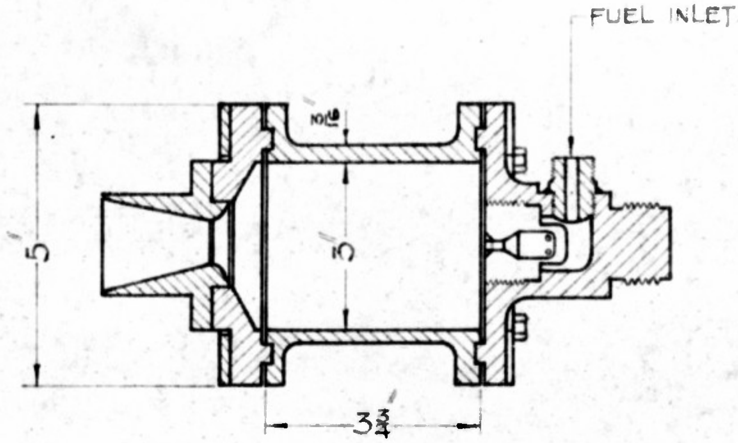


SCALE.- $\frac{3}{8}$

EXPERIMENTAL MONOFUEL MOTOR WITH THRUST HEAD MOUNTED ON RAILS

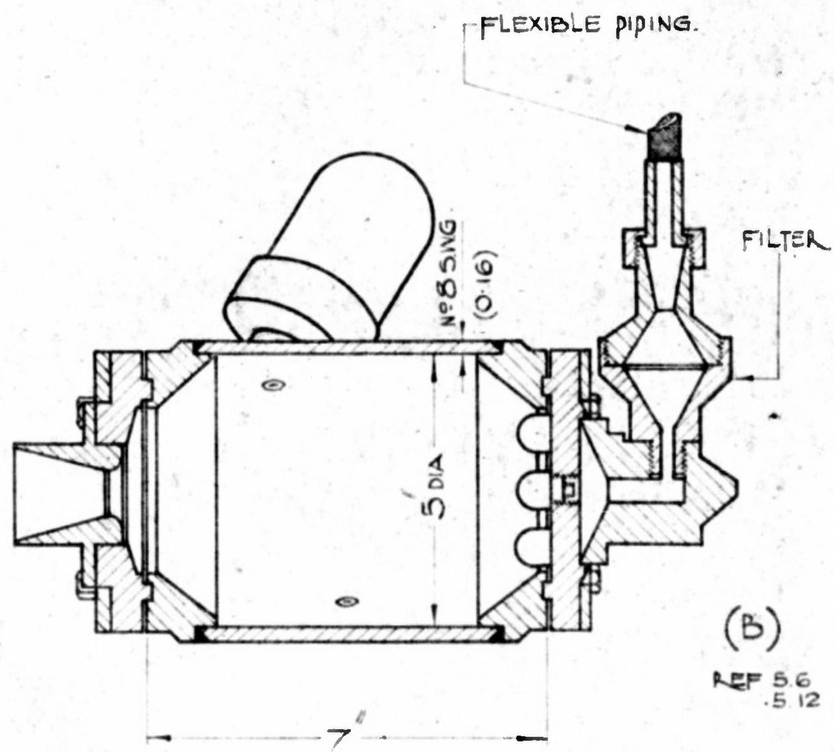
A.D.D 4/46

FIG. 2.



(A)
REF 4.2

EARLY TYPE COMBUSTION CHAMBER (TURNED FROM SOLID.)



(B)
REF 5.6
.5.12

LATER (USED) TYPE COMBUSTION CHAMBER — FABRICATED.

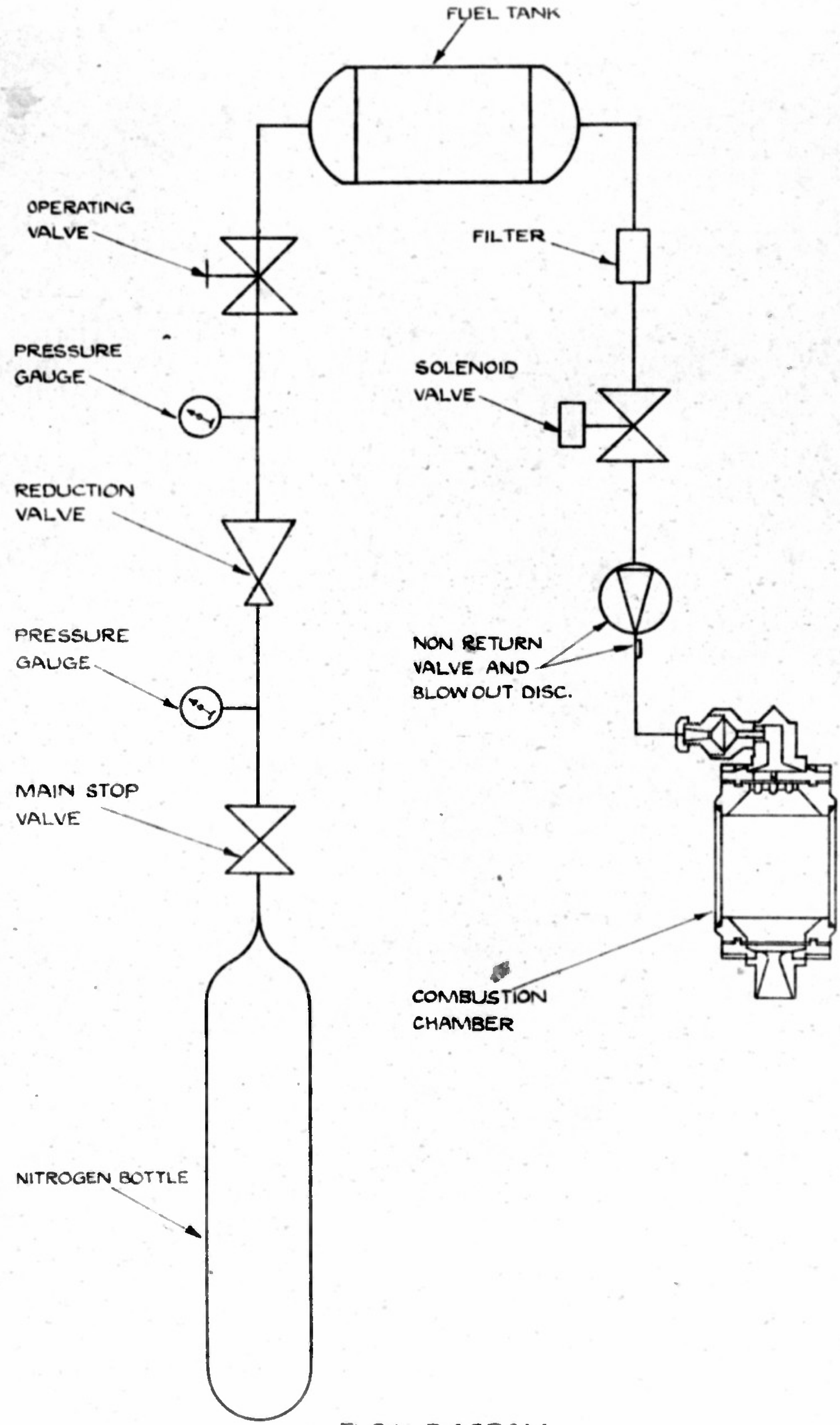
SECTIONED COMBUSTION CHAMBERS.

ADD 4/46.

SCALE: 3/8 FULL SIZE.

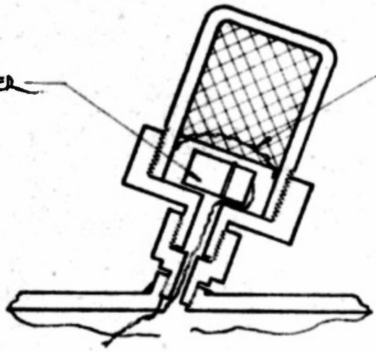
FIG. 3.

REF 4.2
5.8



FLOW DIAGRAM

A D D 4/46



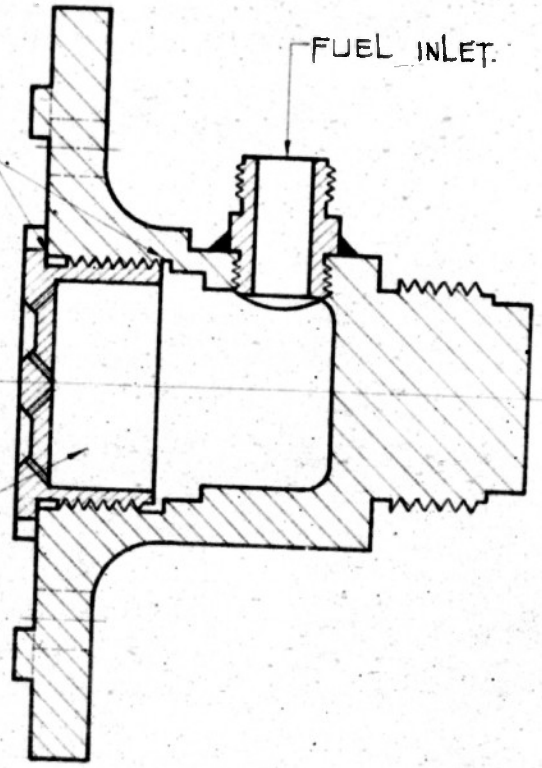
CIGARETTE BURNING PLASTIC PROPELLANT FILLED IGNITER.

A.D.D. 4/46

SCALE: 3/8 FULLSIZE

FIG.5.

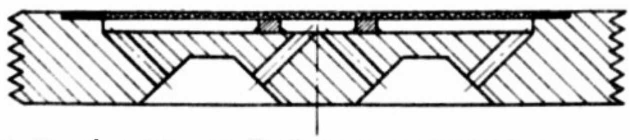
REF 5.6
5.11(a)



IMPINGING JET SPRAY INJECTOR – FIRST TYPE.

A.D.D. 4/46

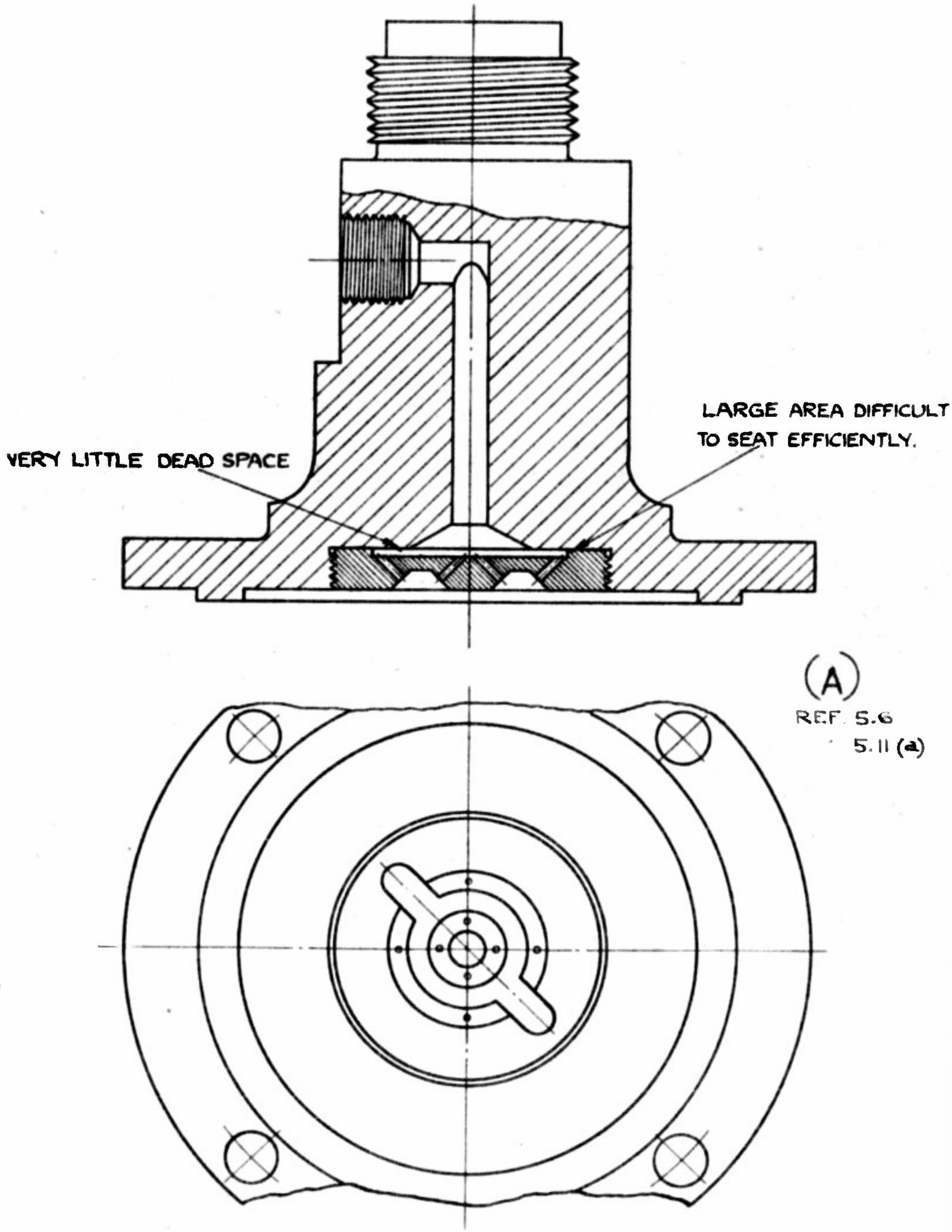
SCALE: FULL SIZE.



WITH GAUZE FILTER AND SUPPORT RING

(B)
REF. 5.6

SCALE:-
[redacted]CE - FULL SIZE



(A)
REF. 5.6
5.11 (a)

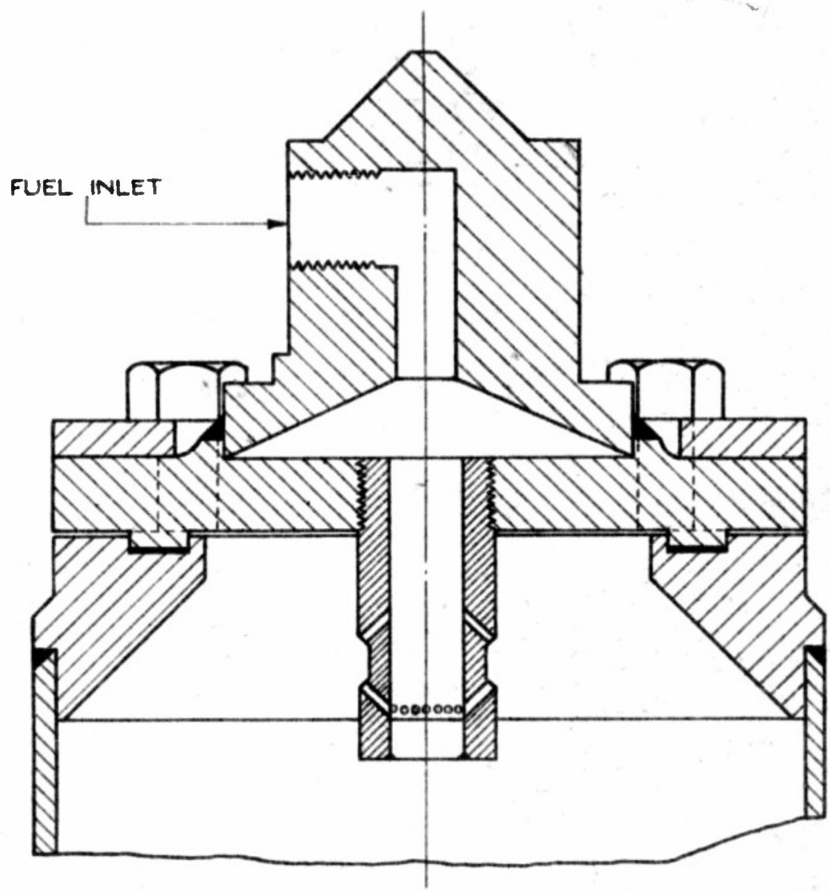
IMPINGING JET SPRAY INJECTOR - SECOND TYPE

SCALE:- FULL SIZE

ADD 4/46

FIG. 7.

REF. 5.6.
5.11 (a)



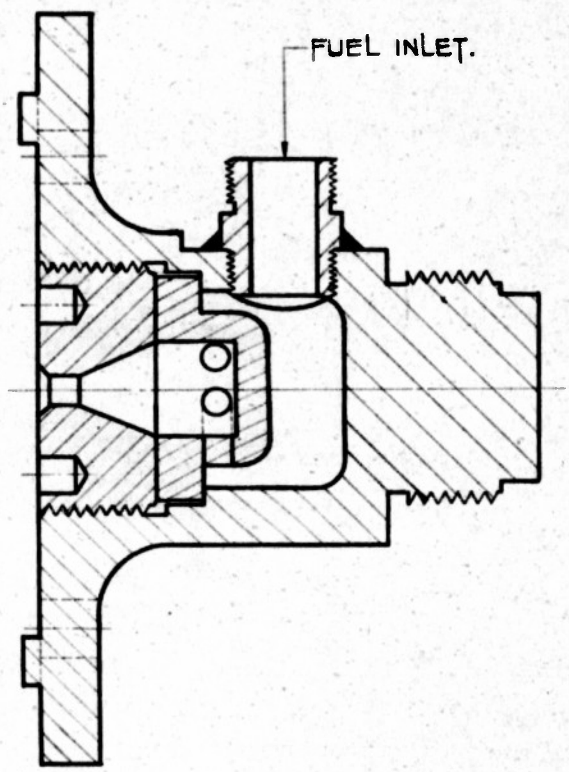
IMPINGING JET SPRAY INJECTOR – THIRD TYPE

SCALE :- FULL SIZE

A.D.D 4/46

FIG. 8.

REF 5.11(b)



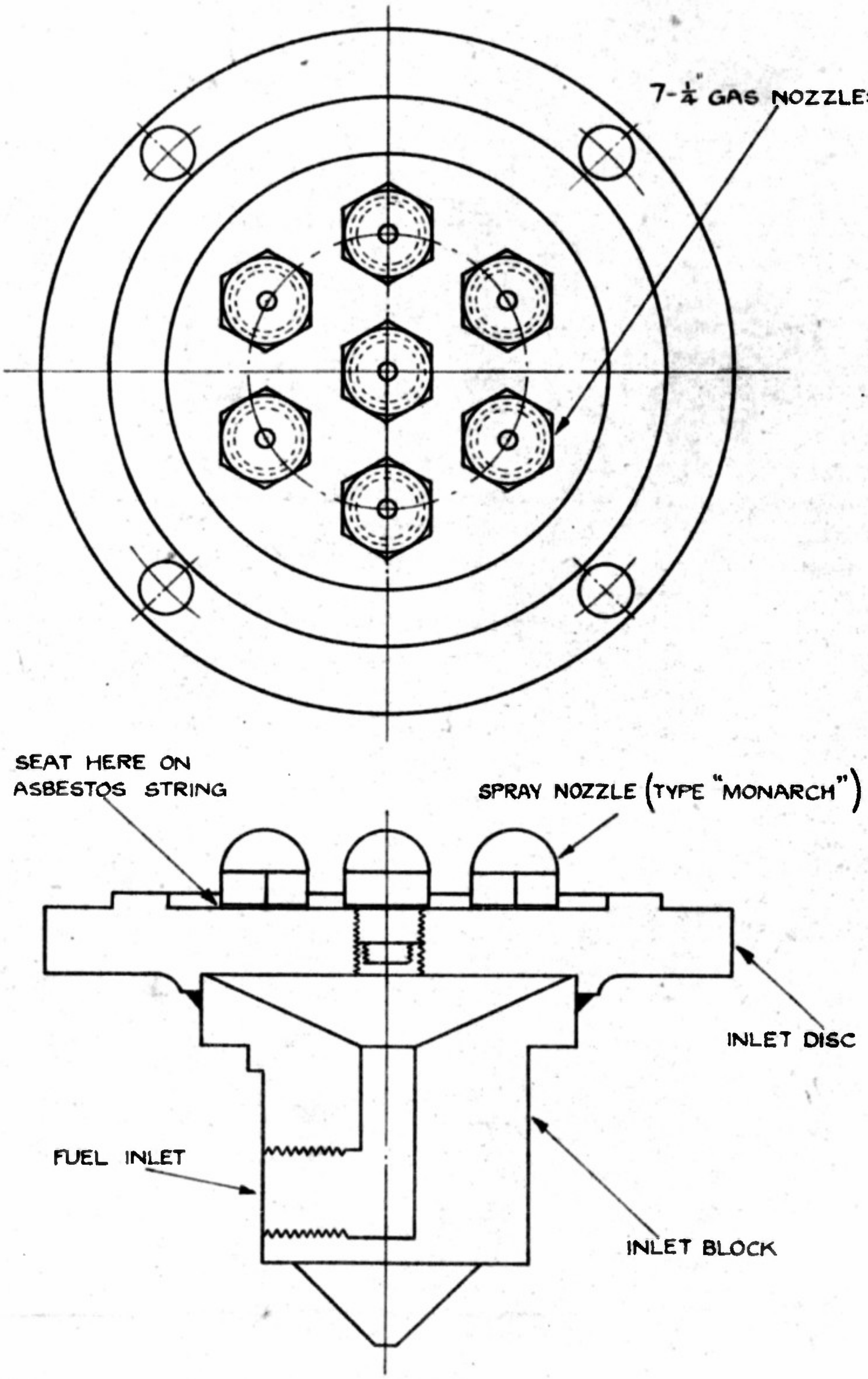
SINGLE SWIRL SPRAY INJECTOR – C.E.A.D. DESIGN.

A.D.D. 4/46.

SCALE: FULLSIZE

FIG. 9.

REF. 5.11 (b)



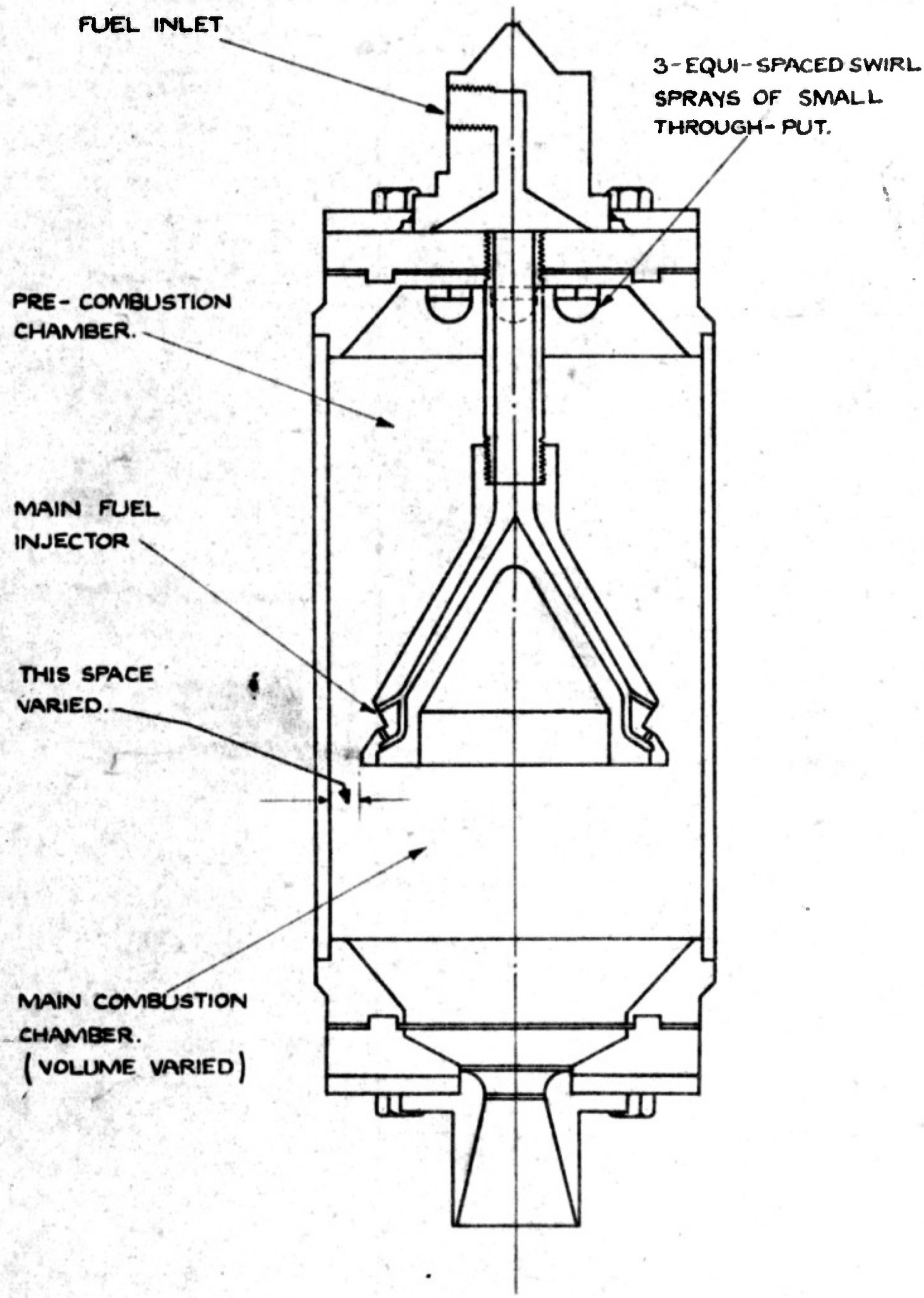
MULTIPLE SWIRL SPRAY INJECTOR

SCALE :- FULL SIZE

A.D.D. 4/46

FIG. 10.

REF 6.5



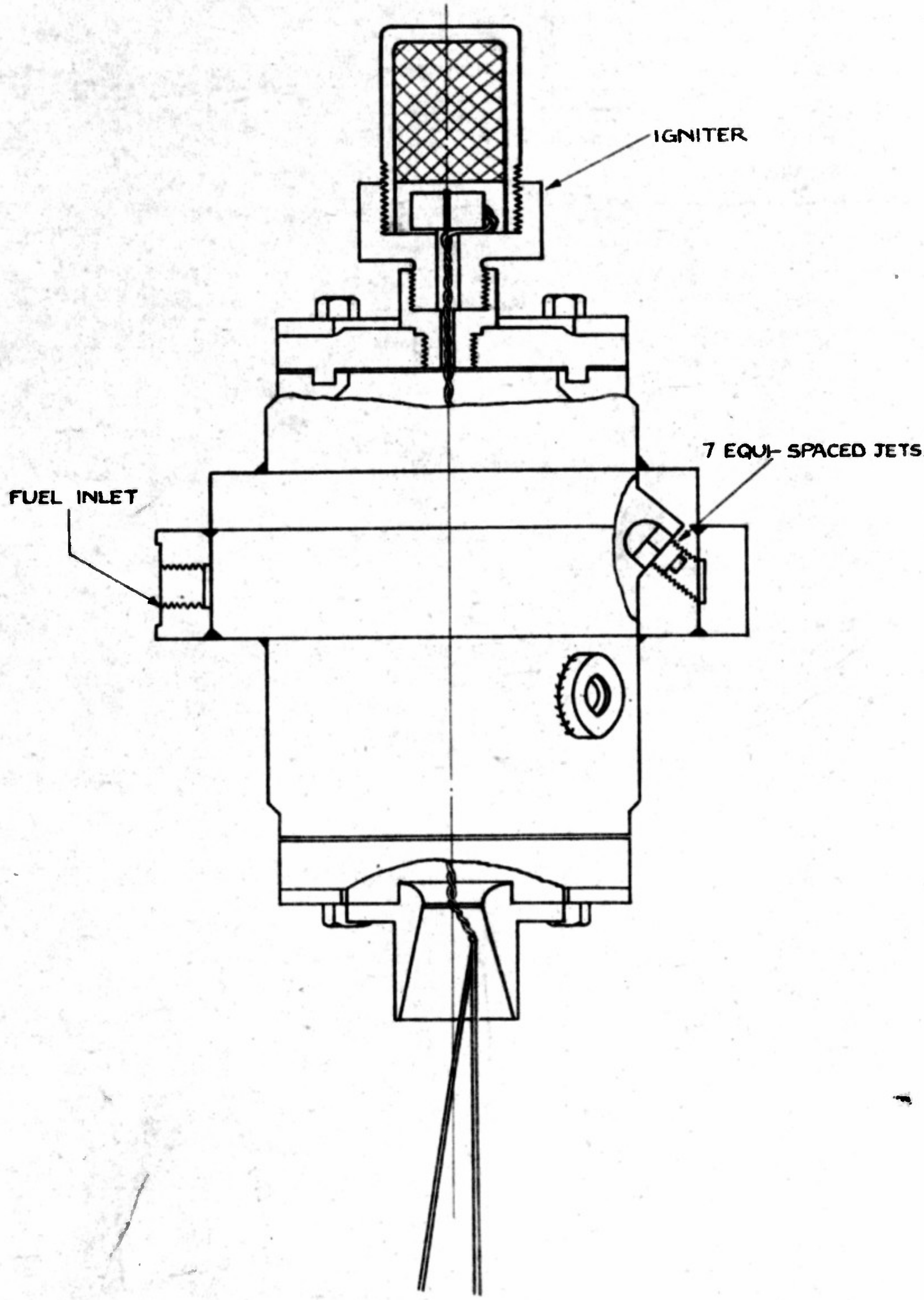
MOTOR USING "PRE-COMBUSTION" METHOD OF FUEL INJECTION

SCALE:- HALF FULL SIZE

A.D.D. 4/46

FIG. 11.

REF. 6·6.



CONTRAFLOW INJECTOR AND COMBUSTION CHAMBER

SCALE:- HALF FULL SIZE

A.D.D. 4/46

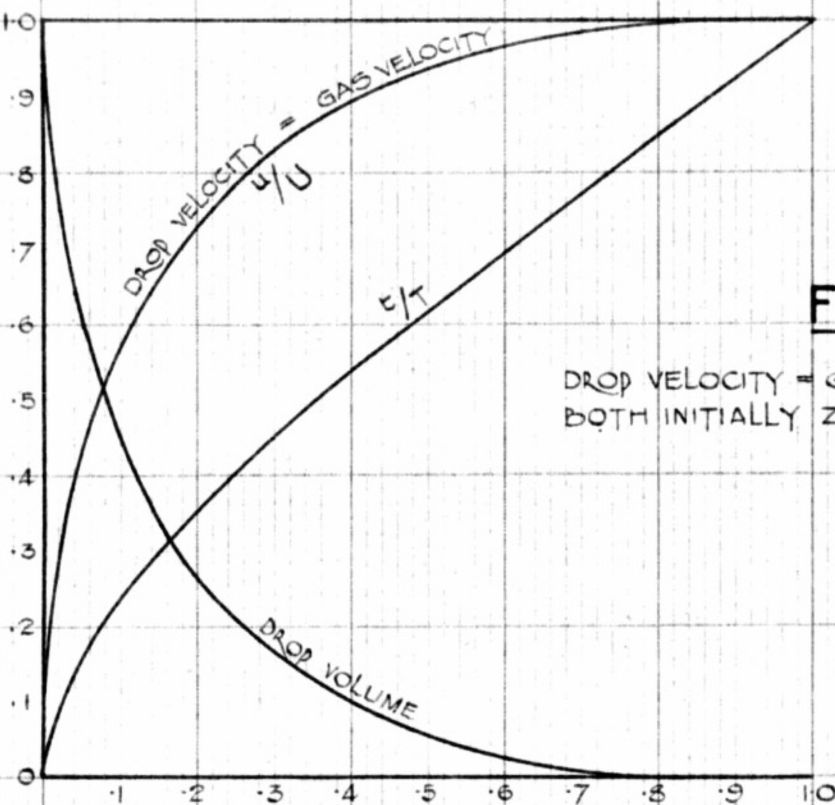


FIG.12.

DROP VELOCITY = GAS VELOCITY BOTH INITIALLY ZERO.

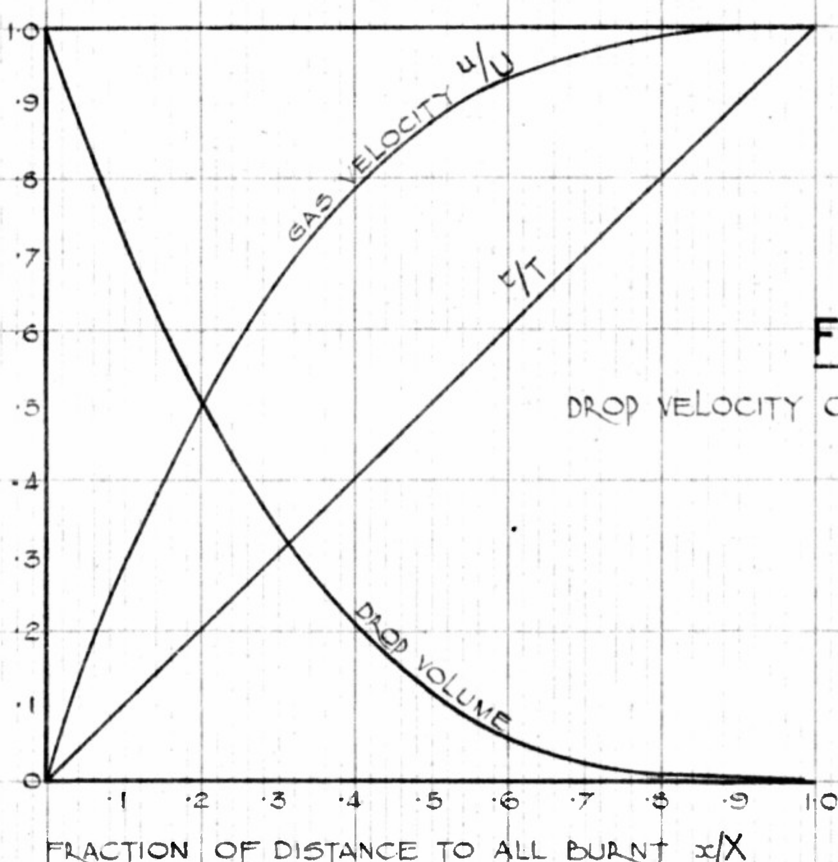


FIG.13.

DROP VELOCITY CONSTANT.

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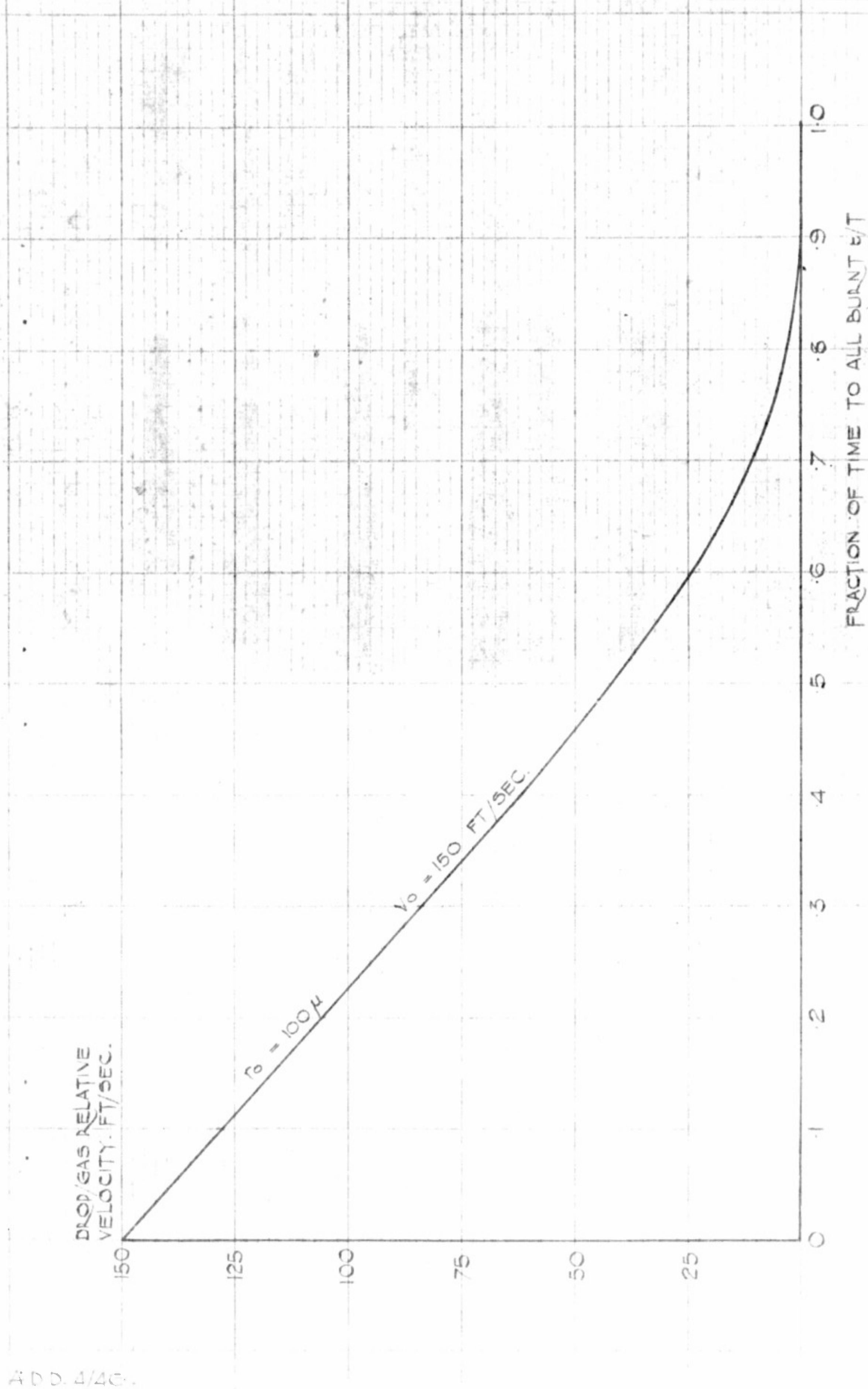
FIG. 14.



A.D.D. 4/40.

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FRAME

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AUTHOR(S): Hutcheon, I. C.
ORIGINATING AGENCY: (Not known)
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ABSTRACT:

The technical report is based chiefly on the work done by the Armament Sign Department. It describes the experimental methods used and results obtained in the investigation of the properties of monergols for the purpose of finding one suitable for rocket propulsion and for developing a rocket motor suitable for propelling the guided missile being considered. Various motors were tested statically at rates of propellant flow up to 1 lb/sec using chiefly liquid nitroglycerine, desensitised by the addition of 30% nitrobenzene, and Myrol as propellants. Conclusions are drawn on the essentials for safe and efficient design, and theories relating to propellant combustion and motor design are expressed.

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DIVISION: Guided Missiles (1)
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SUBJECT HEADINGS: Monopropellants (64500); Propellants, Liquid - Development (75455.7); Engines, Rocket - Design (34108)

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